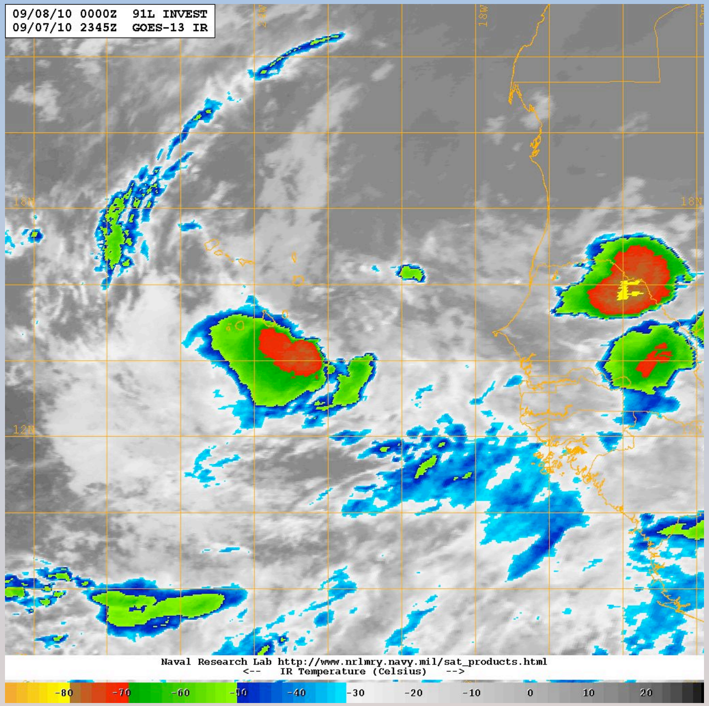
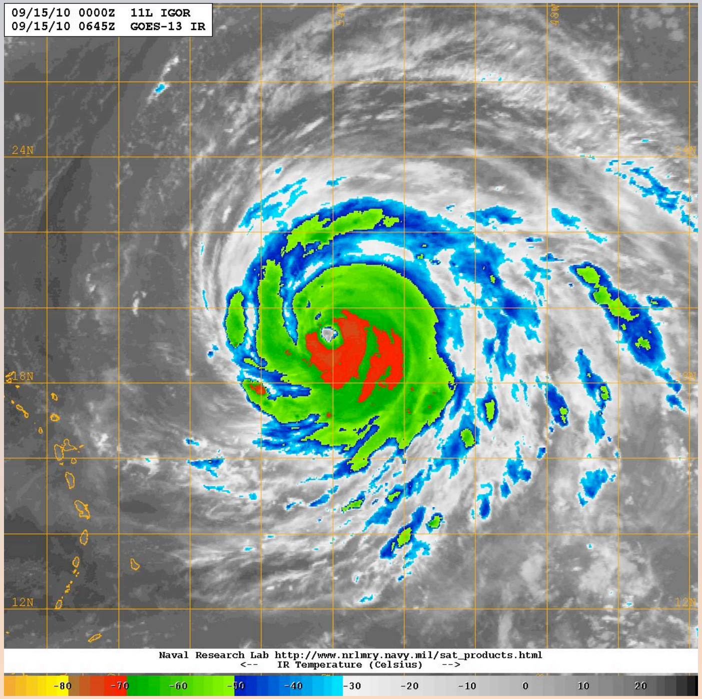
Hurricane Formation



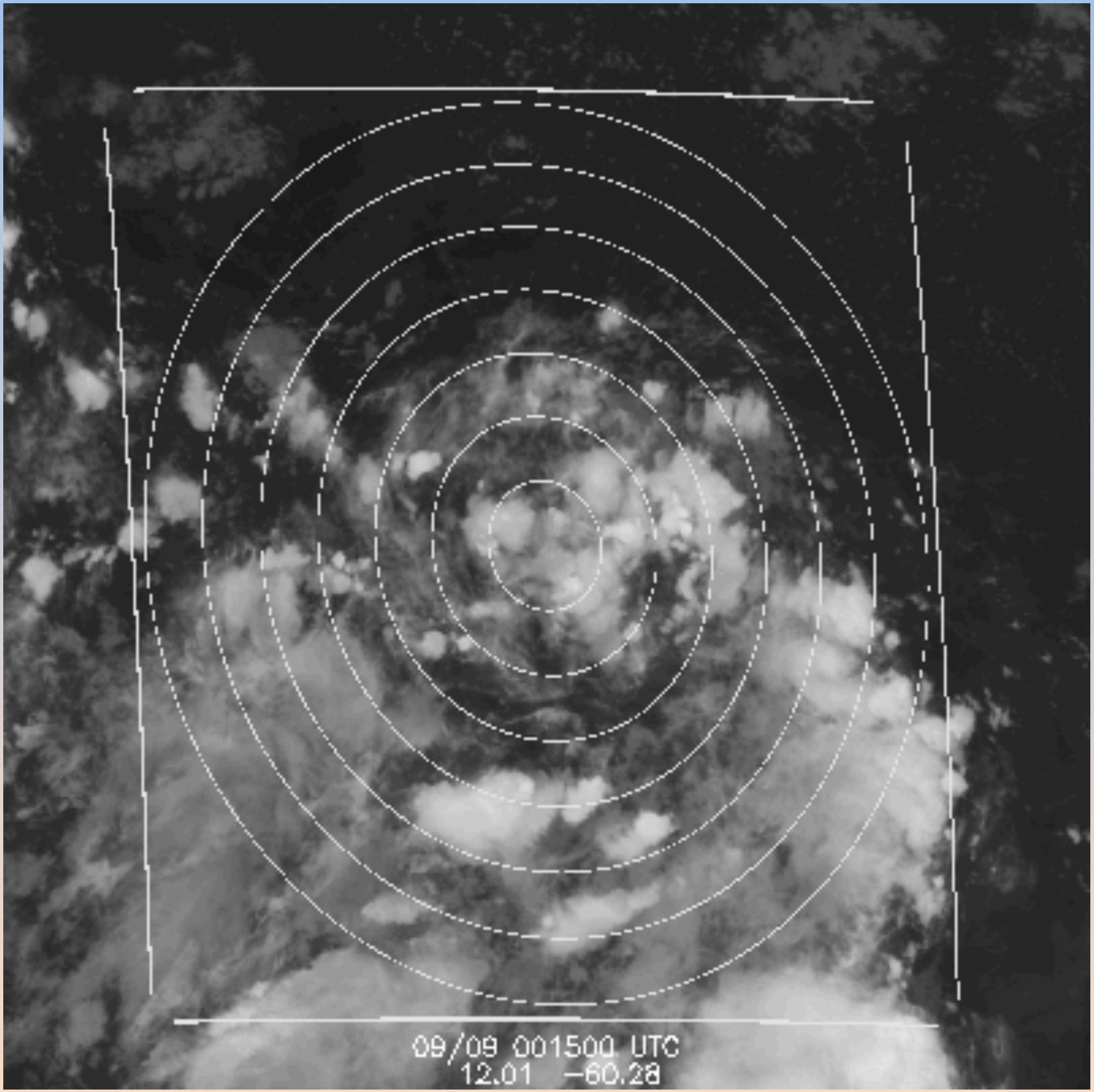
Chris Davis
NCAR

NESL/MMM and ASP



Acknowledgements:

Dave Ahijevych
Mike Montgomery (PREDICT PI)
EOL staff
George Bryan


09/09 001500 UTC
12.01 -60.28

A Century of Research on Hurricane Formation Mechanisms

"…it would seem that the cause of the origin of the tropical cyclone may be found in the countercurrent theory as to initiation of the cyclonic center, while the convective theory accounts for its maintenance after having started."

E. H. Bowie, 1922: Formation and movement of West Indian Hurricanes. Mon. Wea. Rev., 50, 173-179.

1950s: **Upper-tropospheric triggers** of tropical cyclones (Ramage, Riehl, Colón)

1960s: **Linear instabilities** (CISK): (Landers, Charney and Eliassen, Ogura, Gray). First idealized numerical models (Kasahara, Kuo, Ooyama, Rosenthal, Anthes)

1970s: GATE, **easterly waves**, other tropical wave precursors to TC formation (Carlson, Houze, Zipser, Frank(s) for Atlantic TCs)

1980s: **Finite-amplitude** nature of cyclone formation: not a linear instability (Shapiro: wave dynamics; Emanuel: air-sea interaction, McBride, Schubert and Hack)

1990s and 2000s: MJO and tropical waves; wave accumulation; large-scale control versus upscale growth; **top-down versus bottom up**

A Century of Research on Hurricane Formation

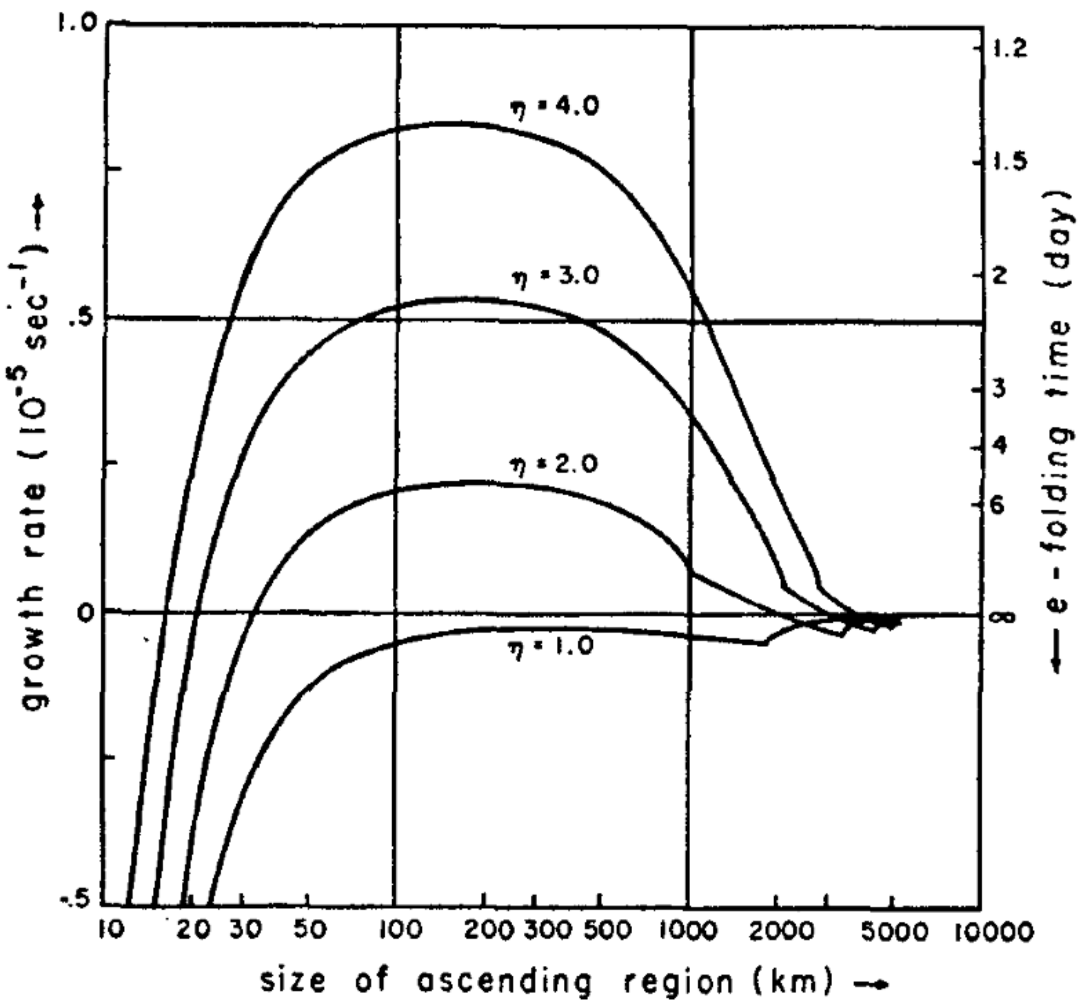


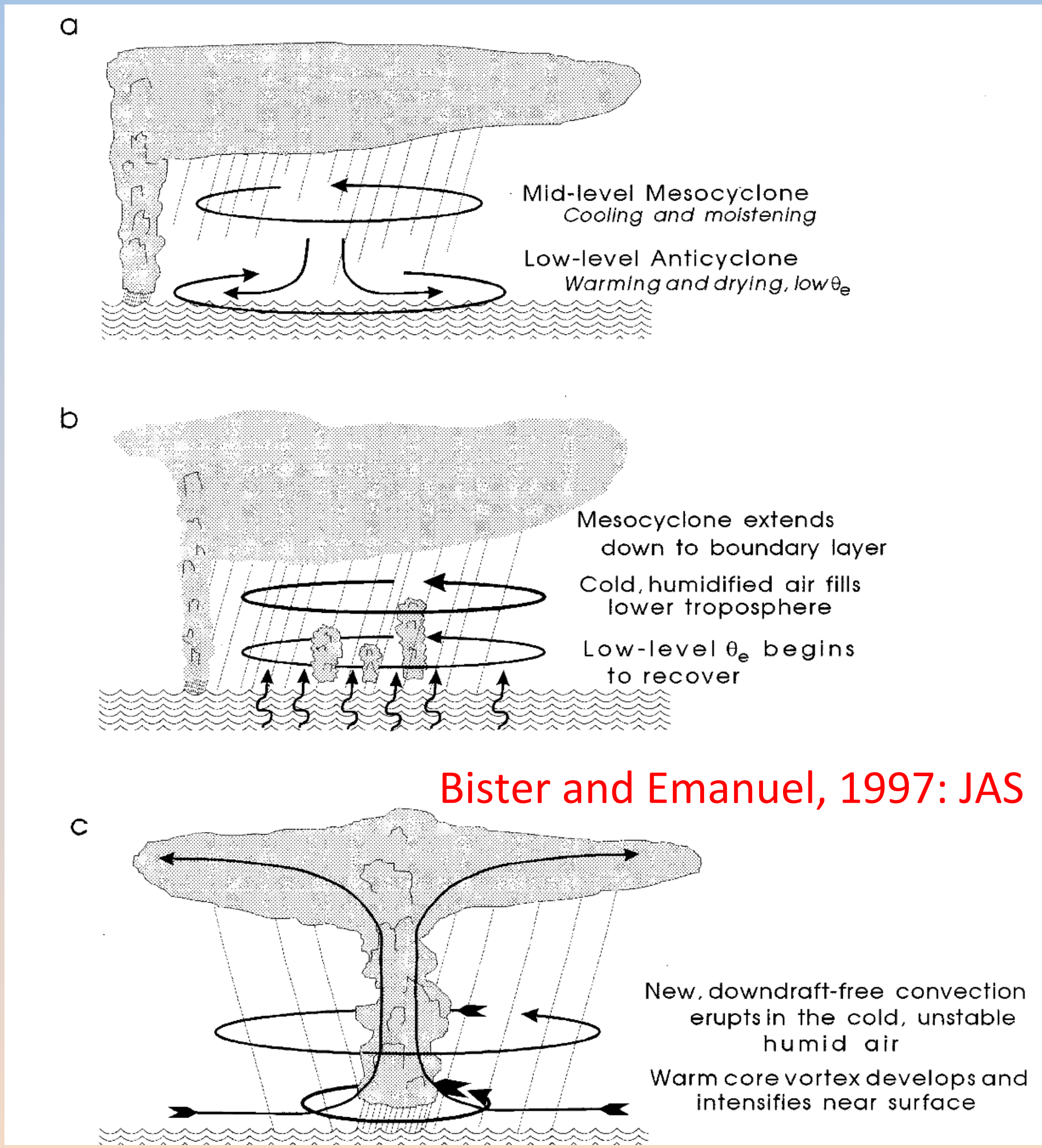
FIG. 3. The growth rate of small-amplitude disturbances as a function of the horizontal scale l (size of ascending region).

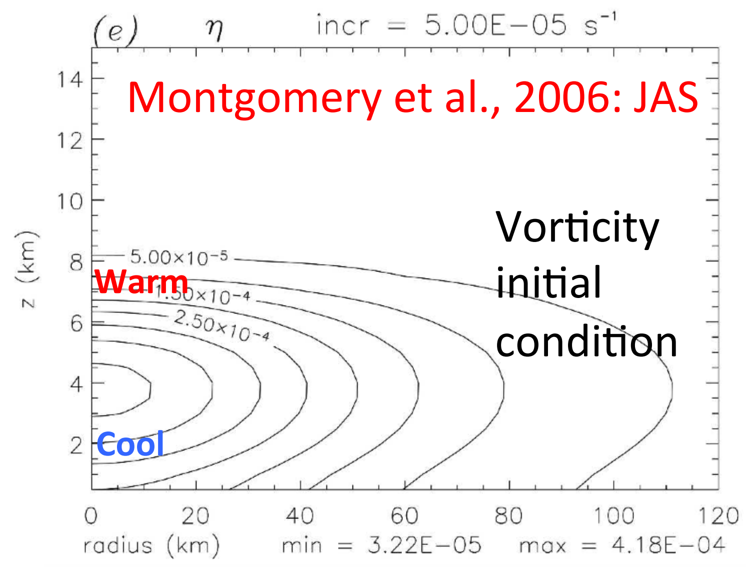
Ooyama's 1969 linear stability analysis

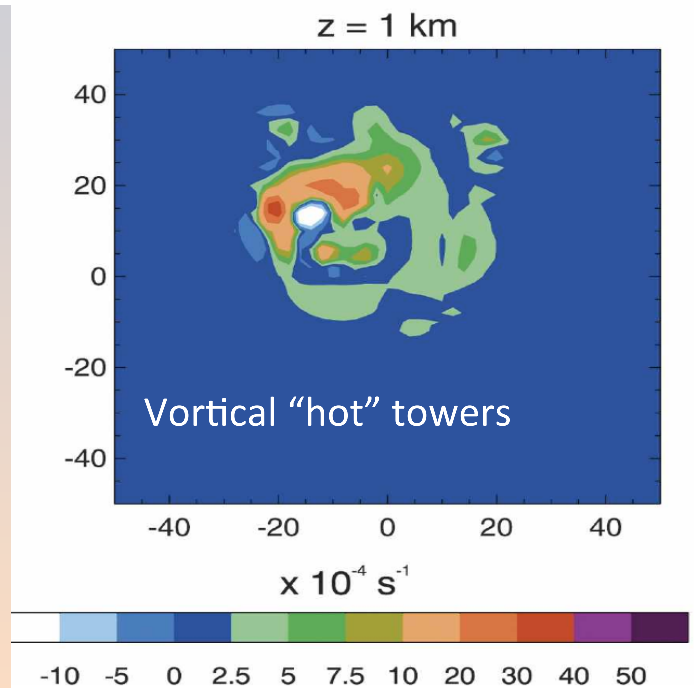
Eta is Measure of conditional instability

Conditionally neutral disturbances don't grow

Top-down vs. Bottom-up?

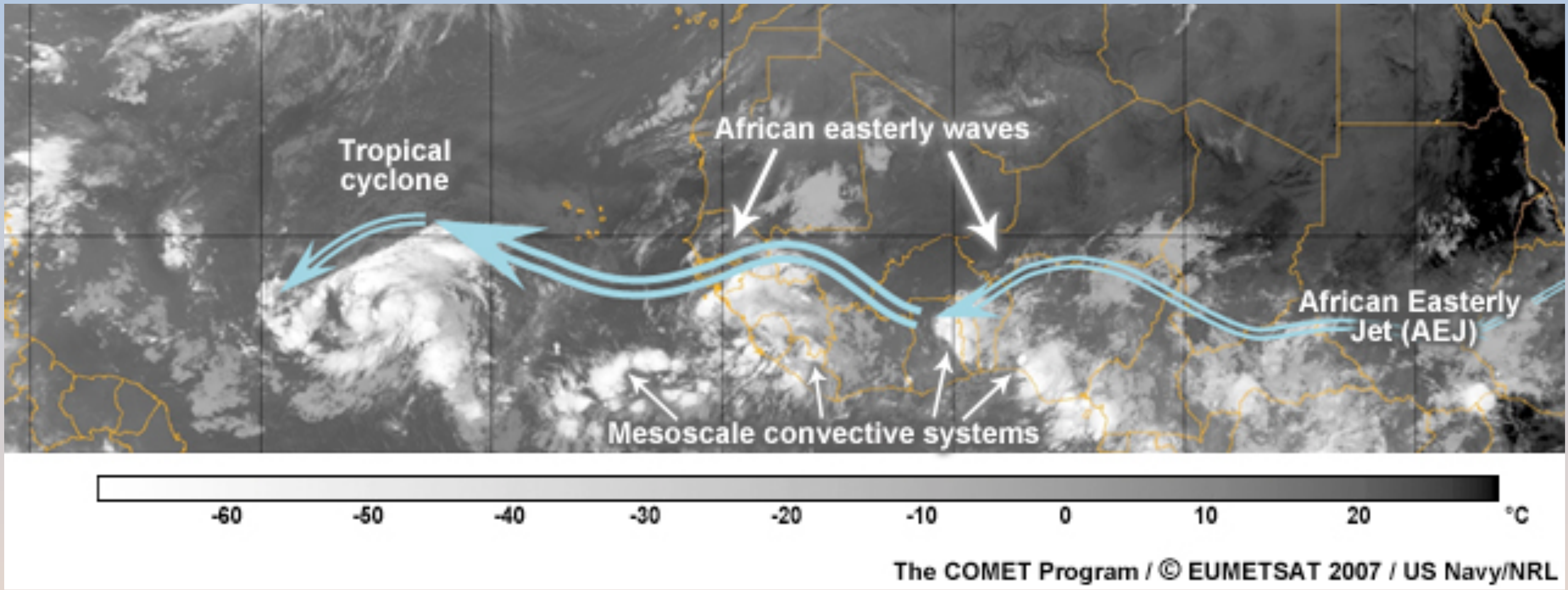






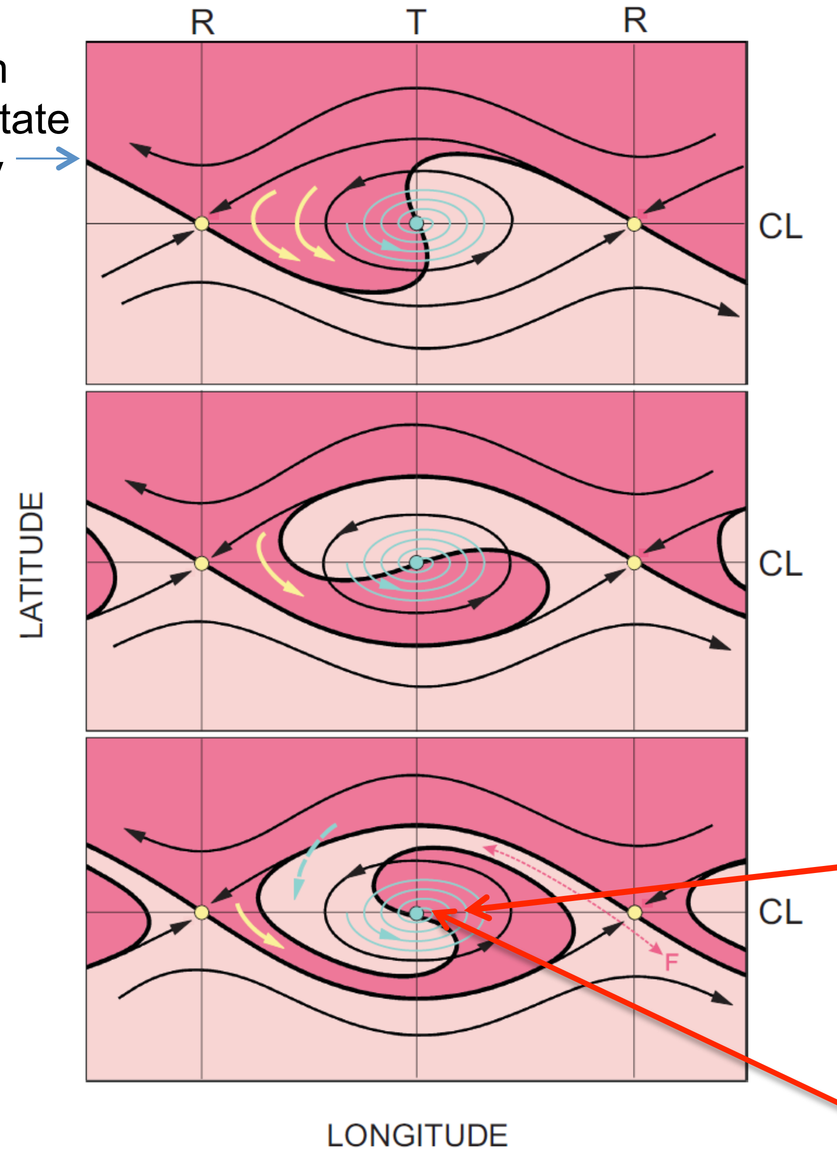
See review article by Tory and Frank, 2010

Tropical Waves as a Dynamical Guide

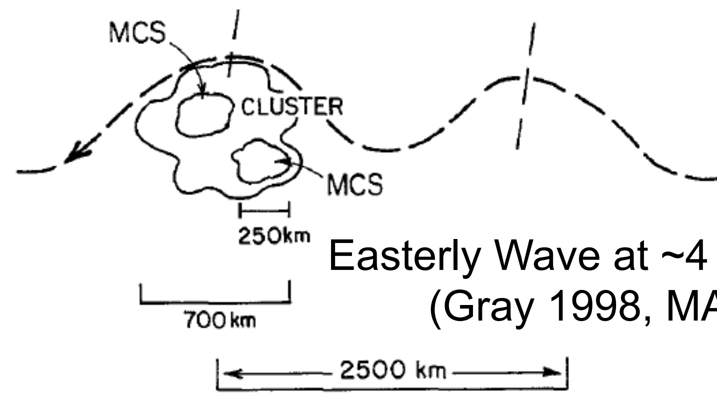


The Zoo of Recirculation

Jump in mean state vorticity



Dunkerton et al. 2009, ACP



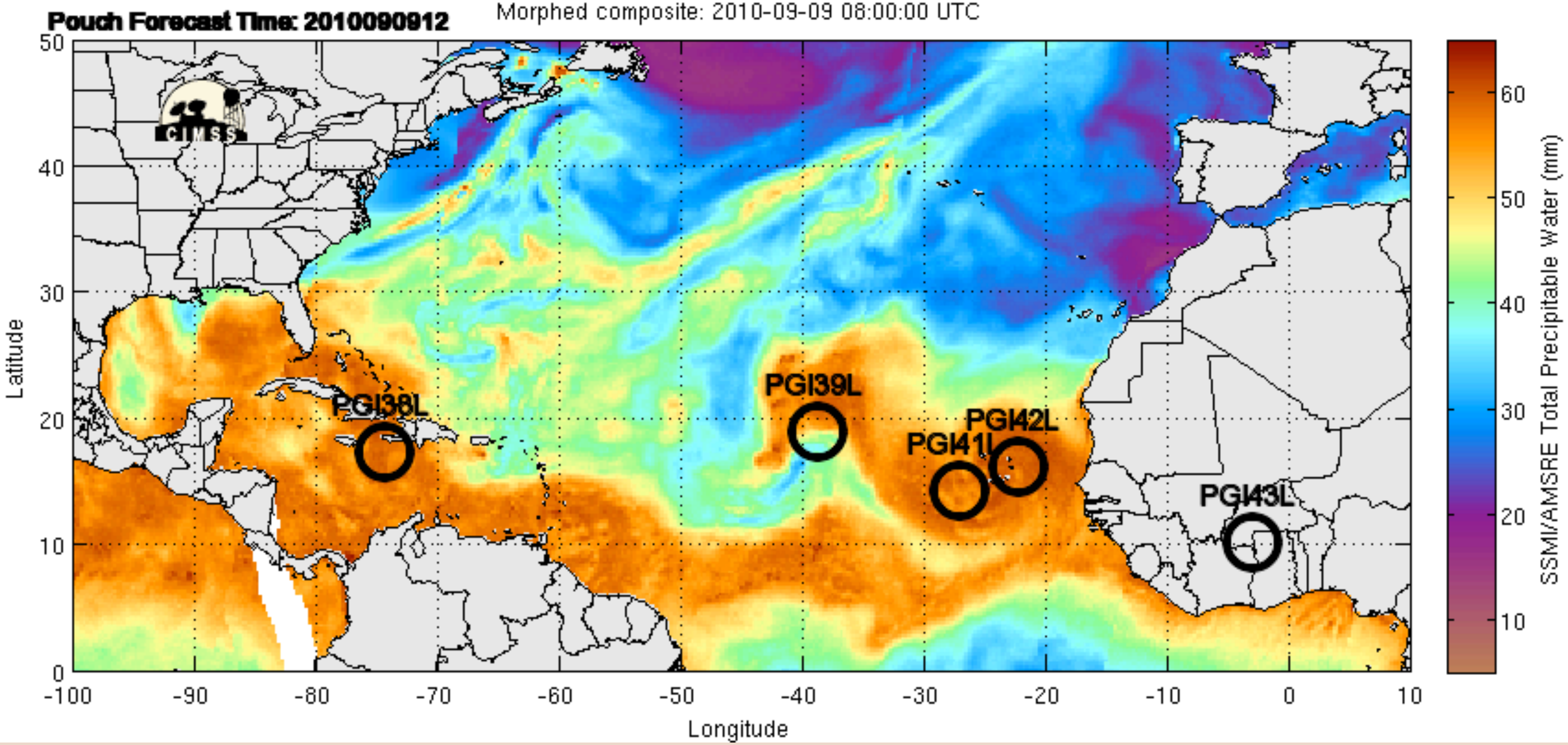
Easterly Wave at ~4 km AGL (Gray 1998, MAP)

Formation of a Cat' s Eye: a Nonlinear Critical Layer

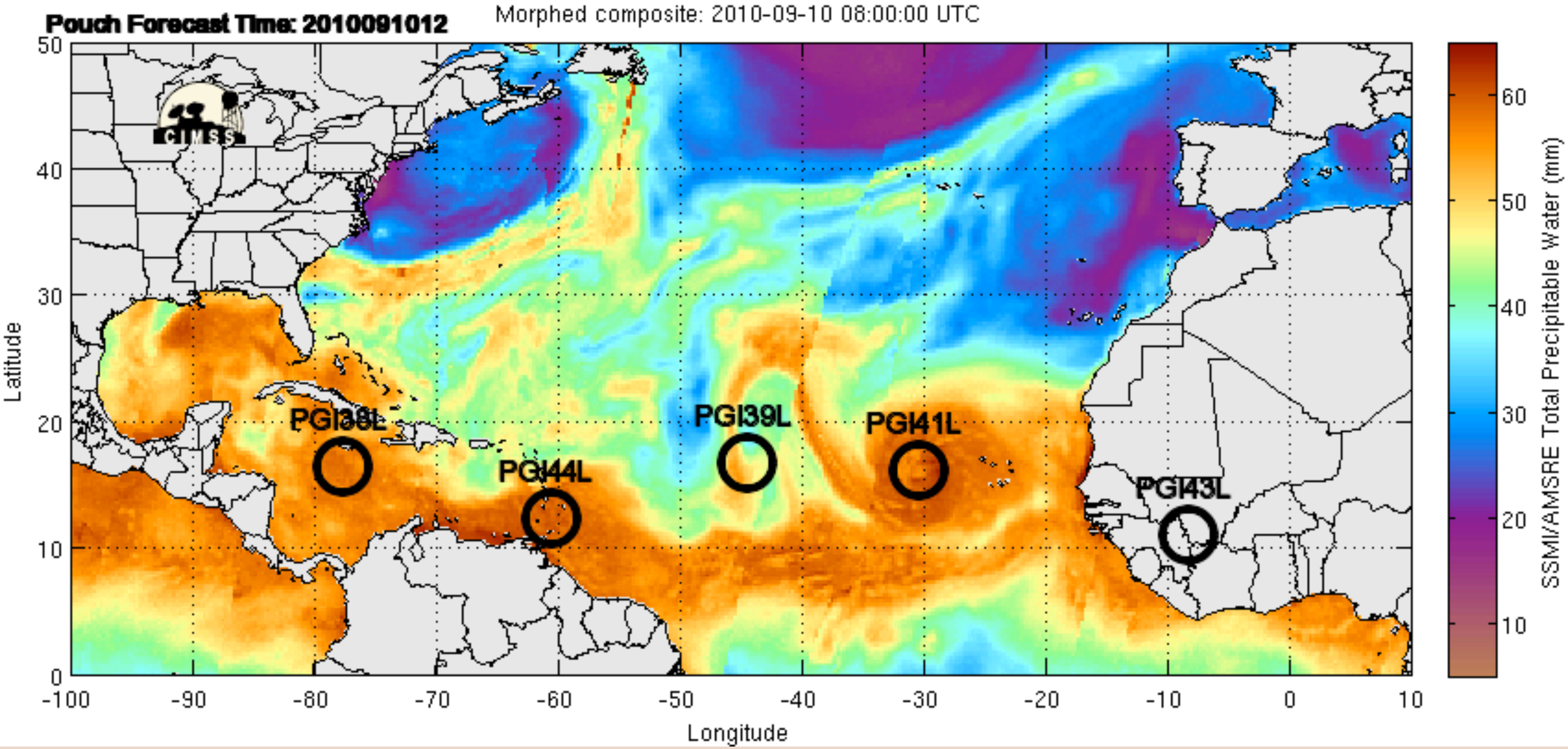
Parcels recirculate: moisture is trapped

r=0 in this talk

08 UTC 9-16 Sept. 2010



Courtesy CIMSS, University of Wisconsin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PGI39L
PGI41L
PGI44L
PGI43L
Latitude
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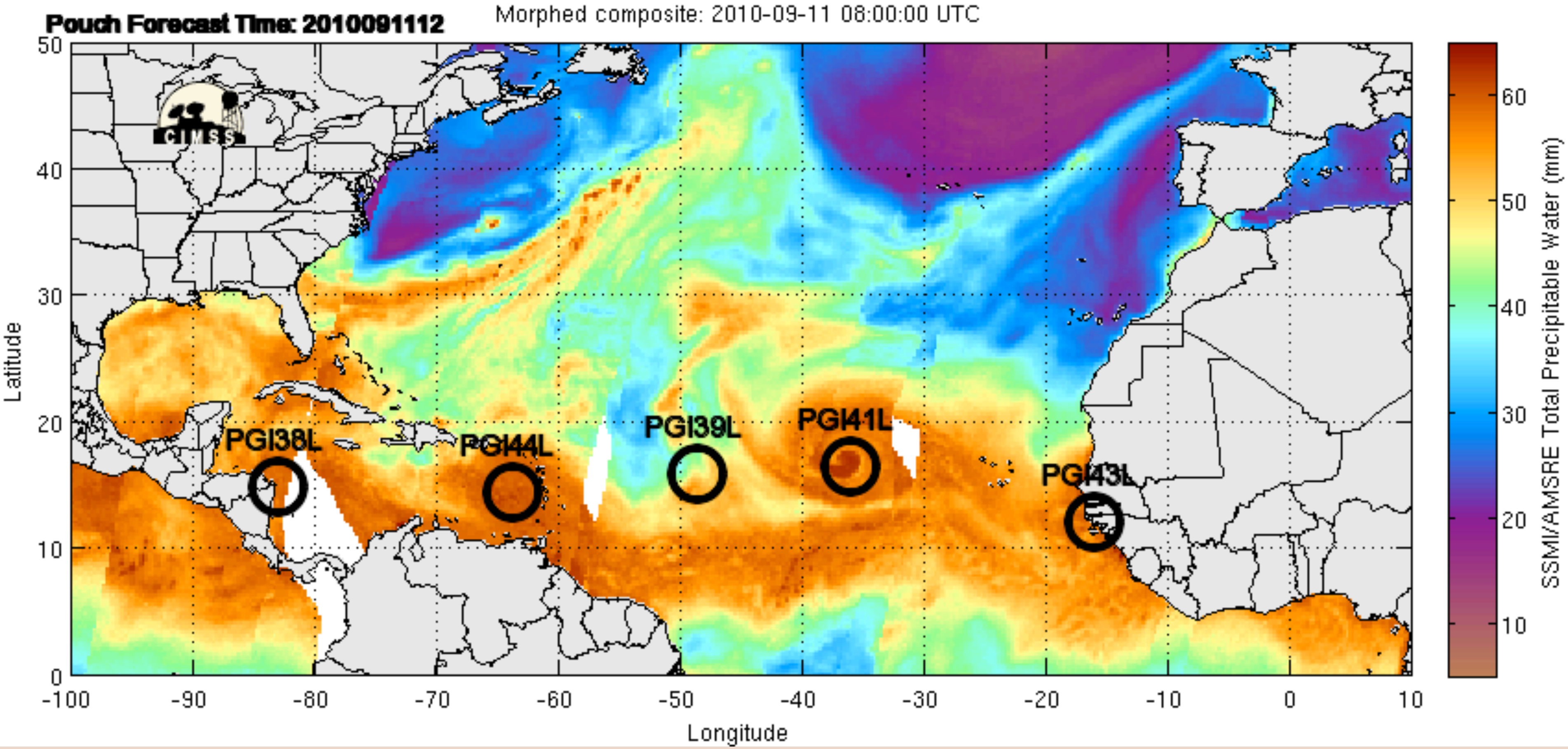
SSMI/AMSRE Total Precipitable Water (mm)
60
50
40
30
20
10



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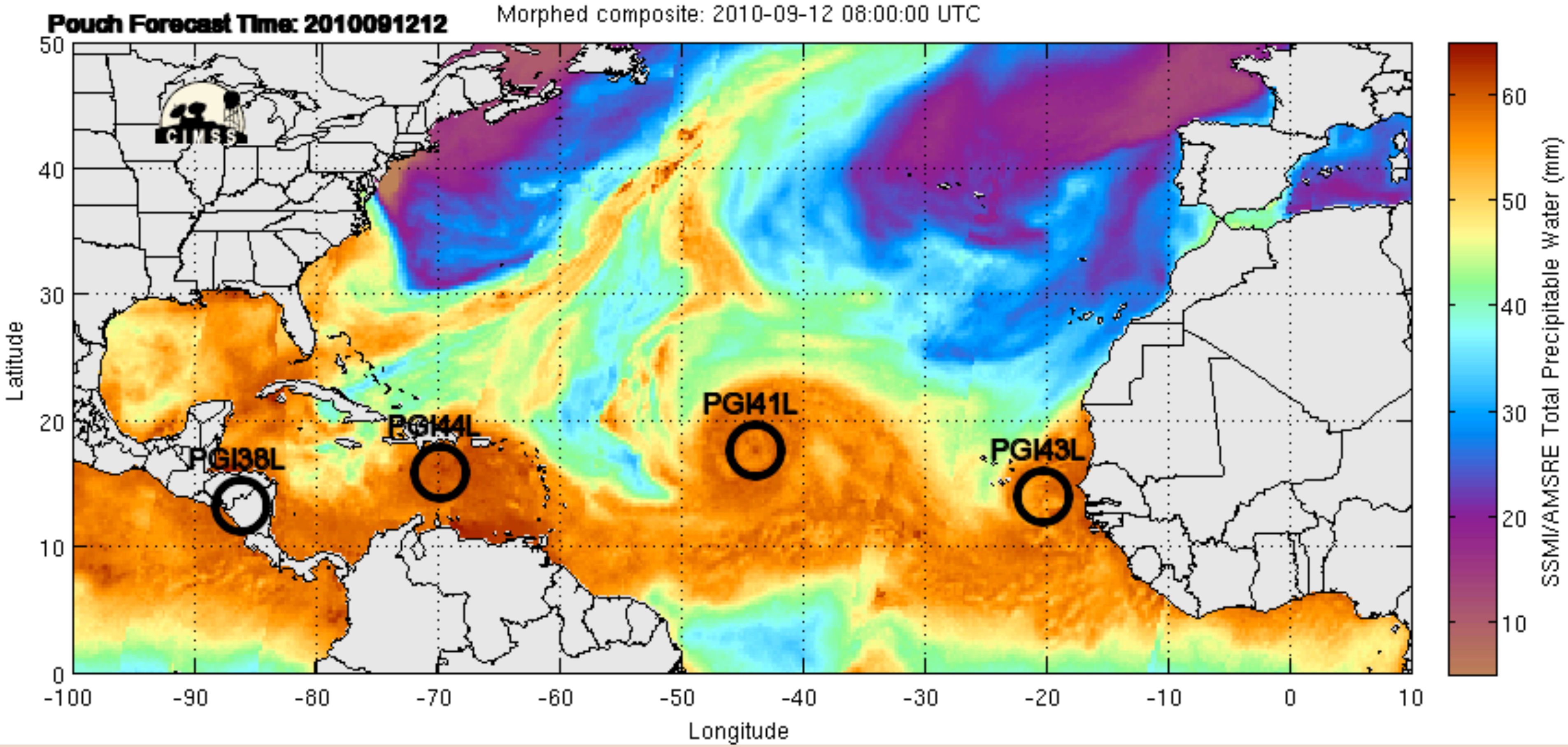
Longitude
SSMI/AMSRE Total Precipitable Water (mm)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Longitude
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PGI38L
PGI43L
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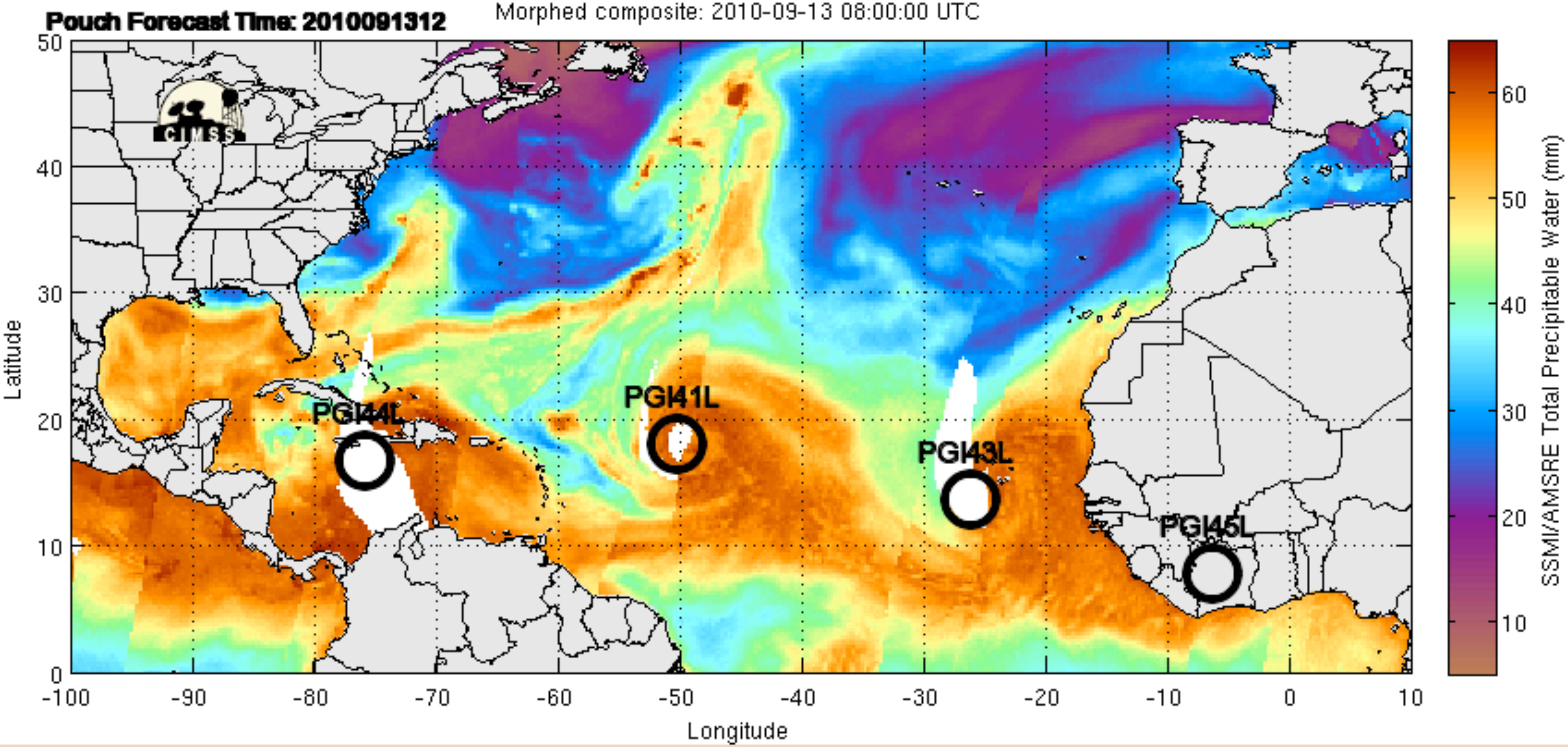
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Longitude
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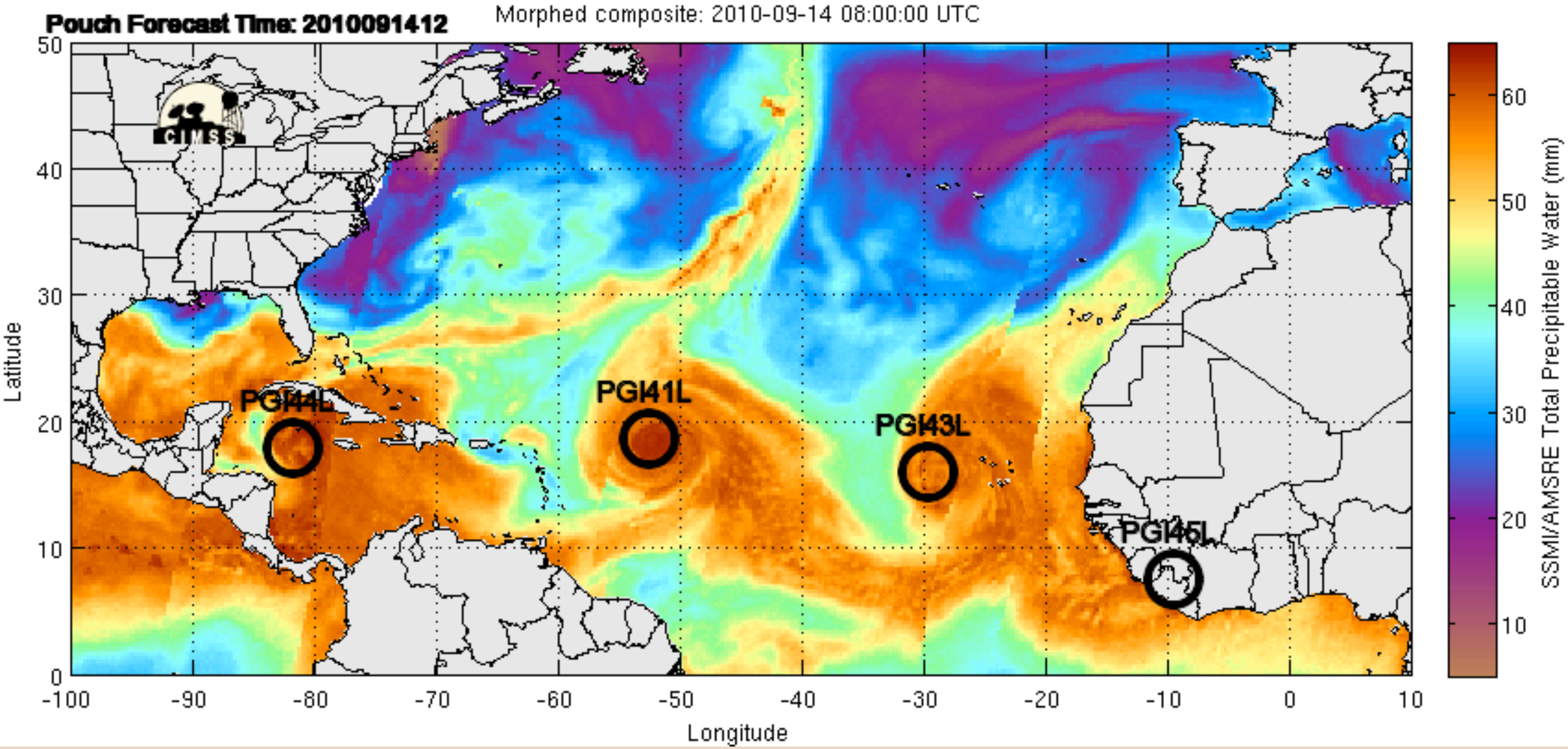
0
10
SSMI/AMSRE Total Precipitable Water (mm)
60
50
40
30
20
10



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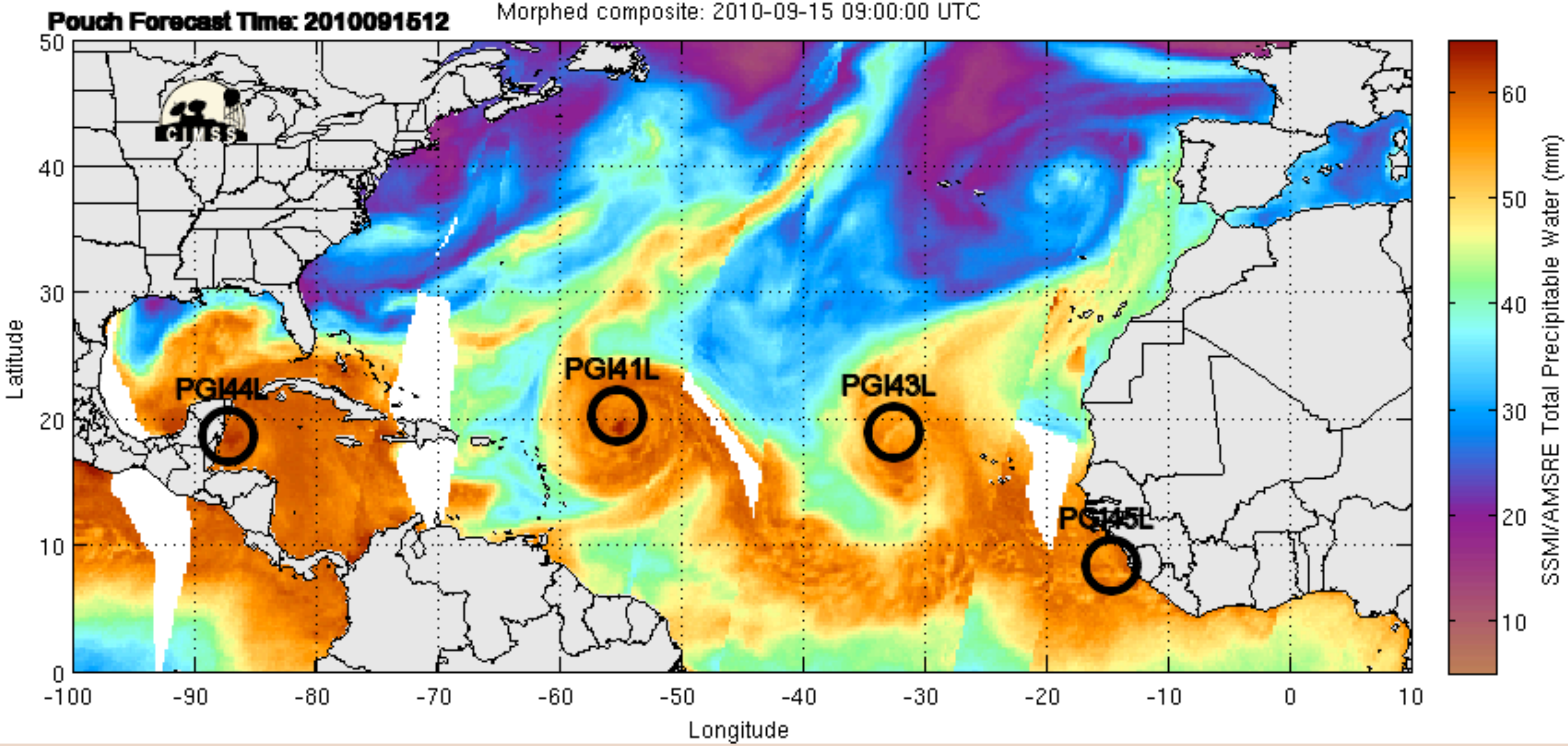
SSMI/AMSRE Total Precipitable Water (mm)



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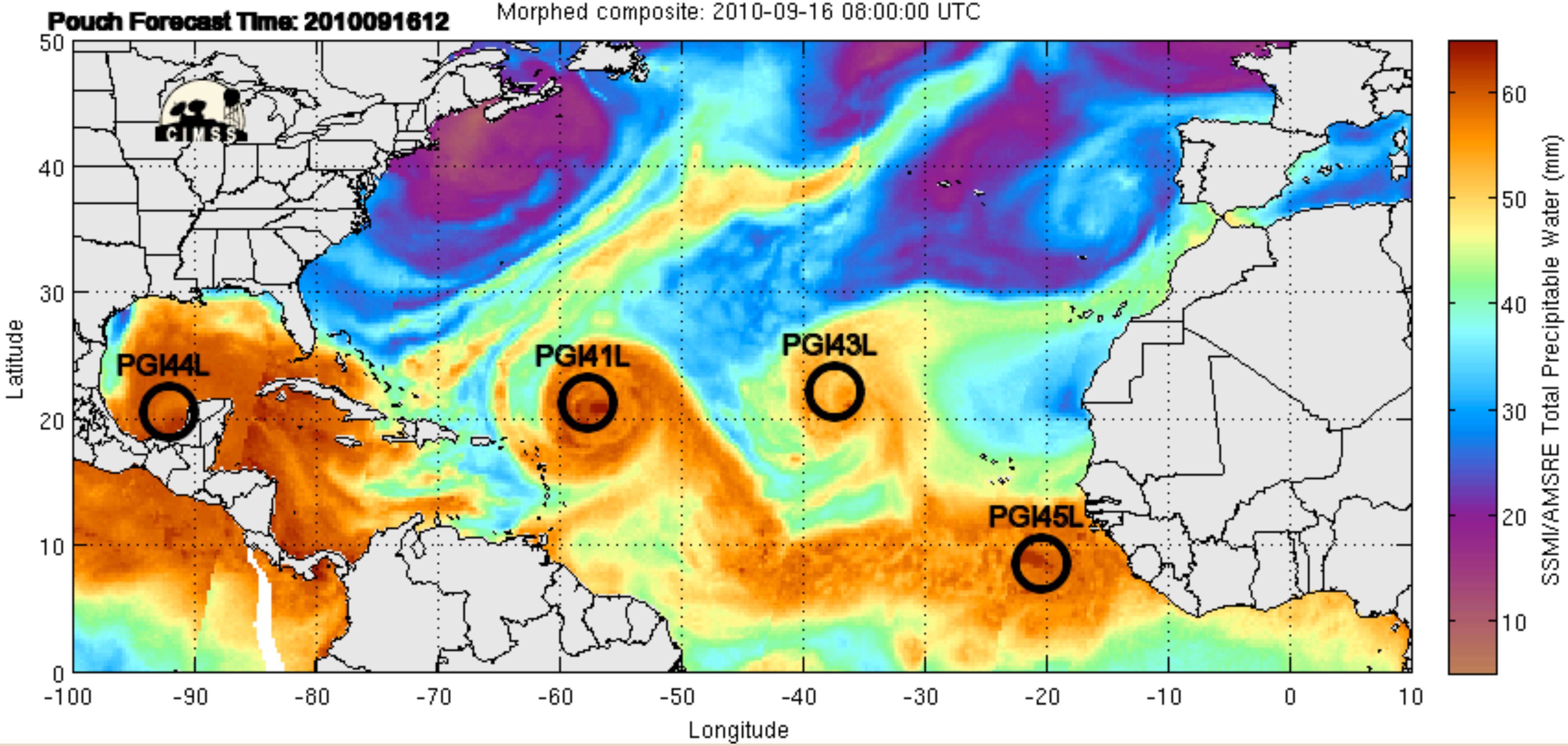
Longitude
SSMI/AMSRE Total Precipitable Water (mm)



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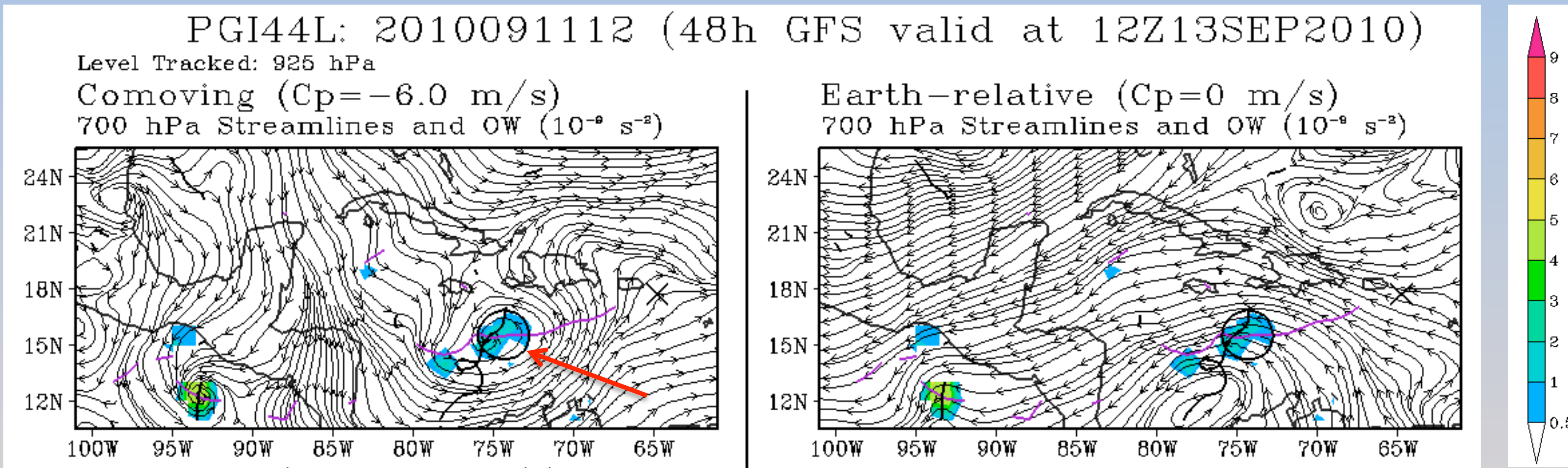
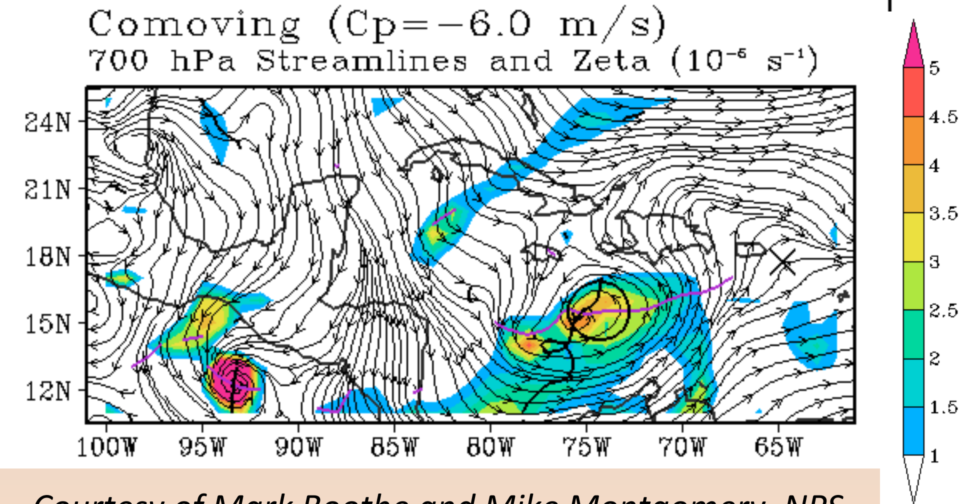
30
20
10
0
-100
-90
-80
-70
-60
-50
-40
-30
-20
-10
0
10
60

Numerical Model Depiction of Recirculation Regions





Courtesy of Mark Boothe and Mike Montgomery, NPS

1. Features usually well captured in short-range forecasts
2. Co-moving frame is crucial
3. Vorticity without deformation is more discriminating

$$OW = (v_x - u_y)^2 - (u_x - v_y)^2 - (v_x + u_y)^2$$

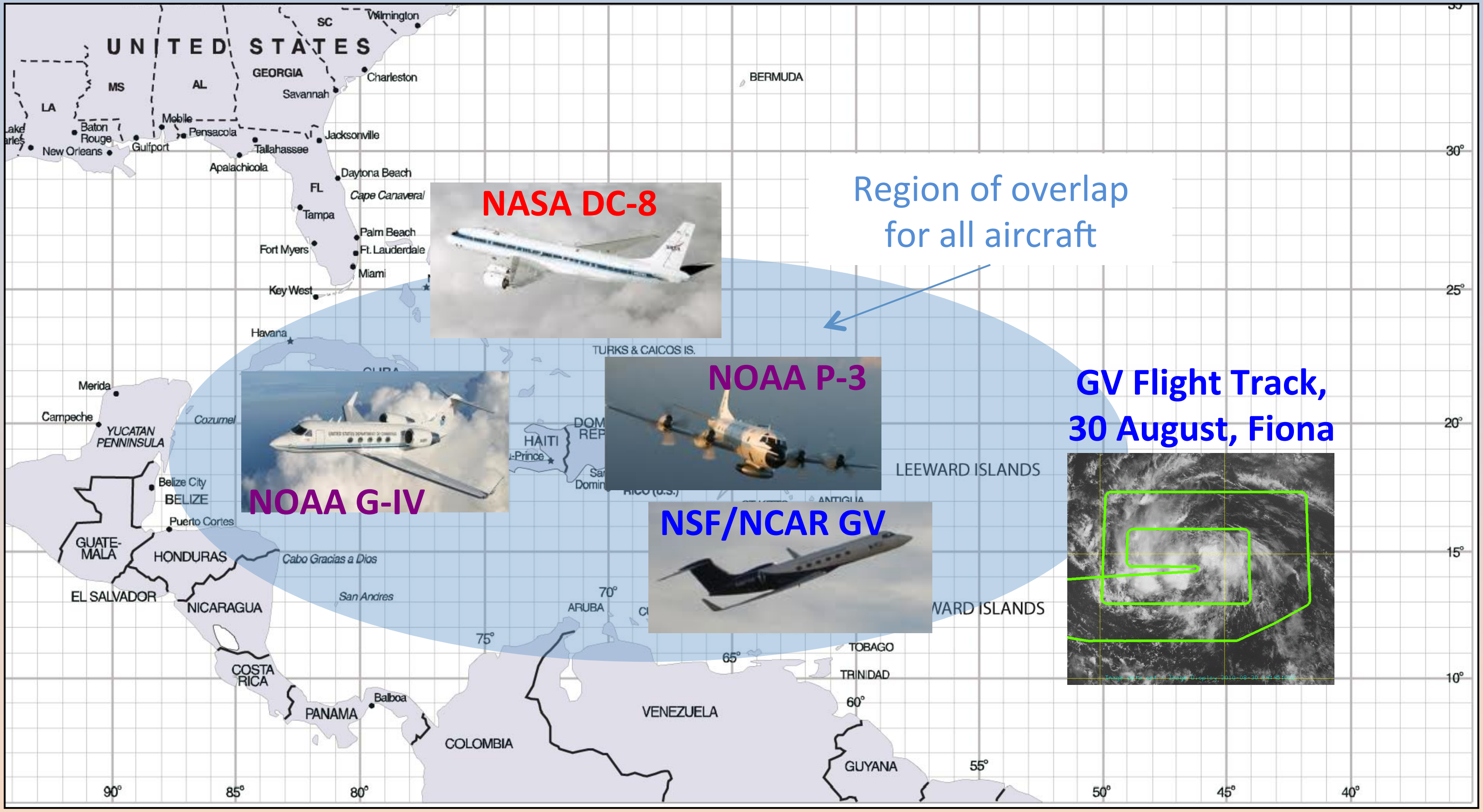
Dropsonde-equipped Aircraft used in 2010

NSF PREDICT: GV (Montgomery et al., 2012: BAMS)

PRE-Depression Investigation of Cloud systems in the Tropics

NOAA IFEX: G-IV and P-3 (Rogers et al., 2013, BAMS)

NASA GRIP: DC-8 (Braun et al., 2013: BAMS)



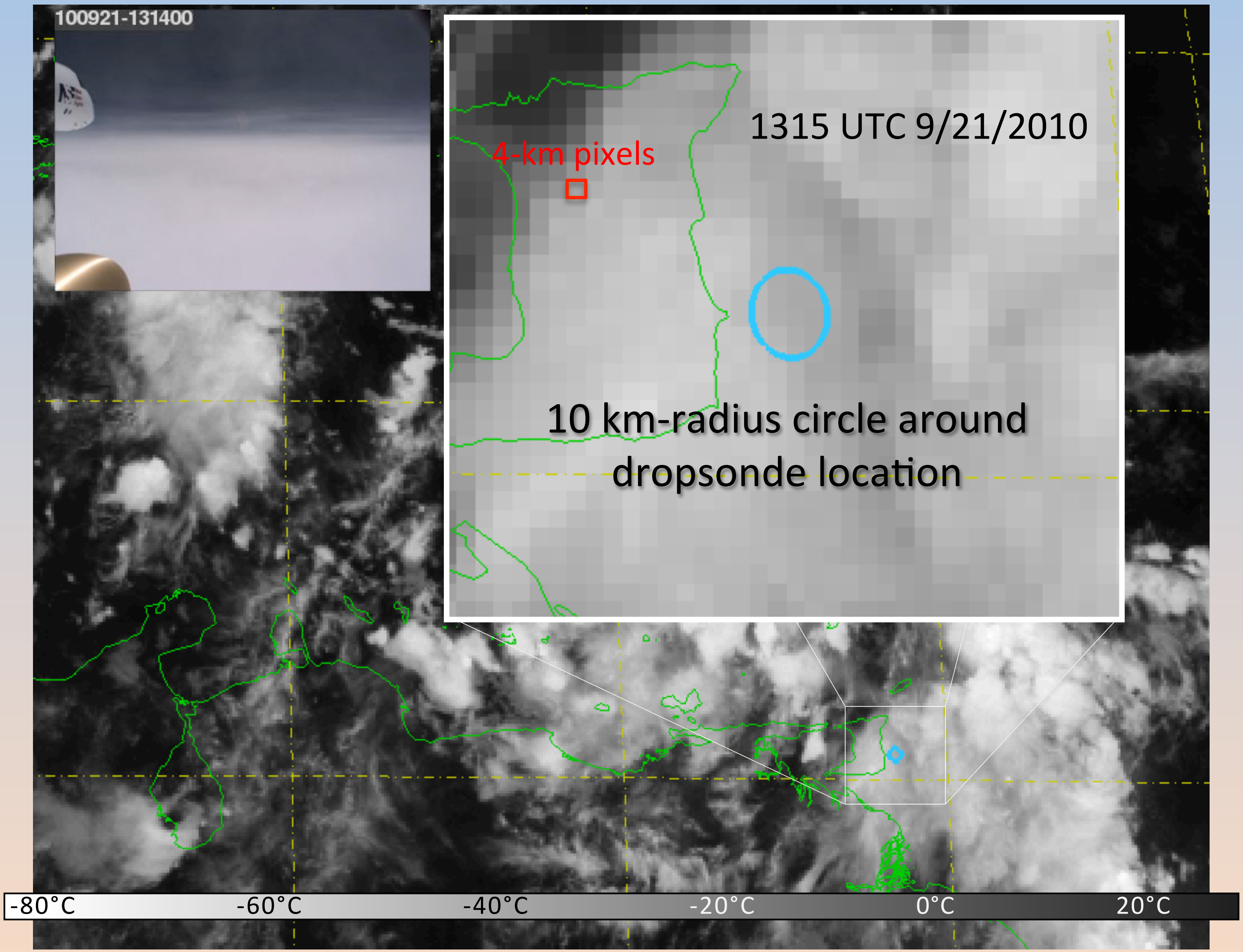
Questions

- Is convection fundamentally different within recirculation regions than elsewhere in the tropics?
- How are these thermodynamic signatures related to dynamics?
- Do these signatures distinguish developing and non-developing cases?
- Can the observations point to the most appropriate theoretical model of hurricane formation?

Stratification of Dropsondes

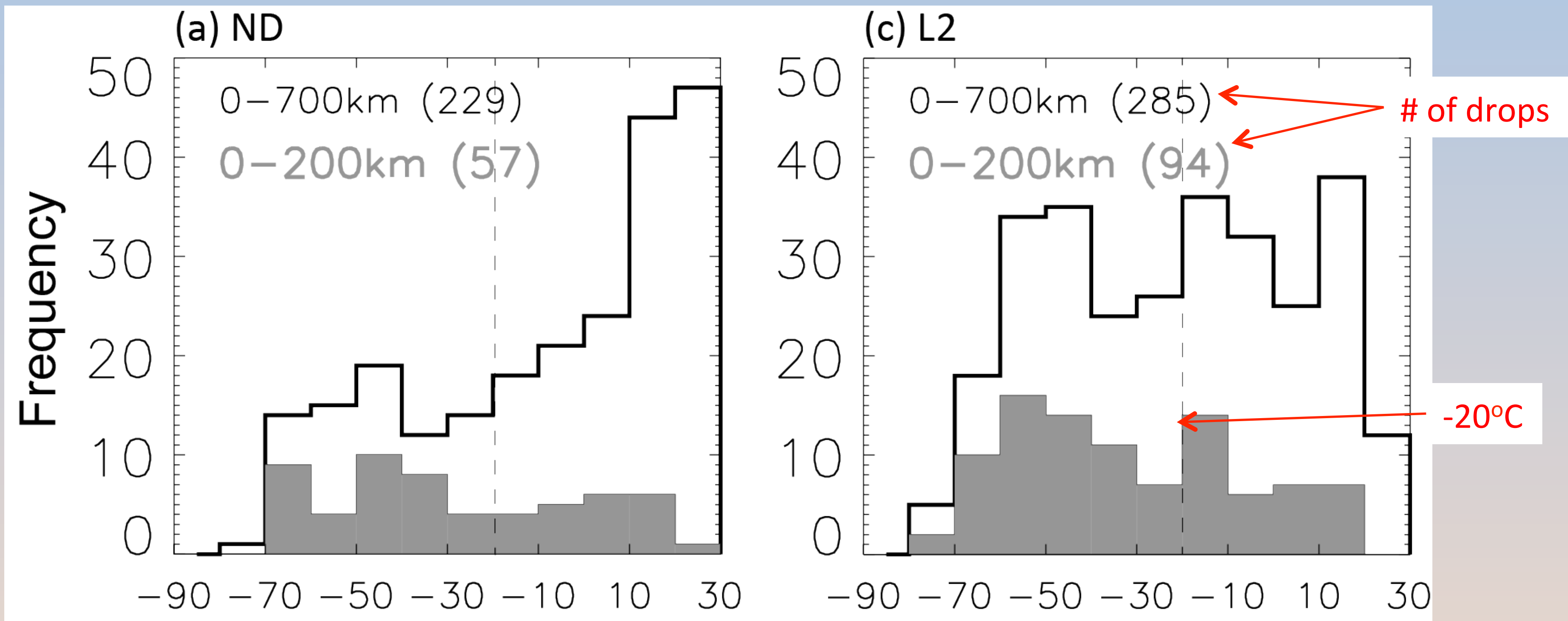
1. Average IR temperature within 10-km of drop
   - "Cold" cloud tops (< -20C)
   - "Warm" cloud tops (> -20C)
2. Stage of development
   - ND – non-developing
   - L2 – developing, < 2 days prior to genesis
3. Radius from "pouch" center *(Dunkerton et al. 2009, ACP)*
   - < 200 km (also examined 300 km)
   - > 200 km

The Dropsonde "Neighborhood"



Histograms of cloud-top temperature

Averaged within 10-km of dropsondes



Perturbations (anomalies)

1. For temperature, remove large-scale environment
    - Changing conditions over longitude/season
    - Reducing variance within composites
2. Reference state defined by NCEP analysis
    - Nearest 6-h analysis
    - 1000-km radius from center
    - Mandatory pressure levels
3. No reference state for relative humidity, or air-sea temperature difference

Profiles in Developing and Non-developing Systems

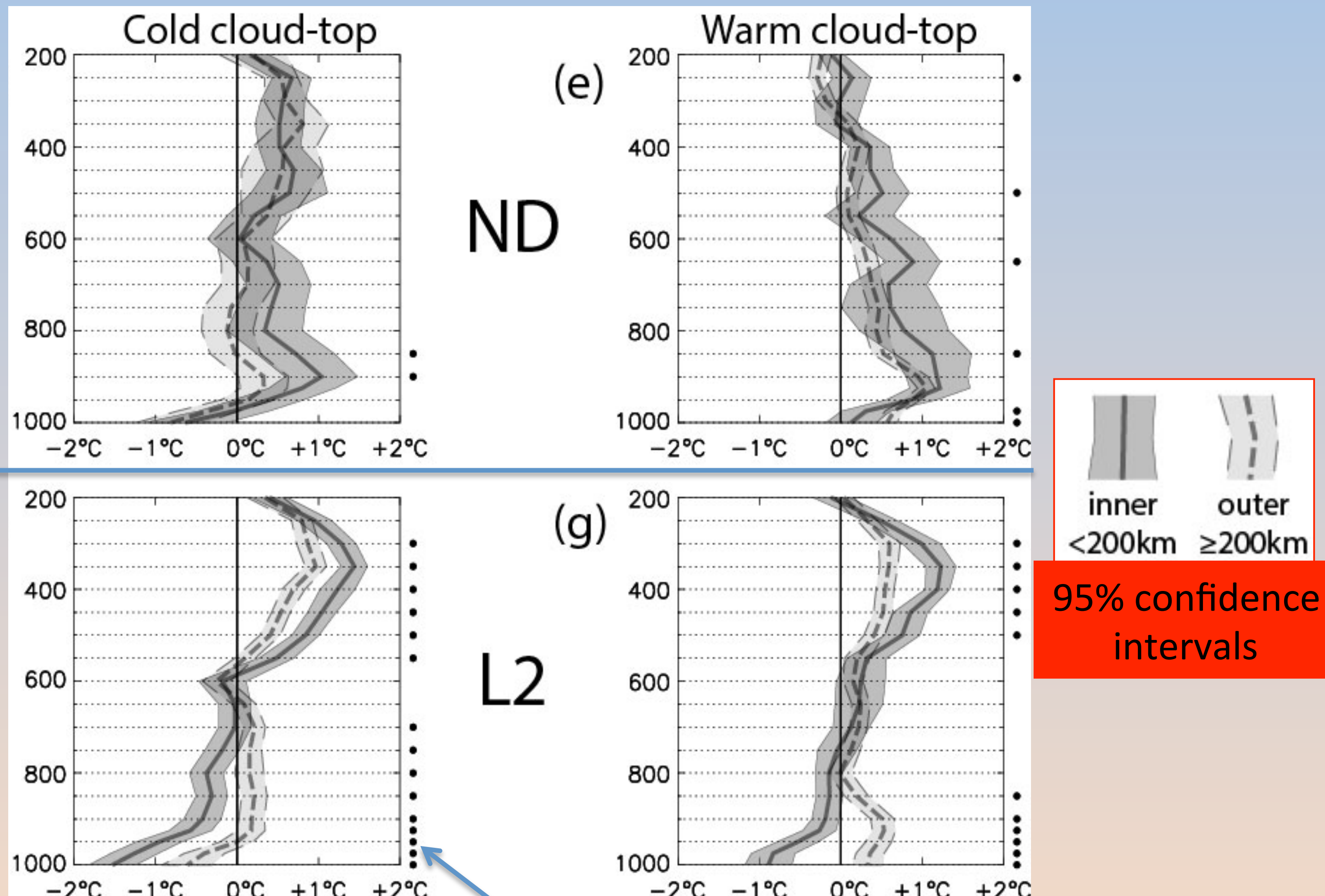
(comparison of inner (< 200 km) and outer (> 200 km) radii)

Non-developing Composite

Less Stable Inner Region

Developing Composite

More Stable Inner Region



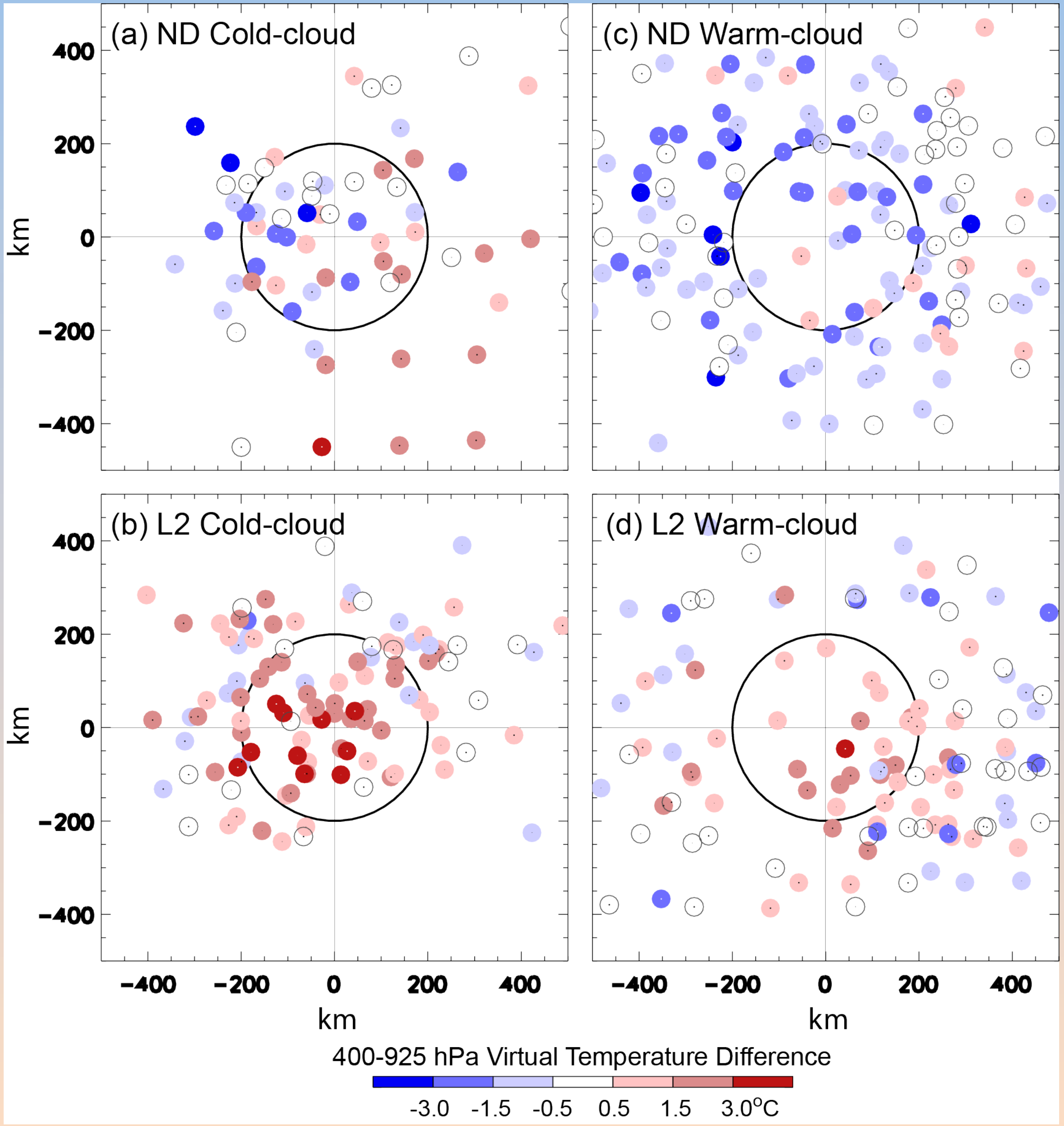
Temperature Anomaly from Large-scale Mean

Statistically significant difference: inner vs. outer

Spatial Distribution of Stratification Anomalies

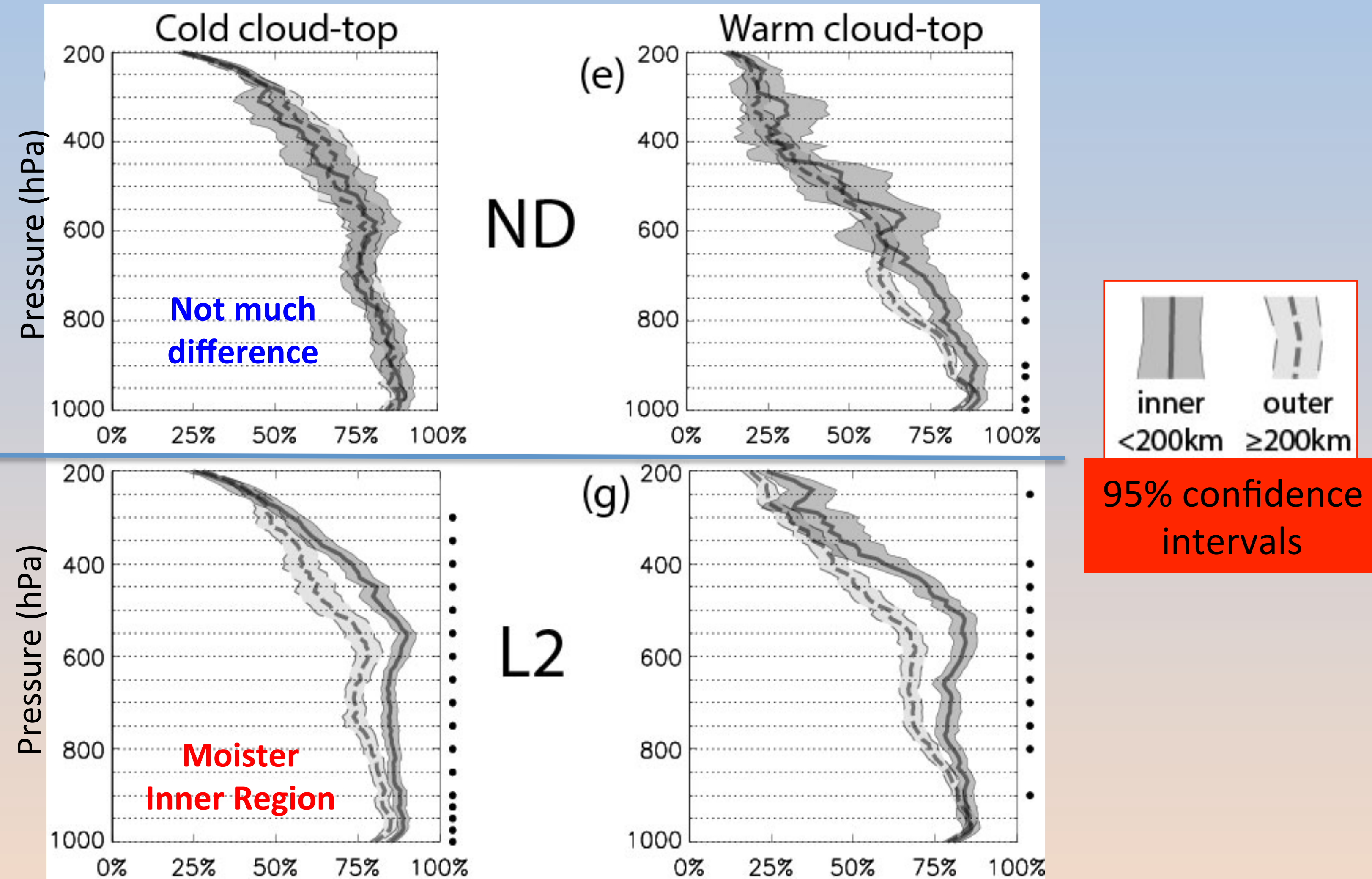
Red:
warm aloft,
cool beneath

Blue:
Cool aloft,
warm beneath



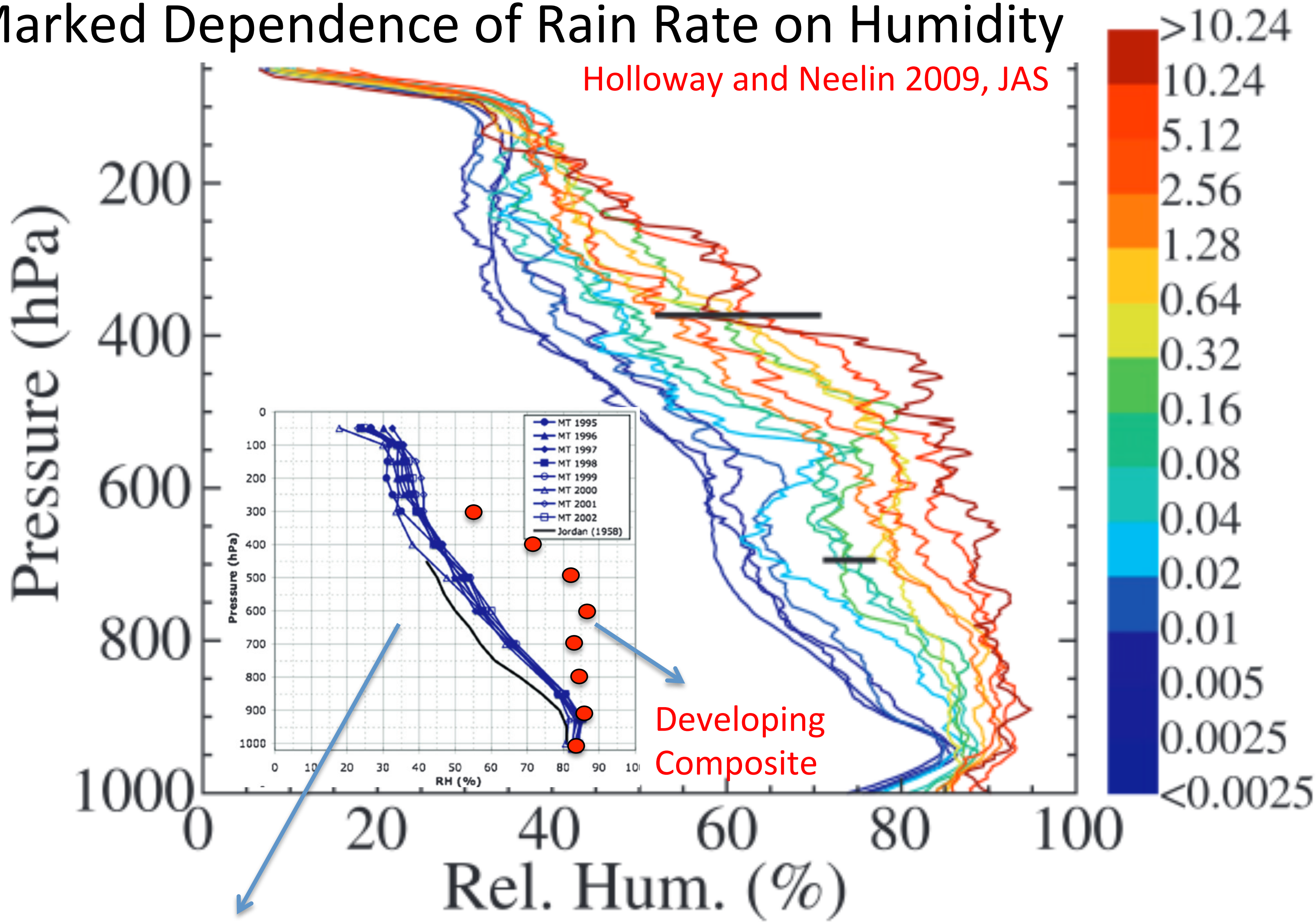
Profiles in Developing and Non-developing Systems

(comparison of inner (< 200 km) and outer (> 200 km) radii)



Relative Humidity

Marked Dependence of Rain Rate on Humidity

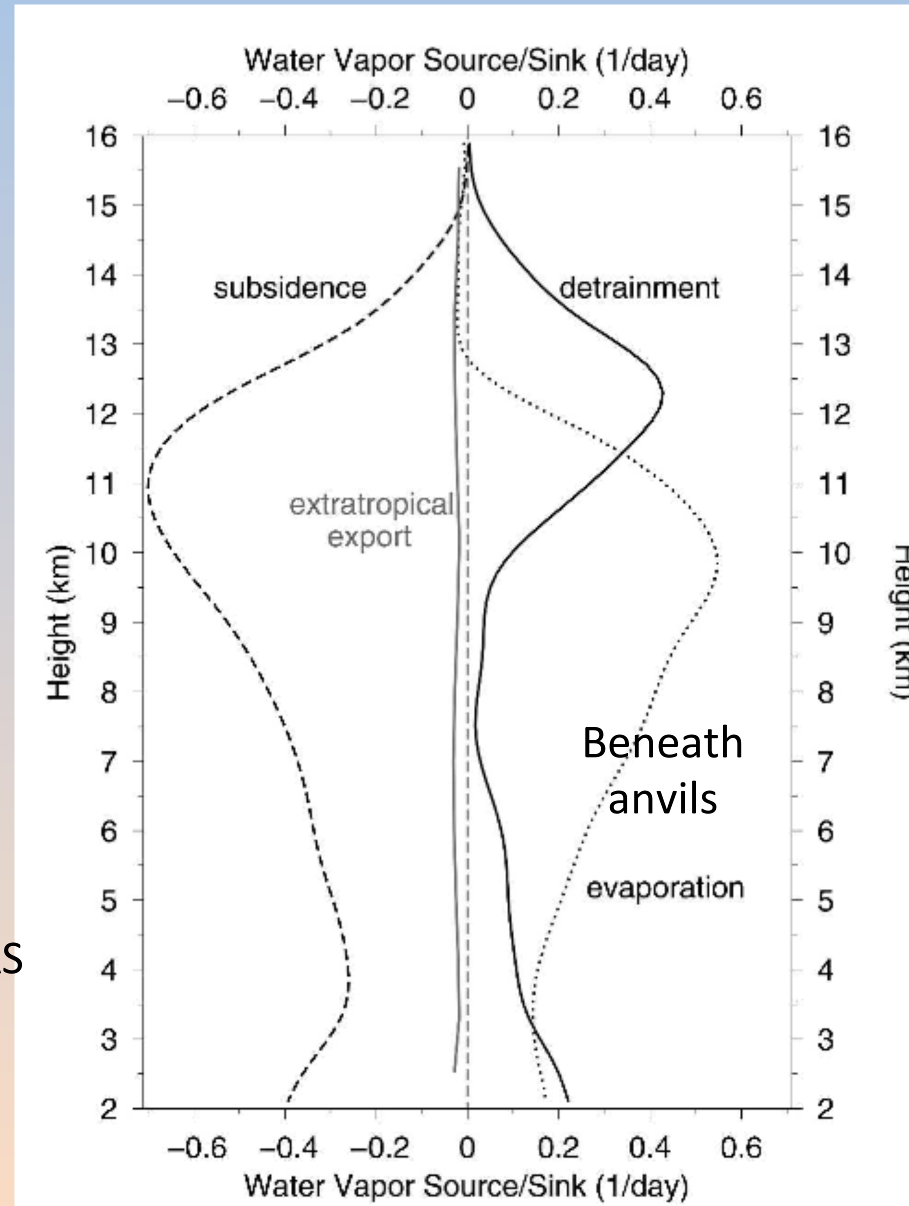


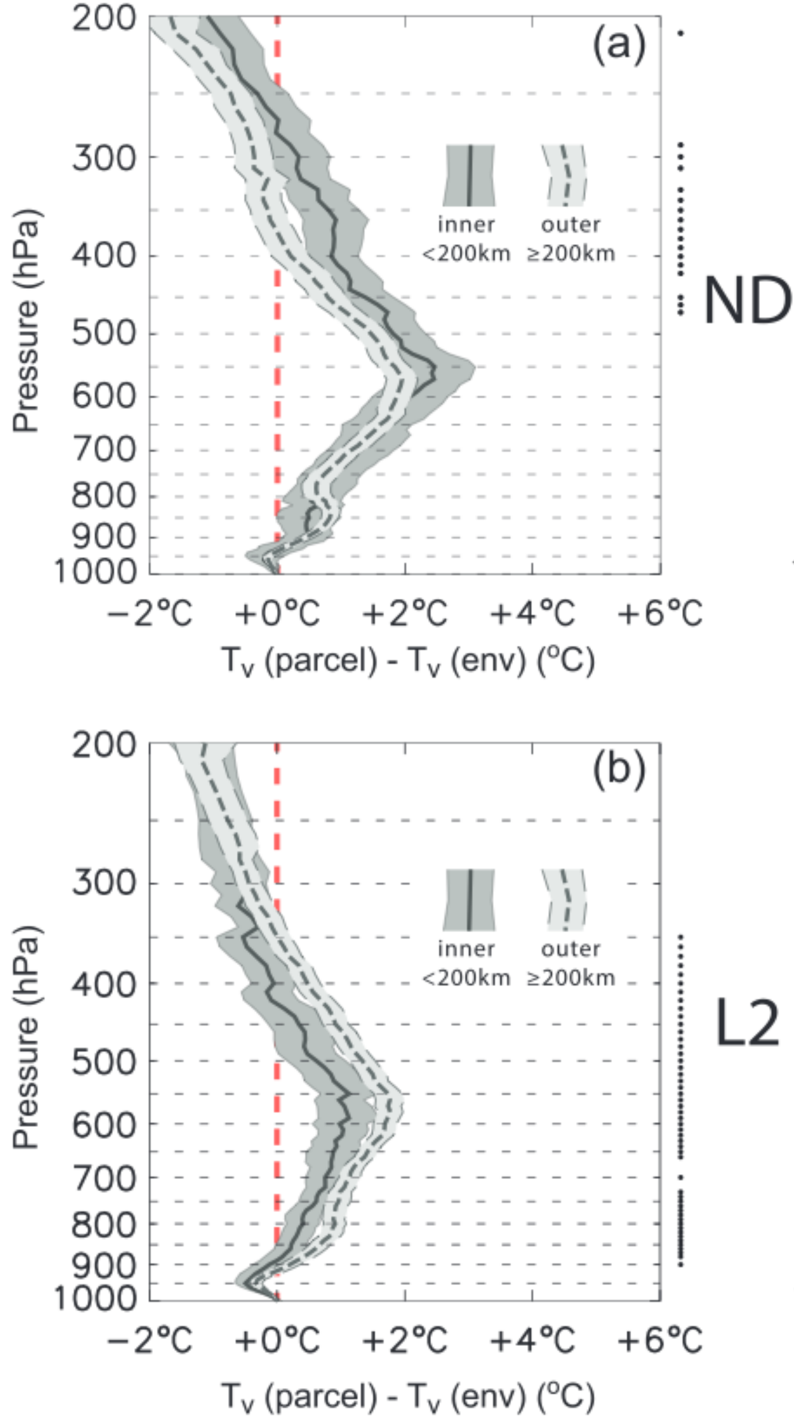
Moist Tropical Sounding Composite
Dunion, 2011: J. Climate

Where does the Moisture Come From?

From the NSF/NCAR GV

Folkins and Martin, 2005: JAS





Buoyancy

of hypothetically lifted air parcels using soundings to define the "environment"

+ means parcel accelerates upward

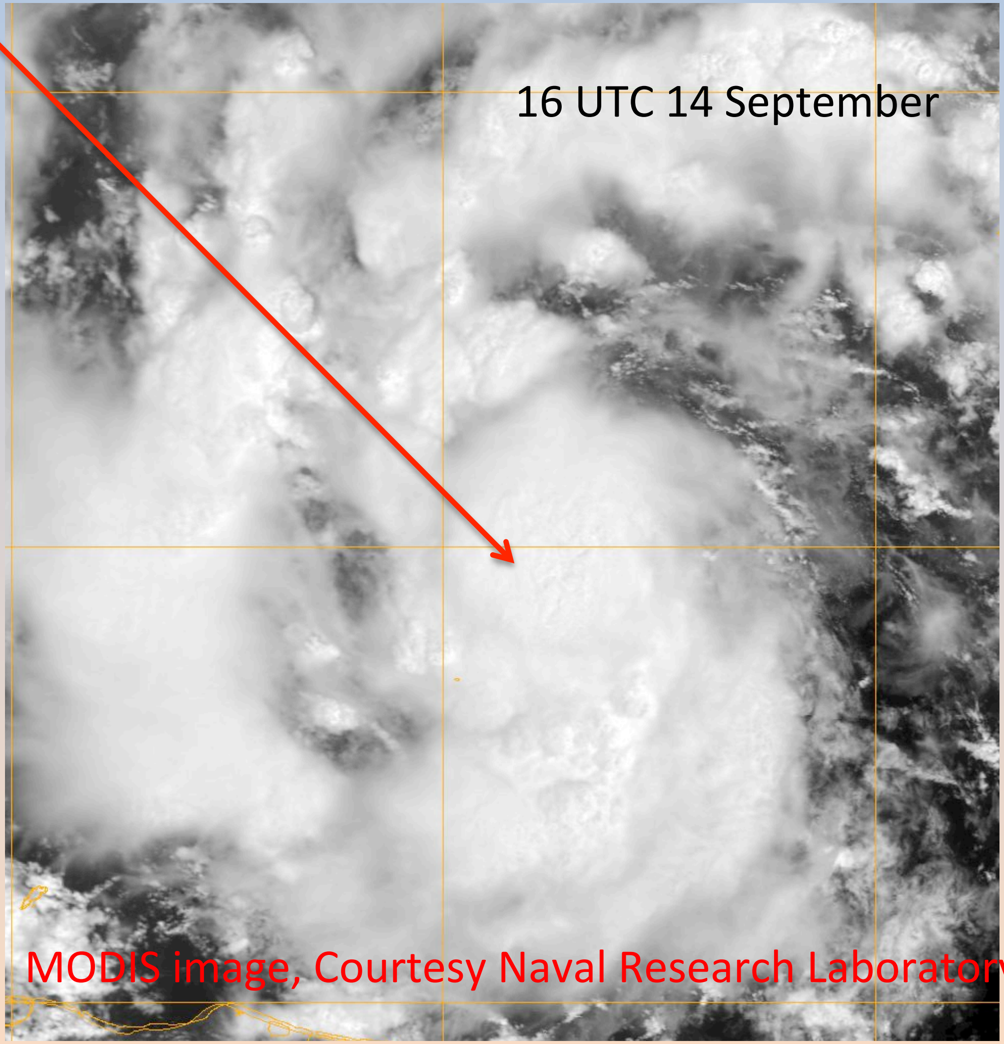
- Lift from 100 m
- Entrain at 10%/km
- Assume ½ of condensate falls out

- Core of developing cases is more stable
- Parcels less buoyant

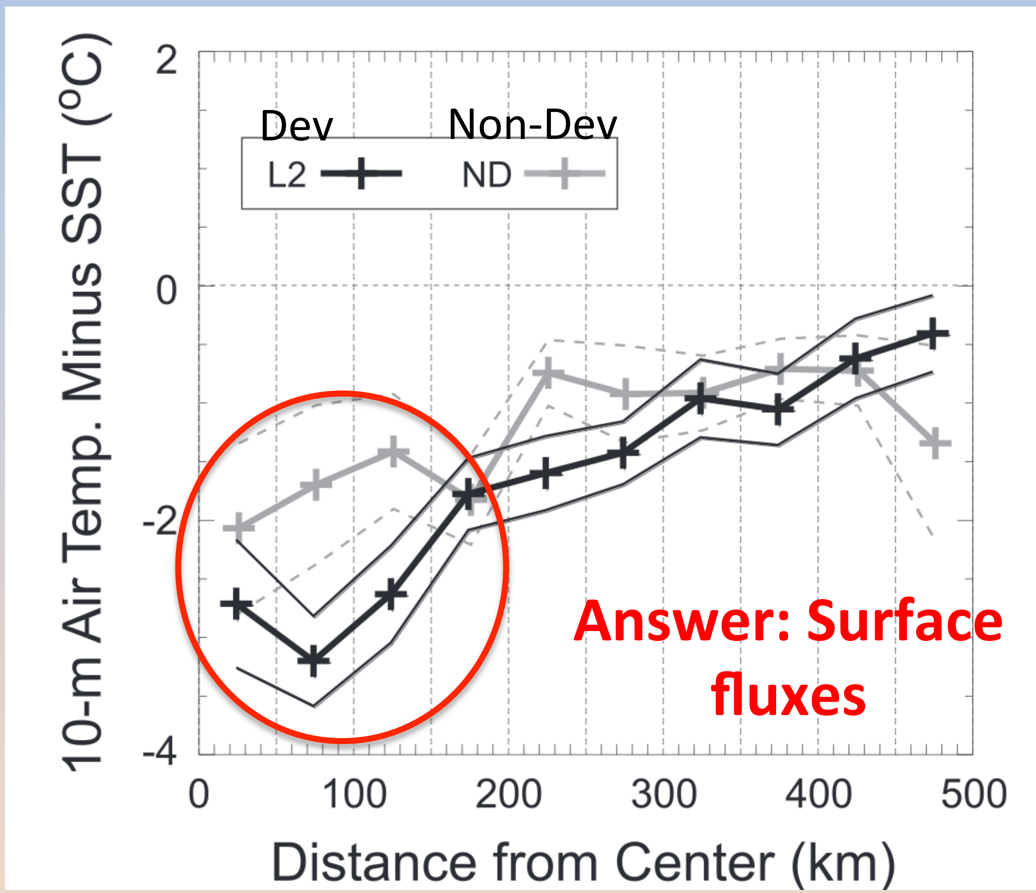
So, wait…. The atmosphere is more stable…so where does the intense convection come from that characterizes TC formation?

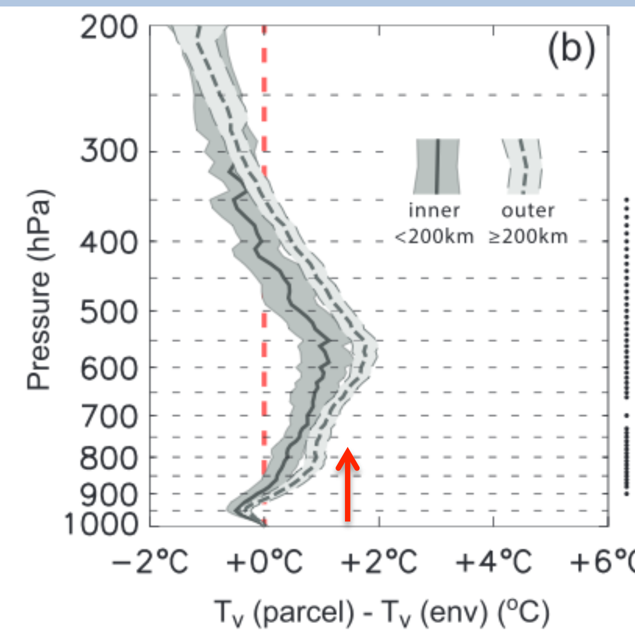
1. Some other process rapidly destabilizes the atmosphere.

2. The really intense convection is coincident but not causal.



Surface fluxes and Boundary-layer Recovery

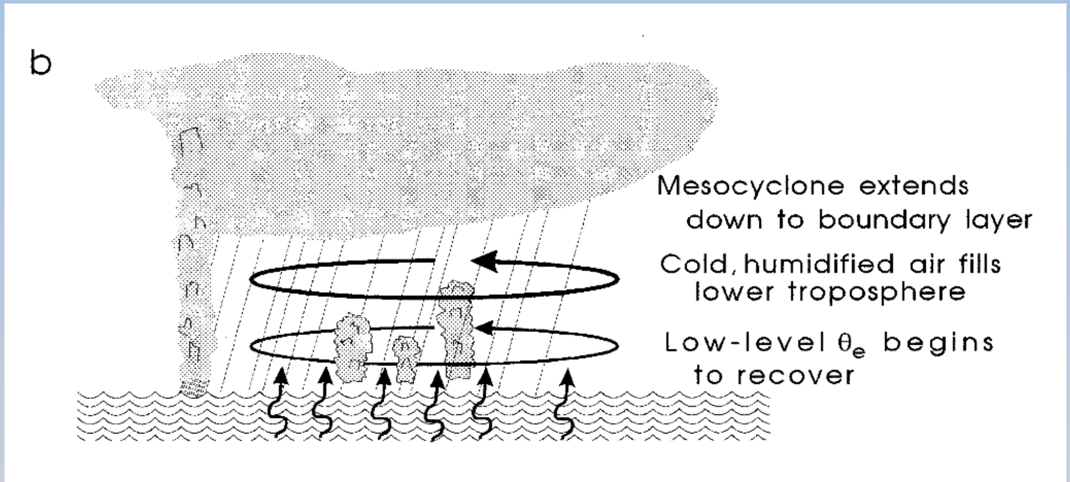




Wind speeds NOT significantly different

Recovery time scale: $T=H/C_EV$, 12-24 h

Scenario echoes Bister and Emanuel's Schematic

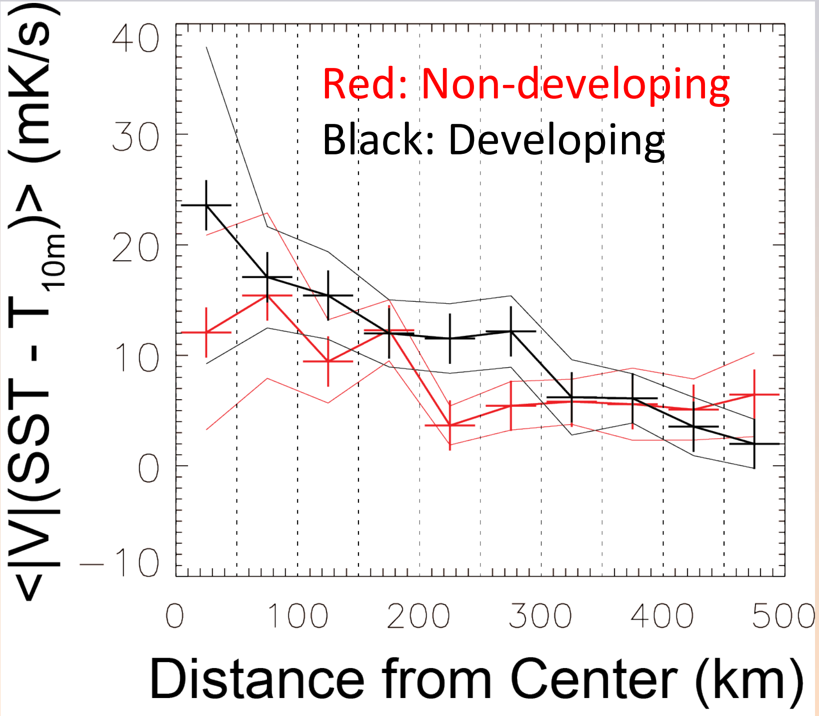


However:

1. Unlikely that mesoscale cyclone descends through the process shown above

2. Importance of storm-induced fluxes suggested but not clear

Average of wind speed times air-sea temp. diff.



Intermittency of Deep Convection

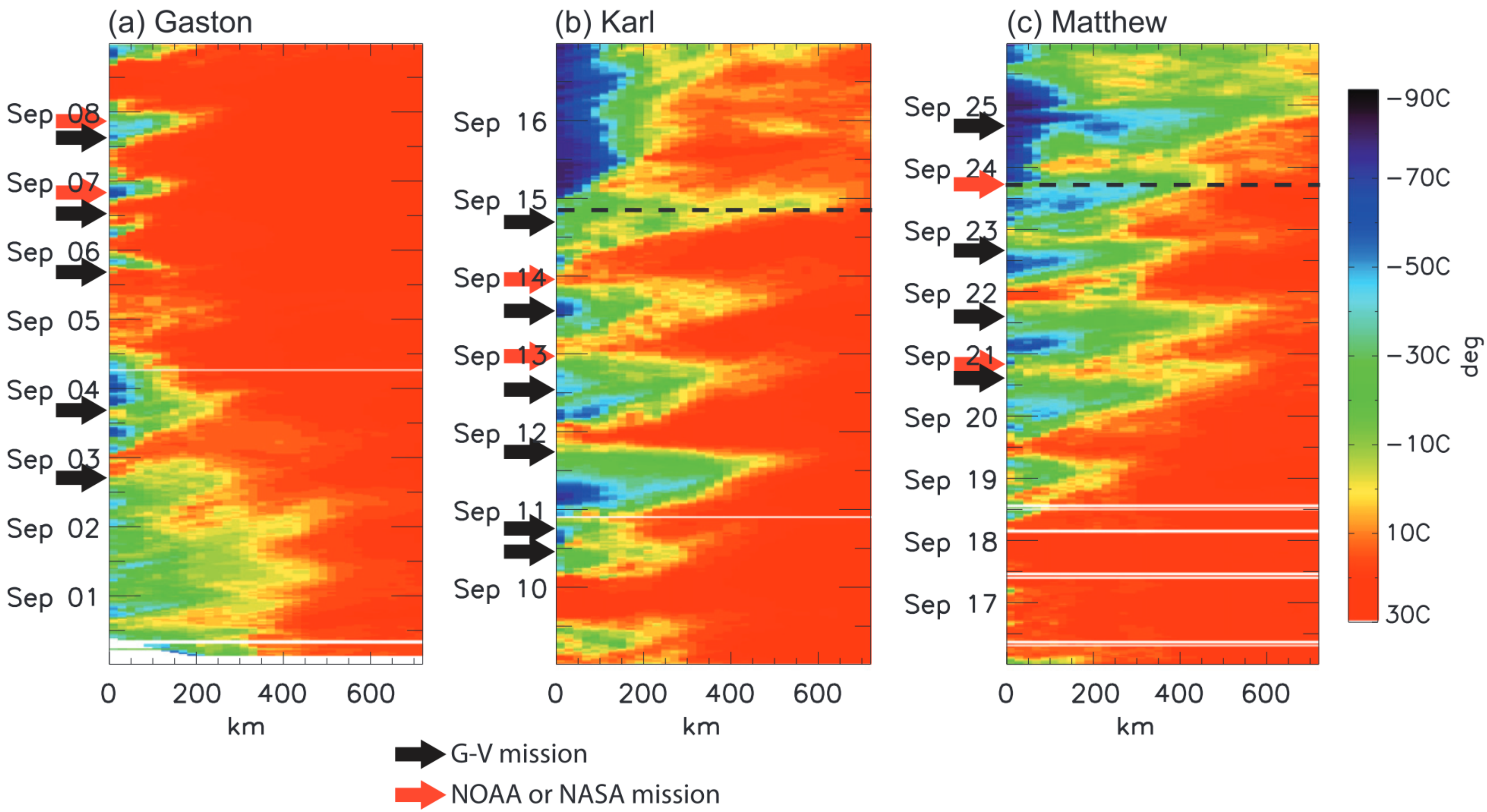
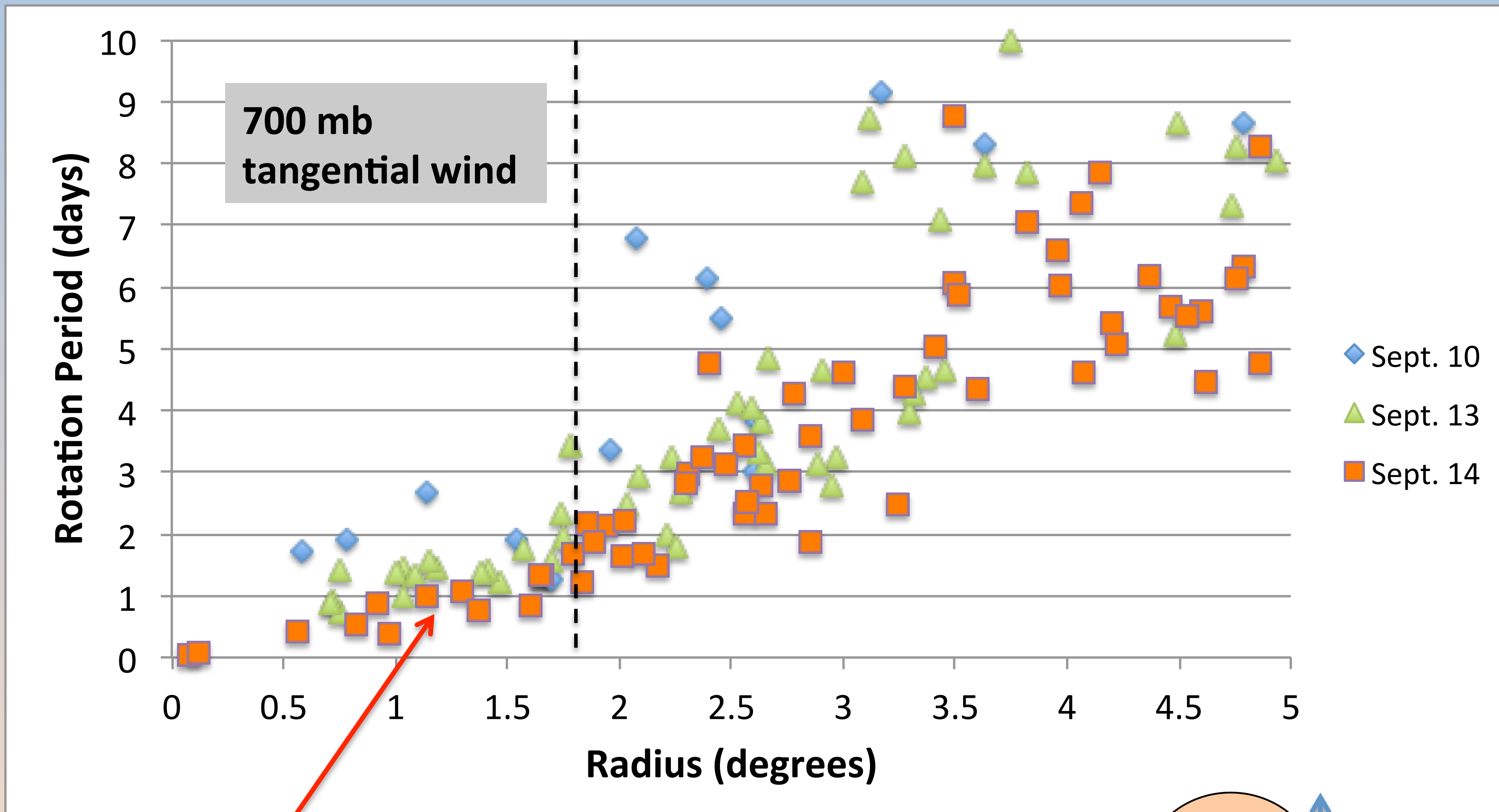
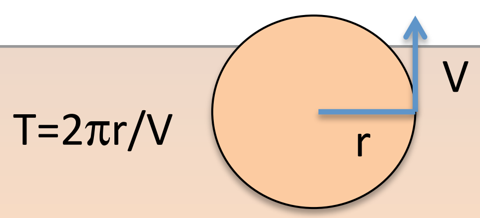


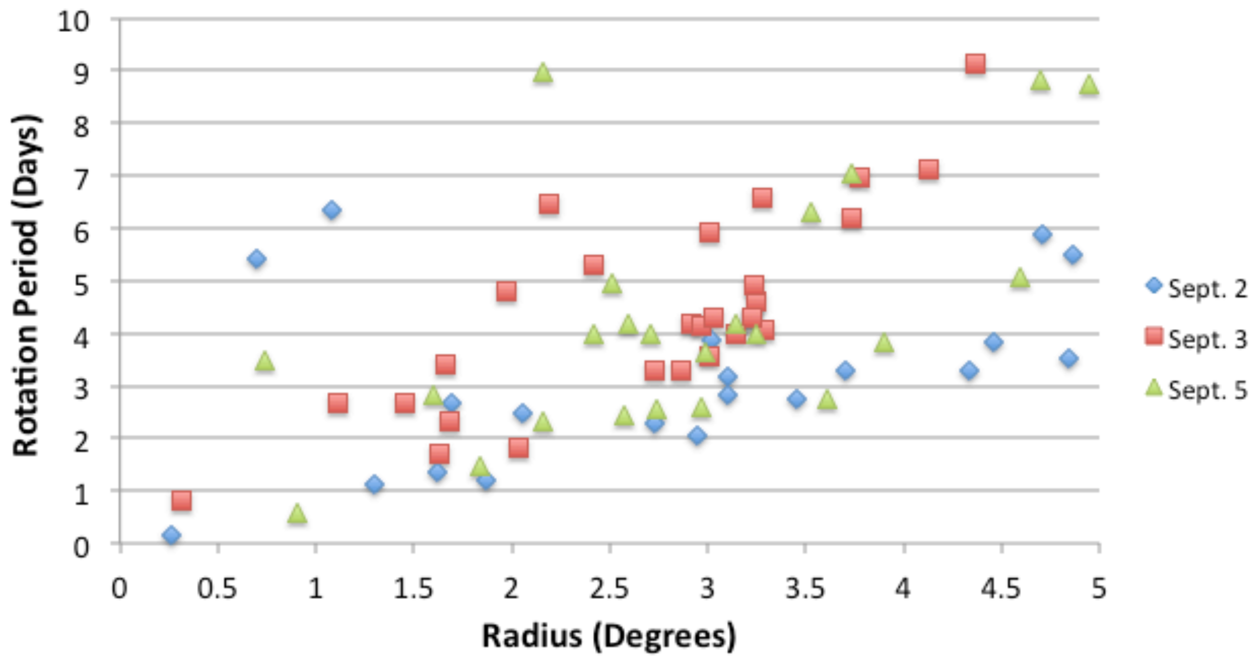
FIG. 3. Time–radius diagrams of cloud-top temperature derived from Geostationary Operational Environmental Satellite (GOES) IR data, where the 75th percentile temperature within each radial ring of 20-km width is plotted. Arrows indicate when dropsonde missions occurred (black for GV, red for NOAA or NASA). Dashed lines denote time of tropical storm formation for Karl and Matthew.

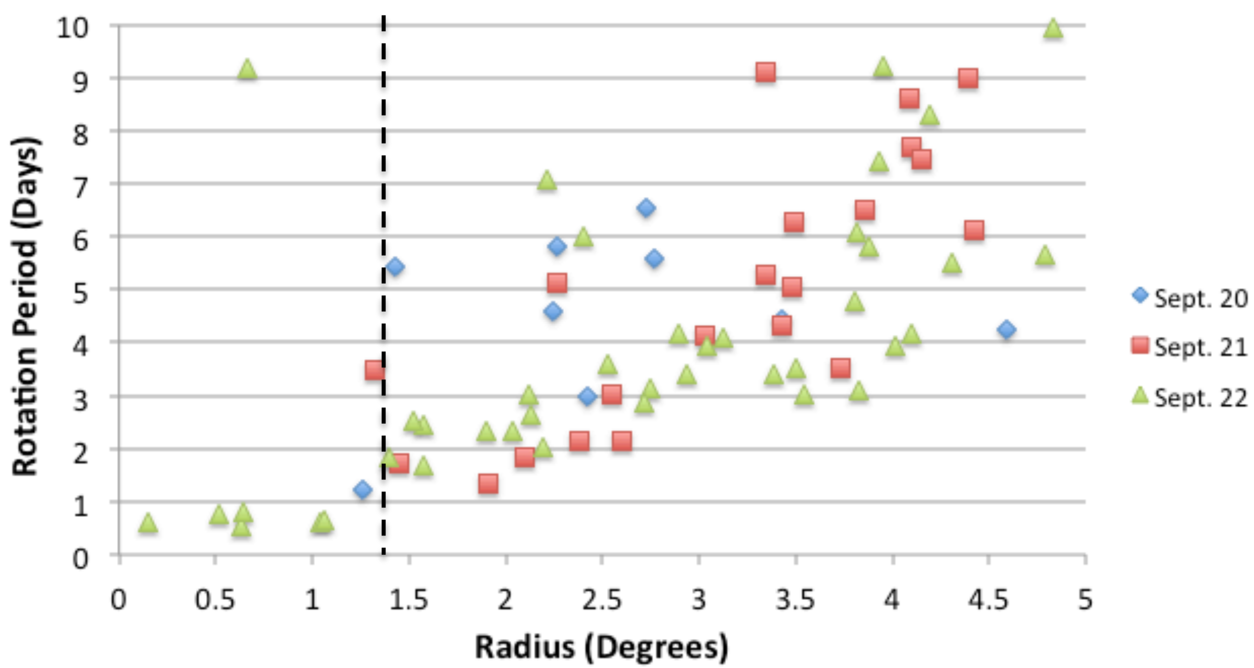
What is Special About "200 km"?



Advective time scale comparable to recovery time scale.







700 mb tangential wind

Gaston: Weakened with time

Matthew: Developed on Sept 23rd

Summary

- Findings are consistent with several previous studies
  - Emanuel (TEXMEX) and Raymond (TEXMEX and TPARC)
  - Dunkerton, Montgomery, Wang, Tory (reanalysis data, TPARC)
  - Both are relevant but not complete
- What is new here?
  - Direct observations that reconcile differences in previous studies
  - Scale for the region of thermodynamic transformation: time scales for recirculation and recovery
  - Formation of a Lagrangian boundary? Radial gradient of potential vorticity for $r > 200$ km

Summary

- Tropical waves and hurricane formation

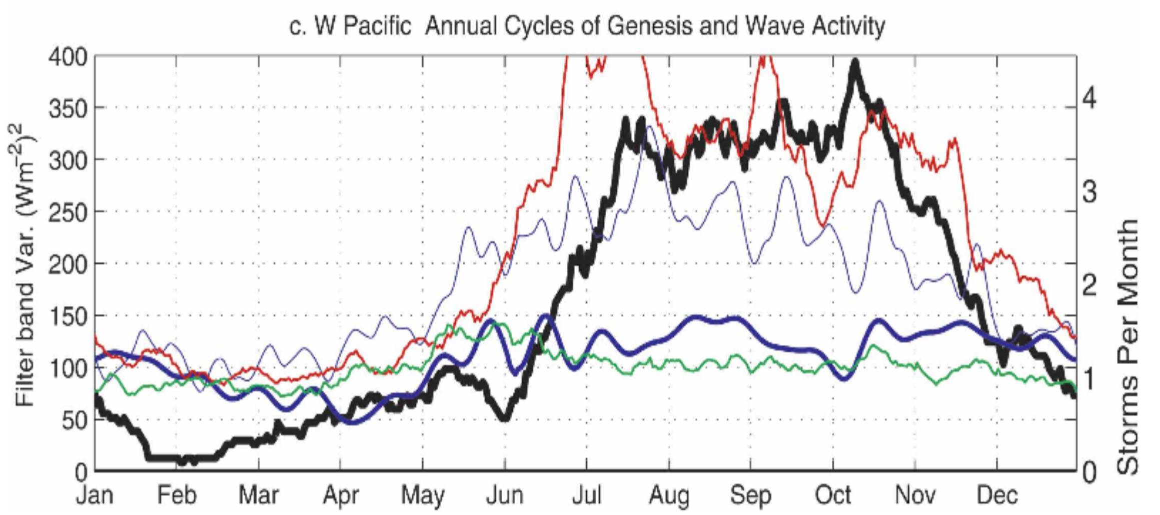


FIG. 4. Mean annual cycles of storm genesis (storms per month) and of OLR variance in the indicated filter bands for each of the six cyclone basins. The line colors are as follows: cycle of cyclogenesis (black); MJO (heavy blue); ER (thin blue); MRG–TD type (red); and Kelvin (green). Variance values are the squared filtered OLR anomalies averaged over the day of the year and smoothed for plotting with a 5-day running mean.

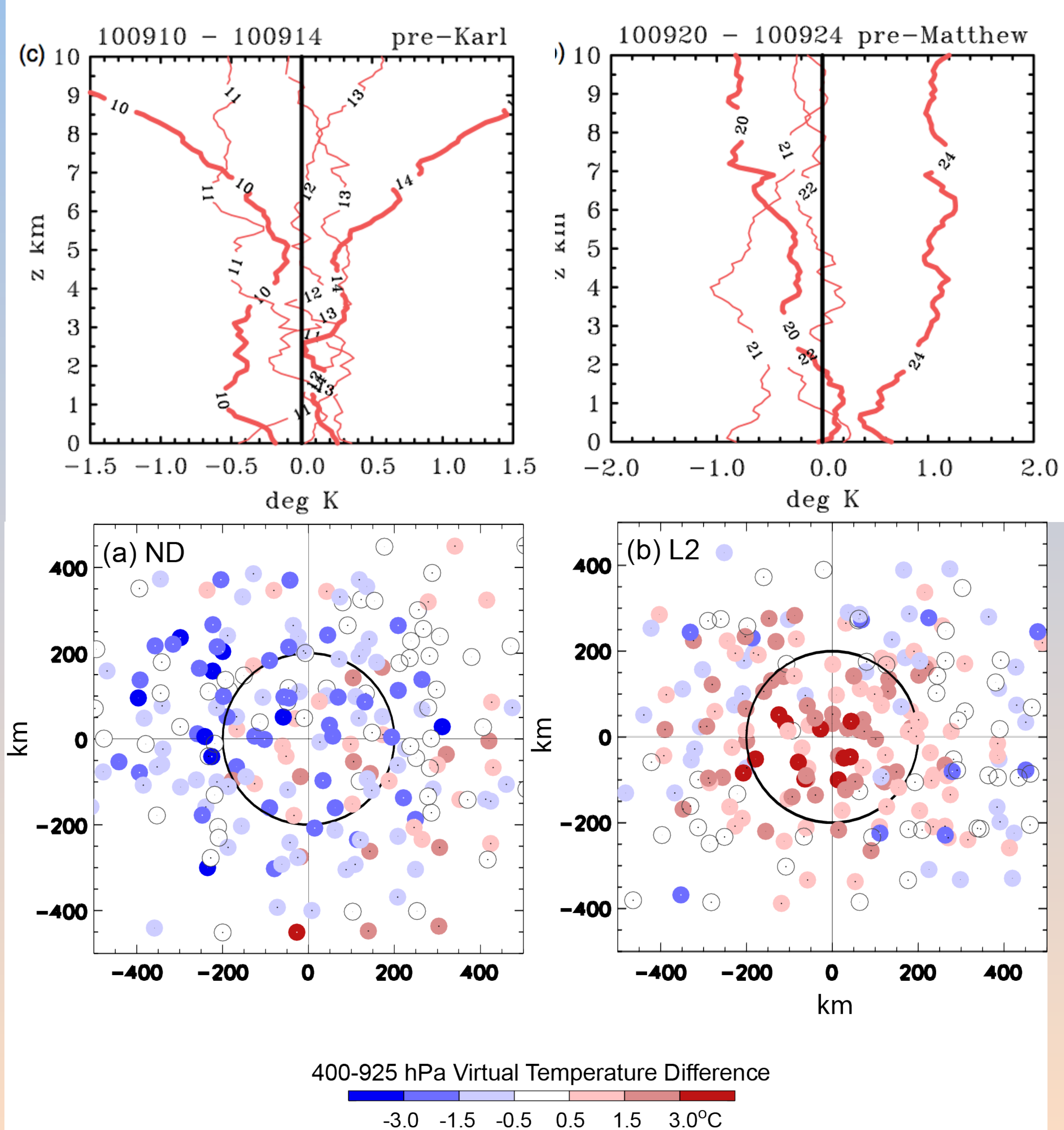
"…the relevant wave structure is the baroclinic, first internal vertical mode, allowing the waves to both modulate vertical shear and to produce opposing vorticity anomalies between the lower and upper troposphere…"

Frank and Roundy, 2006: MWR

Then what happens???
Many wave periods, not many cyclones

- What I have left out
  - Vertical shear and vortex alignment (subject of another talk)
  - Observations that can resolve the evolution of convective features (the next frontier)

Backup Slides

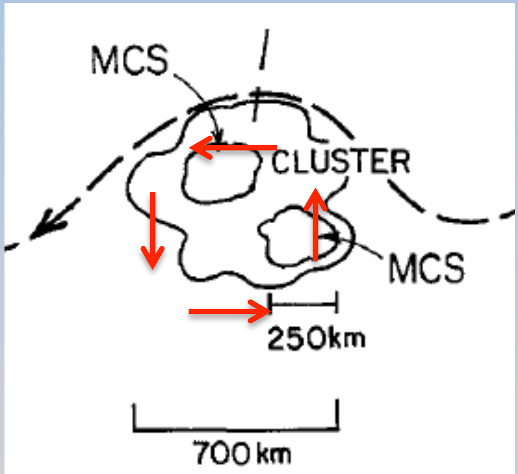


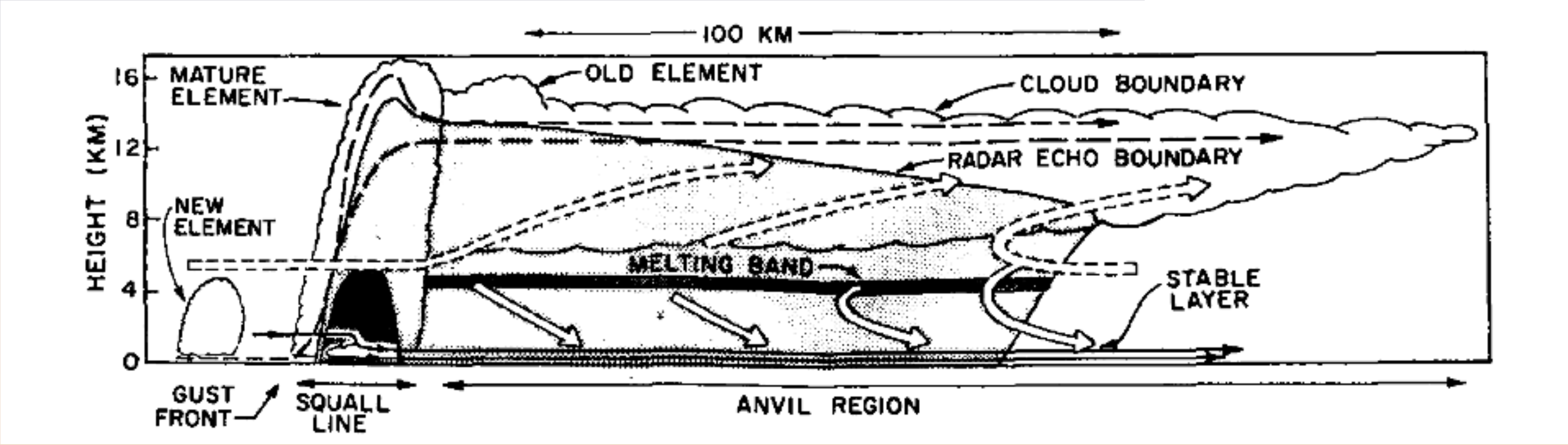
Smith and Montgomery (2011): Profiles warm throughout

Davis and Ahijevych (2013): The big signal is within 200 km of the center (also Z. Wang, 2012)

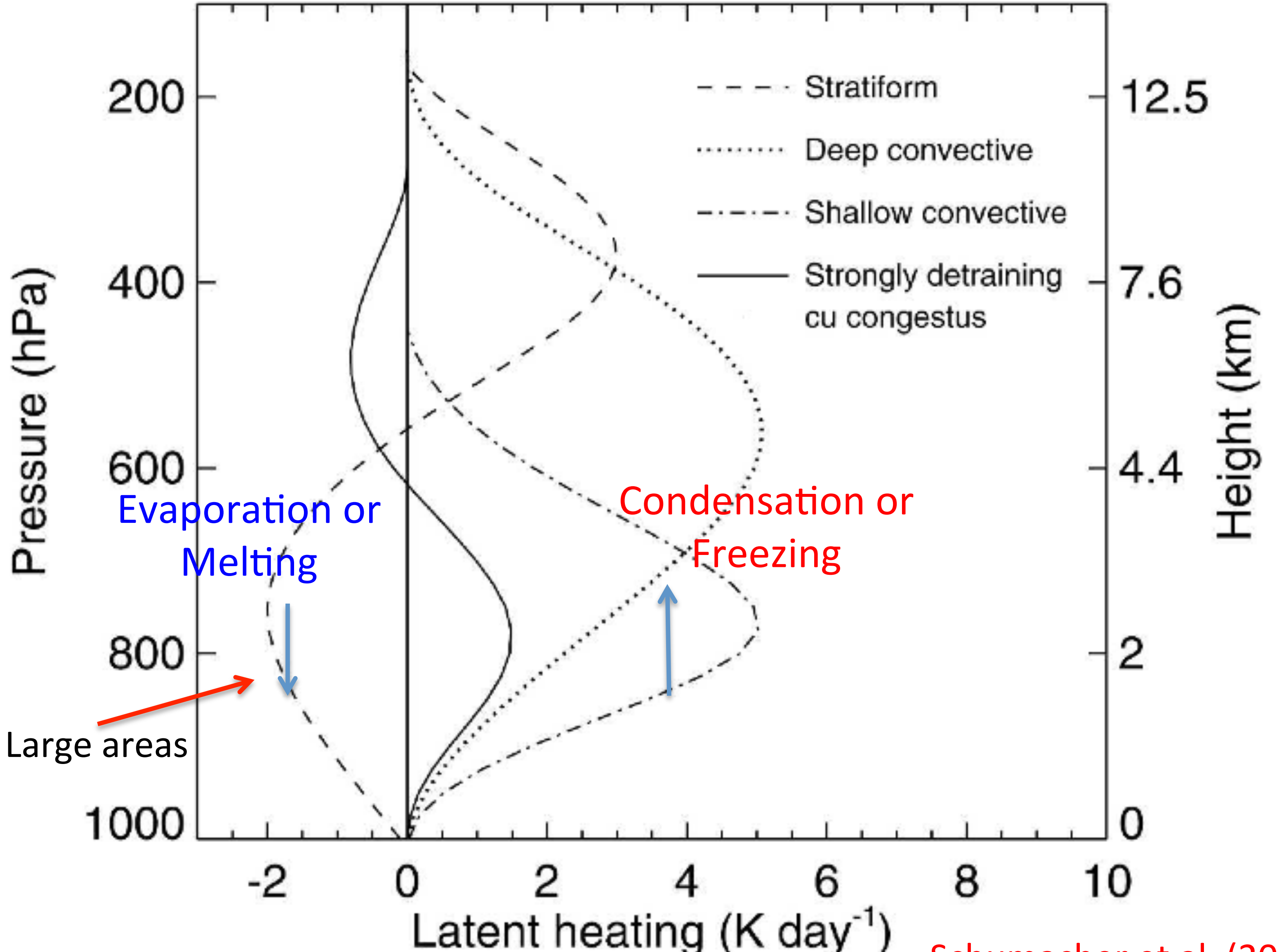
Competing Time Scales

- Anvils moisten lower-to-middle troposphere (convective time scale)
- Moisture is circulated (advective time scale)
- Pulses of convection on quasi-diurnal time scale (recovery time scale)





Gamache and Houze (1982): Mon. Wea. Rev.



Schumacher et al. (2007): JAS

FIG. 1. Idealized latent heating profiles for different precipitating cloud types.

Effects of Vertical Wind Shear

- Introduces convection asymmetry
- Misalignment of vortex also induces shear