天 氣 學 二
(Synoptic Meteorology II)

上課時間: 10:20～12:10 Wednesday, B105

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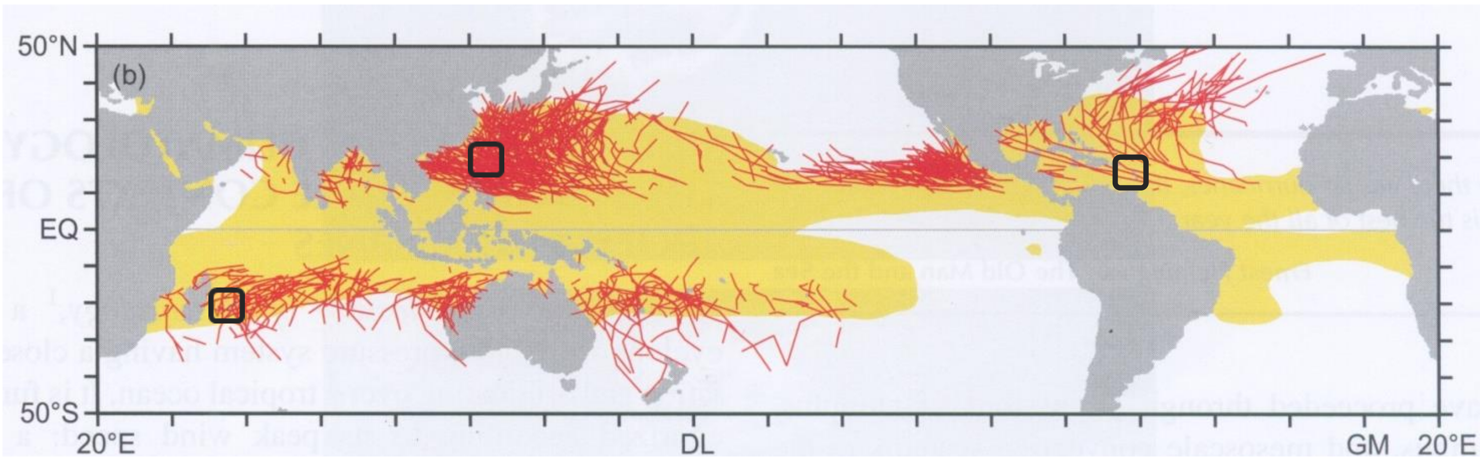
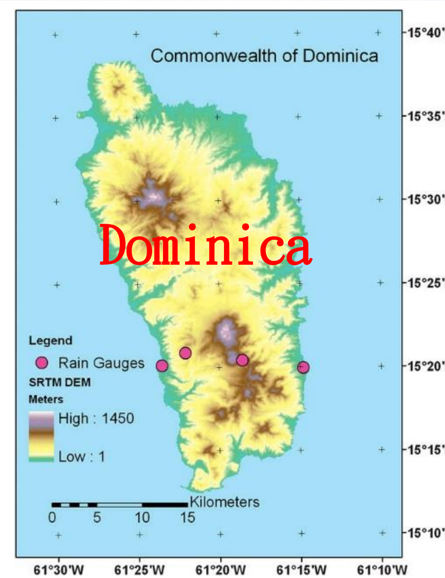
Chapter 3 Tropical Cyclones

3.4 Orographic precipitation associated with TCs

TC-induced orographic precipitation is an international issue and is one of major causes for floods over land and Islands

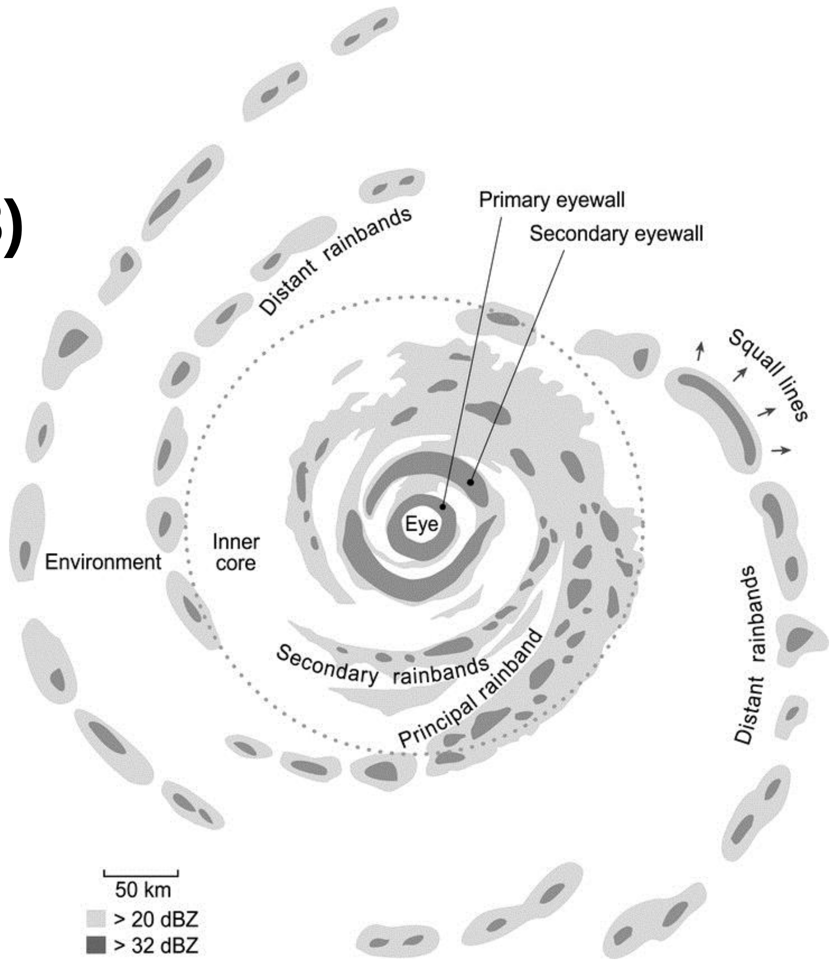




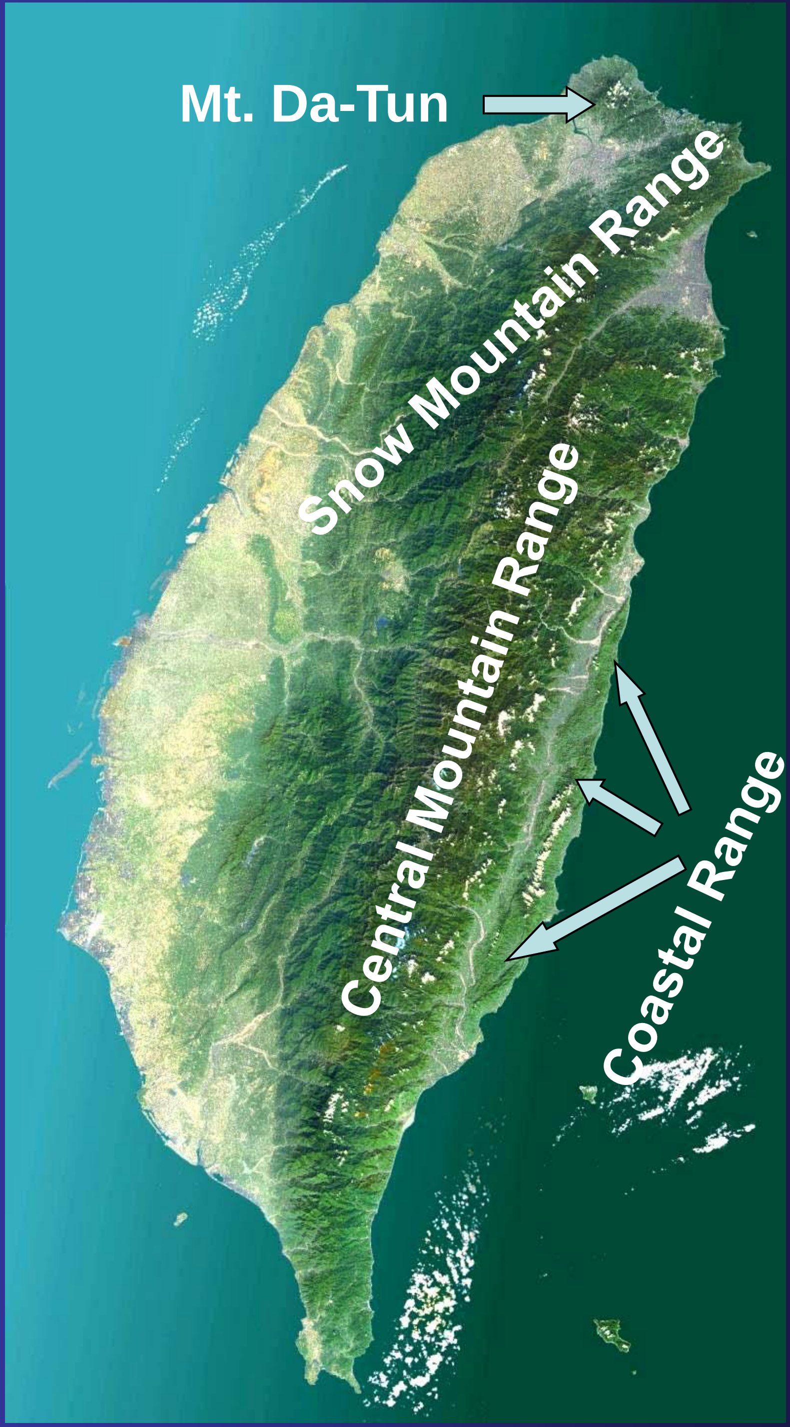
Considerable preexisting precipitation associated with Tropical cyclones

Willoughby (1988)

Houze (2010)



Orographic precipitation is not just a simple “airflow-terrain interaction” problem



Major Mountain Barrier over Taiwan (highest mountain ~4 km MSL)

SMR: Snow Mountain Range

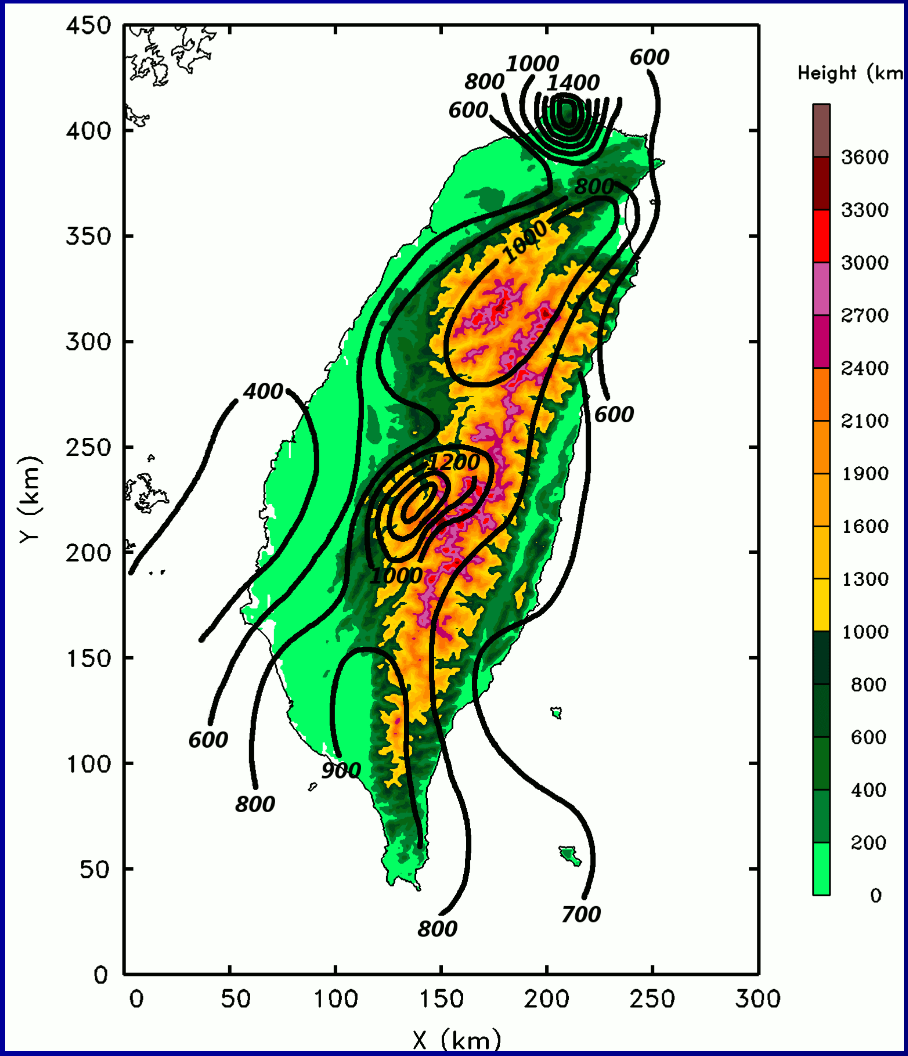
DT: Da-Tun Mountain

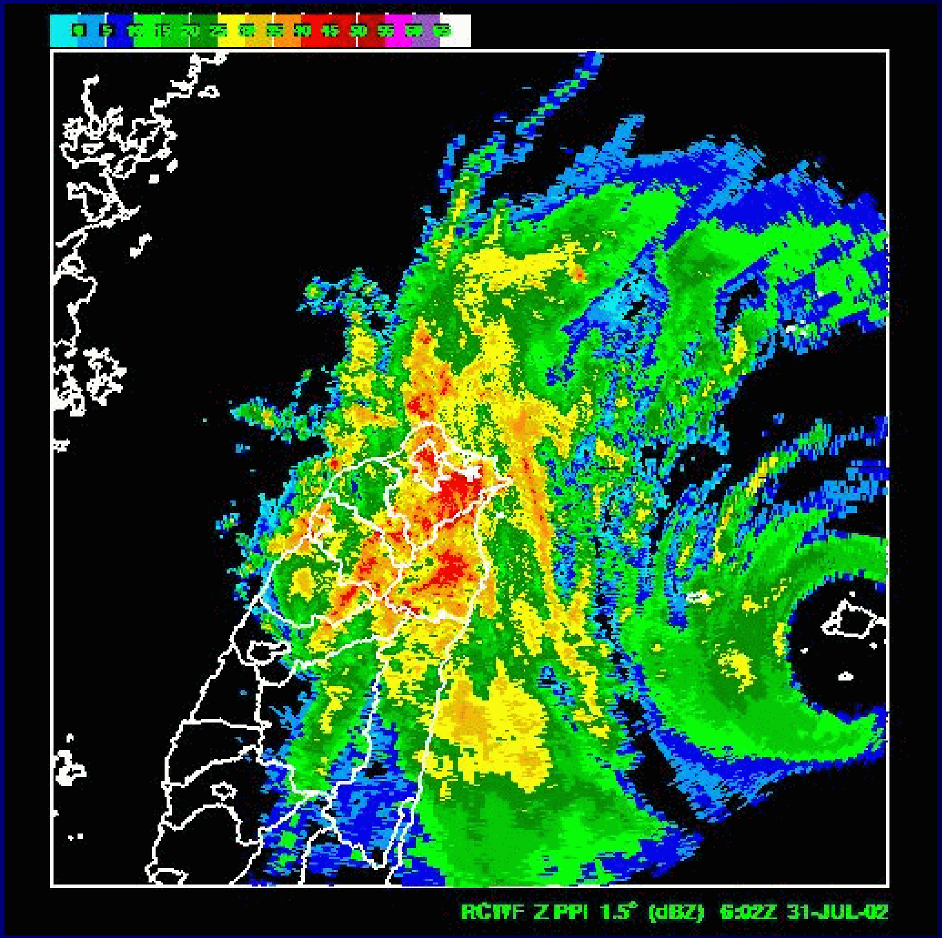
CMR: Central Mountain Range

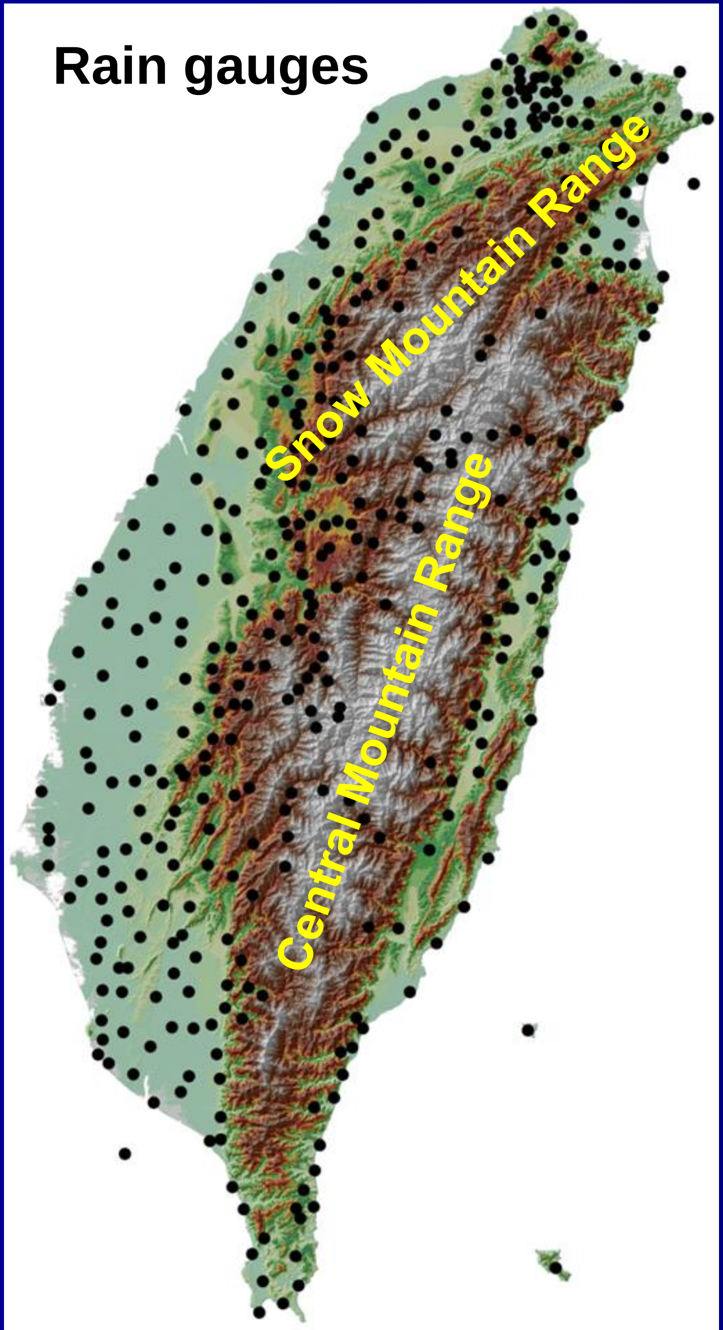
CR: Coastal Range

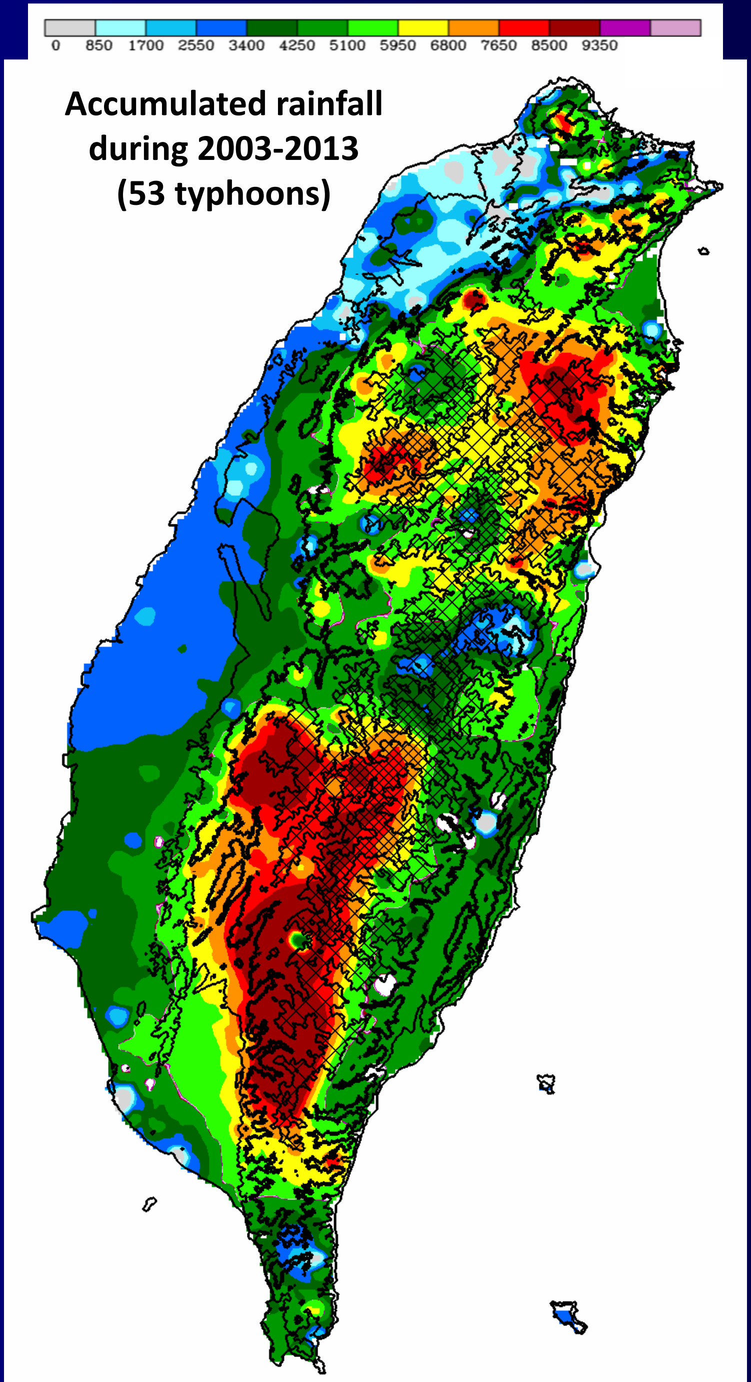
Maximum rainfall accumulation during typhoons from 1897 to 1996 (Yu and Cheng 2014)

Animation of radar echoes for Herb (1996)

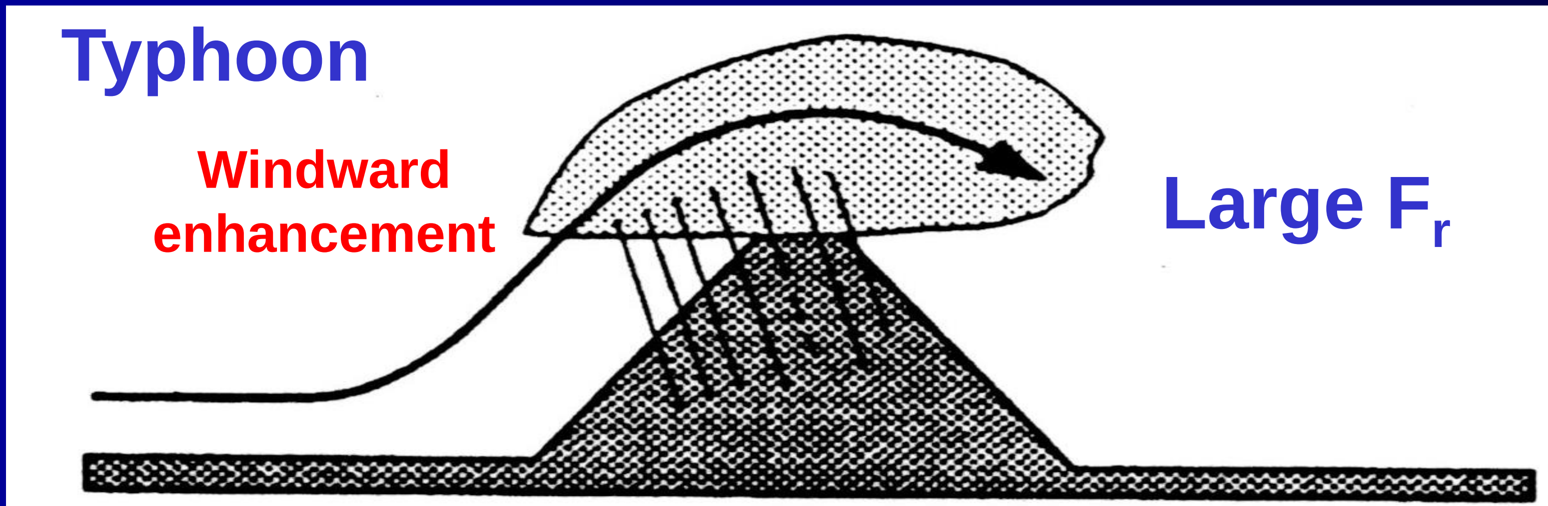





Rain gauges
Snow Mountain Range
Central Mountain Range


0 850 1700 2550 3400 4250 5100 5950 6800 7650 8500 9350
Accumulated rainfall
during 2003-2013
(53 typhoons)

Flow regime in the typhoon environment



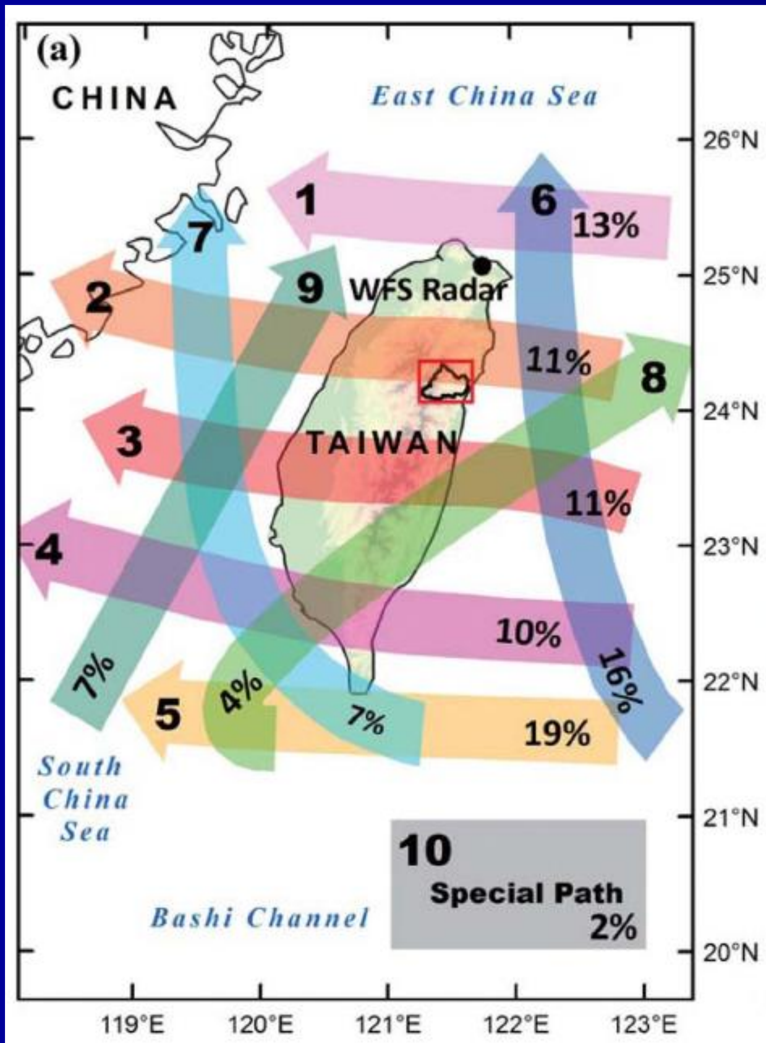
Froude number (F_r)= U/NH

For Taiwan

N~10^{-2} s^{-1} , H~2 km

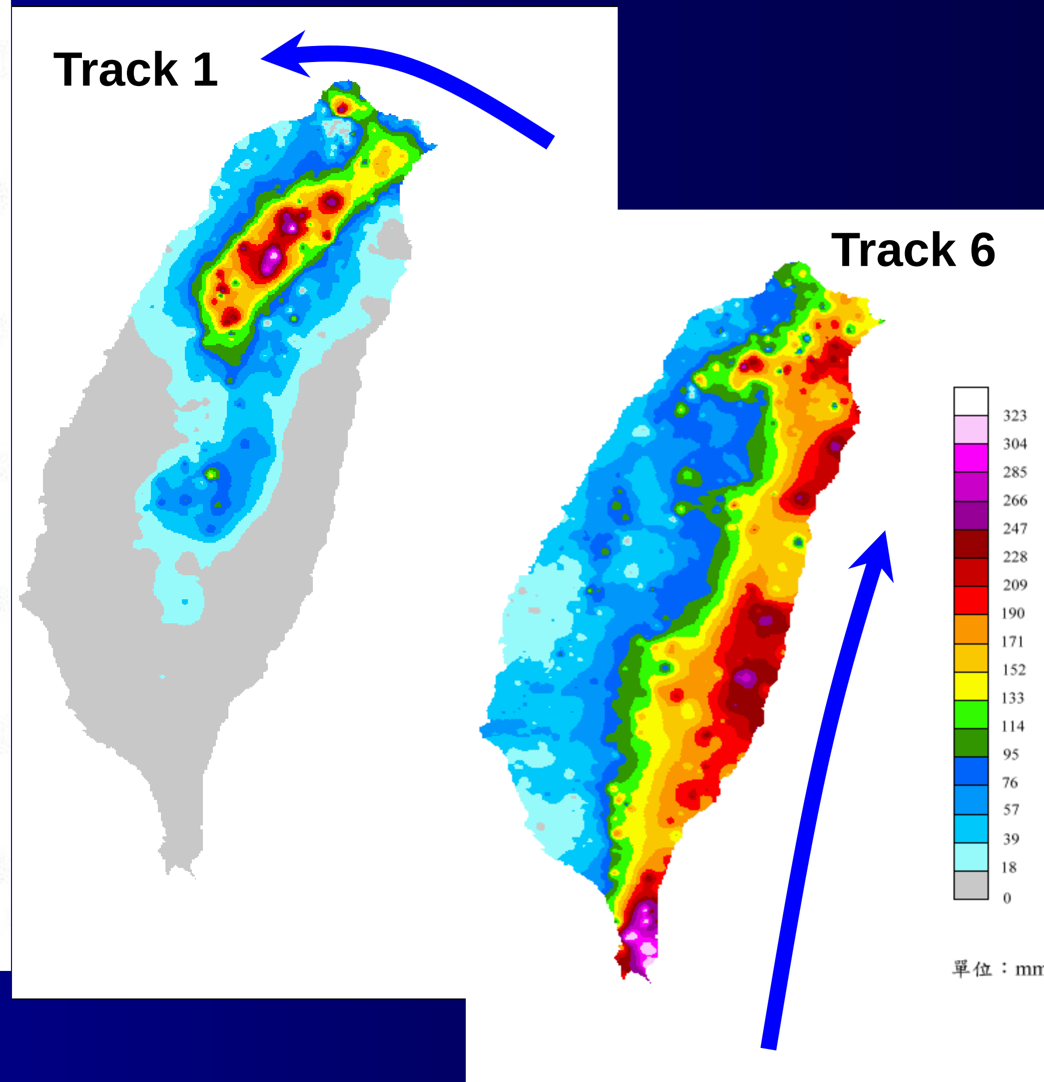
Critical wind speed for F_r=1 is ~20 m s^{-1}

Typhoon track categories



Huang et al. (2012)

Track-precipitation relationship



Fundamental questions to be answered:

- What's the detailed distribution of precipitation over topography in the typhoon environment?

- How do these structures relate to upstream oncoming flow, topographic features and typhoon background precipitation?

- Is the "windward slope enhancement" adequate to describe orographic precipitation associated with typhoons?

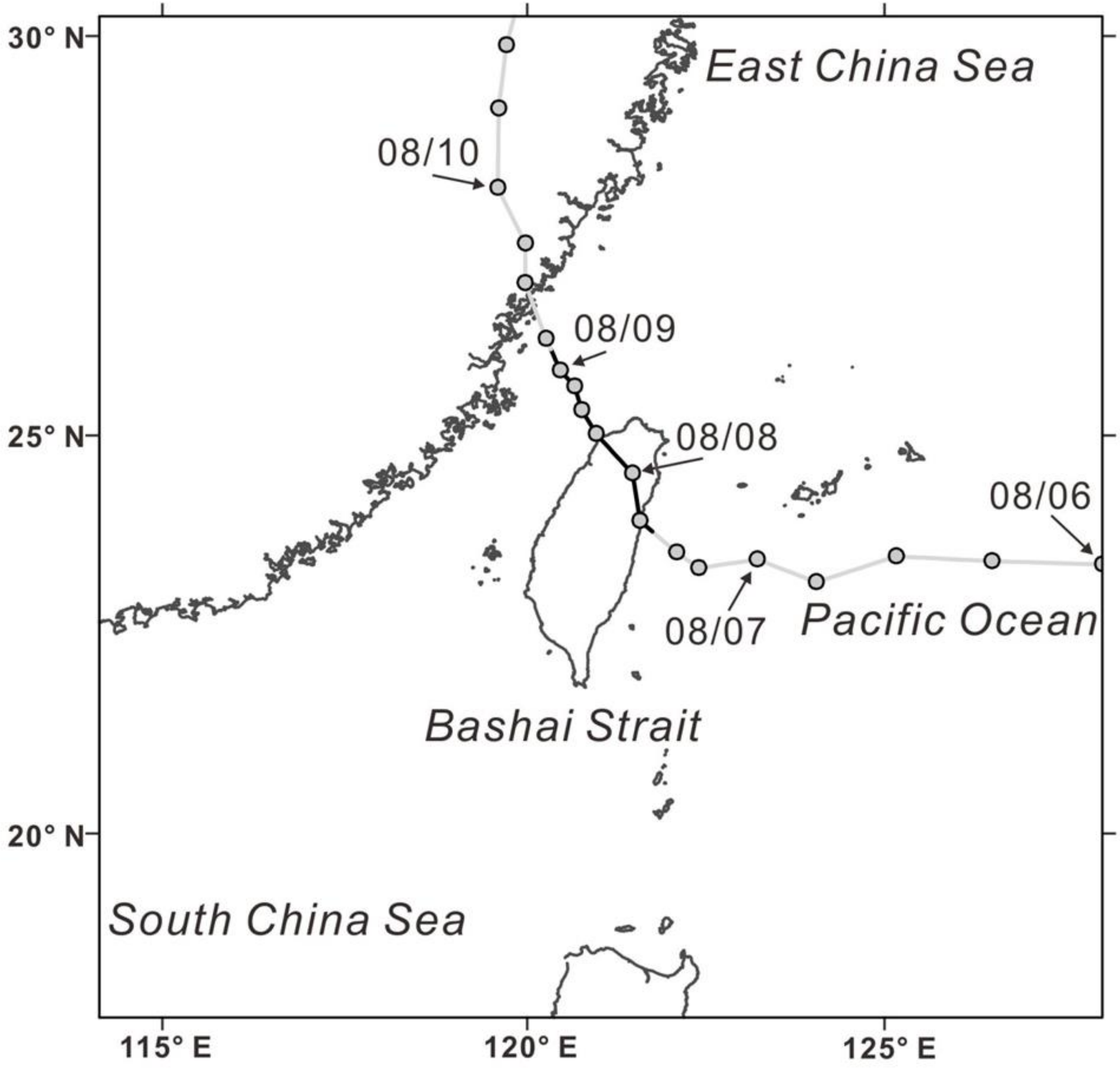
- Are there any other processes important for determining the precipitation intensity over topography in the typhoon environment?

Typhoon Morakot (2009)

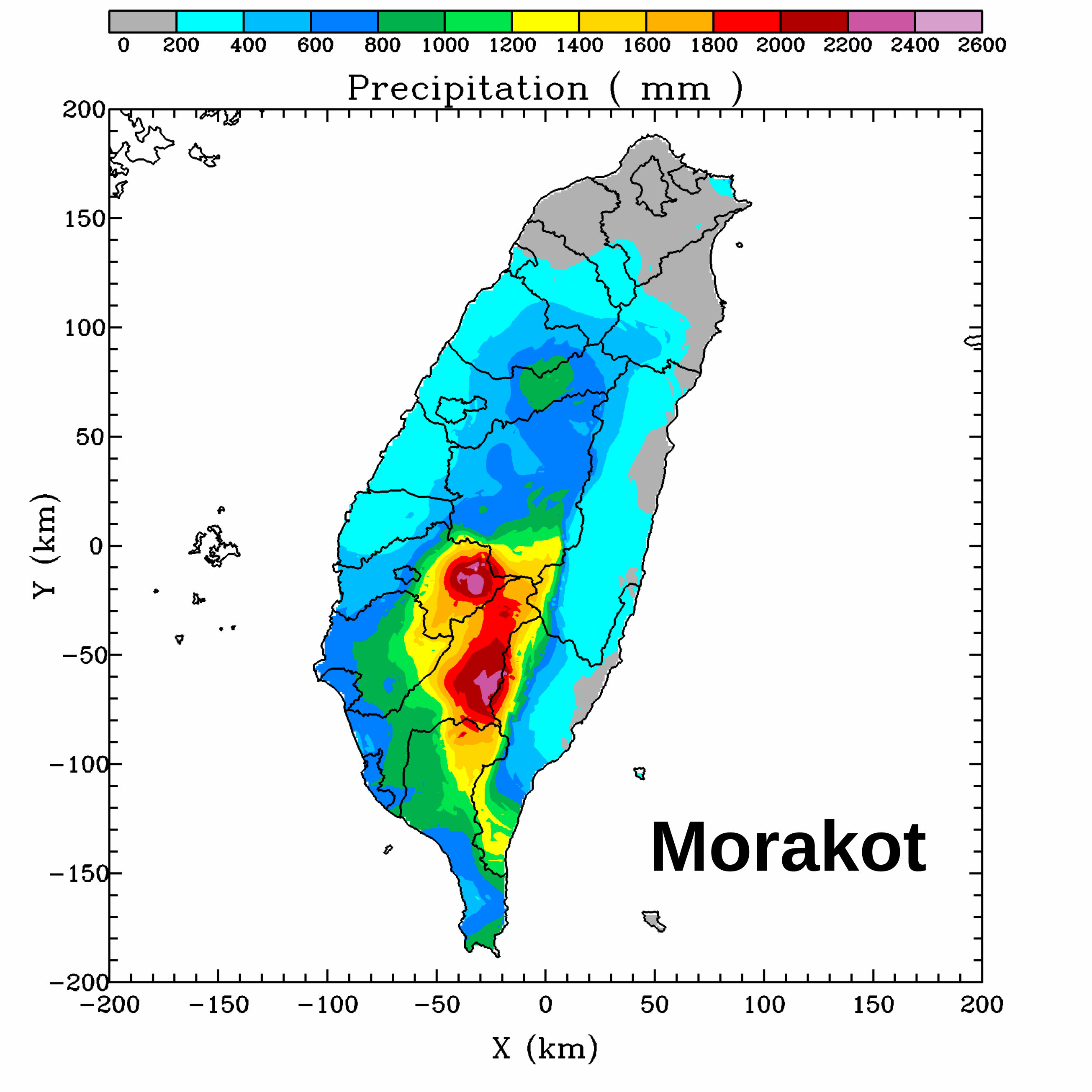
- This typhoon causes the most serious loss of human life in past 50 years in Taiwan (643 deaths, 60 missing, and 1555 injuries)

- The most severe orographic precipitation during the influence of the typhoon in Taiwan meteorological history (3059 mm/event)

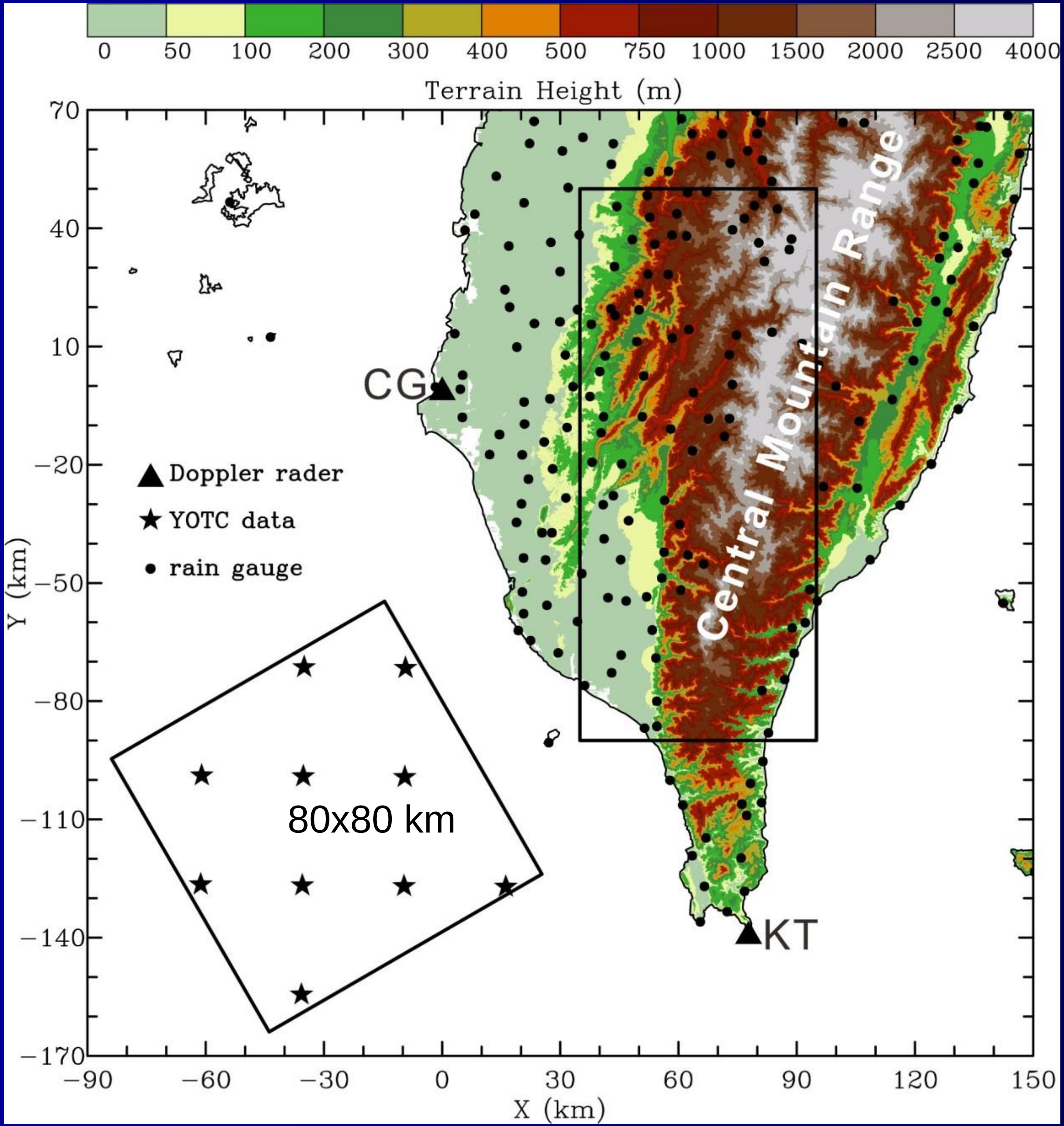
Track of Morakot (2009)



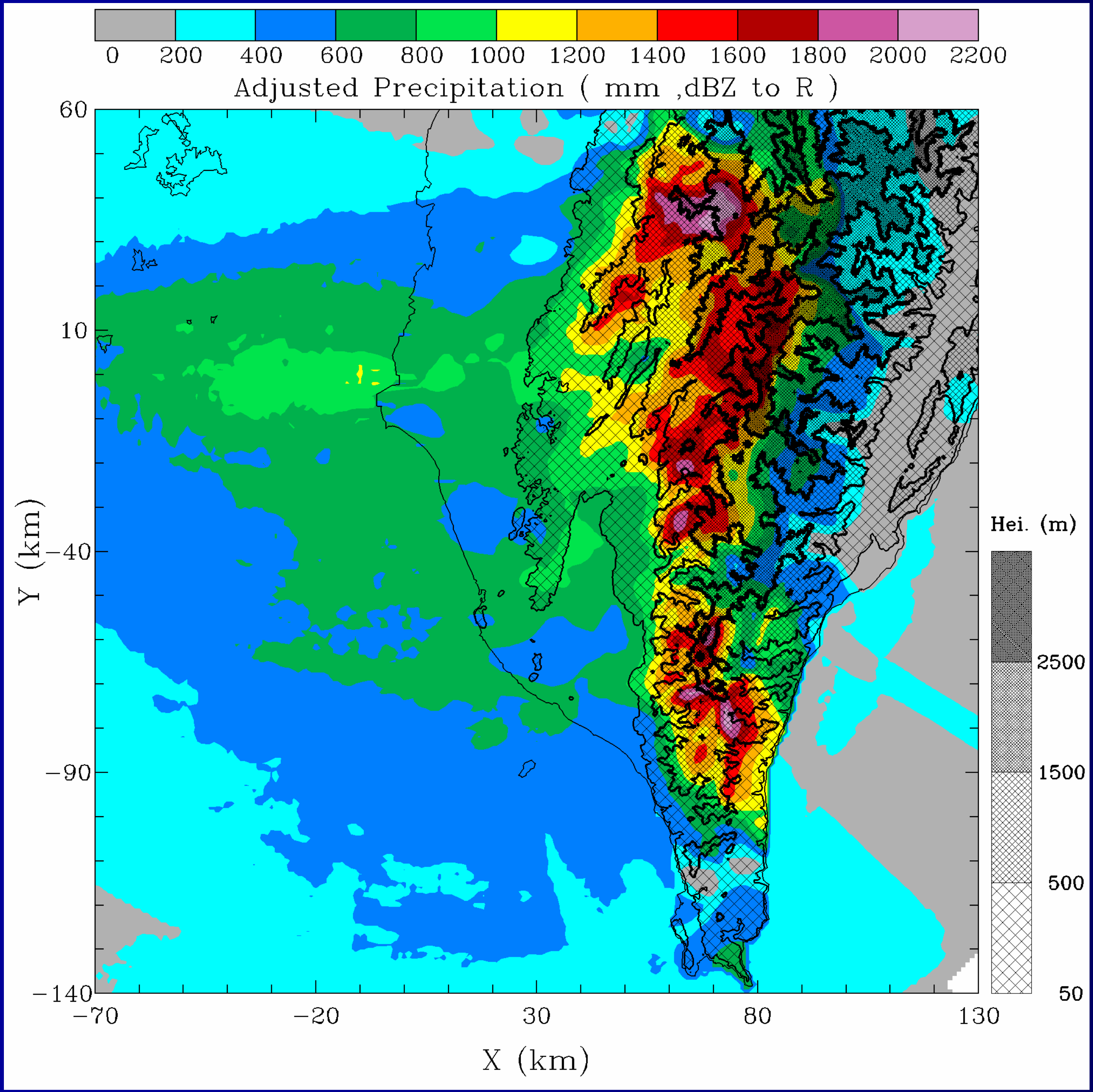
72-h Accumulated Rainfall (mm) during 7-9 August 2009



Study domain and data sources

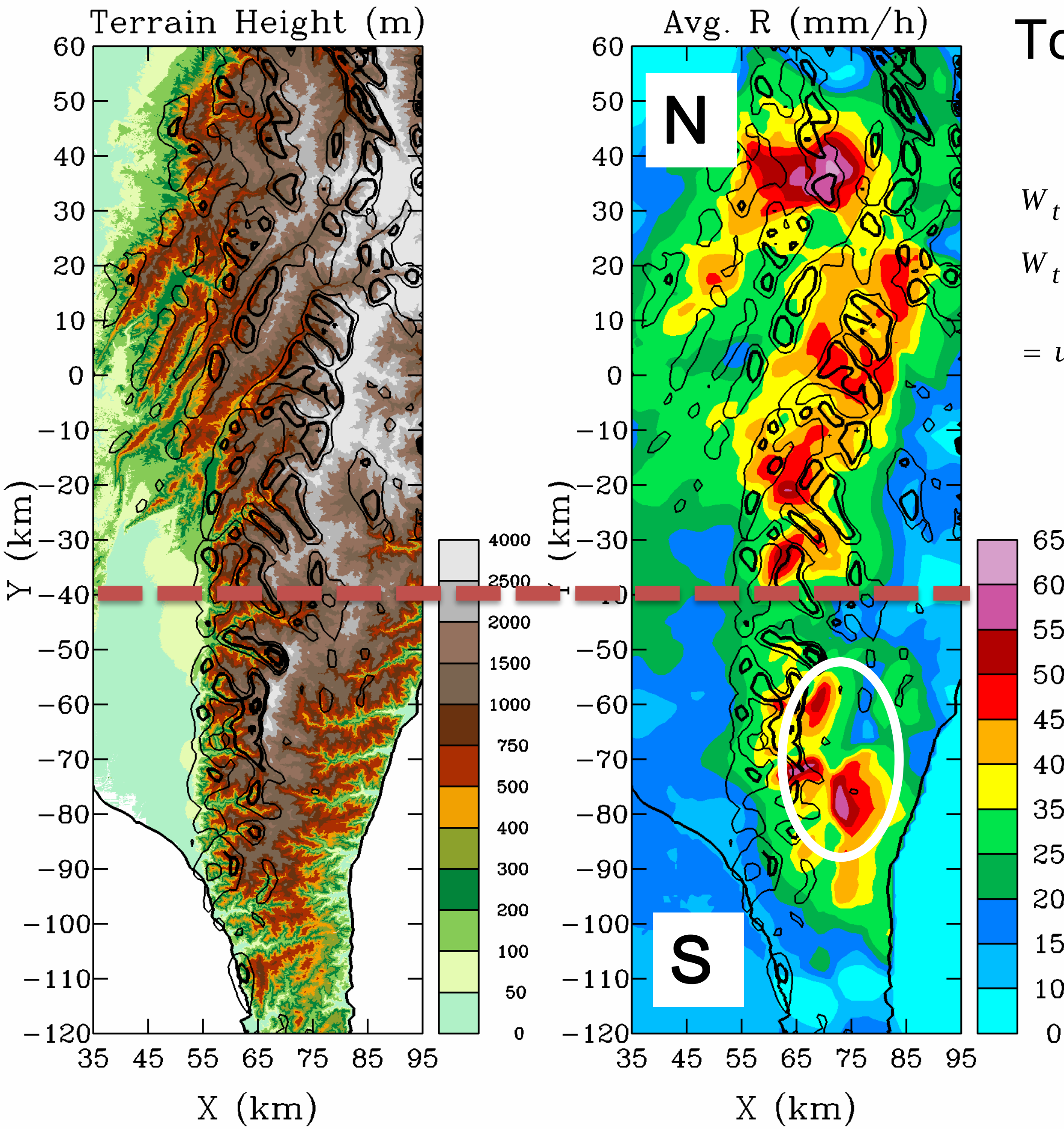


36-h radar-derived accumulative rainfall



- Preci. enhancement over mountains
- Upstream preci is much weaker and relatively uniform
- Preci max over windward slopes with sharp decrease in the lee side for higher, wider northern barrier
- Spillover evident over lower and narrower mountains

Contours of vertical velocity at 2, 5, and 10 m s^{-1}



Topographically forced vertical velocity

$$W_t = \vec{V} \cdot \nabla h$$

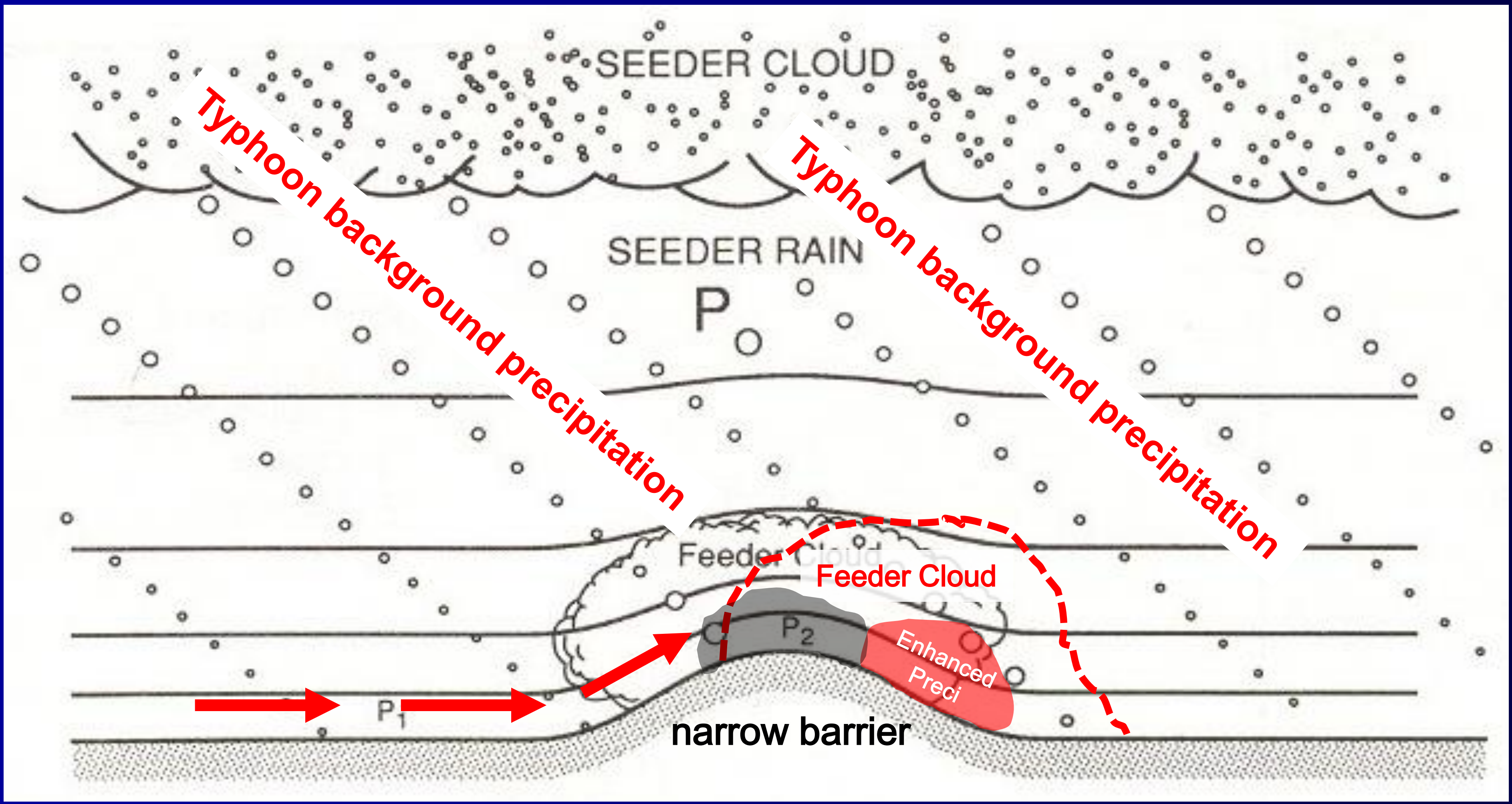
$$W_t(x, y, t)$$

$$= u(h,t)\frac{\partial h(x,y)}{\partial x} + v(h,t)\frac{\partial h(x,y)}{\partial y}$$

Southern barrier

Width of windward slopes~12 km
Oncoming wind speed ~29 m s^{-1}
Time scale of orographic lifting ~7 min

Microphysical interaction between orographically generated hydrometeors and typhoon precipitation



(Base map from Browning 1980)

Cloud formation due to orographic lifting

(possible spillover for narrow barrier or strong winds)

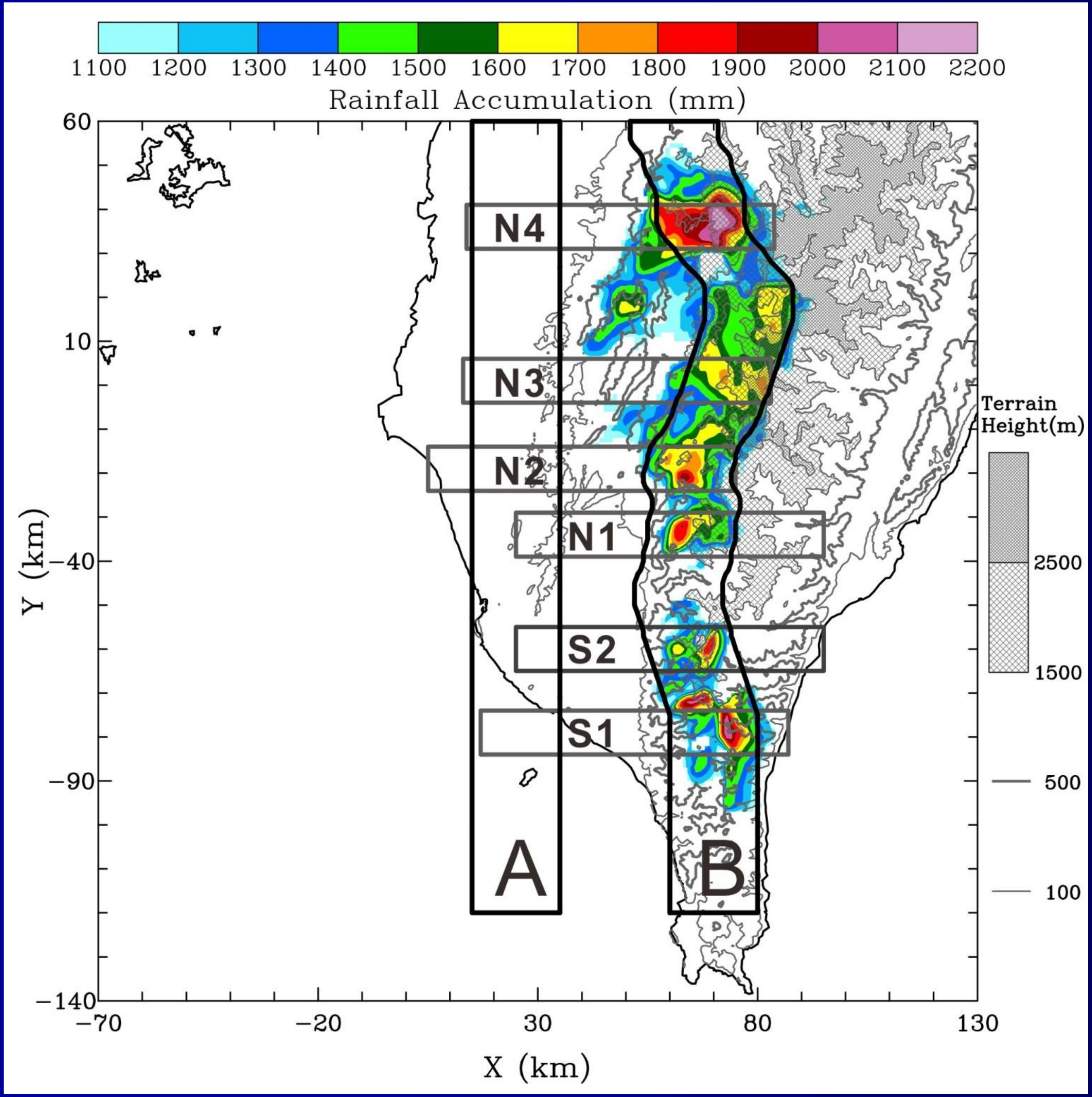
Using a simplified growth equation of the seeder cloud,
Yu and Cheng (2013, JAS) show that precipitation enhancement (*ΔR*) due to seeder-feeder process can be approximated by

$$\Delta R = \frac{3 R_{bg} M_f}{2 \rho_w D} \times H \qquad (10)$$

R_{bg}: rainfall rate of typhoon background precipitation
H : mountain height
M_f : liquid water content of the feeder cloud
D : diameter of the seeder cloud particle
ρ_w: density of liquid water

Assuming that M_f is proportional to the wind speed of oncoming flow for a given terrain profile, simple relationship between ΔR , R_{bg}, and U**:**

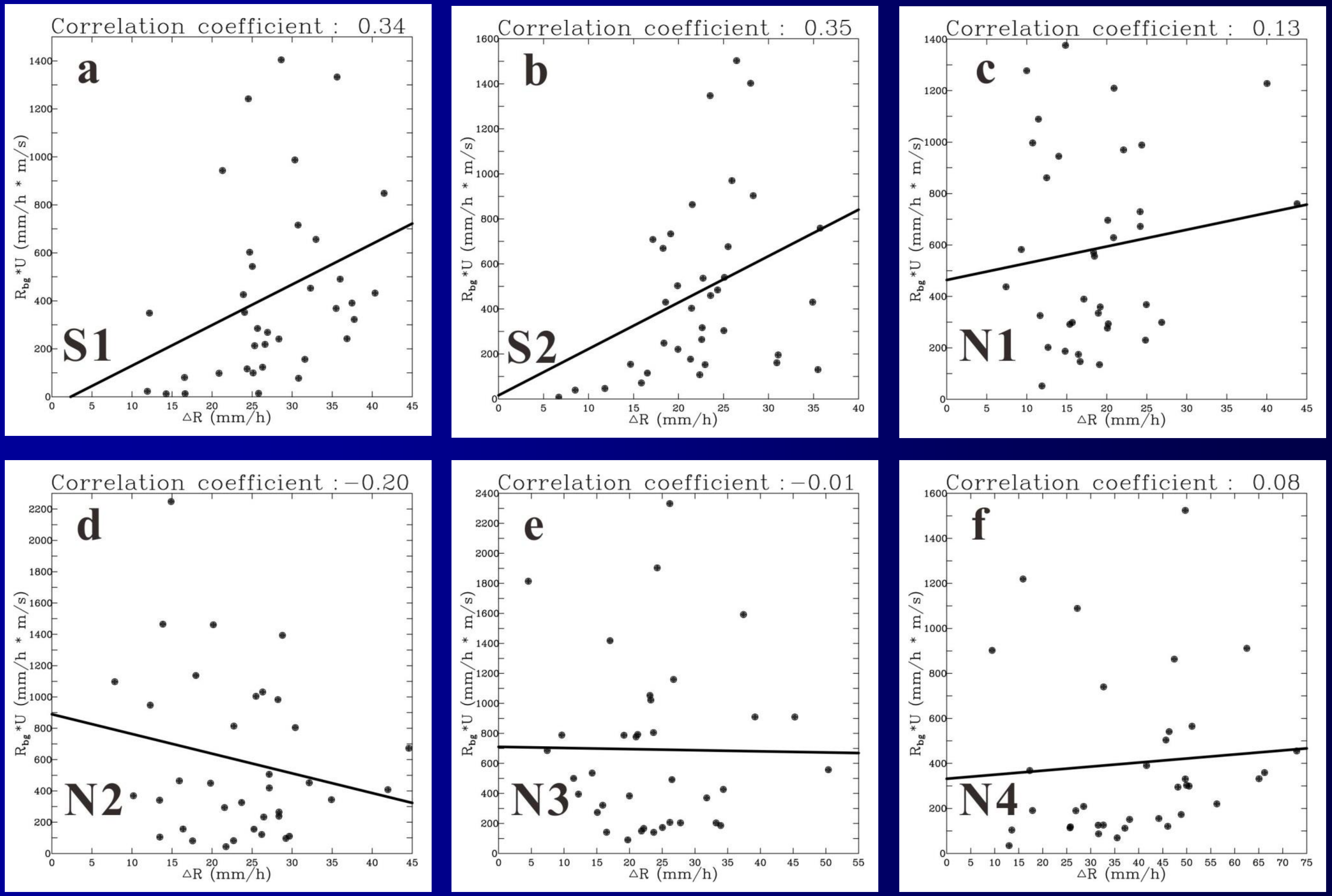
$$\Delta R \propto R_{bg} U \qquad (11)$$



Cross sections over northern barrier: N1, N2, N3, N4

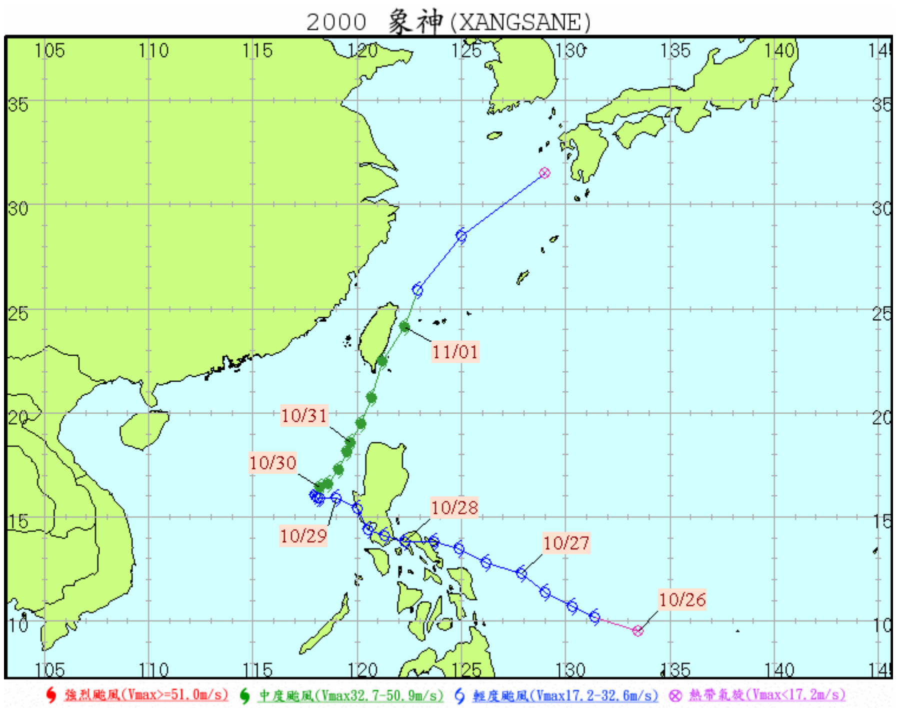
Cross sections over southern barrier: S1, S2

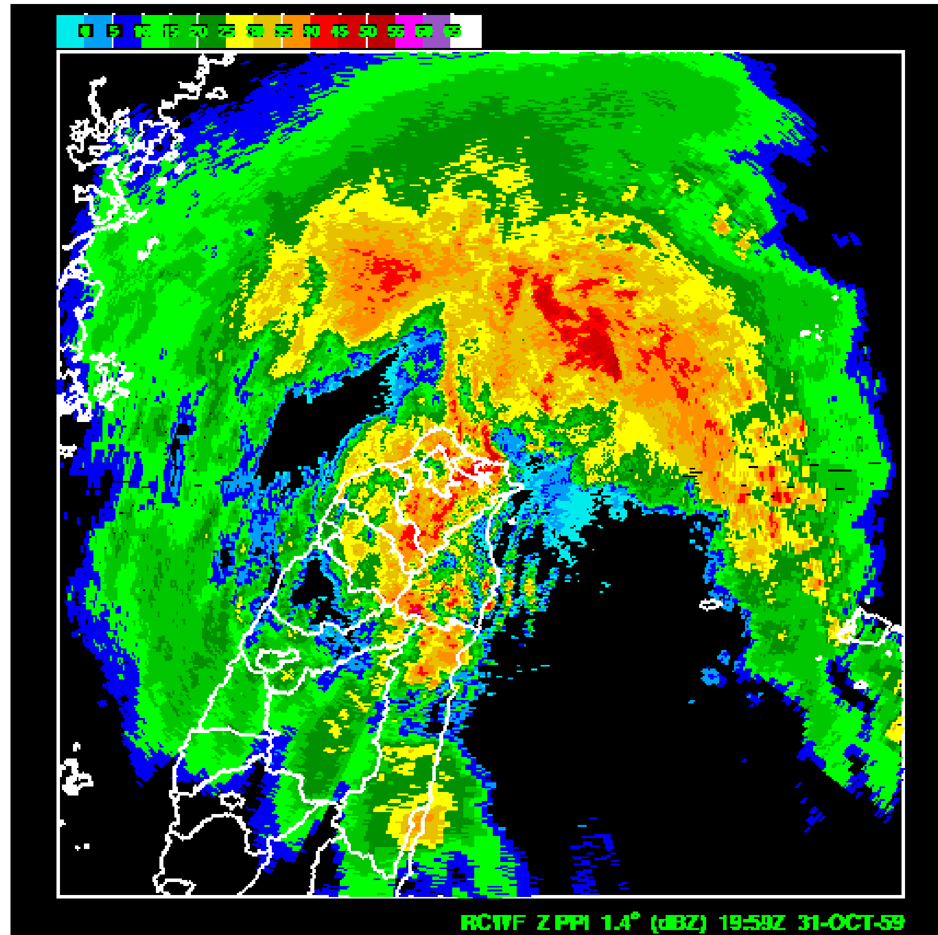
Scatterplots of orographic enhancement ΔR versus $R_{bg}U$ calculated from S1-2 and N1-4



Animation of Wu-Fen-San radar maps

Track of Xangsane (2000)





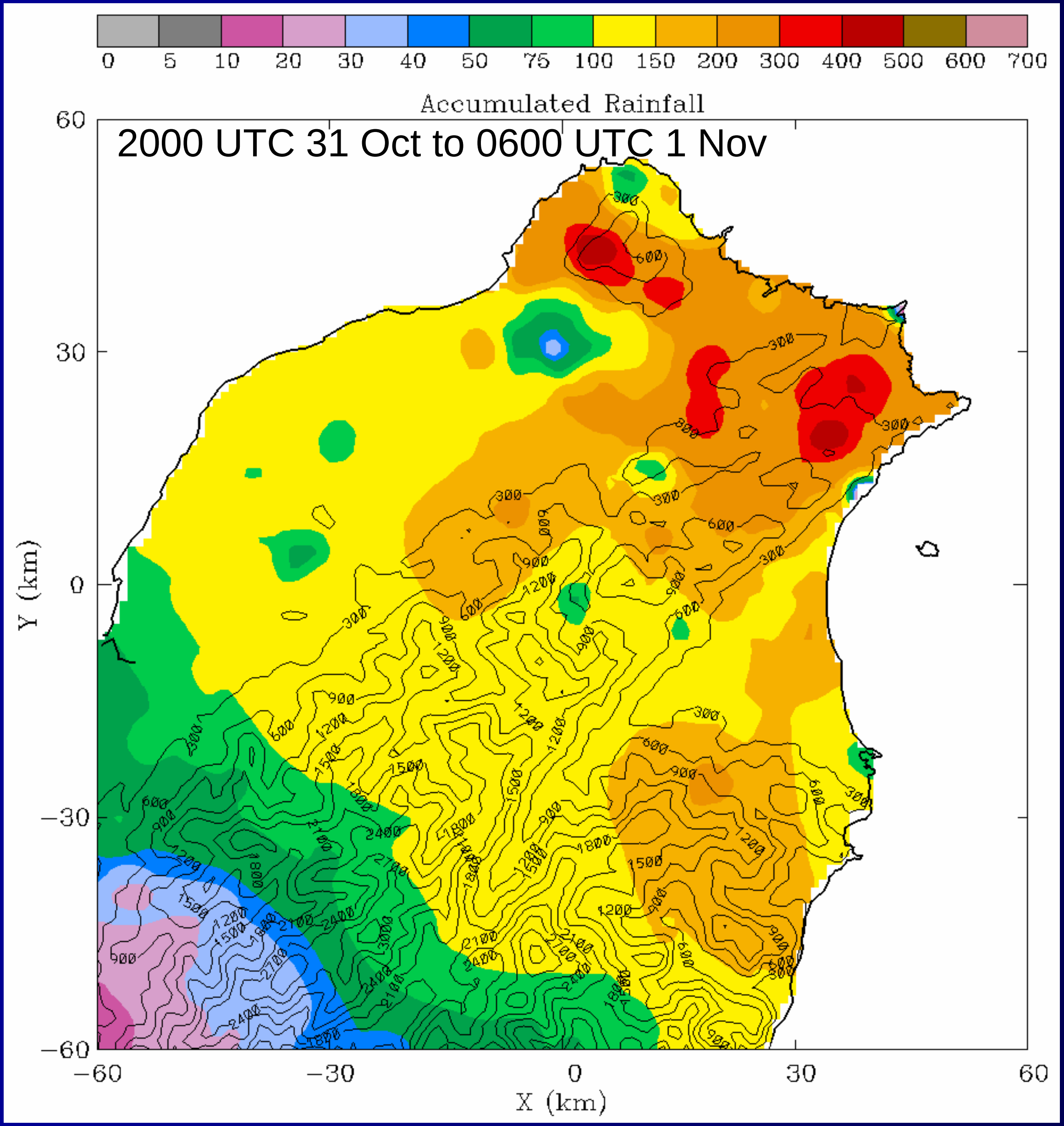
Xangsane (2000)

- This typhoon caused severe rainfall and serious loss of human life (64 deaths and 25 missing)

- A singapore Airlines aircraft crashed during this event (82 passengers killed)

- Good and persistent coverage of radar echoes on both inland and upstream regions

10-hr Accumulated Rainfall (mm) over the northern Taiwan

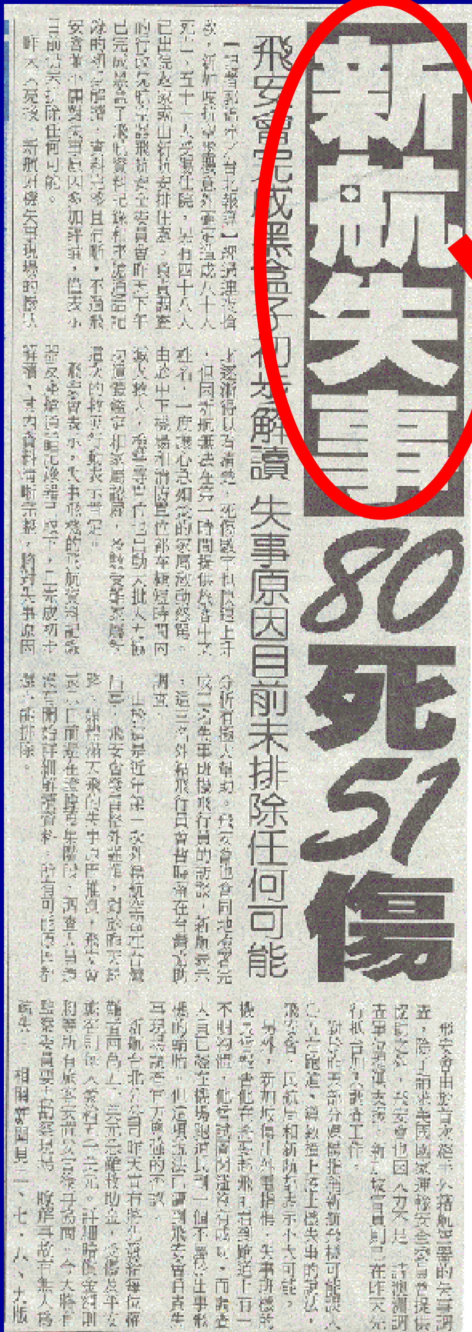


Xangsane Typhoon (2000)

(Photos adapted from the textbook of Taiwan Natural Disasters, Wu et al. 2005)

- significant property damage
- 64 death and 25 lost

Headlines for Typhoon Xangsane


新航失事 80死51傷

飛安會完成黑盒子初步解讀 失事原因目前未排除任何可能

Aircraft Crash

Singapore Airlines


聯合報 中華民國八十九年十一月二日 星期四

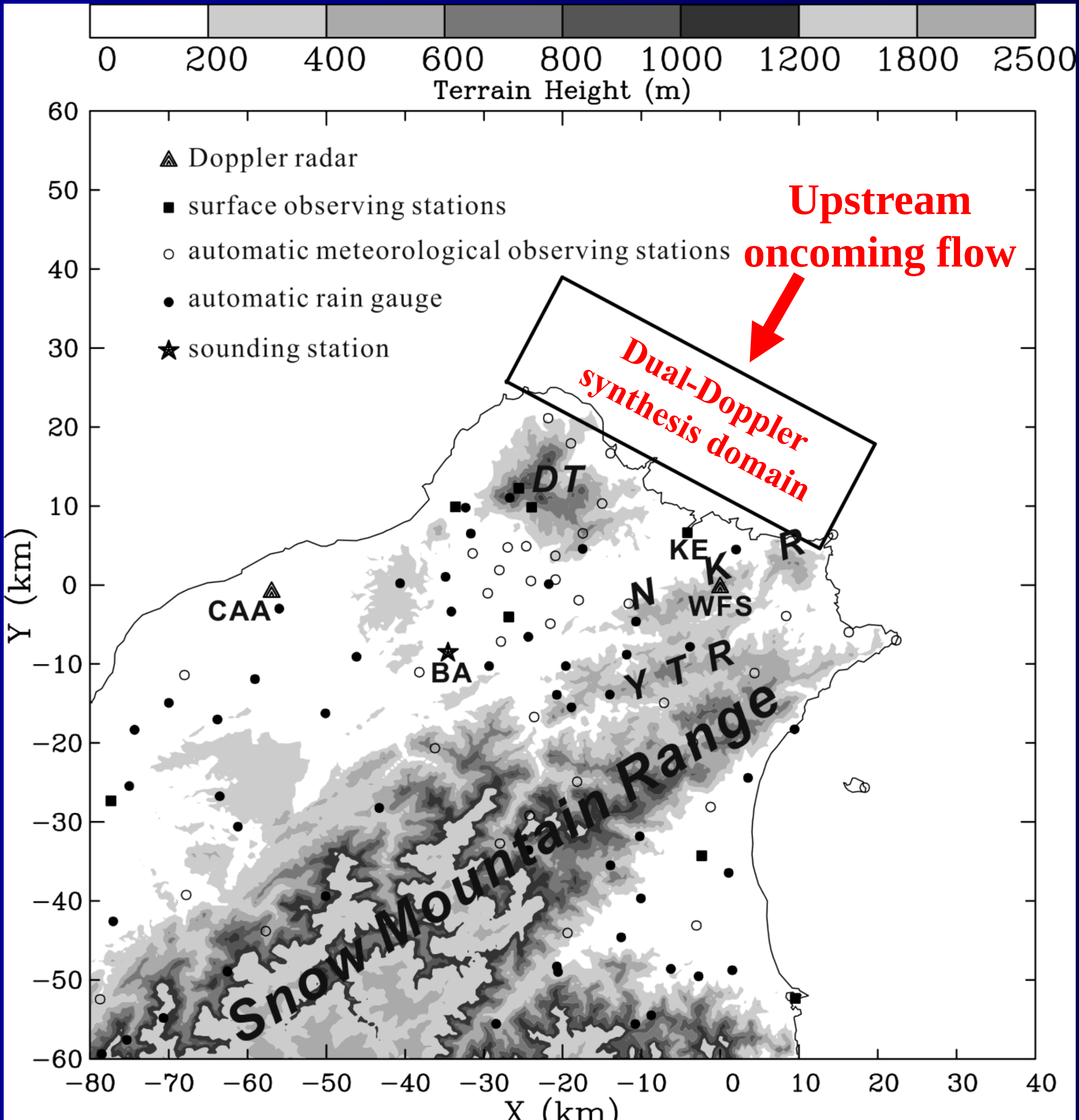
象神浩劫

基隆一護理之家14老人淹死 一貫道天道學院15學員罹難

全台55死0失蹤25人受傷 ……積水達兩層樓高 北縣也有20人遇難

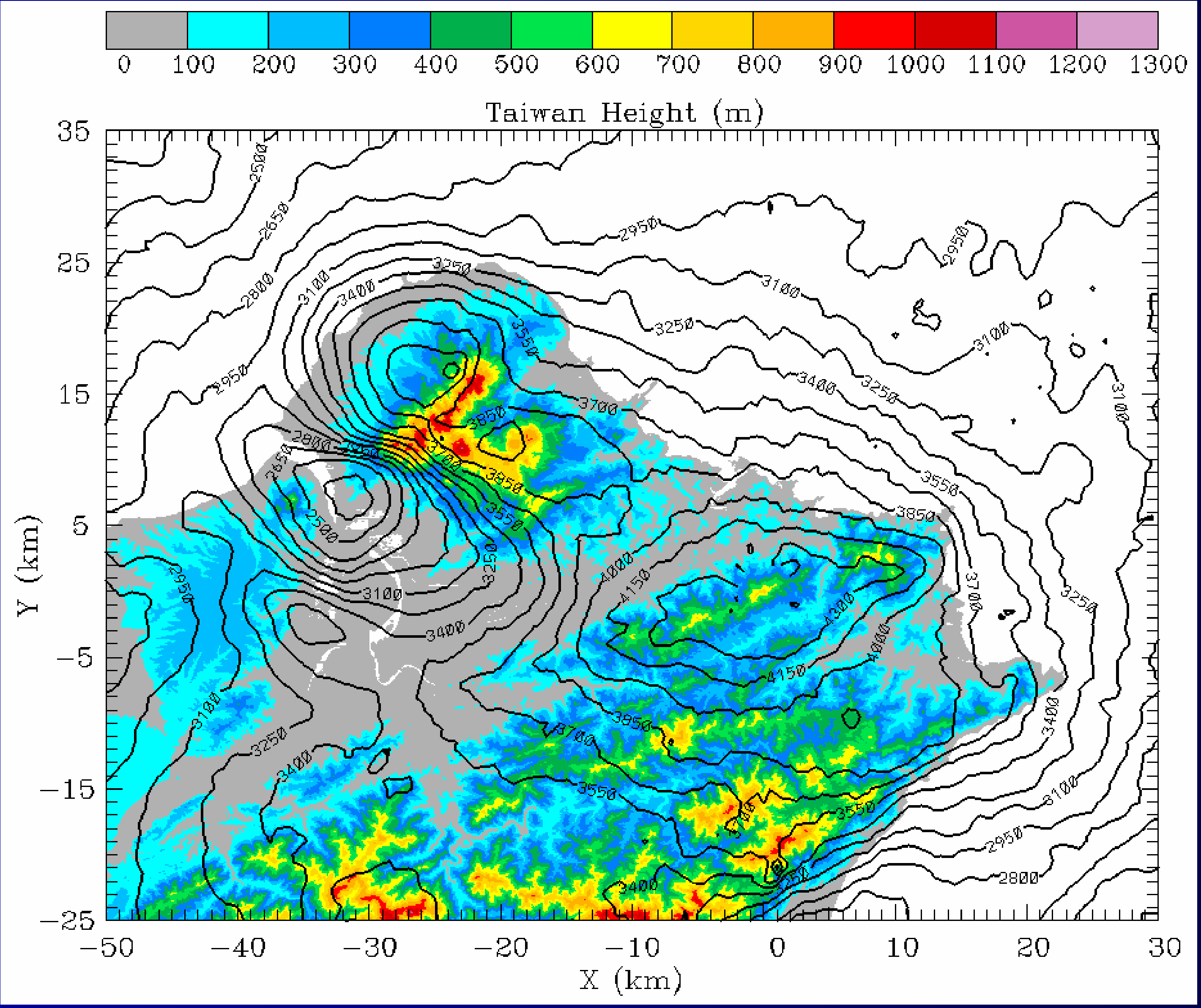
風雨劫

Xangsane disaster

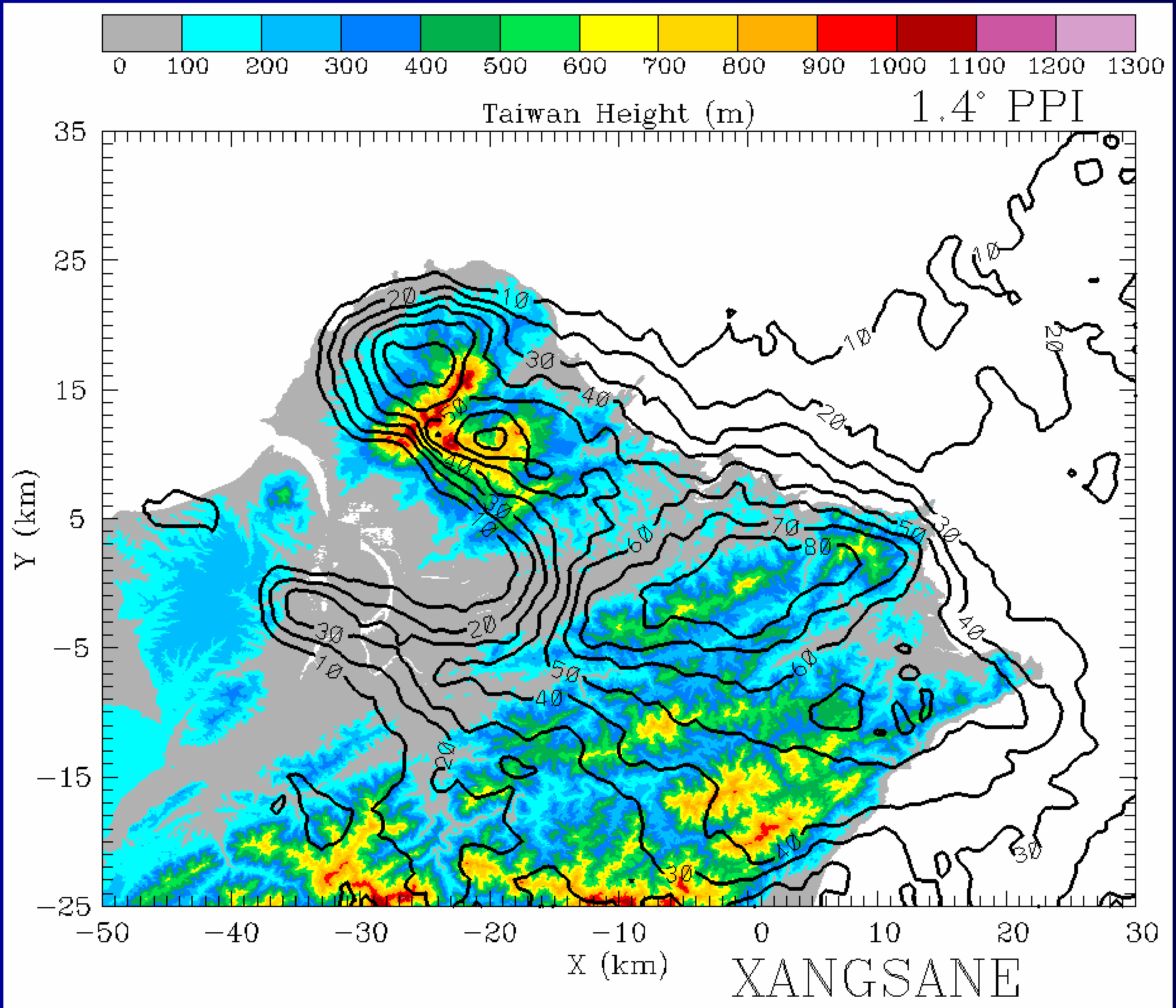


0
200
400
600
800
1000
1200
1800
2500
Terrain Height (m)
Doppler radar
surface observing stations
automatic meteorological observing stations
automatic rain gauge
sounding station
Upstream
oncoming flow
Dual-Doppler
synthesis domain
DT
KE
K
R
N
WFS
CAA
BA
Y T R
Snow Mountain Range
Y (km)
X (km)

10-hr accumulated reflectivity (dBZ)
(2000 UTC 31 Oct. ~ 0600 UTC 1 Nov.)

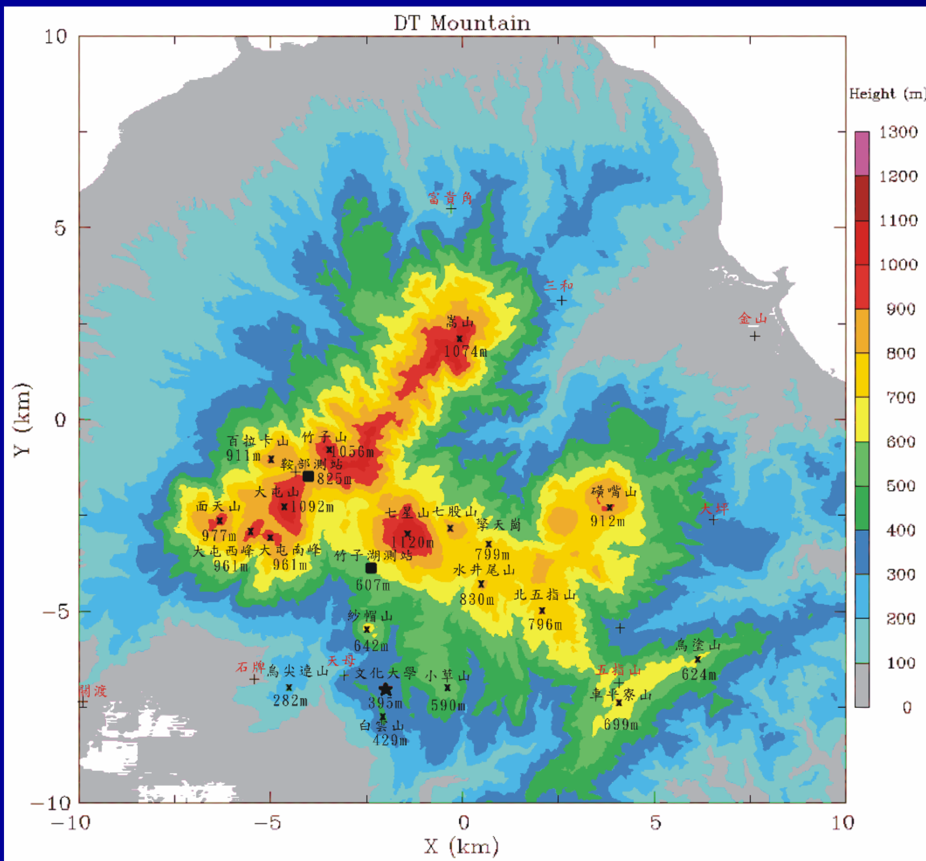


Frequency distribution of heavy precipitation (>40 dBZ)

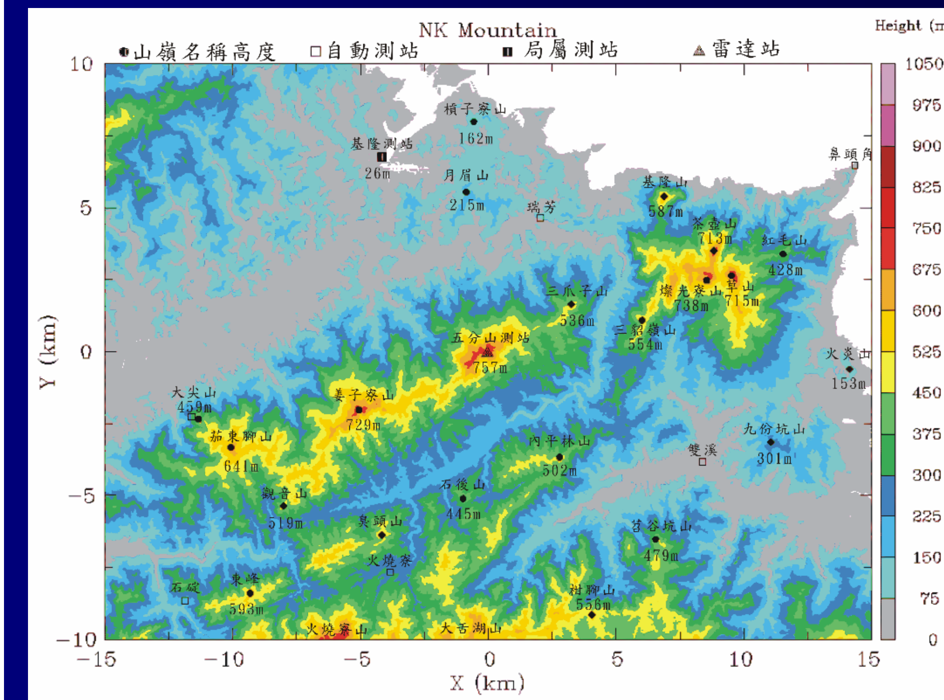


Mt. Da-Tun (DT)

Nangang-Keelung Range (NKR)

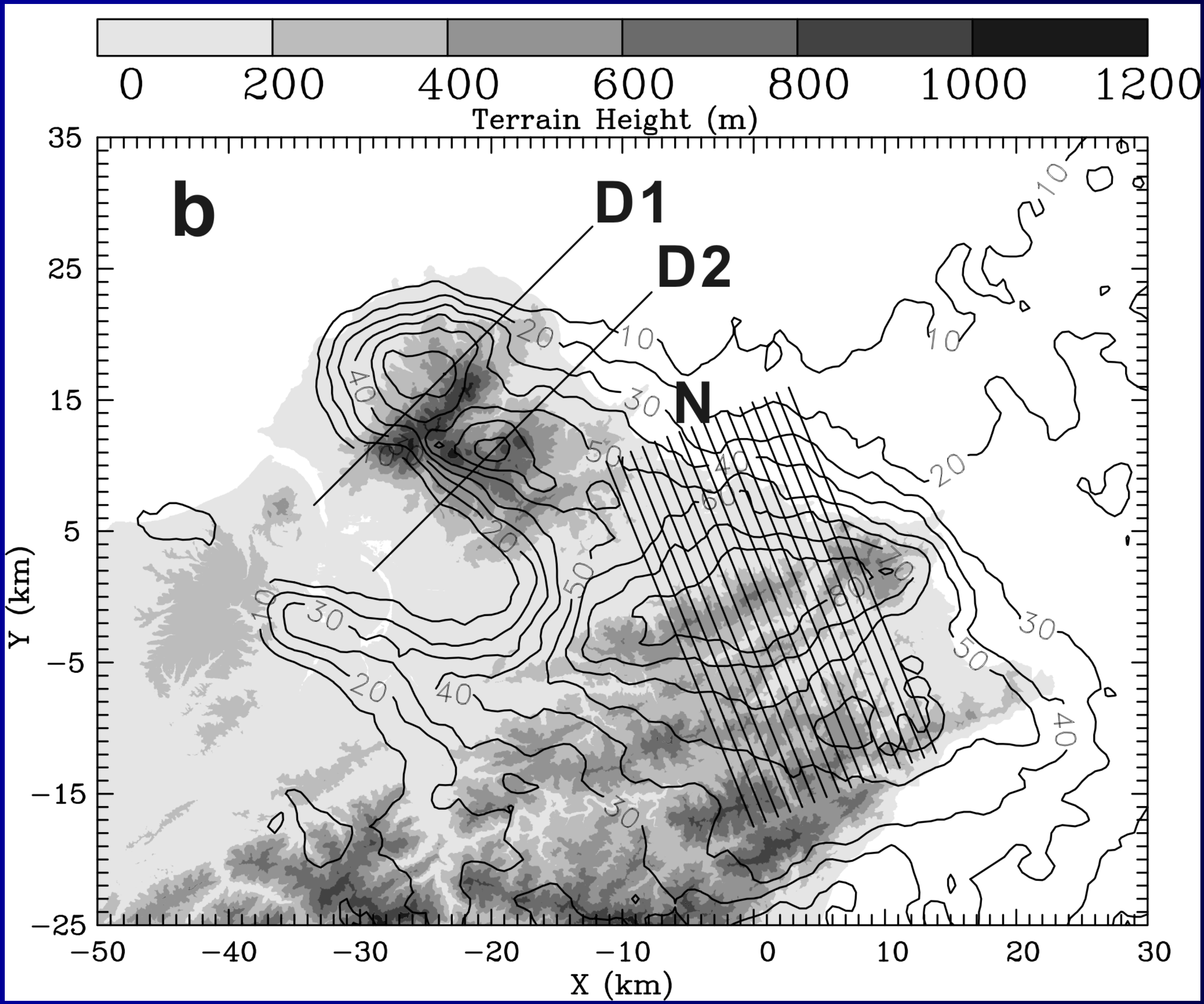


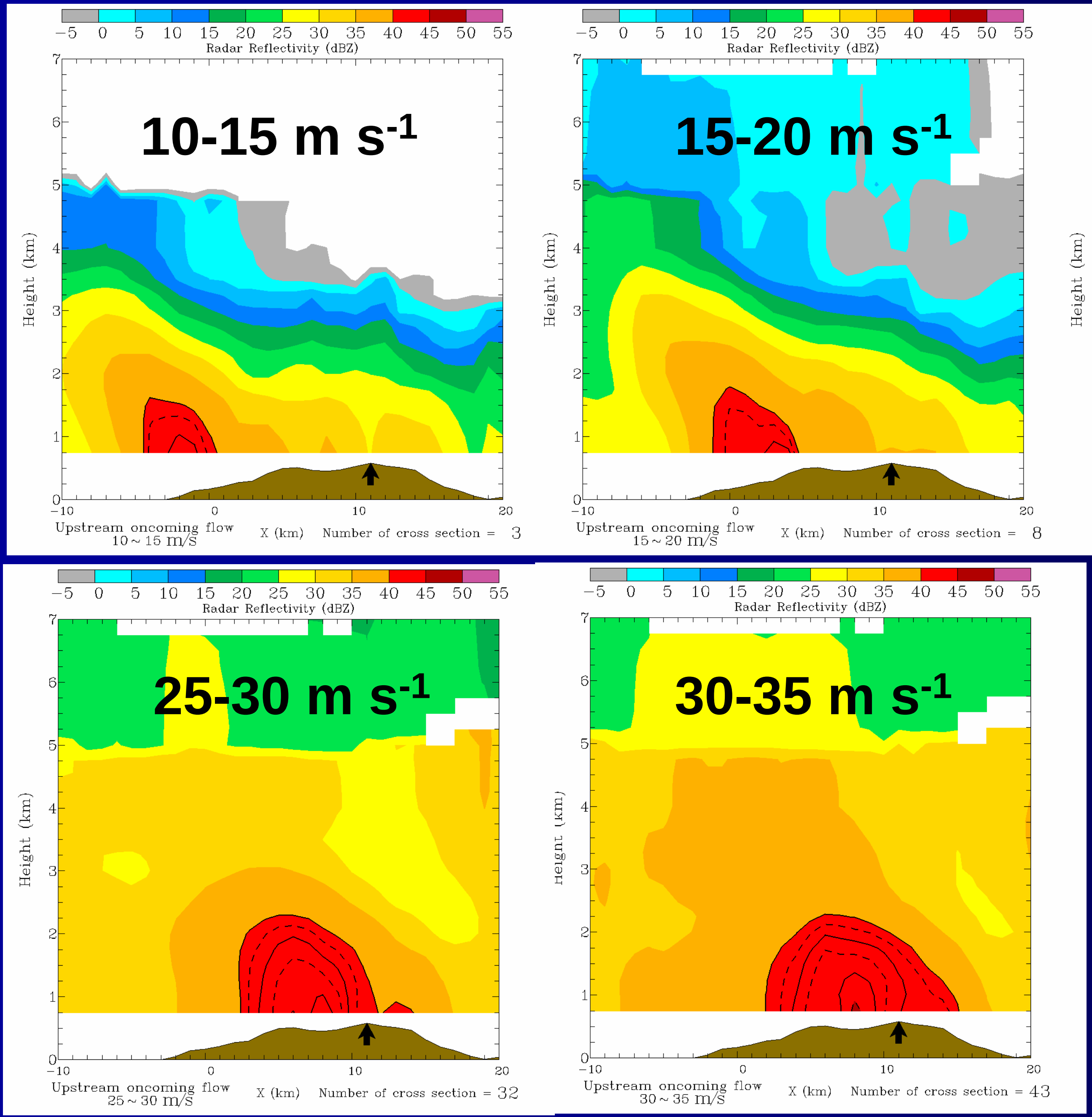
Maxi Height: 1120 m (MSL)
Half-width: 10 km



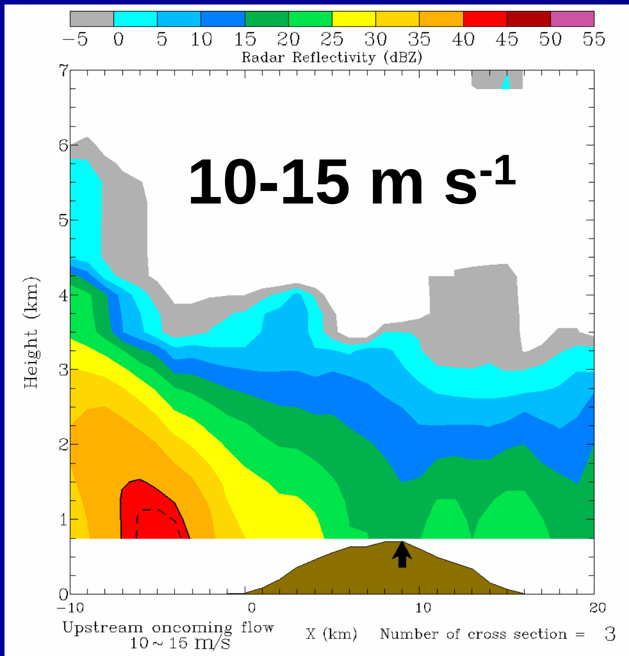
Maxi Height: 757 m (MSL)
Half-width: 5 km

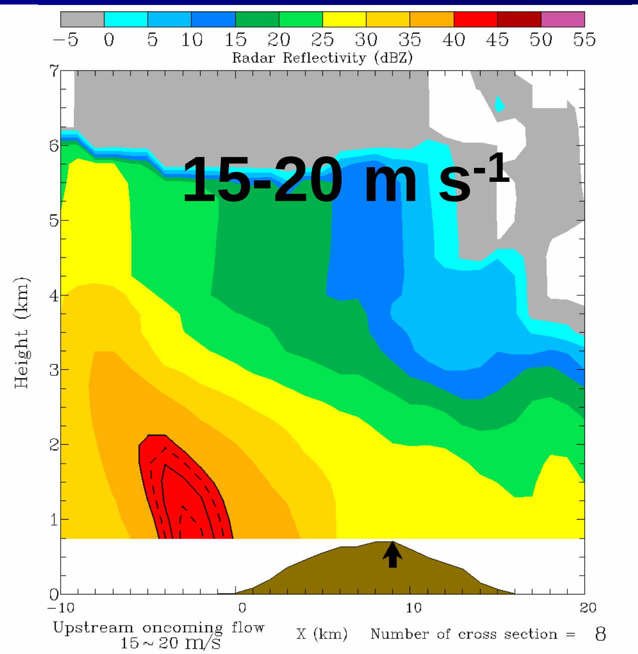
Frequency Distribution of Heavy Precipitation(>40 dBZ)

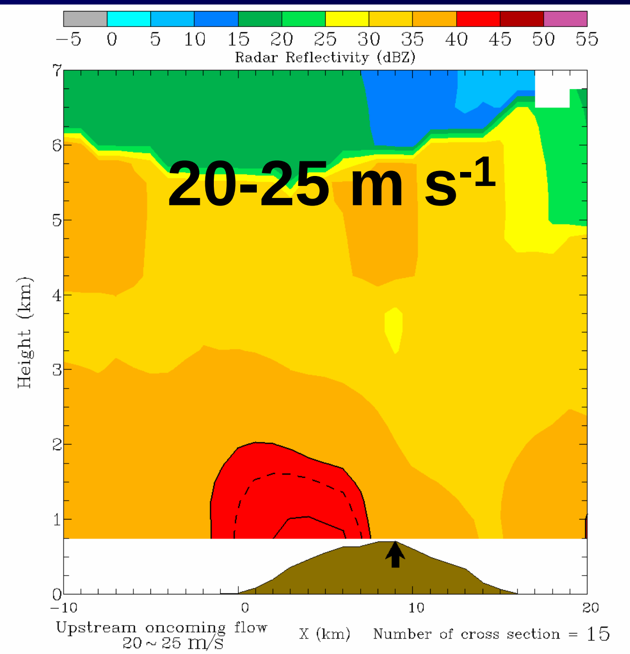


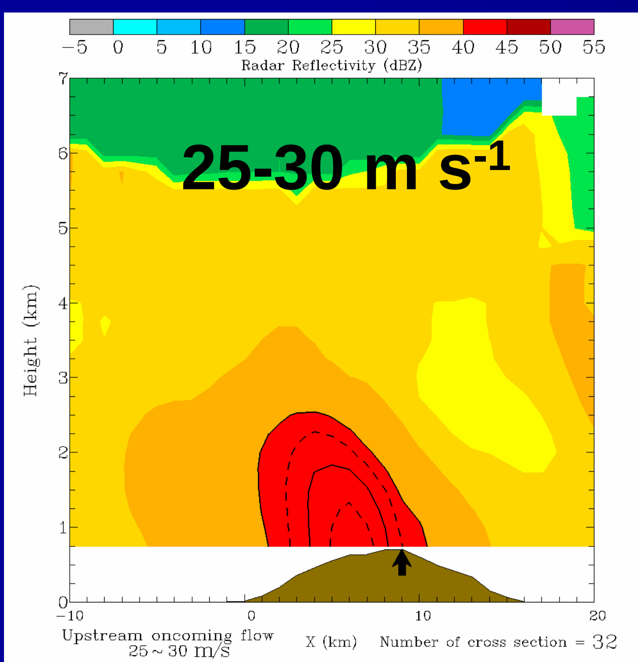

Radar Reflectivity (dBZ)
−5 0 5 10 15 20 25 30 35 40 45 50 55
10-15 m s-1
15-20 m s-1
20-25 m s-1
25-30 m s-1
30-35 m s-1
Height (km)
X (km)
Upstream oncoming flow
10 ~ 15 m/s
15 ~ 20 m/s
20 ~ 25 m/s
25 ~ 30 m/s
30 ~ 35 m/s
Number of cross section = 3
Number of cross section = 8
Number of cross section = 15
Number of cross section = 32
Number of cross section = 43

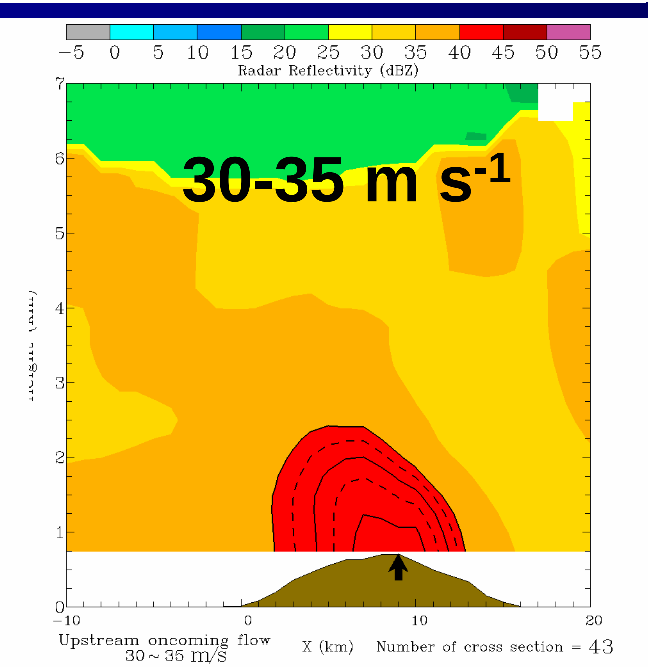
D1


−5 0 5 10 15 20 25 30 35 40 45 50 55
Radar Reflectivity (dBZ)
10-15 m s-1
Height (km)
0 1 2 3 4 5 6 7
−10 0 10 20
Upstream oncoming flow
10 ~ 15 m/s
X (km)
Number of cross section = 3

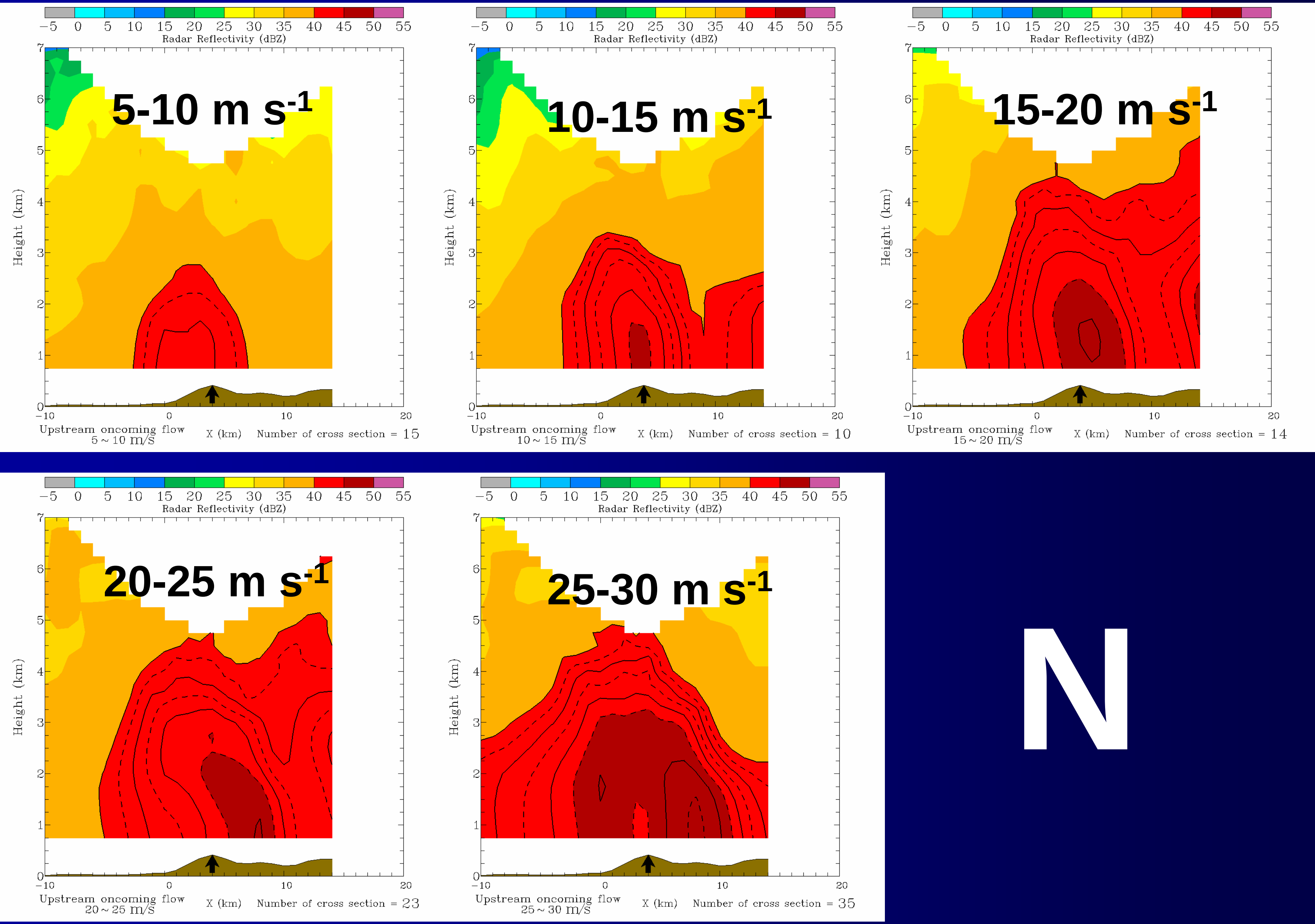

−5 0 5 10 15 20 25 30 35 40 45 50 55
Radar Reflectivity (dBZ)
15-20 m s-1
Height (km)
0 1 2 3 4 5 6 7
−10 0 10 20
Upstream oncoming flow
15 ~ 20 m/s
X (km)
Number of cross section = 8


−5 0 5 10 15 20 25 30 35 40 45 50 55
Radar Reflectivity (dBZ)
20-25 m s-1
Height (km)
0 1 2 3 4 5 6 7
−10 0 10 20
Upstream oncoming flow
20 ~ 25 m/s
X (km)
Number of cross section = 15


−5 0 5 10 15 20 25 30 35 40 45 50 55
Radar Reflectivity (dBZ)
25-30 m s-1
Height (km)
0 1 2 3 4 5 6 7
−10 0 10 20
Upstream oncoming flow
25 ~ 30 m/s
X (km)
Number of cross section = 32

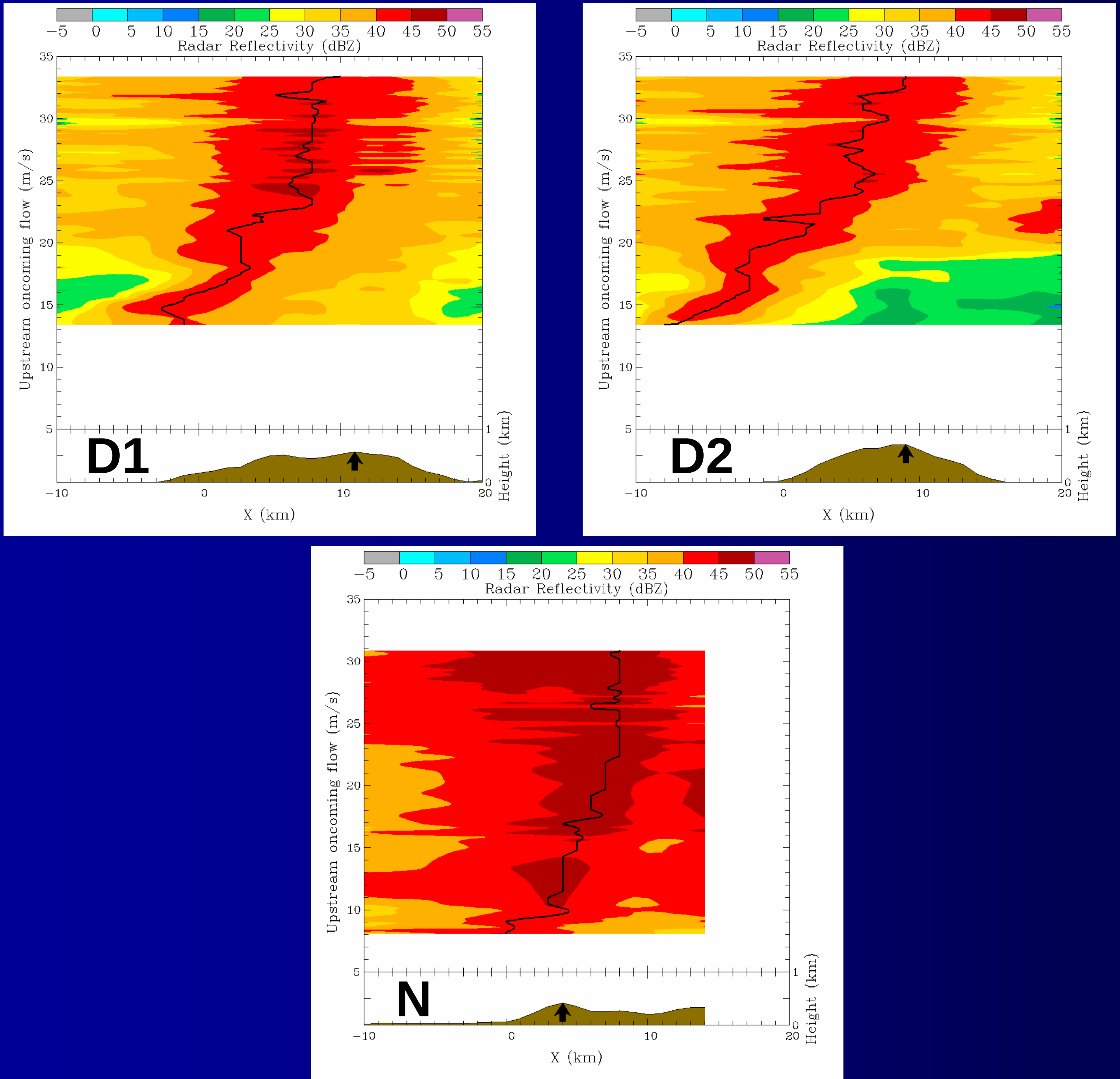

−5 0 5 10 15 20 25 30 35 40 45 50 55
Radar Reflectivity (dBZ)
30-35 m s-1
0 1 2 3 4 5 6 7
−10 0 10 20
Upstream oncoming flow
30 ~ 35 m/s
X (km)
Number of cross section = 43

D2



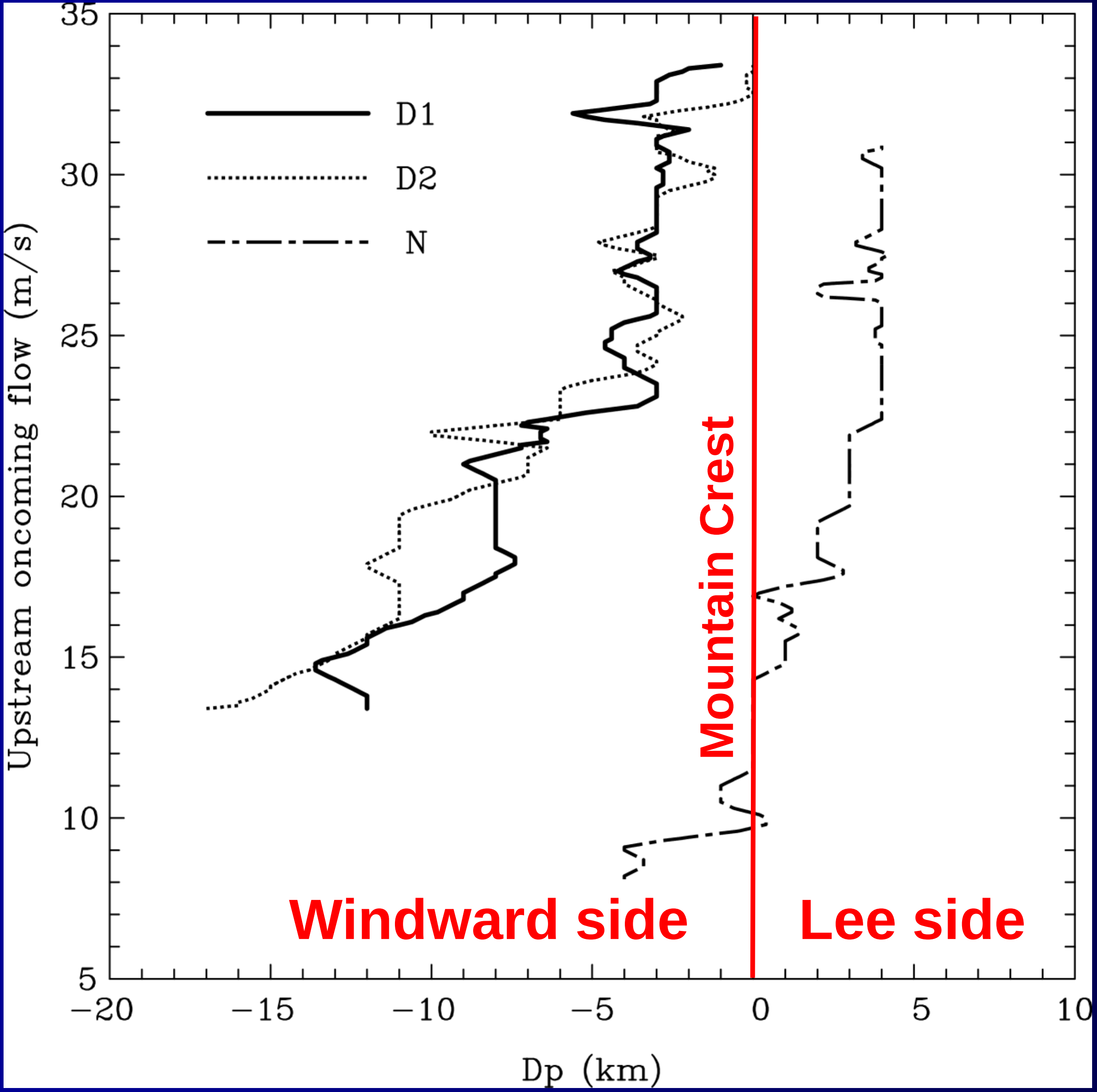
5-10 m s-1
10-15 m s-1
15-20 m s-1
20-25 m s-1
25-30 m s-1
Radar Reflectivity (dBZ)
Height (km)
X (km)
Upstream oncoming flow 5 ~ 10 m/s
Number of cross section = 15
Upstream oncoming flow 10 ~ 15 m/s
Number of cross section = 10
Upstream oncoming flow 15 ~ 20 m/s
Number of cross section = 14
Upstream oncoming flow 20 ~ 25 m/s
Number of cross section = 23
Upstream oncoming flow 25 ~ 30 m/s
Number of cross section = 35

N

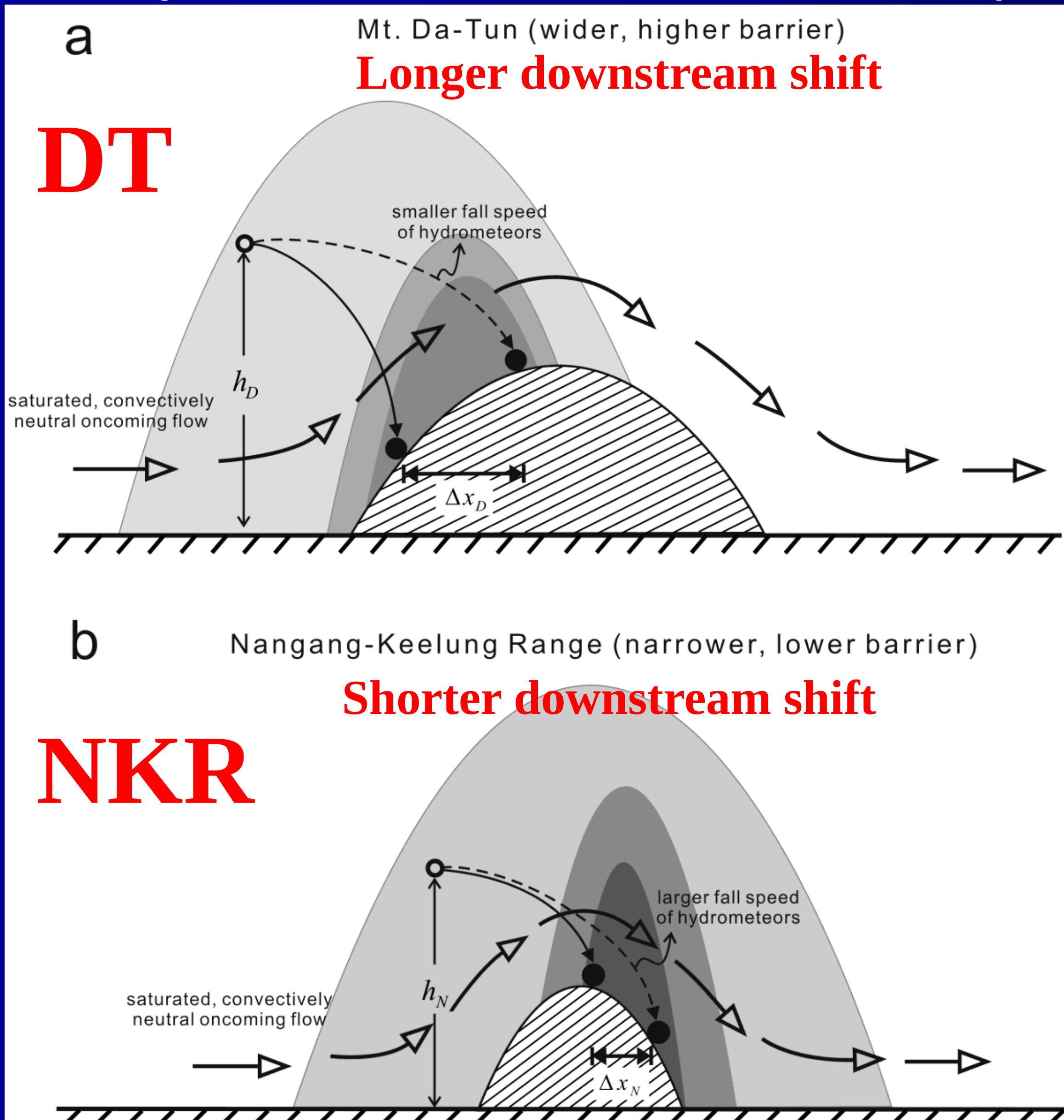


Radar Reflectivity (dBZ)
−5 0 5 10 15 20 25 30 35 40 45 50 55
Upstream oncoming flow (m/s)
Height (km)
X (km)
D1
D2
N

Location of low-level heaviest precipitation with respect to intensities of upstream oncoming winds



Schematic diagram illustrating the downstream shift of hydrometeors over DT and NKR (Yu and Cheng 2008)



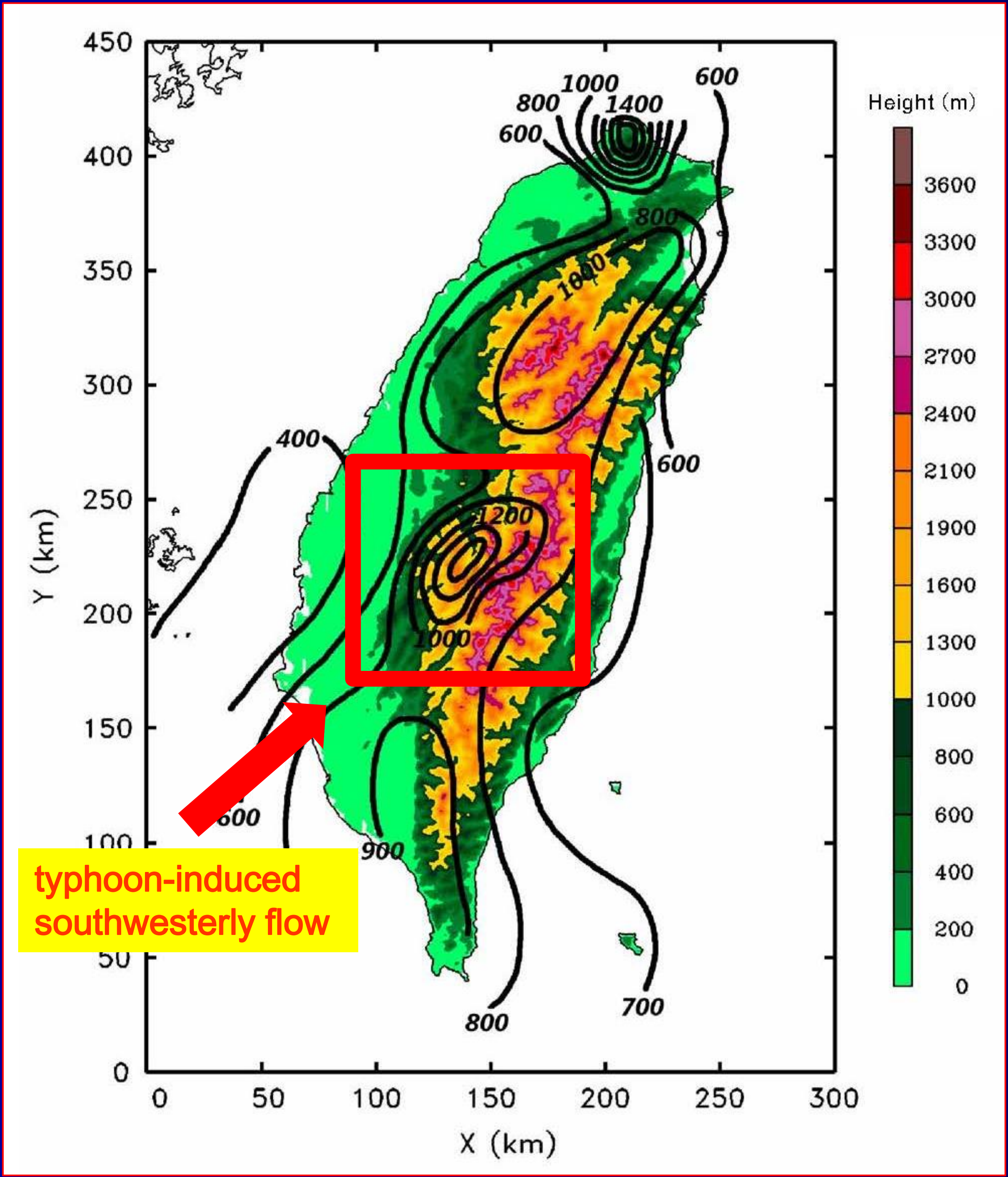
$$\Delta x = t_r \times \Delta u$$

$$= \underbrace{\left|\frac{h}{(w_{air} + v_t)}\right|}_{residence\ \ time} \times \Delta u$$

$\Delta u \sim 20\ \mathrm{m\ s^{-1}}$ over DT and NKR

DT: higher *h*, smaller fall speed

NKR: lower *h*, larger fall speed

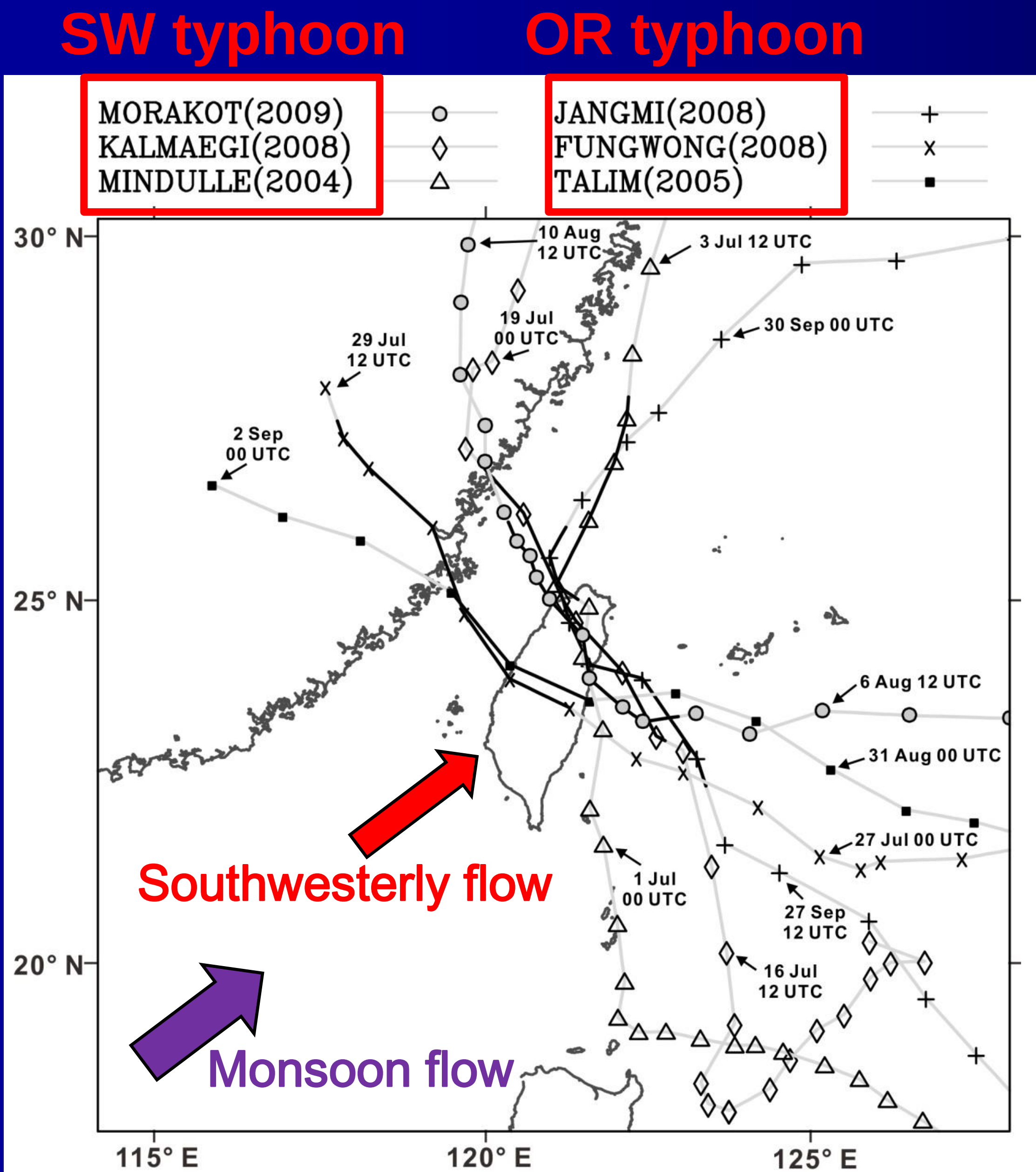


Distribution of maximum rainfall during the influence of typhoons

(1897-1996)

Yu and Cheng (2014)

The best track of the six studied typhoons



SW (OR) typhoon defined as with (without) obvious combination of typhoon outer circulations with southwesterly monsoon flow

Objectives:

To explore kinematics of southwesterly flow associated with SW and OR typhoons

Horizontal distribution of the accumulated rainfall for each of the studied typhoons

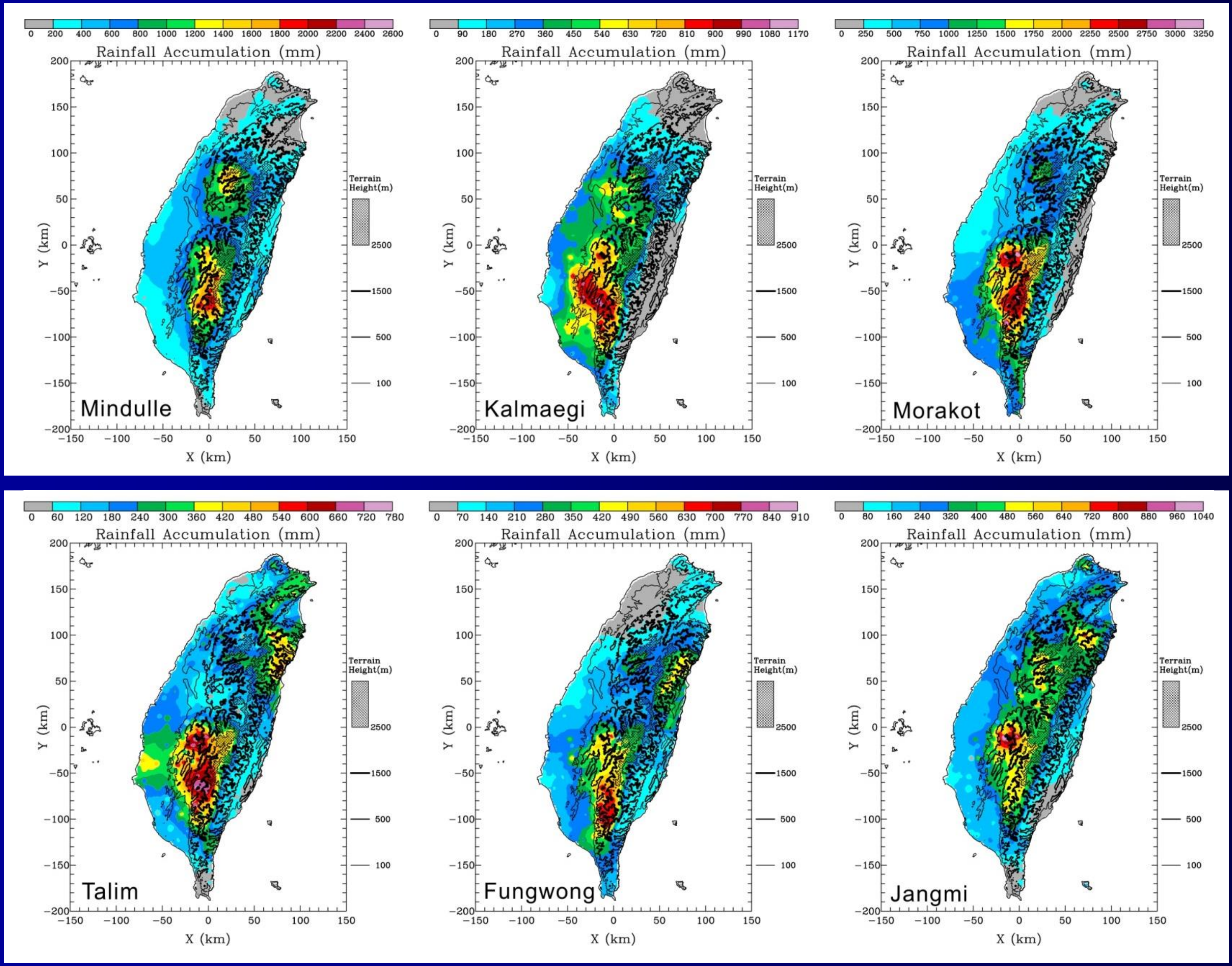
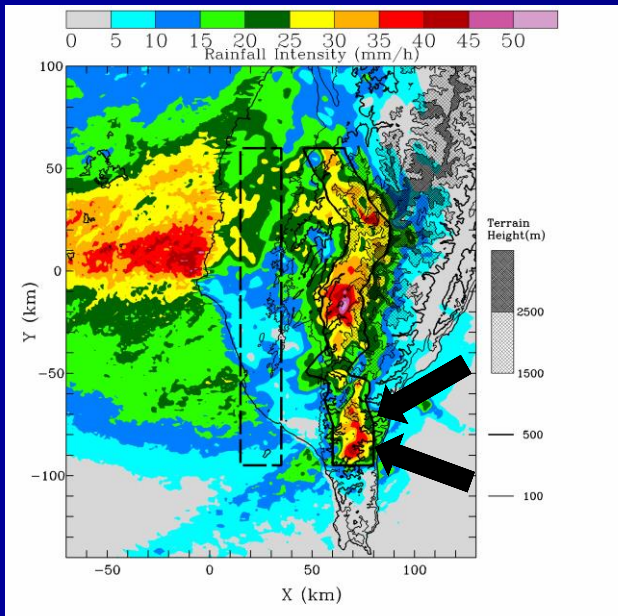


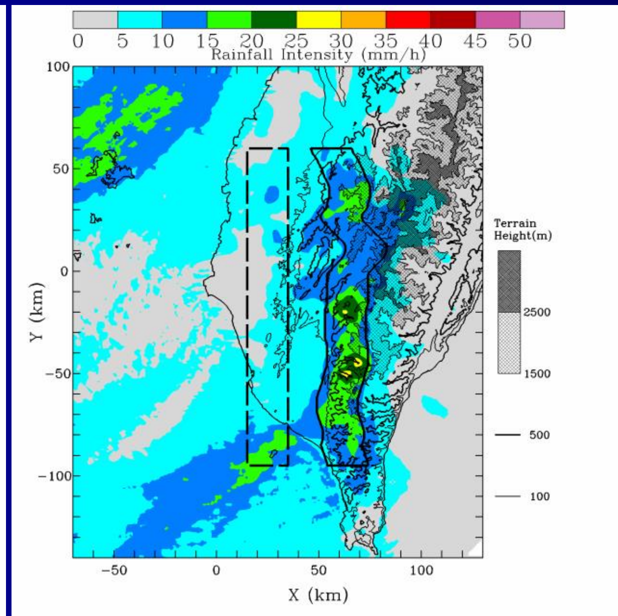
Table 2. The magnitudes of the upstream cross-barrier flow (U, m s^{-1}), typhoon background precipitation (R_{bg}, mm h^{-1}), orographic precipitation (R_{mt}, mm h^{-1}), and precipitation enhancement (ΔR, mm h^{-1}) for each of the studied typhoons. Variables with an overbar represent the mean values averaged for the SW and OR typhoons.

		U	R_{bg}	R_{mt}	ΔR	$R_{bg} \times U$	U	R_{bg}	R_{mt}	ΔR
	Mindulle	20.3	11.0	23.4	12.4	223.3				
SW typhoon	Kalmaegi	11.9	10.0	19.4	9.4	119.0	20.1	12.6	27.2	14.6
	Morakot	28.1	16.7	38.7	22.0	469.3				
	Talim	19.6	12.4	26.9	14.5	243.0				
OR typhoon	Fungwong	14.4	9.2	14.9	5.7	132.5	16.2	10.2	20.5	10.3
	Jangmi	14.6	9.1	19.8	10.6	132.9				

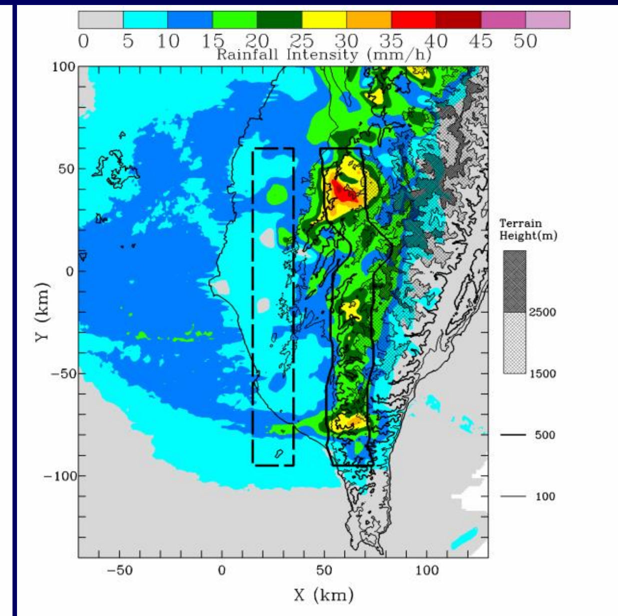
2005 TALIM



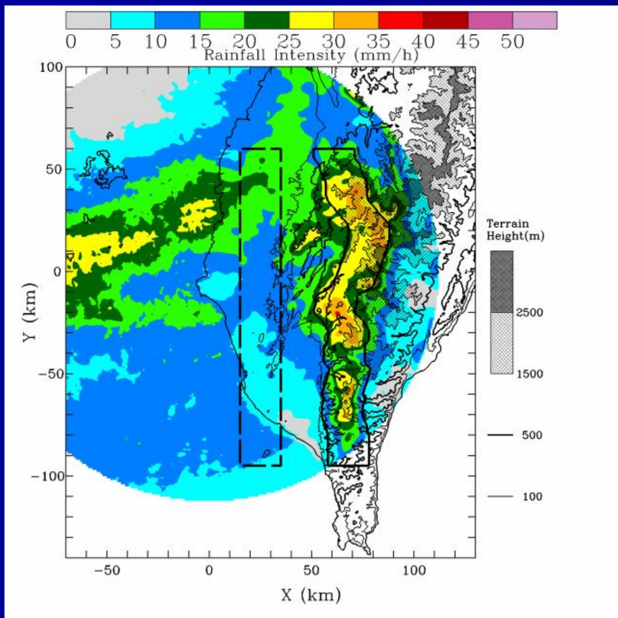
2008 FUNGWONG



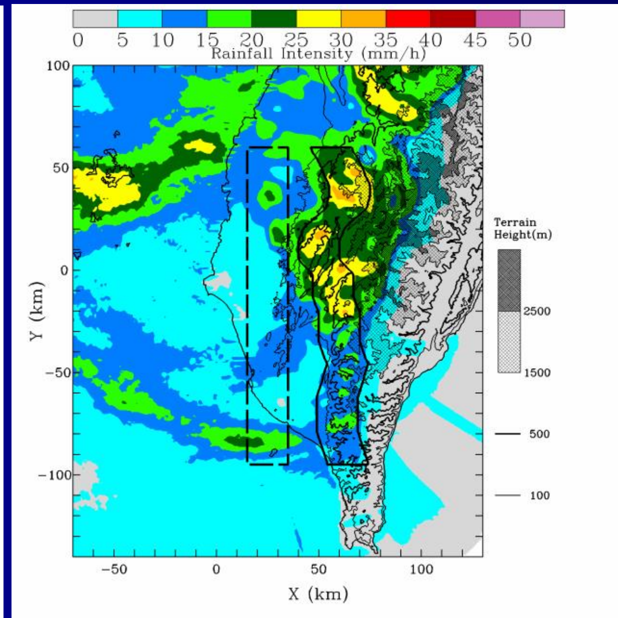
2008 JANGMI



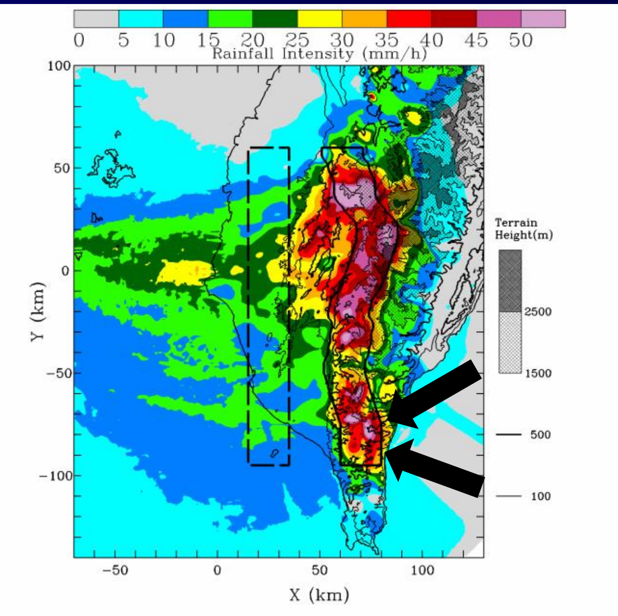
2004 MINDULLE



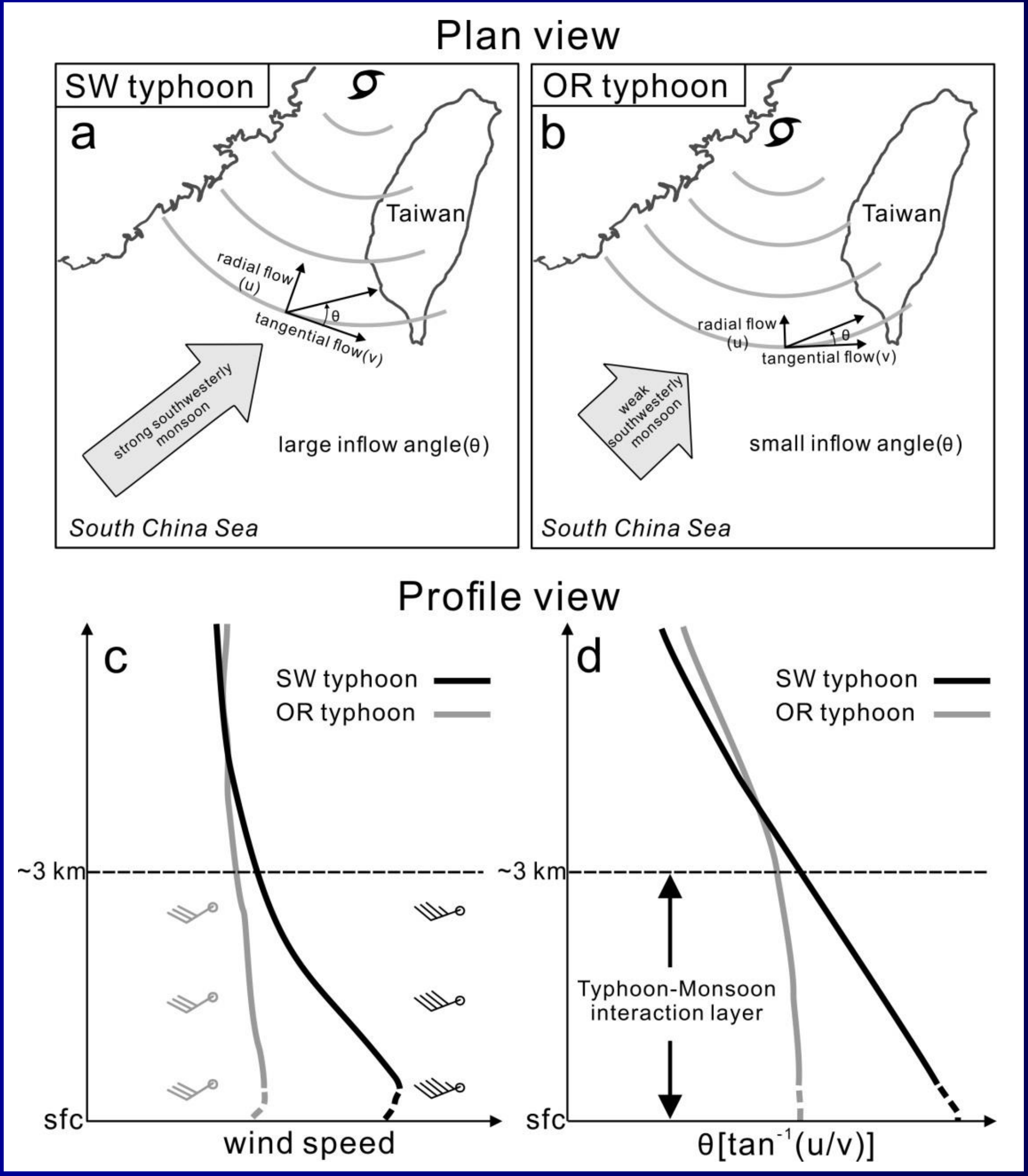
2008 KALMAEGI



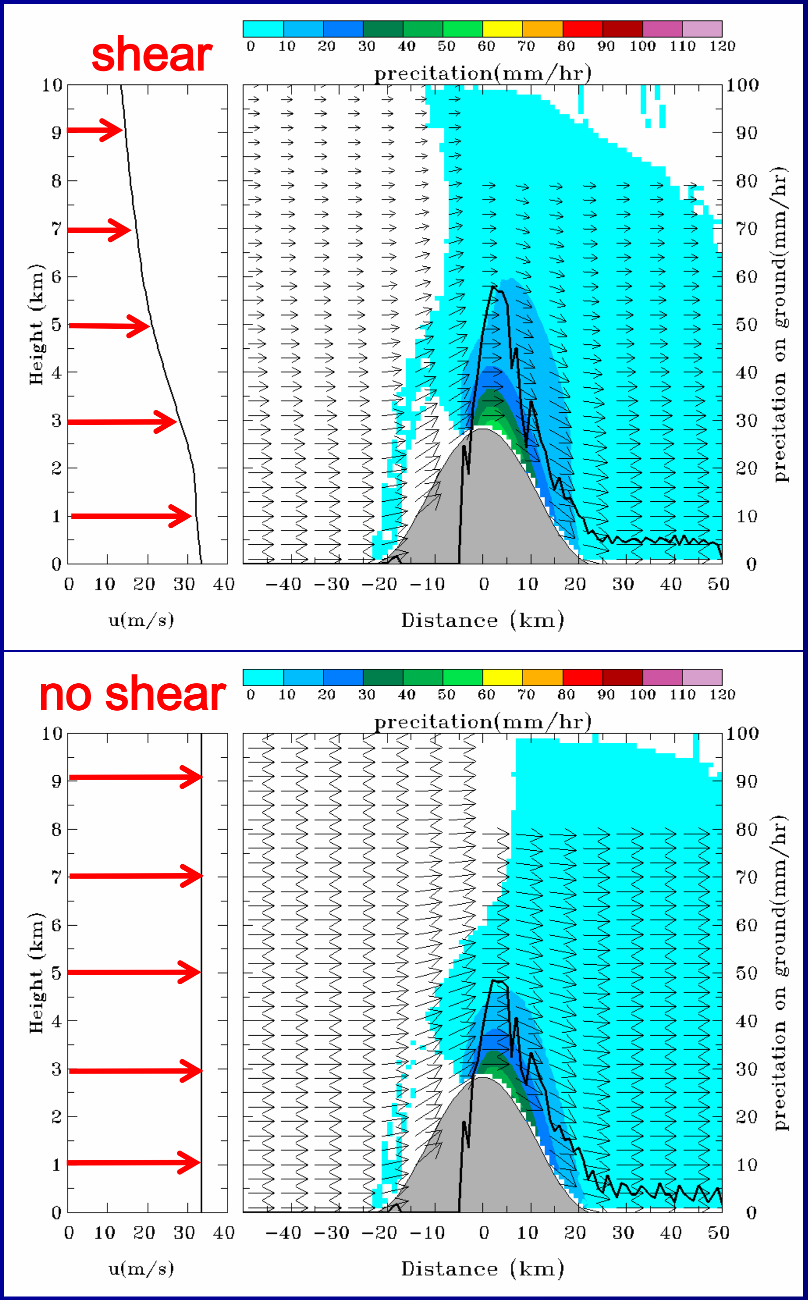
2009 MORAKOT



Schematic diagram for SW and OR typhoons



Evaluation of shear profiles via idealized orographic precipitation model

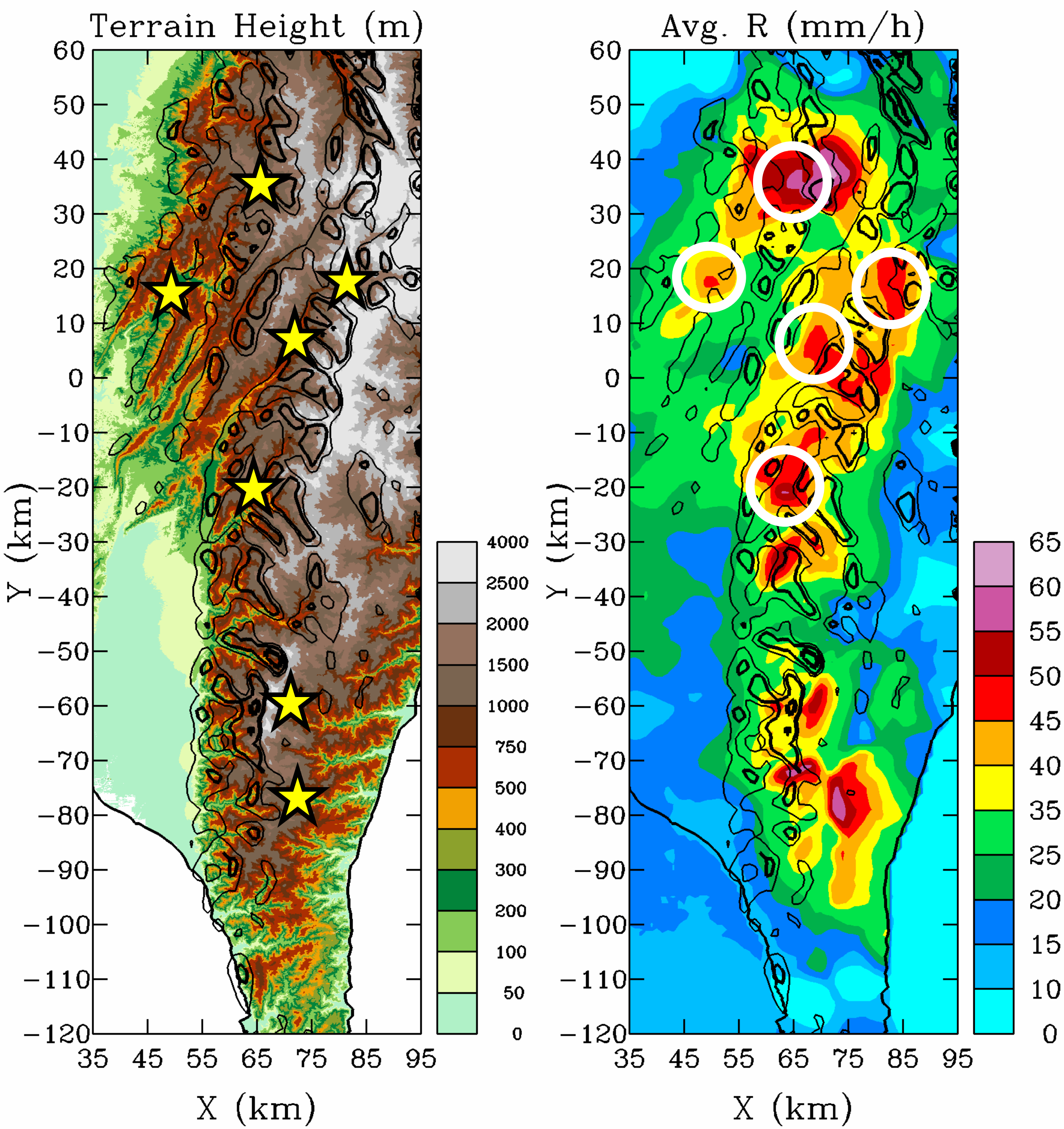


08/07 2100 UTC Typhoon Morakot (2009)

Rainfall intensity 57.9 mm h^{-1}

20% increase in rainfall intensity considering shear features like SW typhoon

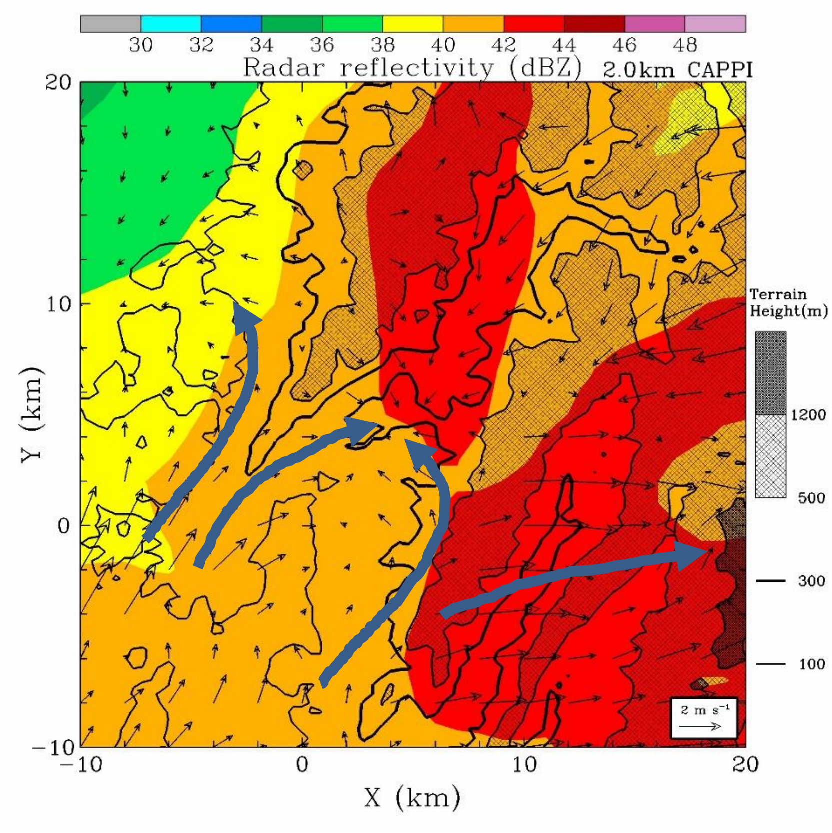
Rainfall intensity 48.4 mm h^{-1}



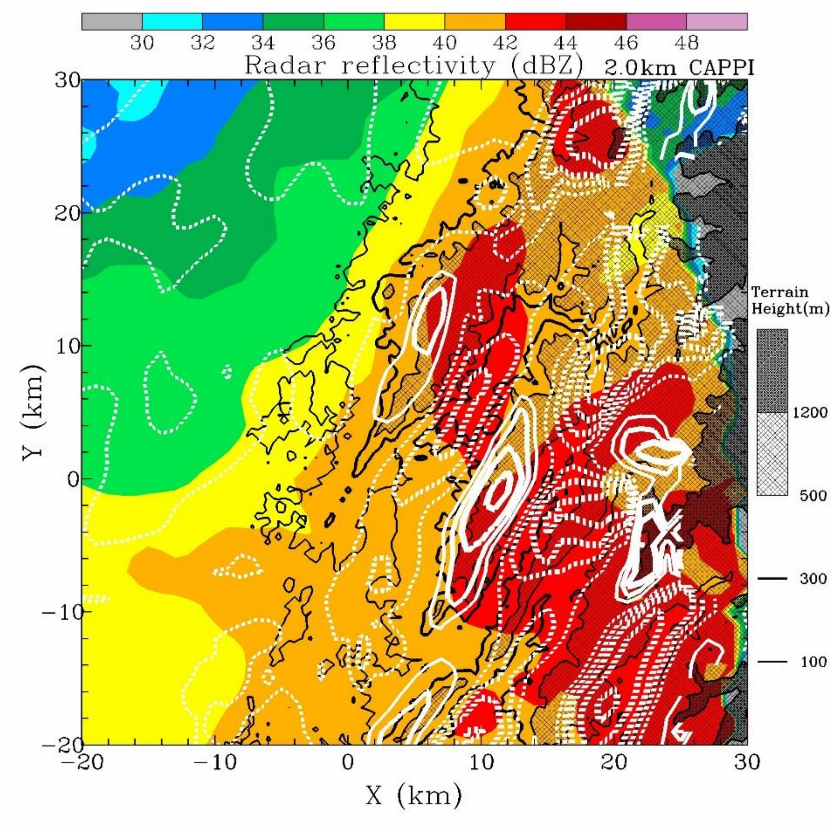
Terrain Height (m)
Avg. R (mm/h)
Y (km)
X (km)
60
50
40
30
20
10
0
−10
−20
−30
−40
−50
−60
−70
−80
−90
−100
−110
−120
35
45
55
65
75
85
95
4000
2500
2000
1500
1000
750
500
400
300
200
100
50
0
65
60
55
50
45
40
35
25
20
15
10
0

Syu (2018, Master thesis)

- Perturbation wind

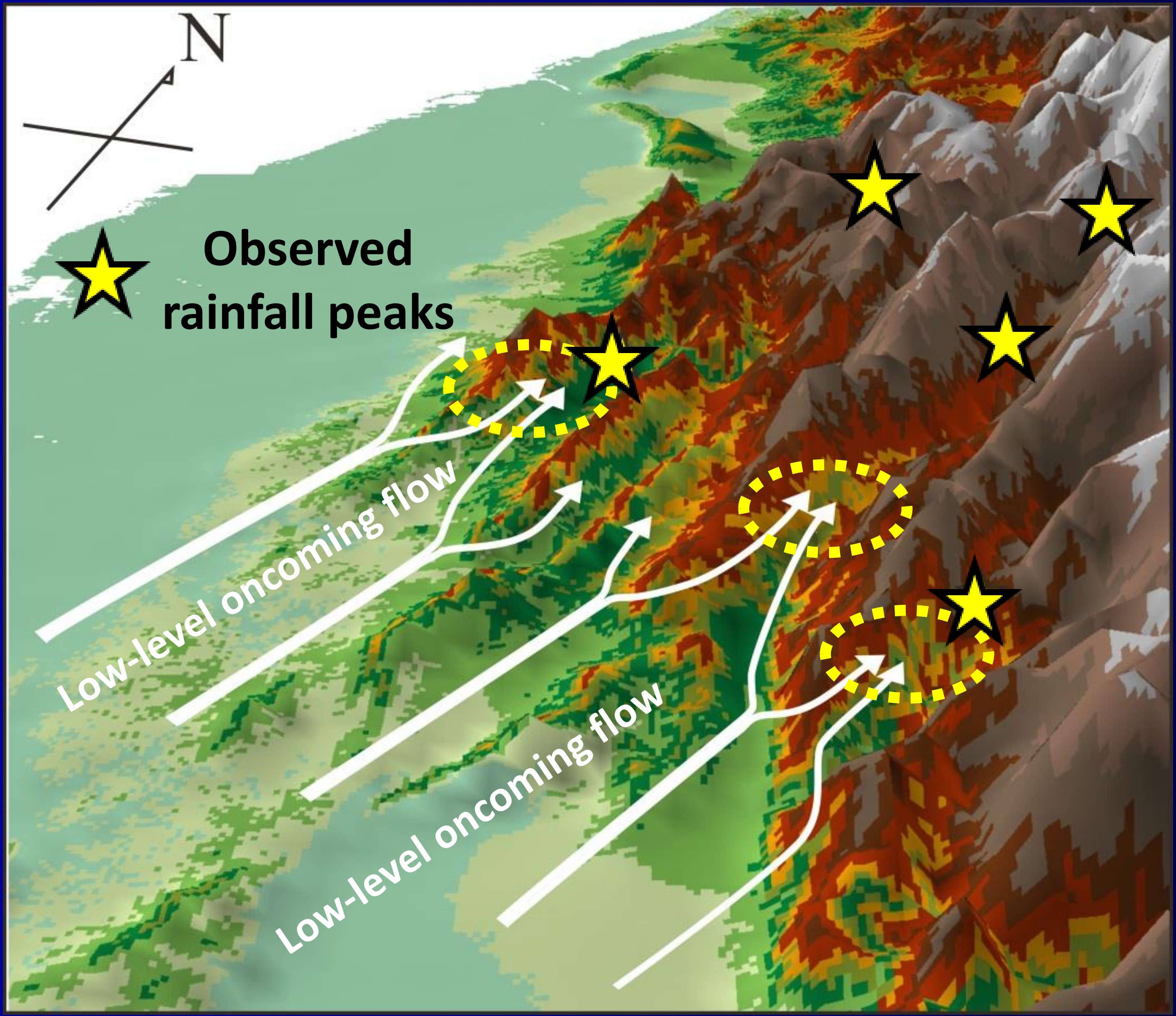


- Cross(lateral) valley flow convergence

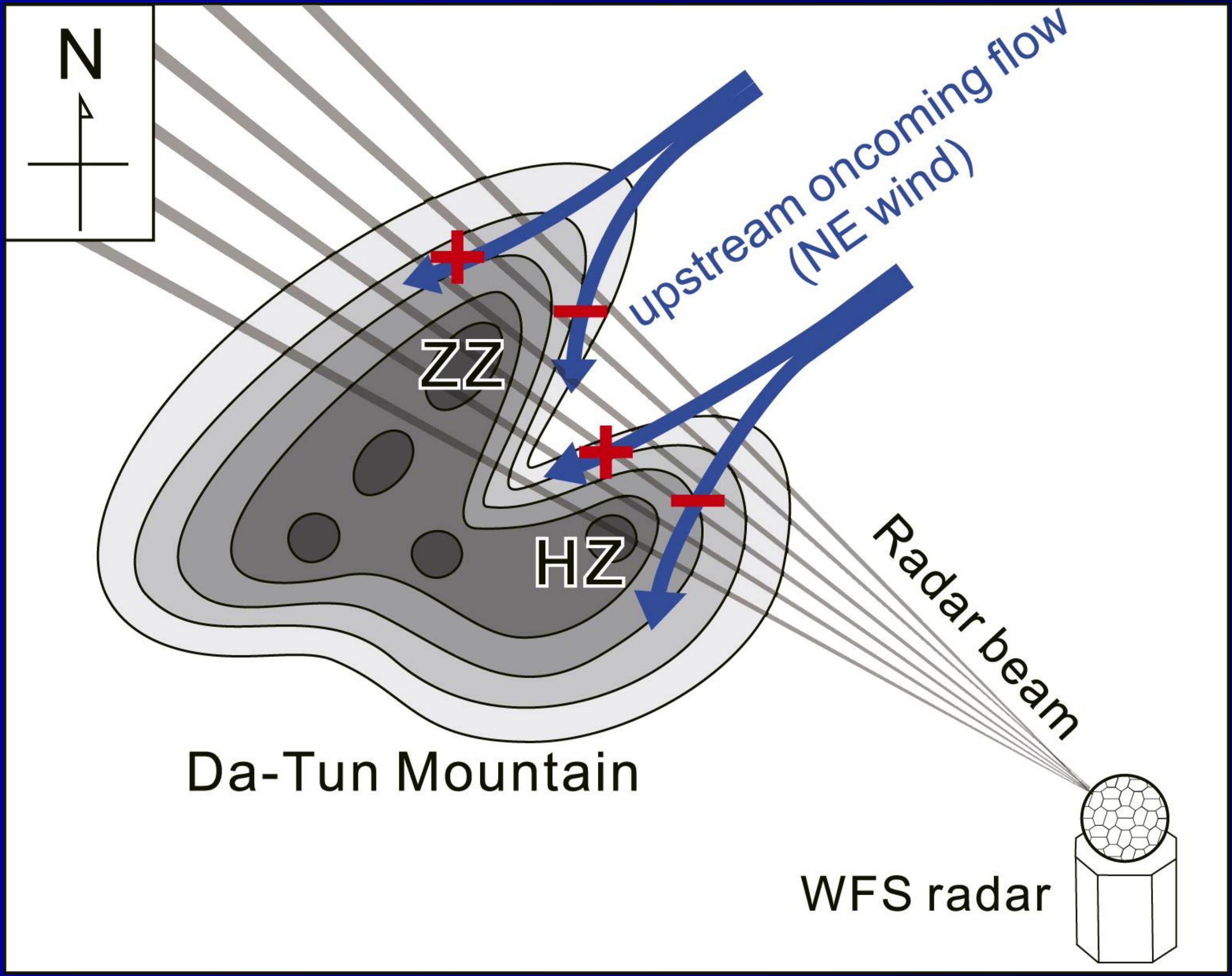


solid line：Divergence
dotted line：Convergence

Possible valley effects on precipitation enhancement



Spatial pattern of radial velocities observed from WFS radar when upstream northeasterly flow is deflected by the windward ZZ and HZ ridge arms. (Cheng and Yu 2019)



Major findings

- Upslope lifting is overall important under large Froude number flow regimes

- Confirm the importance of the seeder-feeder mechanism in the typhoon environment

Implications:

--- Seeder-feeder effect would be more prominent in TCs (stronger winds and background rainfall) than in other weather systems

--- Narrower barrier may have a higher potential to produce heavy rainfall

--- Predicting rainfall over narrow and low mountain ranges would be more challenging than over wide and high mountains

- Provide insight into why SW typhoons can produce stronger orographic precipitation

- Valley effects play a role in the precipitation enhancement