8.1 Recent research related to TC rainfall

Tim Marchok
NOAA / GFDL
Princeton, NJ USA

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Tropical Cyclone Landfall Processes

Jeju, Republic of Korea

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8.1 Rainfall research working group

- Dan Cecil (USA)
- Jau-Ming Chen (Taiwan)
- Lianshou Chen (China)
- Xiaopeng Cui (China)
- Richard Dare (Australia)
- Anthony Didlake (USA)
- Russ Elsberry (USA)
- Tom Galarneau (USA)
- Haiyan Jiang (USA)
- Tim Marchok (USA)
- Frank Marks (USA)
- Gabriele Villarini (USA)

Objective: Summarize our understanding of major advances in recent research on TC rainfall, to include TC rainfall & flooding climatology, rainband dynamics, outer mesoscale convective systems, impact of vertical shear on TC rainfall, remote rainfall.

Motivation

- Typhoon Morakot: Deadliest typhoon in Taiwan's history, 789 deaths, >3000 mm total rainfall.
- Rappaport (2014): Freshwater flooding from TC rainfall accounted for 25% of all U.S. TC deaths, 1963-2012.

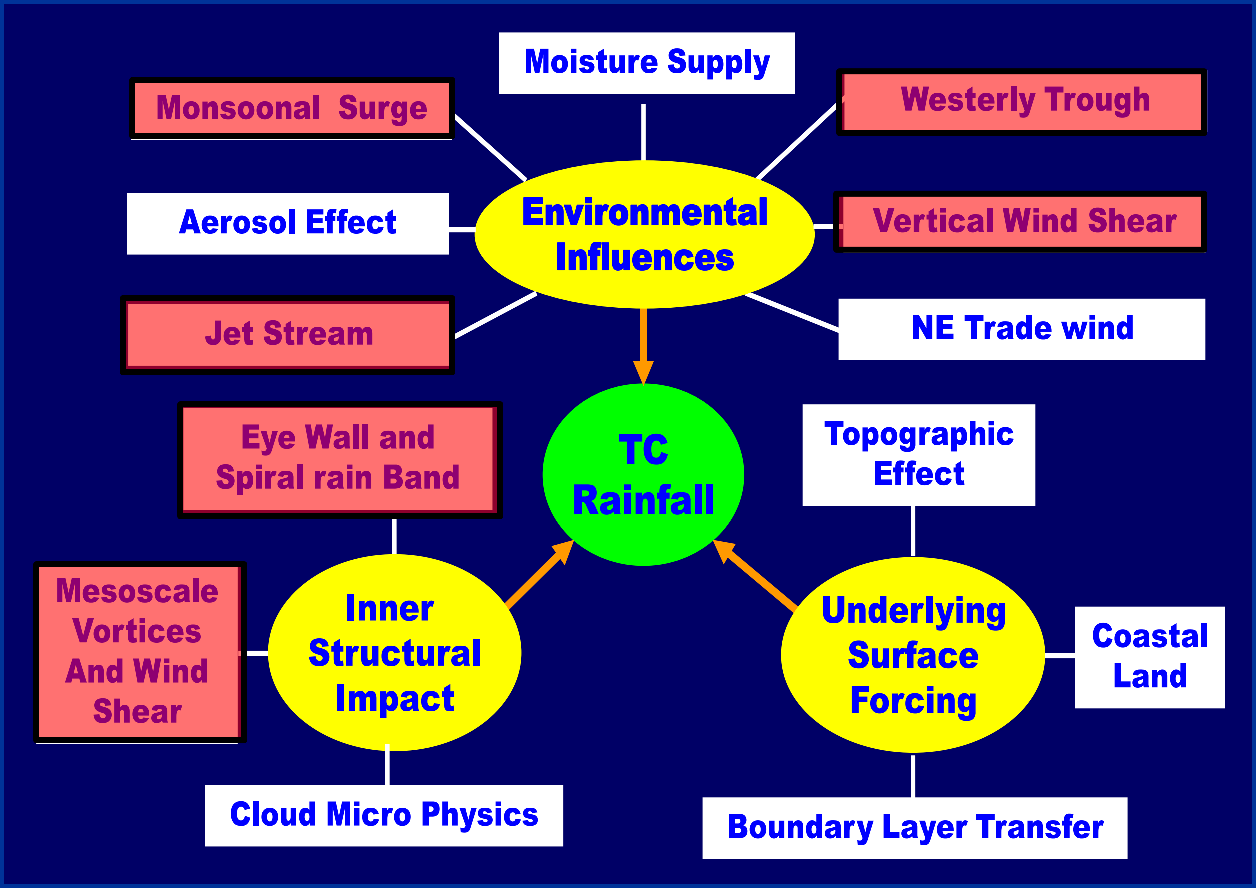
Cyclone Phailin (2013)

Typhoon Morakot (2009)

Elsberry et al (2013)

Hurricane Irene (2011)

TC rainfall processes



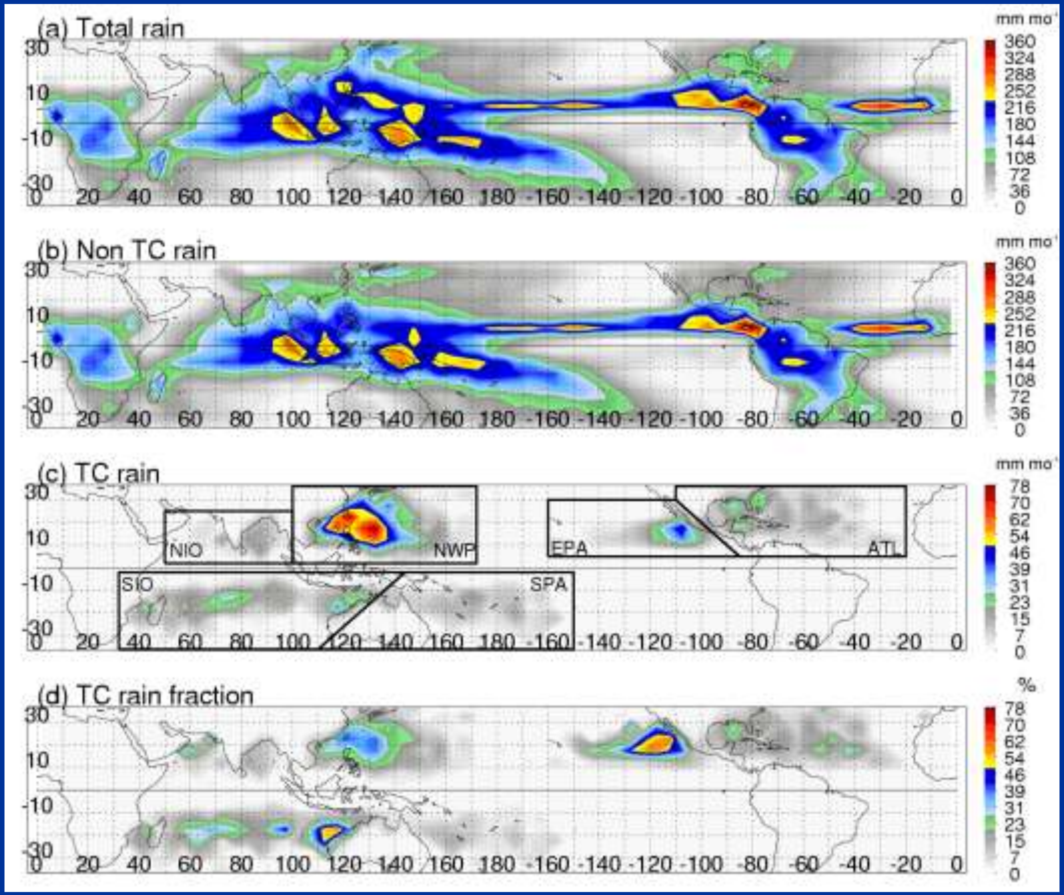
(from Lianshou Chen)

Outline

- TC rainfall & flooding climatology
- TC rainband complexes
- Long-lasting rainbands & outer MCSs
- Impact of vertical wind shear on TC rainfall
- Remote rainfall
- Rainfall reinforcement

TC rainfall climatology: Global view

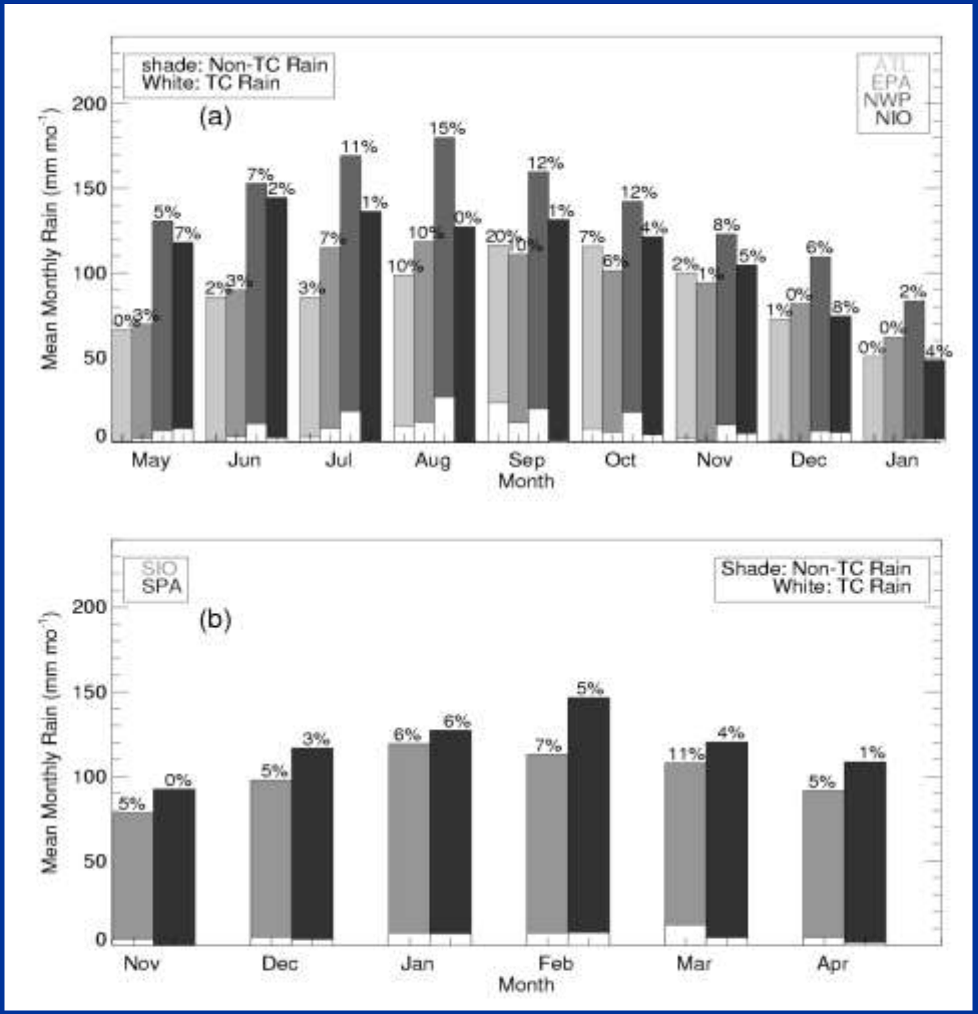
- TRMM data (1998-2006)
- Basin-wide TC rainfall fractions:
  - AL: 8-9%
  - EP: 7%
  - WP: 11%
  - NI: 5%
  - SI: 7-8%
  - SP: 3-4%
- Regional max % TC rainfall fractions:
  - EP: Mexico, near Baja coast: 55%
  - SI: near Australia: 55%
  - WP: near Taiwan: 35-40%



Jiang and Zipser (2010)

TC rainfall climatology: Global view

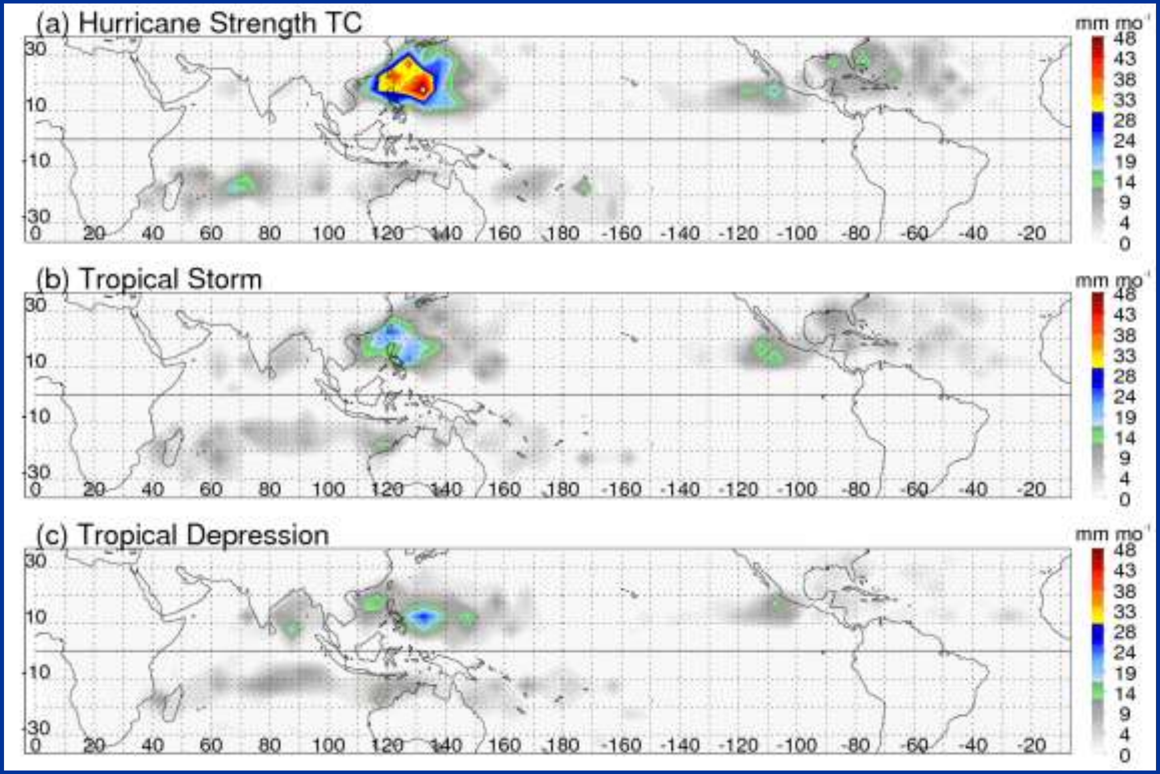
- Peak month(s) for % TC rainfall:
  - AL: Sep (20%)
  - EP: Aug & Sep (10%)
  - WP: Aug (15%)
  - NI: May (7%)
  - SI: Feb (7%)
  - SP: Jan (7%)



Jiang and Zipser (2010)

TC rainfall climatology: Global view

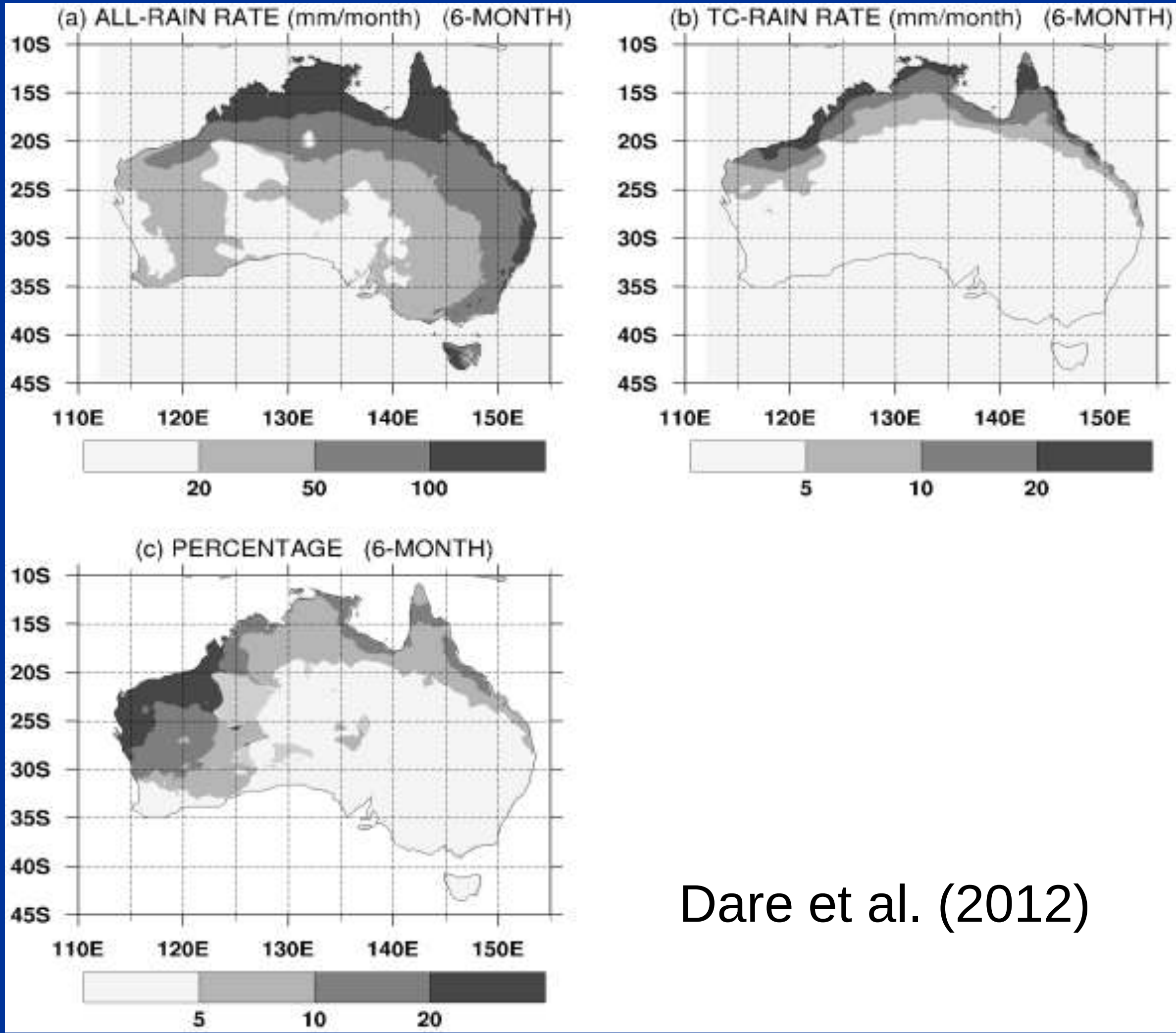
- TCs of hurricane intensity contribute the greatest amounts in AL, EP, WP, SP
- TDs contribute the most in NI
- TSs contribute the most in SI



Jiang and Zipser (2010)

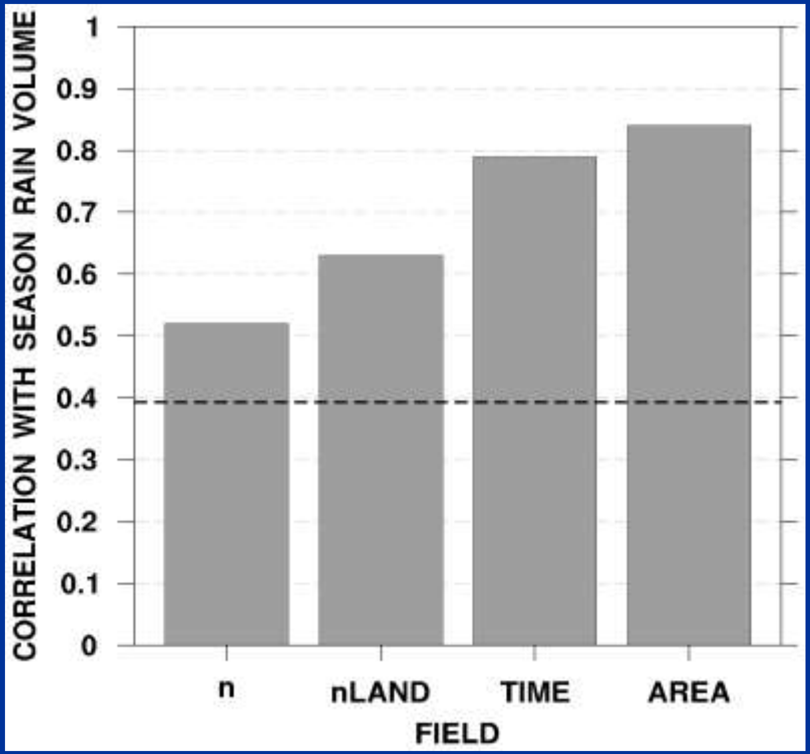
TC rainfall climatology: Australia

- 1969-2011
- For TC rainfall, largest amounts found near northern coastline.
- % TC rainfall maximized near northwest Australia coast (~40%)

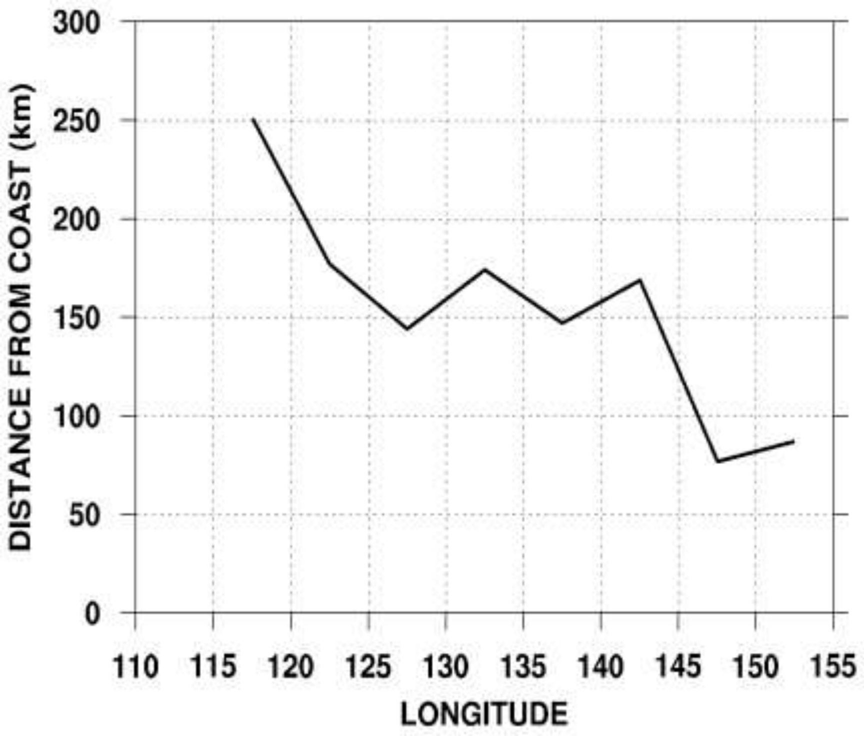


Dare et al. (2012)

TC rainfall climatology: Australia



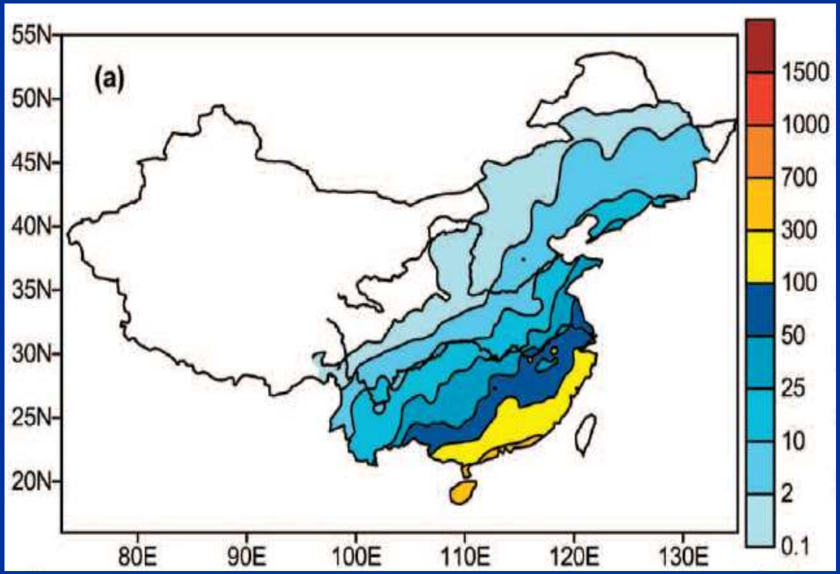
Highest correlation with seasonal rain volume is with TC area covered (Dare 2013)



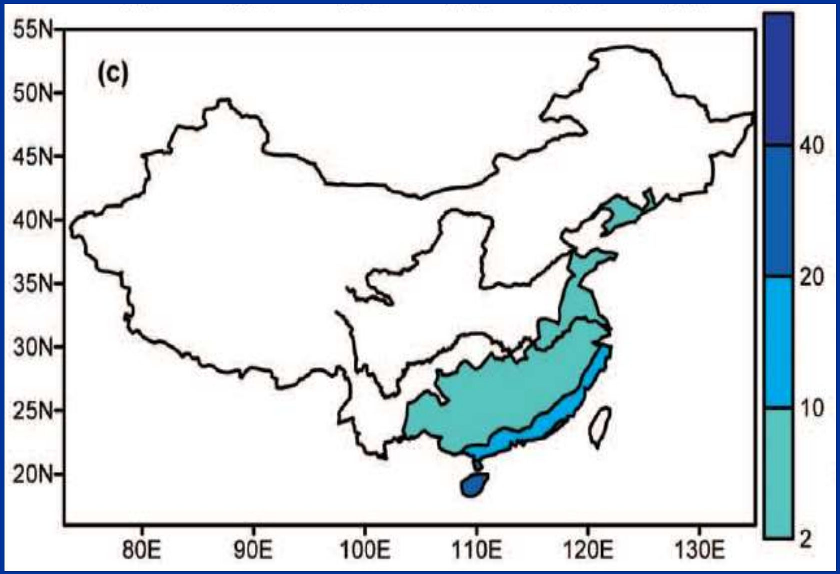
Distance inland from coast where the TC rain amount falls to half the coastal value (Dare et al. 2012).

TC rainfall climatology: China

1965-2009



TC rainfall in mainland China, 1965-2009
(Zhang et al. 2013)

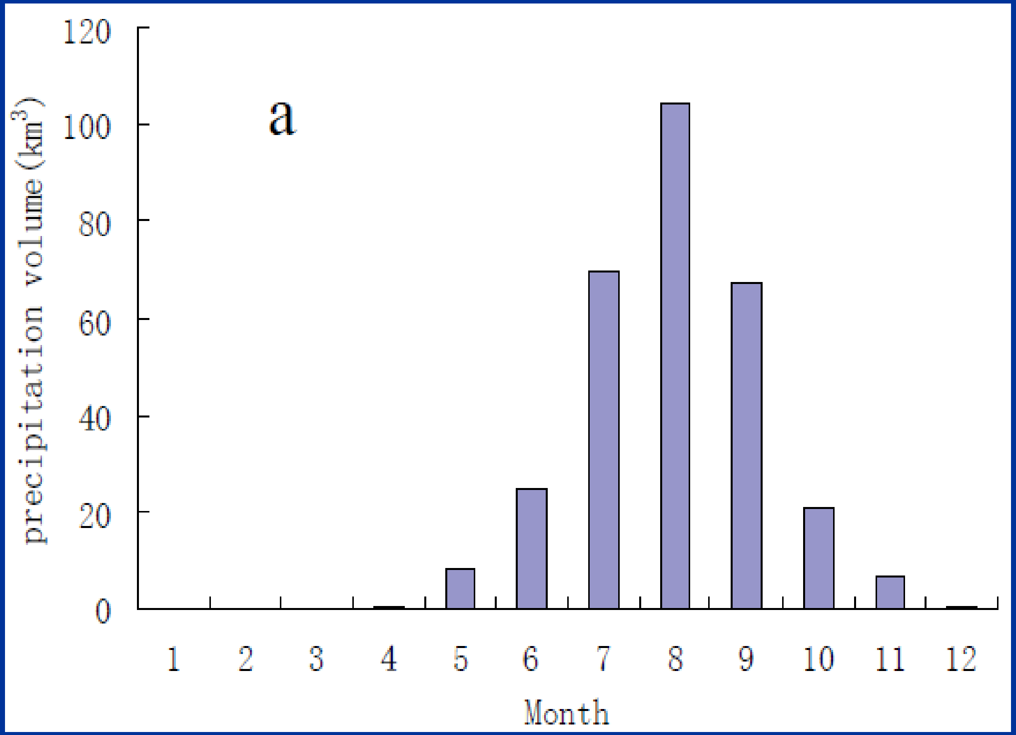


% *annual* rainfall attributable to TCs in mainland China, 1965-2009
(Zhang et al. 2013)

TC rainfall climatology: China

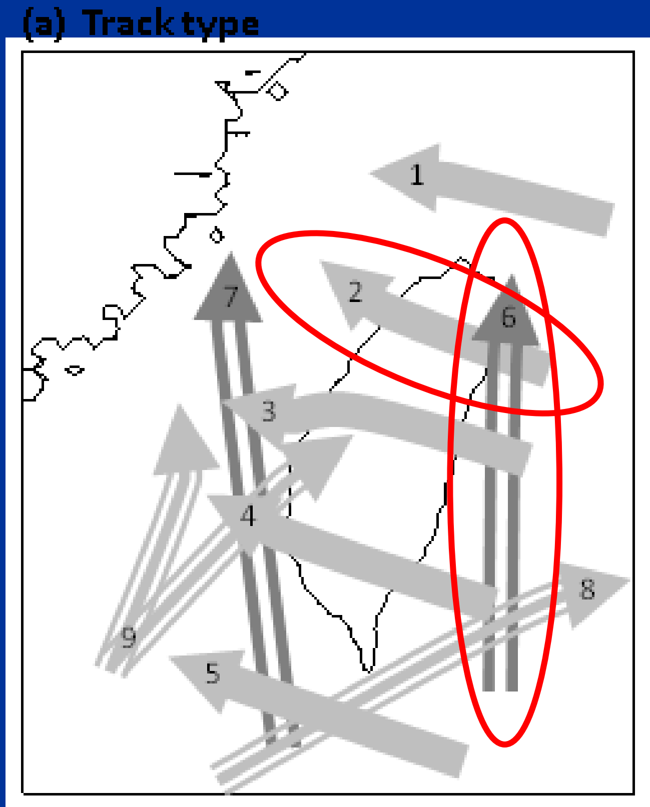
Gradual increase from April, peak in August

TC rainfall volume in China by month (1957-2004)



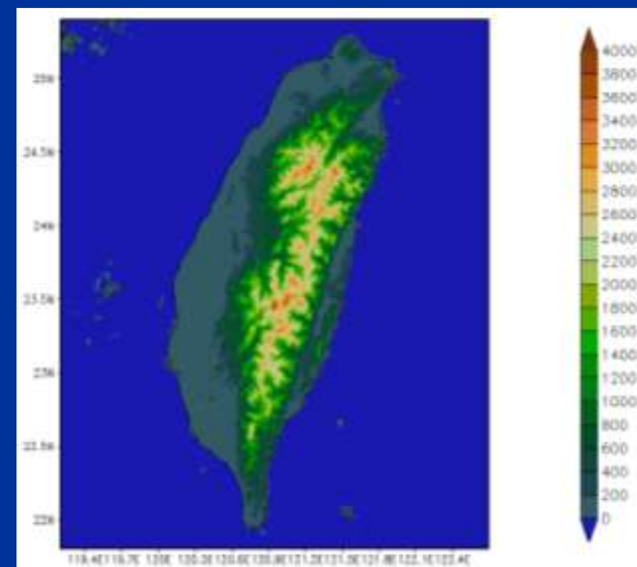
Ren et al. (2011)

TC rainfall climatology: Taiwan



Chen and Shih (2012)

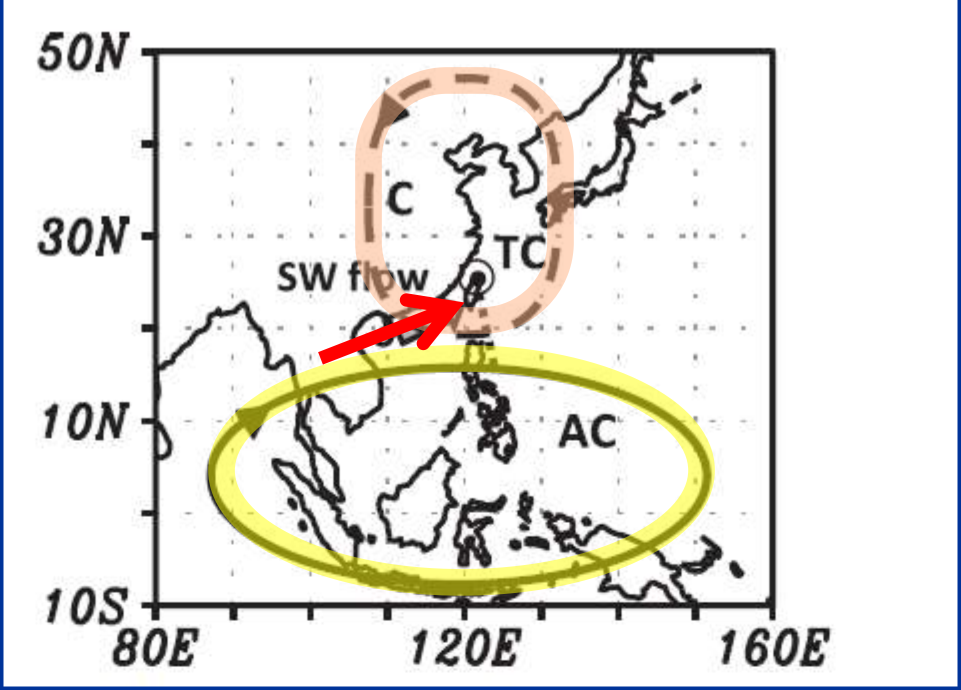
Of 9 typical TC tracks identified by Taiwan's CWB, #2 and #6 are identified in particular as being associated with heavy rainfall events in Taiwan.



Rogers et al (2009)

Topography plays a major role in enhancing TC rainfall in Taiwan

TC rainfall climatology: Taiwan



Chen and Shih (2012)
Chen et al. (2013)

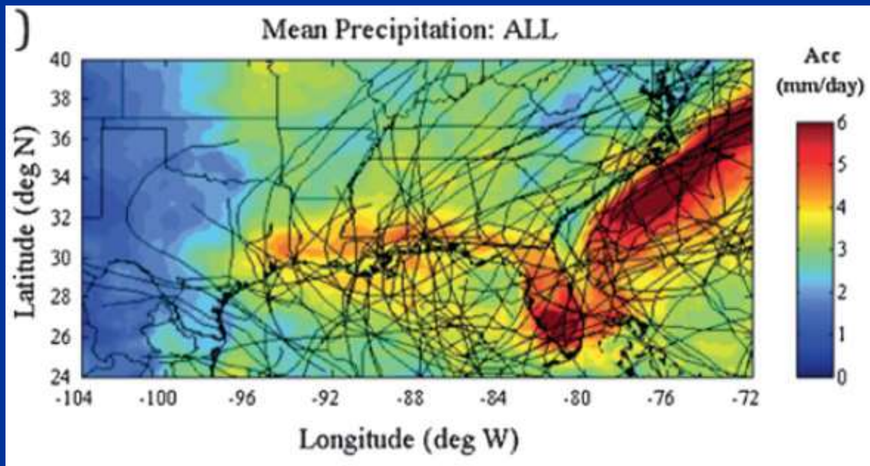
TC interaction with seasonal SW flows helps lead to prolonged heavy rainfall.

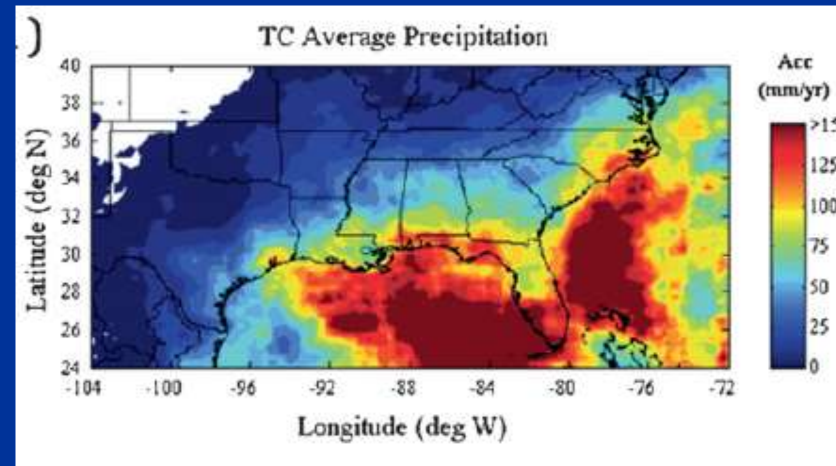
TC-southwesterly flow interactions are modulated by ISOs, both the MJO and the 10-24 day oscillation associated with the Asian summer monsoon.

The interplay between the TC and one or both of these ISOs generate cyclonic (anticyclonic) anomalies to the north (south) of the TC, providing a channel for prolonged SW flow to a TC in the Taiwan region.

TC rainfall climatology: USA

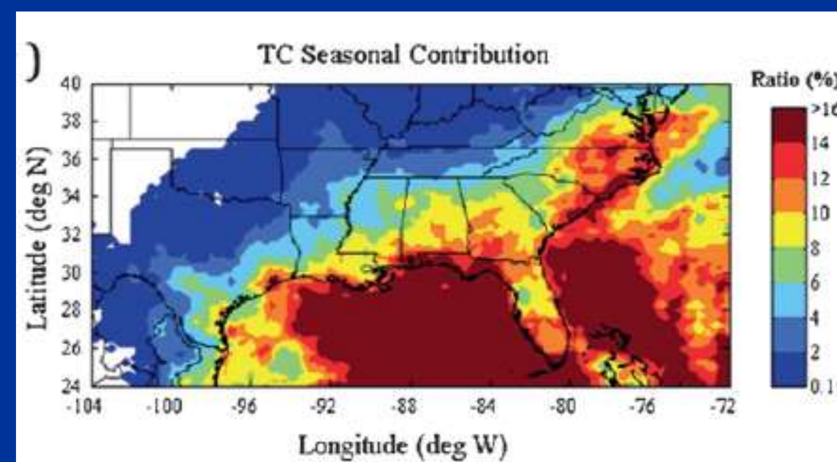
1998-2009





Prat and Nelson (2013)

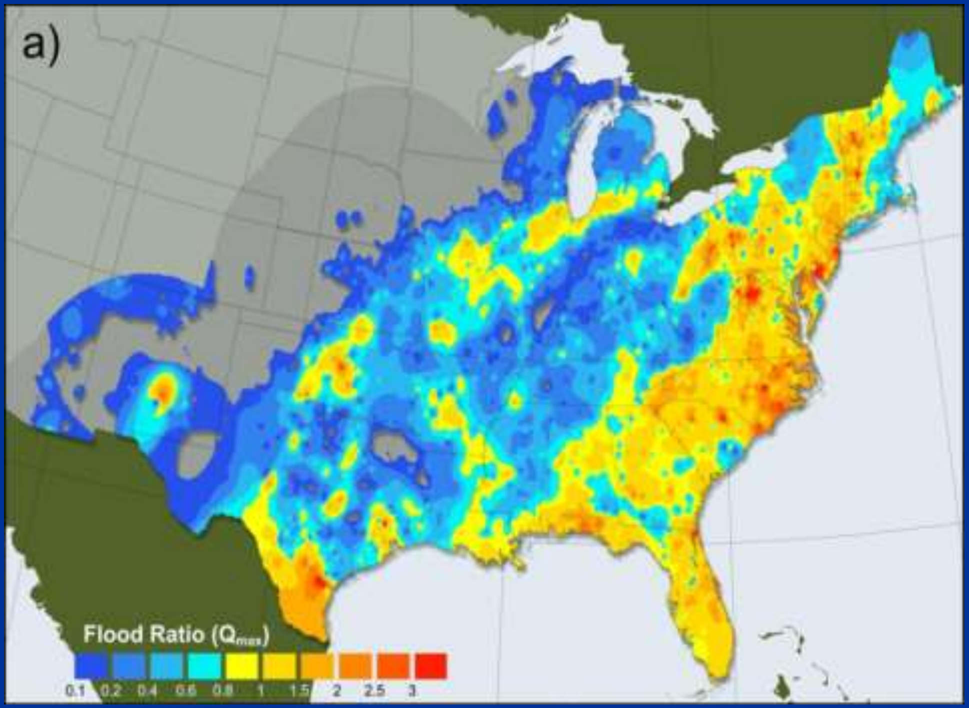
- % contribution highest along Gulf & eastern U.S. coasts
- Domain-wide seasonal TC rainfall contribution (7%) consistent with results of Jiang and Zipser (2010, 8-9%)



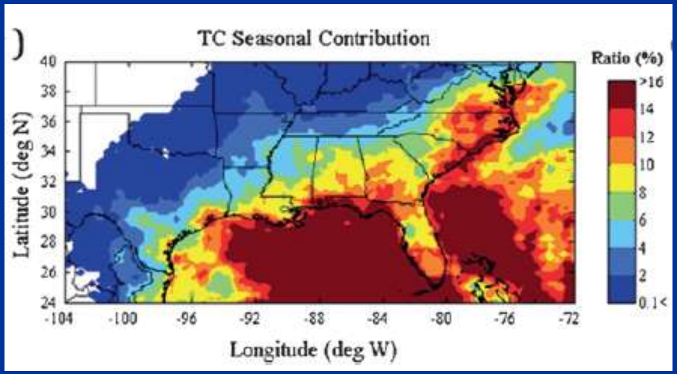
TC flooding climatology: USA

USGS stream gage data from 1981-2011 analyzed to compare TC-related flooding with climatological flooding.

TC flood ratio values > 1 indicate flooding greater than the 10-year flood peak values.



Villarini et al. (2014)



- TC flood ratio values indicate rainfall impacts further inland and more widespread than rainfall accumulations and % contributions alone would indicate.

Outline

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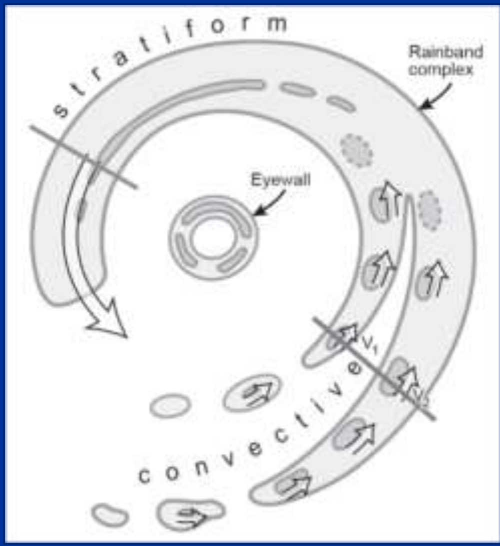
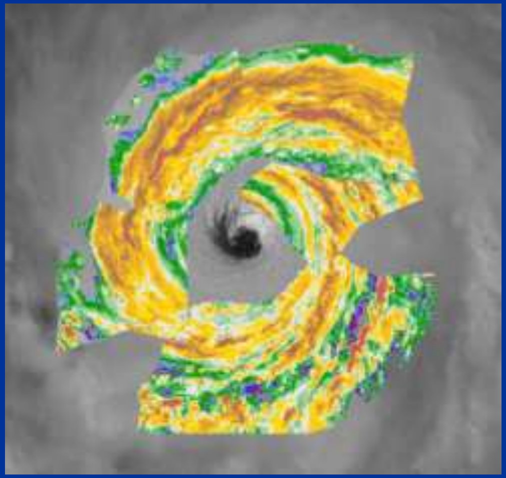
TC rainband complexes

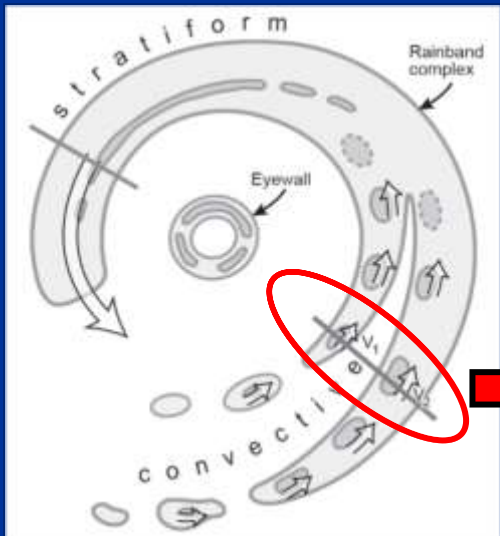


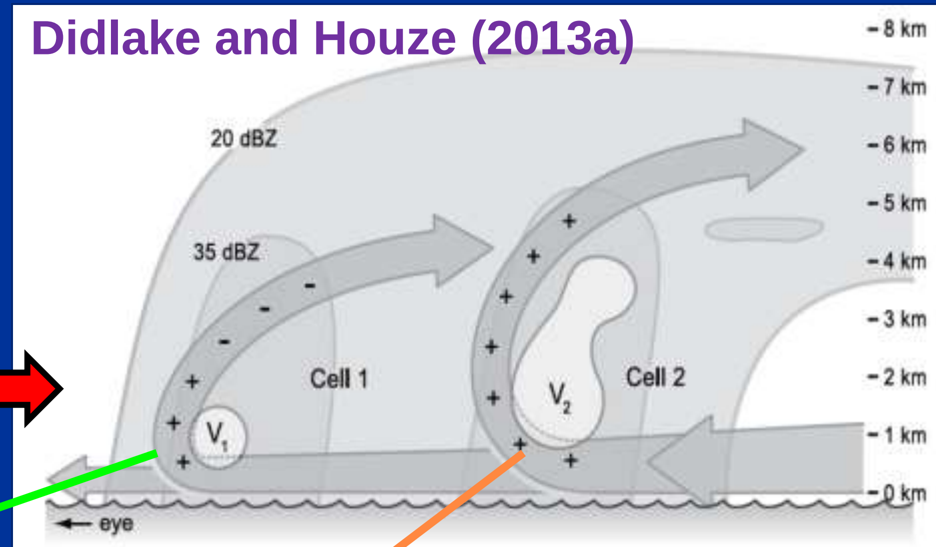
Discussion Item #10 from Friday's breakout session on TC structure: "*Prediction of impacts such as surge and rainfall are expected to come from improved understanding of outer wind structure*."



Didlake and Houze (2013a, b):
High temporal & spatial resolution sampling from the ELDORA doppler radar during a flight into Hurricane Rita allowed for detailed 3-D analyses of rainband structures

TC rainband complexes: Convective cells

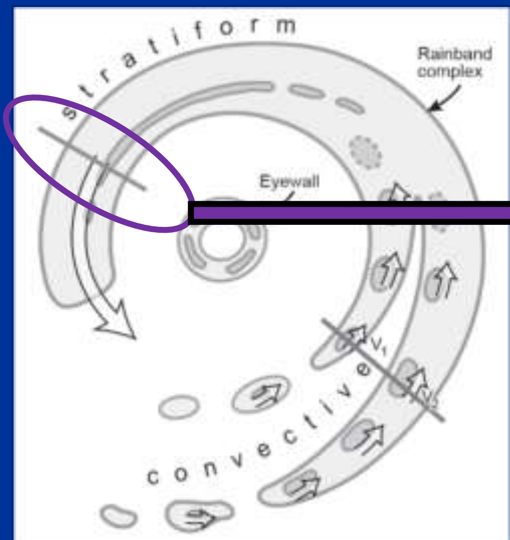


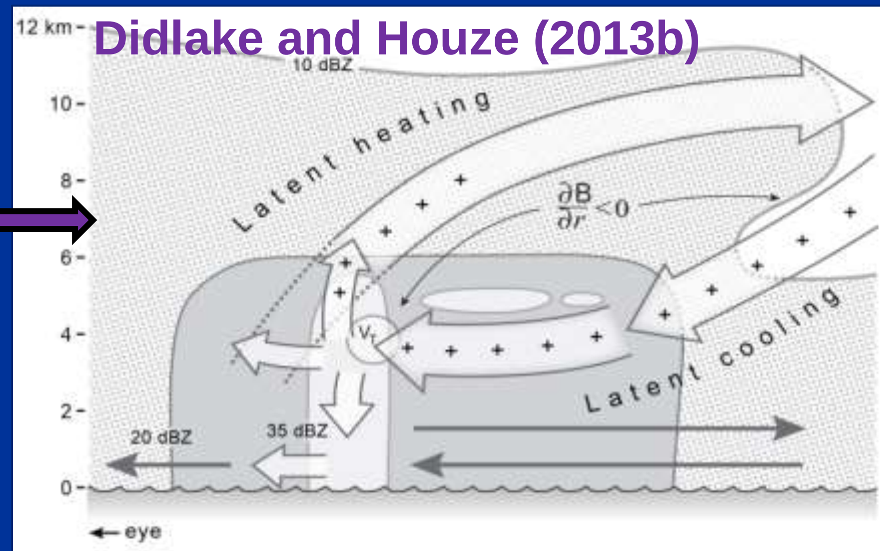


- Weaker, shallower reflectivity cores.
- Weaker updrafts
- Shallower, but stronger inflow layer
- V_T jet – and outflow – confined to lower levels.

- More intense reflectivity, heavier rain.
- Increased CAPE, more buoyant updrafts
- Deeper inflow layer
- V_T jet – and outflow – extend deeper into the troposphere

TC rainband complexes: Stratiform region





- Broad stratiform band in left-of-shear half of the storm.
- Mesoscale ascending outflow & descending inflow driven by latent heating & latent cooling patterns
- Increased rainfall along line where descending inflow halts
- Descending inflow strengthens the outer core of vortex

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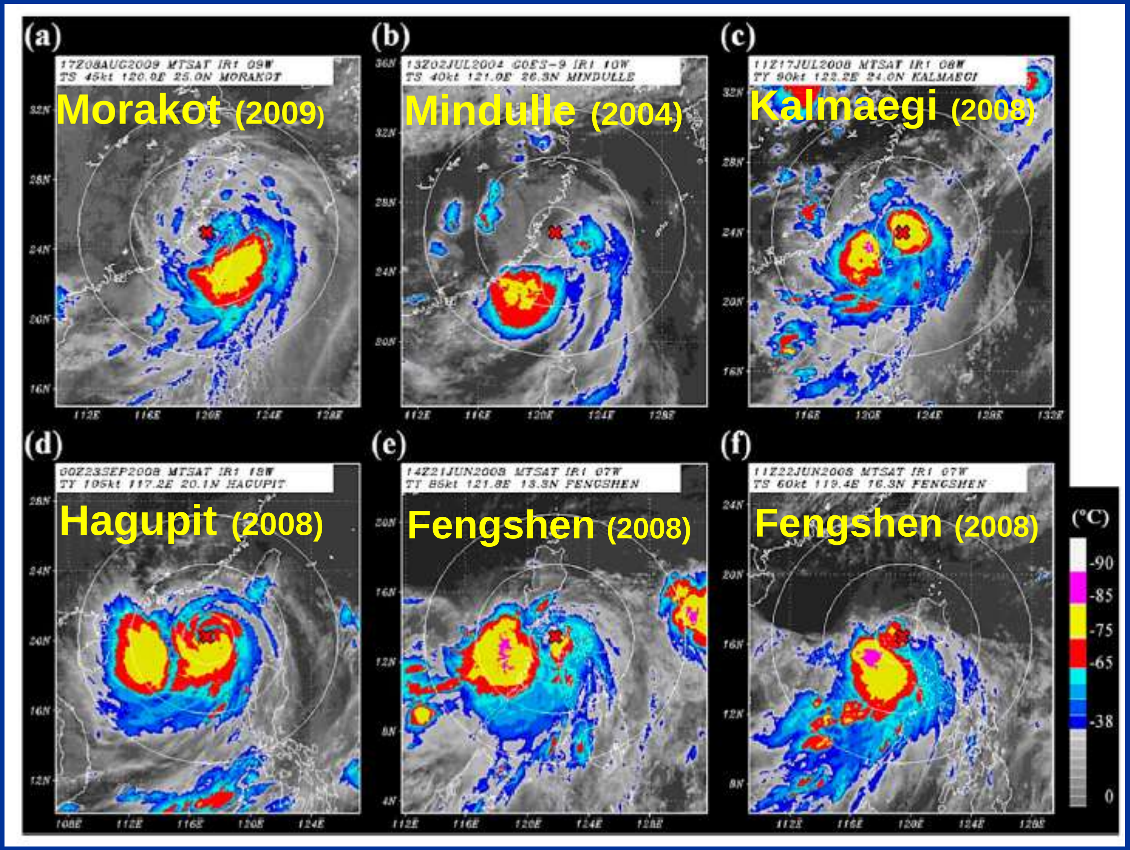
Long-lasting rainbands & outer MCSs



Lee et al. (2012)

Outer MCS defined:

1. Convective system that develops in a distant rainband of a TC.
2. Large cold cloud shield (A_{208K} > 72K km^2)
3. Must persist > 6h

Outer Mesoscale Convective Systems (OMCSs) occurred in 22% of all WPAC TCs from 1999-2009 (total OMCS count = 109)

Long-lasting rainbands & outer MCSs

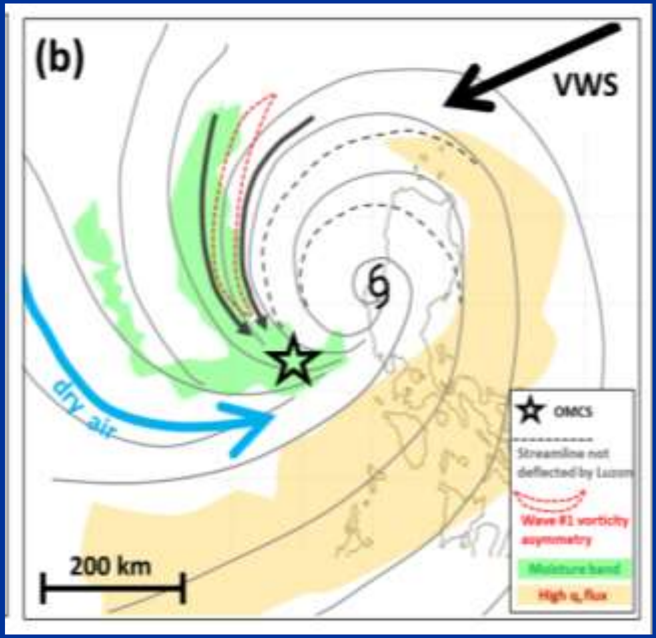
Chen et al (2014)

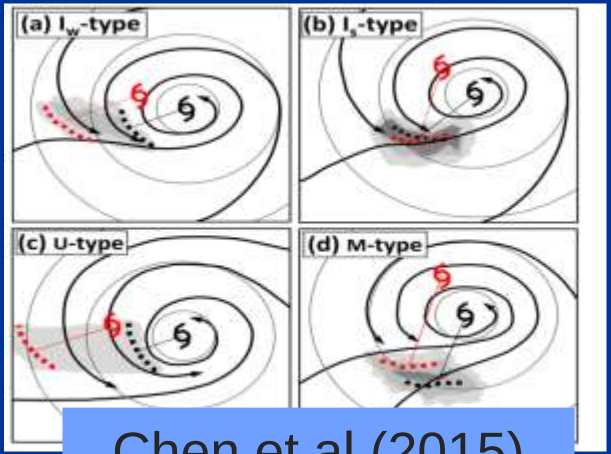
Common characteristics of WPAC OMCSs:

1. Extended monsoonal flow to the SW of the TC that wraps around southern and eastern quadrants

2. A narrow moisture band that extends north to south well to the west of the TC center.

3. The OMCS forms where the southeren end of the north-south moisture band interacts with the monsoonal flow.





Chen et al (2015)

Long-lasting rainbands & outer MCSs

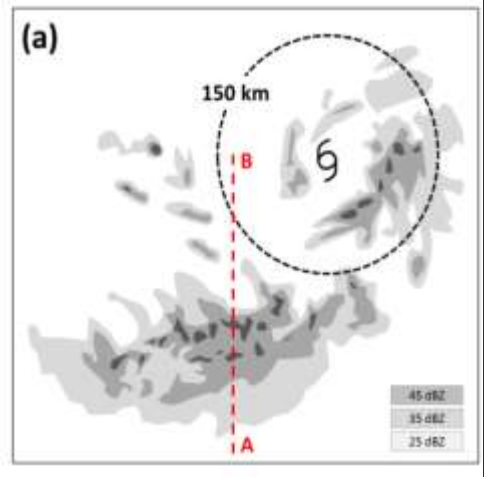
Chen et al (2014)

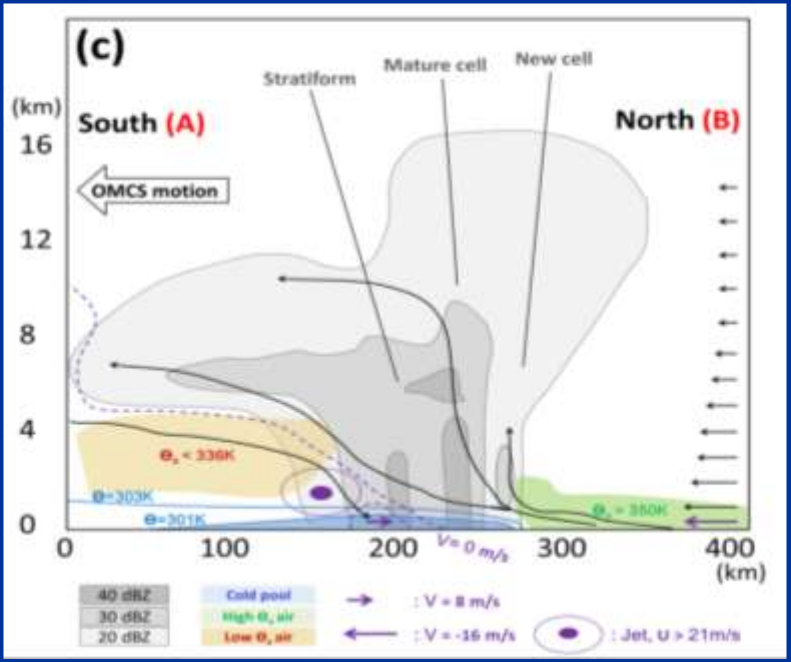
Kinematic structure of WPAC OMCS convection :

1. Line of convective cells and a large stratiform region to the south of that line.

2. Strong surface cold pool ($\Delta\theta < -3^{o}K$) associated with stratiform region.

3. New cells continuously form when air with high θ_e values from the north converges with the leading edge of the surface cold pool.





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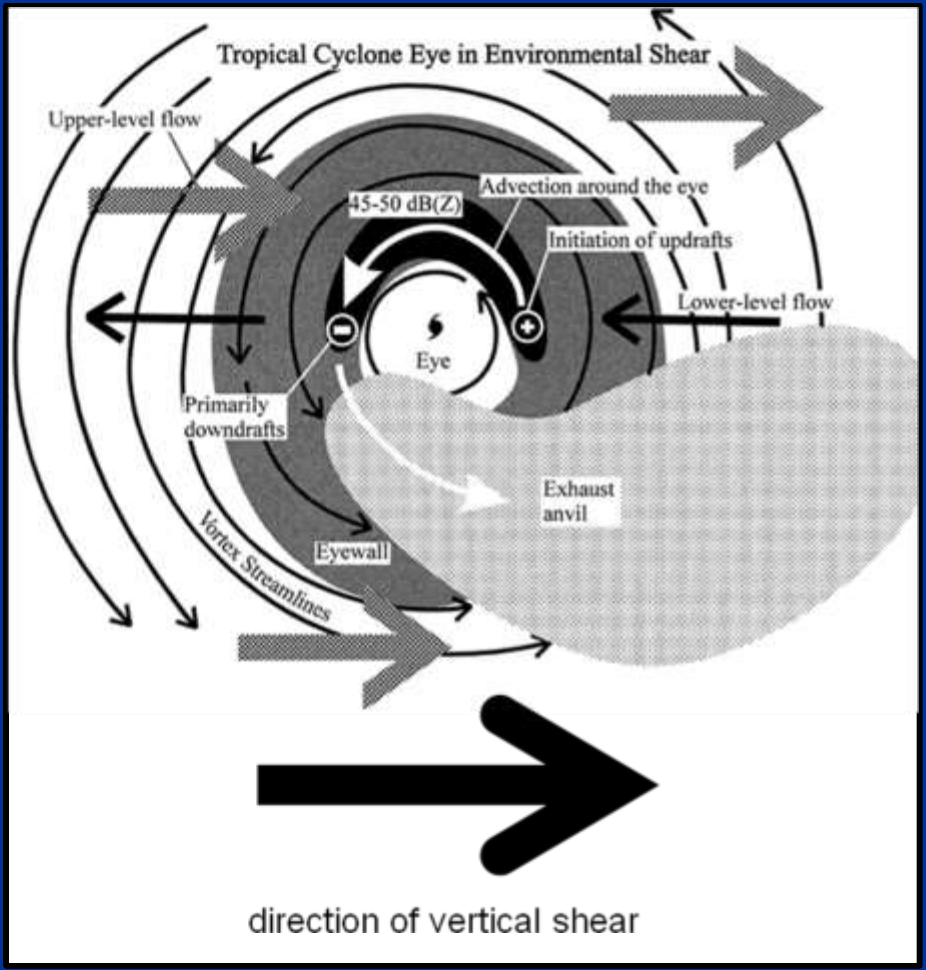
Impact of vertical wind shear on TC rainfall



Black et al. (2002)

VWS creates asymmetries in convection and rainfall that are downshear and cyclonically downwind (NH: downshear-left):

Corbosiero and Molinari (2002)
Chen et al (2006)
Cecil (2007)
Rogers et al (2003)
Ueno (2007, 2008)
Wingo and Cecil (2010)
Xu et al (2014)
Yu et al (2014)
.
.

Reasor et al (2013): Convective *initiation* starts downshear-right, peak ascent is just left of downshear, peak reflectivity and radar echoes are downshear-left.

Impact of vertical wind shear on TC rainfall

Chen et al (2006)

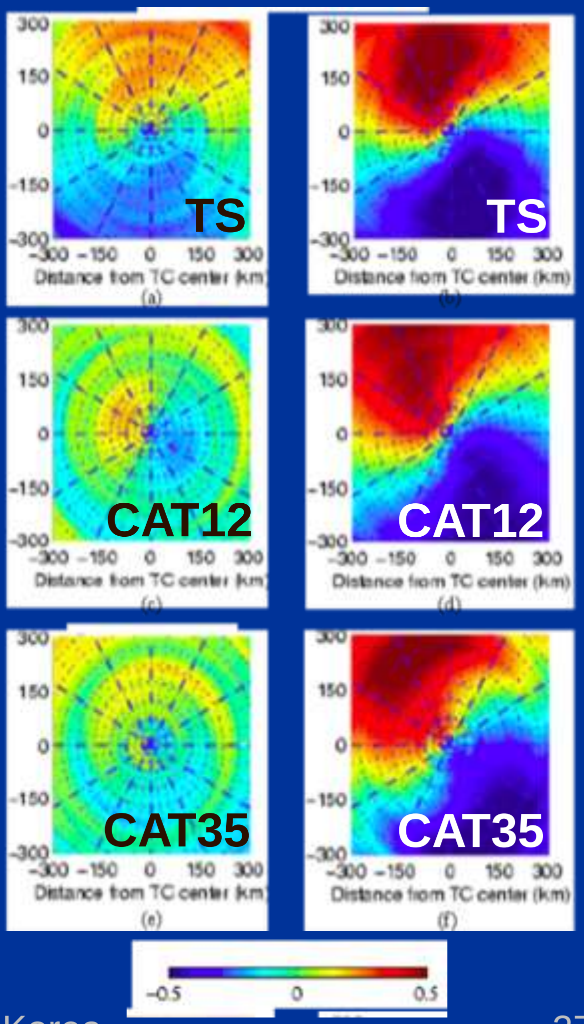
Amplitude of the rainfall asymmetry due to VWS can vary with:

- Storm intensity
- Magnitude of VWS

Color shading represents the fraction of the wavenumber-1 rainfall asymmetry (related to 850-200 mb VWS) normalized by the mean value.

Weak Shear ($< 5\ ms^{-1}$)

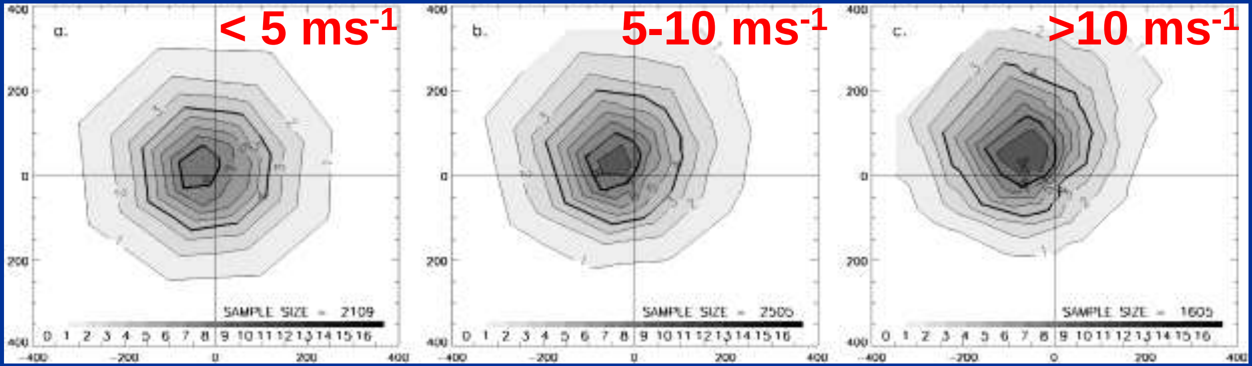
Strong Shear ($> 7.5\ ms^{-1}$)



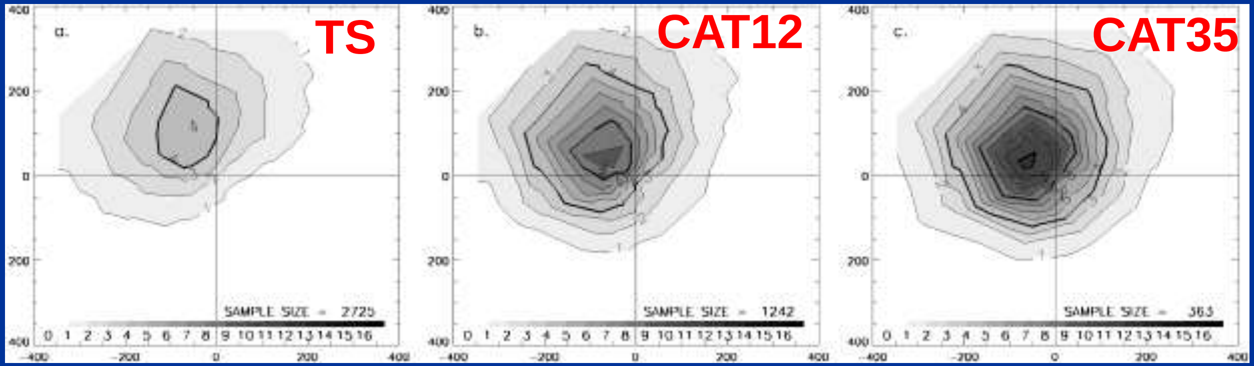
Shear

Impact of vertical wind shear on TC rainfall

Similar results from Wingo and Cecil (2010)



Composite mean rain rates for hurricanes under varying shear magnitudes



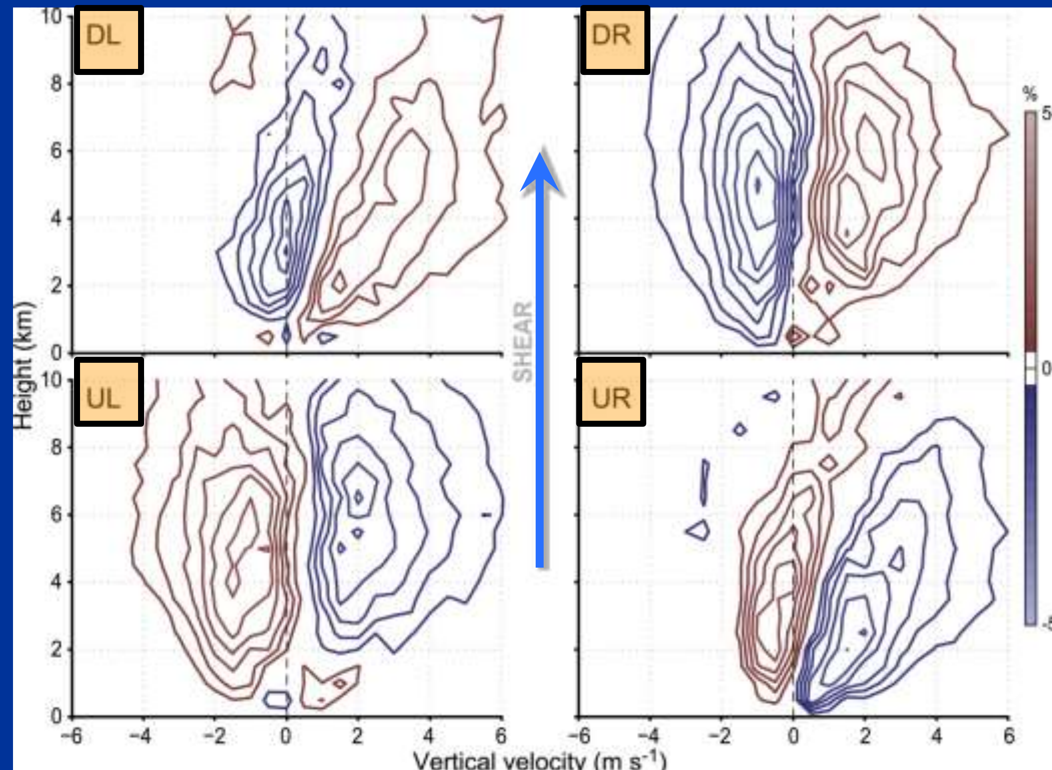
Composite mean rain rates in a strong shear (>10 ms-1) environment

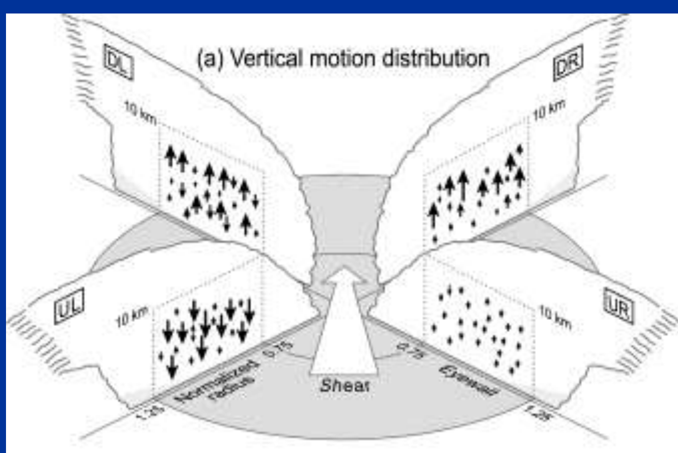
Shear

Impact of vertical wind shear on TC rainfall

DeHart et al (2014)

- More updrafts, fewer downdrafts in DR quad
- Preference for stronger updrafts in DL, esp. aloft
- Downdrafts favored, updrafts suppressed, in the Upshear quadrants

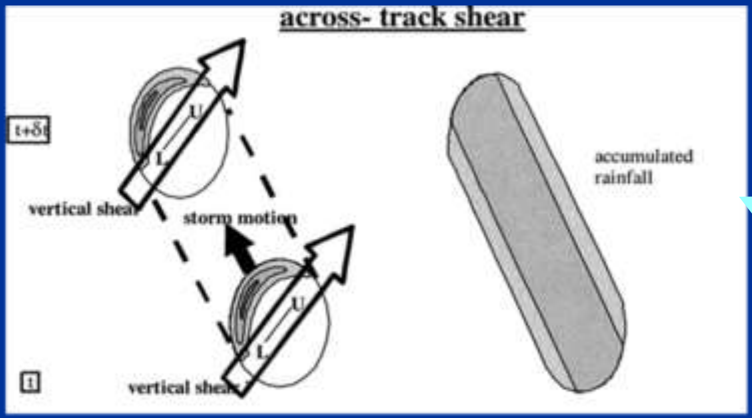




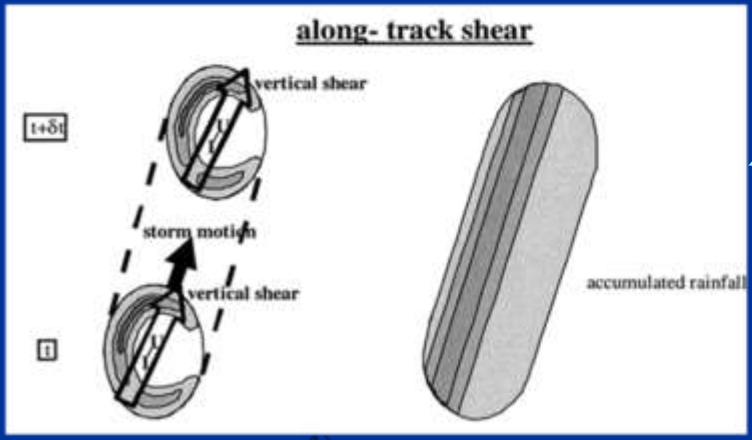
Anomaly Contoured Frequency by Altitude Display (CFAD) of eyewall vertical velocity in each quadrant

Impact of vertical wind shear on TC rainfall

Rogers et al (2003)



(a)



(b)

Shear direction relative to storm track helps determine rainfall accumulation patterns

Shear directed *across* the storm track leads to more uniform distribution of the rainfall asymmetry.

Shear directed *parallel to* the storm track leads to a distribution of the rainfall asymmetry on the left side of the track.

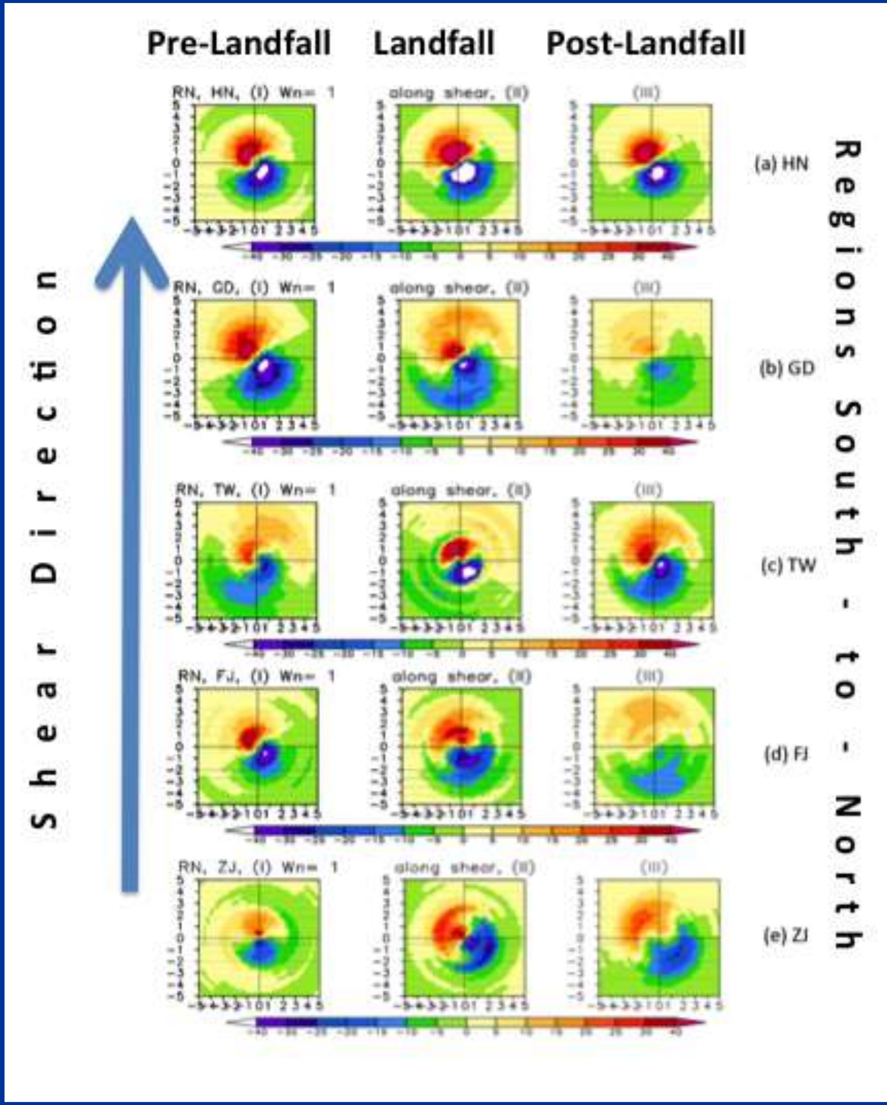
Both of the above have implications for rainfall distributions during ET

Impact of vertical wind shear on TC rainfall

Yu et al (2014)

For regions in China and Taiwan, Downshear and Downshear-Left rainfall enhancement dominates other factors in determining rainfall asymmetries.

This applies before, during and after landfall.



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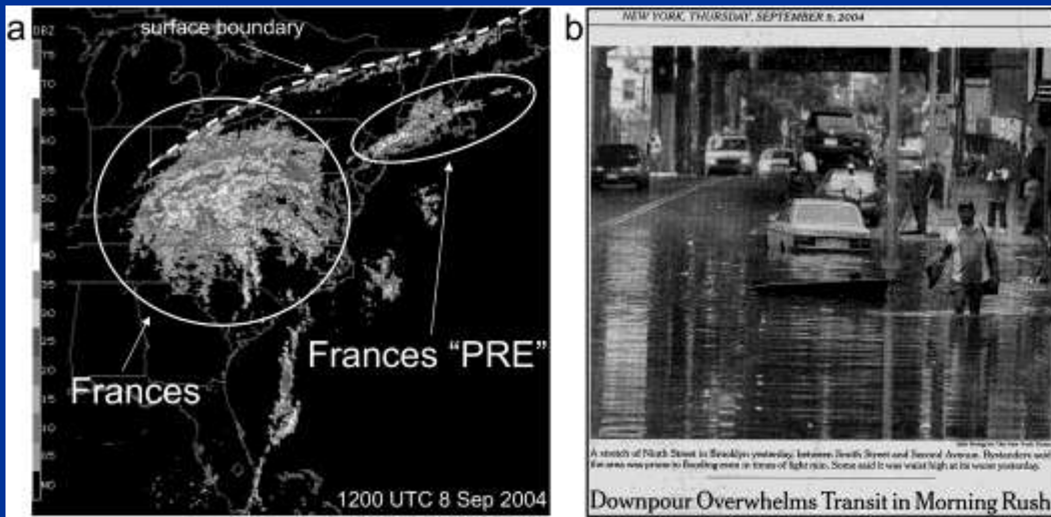
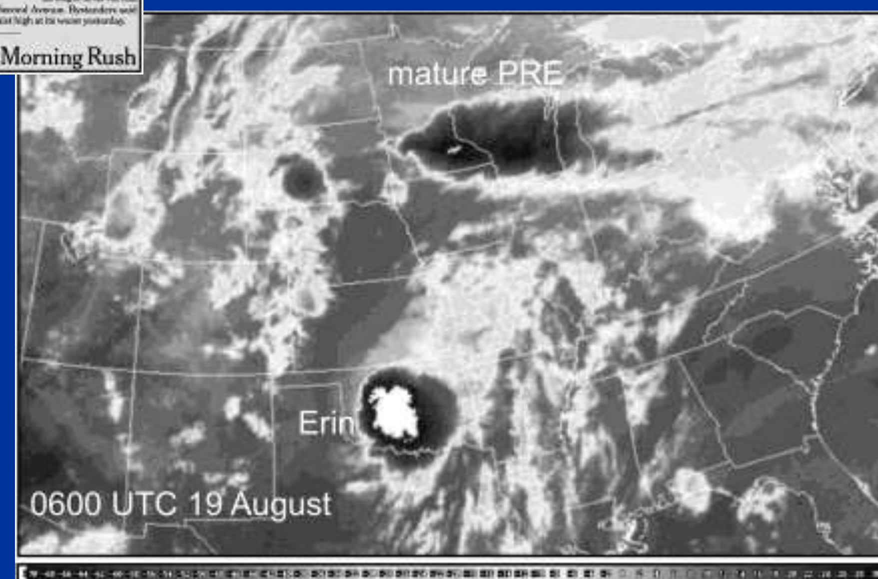
Remote rainfall: Predecessor Rain Events (PREs)



PREs: Subsynoptic-scale regions of high-impact heavy rainfall that occur ahead of tropical cyclones

Galarneau et al (2010)



Criteria:

1. Reflectivity values > 35 dBZ within a coherent area for at least 6 hours.
2. Avg rainfall > 100 mm / 24h over life of PRE.
3. Clear radar separation between TC and coherent area of rain.
4. Advection of moisture away from TC to the area of the PRE.

PREs: Typical synoptic patterns

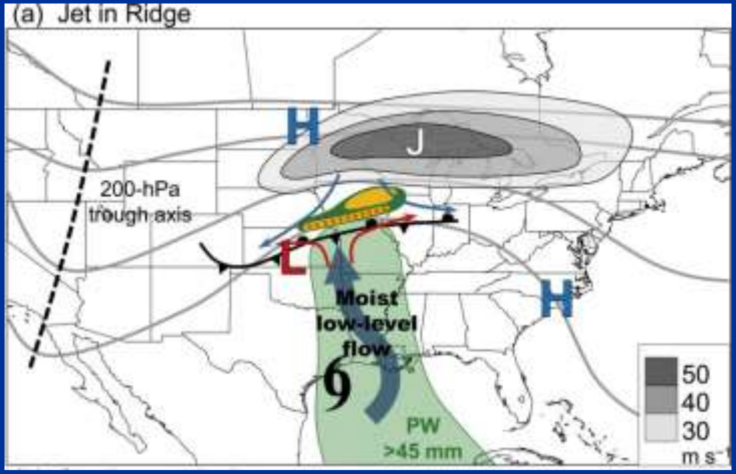
Moore et al (2013) compositing study

Jet in Ridge: TC has <u>*indirect*</u> role, by supplying anomalously high *q* air to the PRE region.

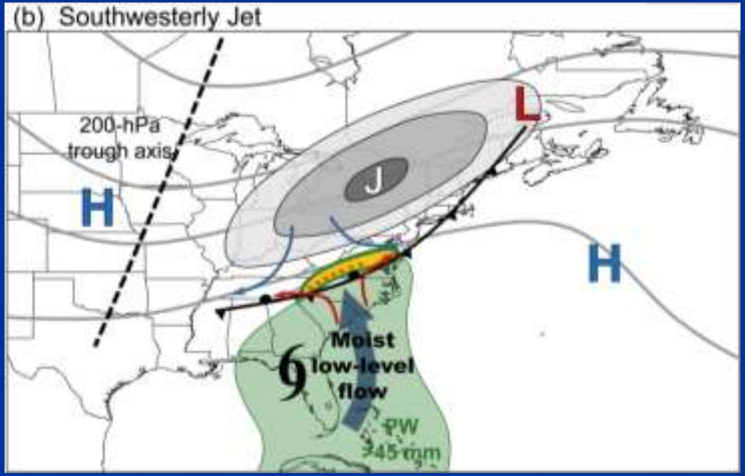
SW Jet & DC: TC has <u>*direct*</u> role:

a) Strong ∇p drives high *q* air poleward
b) Combined diabatic outflow from TC & developing PRE strengthen upper Jet

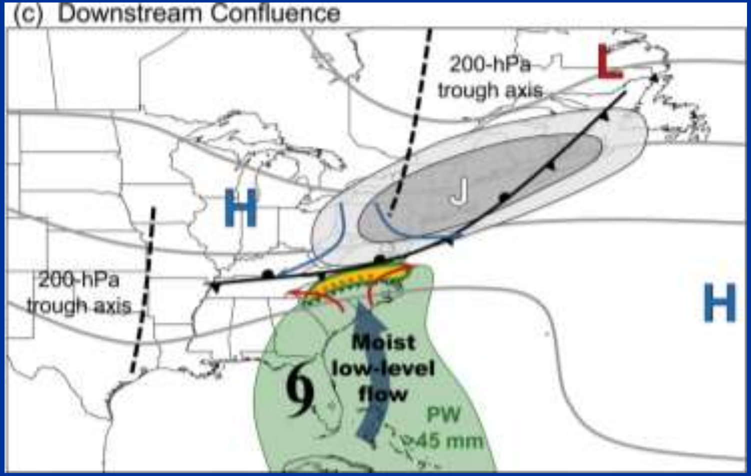
Jet in Ridge



Southwesterly Jet



Downstream Confluence



PREs: Synoptic patterns & Jet development

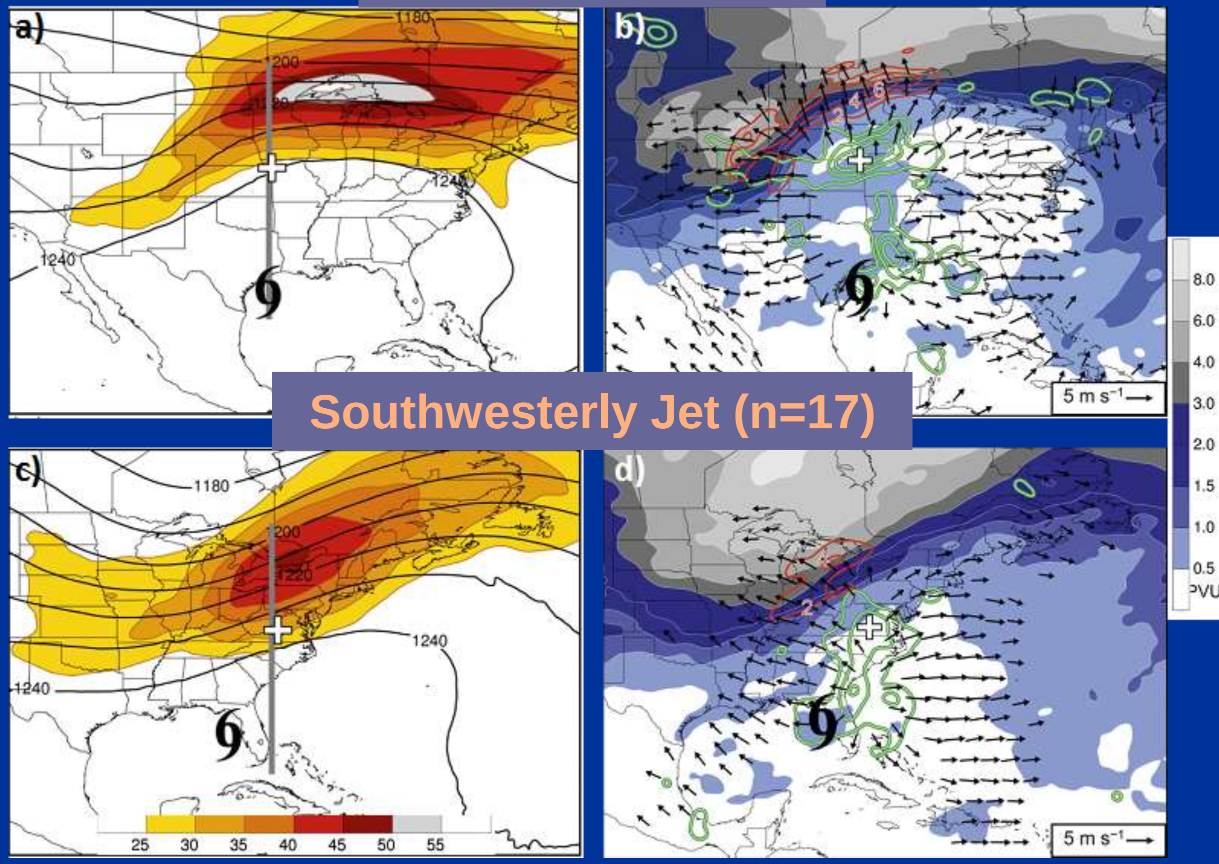
Jet in Ridge: Diabatic outflow from developing PRE acts to strengthen the upper-level jet streak.

Southwesterly Jet: Diabatic outflow from ***both*** the developing PRE and the TC act to strengthen the upper-level jet streak.

Moore et al (2013)

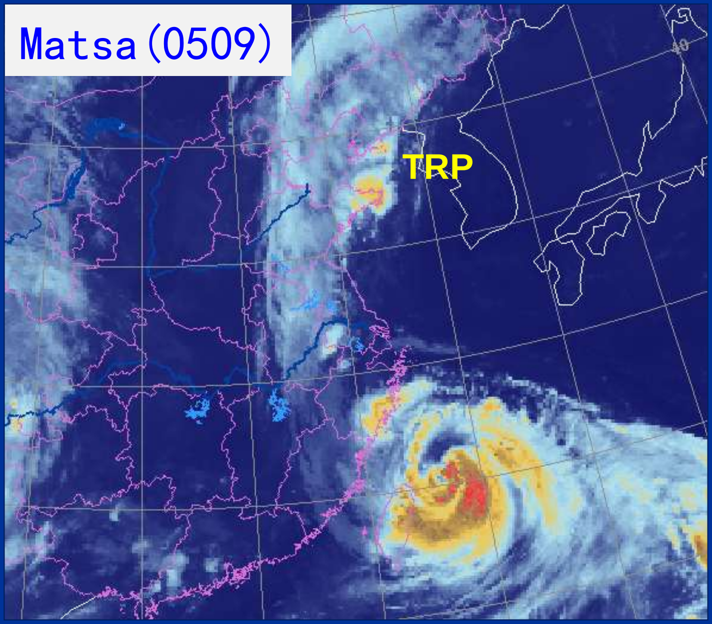
Jet in Ridge (n=7)

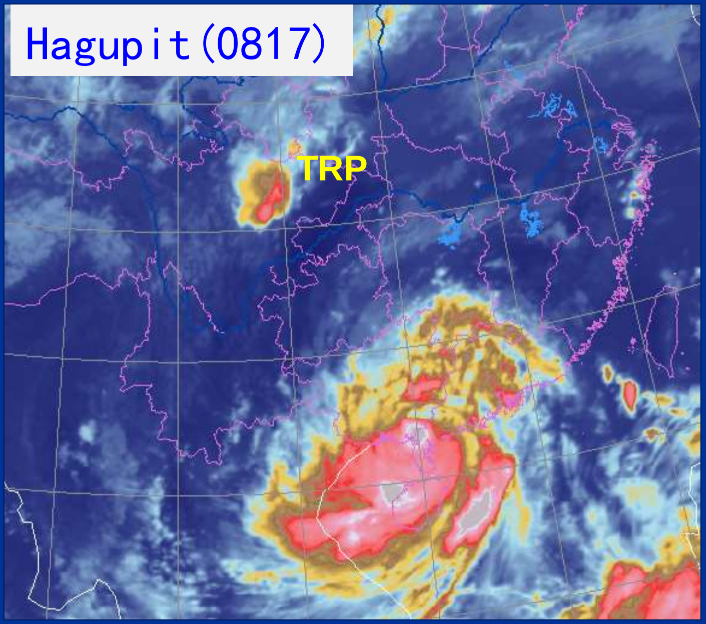
Southwesterly Jet (n=17)



Strengthening and anchoring of the upper-level jet by the TC and/or developing PRE help facilitate development of the PRE (Bosart et al. 2012)

Remote rainfall near China

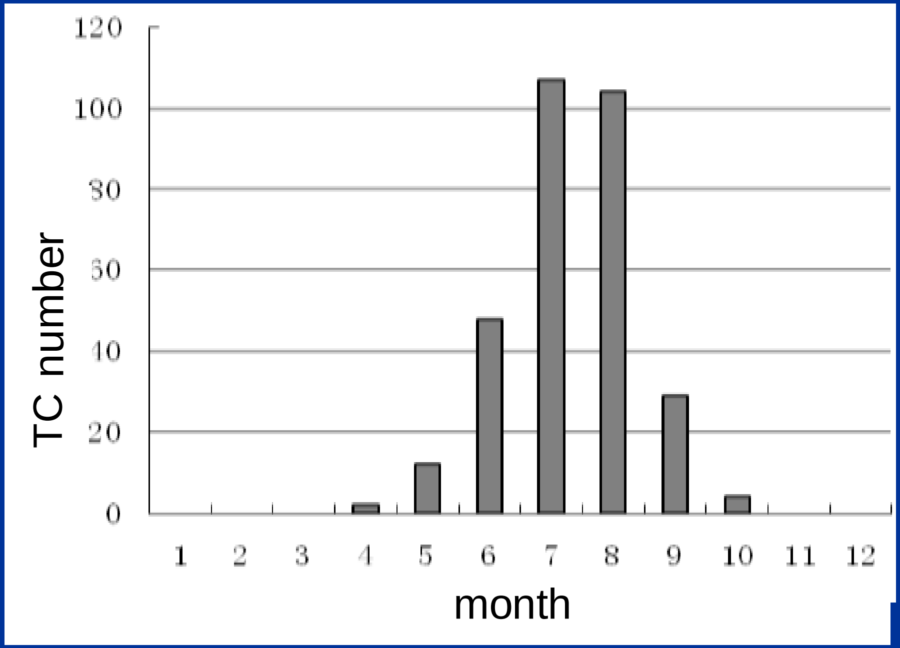




- Cong et al. (2012): 14.7% of TCs (1971-2006) passing near or making landfall in China were associated with remote rainfall.
- Referred to as a tropical cyclone remote precipitation (TRP) event.
- Two regions in China with high frequency of TRP events:
  - Bohai Sea (left figure)
  - Interior, middle-northwest of mainland China (right figure)

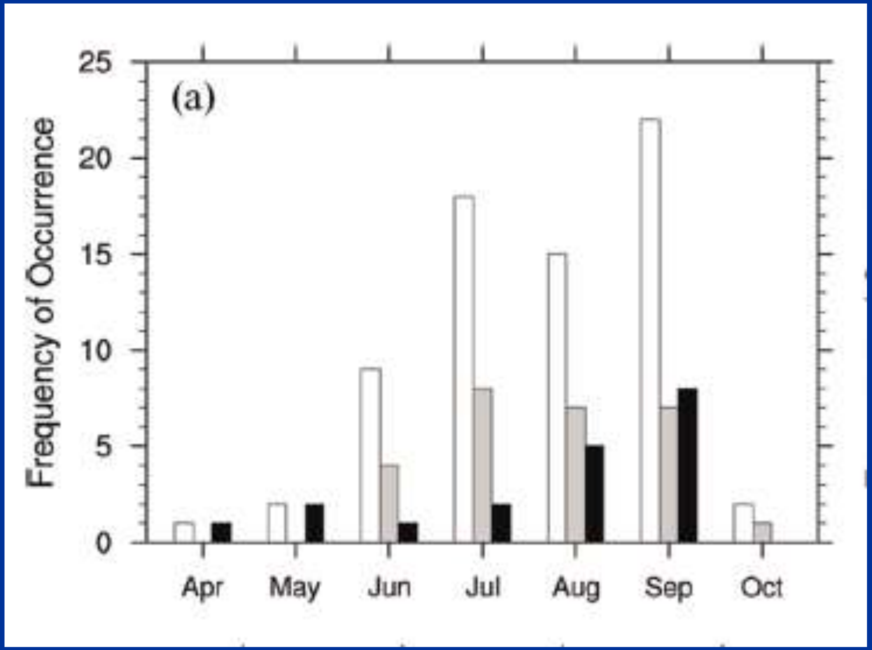
Remote rainfall frequency: China, Korean peninsula

China



Cong et al. (2011)

Korean peninsula



Byun and Lee (2012)

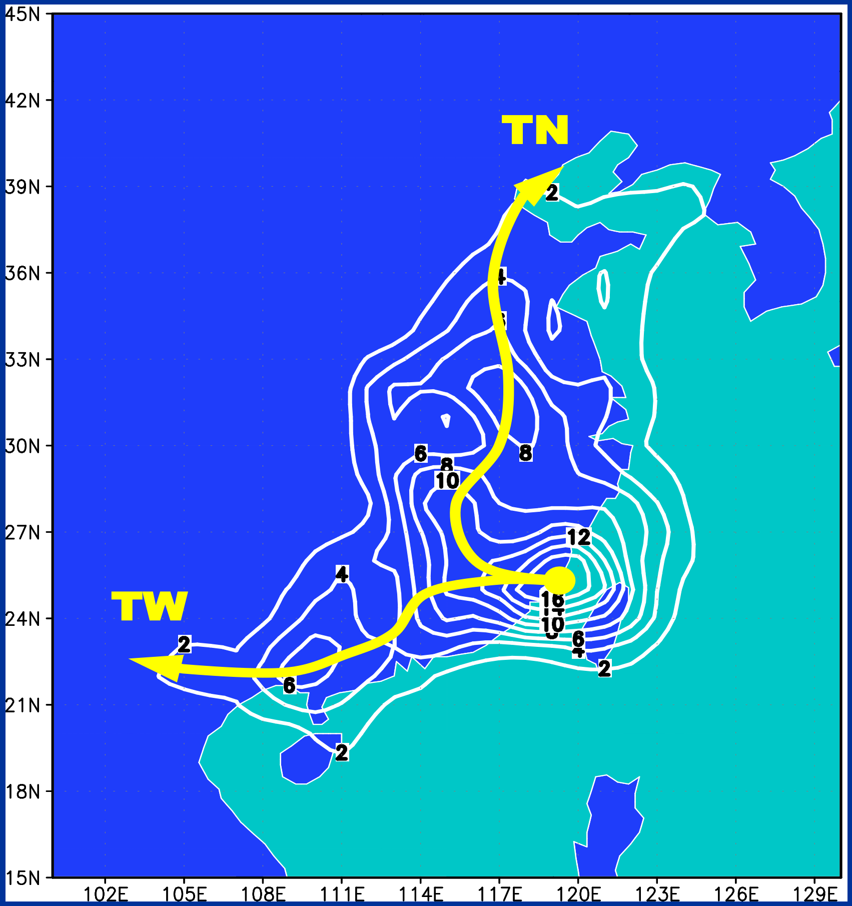
- The highest frequency of TRP (remote rainfall) events have occurred in the months of July – September.

Outline

- TC rainfall & flooding climatology
- TC rainband complexes
- Long-lasting rainbands & outer MCSs
- Impact of vertical wind shear on TC rainfall
- Remote rainfall
- Rainfall reinforcement

Rainfall reinforcement associated with landfalling TCs (RRLTC)

- Dong et al. (2012) describe landfalling storms in China that regain strength after landfall, leading to enhanced rainfall
- E.g., TC Bilis (2006)
- ~10% of the landfalling storms in China from 1949-2006 experienced RRLTC
- Favored landfalling tracks for RRLTC cases:
  - Northward (TN): 51%
  - Westward (TW): 27%



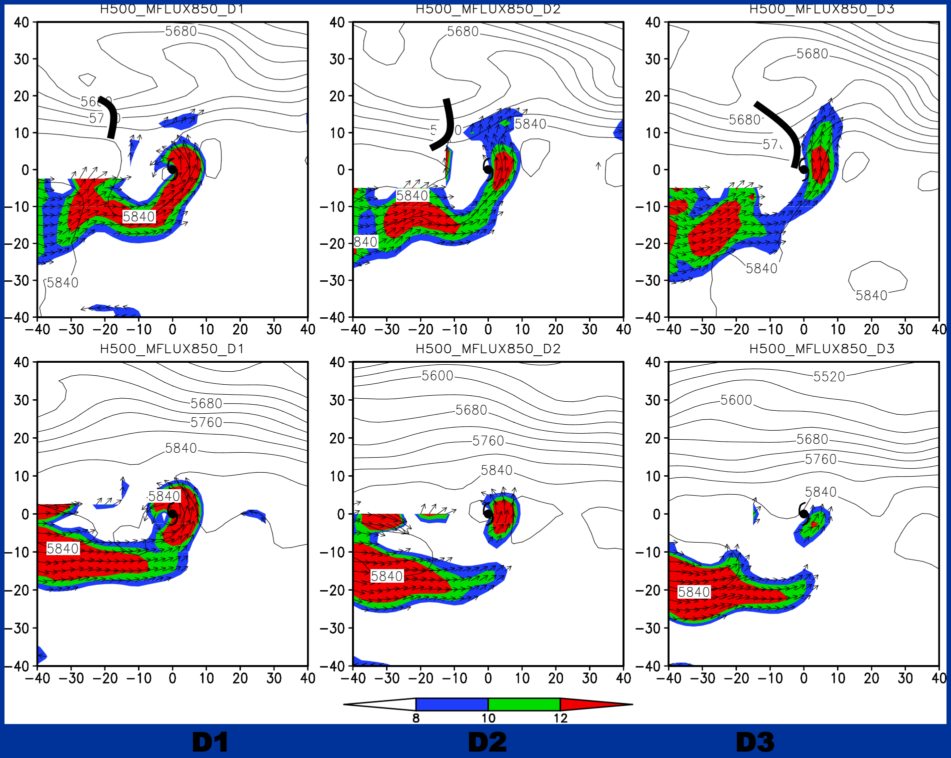
Dong et al. (2010)

Rainfall reinforcement associated with landfalling TCs (RRLTC) for northward (TN) tracks

t = landfall | **t = landfall + 1d** | **t = landfall + 2d**

Composite: Landfalling cases that *DO* exhibit RRLTC

Composite: Landfalling cases that do *NOT* exhibit RRLTC



Dong et al. (2010)

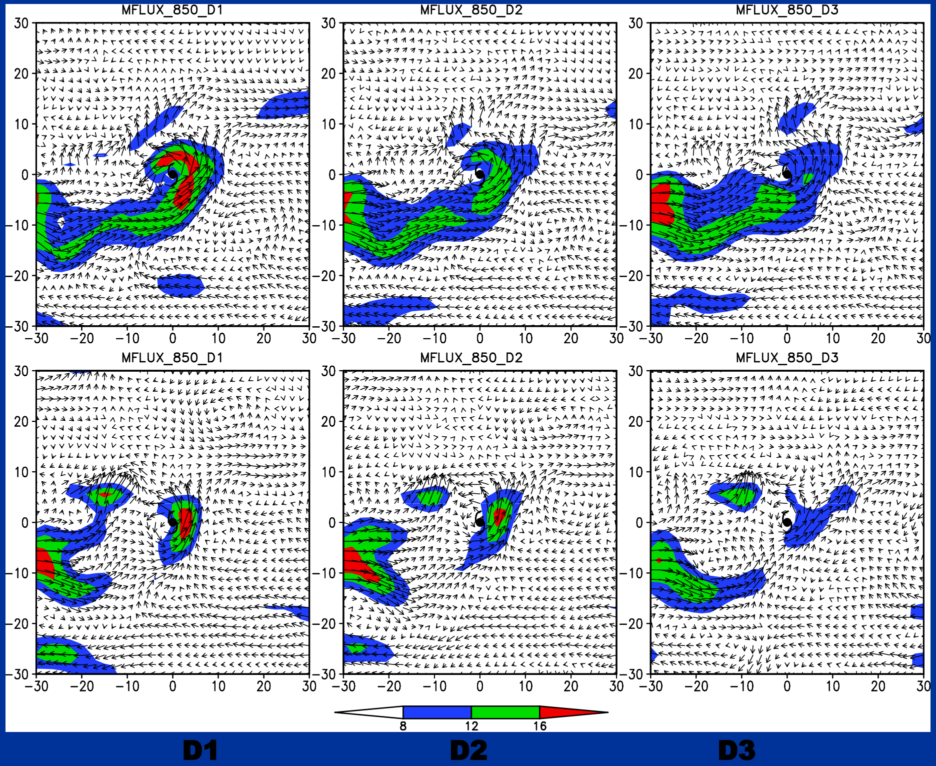
The RRLTC cases for TN tracks have a well-defined 500 mb trough to the west and a surge of 850 mb moisture flux. The non-RRLTC cases lack this definition.

Rainfall reinforcement associated with landfalling TCs (RRLTC) for westward (TW) tracks

t = landfall | **t = landfall + 1d** | **t = landfall + 2d**

Composite: Landfalling cases that *DO* exhibit RRLTC

Composite: Landfalling cases that do *NOT* exhibit RRLTC



Dong et al. (2010)

The RRLTC cases for TW tracks see an enhanced 850 mb moisture flux due to interaction with SW monsoon surges.

Summary & Discussion

- Numerous studies on TC rainfall climatology have appeared over the past 5-10 years. Studies on TC-related freshwater flooding climatology are just starting to appear.

- Rainband dynamics can affect TC rainfall both directly through internal convective & stratiform processes as well as indirectly through intensity & structure change with a feedback to future rainfall.

- In the WestPac, Outer Mesoscale Convective Systems (OMCSs) provide a mechanism for long-lived outer rainbands and prolonged intense rainfall. Do OMCSs exist in TCs in other basins with monsoon flow?

Summary & Discussion

- Vertical wind shear has an impact on not only intensity and structure, but rainfall as well.

- Remote rainfall: Predecessor Rain Event (PRE), Tropical Cyclone Remote Precipitation (TRP) event… forecast challenge?

- Discussion of OMCSs, remote rainfall, PREs, etc, highlights the fact that while the inner core region may have some of the most intense rain rates, some of the more prolonged, damaging and life-threatening rains may occur hundreds of km away from the TC center.