Orographic Modification of Precipitation Processes in a Tropical Cyclone Moving over a Continental Mountain Range

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PhD Defense
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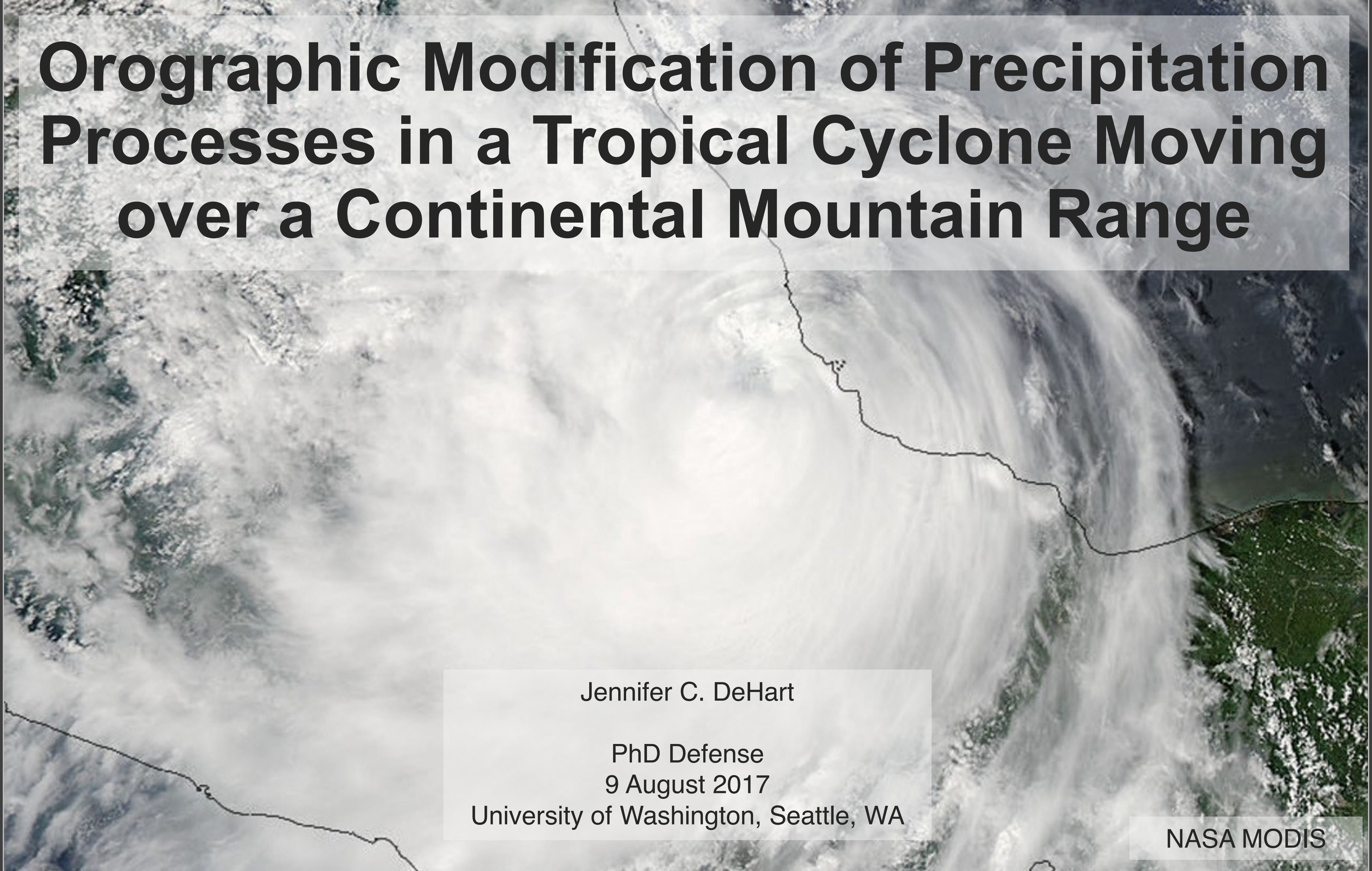
University of Washington, Seattle, WA



NASA MODIS

Tropical cyclone (TC) impacts

Rainfall intensified near terrain

<u>Rainfall records</u>

12-h: 1,144 mm – TC Denise (1996)

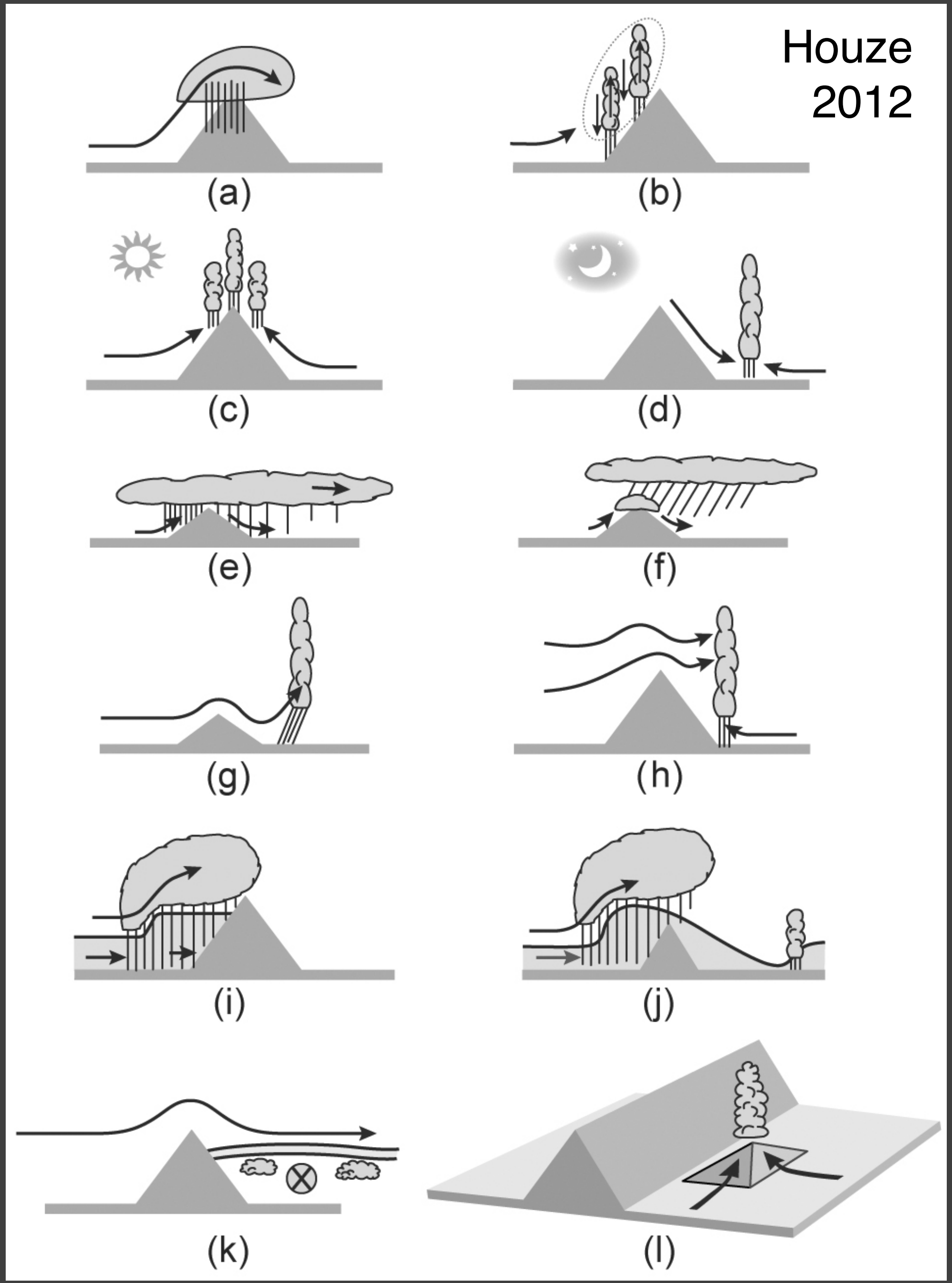
24-h: 1,825 mm – TC Denise (1996)

72-h: 3,929 mm – TC Gamede (2007)

96-h: 4,869 mm – TC Gamede (2007)

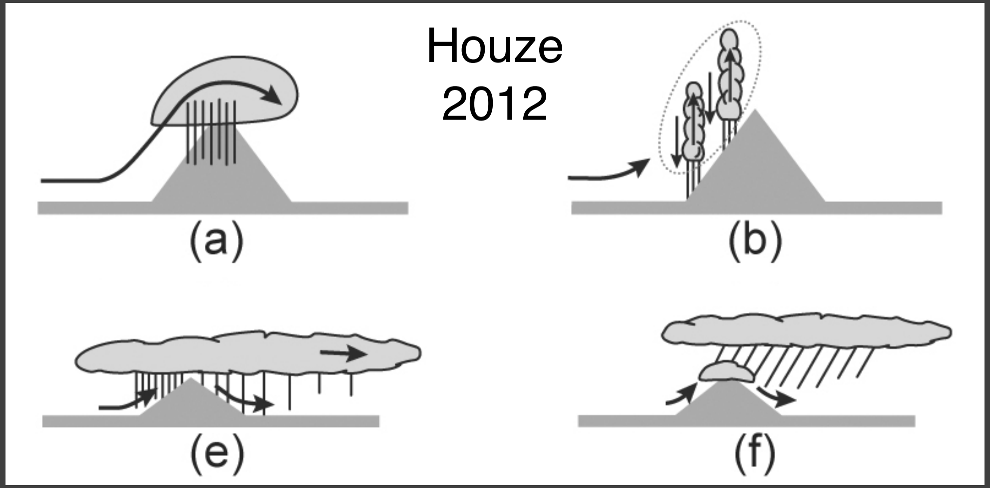
How do clouds change as they move over terrain?

- Orographic modification
- Numerous possibilities!
- Specific process determined by the kinematic / thermodynamic environment

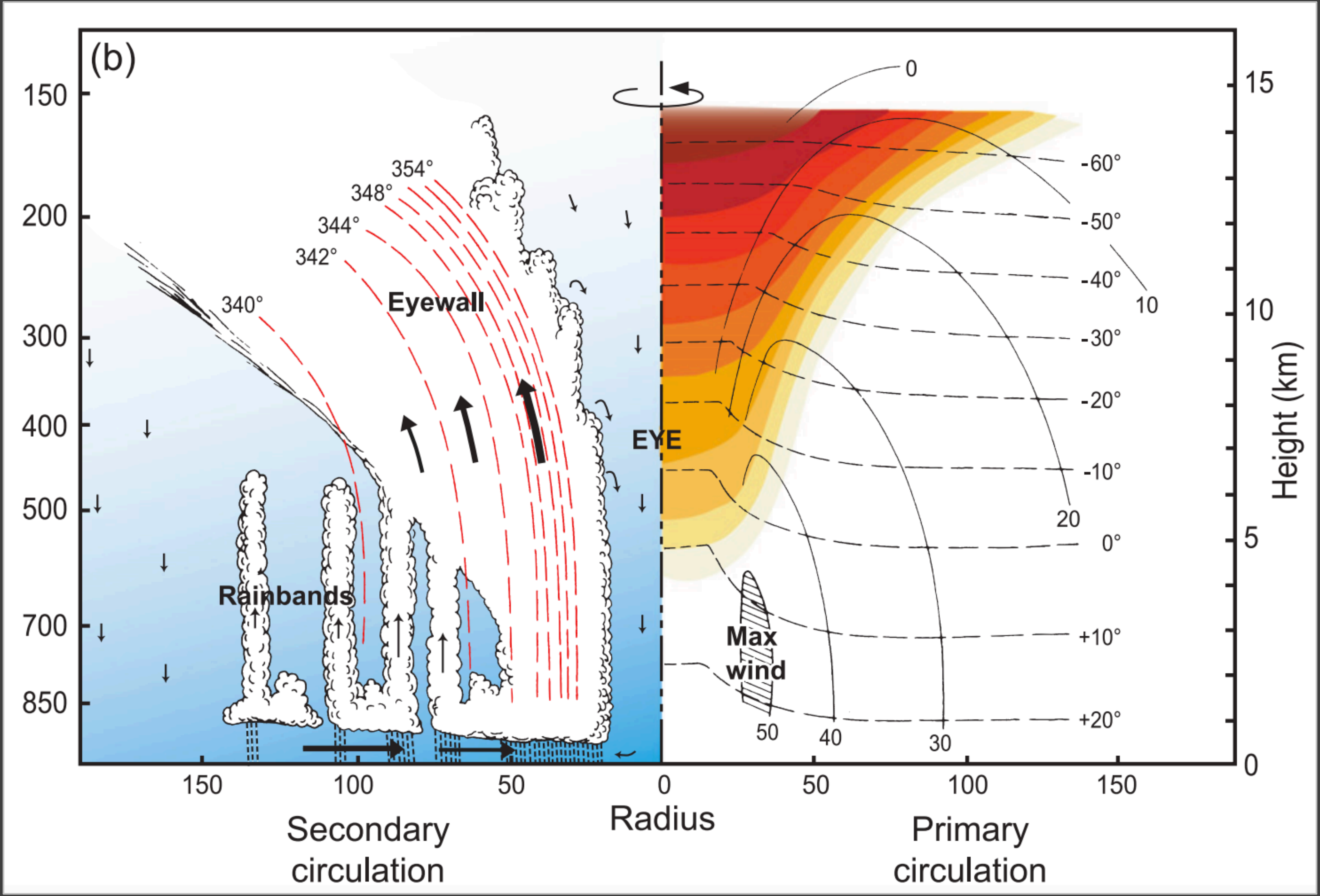


How do clouds change as they move over terrain?

- Orographic modification
- Numerous possibilities!
- Specific process determined by the kinematic / thermodynamic environment
- Example processes:
  - Larger falling raindrops collect cloud water / tiny raindrops generated by orographic ascent
  - Convection



TCs: strong radial variations

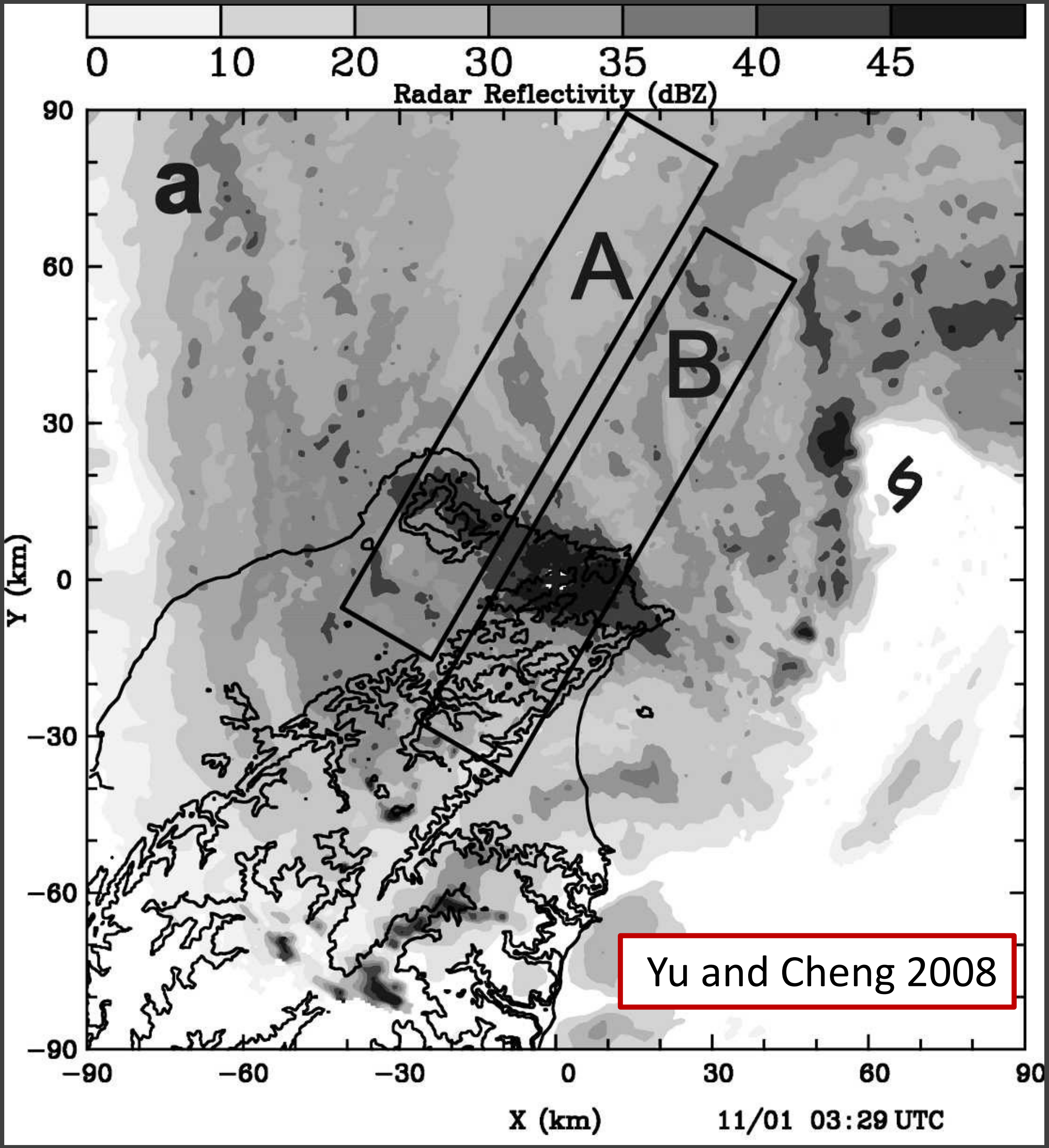


Houze 2010
Wallace and Hobbs

Cloud water

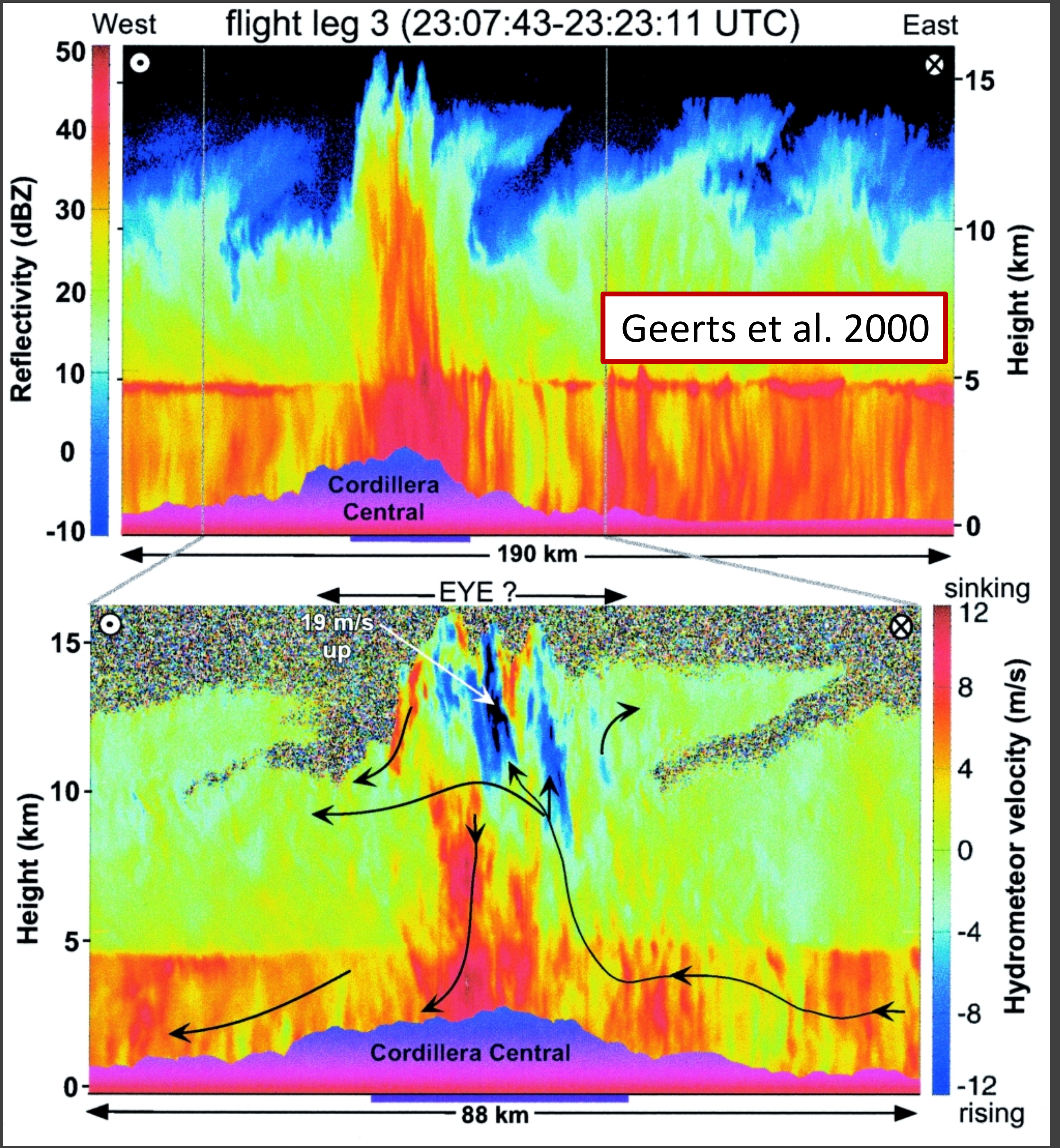
- Warm rain processes prevalent in the literature
  - Larger raindrops collecting orographically-generated cloud water / tiny raindrops

- **Primarily horizontal maps of reflectivity, precipitation**
- **When available, vertical resolution usually insufficient**

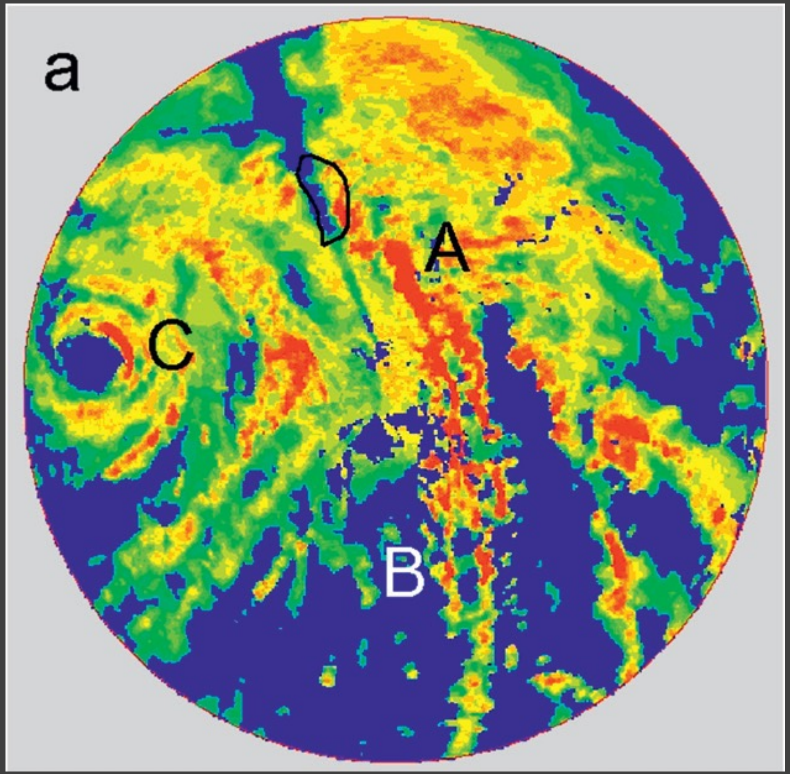


Convection

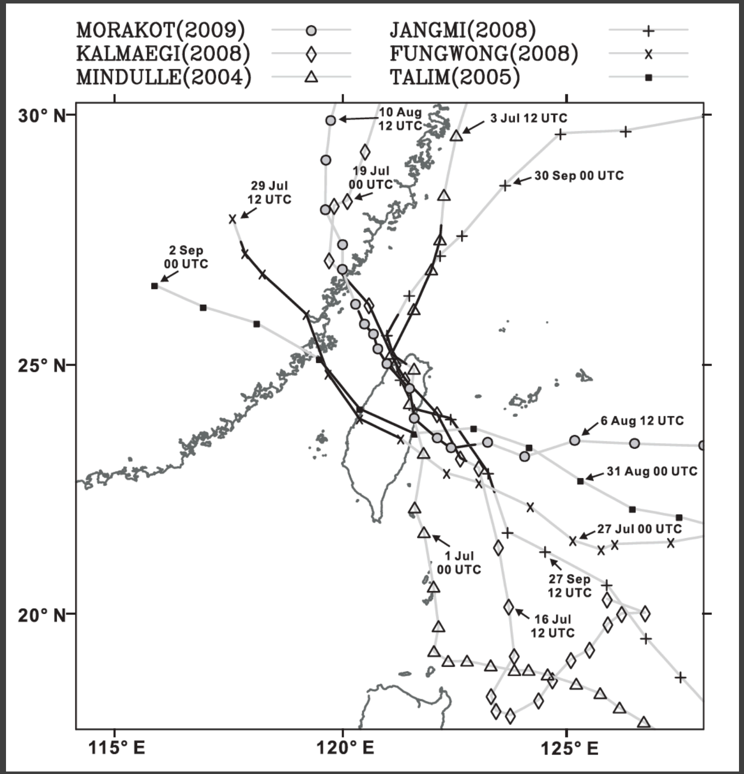
- Other processes can occur under proper circumstances
  - Deep convection observed in the eye of Hurricane Georges (1998) as it passed over Hispaniola
  - Potential instability in the eye



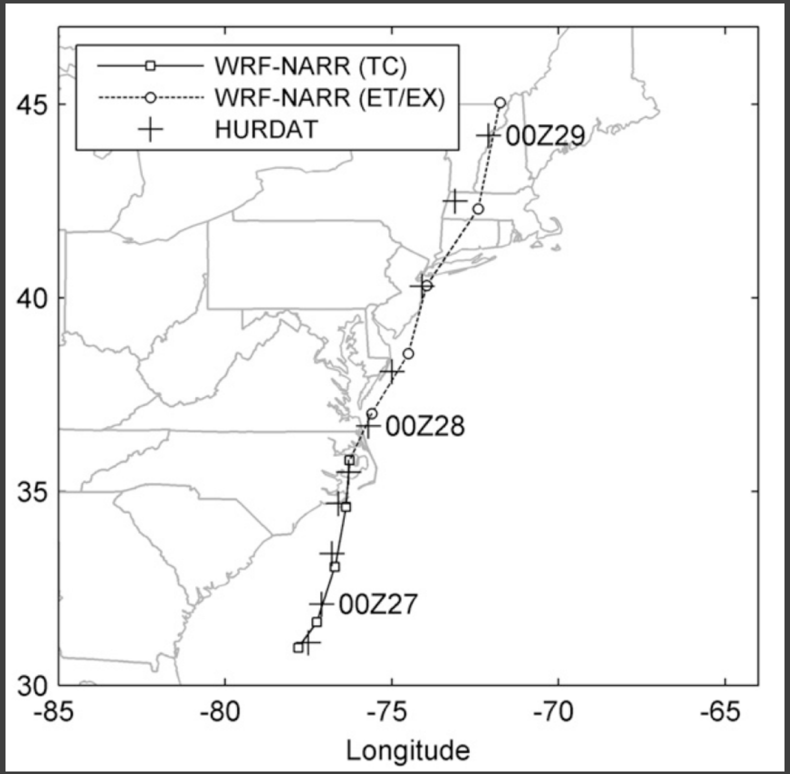
Lack of complete landfall



Smith et al. 2009



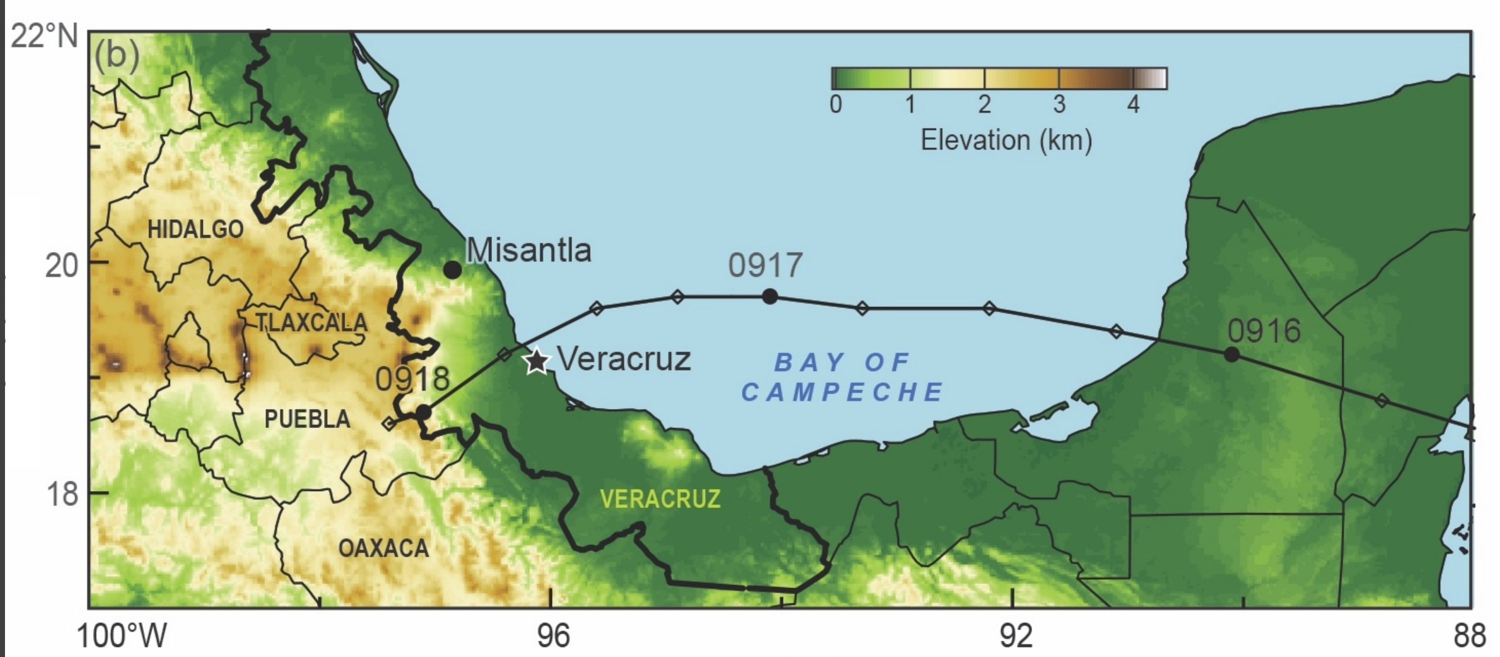
Yu and Cheng 2014



Liu and Smith 2014

Hurricane Karl (2010)

- NASA Genesis and Rapid Intensification Processes (GRIP) campaign
  - **Airborne radar with high vertical resolution**
- Landfall with no chance for regeneration
  - **Karl decayed completely**

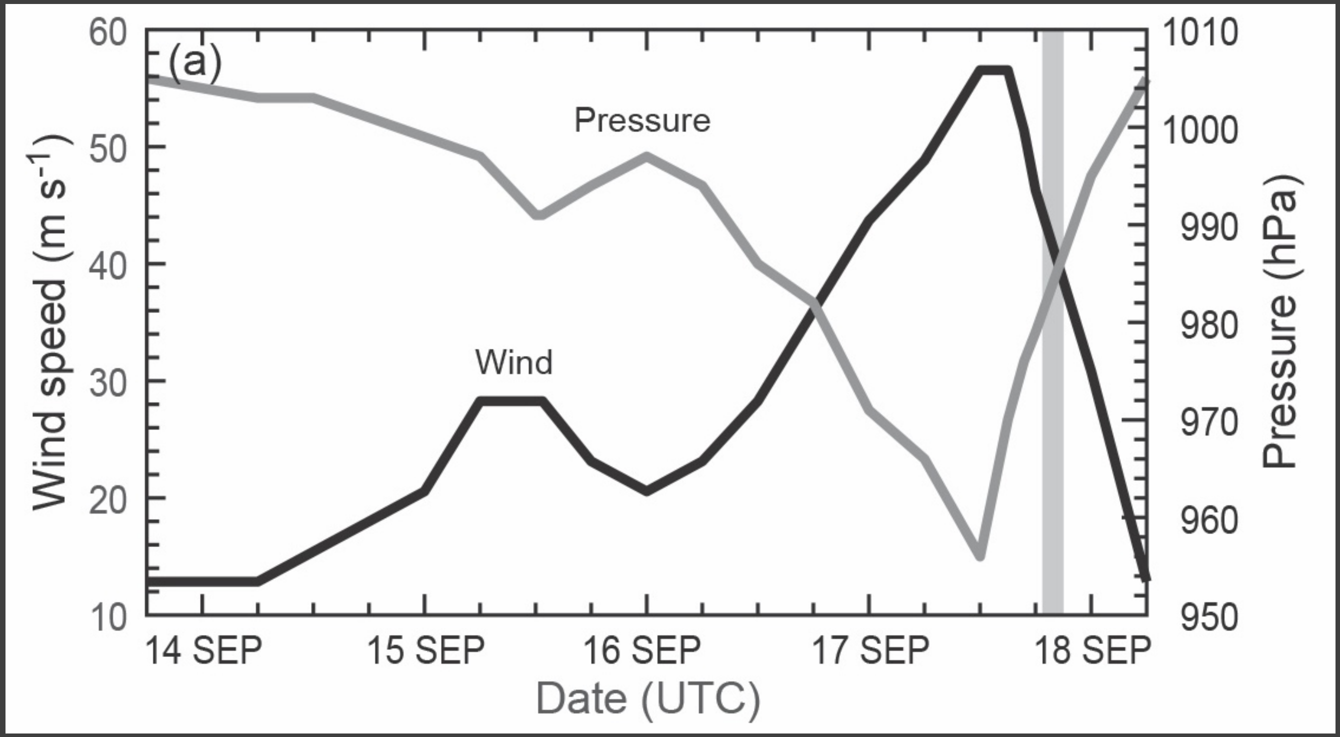


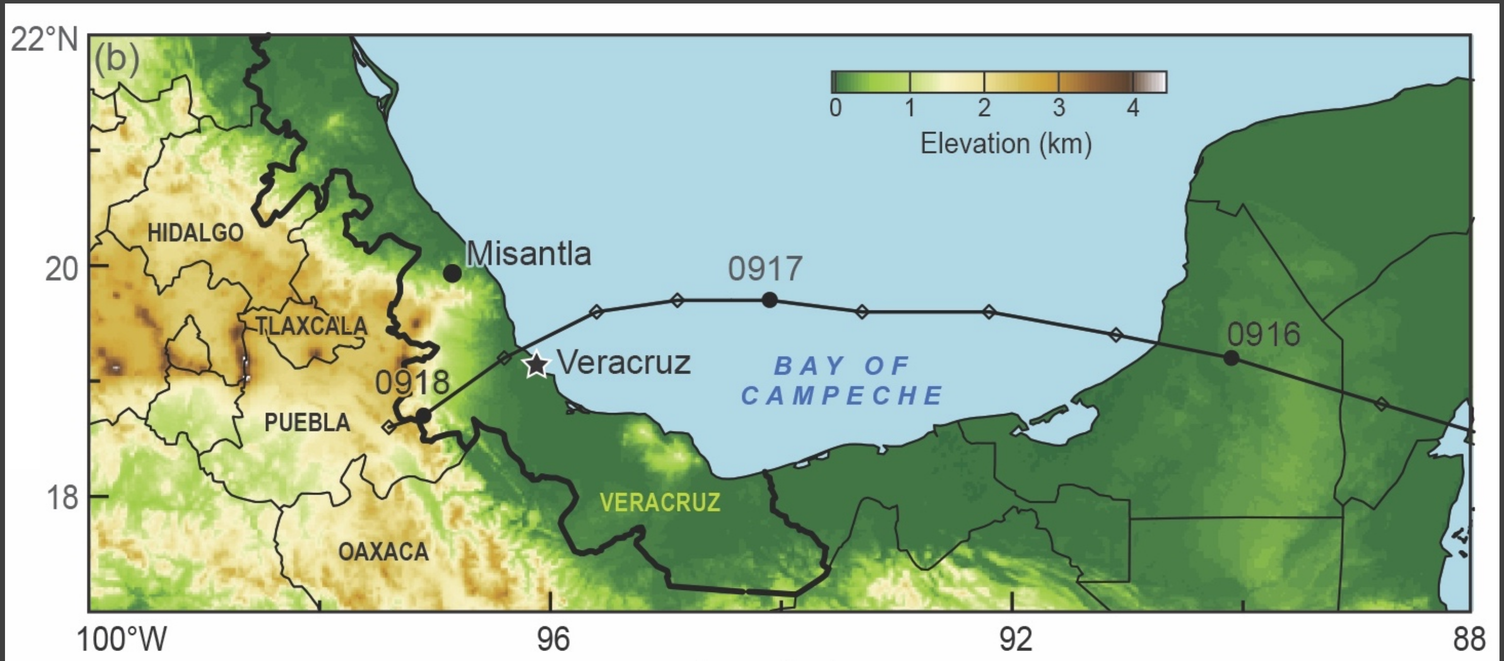
Questions

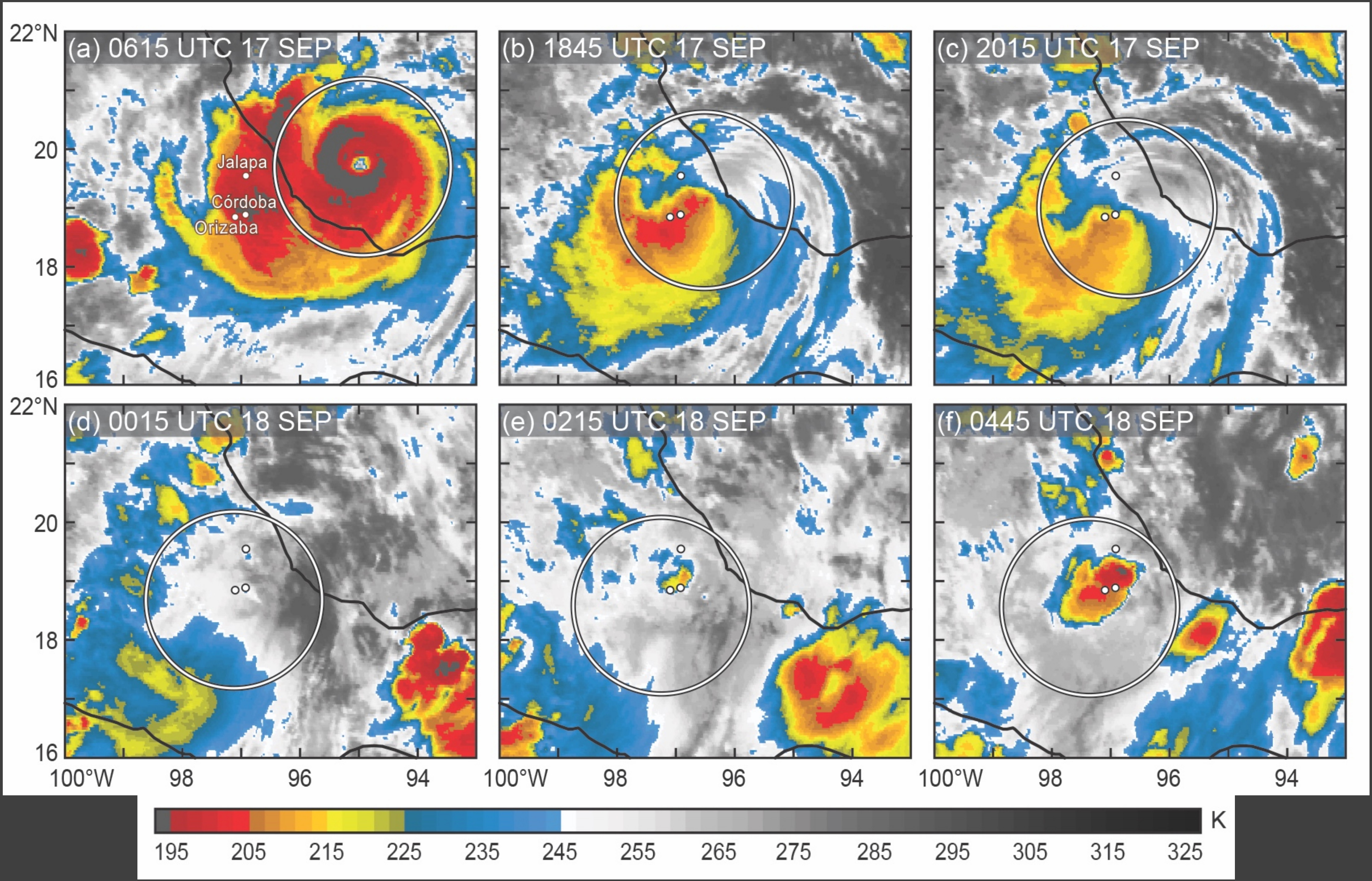
- Does the orographic modification of precipitation in Hurricane Karl occur through warm rain processes?
- Do the modification processes change during landfall as Karl weakens?

Hurricane Karl

- Category 3 hurricane before landfall
- Flooding and landslides responsible for large fraction of the damage (Stewart 2011)
- Rapid decay

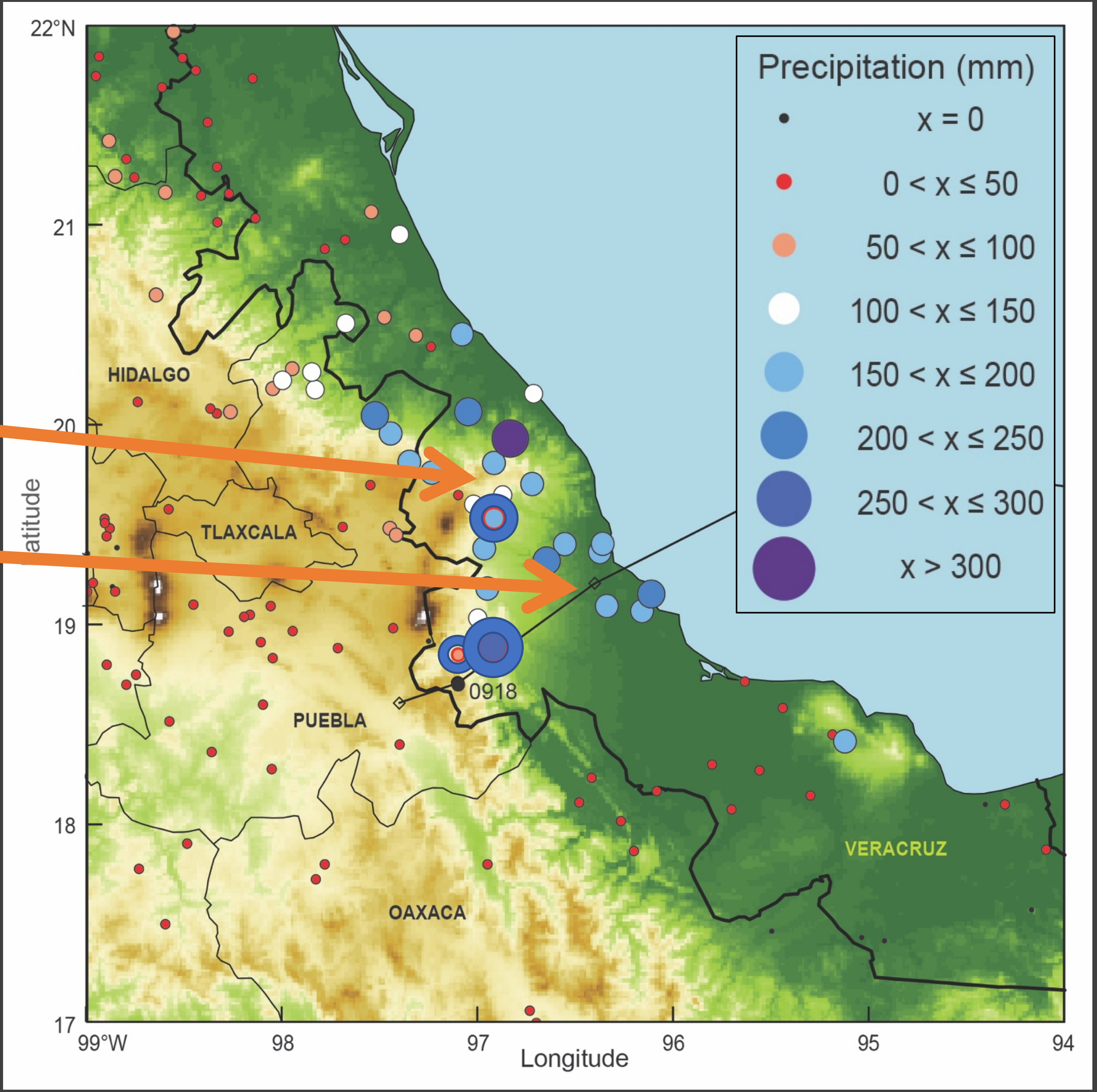




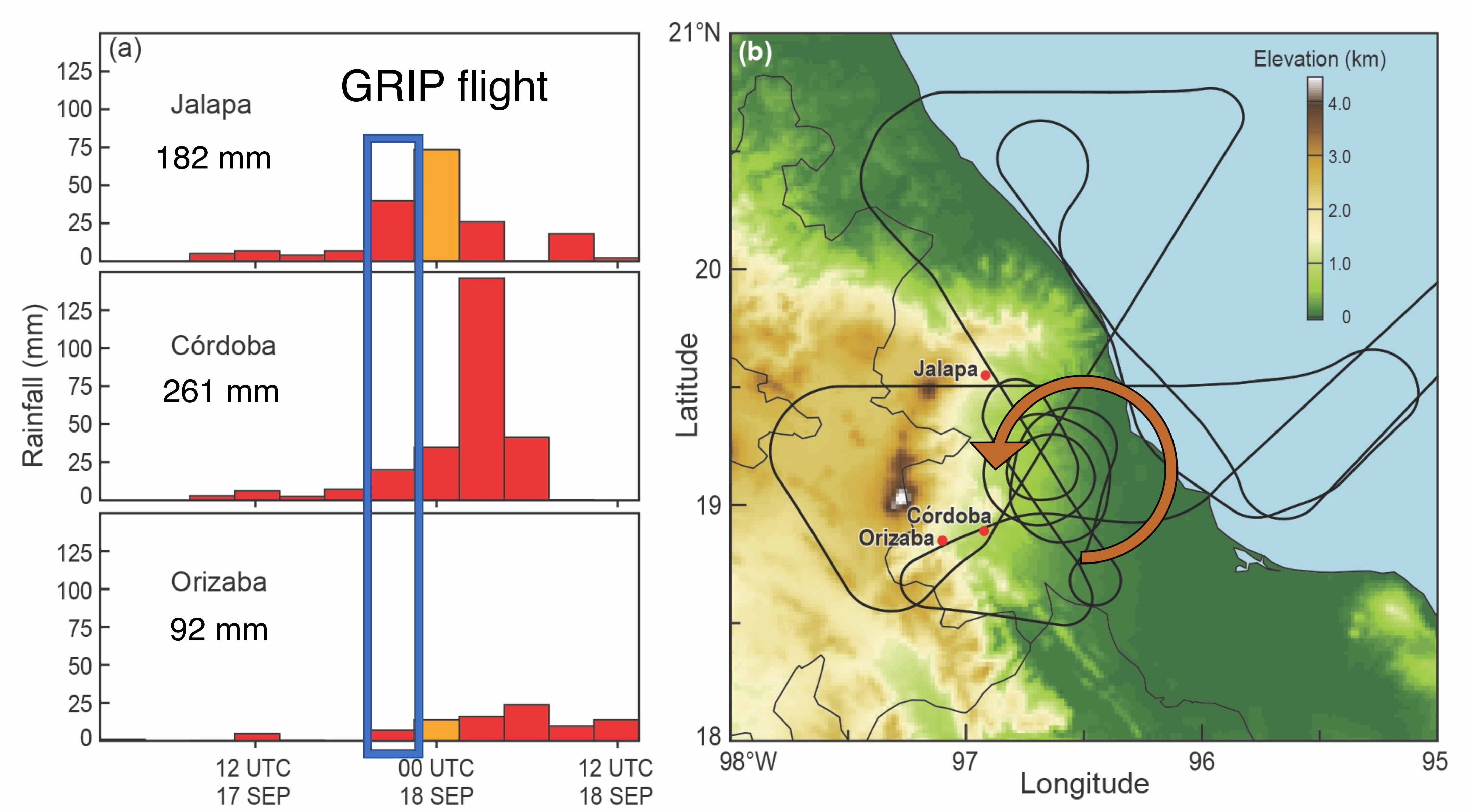

(a) 0615 UTC 17 SEP
(b) 1845 UTC 17 SEP
(c) 2015 UTC 17 SEP
(d) 0015 UTC 18 SEP
(e) 0215 UTC 18 SEP
(f) 0445 UTC 18 SEP
Jalapa
Córdoba
Orizaba
22°N
20
18
16
100°W
98
96
94
K
195
205
215
225
235
245
255
265
275
285
295
305
315
325

24-h rainfall

- 13 UTC 9/17 – 13 UTC 9/18
- Peaks along the sloping terrain and near the inner core
- Only have time series at 3 locations

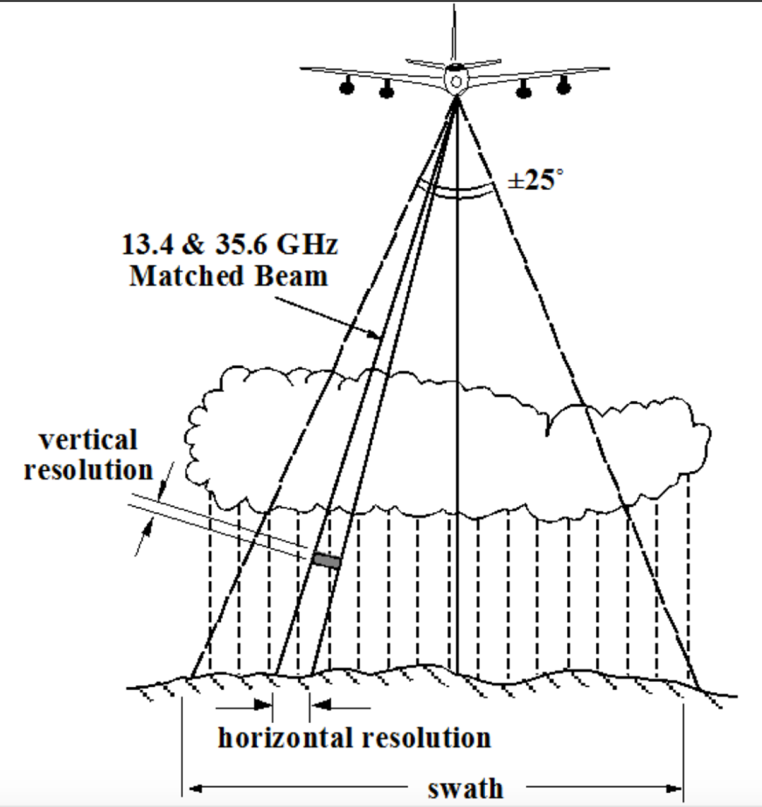


3-h precipitation

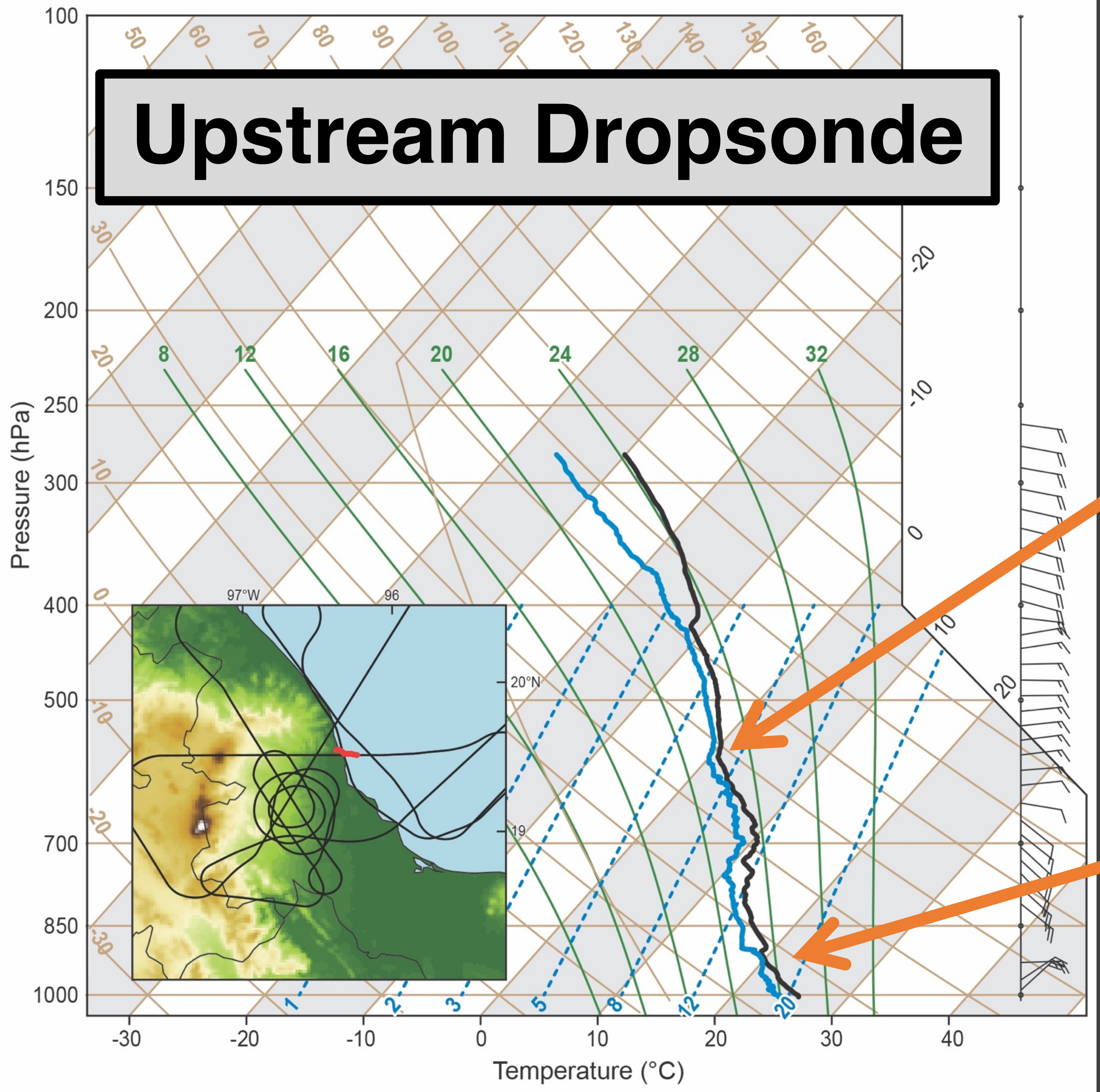


NASA GRIP

- DC-8 aircraft
  - 12 km flight altitude
  - Dropsondes
  - Airborne Second Generation Precipitation Radar (APR-2)
    - Ku- / Ka-band (13.4 / 35.6 GHz)
    - Observes hydrometeor characteristics (size, amount)
    - High vertical resolution (37 m)
    - Ku-band beam closest to vertical



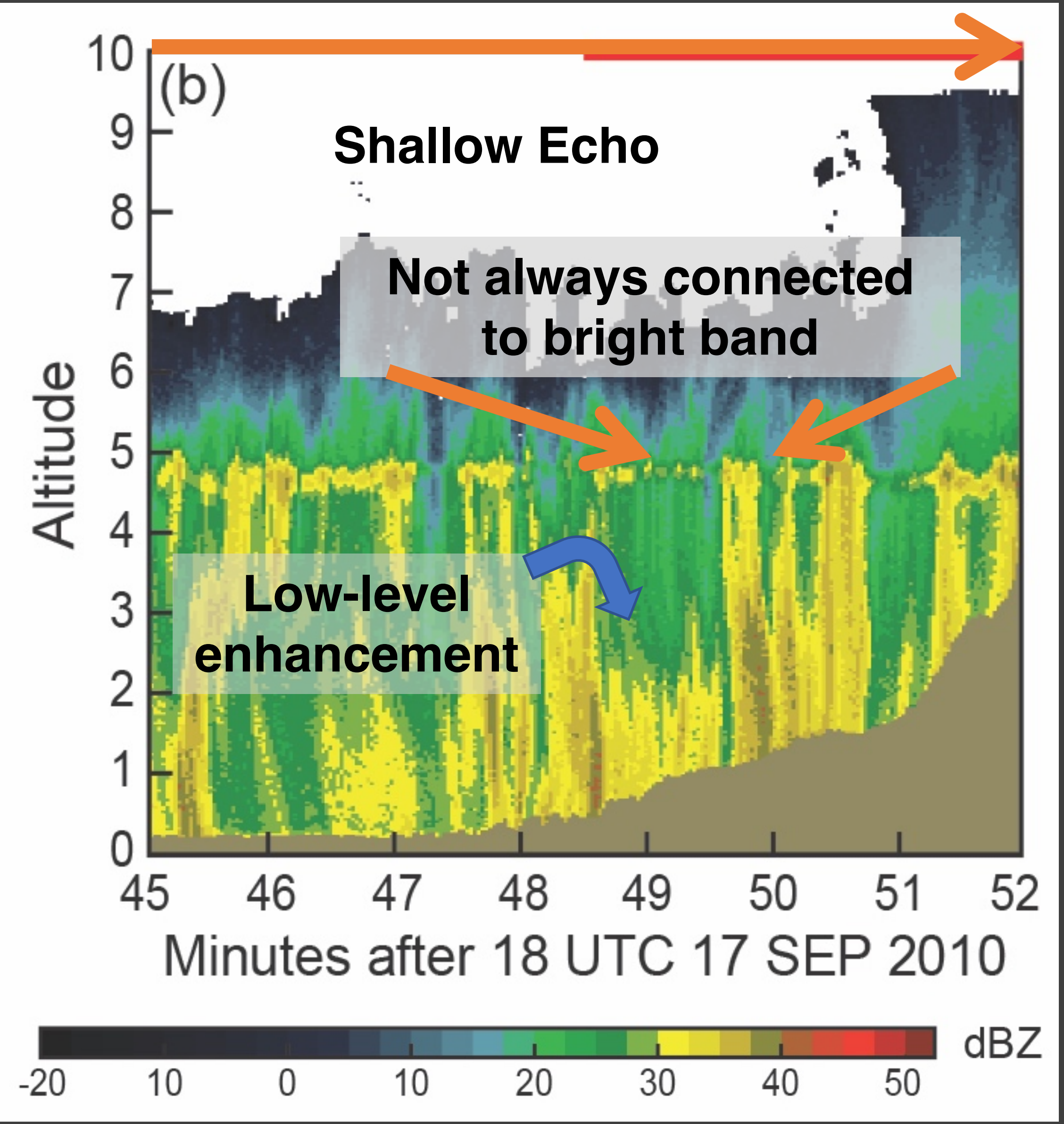
Upstream Dropsonde

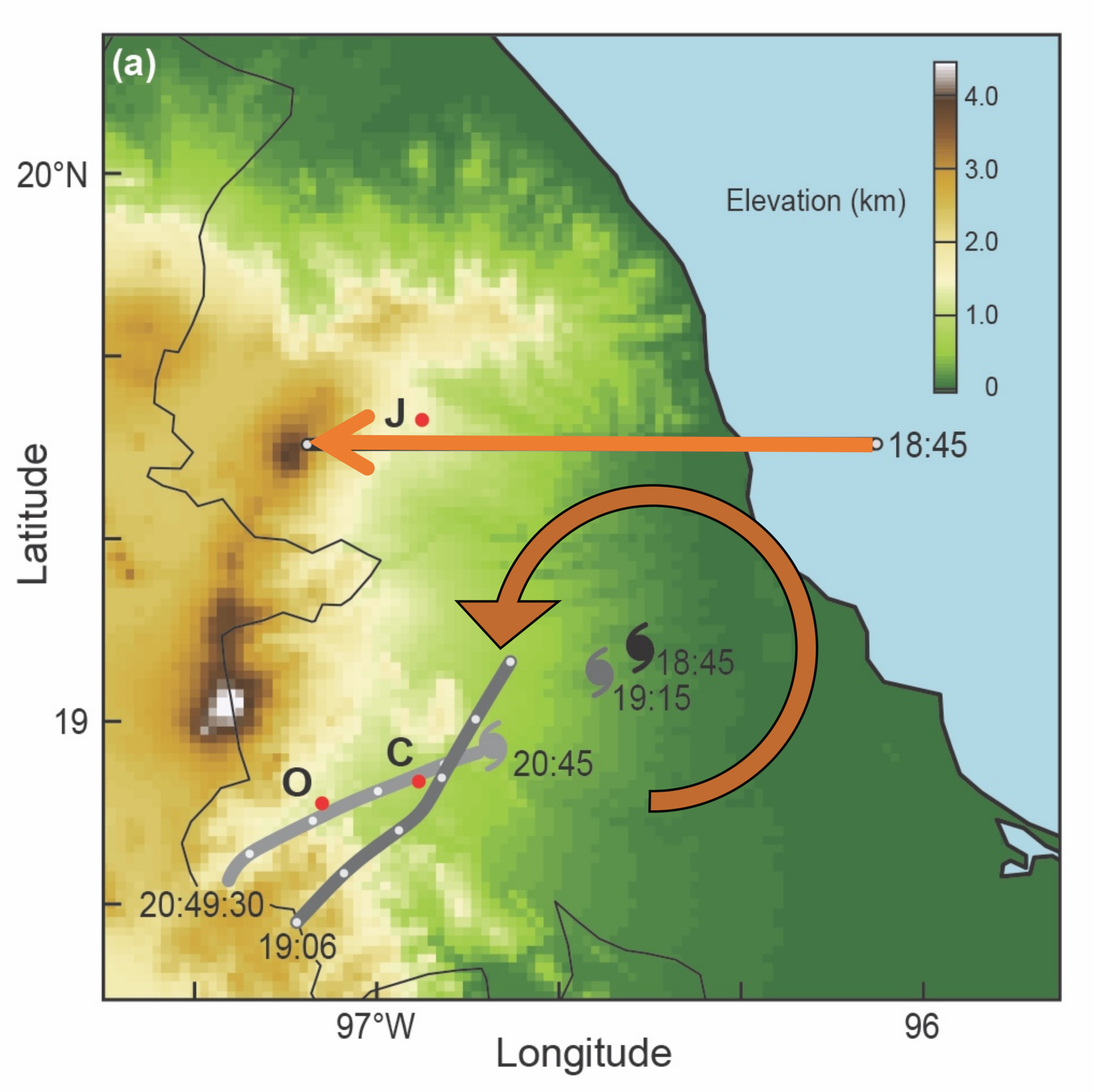


Rich in moisture

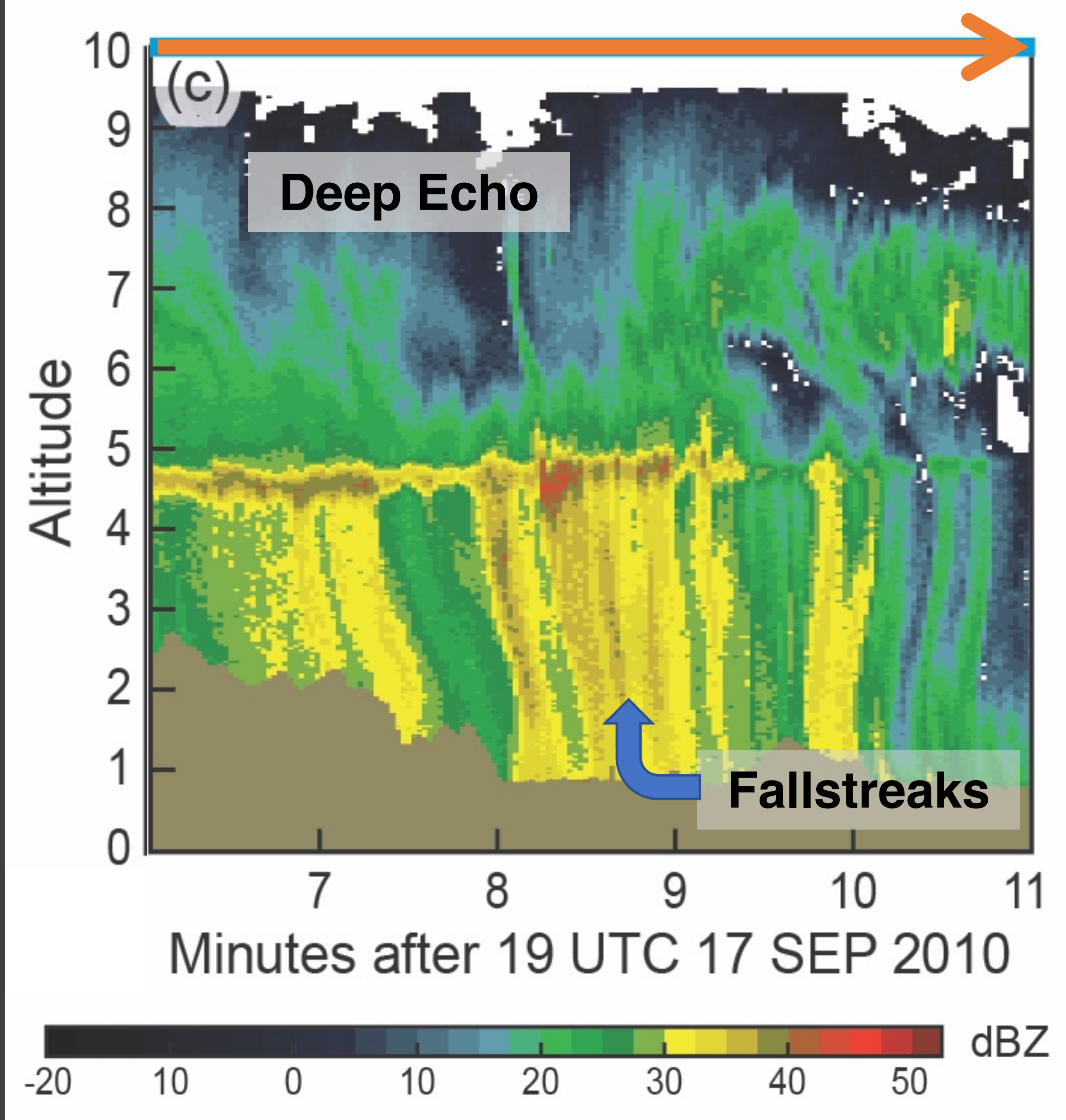
Slight low-level instability

Flight leg #1

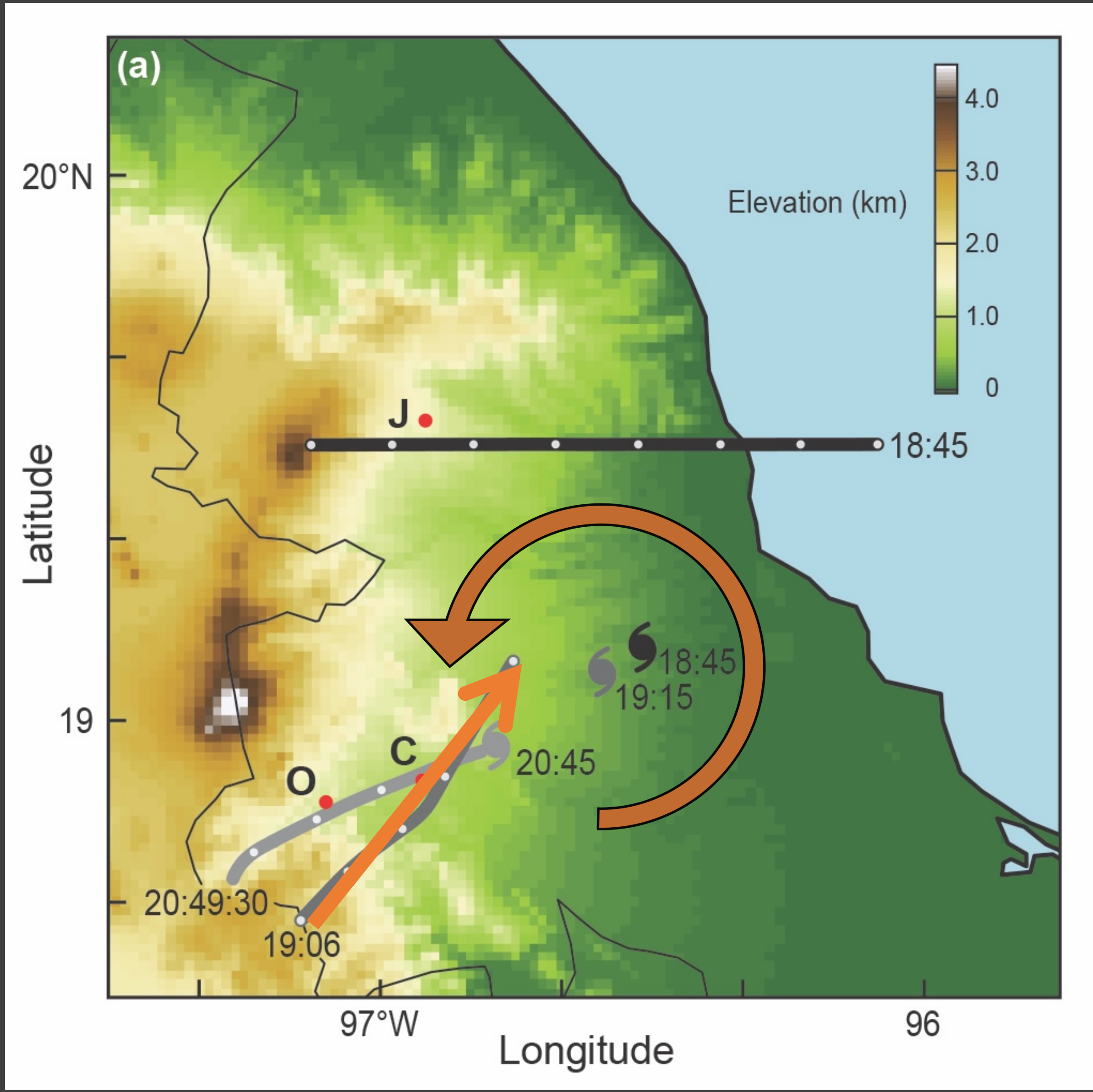

(b)
Shallow Echo
Not always connected to bright band
Low-level enhancement
Altitude
10
9
8
7
6
5
4
3
2
1
0
45
46
47
48
49
50
51
52
Minutes after 18 UTC 17 SEP 2010
-20
10
0
10
20
30
40
50
dBZ


(a)
20°N
19
Latitude
97°W
96
Longitude
Elevation (km)
4.0
3.0
2.0
1.0
0
J
C
O
18:45
18:45
19:15
20:45
20:49:30
19:06

Flight leg #2

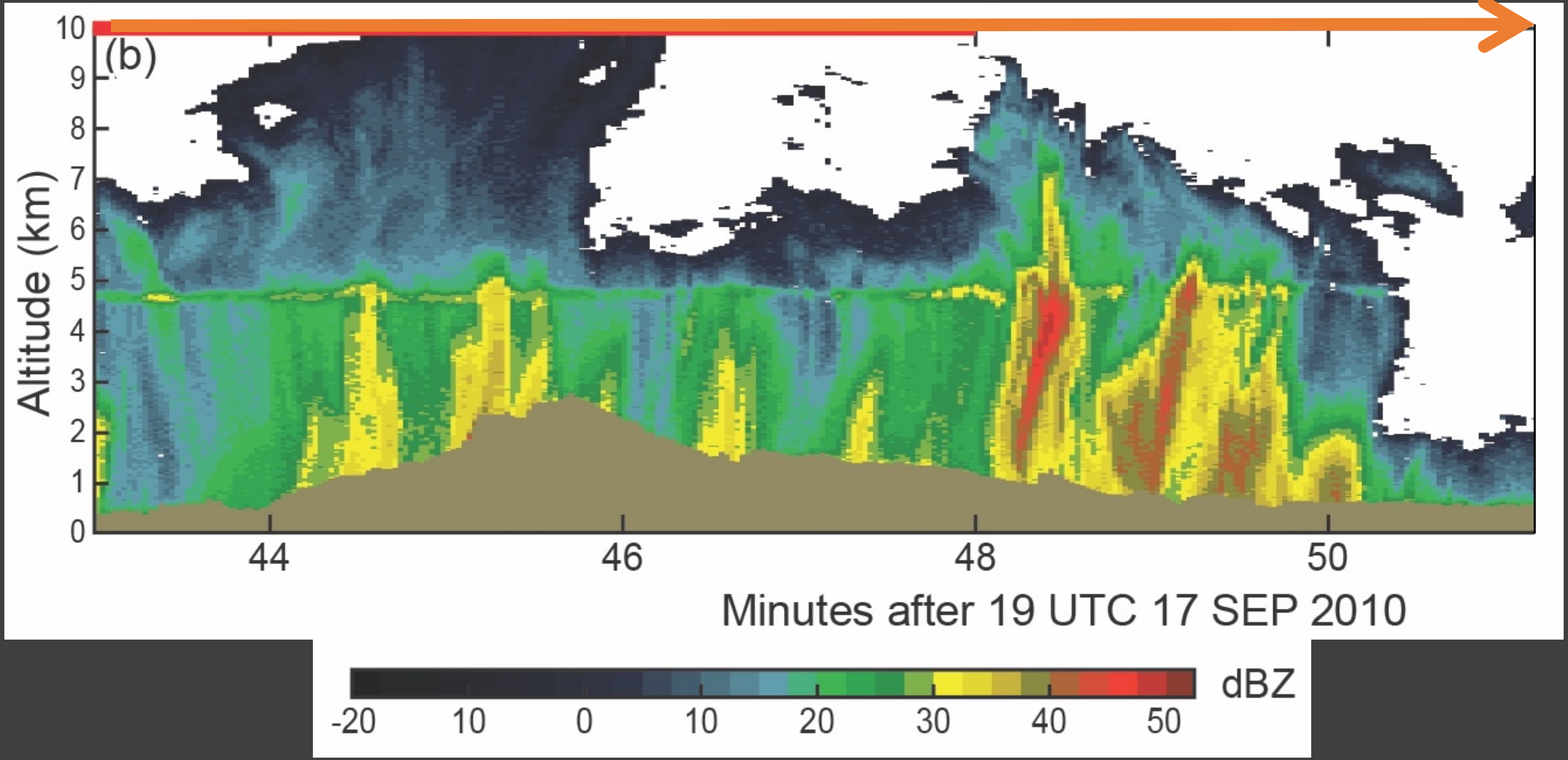


(c)
Deep Echo
Fallstreaks
Altitude
10
9
8
7
6
5
4
3
2
1
0
7
8
9
10
11
Minutes after 19 UTC 17 SEP 2010
-20
10
0
10
20
30
40
50
dBZ

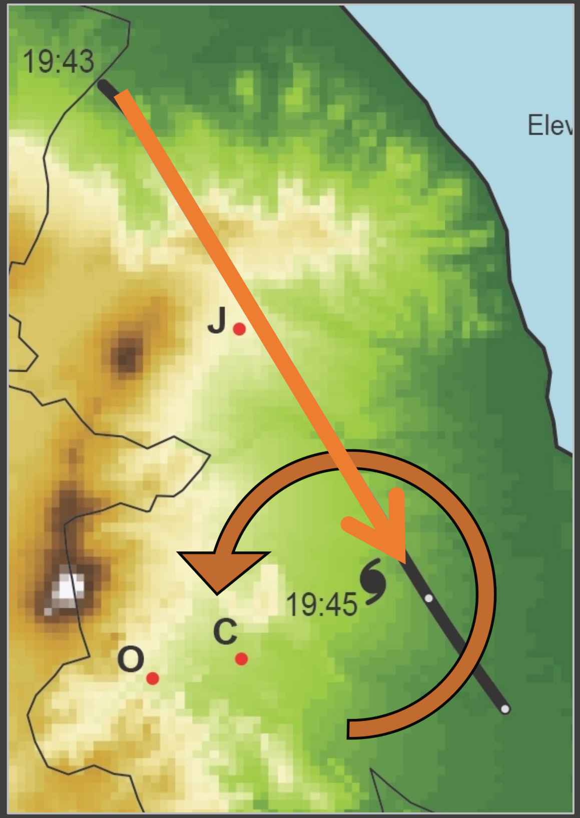


(a)
20°N
19
Latitude
97°W
96
Longitude
Elevation (km)
4.0
3.0
2.0
1.0
0
J
O
C
18:45
18:45
19:15
20:45
20:49:30
19:06

Flight leg #3

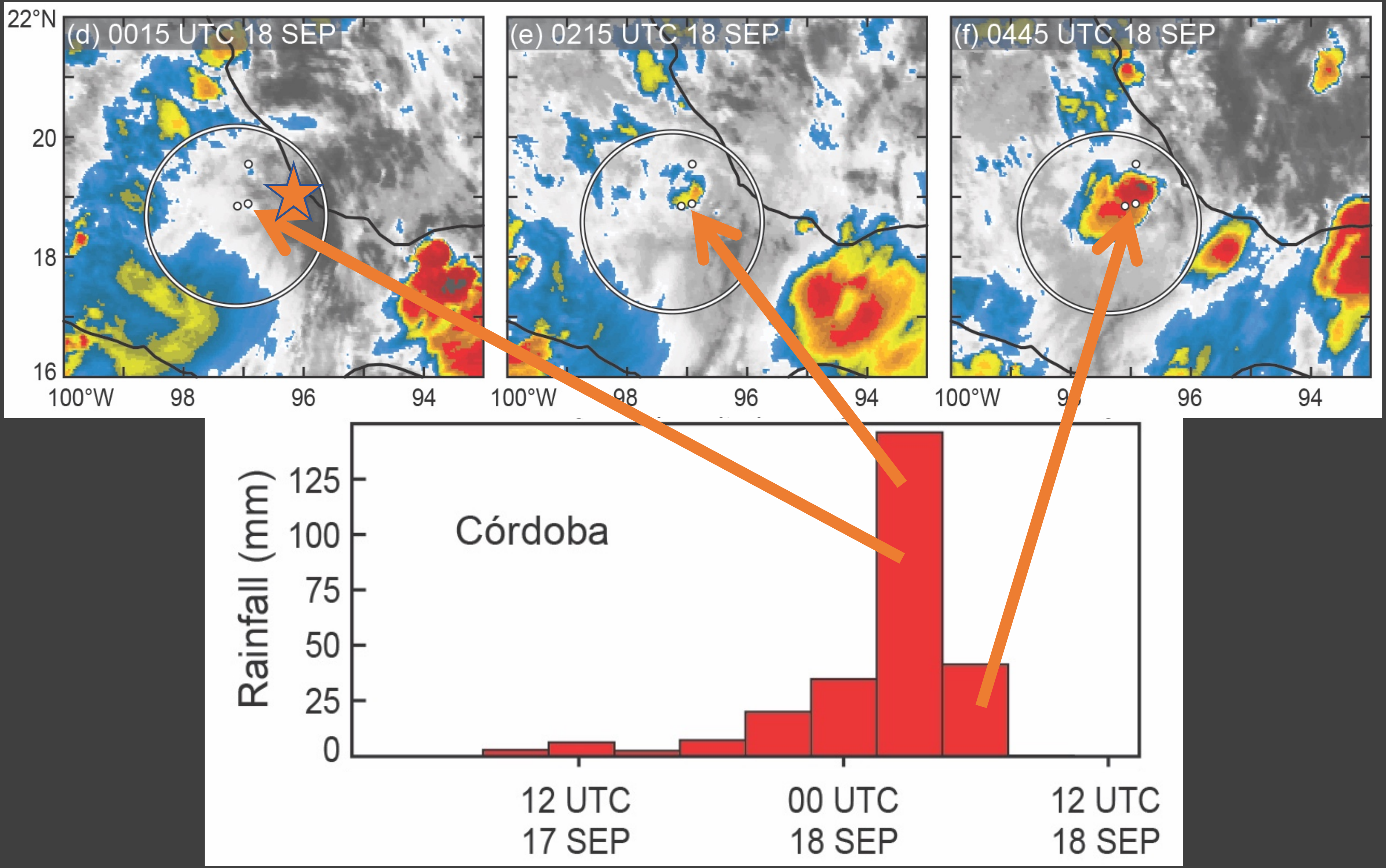


(b)
Altitude (km)
10
9
8
7
6
5
4
3
2
1
0
44
46
48
50
Minutes after 19 UTC 17 SEP 2010
dBZ
-20
10
0
10
20
30
40
50

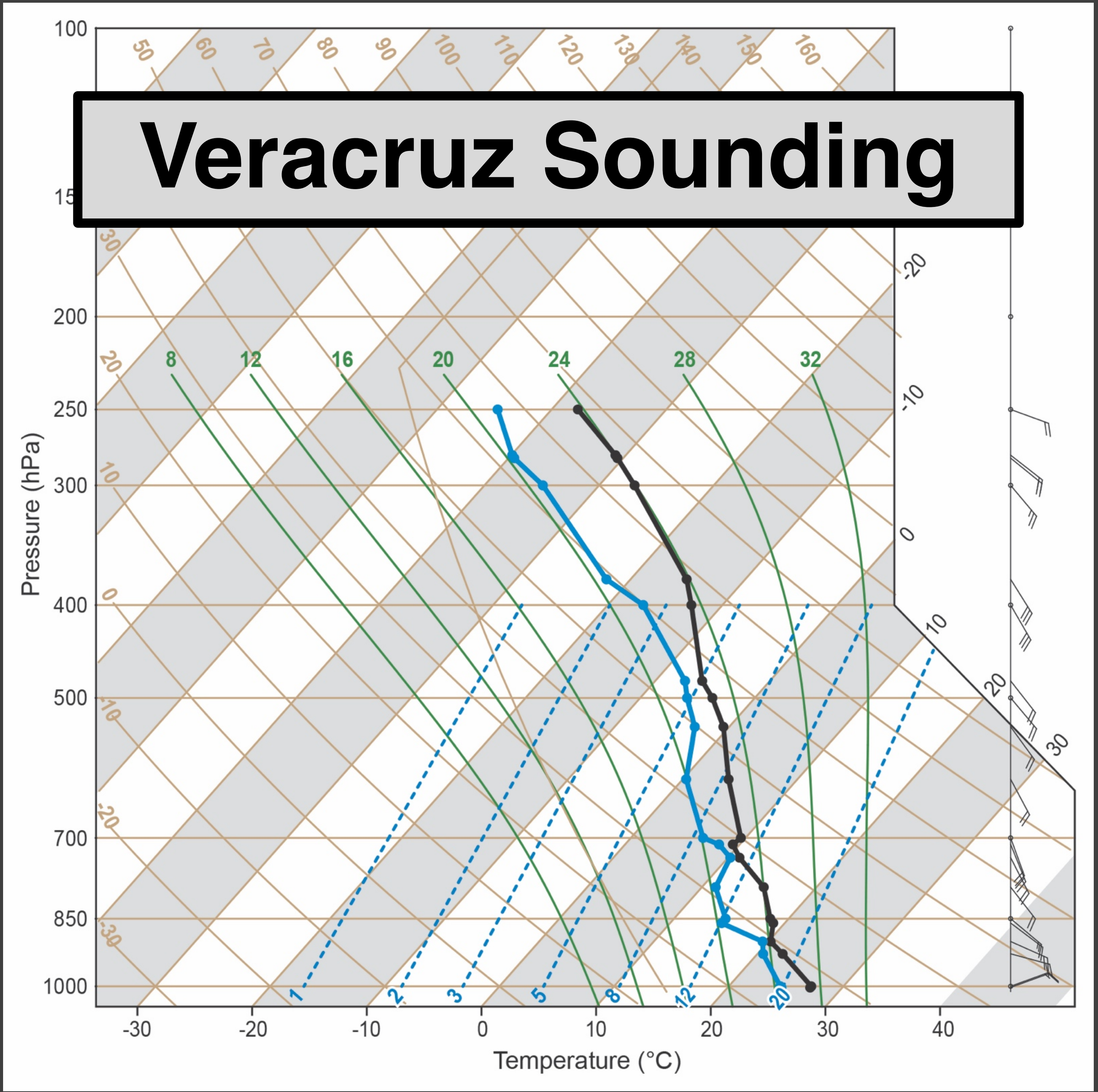


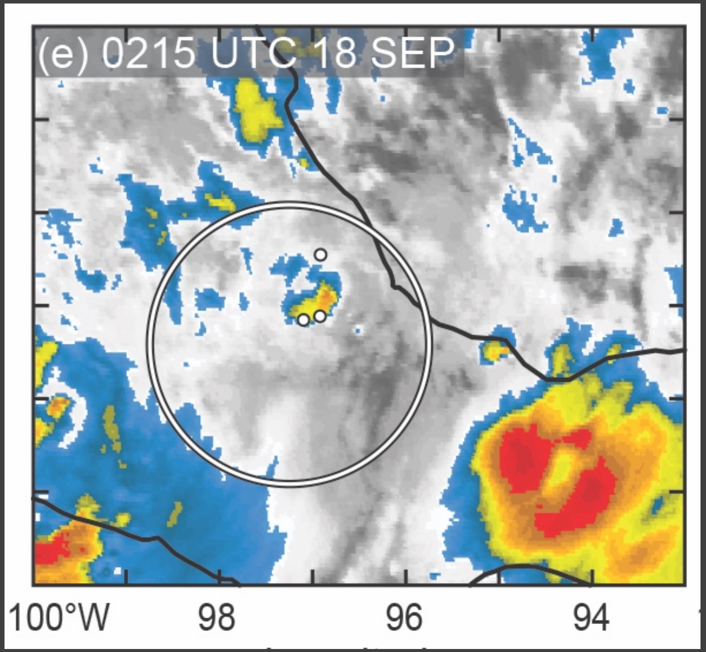
19:43
Elev
J
19:45
C
O

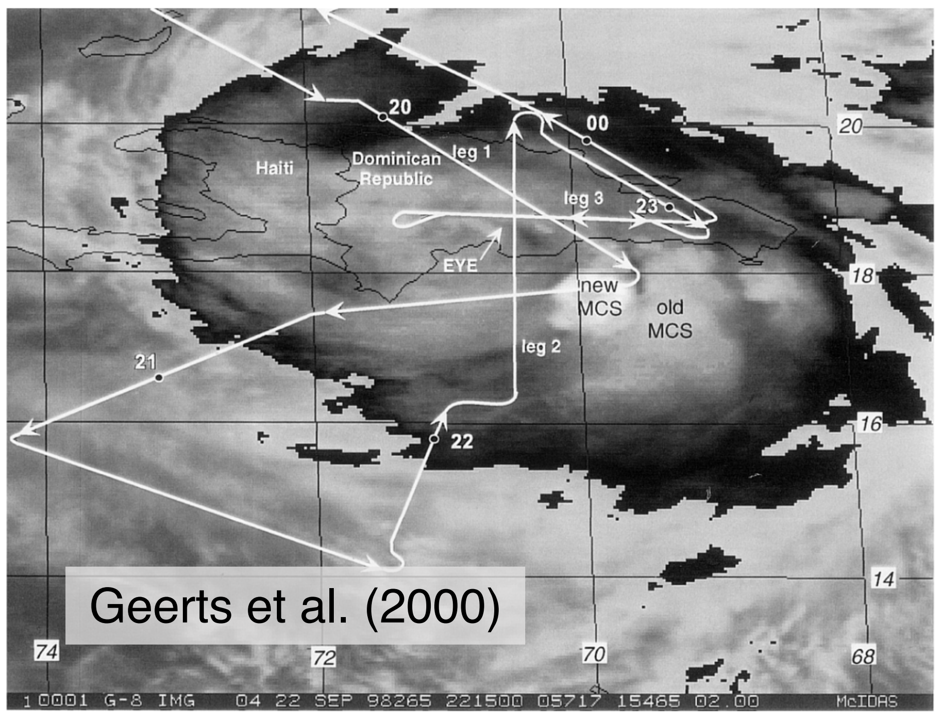
Remnant Convection



Veracruz Sounding







Geerts et al. (2000)

Summary of Radar Analysis

- Processes
  - Different vertical precipitation structures exist in regions of upslope and downslope / flat flow
  - Enhancement occurs at low levels
    - Not uniform, nearby thermodynamic environment supports shallow convection

- Impact of landfall
  - Strong changes to the overall storm structure
  - Deep convection developed after Karl dissipated
    - Modification processes are not static during landfall
  - Precipitation modest compared to other TCs

What about the terrain height?

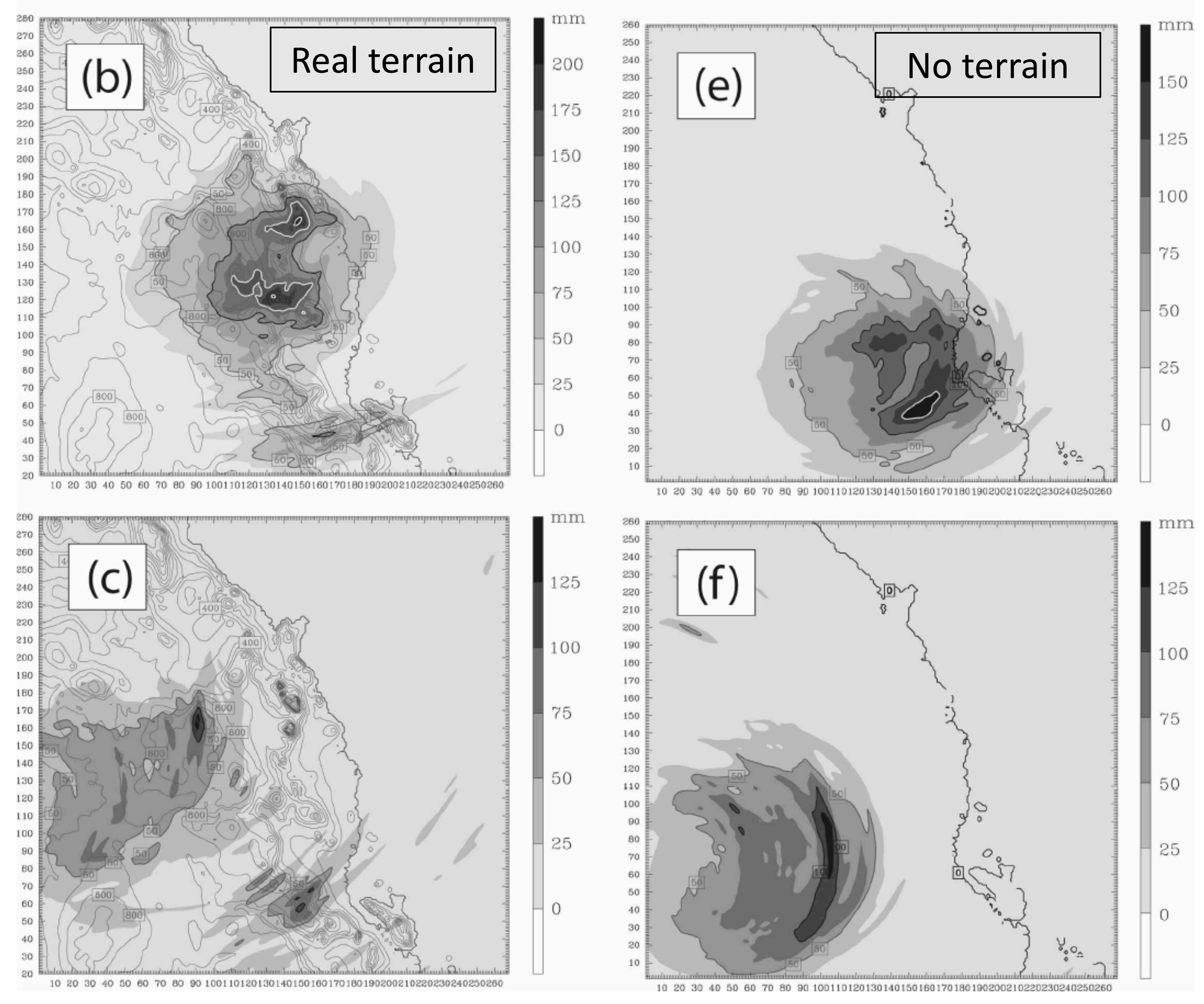
- Prior studies show that terrain height affects the rate of storm weakening
- Assumption that precipitation increases with terrain height

- **How do precipitation processes in a landfalling TC respond to the height of a topographic barrier?**

Continental Barrier

- Larry (2006) made landfall over Australia
  - Rain initially larger when terrain present, but Larry weakens quickly
  - Inland precipitation reduced

- **Terrain height ~800 m**
- **Three-dimensional processes unexamined**

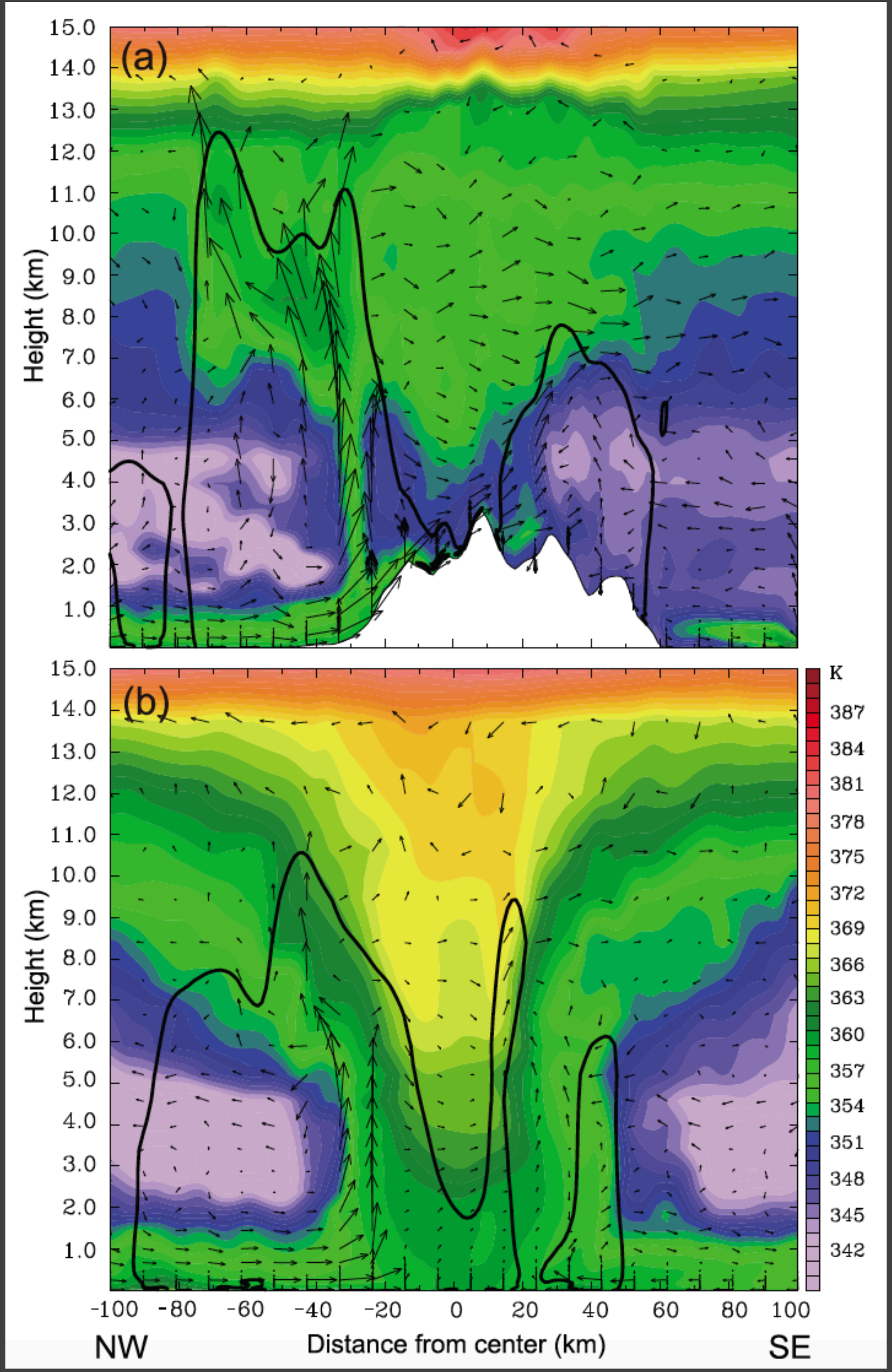


Ramsay and Leslie 2008

3-D Structure

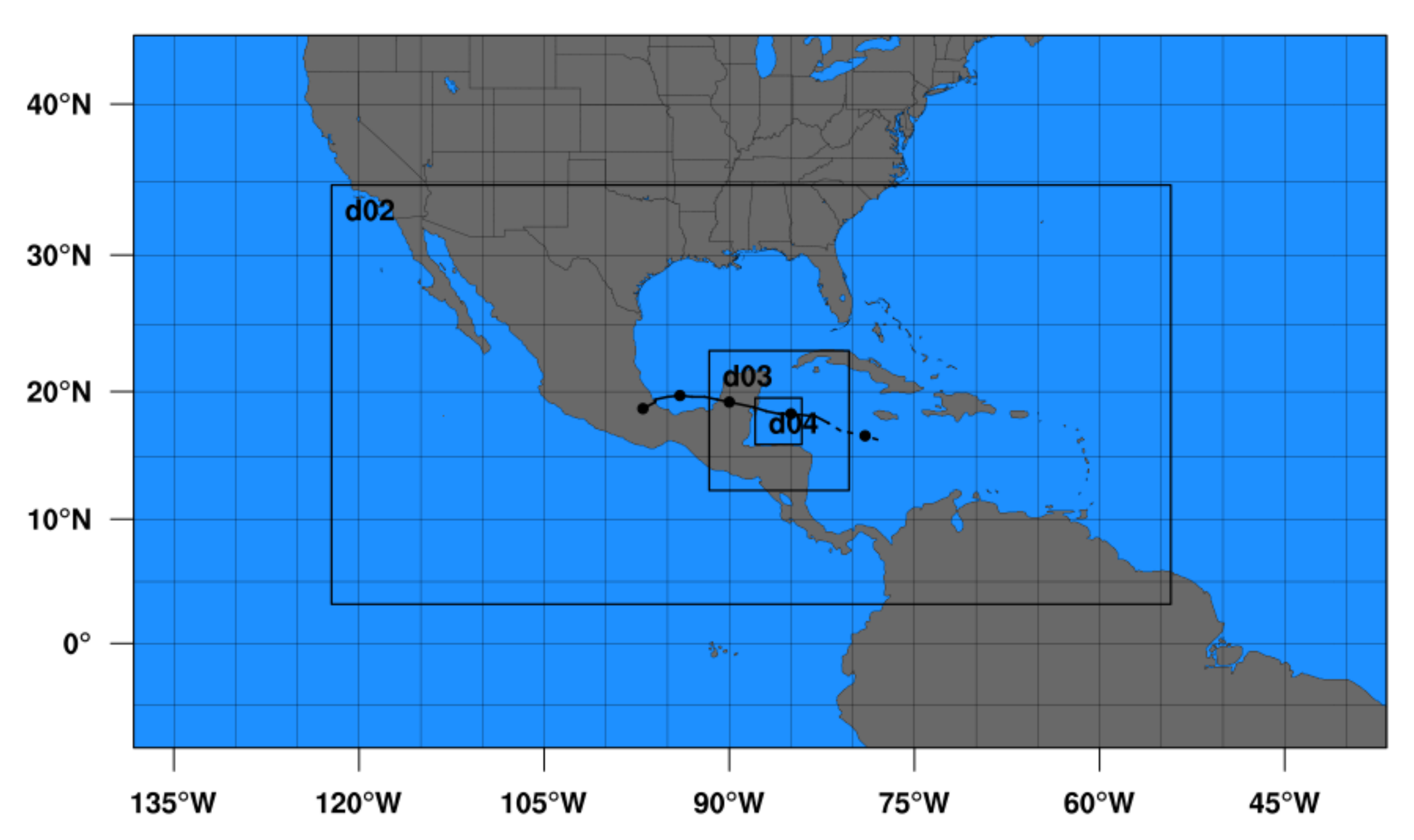
- Nari (2001) made landfall over Taiwan
  - Precipitation generally scaled with terrain height
  - More dominant cold rain processes
  - (Yang et al. 2008; Yang, Braun, and Chen 2011; Yang, D. Zhang, Tang, and Y. Zhang 2011; Yang, Wang, Zhang, and Weng 2011)

- **Don't fully consider precipitation type**
- **Outer regions neglected**
- **Evolution insufficiently examined**

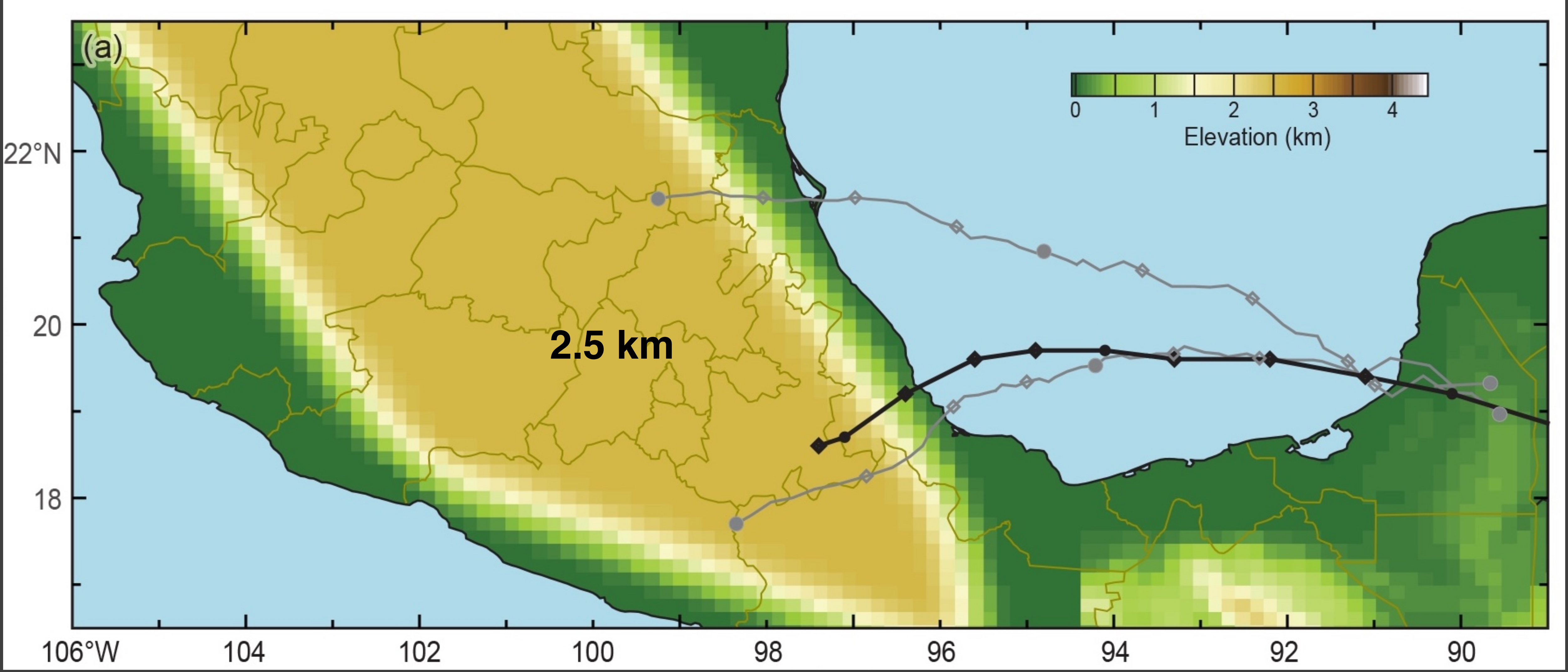


WRF Simulations

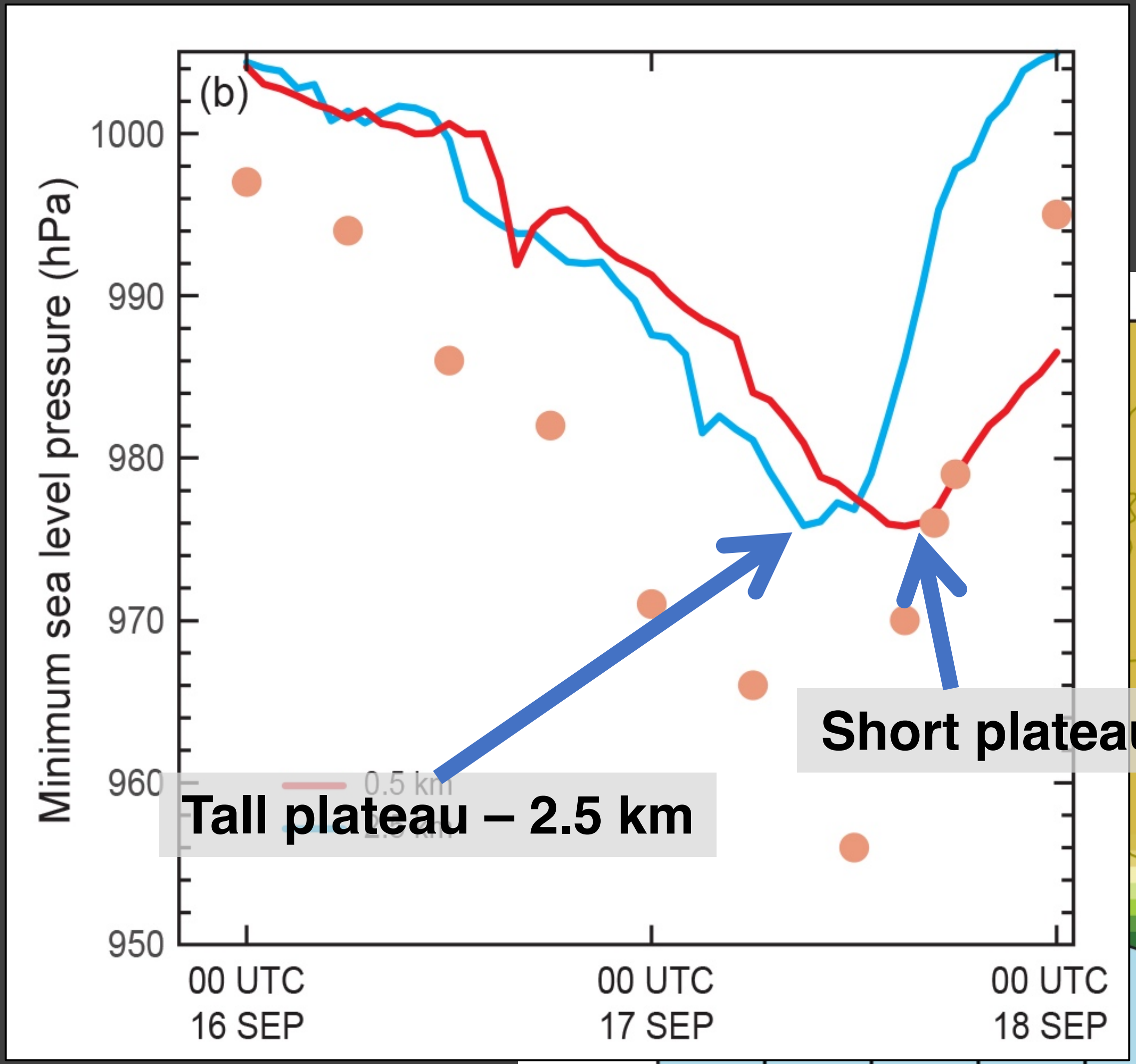
Version	WRF-ARW 3.8.1
Start Time	0000 UTC 15 September
Initialization	ERA-Interim
Domains	54, 18, 6, 2 km
Vertical Levels	40
Microphysics	Goddard
Boundary Layer	Mellor-Yamada-Janjic (MYJ)

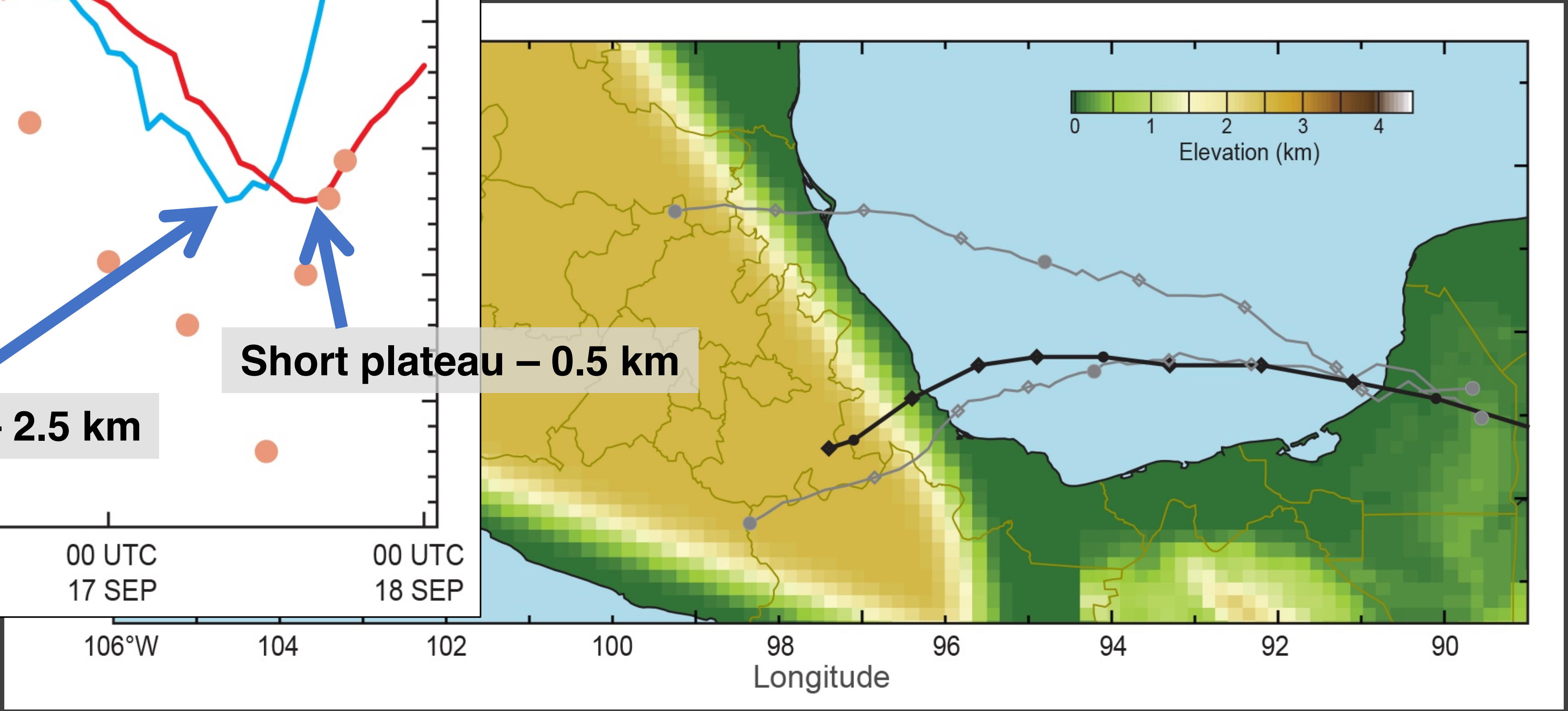


Storm Tracks + Tall Plateau

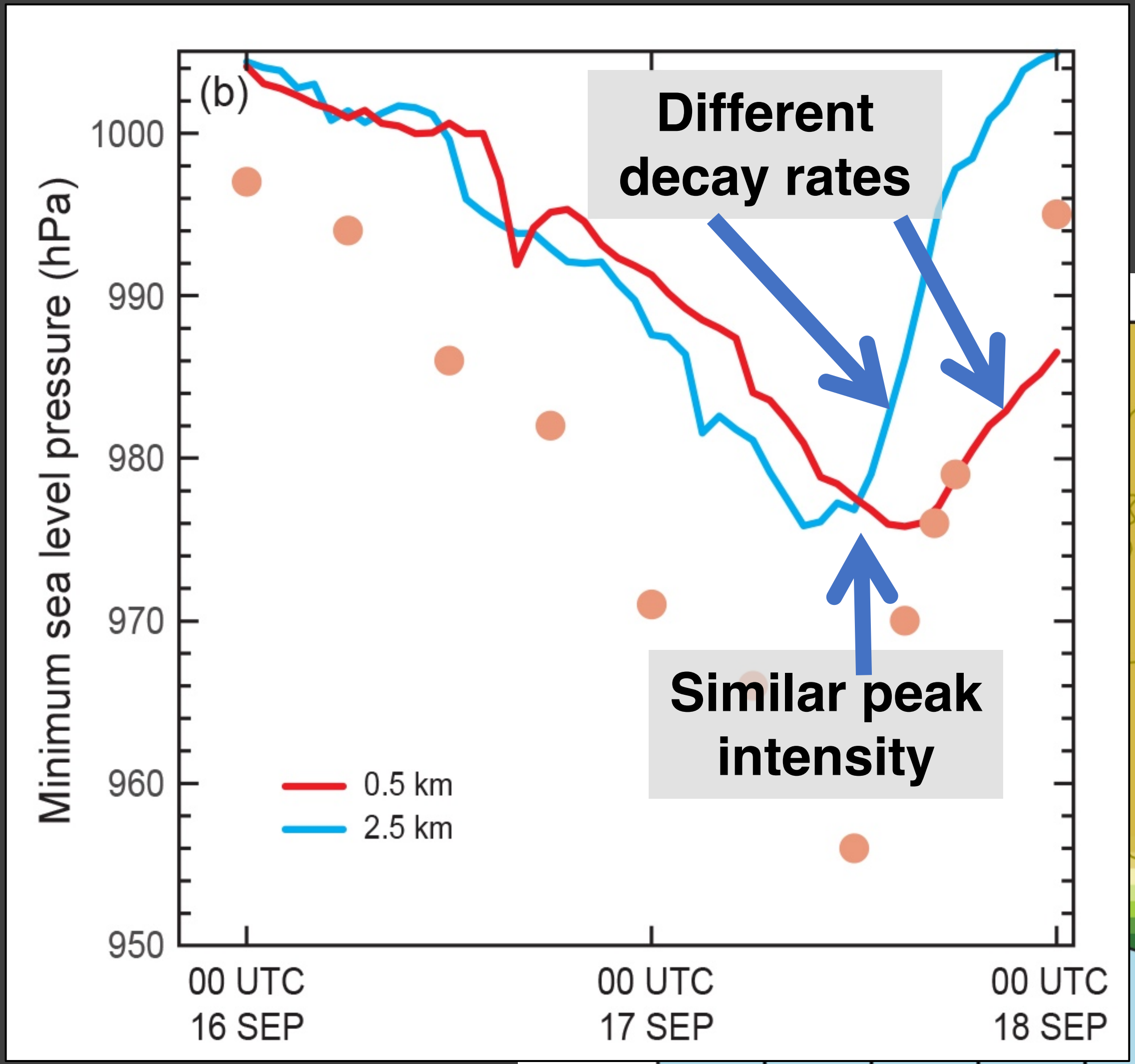


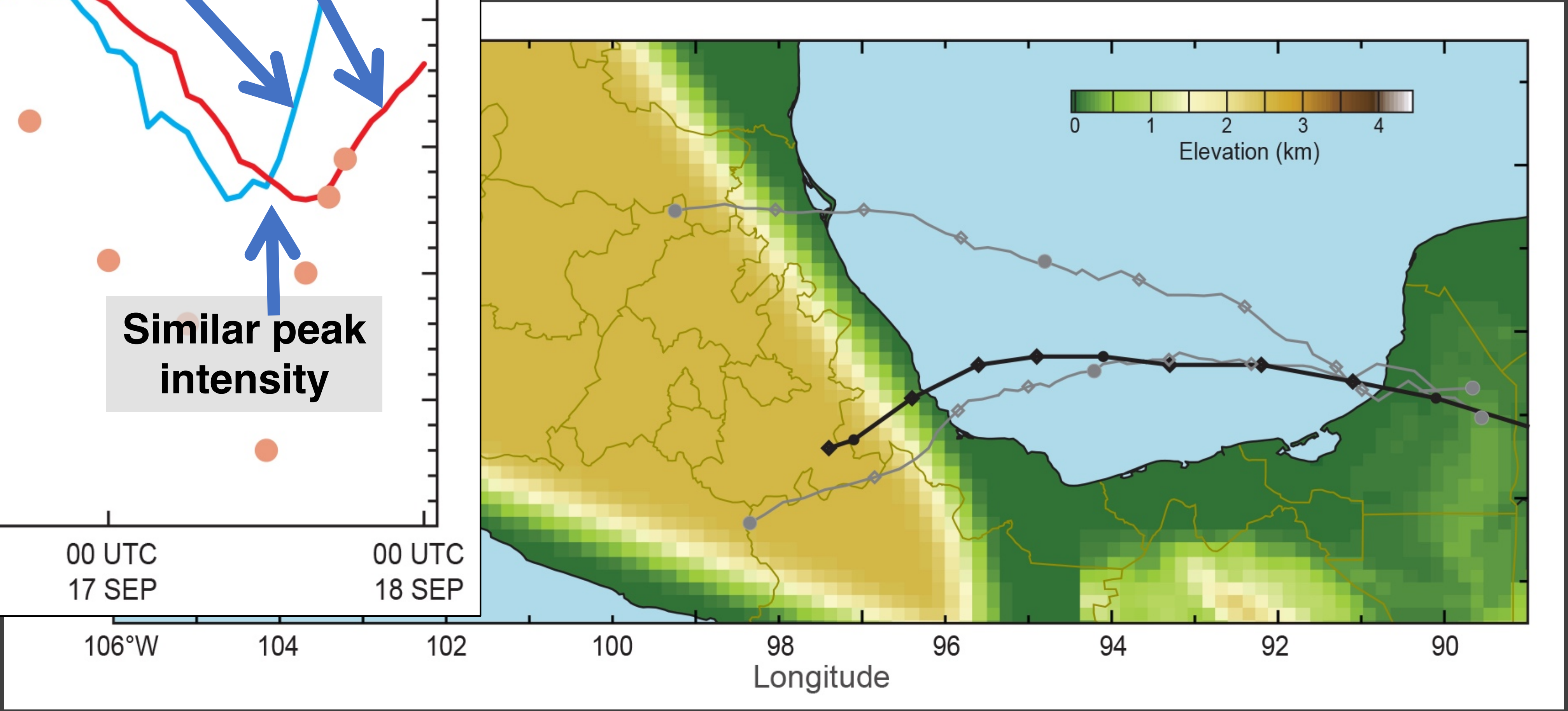
Control Members





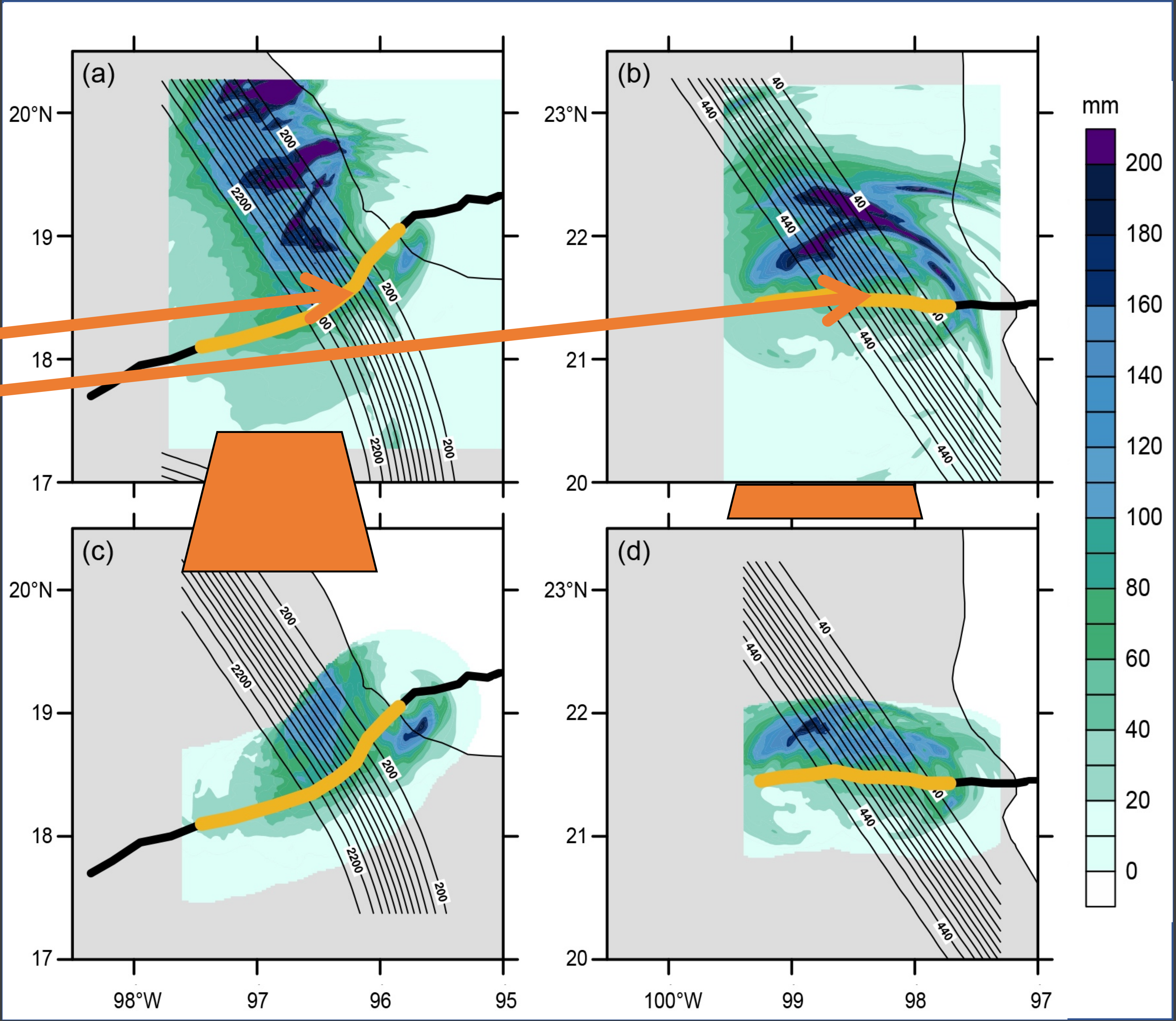
Control Members



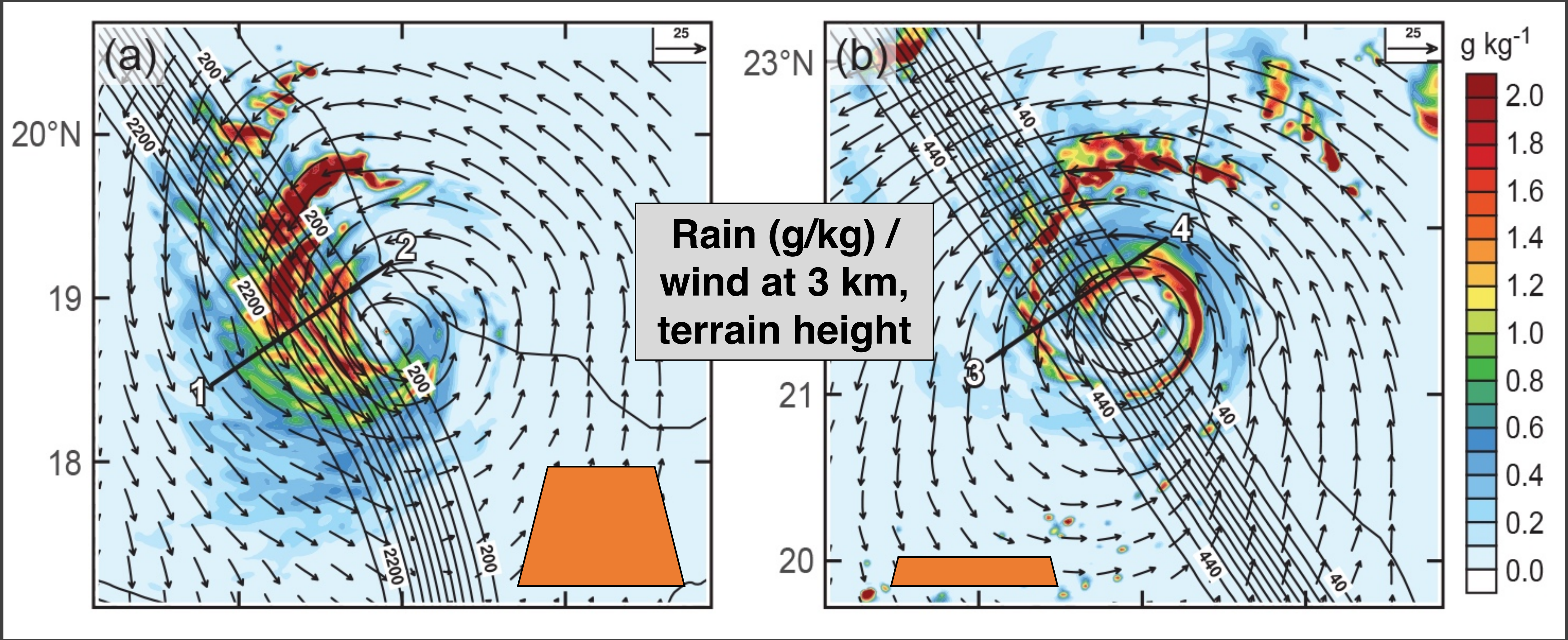


Simulated Precipitation

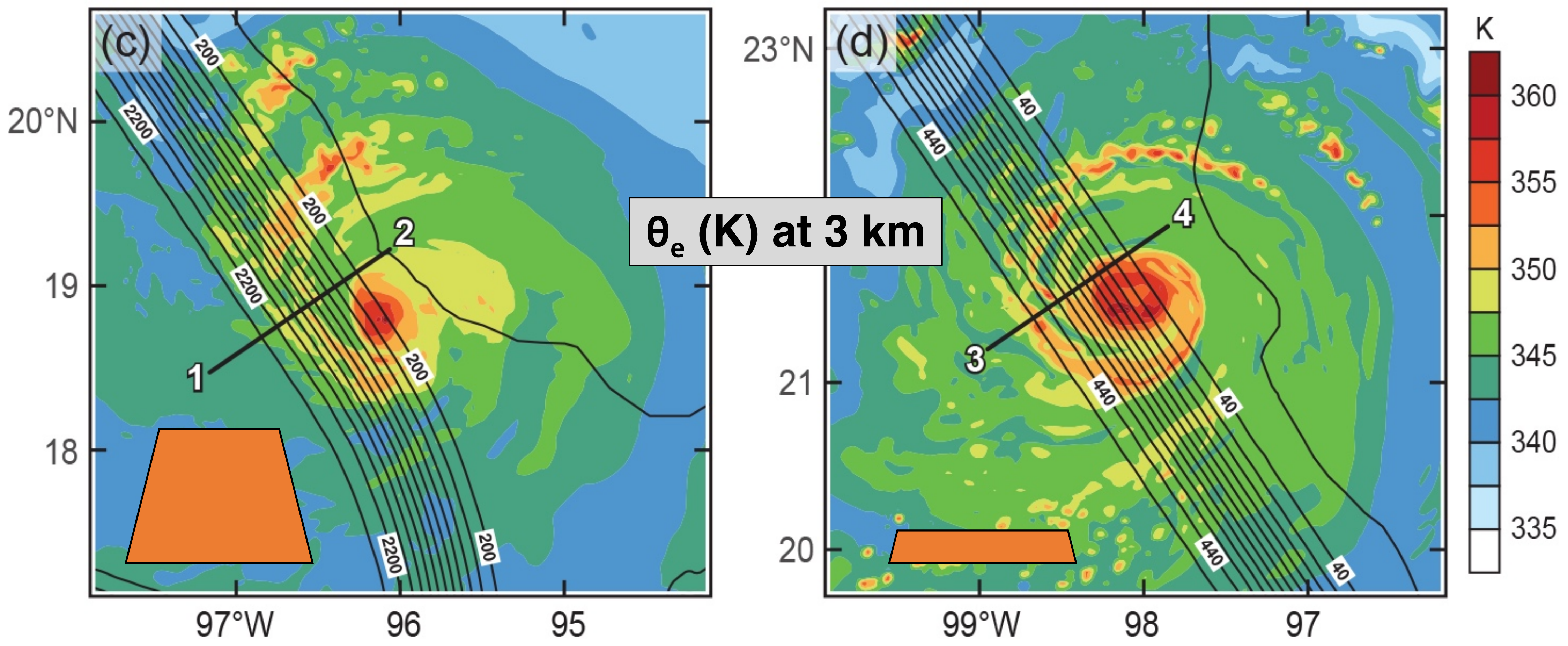
"Midpoint"



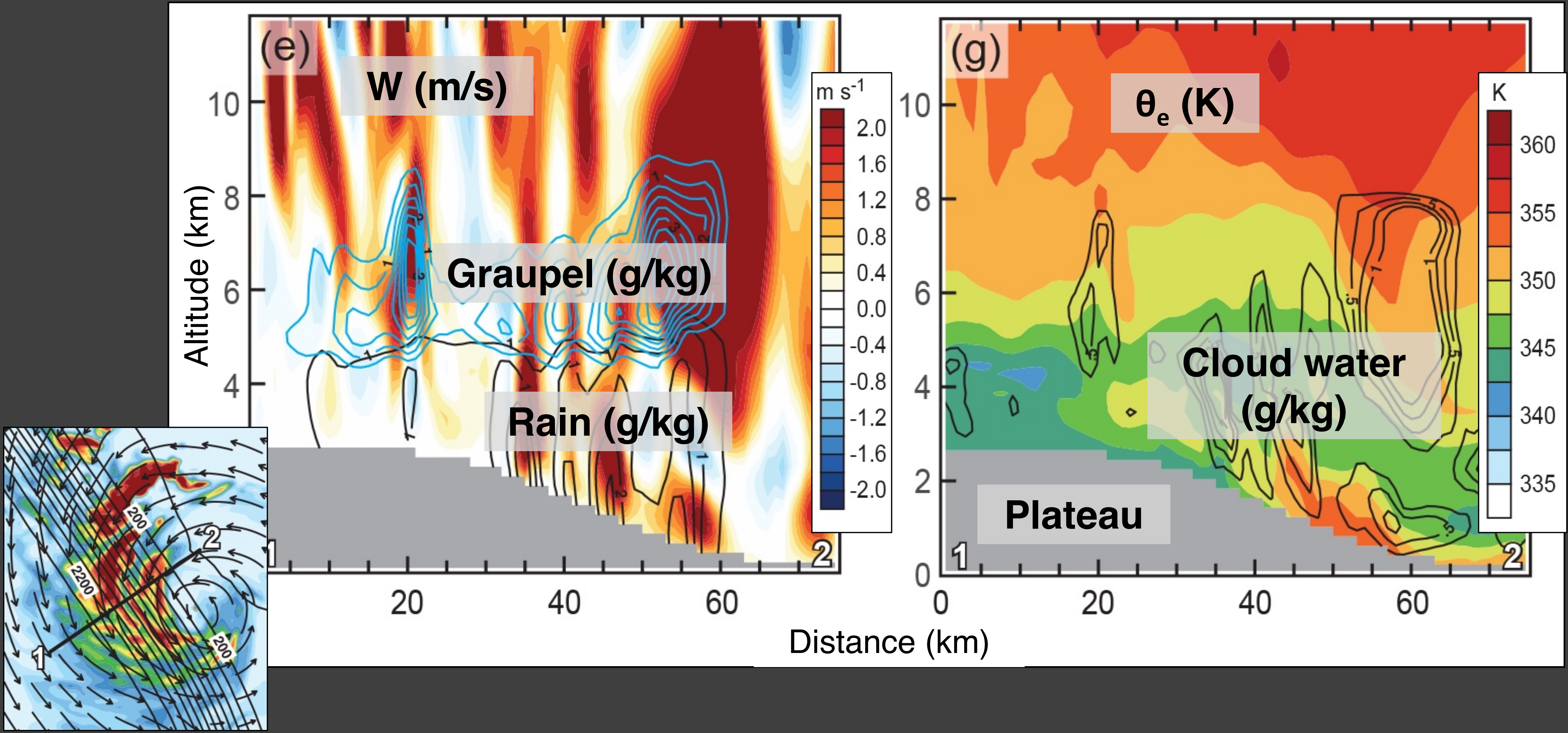
2 h before midpoint



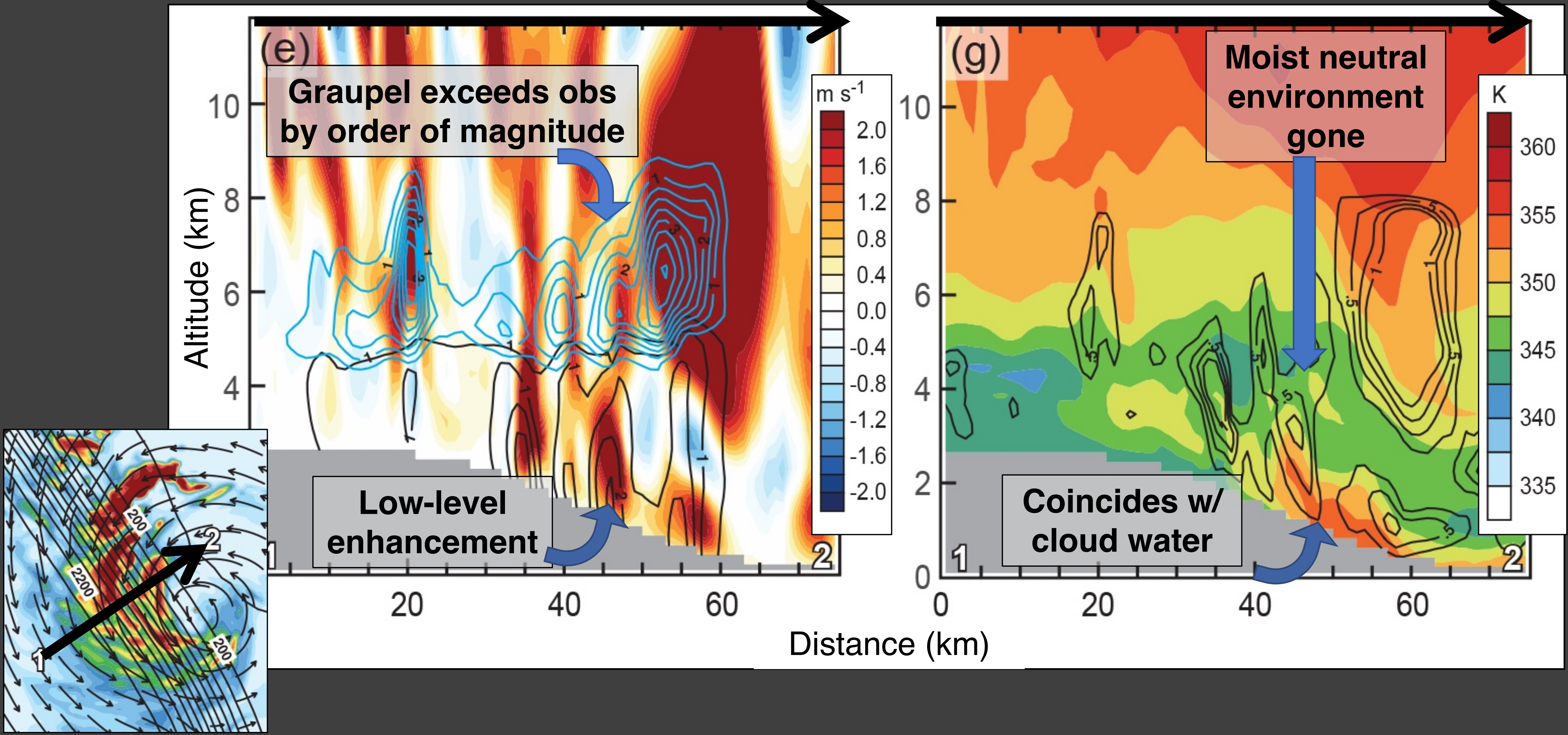
2 h before midpoint



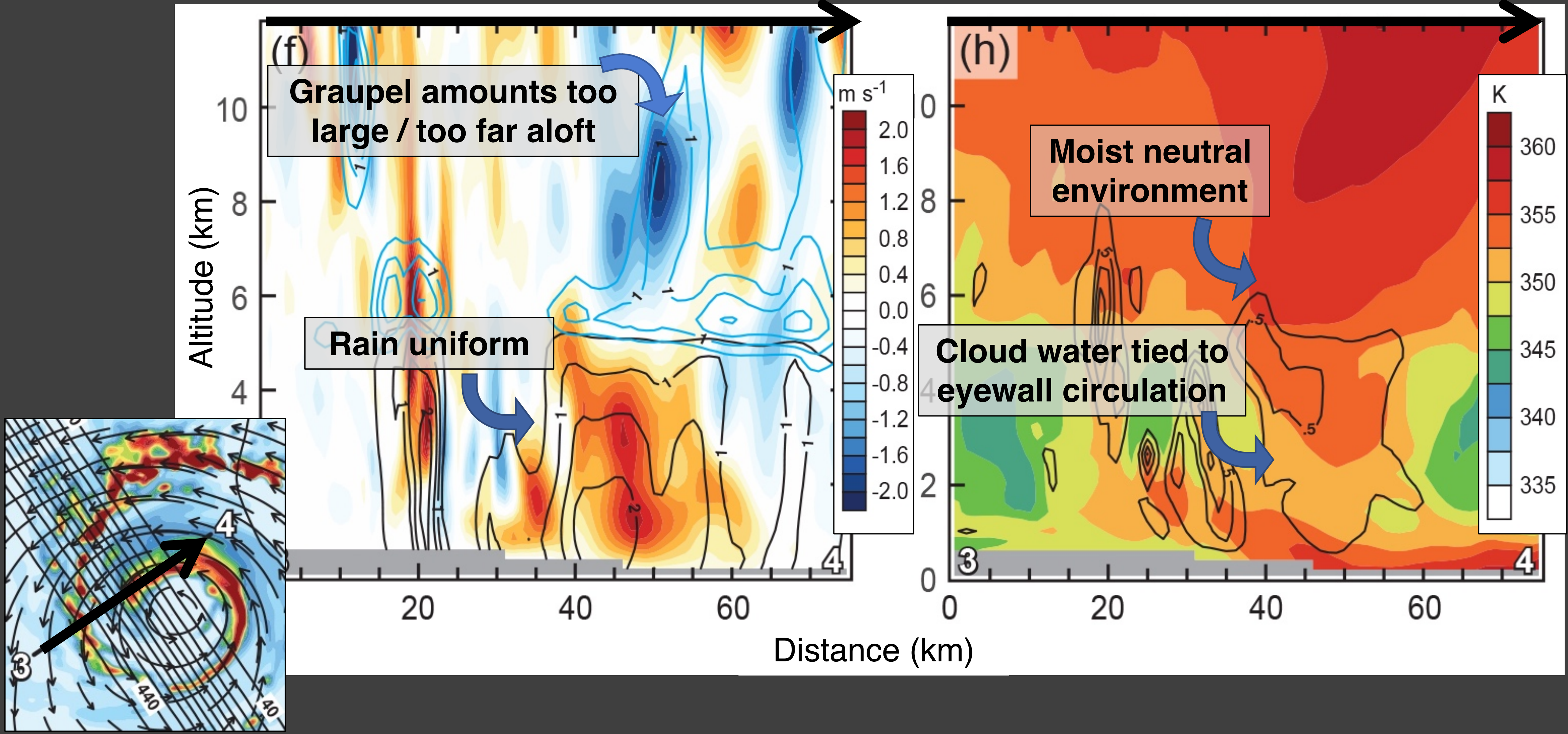
2 h before midpoint



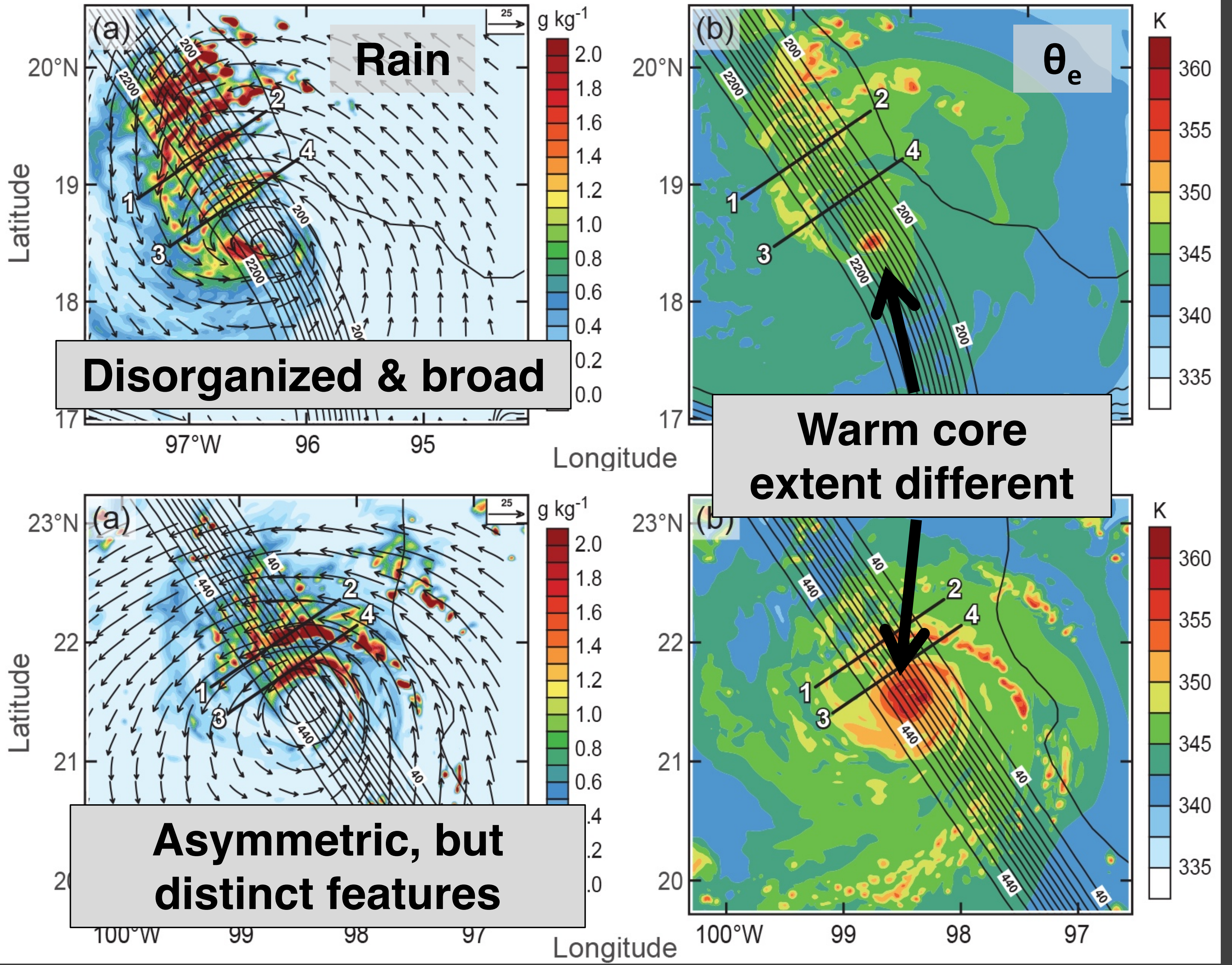
2 h before midpoint



2 h before midpoint

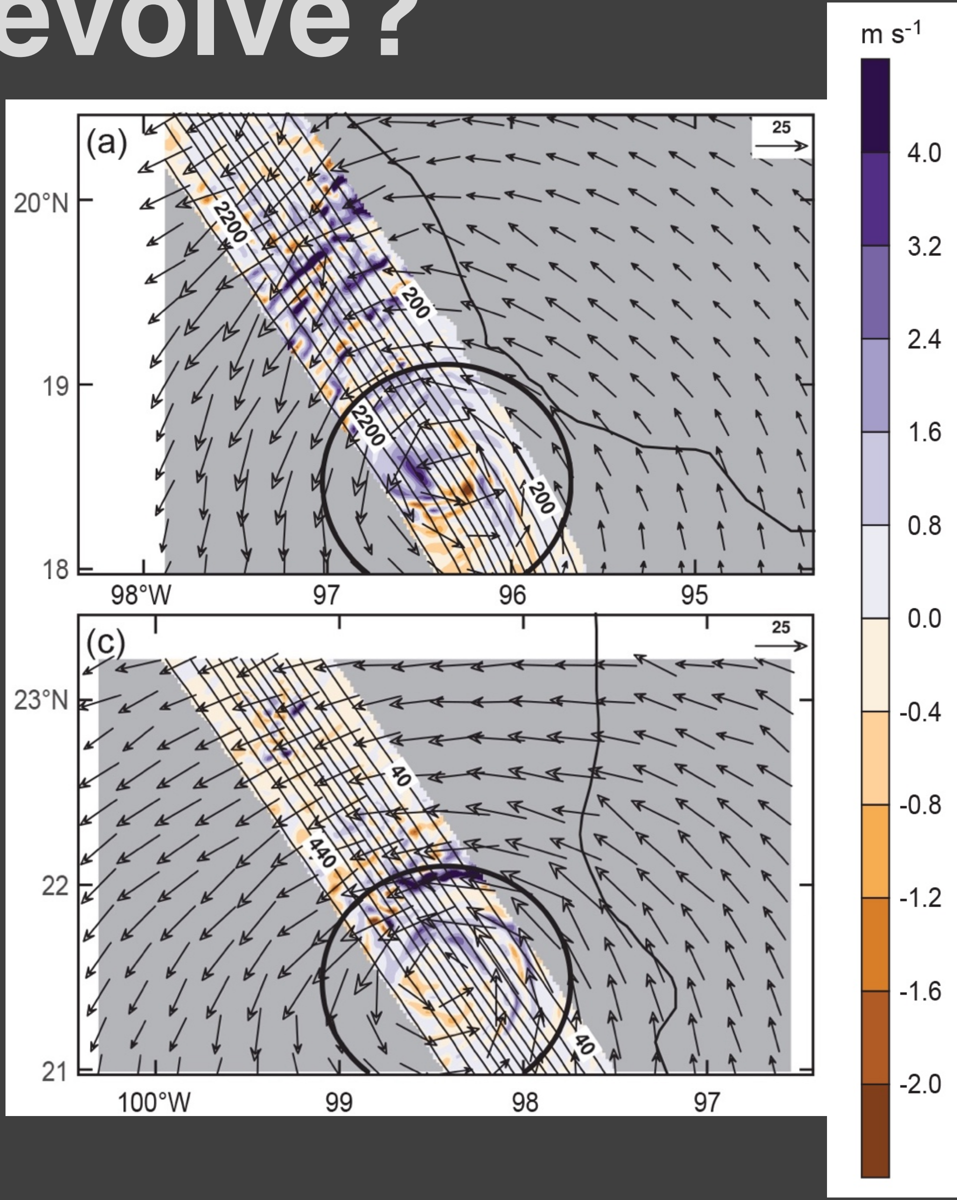


midpoint

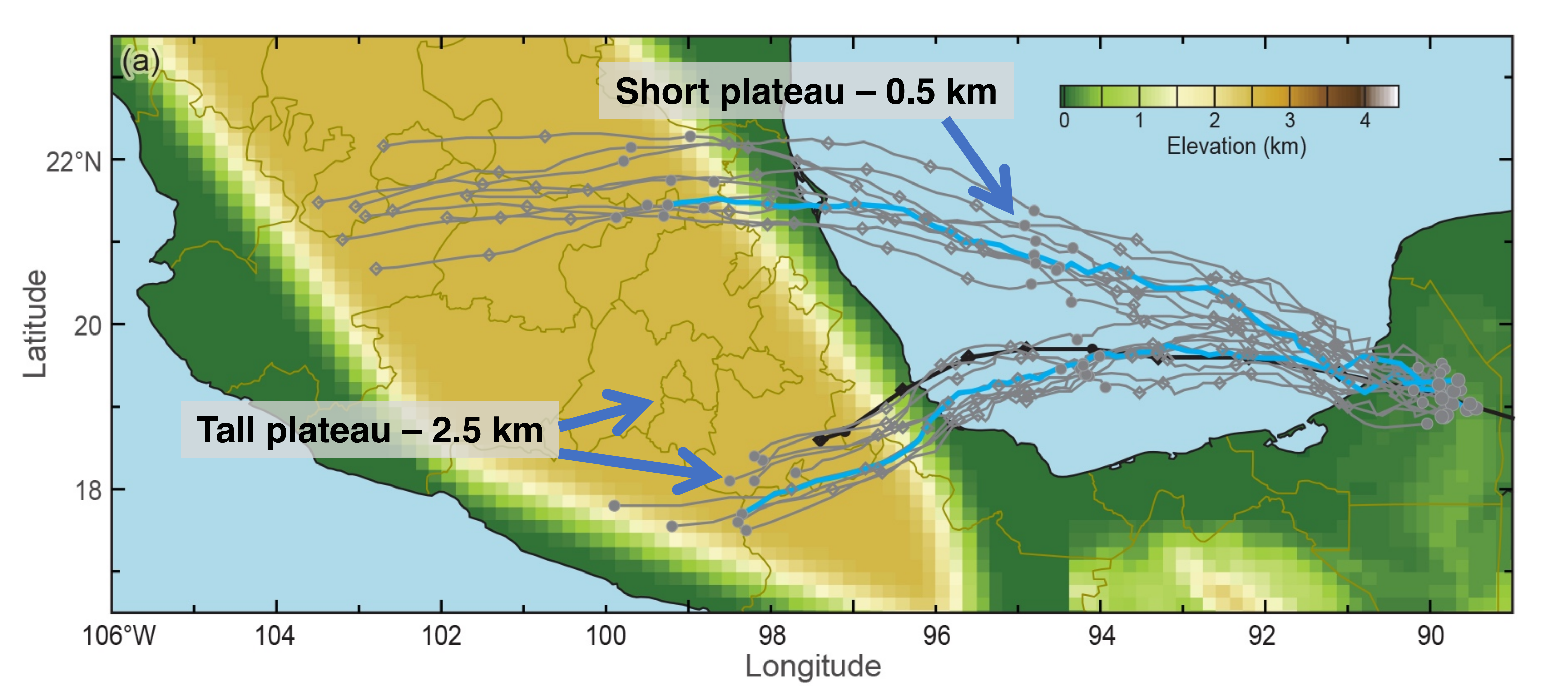

Rain
θe
Disorganized & broad
Warm core extent different
Asymmetric, but distinct features
(a)
(b)
g kg-1
K
Latitude
Longitude
20°N
19
18
17
97°W
96
95
23°N
22
21
20
100°W
99
98
97
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
360
355
350
345
340
335
1
2
3
4
200
2200
40
440
25

How do the simulated structure and microphysical variables evolve?

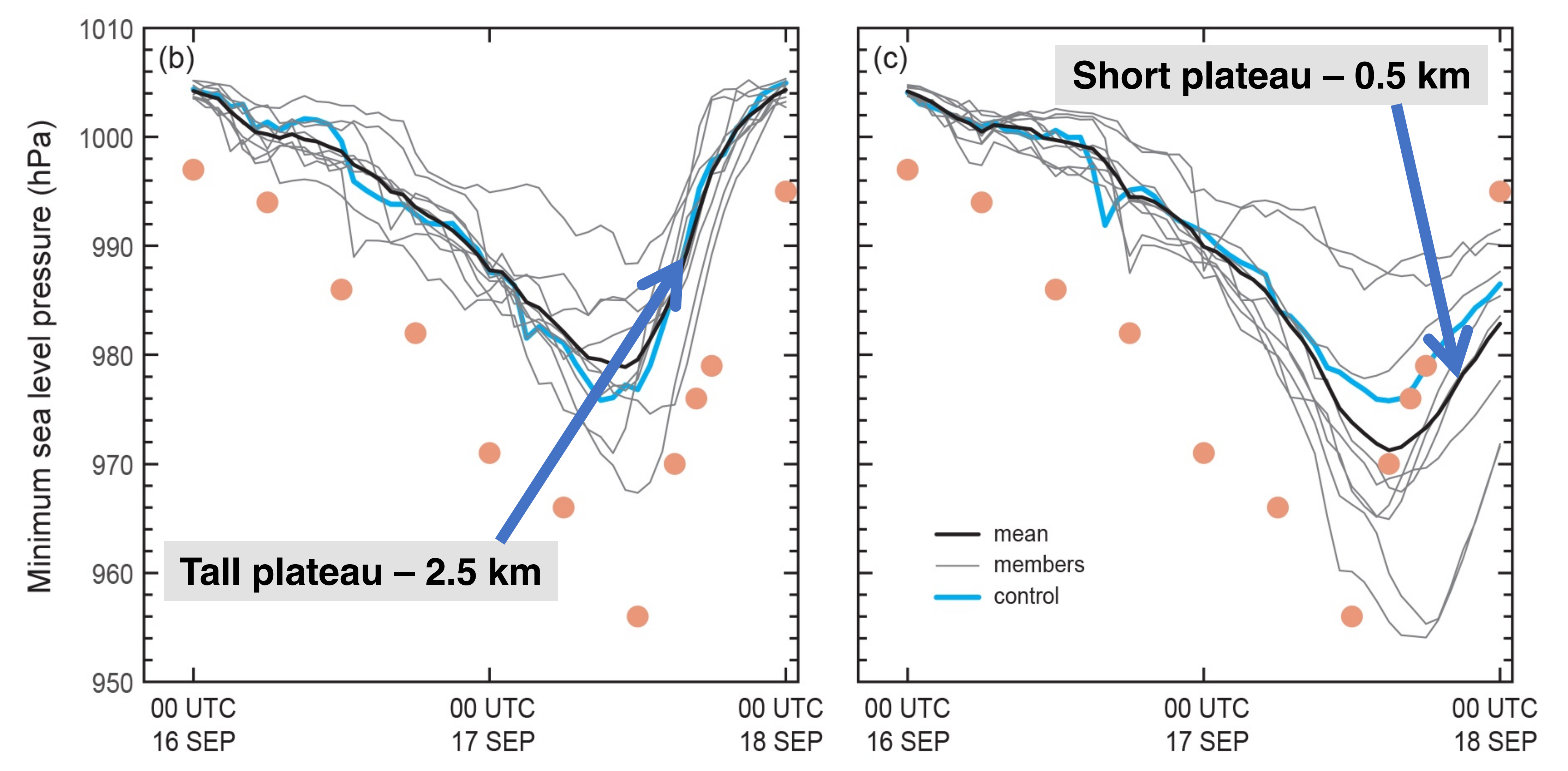
- Isolate 9-h period around midpoint
- Include only data along sloping terrain
- Separate data by 75-km radius
  - Outside: 0.5º S to 2.0º N
- Small ensemble (10 members)



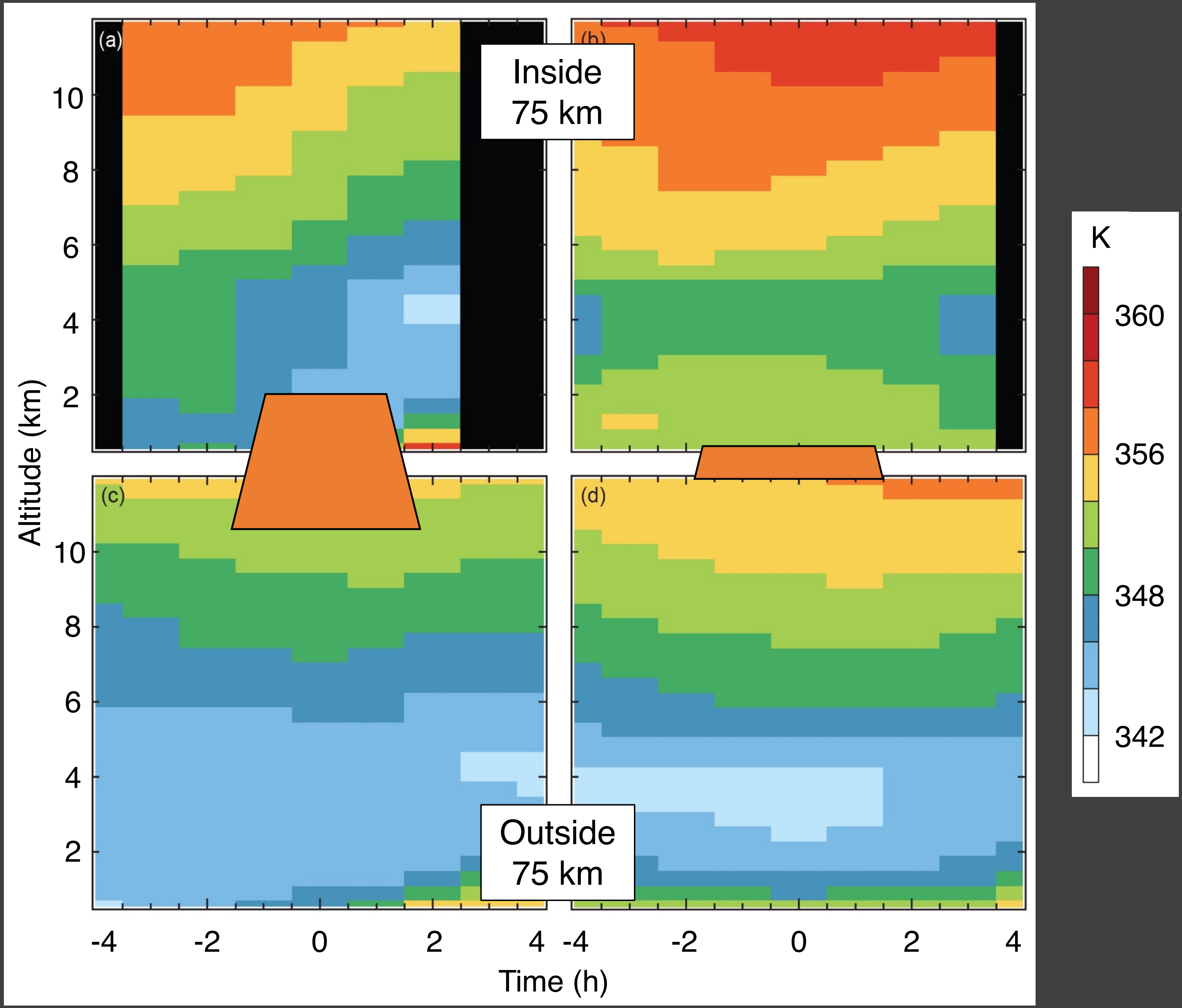
Storm Tracks



Storm Intensities

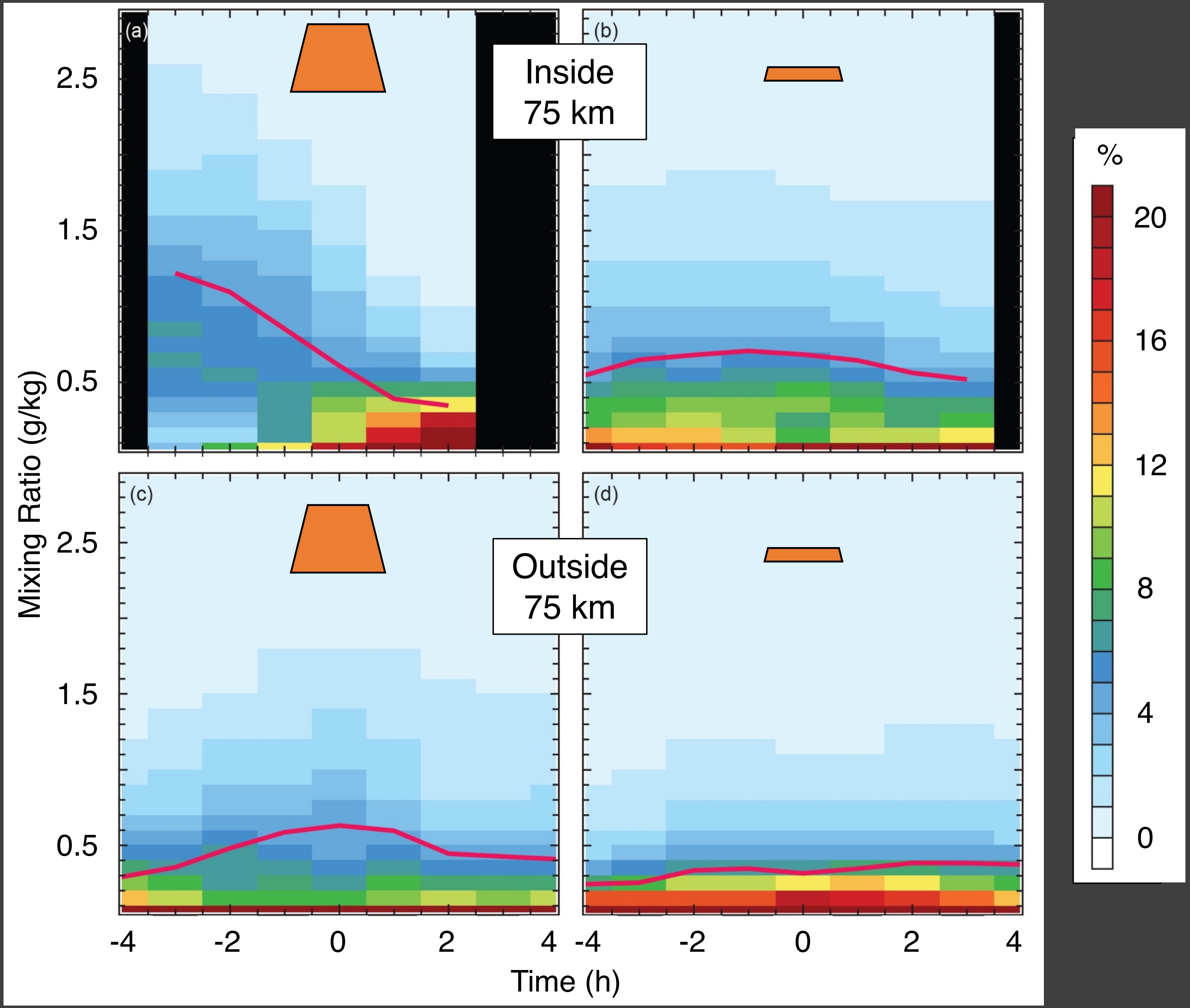


Average θ_e



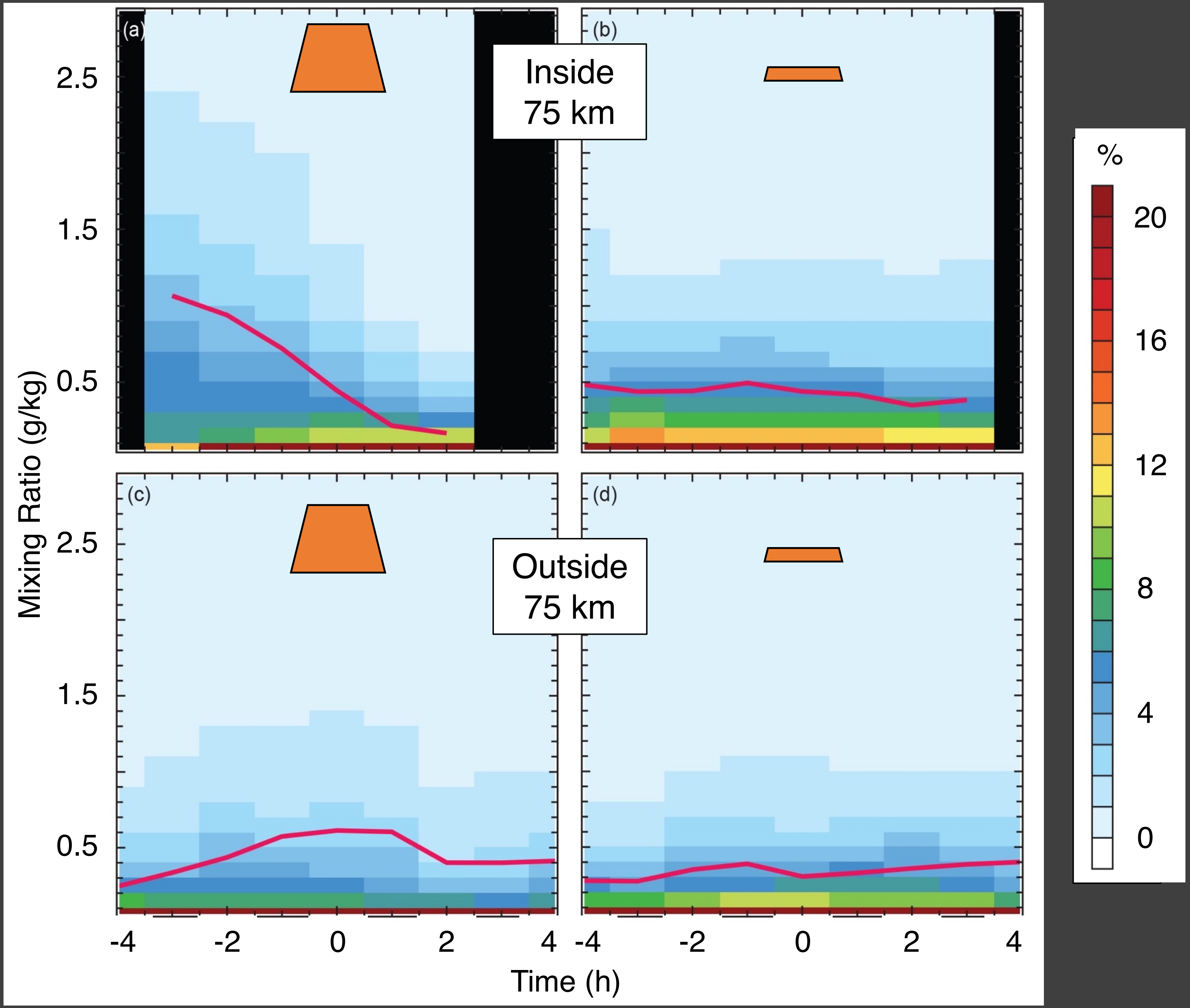
Rain Frequency

0.5 – 2.0 km above each plateau



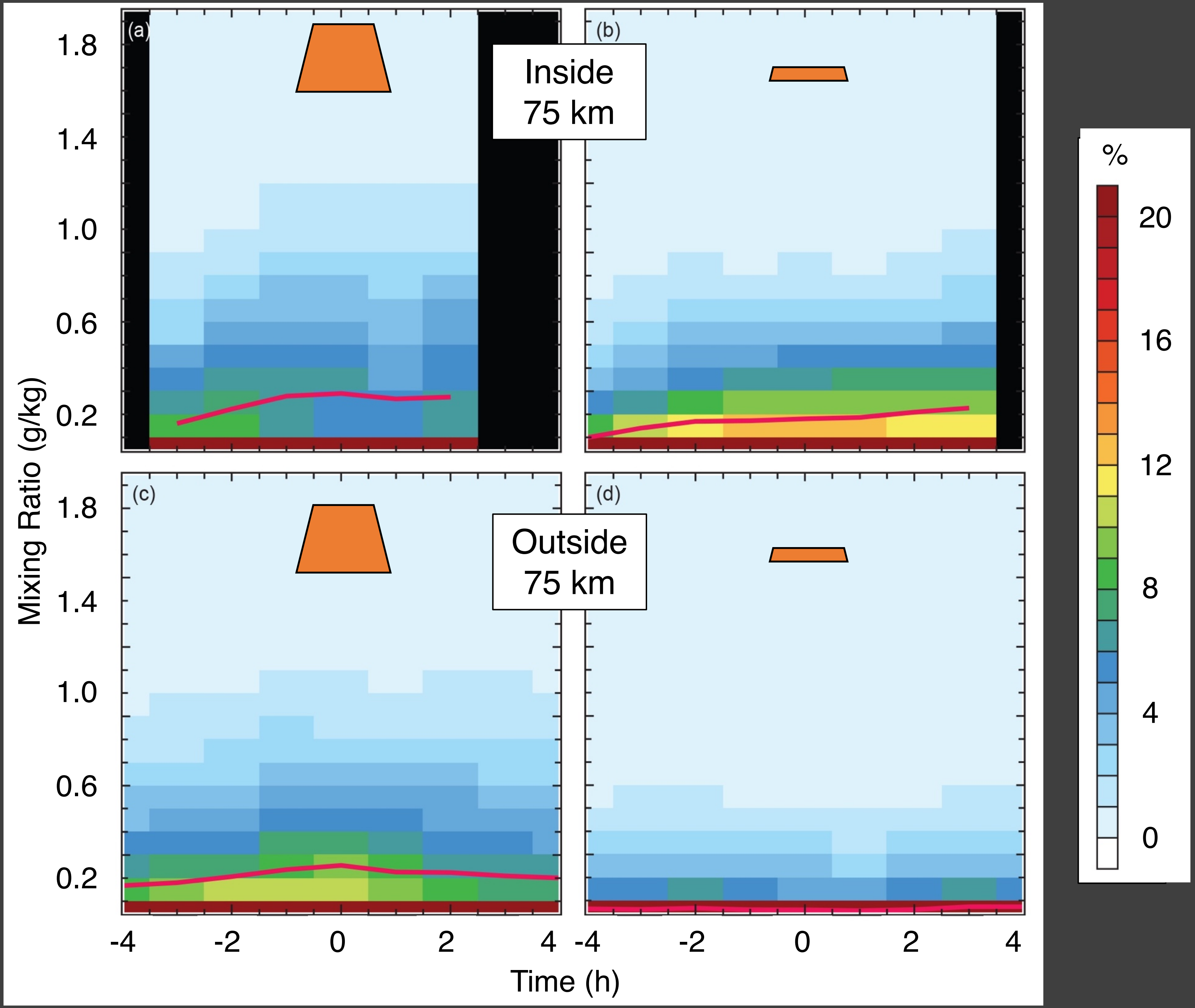
Graupel Frequency

5.0 – 7.0 km above sea level



Cloud water Frequency

0.5 – 2.0 km above each plateau



Conclusions

- Terrain height affects rate of decay
    - Storm structure
        - Warm core size, organization of precipitation features
    - Precipitation processes
        - Tall plateau: moist neutral processes disappear, mix of warm & cold microphysical processes near the center, widespread convection at larger radii
        - Short plateau: moist neutral processes retained, eyewall / rainband remain intact

- Microphysical issues
    - Graupel mixing ratios exceed observations
        - Problematic given the strong control on surface precipitation
    - Tall plateau precipitation pattern similar to observations, but likely obtained realistic result through unrealistic processes


Powell's
Books
317


1794
OLD NAVY
NIKE


818

Conclusions

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  - Storm structure
    - Warm core size, organization of precipitation features
  - Precipitation types
    - Tall plateau: moist neutral processes disappear, mix of warm & cold microphysical processes near the center, widespread convection at larger radii
    - Short plateau: moist neutral processes retained, eyewall / rainband remain intact

- Microphysical issues
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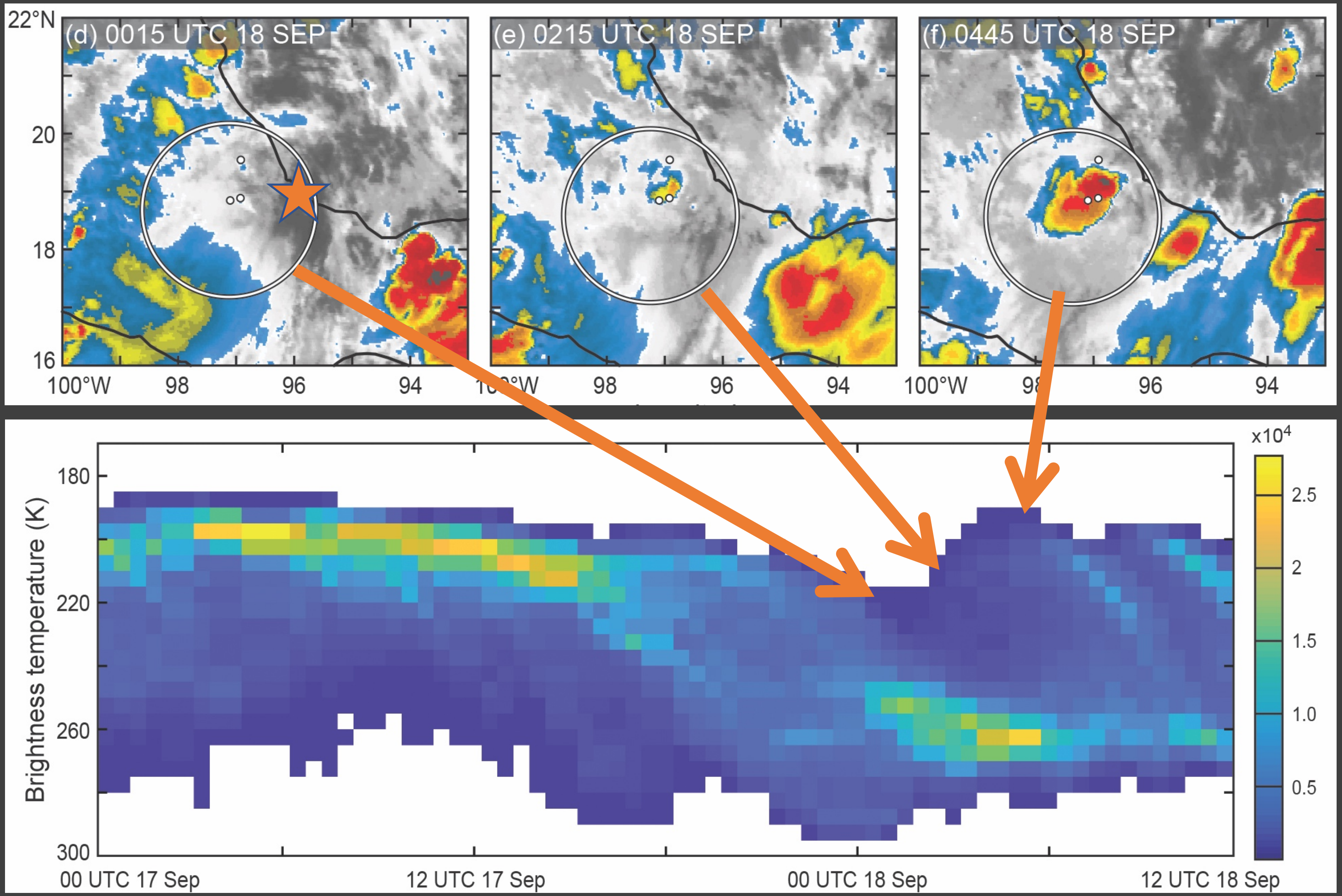
Extra slides

Future work

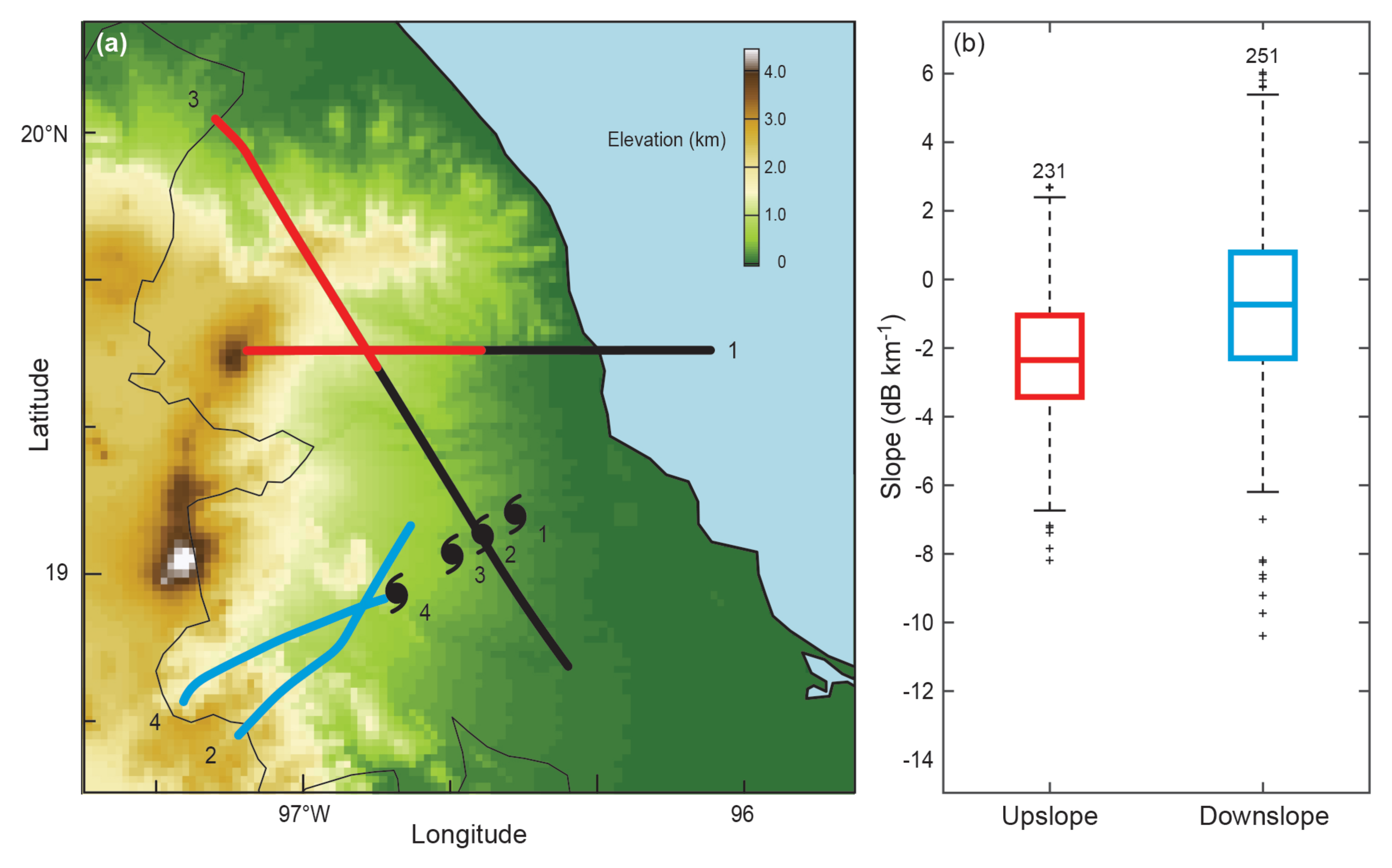
- Observations!
  - Microphysics, kinematics, and thermodynamics
  - Additional case studies and statistical analyses
  - Model / microphysical scheme validation

- Consider environmental / storm factors
  - Vertical wind shear, initial storm intensity, storm translation speed, etc

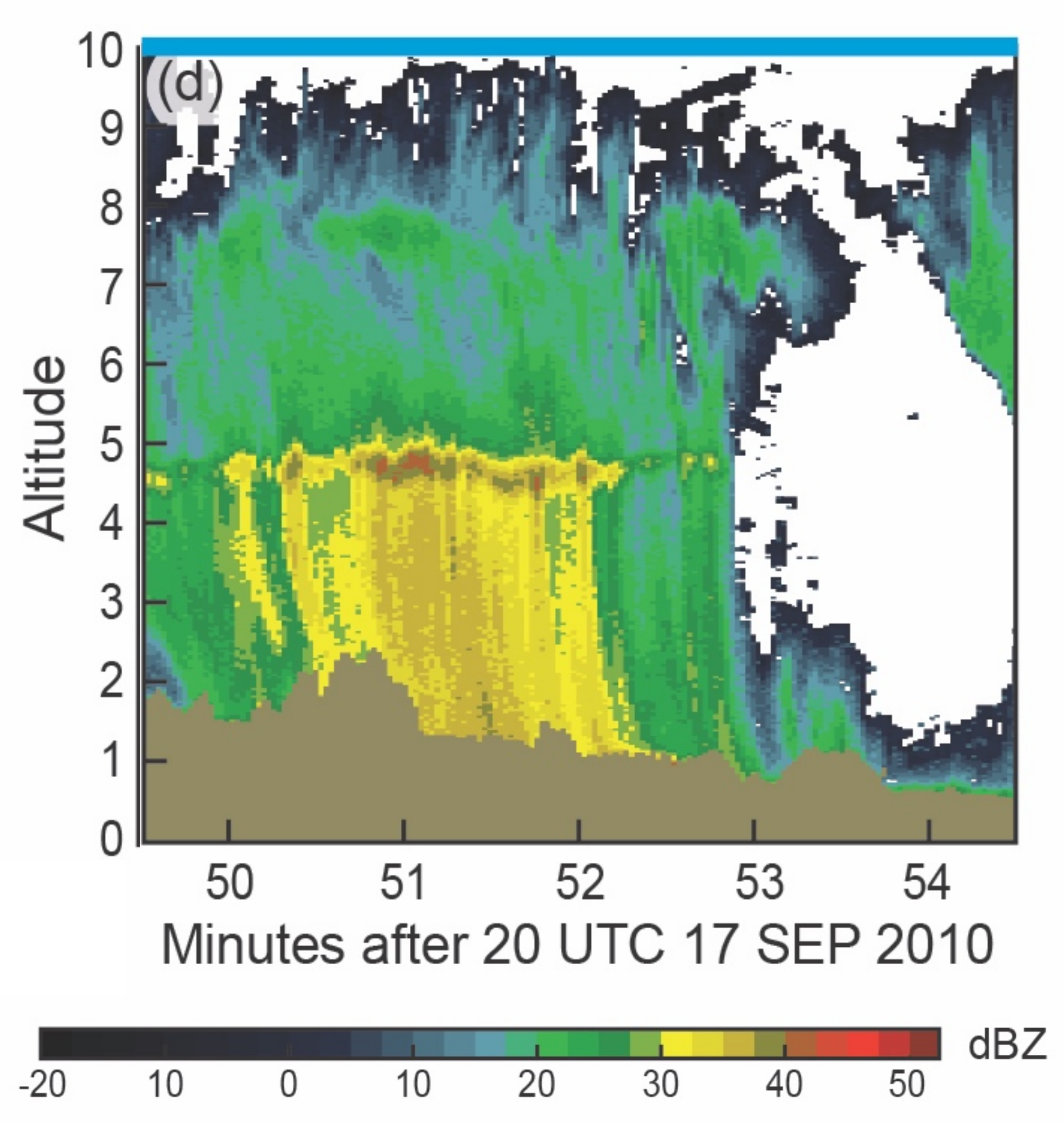
Remnant Convection



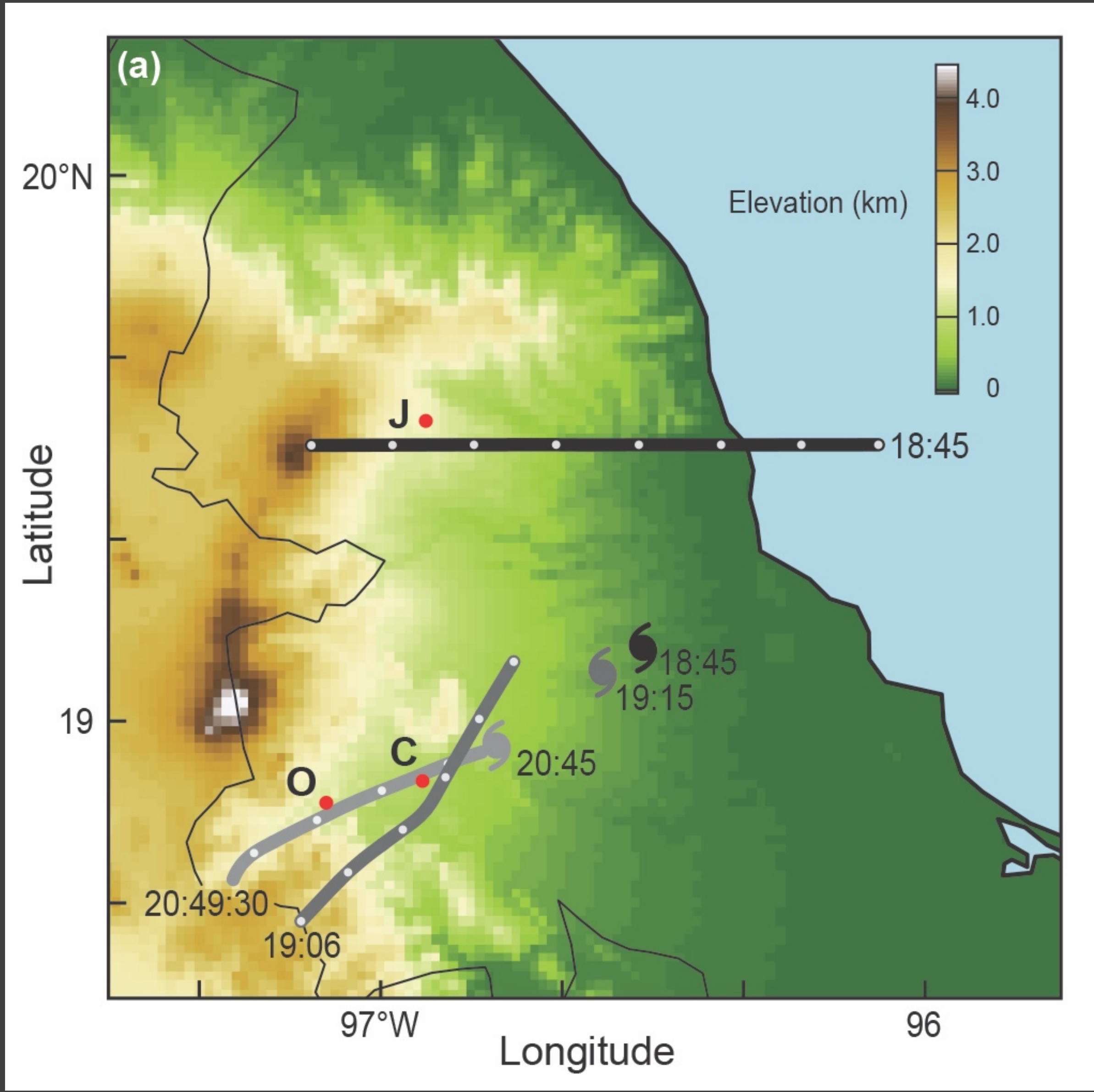
Reflectivity Slopes



Flight leg #3

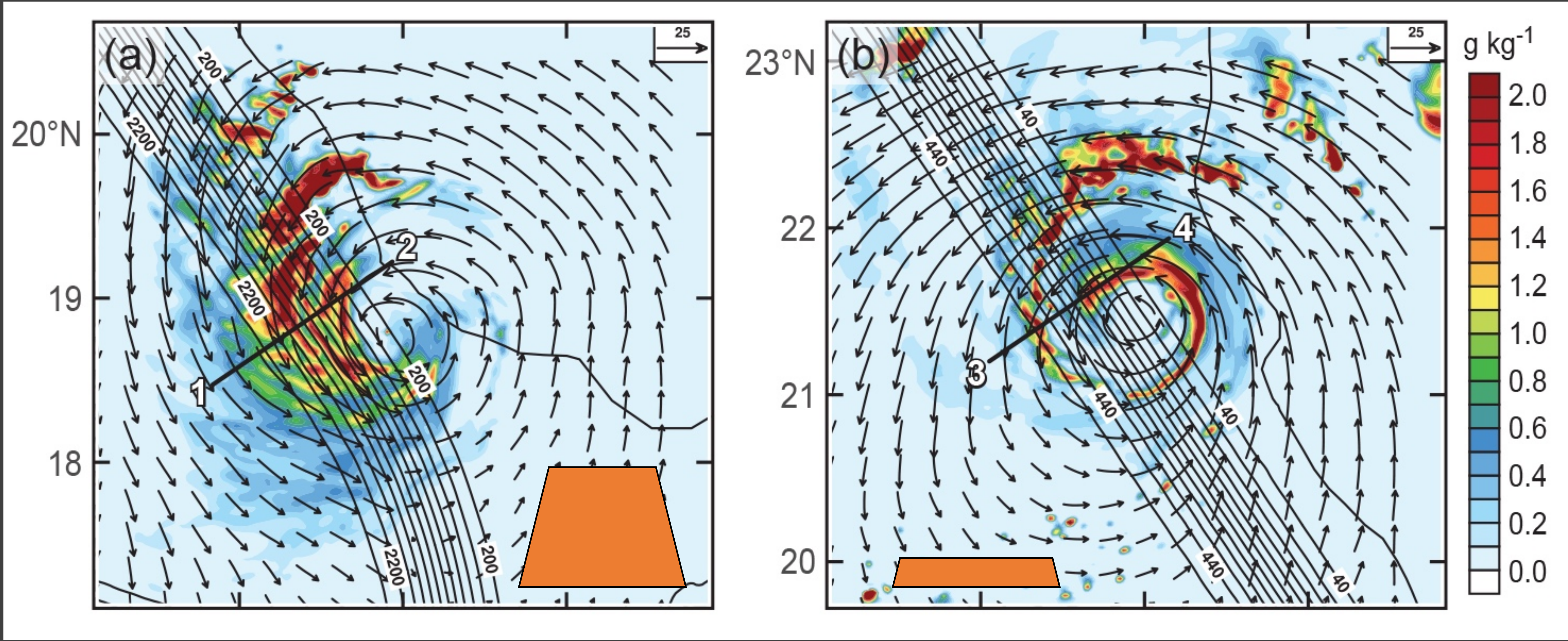


(d)
Altitude
10
9
8
7
6
5
4
3
2
1
0
50
51
52
53
54
Minutes after 20 UTC 17 SEP 2010
dBZ
-20
10
0
10
20
30
40
50

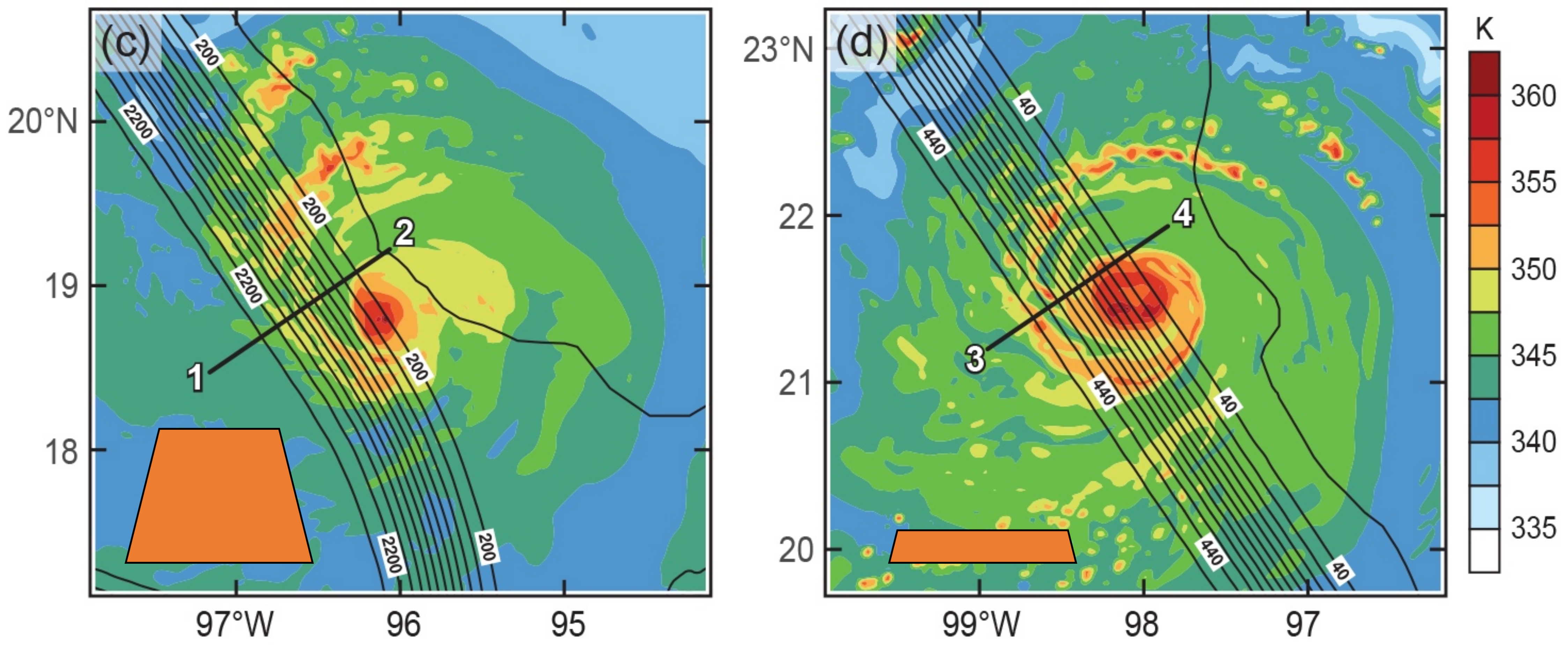


(a)
20°N
19
Latitude
Elevation (km)
4.0
3.0
2.0
1.0
0
J
18:45
18:45
19:15
C
20:45
O
20:49:30
19:06
97°W
96
Longitude

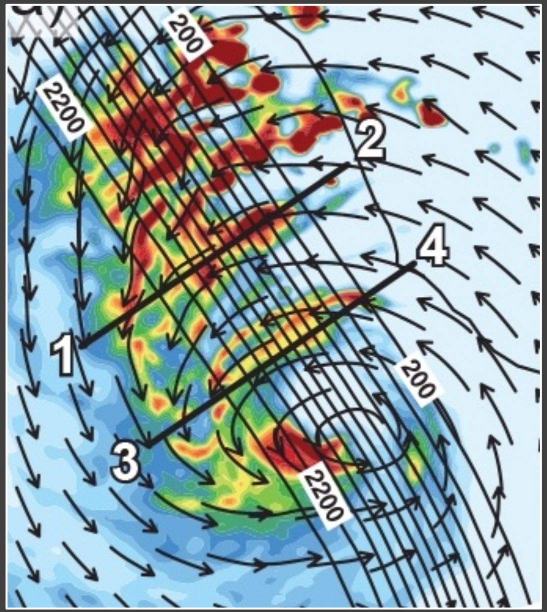
2 h before midpoint

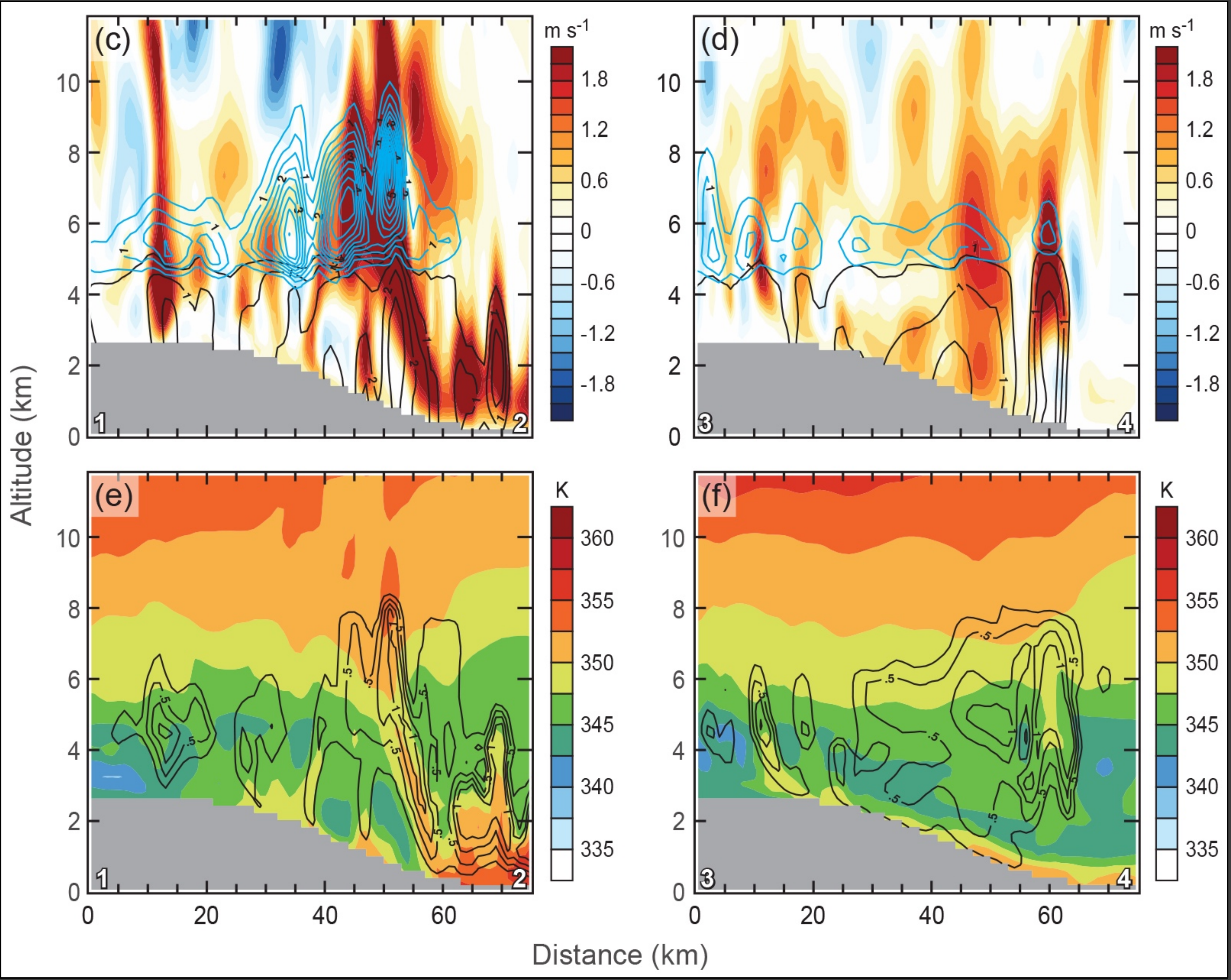


2 h before midpoint

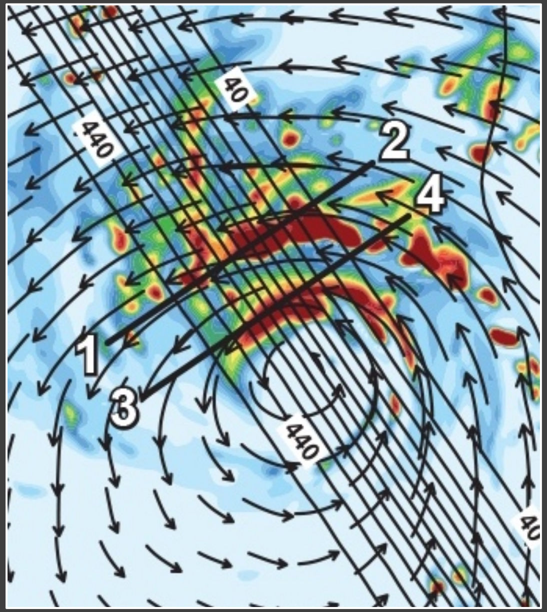


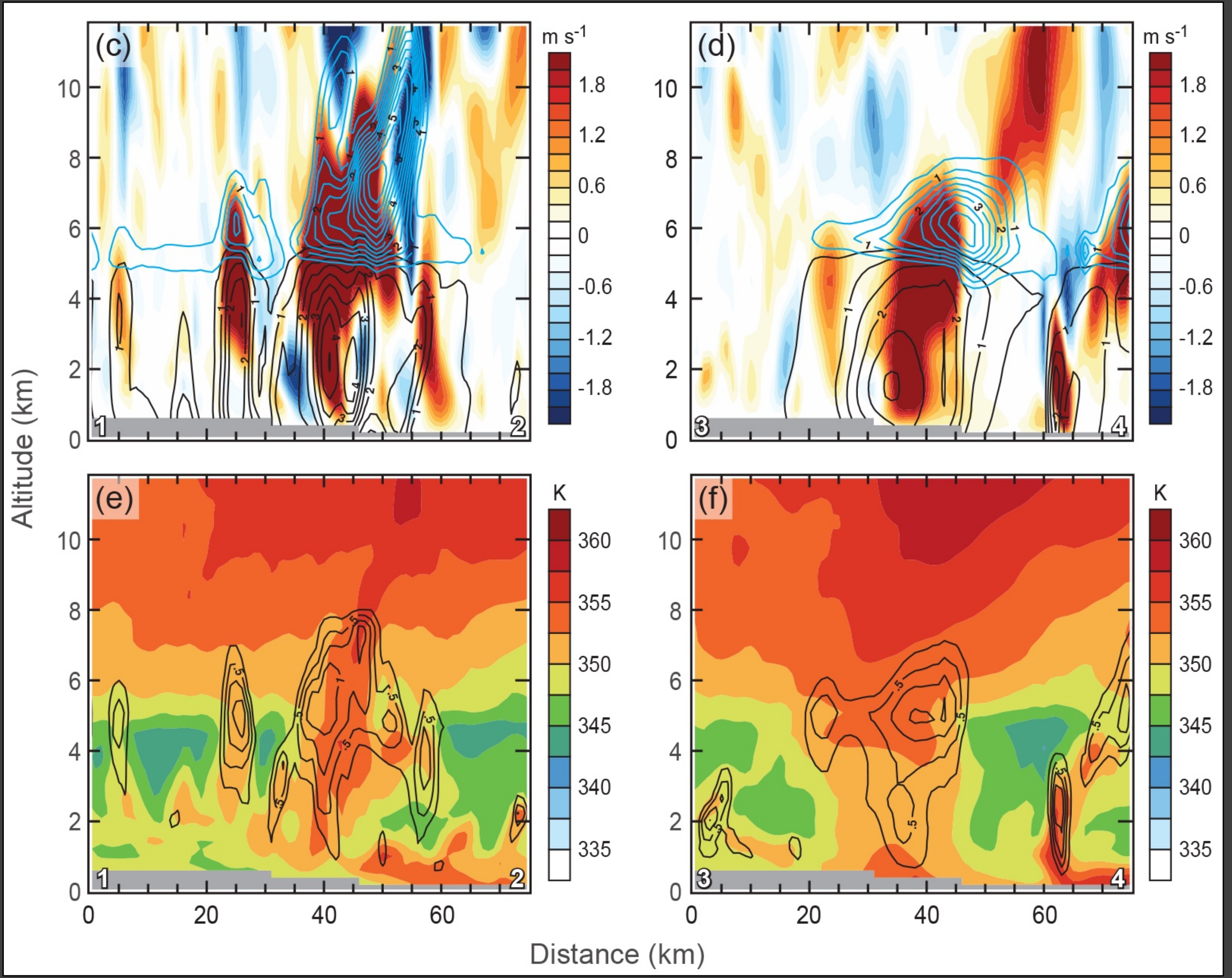
midpoint


200
2200
1
2
3
4
200
2200


(c)
(d)
(e)
(f)
m s-1
1.8
1.2
0.6
0
-0.6
-1.2
-1.8
K
360
355
350
345
340
335
Altitude (km)
Distance (km)
0
2
4
6
8
10
20
40
60
1
2
3
4

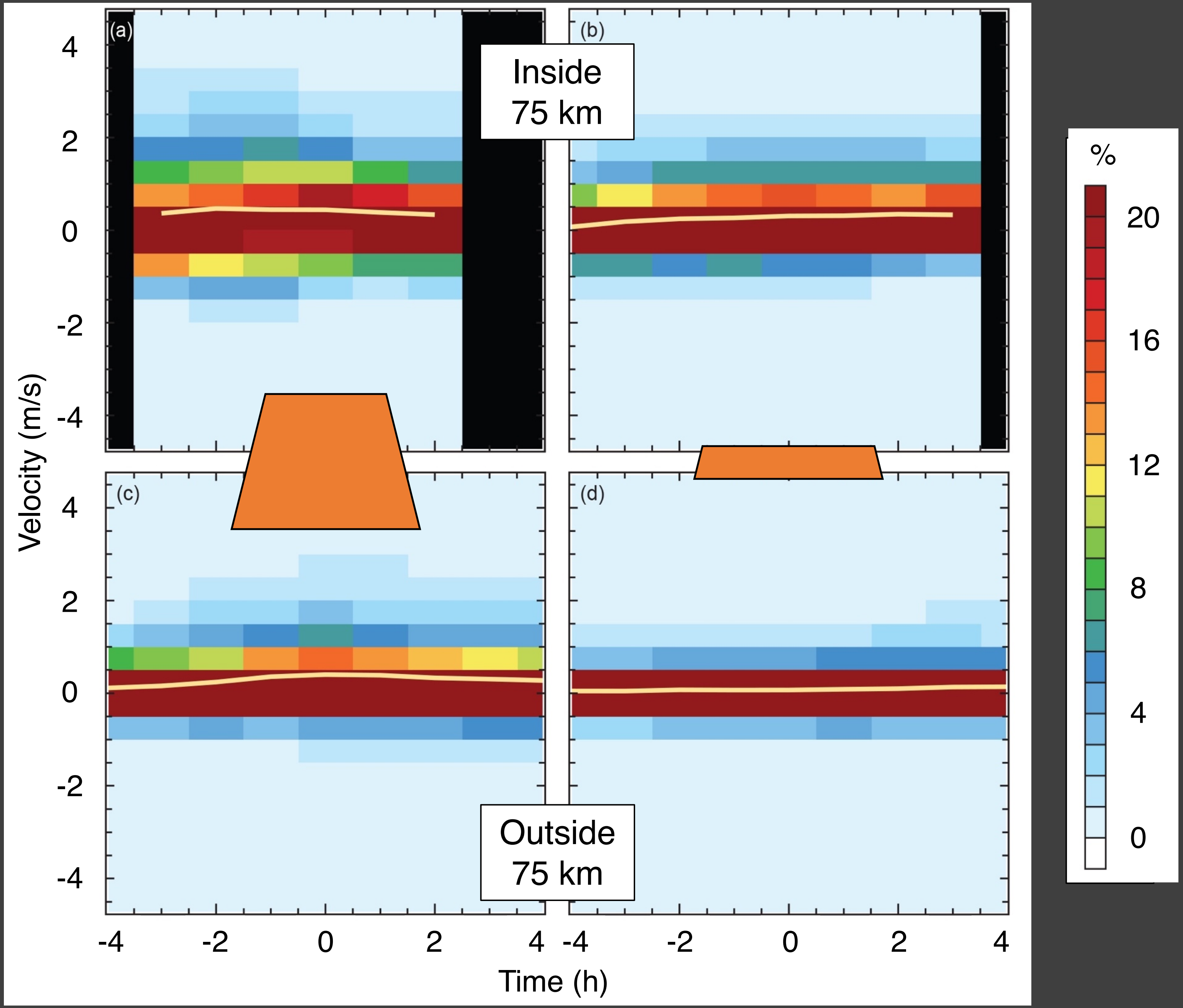
midpoint

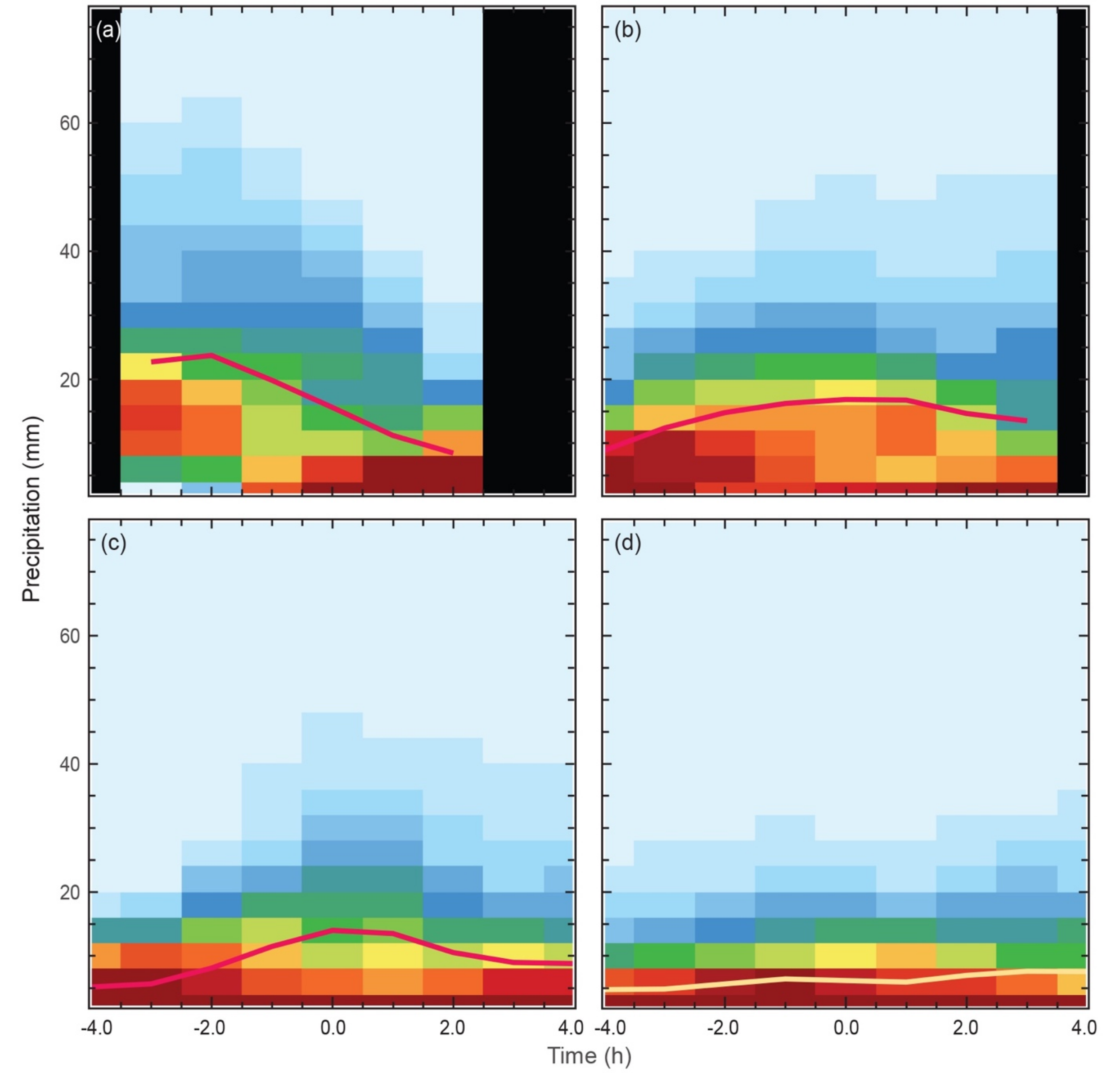

1
2
3
4
40
440
440
40

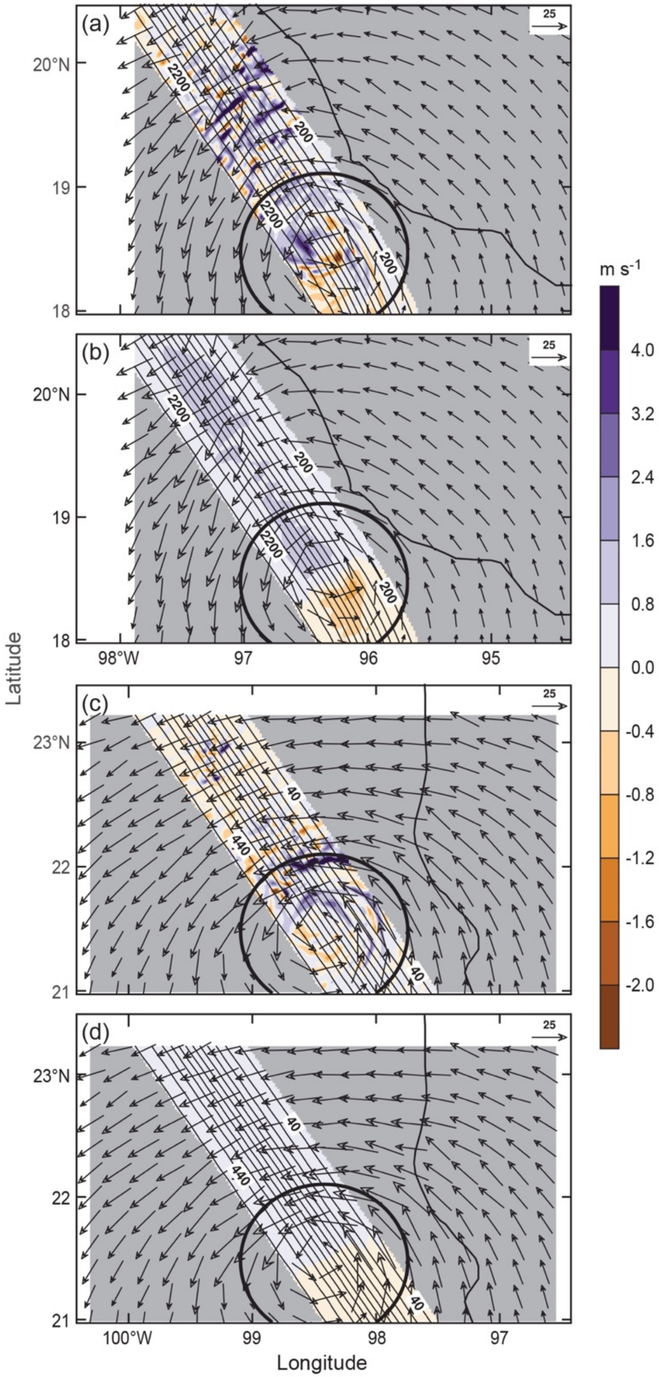

(c)
(d)
(e)
(f)
m s-1
1.8
1.2
0.6
0
-0.6
-1.2
-1.8
K
360
355
350
345
340
335
Altitude (km)
Distance (km)
0
20
40
60
2
4
6
8
10

Vertical velocity

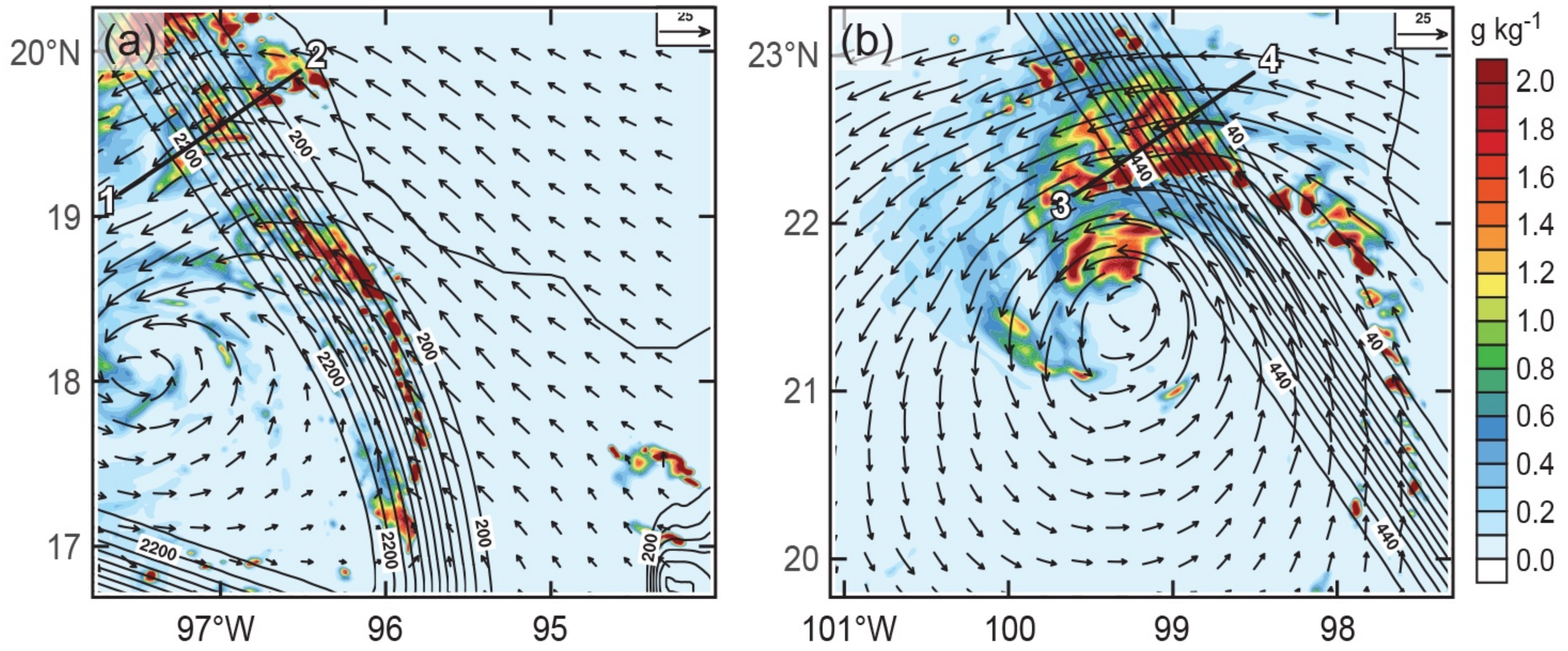
0.5 – 2.0 km above each plateau



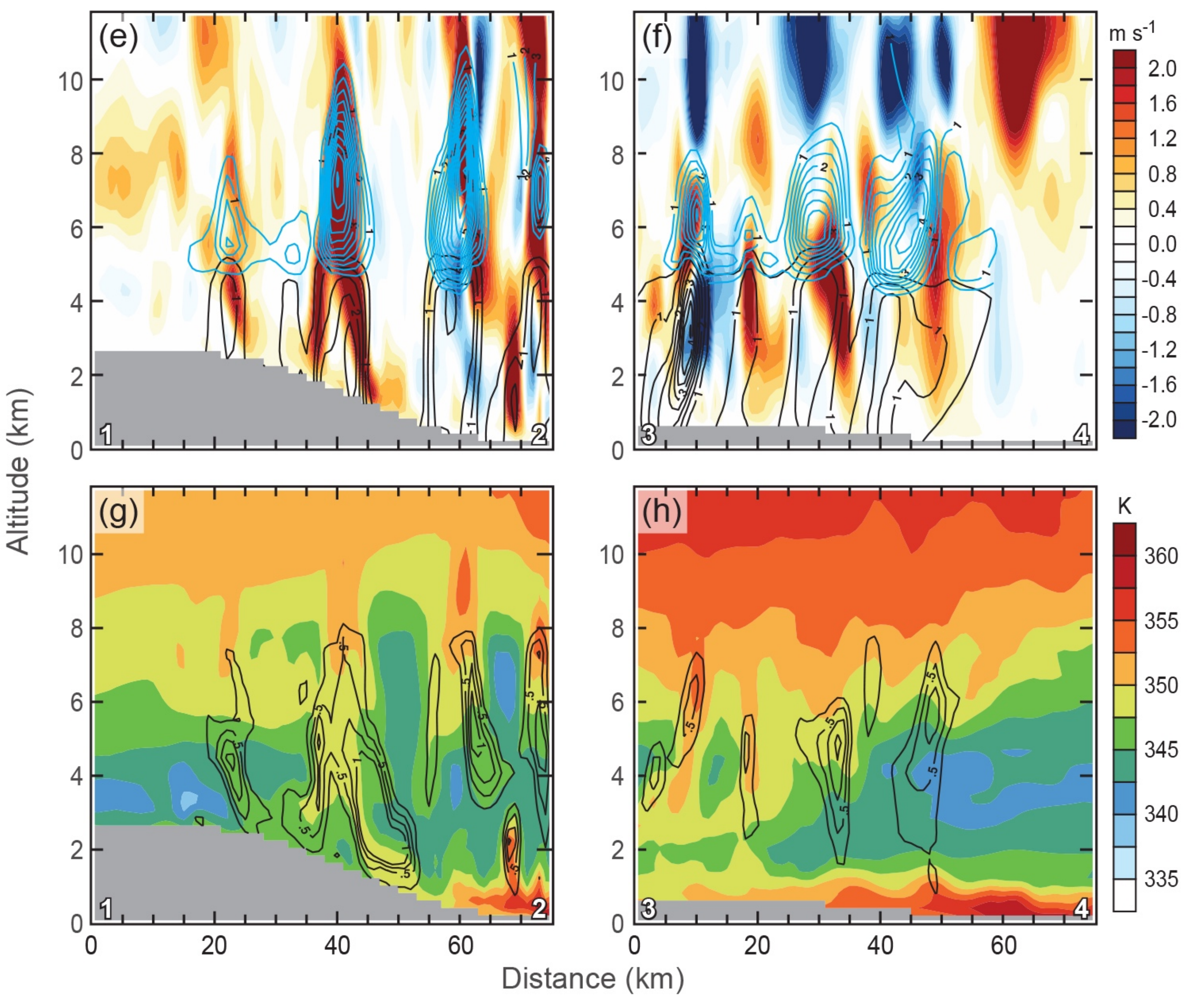

(a)
(b)
(c)
(d)
Precipitation (mm)
60
40
20
-4.0
-2.0
0.0
2.0
4.0
Time (h)



(a)
(b)
(c)
(d)
25
2200
200
440
40
20°N
19
18
23°N
22
21
98°W
97
96
95
100°W
99
98
97
Latitude
Longitude
m s-1
4.0
3.2
2.4
1.6
0.8
0.0
-0.4
-0.8
-1.2
-1.6
-2.0



(a)
(b)
1
2
3
4
2200
200
440
40
25
20°N
19
18
17
97°W
96
95
23°N
22
21
20
101°W
100
99
98
g kg-1
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0



(e)
(f)
(g)
(h)
m s-1
2.0
1.6
1.2
0.8
0.4
0.0
-0.4
-0.8
-1.2
-1.6
-2.0
K
360
355
350
345
340
335
Altitude (km)
Distance (km)