Water Budget and Precipitation Efficiency of Typhoon Morakot (2009)

Ming-Jen Yang 楊明仁

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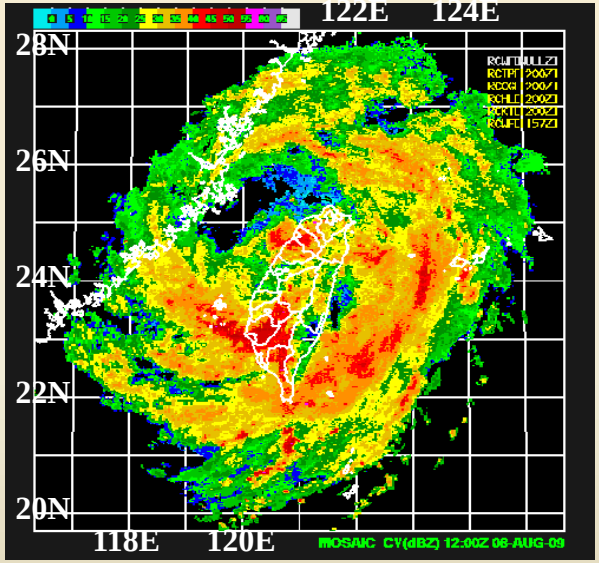
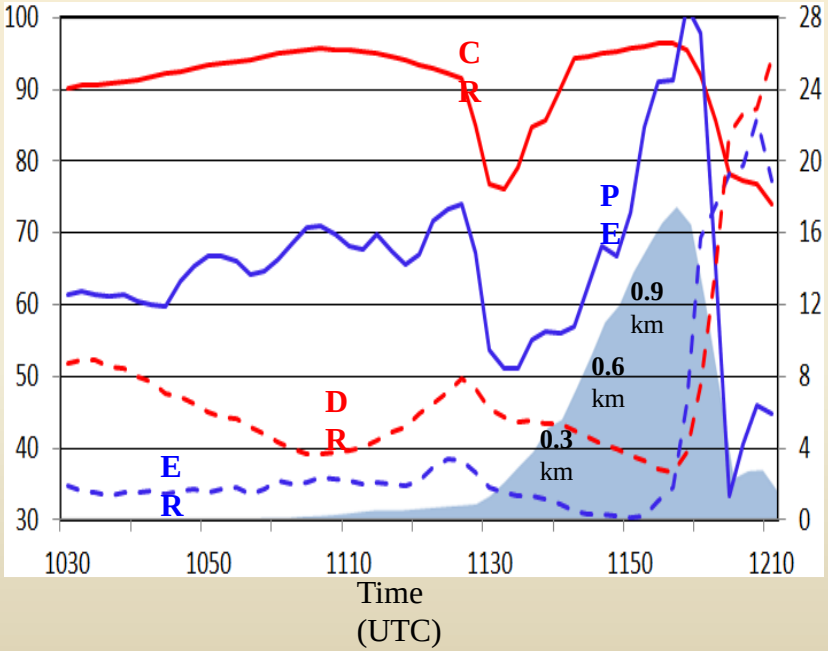


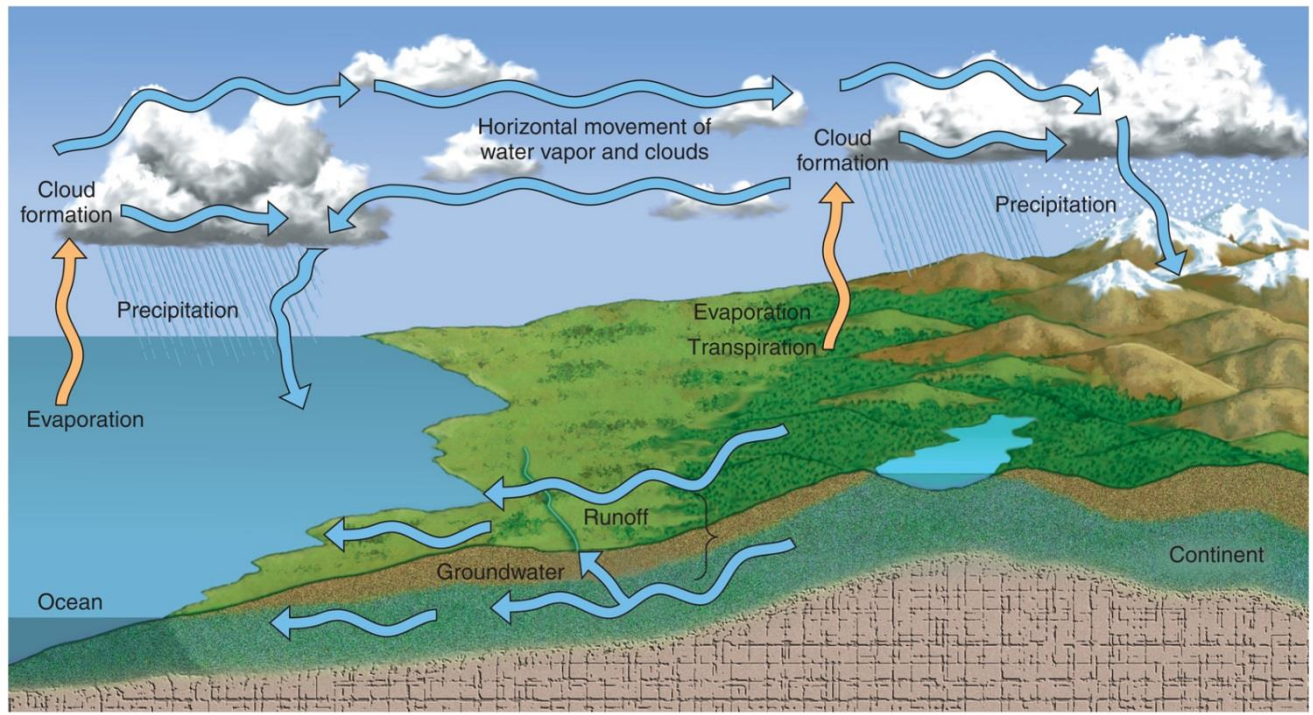


Acknowledgement: Dr. Hsiao-Ling Huang 黃小玲博士, Prof. Chung-Hsiung Sui 隋中興教授

Seminar at 中央大學水文暨海洋科學研究所 (2018/09/18)

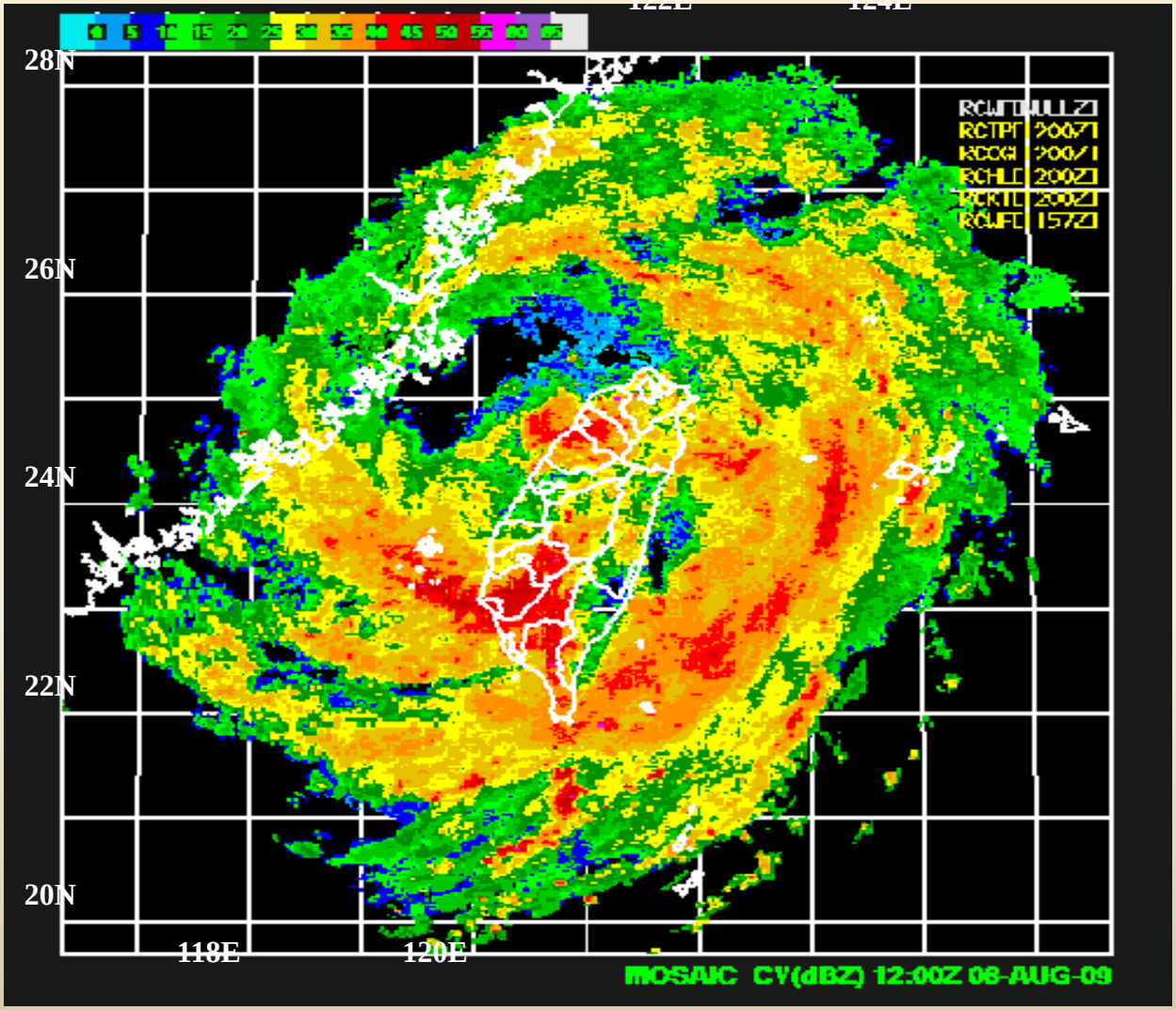
Hydrological Cycle and Precipitation Efficiency

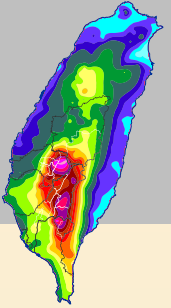
- The **occurrence of precipitation** is determined by the **environmental dynamics** and **microphysics** of weather and climate systems.
- **Precipitation efficiency** (**PE**) is used to evaluate **how efficiently the convective system produces precipitation**.



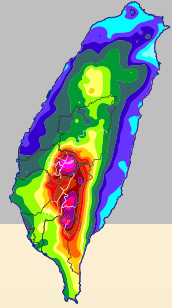
Typhoon Morakot (2009)

Radar Reflectivity Composite





Uniqueness of Typhoon Morakot



1. **Morakot occurred in a dry monsoon season**
2. **Long duration and record-breaking rainfall (> 3 m)**
3. **Weakening steering flow; small translation speed; long influencing time (> 64 hours)**
4. **Asymmetric precipitation structure embedded in large-scale convection zone**
5. **Coexistence of southwesterly monsoon and typhoon**
6. **Continuous formation of outer rainbands**
7. **Mountain lifting effect**

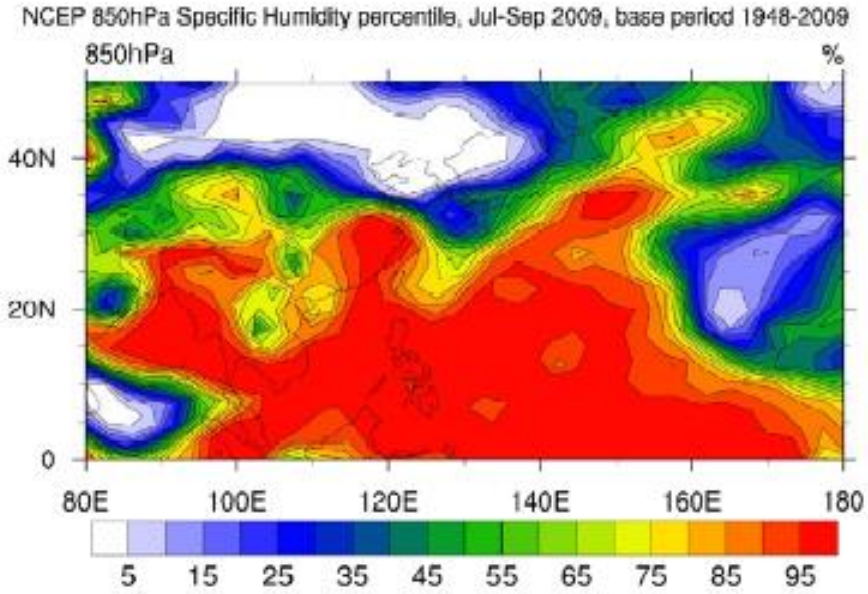
莫拉克颱風檢討報告 (國科會 2010)
TAO Special Issue on Typhoon Morakot (Wu and Yang 2011)

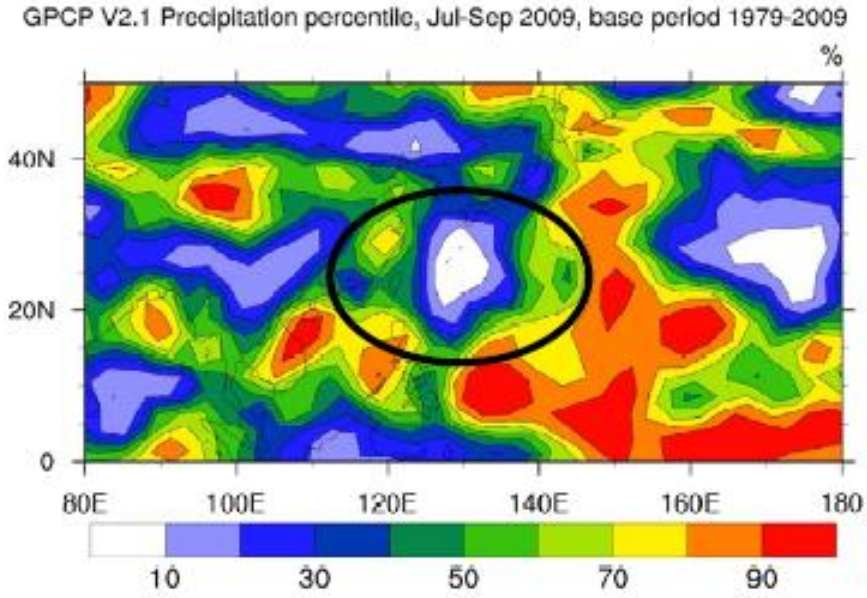
SST and Precipitation

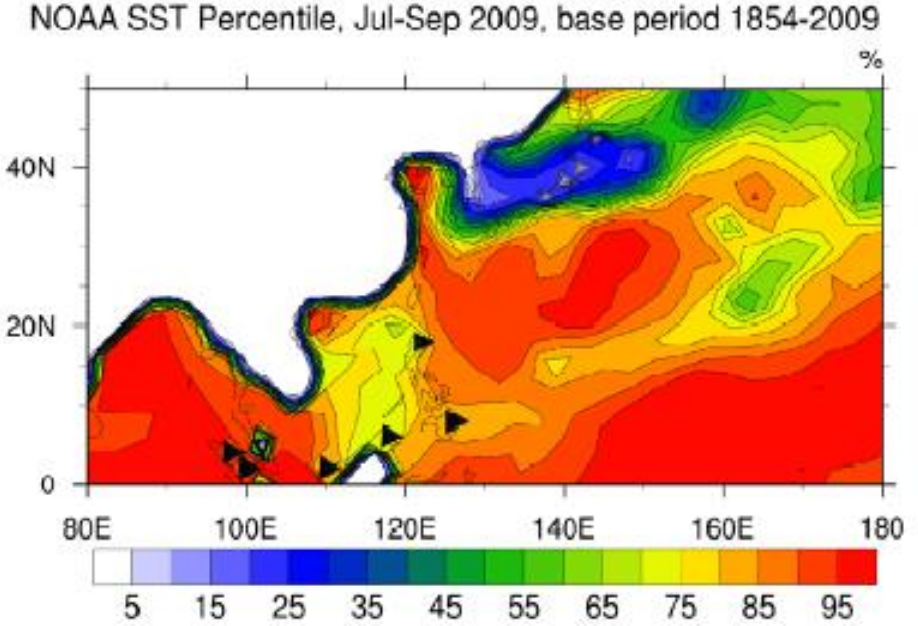
How anomalous was the 2009 typhoon season?

- **humid, high SST > PR95**
- **but less precipitation < PR10**

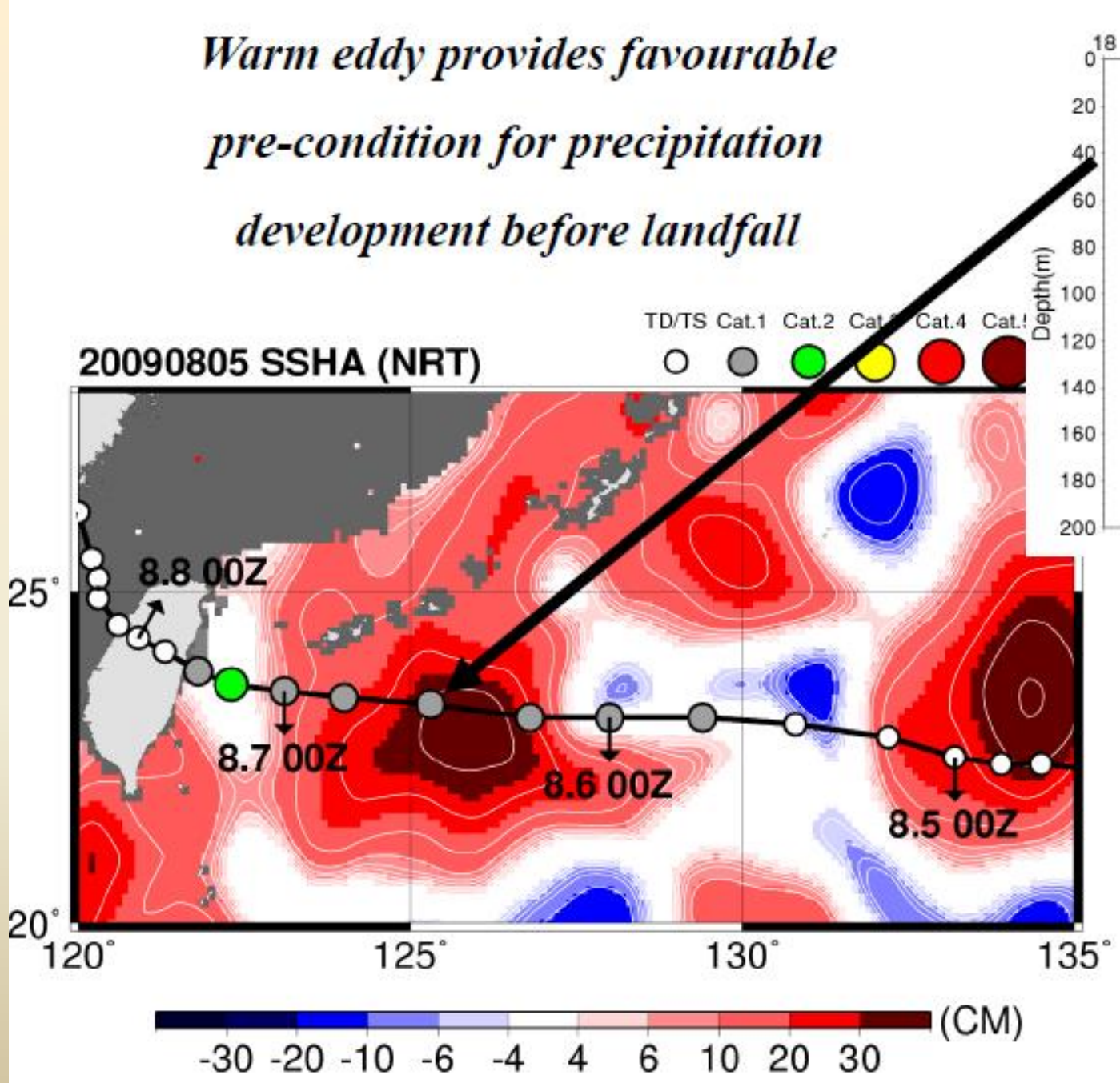
C.-H. Wong

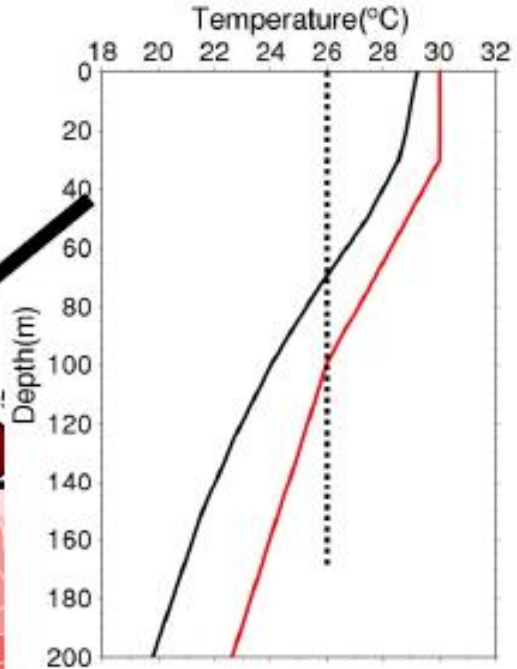






Warm eddy provides favourable pre-condition for precipitation development before landfall

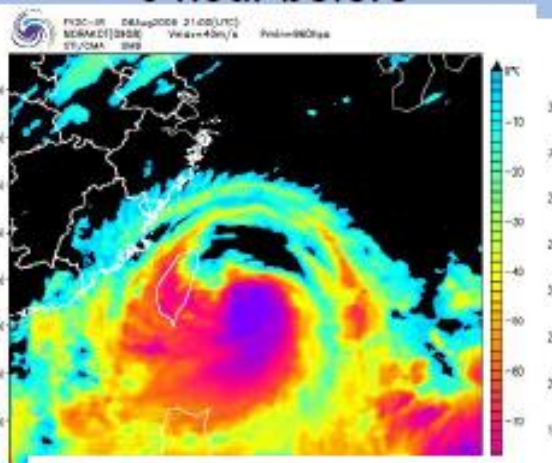




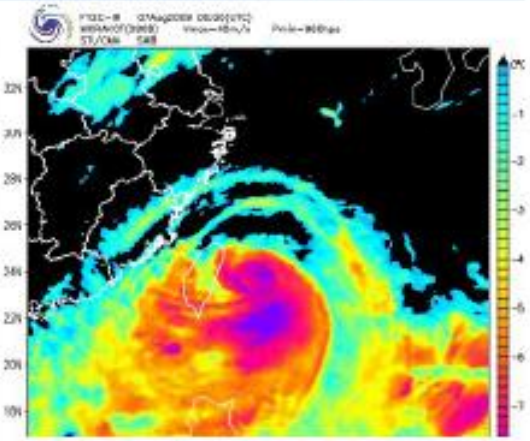
I.-I. Lin
林依依教授

Structure of Morakot while landfalling Taiwan

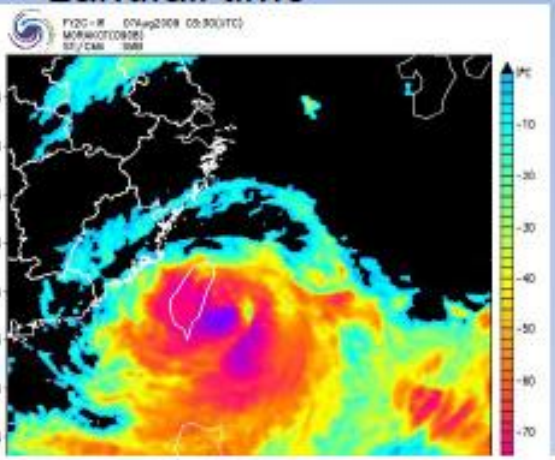
-6 hour before



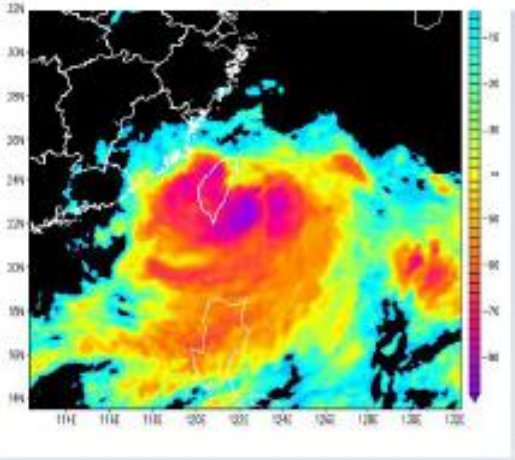
-3 hour before

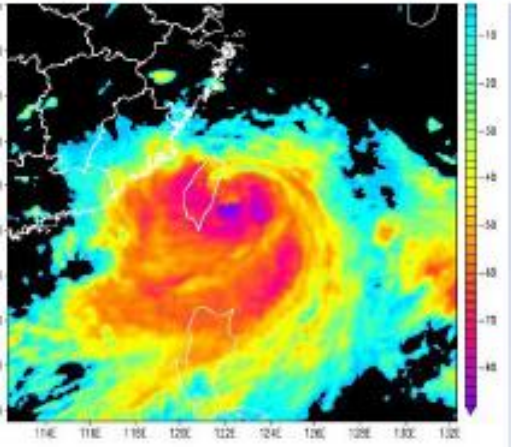


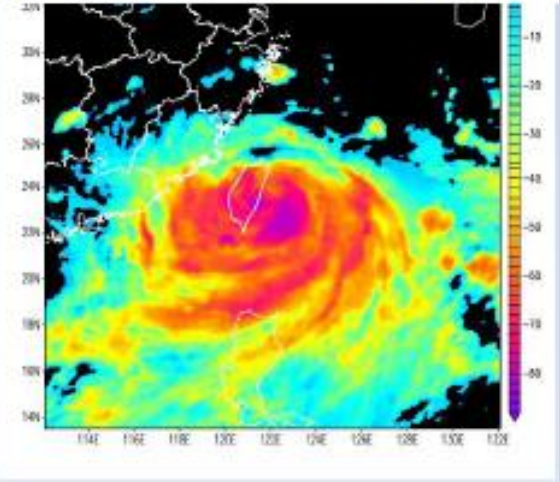
Landfall time



Asymmetric structure,
strong convective in the south part of Morakot

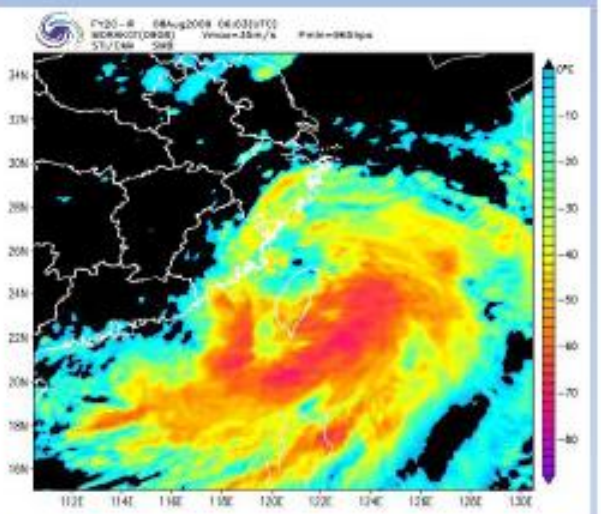


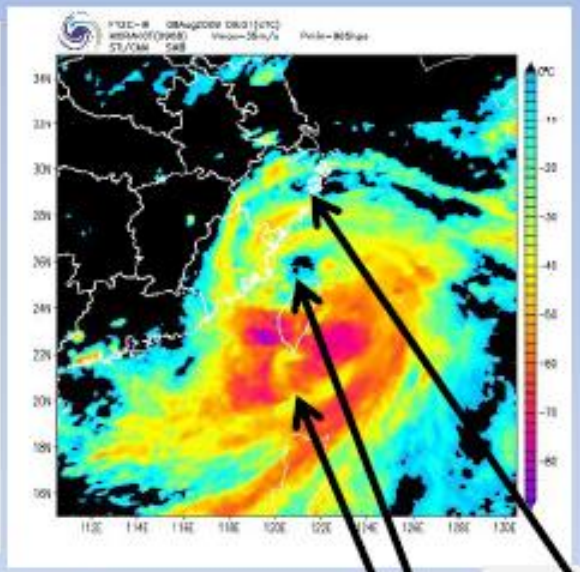


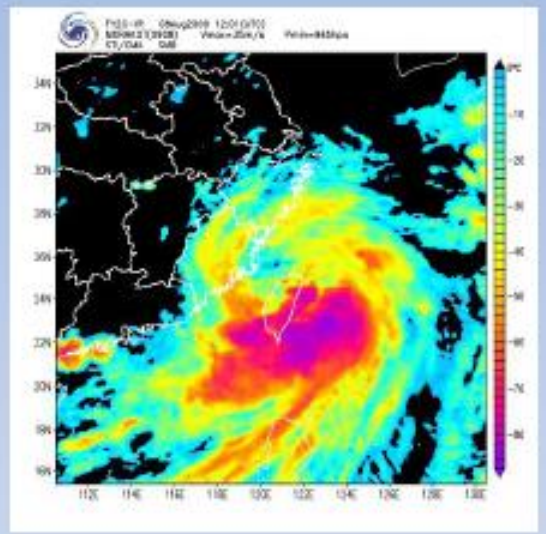


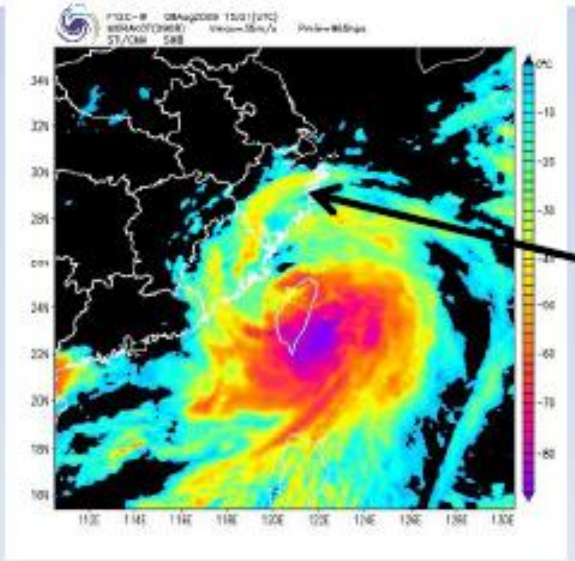
R. L. Elsberry (NPS)

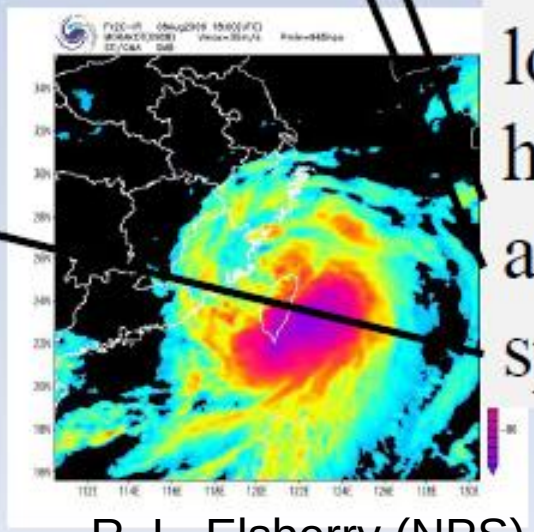
Structure of Morakot in the Taiwan strait



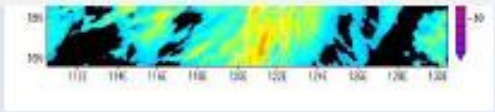








loose structure,
hollow and big eye
asymmetric structure
spiral rainband



R. L. Elsberry (NPS)

Structure of Morakot while landfalling China mainland

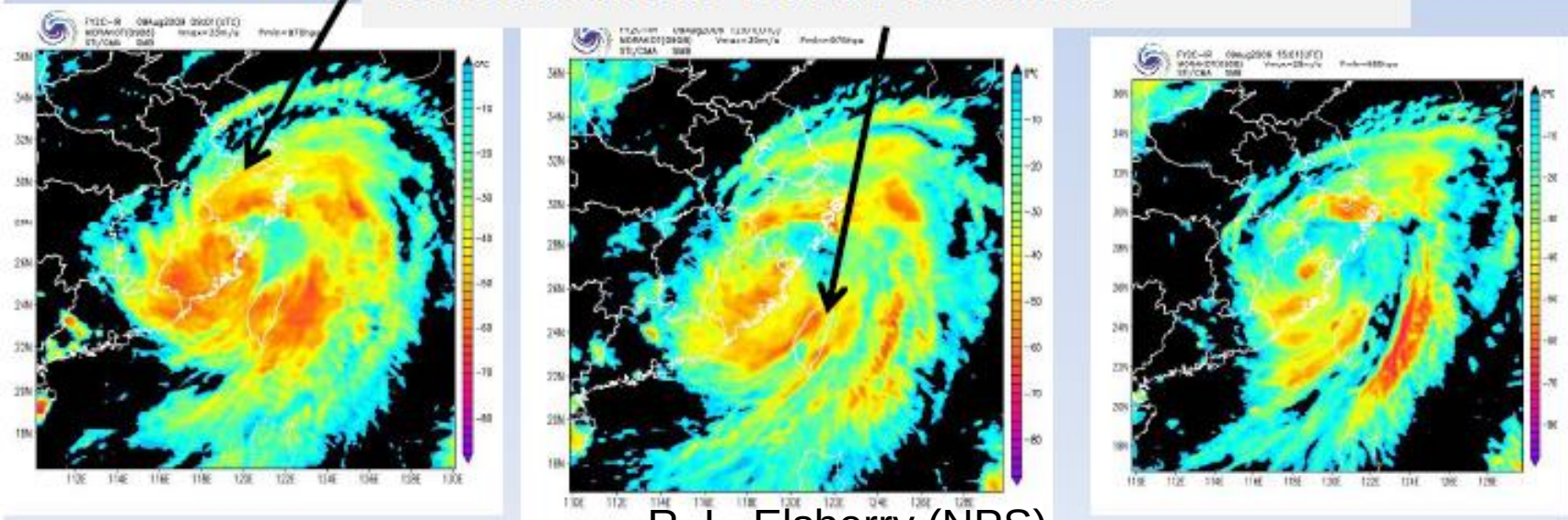
-8 hour before

-6 hour before

2 hour before

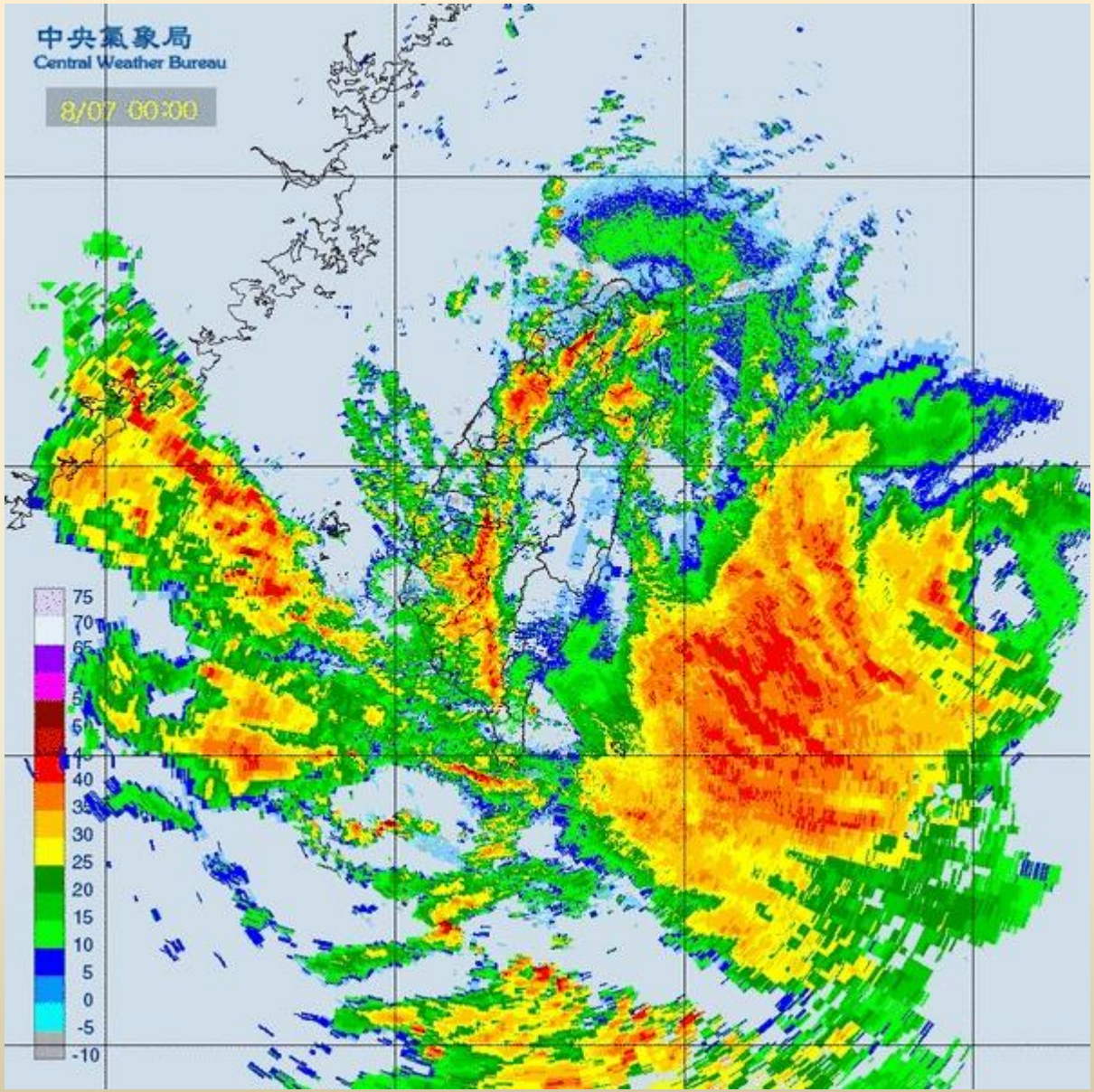
Disorganization structure
decreased convection

1 hour after



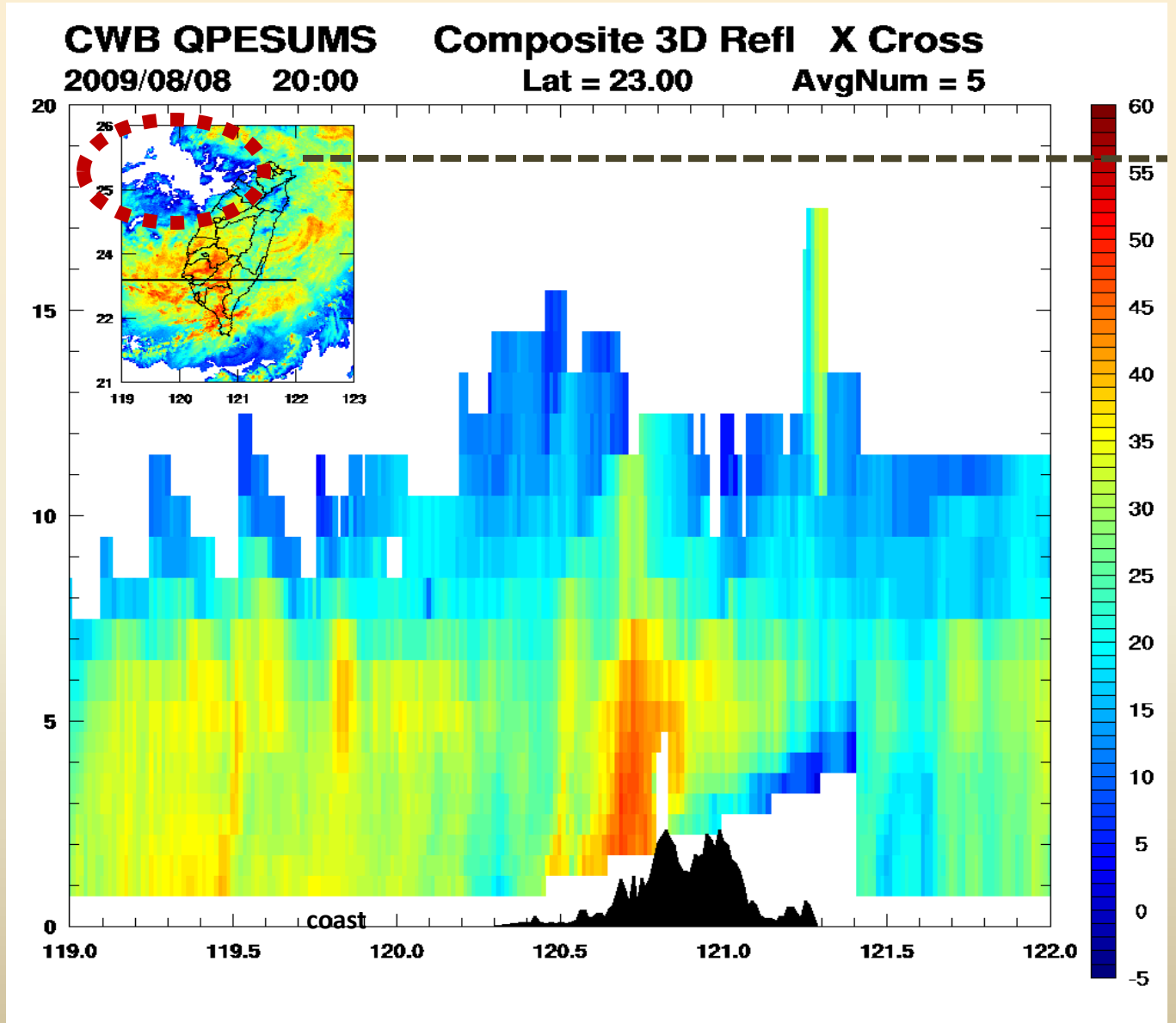
R. L. Elsberry (NPS)

Radar Reflectivity Loop of Morakot (2009)



Continuous formation of the outer rainbands over the Taiwan Strait

Ben Jou
周仲島教授



Typhoon Morakot (2009)

before

after

More than 100 houses affected

Over all in Taiwan: Life losses close to 700.

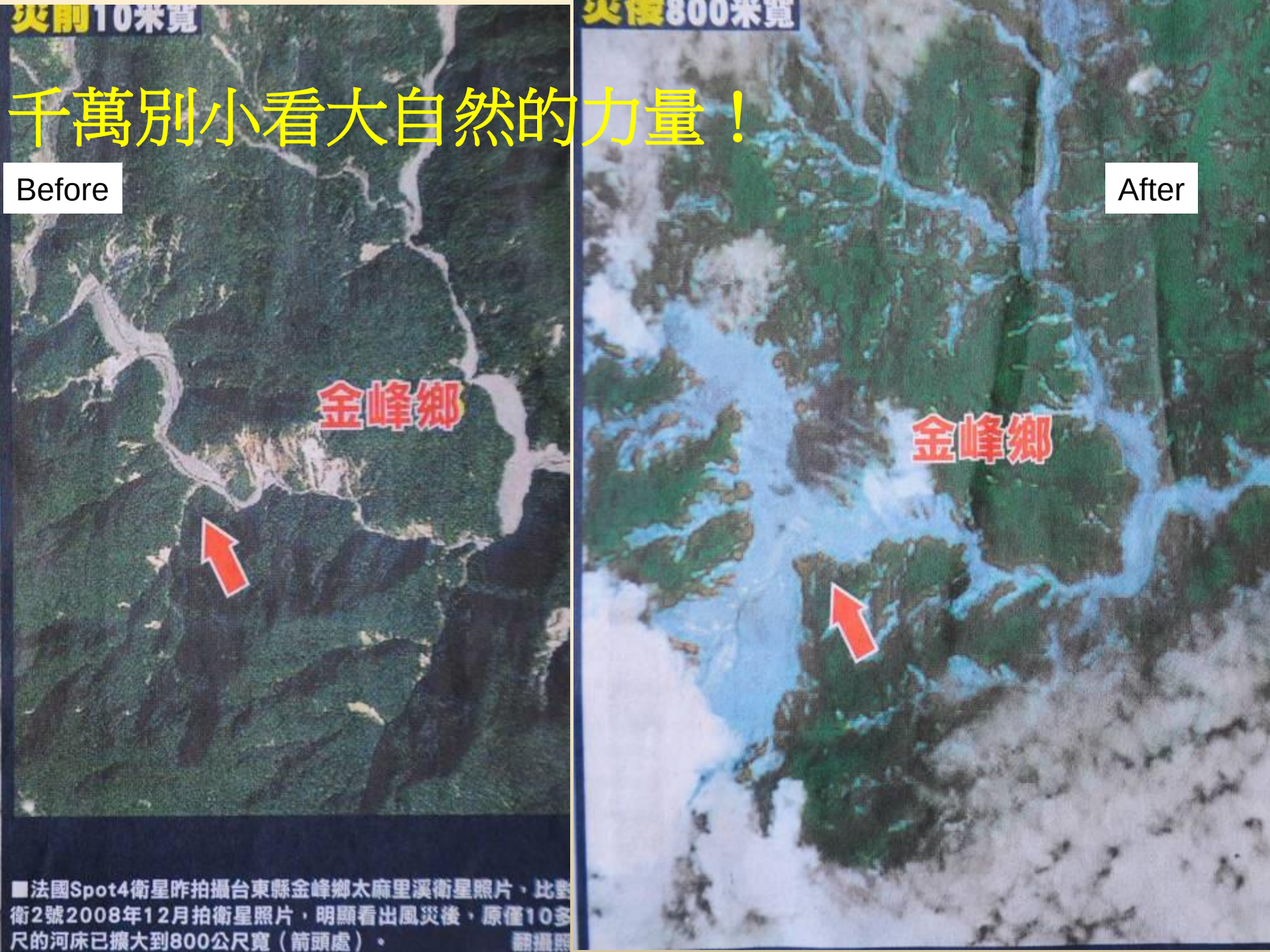
Morakot

- 614 deaths confirmed, 92 still reported as missing.
- More than 1.6 million people evacuated.
- Direct economic loss estimated at US$ 5.3 billion.

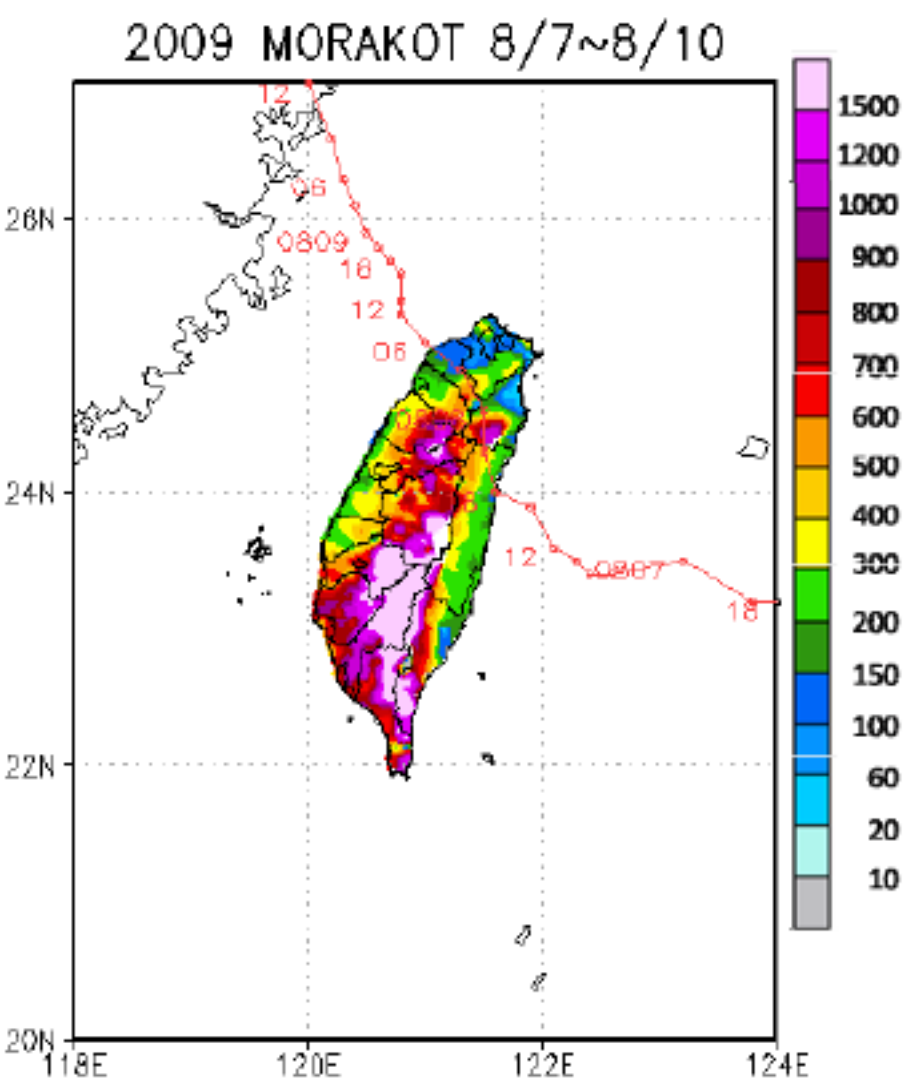
(UN OCHA report) (over Taiwan and mainland China)

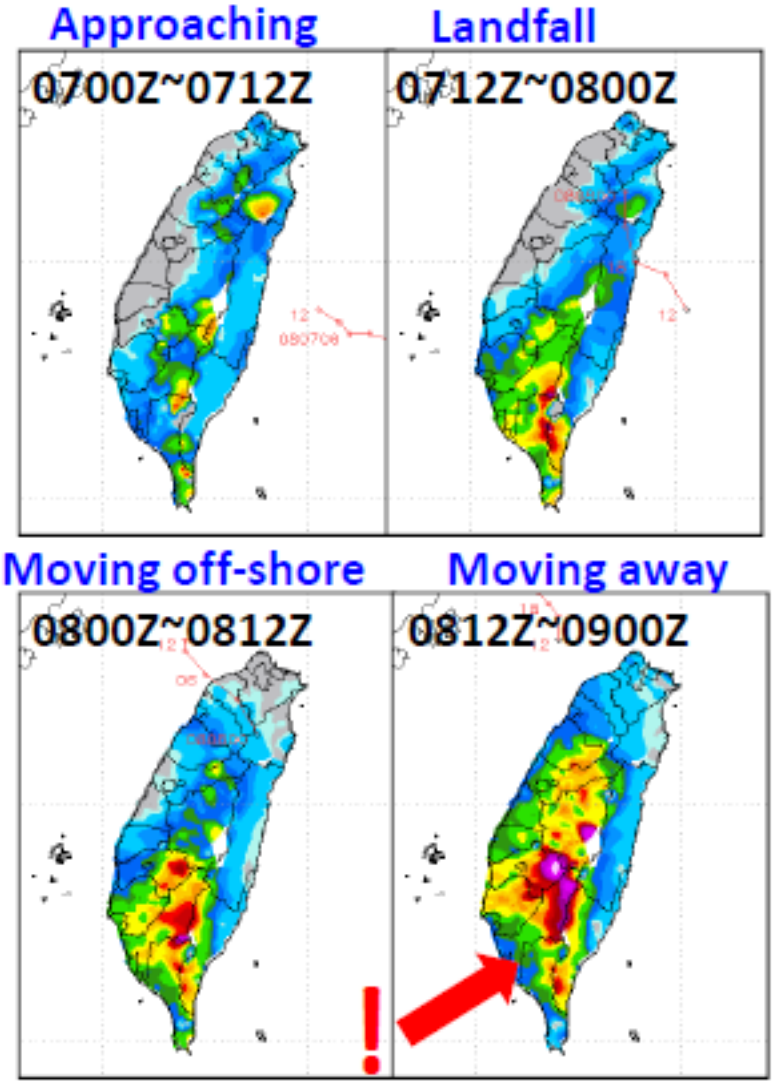
http://itasa2010.files.wordpress.com/2009/08/typhoon_morakot.jpg


HOTEL


災前10米寬
千萬別小看大自然的力量！
Before
金峰鄉
災後800米寬
After
金峰鄉
■法國Spot4衛星昨拍攝台東縣金峰鄉太麻里溪衛星照片，比對
衛2號2008年12月拍衛星照片，明顯看出風災後，原僅10多
尺的河床已擴大到800公尺寬（箭頭處）。
翻攝照

Rainfall during the Morakot period

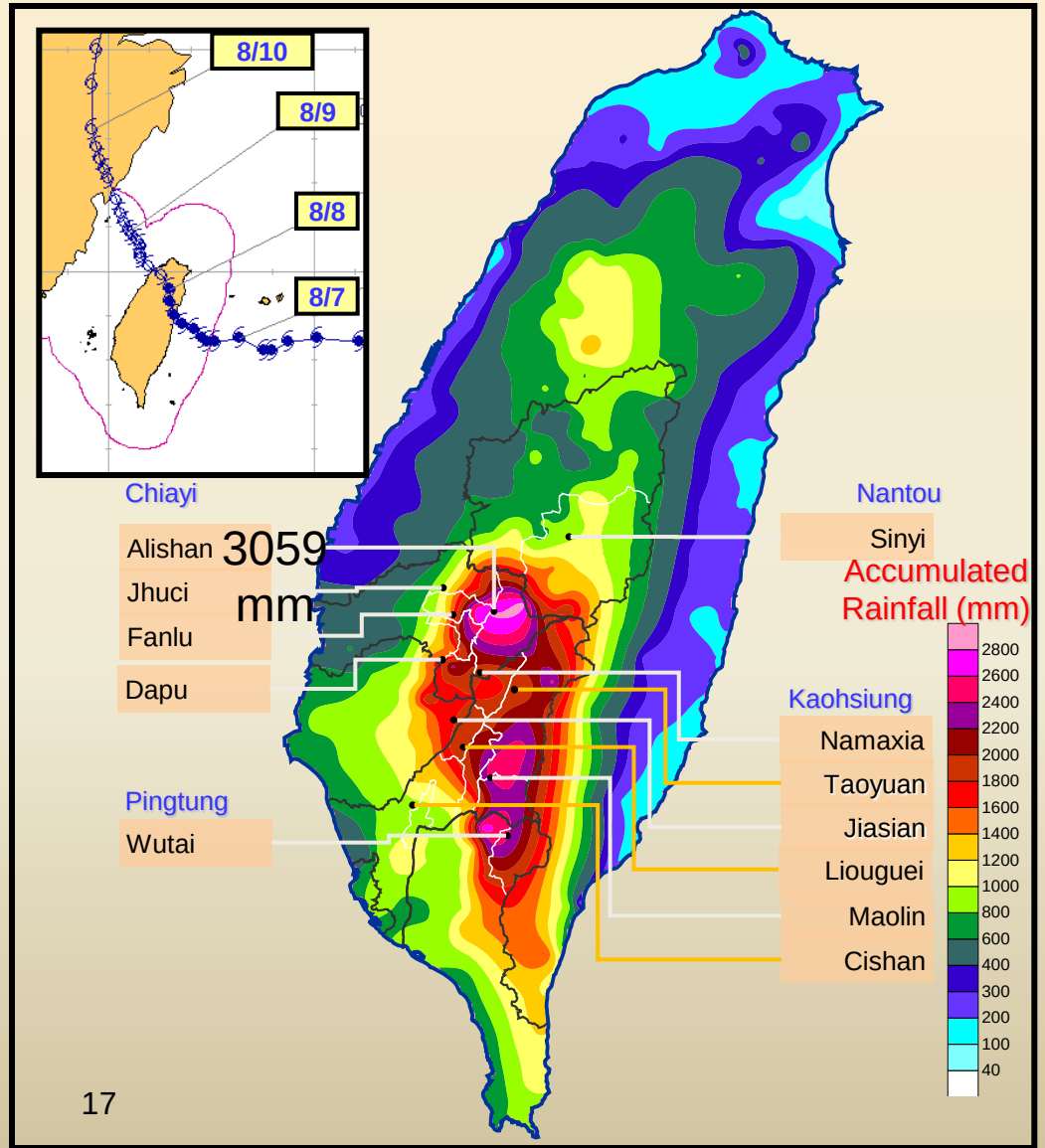




Heaviest rainfall occurred when Morakot was leaving Taiwan.

C.-S. Lee 李清勝教授

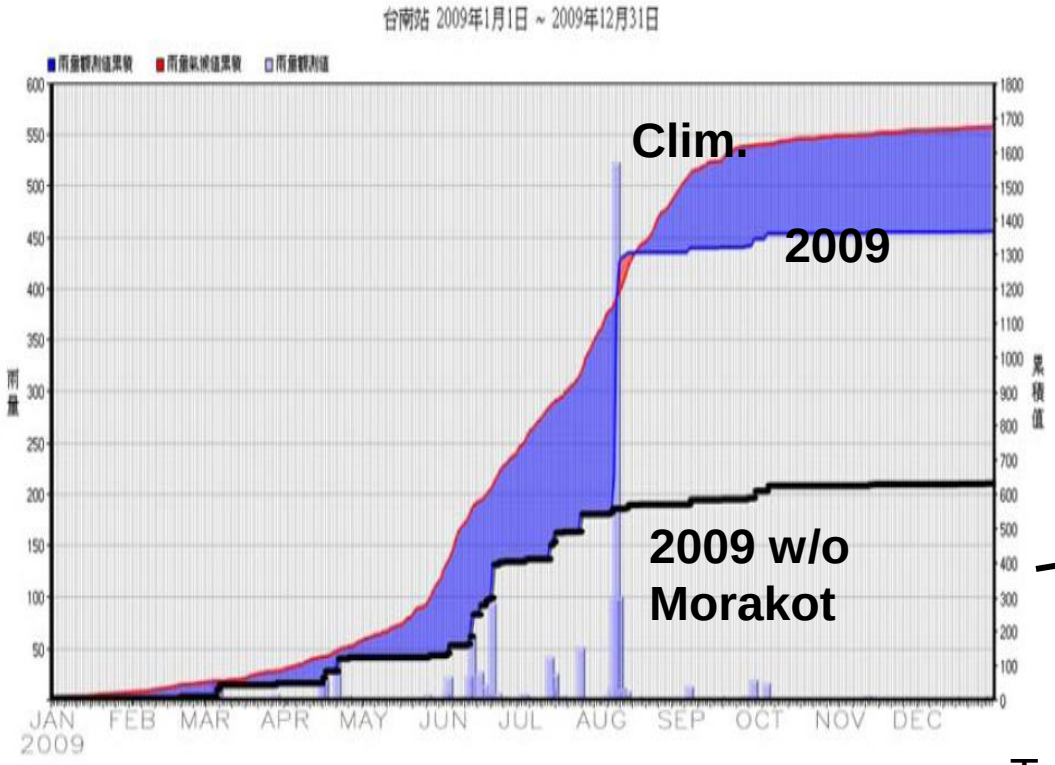
Long duration Record-breaking rainfall

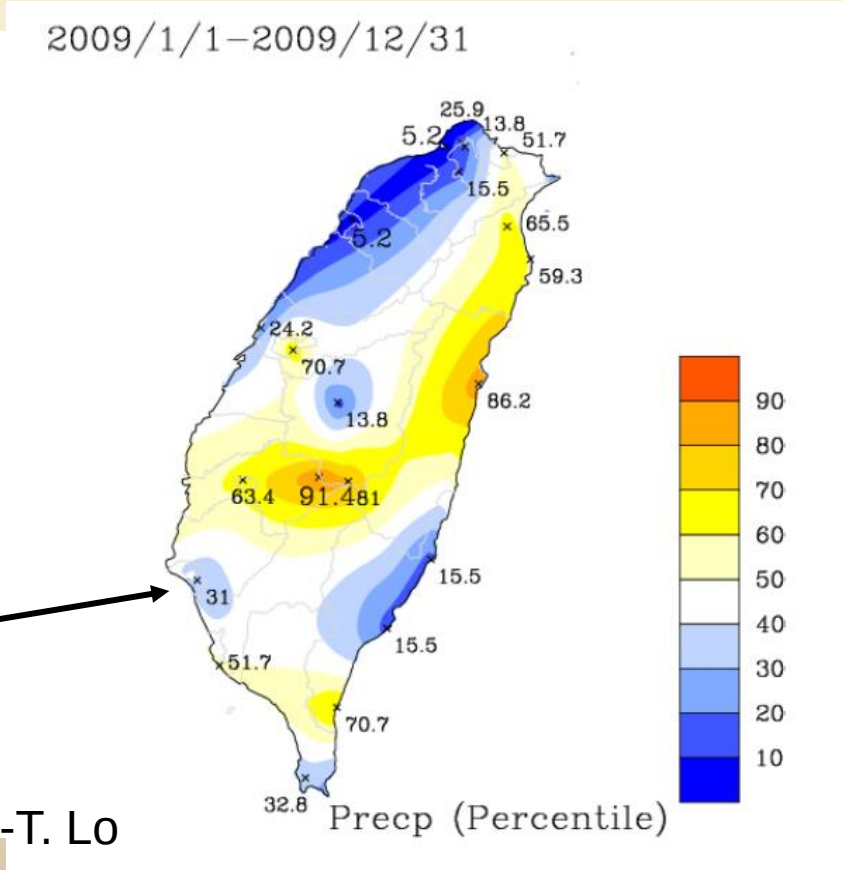


Source: CWB
中央氣象局

Even with the record-breaking rainfall, 2009 annual rainfall is still below average

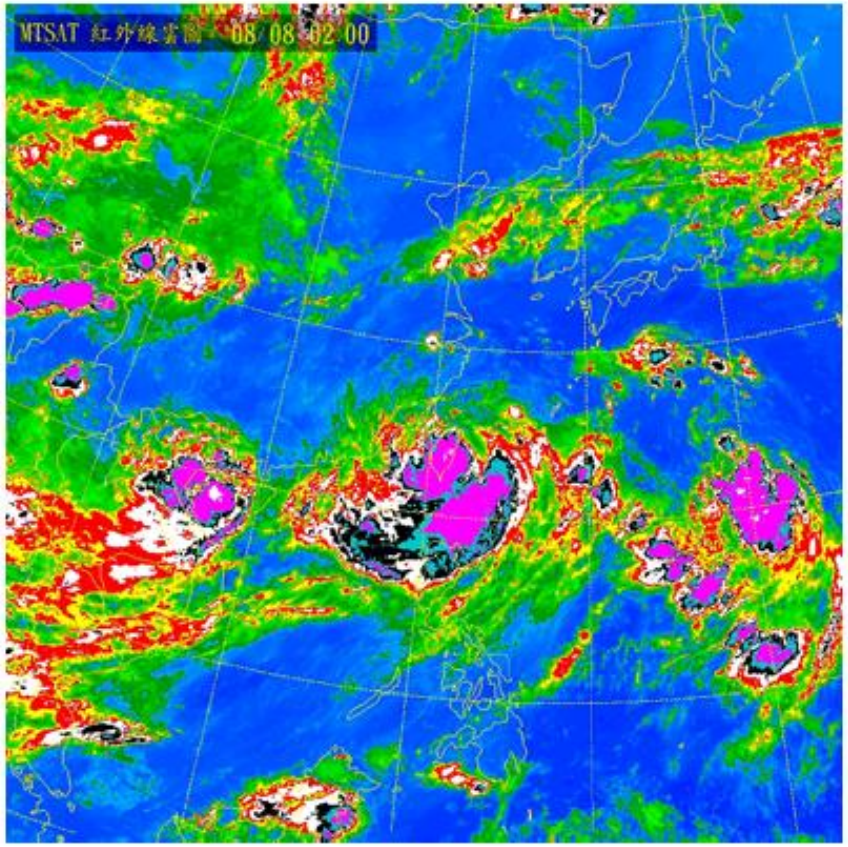
Tainan

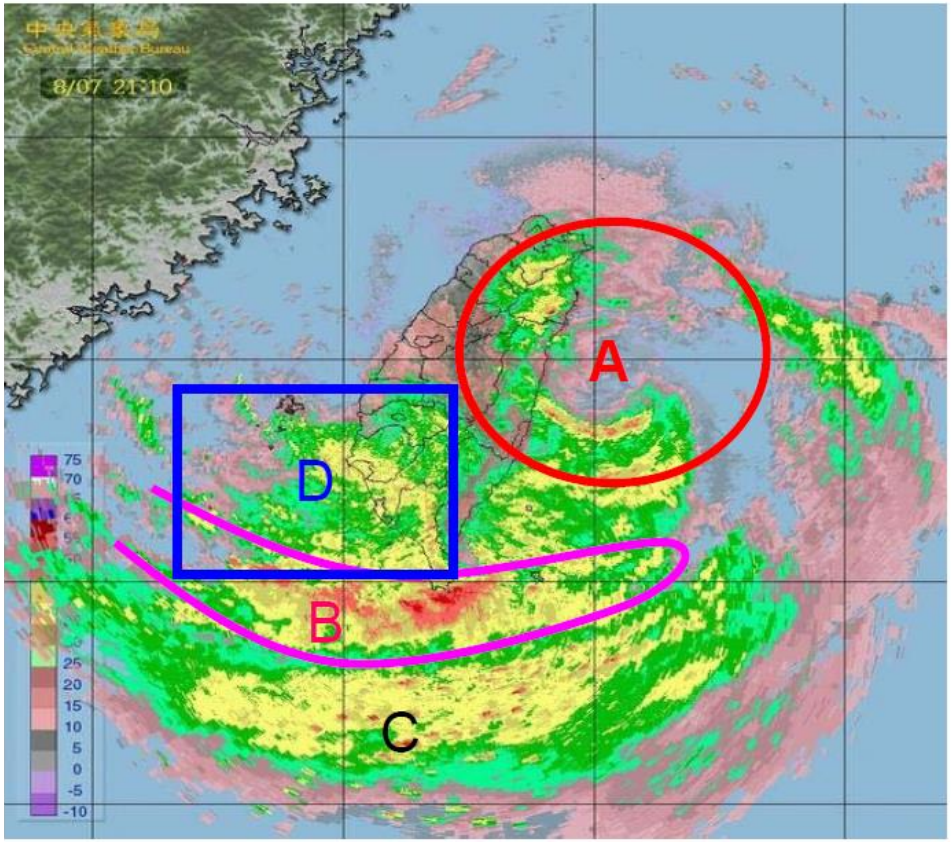




T.-T. Lo

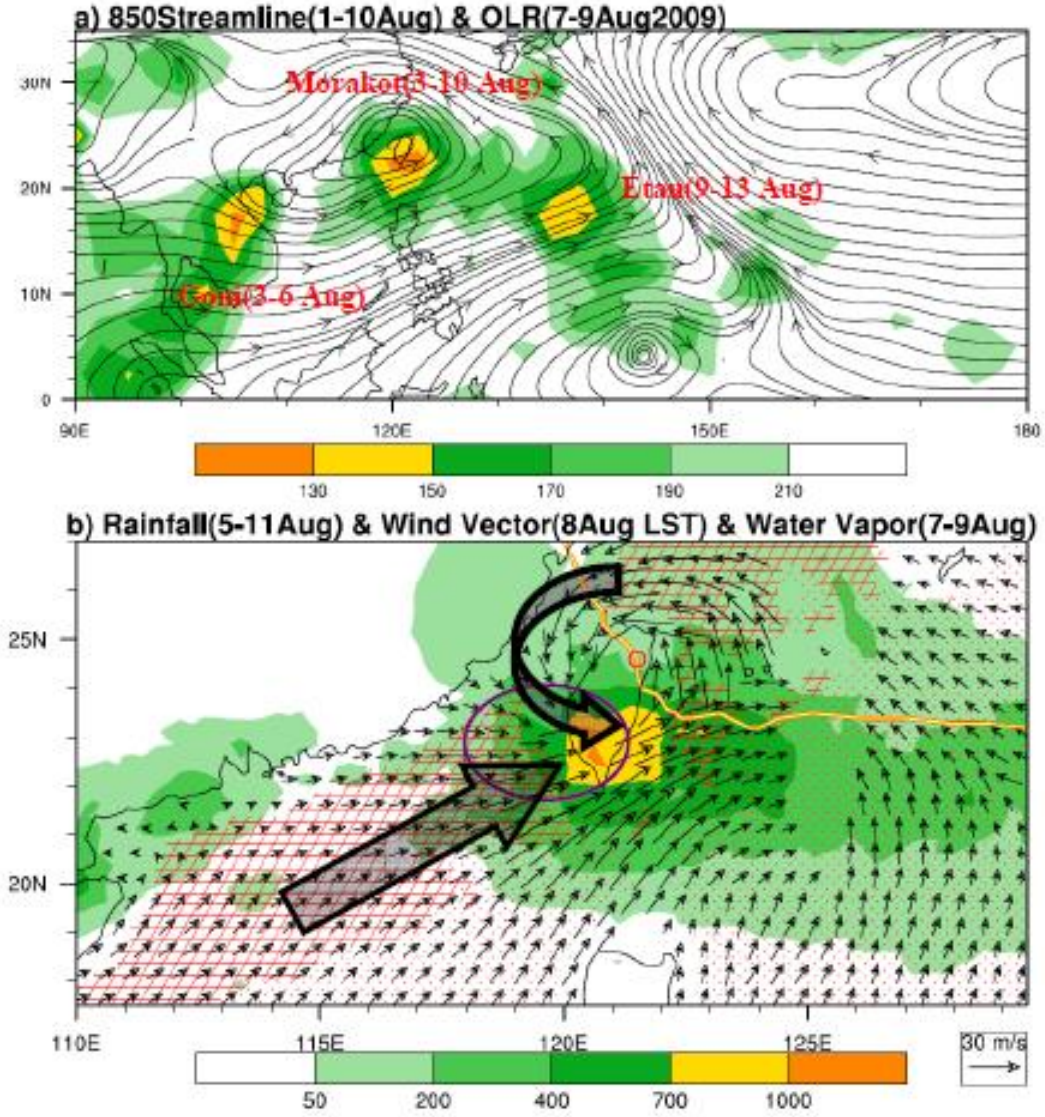
Asymmetric structure embedded with Large-scale convection zone





T.-C. Chen
陳台琦教授

Typhoon Goni, Morakot, and Etau in a Monsoon Gyre, Moist Southwesterly



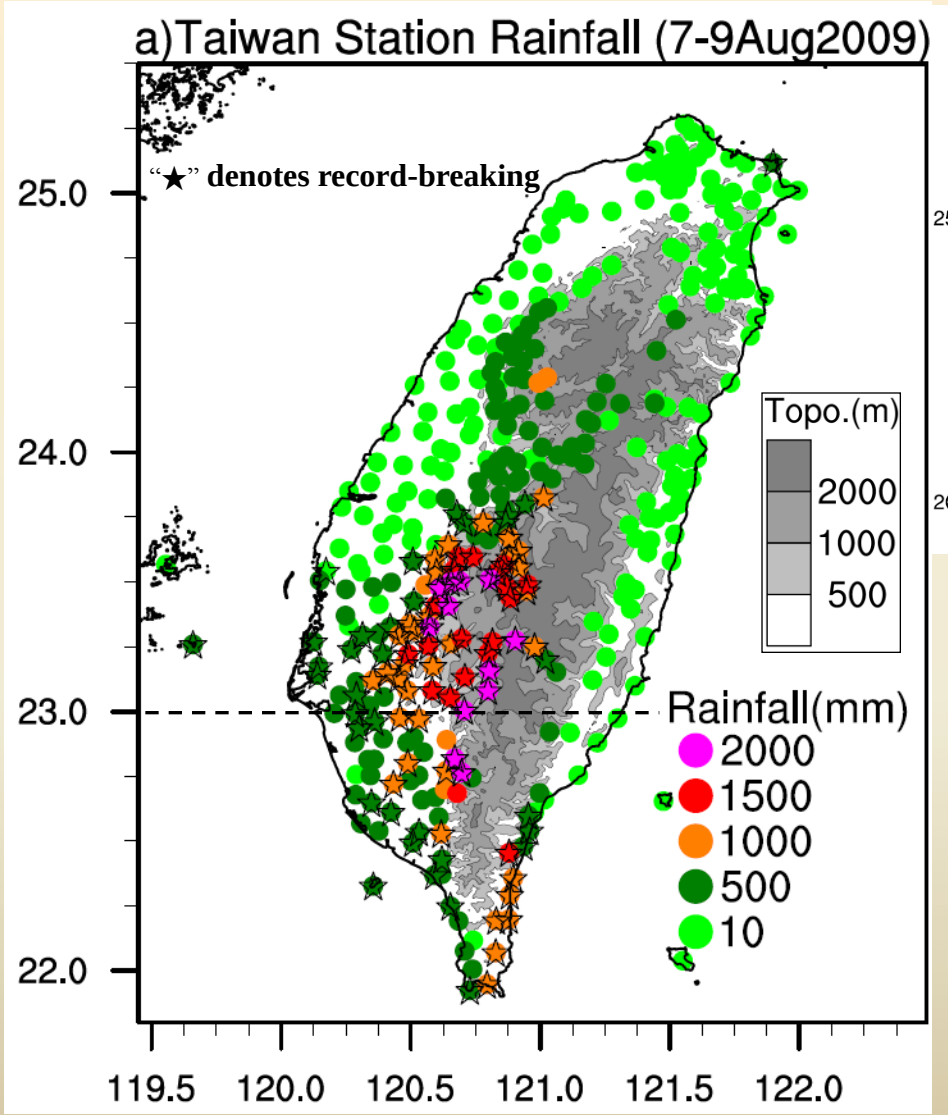
洪志誠 教授

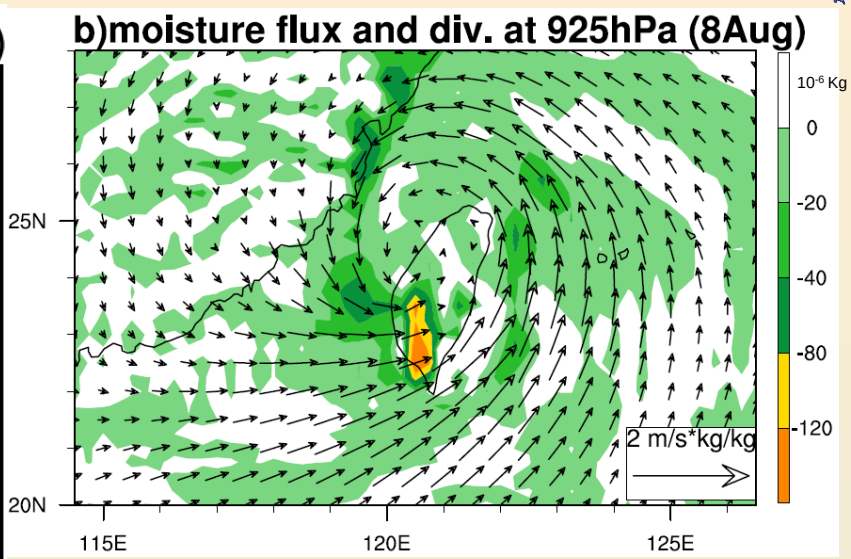
Hong et al., 2010:

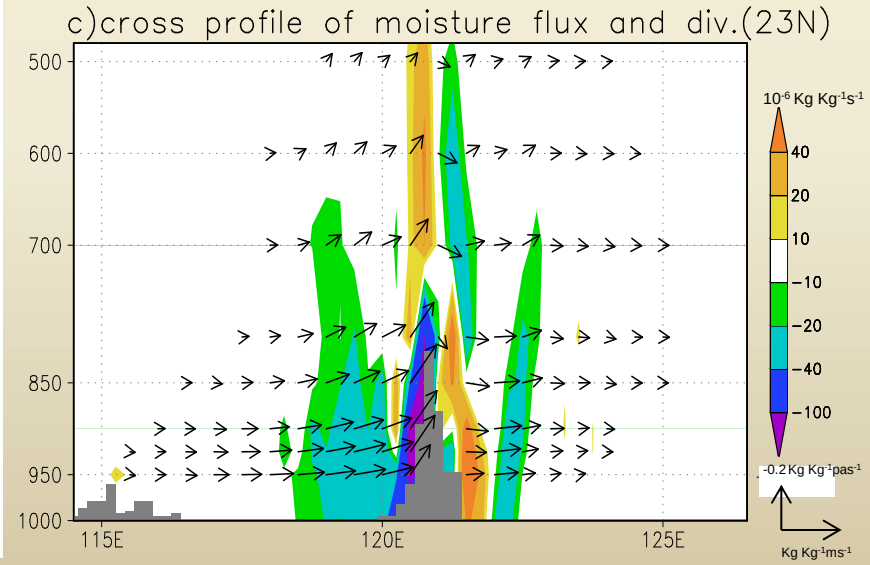
Accepted by

Geophys. Res. Lett.

Convergence between the NW-ly typhoon flow and SW-ly monsoon flow
Monsoon & Terrain Effect







H.-H. Hsu 許晃雄 教授

Multiscale: 40-50 day ISO
10-30 day perturbation, and typhoon

2009/7/20~2009/8/18 850hPa UV (vector) & q (shaded)

Wavelet analysis

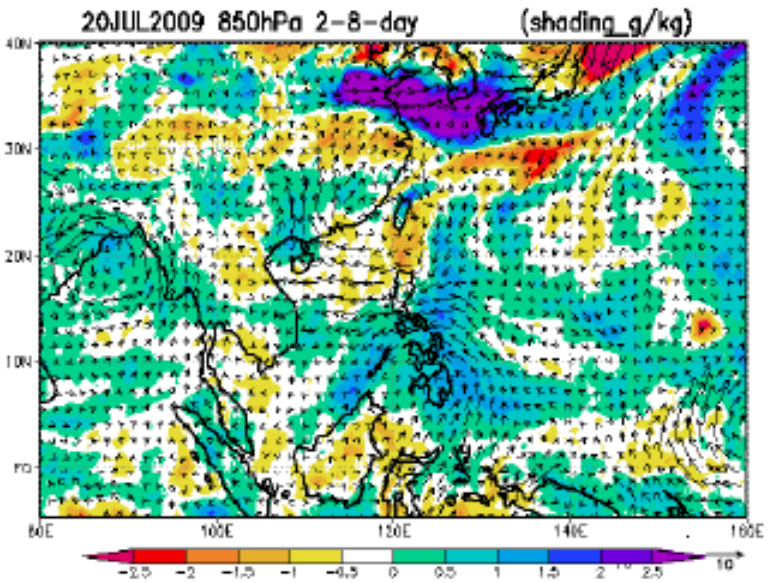
2-8 days → TC

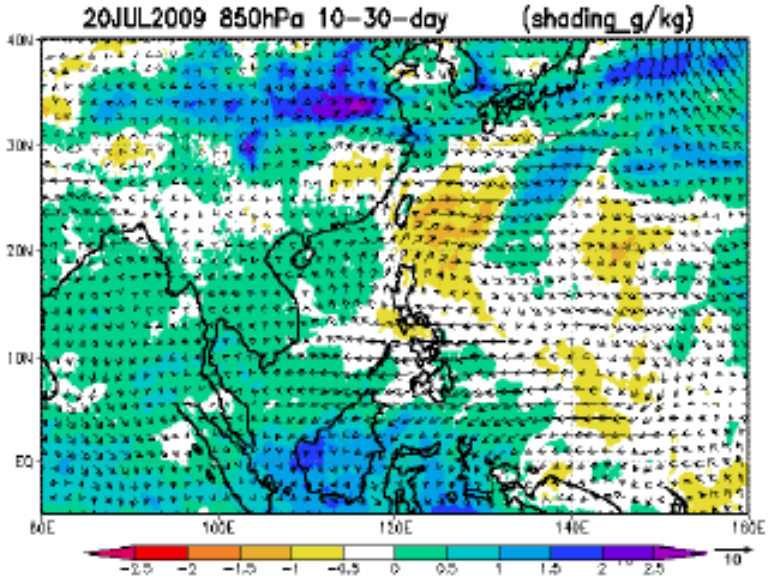
10-30 days → submonthly wave

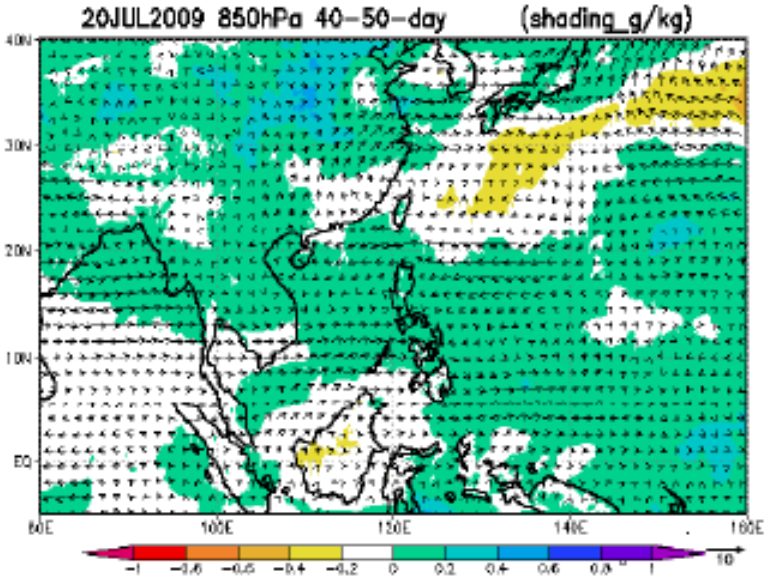
40-50 days → ISO

Hong et al. 2010

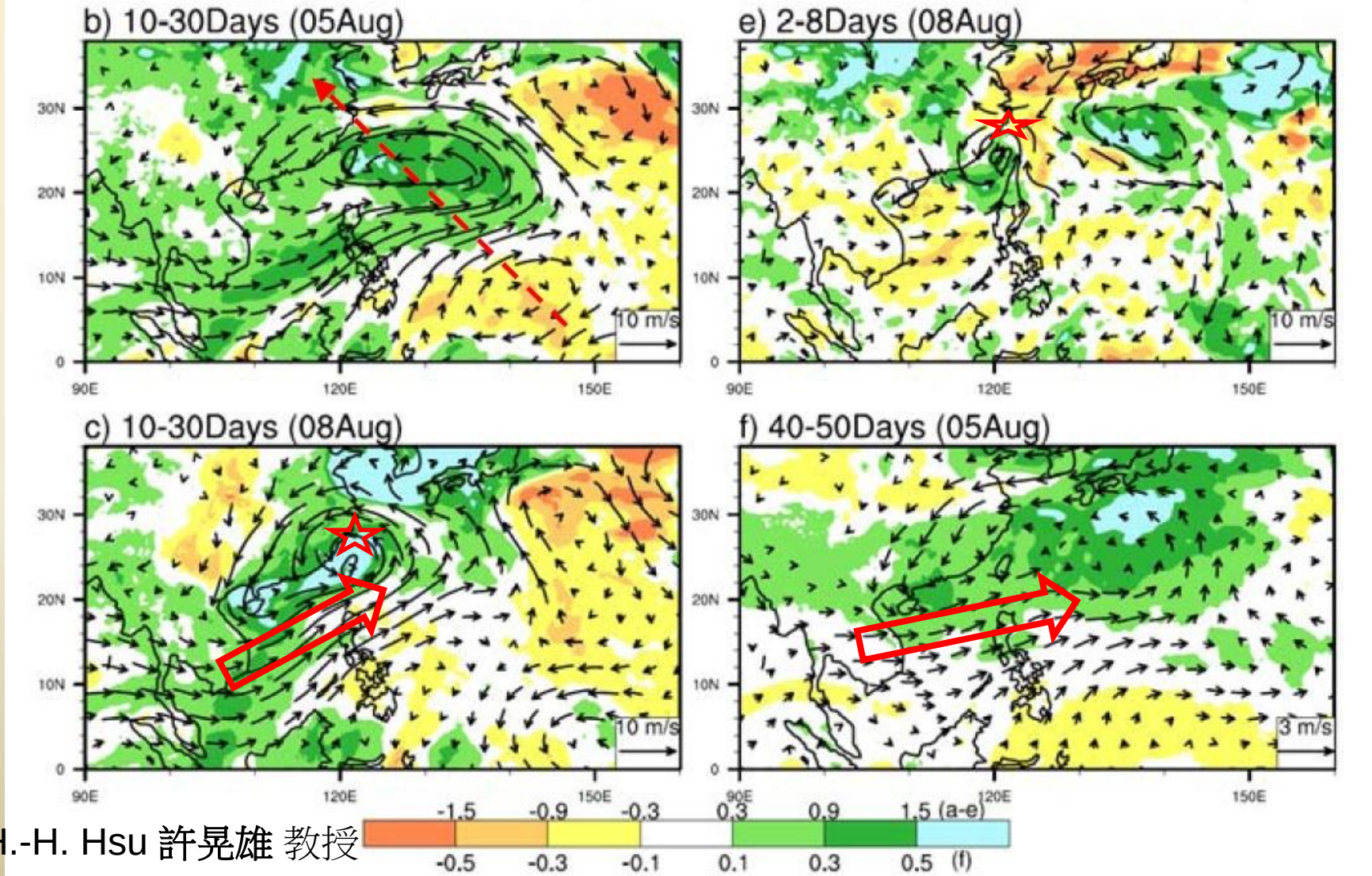
• 10-30 days : contributes the largest amount of moisture







40-50 day ISO provides water vapor channel from the Indian Ocean/South China Sea, transporting moisture into Typhoon Morakot



H.-H. Hsu 許晃雄 教授

Background Summary

- Morakot's landfall on Taiwan occurred concurrently with the **southwesterly monsoonal flow**, **very slow TC movement** **and the continuous formation of mesoscale convection**. (Chien and Kuo 2011; JGR)
- The terrain of Taiwan strongly determines Morakot's **rainfall distribution** at the time of landfall. (Fang et al. 2011 in WAF; Huang et al. 2011 and Yen et al. 2011 in TAO)
- **PE** (Precipitation Efficiency) was used to predict rainfall from grid-scale vapor convergence in operational model forecasts (Doswell et al. 1996; Auer and Marwitz 1968; Heymsfield and Schotz 1985; Chong and Hauser 1989; Li et al. 2002a; Tao et al. 2004; Sui et al. 2005).
- Yang et al. (2011; MWR) investigates the evolution of the **water vapor, cloud, and precipitation budgets** of Nari (2001) prio to and after landfall on Taiwan.
- The water budget study may help us to understand the basic **physical mechanisms** producing the **heavy rainfall on Taiwan** for Morakot, and improve the microphysical parameterization for TCs in the future.

Budget Equations

[Gamache et al. (1992), Braun (2006), Yang et al. (2011)]

Water vapor budget: q_v

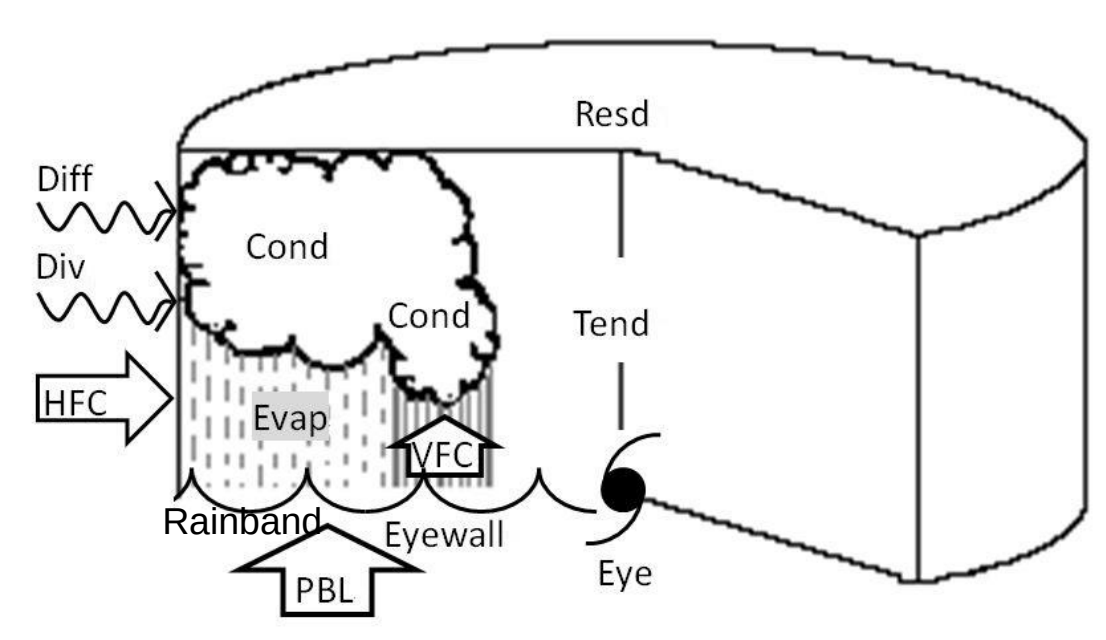
$$\text{Tend} = \text{HFC} + \text{VFC} + \text{Div} + \text{Diff} + \text{Cond}_\text{T} + \text{Evap} + \text{PBL} + \text{Resd.}$$

Cloud budget: $q_c = q_w + q_i$

$$\text{Tend} = \text{HFC} + \text{VFC} + \text{Div} + \text{Diff} + \text{P} - \text{Cond}_\text{T} - \text{Evap} + \text{PBL} + \text{Resd.}$$

where Cond_T is the total condensation and deposition;
Evap is the evaporation and sublimation;
HFC is the net horizontal flux convergence;
VFC is the vertical flux convergence;
Div is the divergence term
Diff is the numerical diffusion
PBL is the boundary layer source and vertical (turbulent) diffusion
P is the precipitation flux
Resd is the residual term

Conceptual Model for TC Water Budget

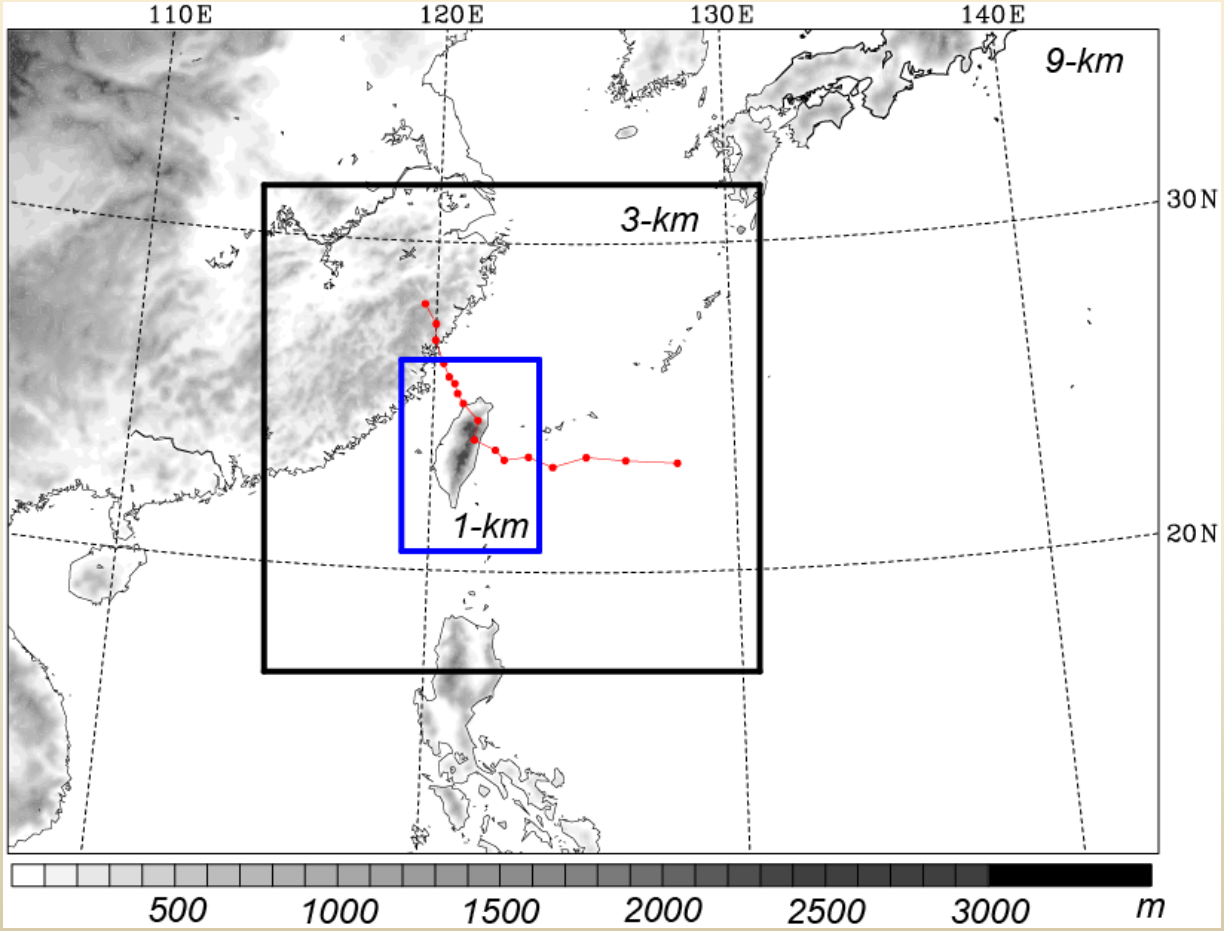


CMPE (Cloud Microphysics Precipitation Efficiency; CMPE2, Sui et al. 2007):

$$PE = P/Cond_T = P/[SI_{qv} + sgn(Q_{CM})Q_{CM}]$$

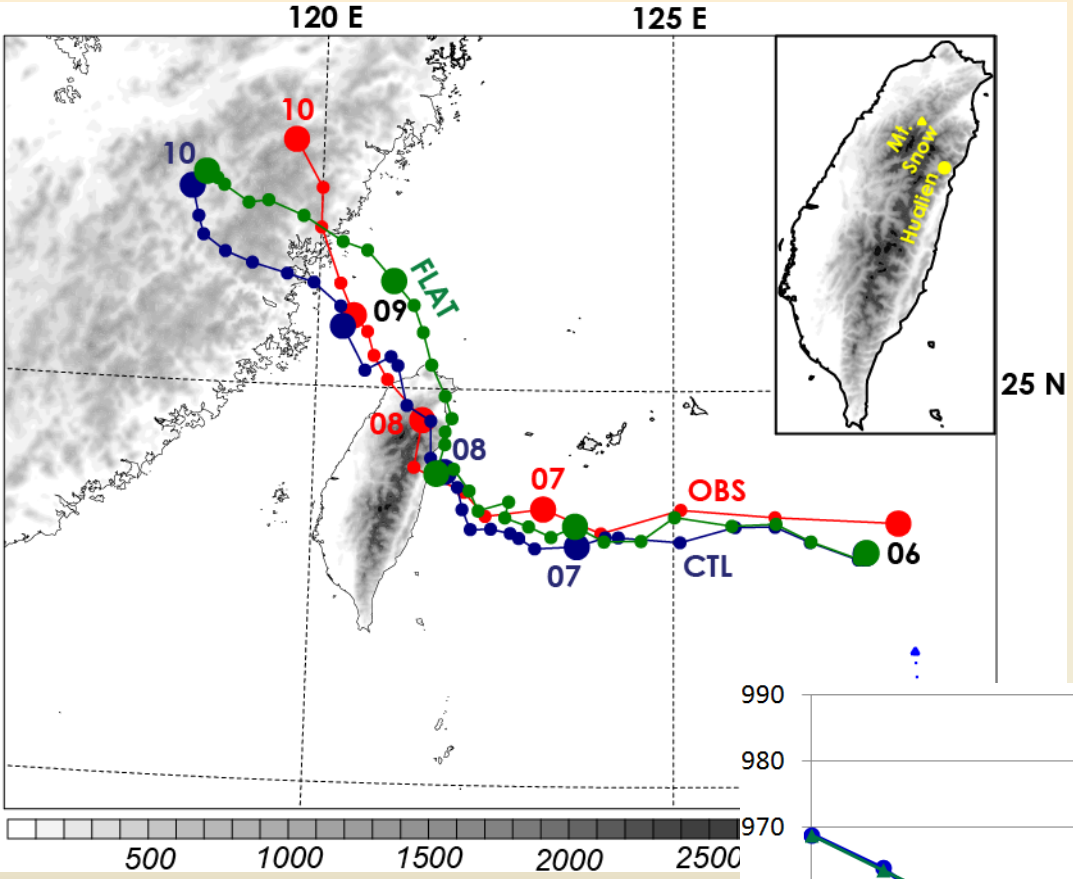
WRF domain and physics for Morakot Simulation

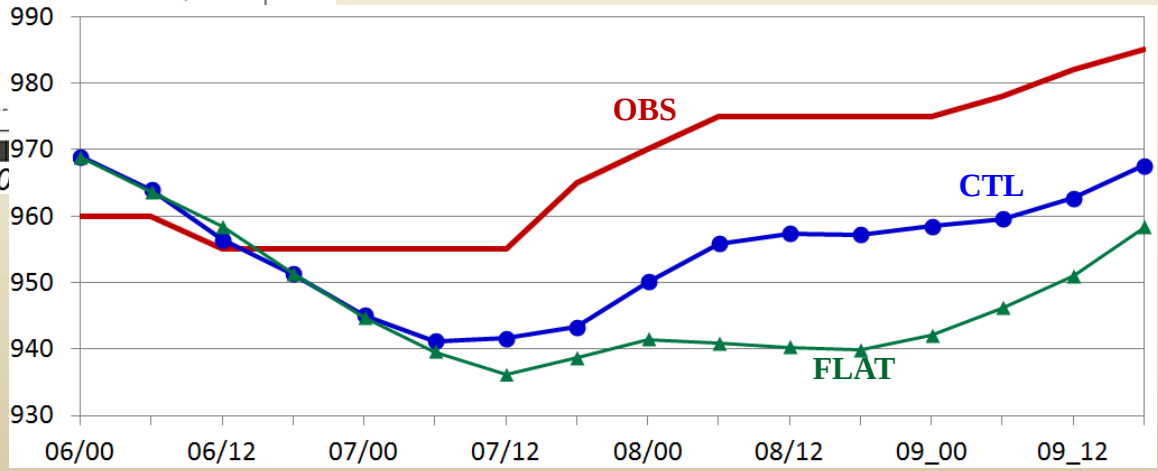
- 9/3/1 km (416x301 / 541x535/ 451x628)



- ✓ 31 sigma (σ) levels
- ✓ Two-way feedbacks
- ✓ **No CPS is used**
- ✓ WRF Single-Moment 6-class scheme (WSM6)
- ✓ YSU PBL scheme
- ✓ IC/BC: ECMWF 1.125° lat/lon
- ✓ Initial time: 0000 UTC, 6 Aug 2009
- ✓ Integration length: 96 h

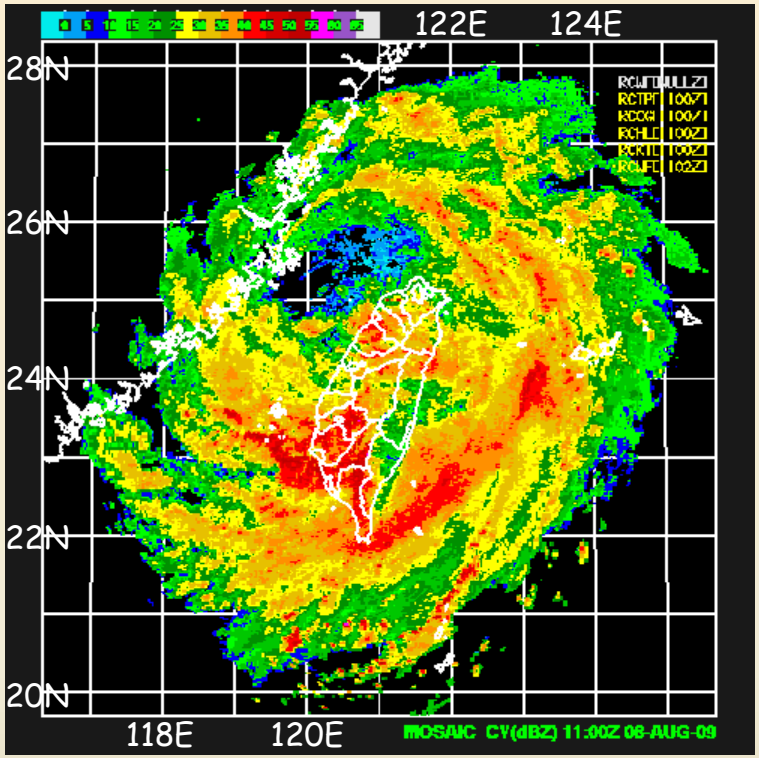
Tracks from the CWB (OBS) and WRF (CTL/FLAT)



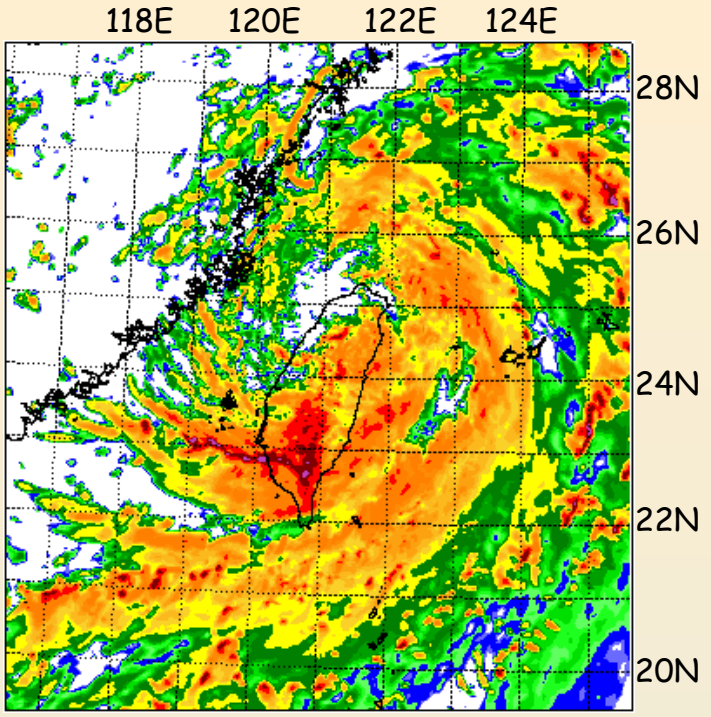


08/08/11 UTC

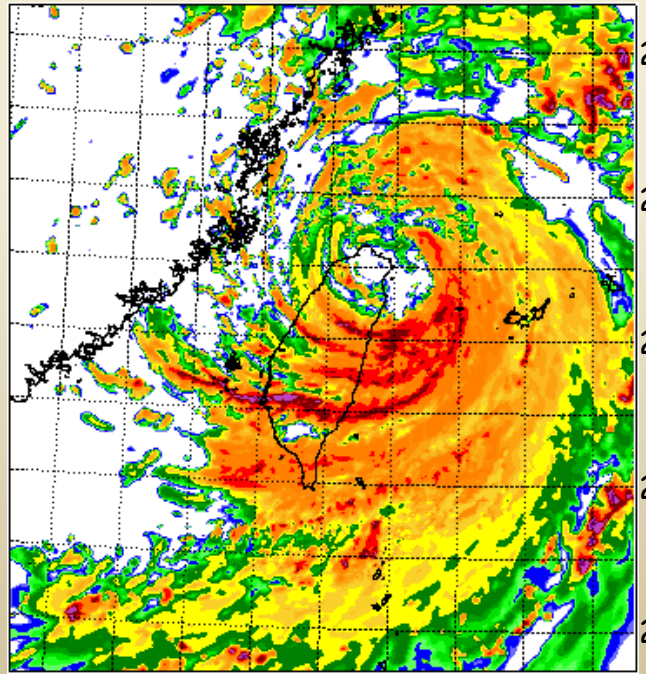
OBS @ CWB



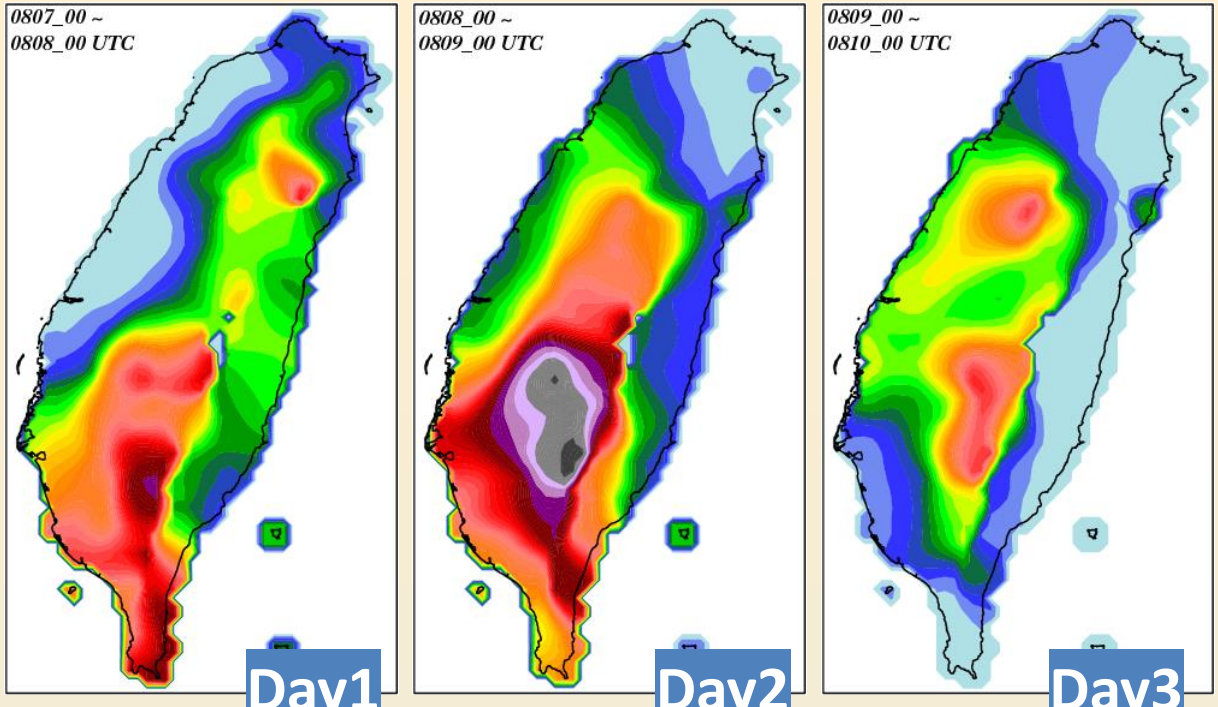
CTL



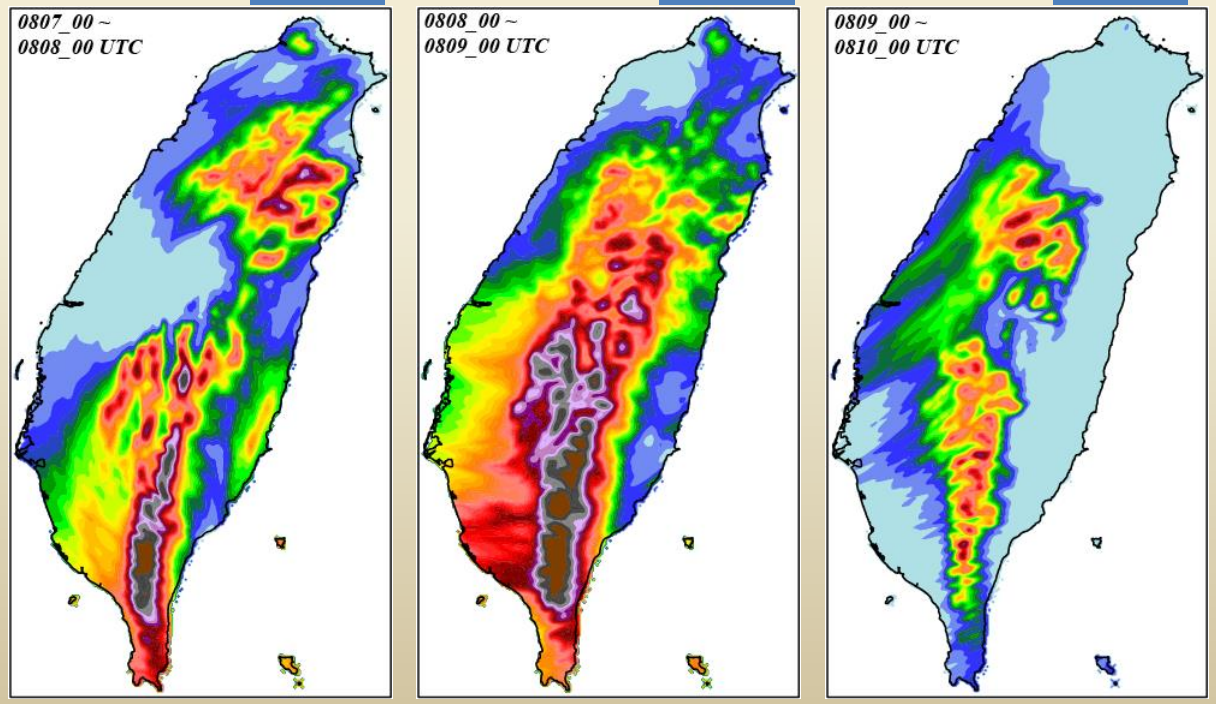
FLAT

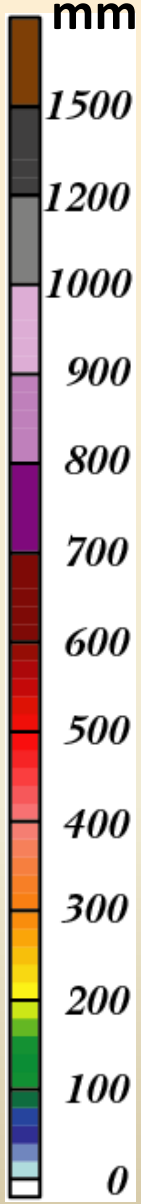


CWB:
OBS

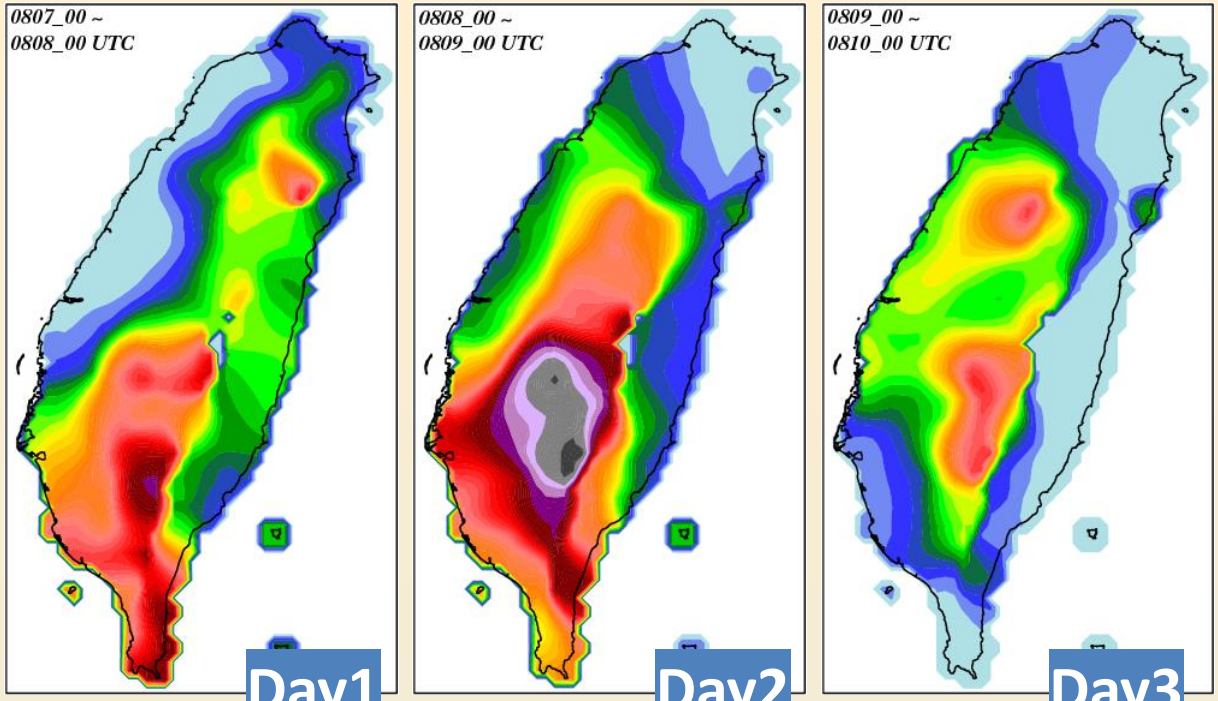


WRF:
CTL

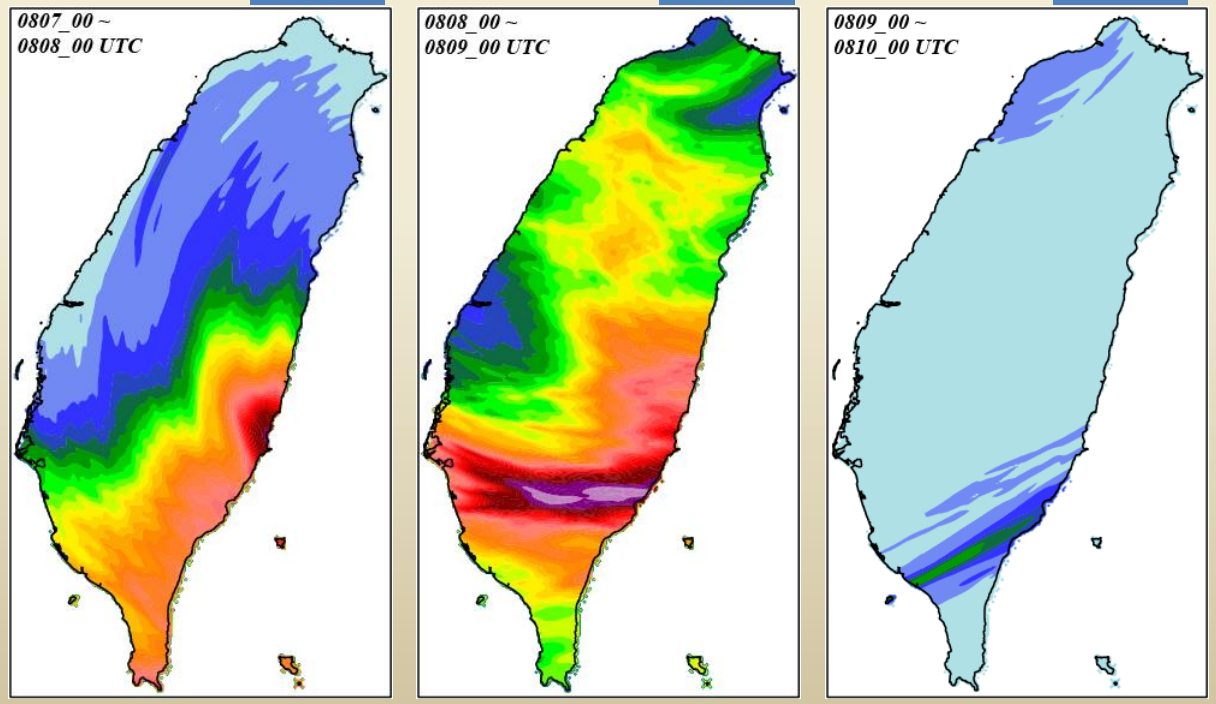


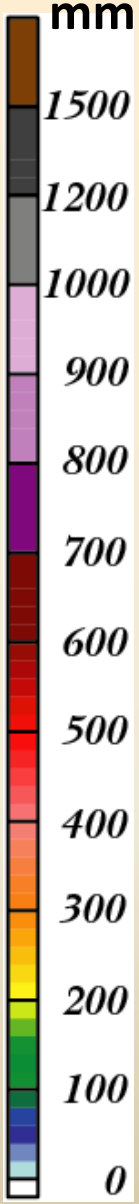


CWB:
OBS



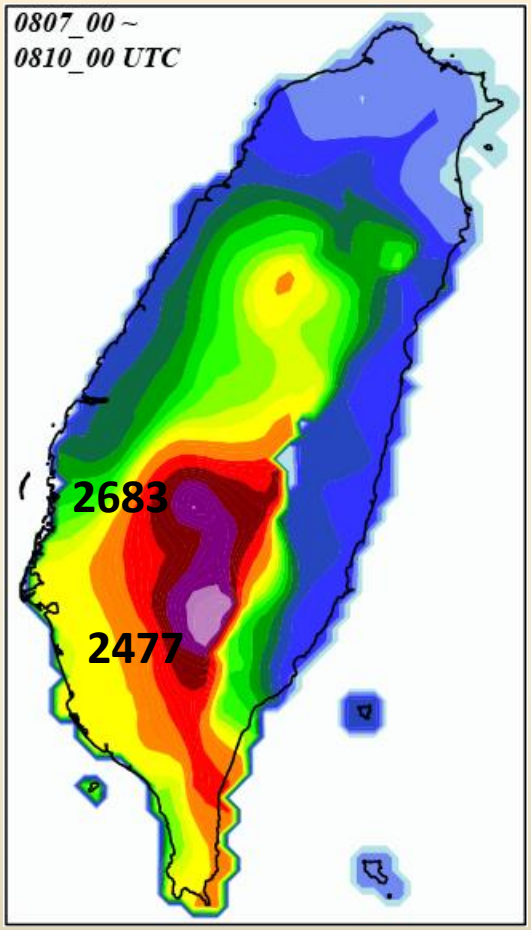
WRF:
FLAT



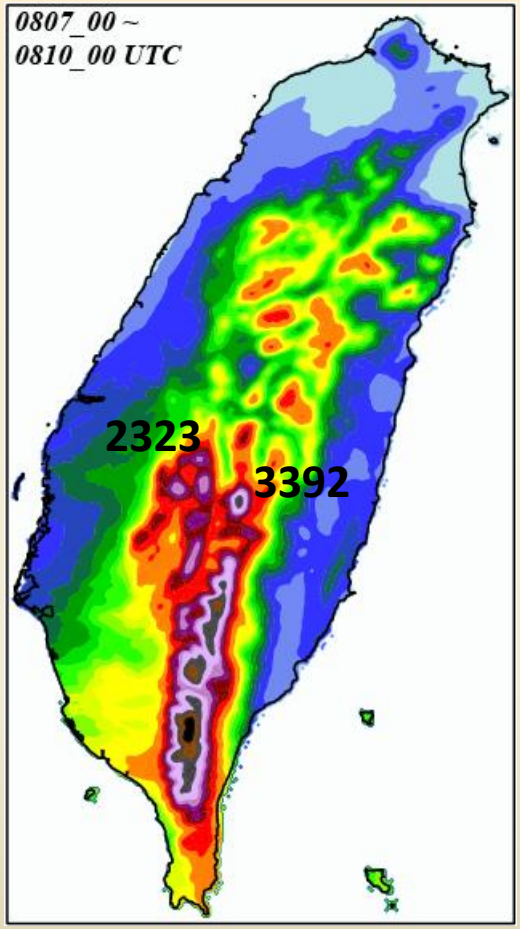


72-h Rainfall (08/07/00 ~ 08/10/00 UTC)

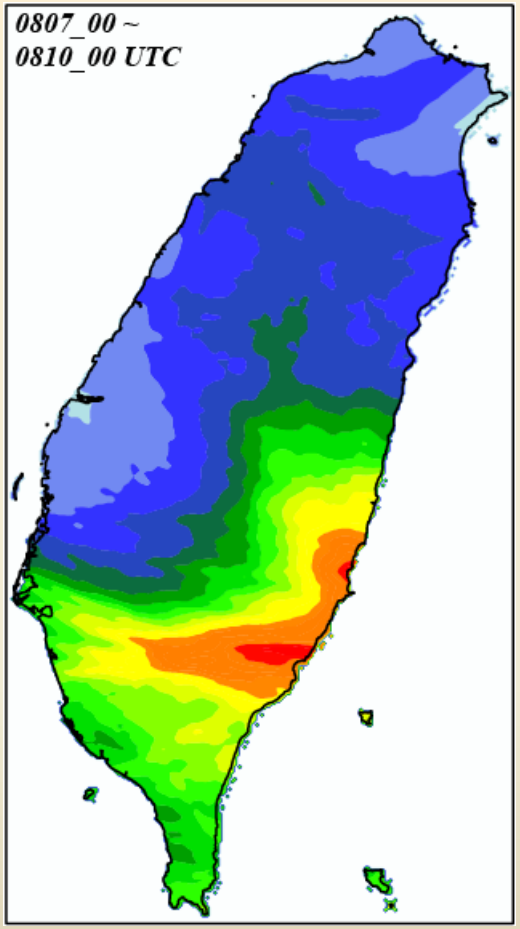
CWB_OBS

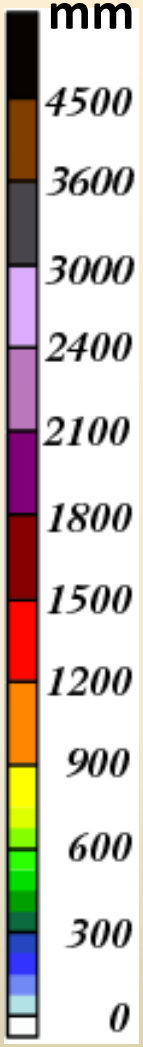


WRF_CTL

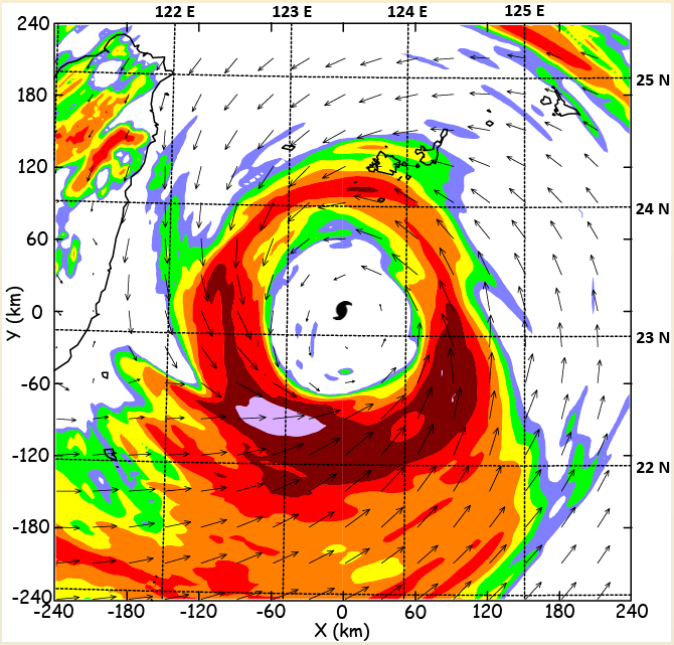


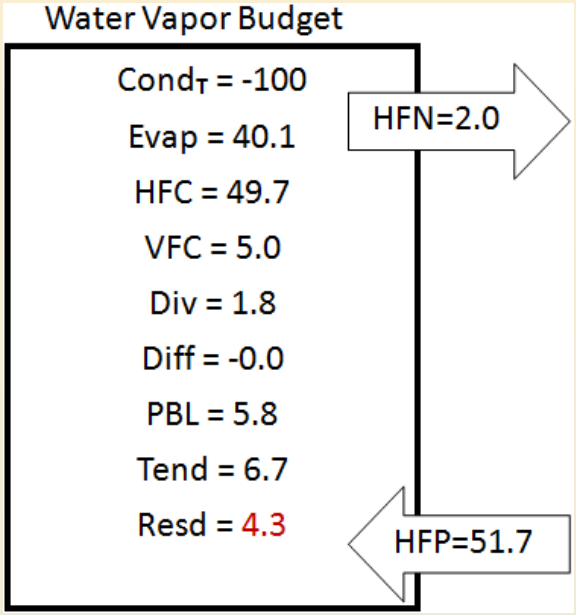
WRF_FLAT

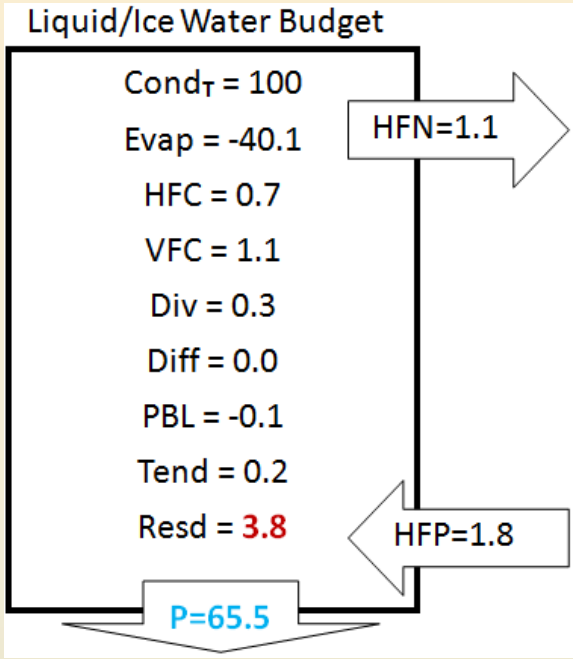


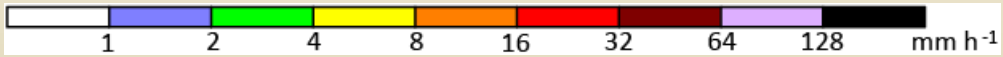


Oceanic Stage (0000 ~ 0100 UTC 7 August 2009) within the TC vortex circulation





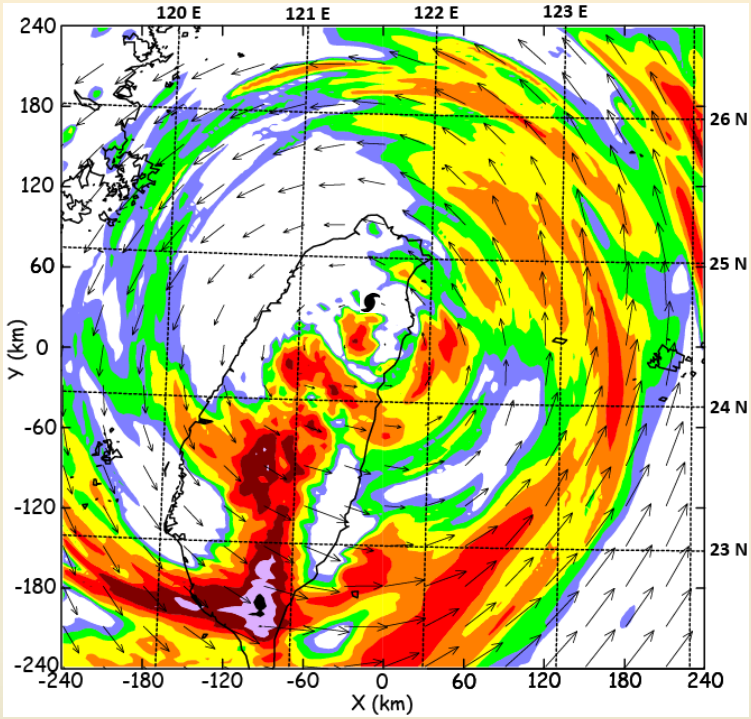


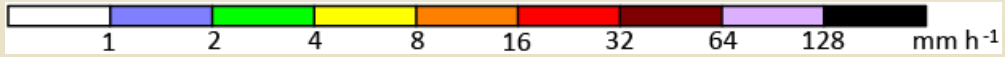


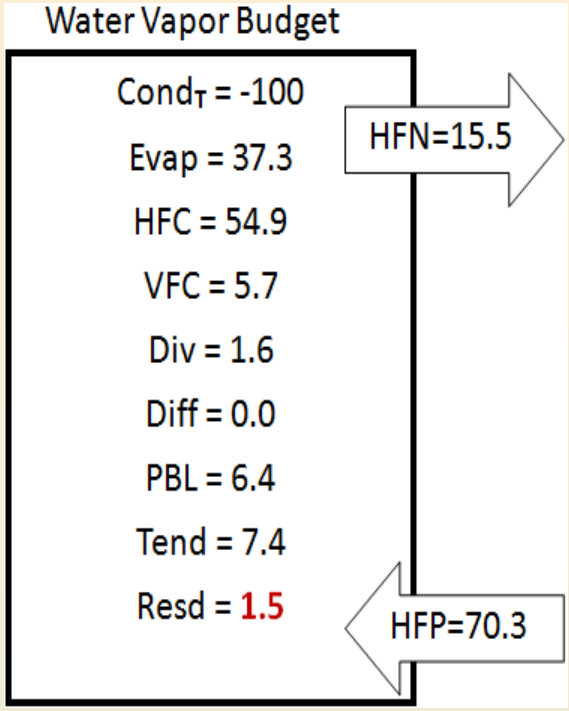
Water Vapor Budget: $\text{Tend} = \text{HFC} + \text{VFC} + \text{Div} + \text{Diff} + \text{Cond}_T + \text{Evap} + \text{PBL} + \text{Resd.}$

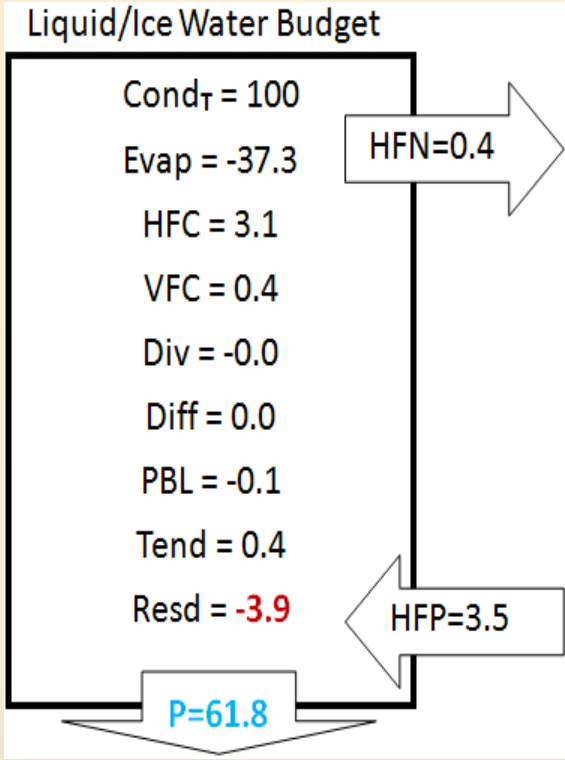
Liquid/Ice Water Budget: $\text{Tend} = \text{HFC} + \text{VFC} + \text{Div} + \text{Diff} + \text{P} - \text{Cond}_T - \text{Evap} + \text{PBL} + \text{Resd.}$

Landfall Stage (00730 ~ 0830 UTC 8 August 2009) within the TC vortex circulation



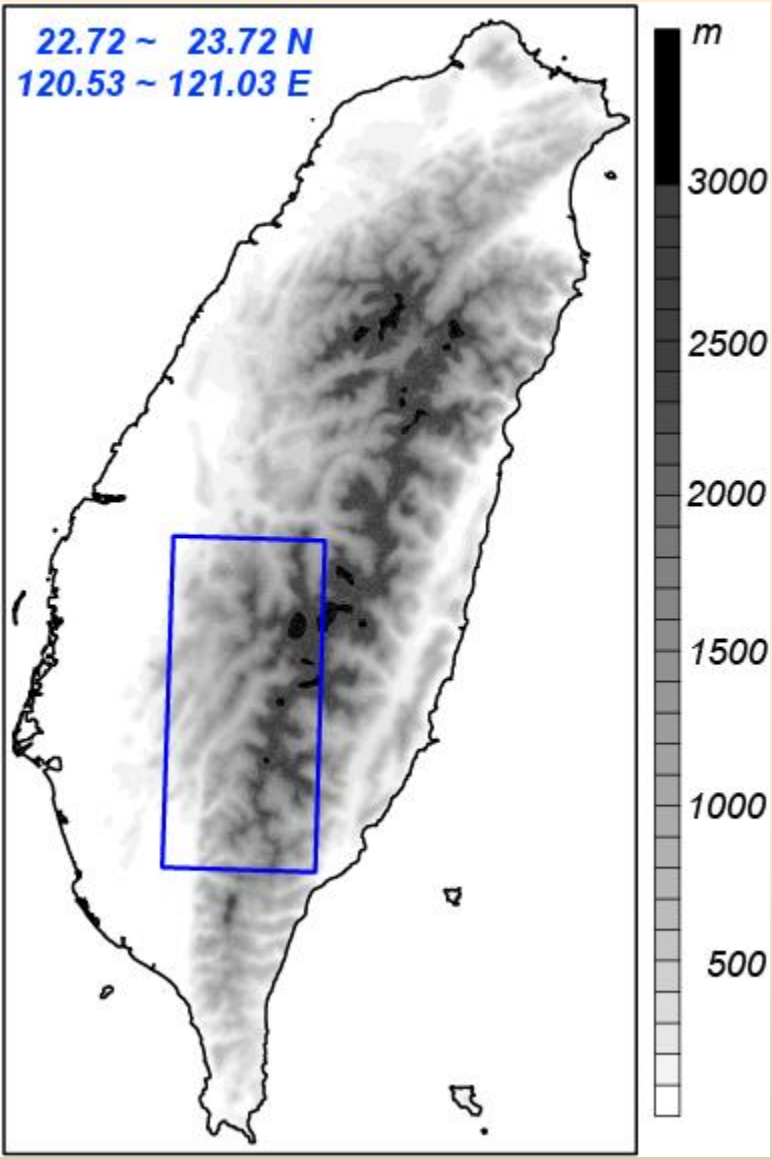




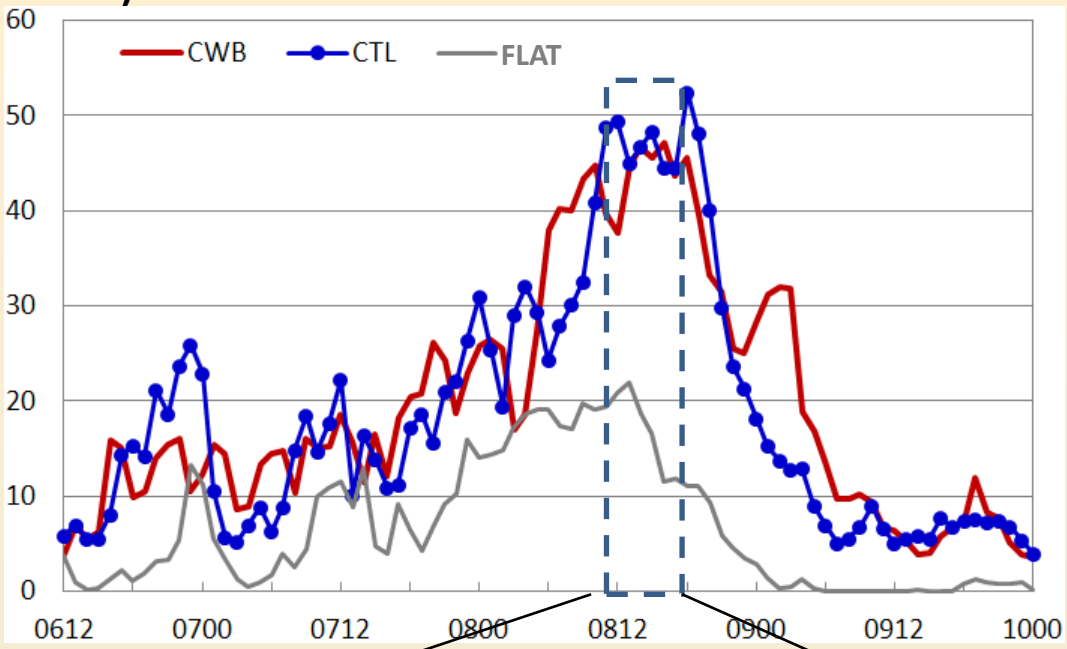


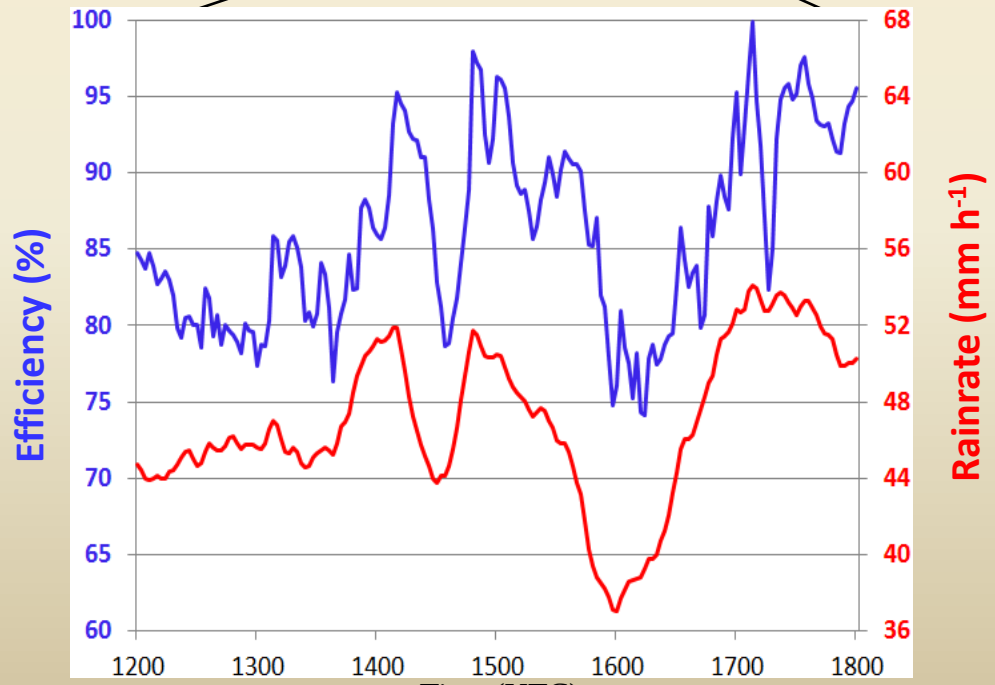
Water Vapor Budget: $\text{Tend} = \text{HFC} + \text{VFC} + \text{Div} + \text{Diff} + \text{Cond}_T + \text{Evap} + \text{PBL} + \text{Resd.}$

Liquid/Ice Water Budget: $\text{Tend} = \text{HFC} + \text{VFC} + \text{Div} + \text{Diff} + \text{P} - \text{Cond}_T - \text{Evap} + \text{PBL} + \text{Resd.}$

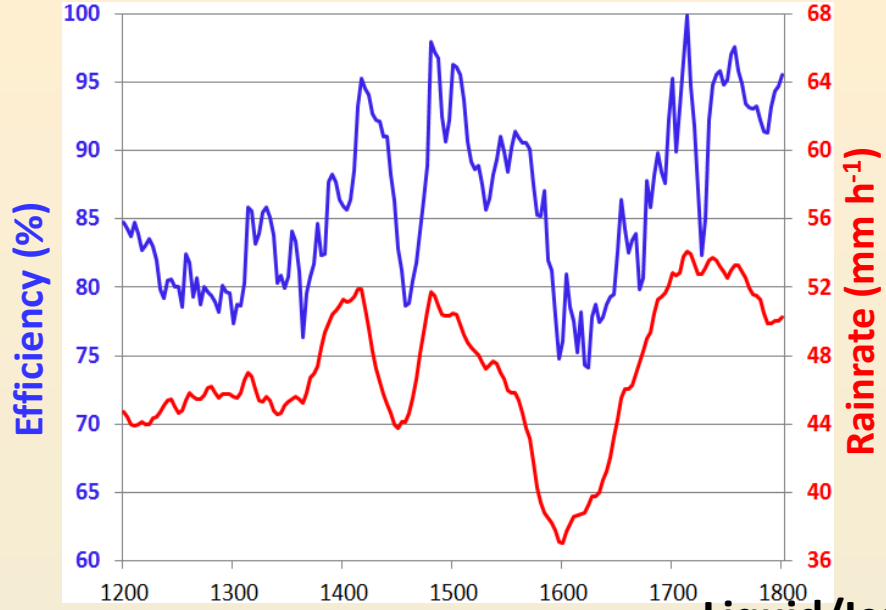

22.72 ~ 23.72 N
120.53 ~ 121.03 E
m
3000
2500
2000
1500
1000
500

(mm h^{-1})

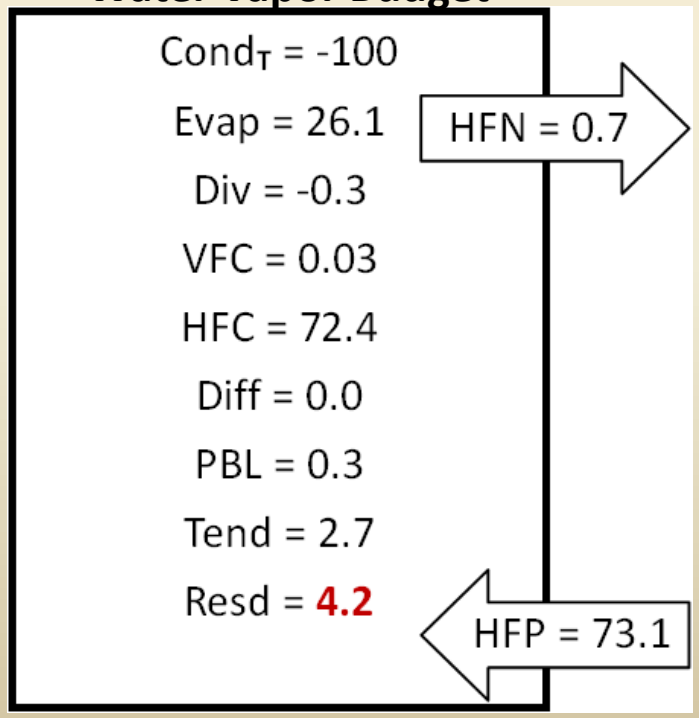

CWB
CTL
FLAT
60
50
40
30
20
10
0
0612
0700
0712
0800
0812
0900
0912
1000


Efficiency (%)
Rainrate (mm h-1)
100
95
90
85
80
75
70
65
60
68
64
60
56
52
48
44
40
36
1200
1300
1400
1500
1600
1700
1800
Time (UTC)

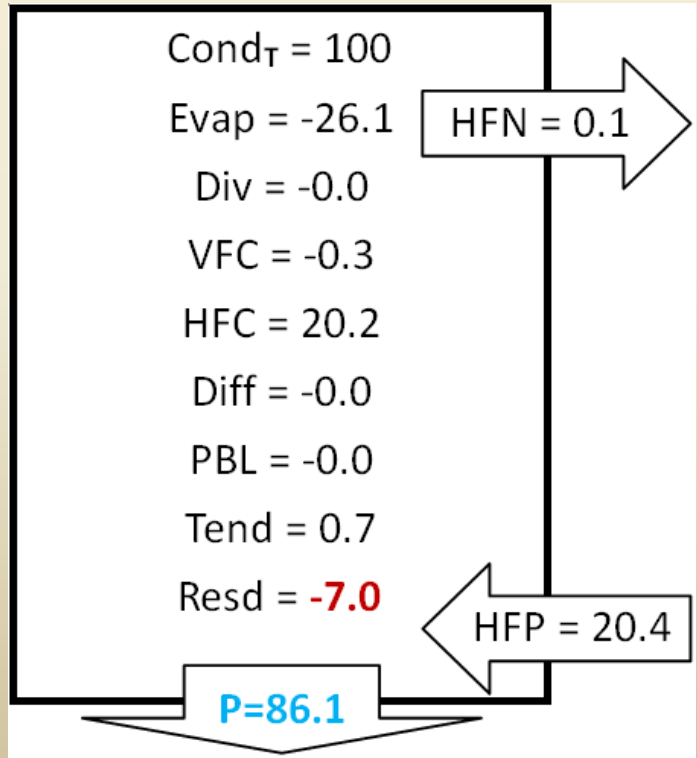
Within the box area over the mountains



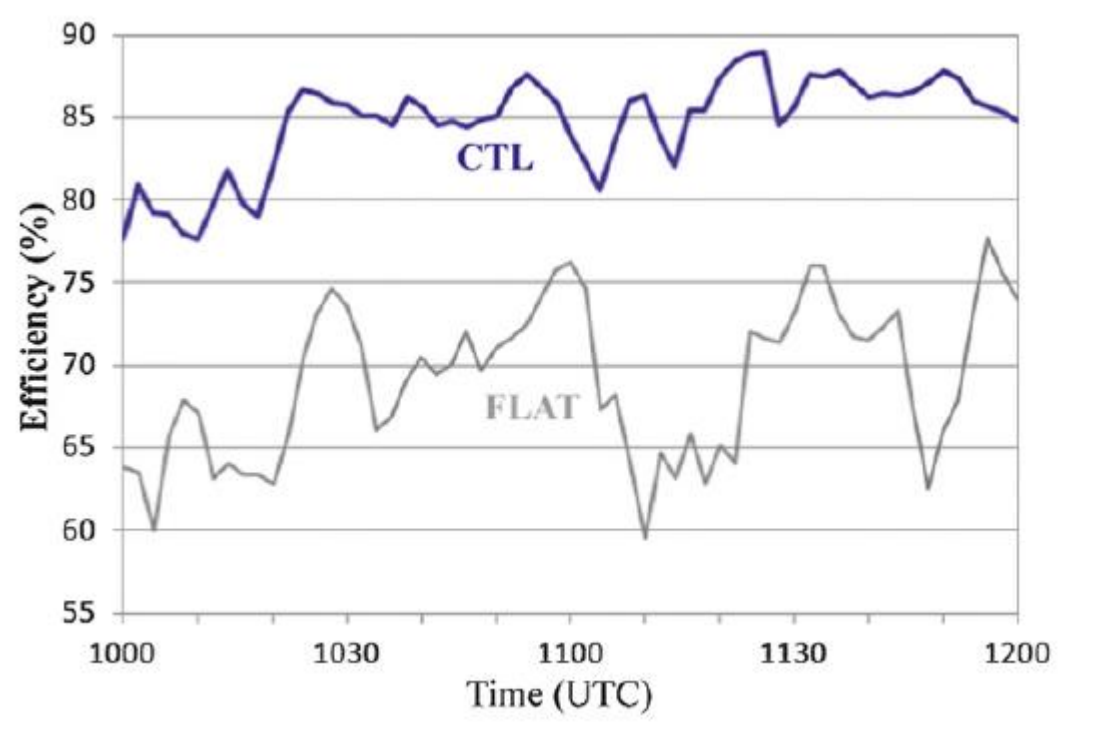
Water Vapor Budget



Liquid/Ice Water Budget



PEs of the CTL and FLAT run over the box area



Further decomposition of microphysical parameters into three components

Condensation Ratio:

$$CR = Cond_C/Cond_T$$

Deposition Ratio:

$$DR = (Dep_S + Dep_G + Dep_I)/Cond_T$$

Evaporation Ratio:

$$ER = Evap_R/Cond_T$$

where $Cond_T$ is the total condensation and deposition;

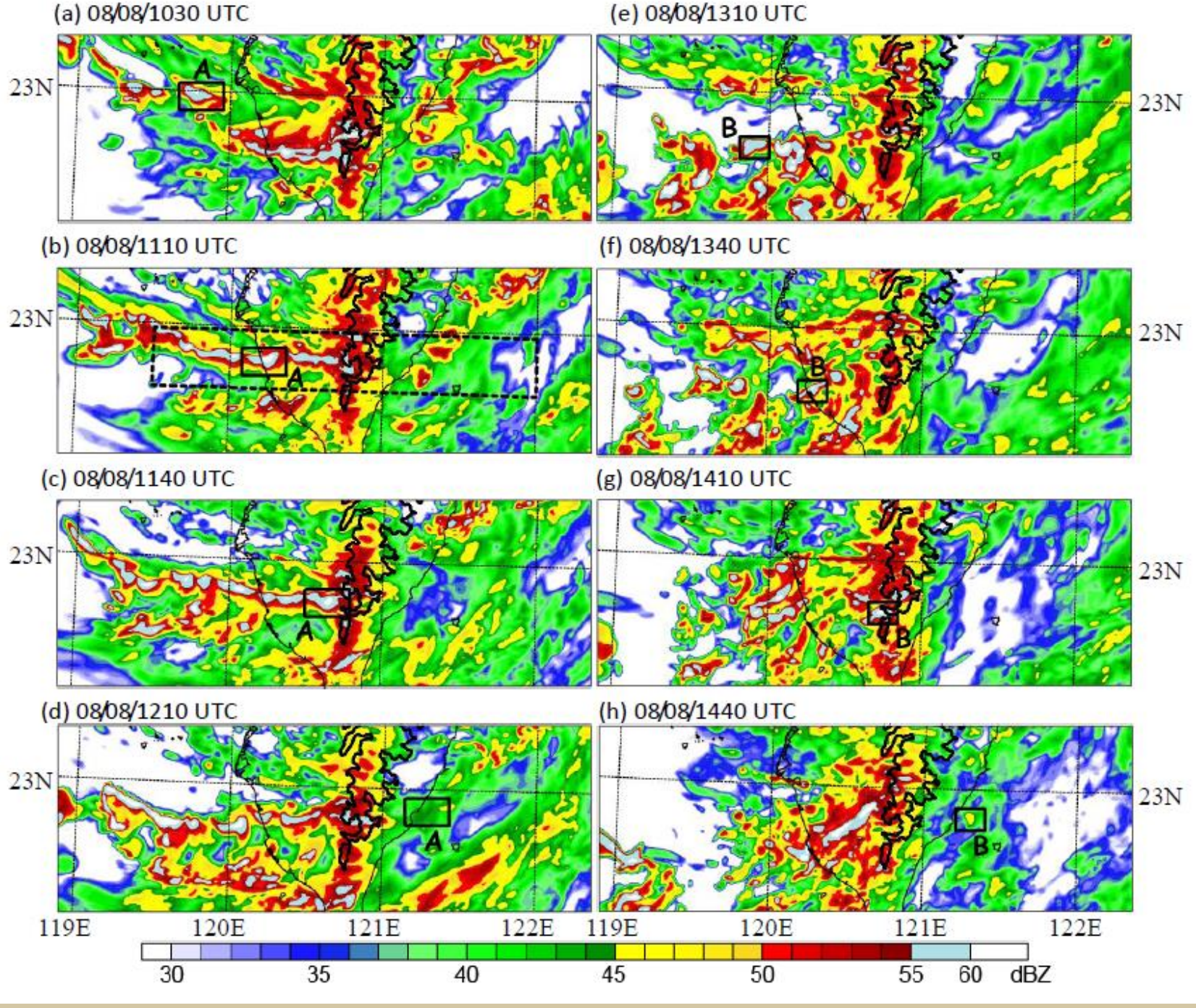
$Cond_C$ is the cloud water condensation;

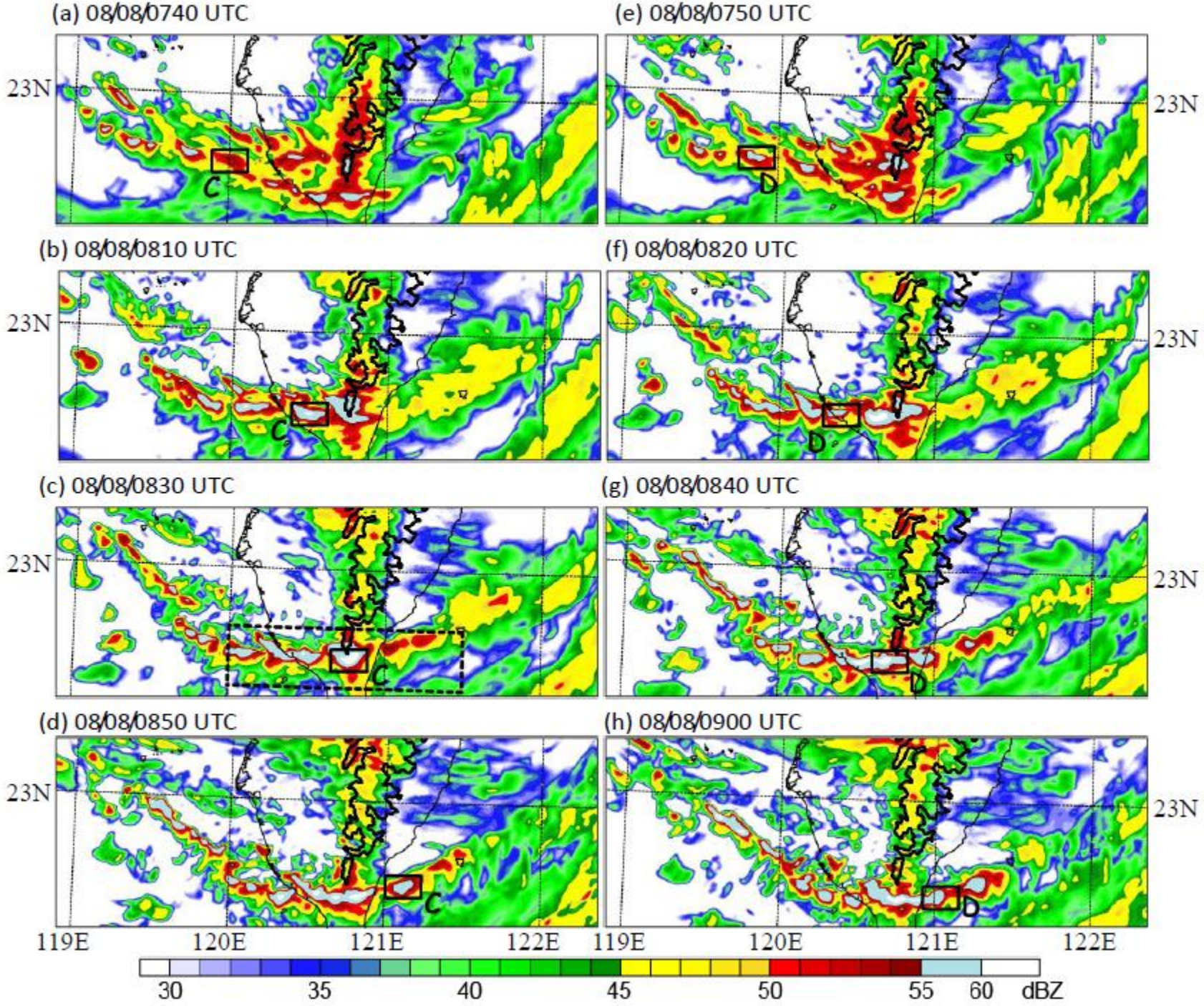
Dep_S is the snow deposition;

Dep_G is the graupel deposition;

Dep_I is the cloud ice deposition;

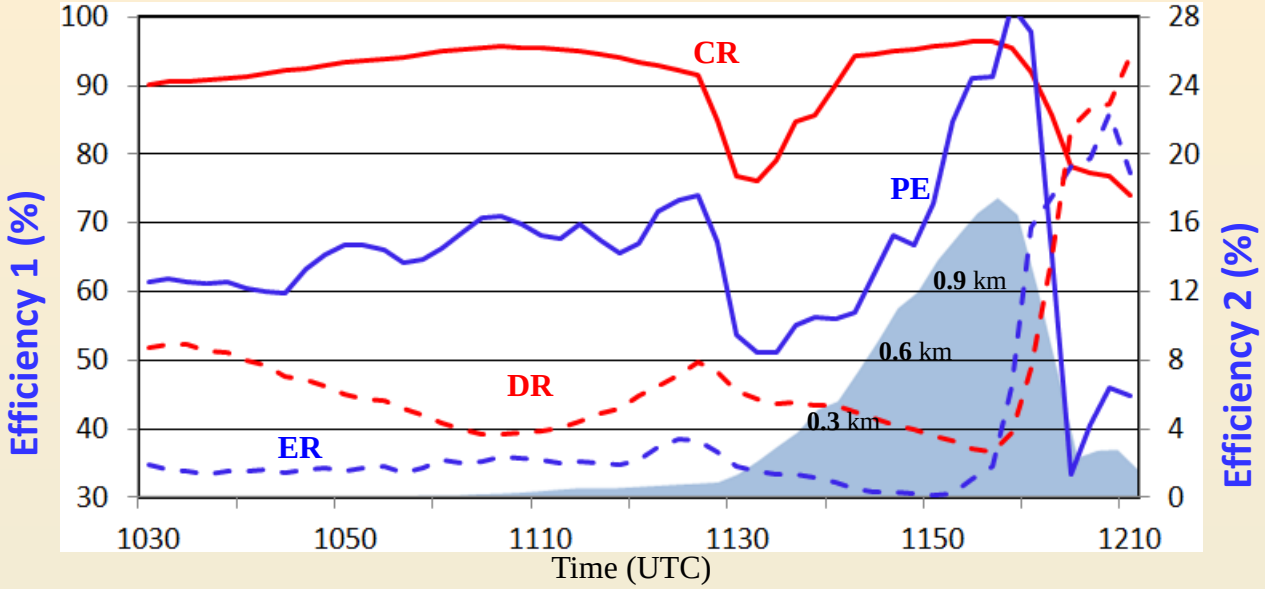
$Evap_R$ is the raindrop evaporation


(a) 08/08/1030 UTC
(b) 08/08/1110 UTC
(c) 08/08/1140 UTC
(d) 08/08/1210 UTC
(e) 08/08/1310 UTC
(f) 08/08/1340 UTC
(g) 08/08/1410 UTC
(h) 08/08/1440 UTC
A
B
23N
119E
120E
121E
122E
30
35
40
45
50
55
60
dBZ

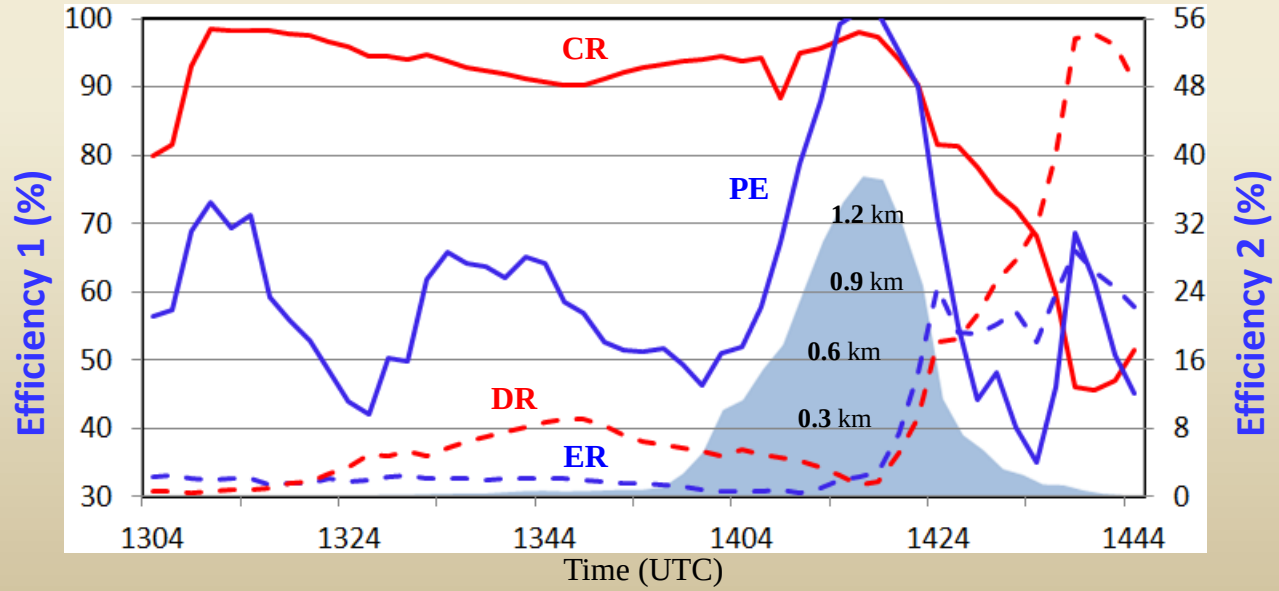

(a) 08/08/0740 UTC
(e) 08/08/0750 UTC
(b) 08/08/0810 UTC
(f) 08/08/0820 UTC
(c) 08/08/0830 UTC
(g) 08/08/0840 UTC
(d) 08/08/0850 UTC
(h) 08/08/0900 UTC
23N
C
D
119E
120E
121E
122E
30
35
40
45
50
55
60
dBZ

Lagrangian evolution of microphysical parameters

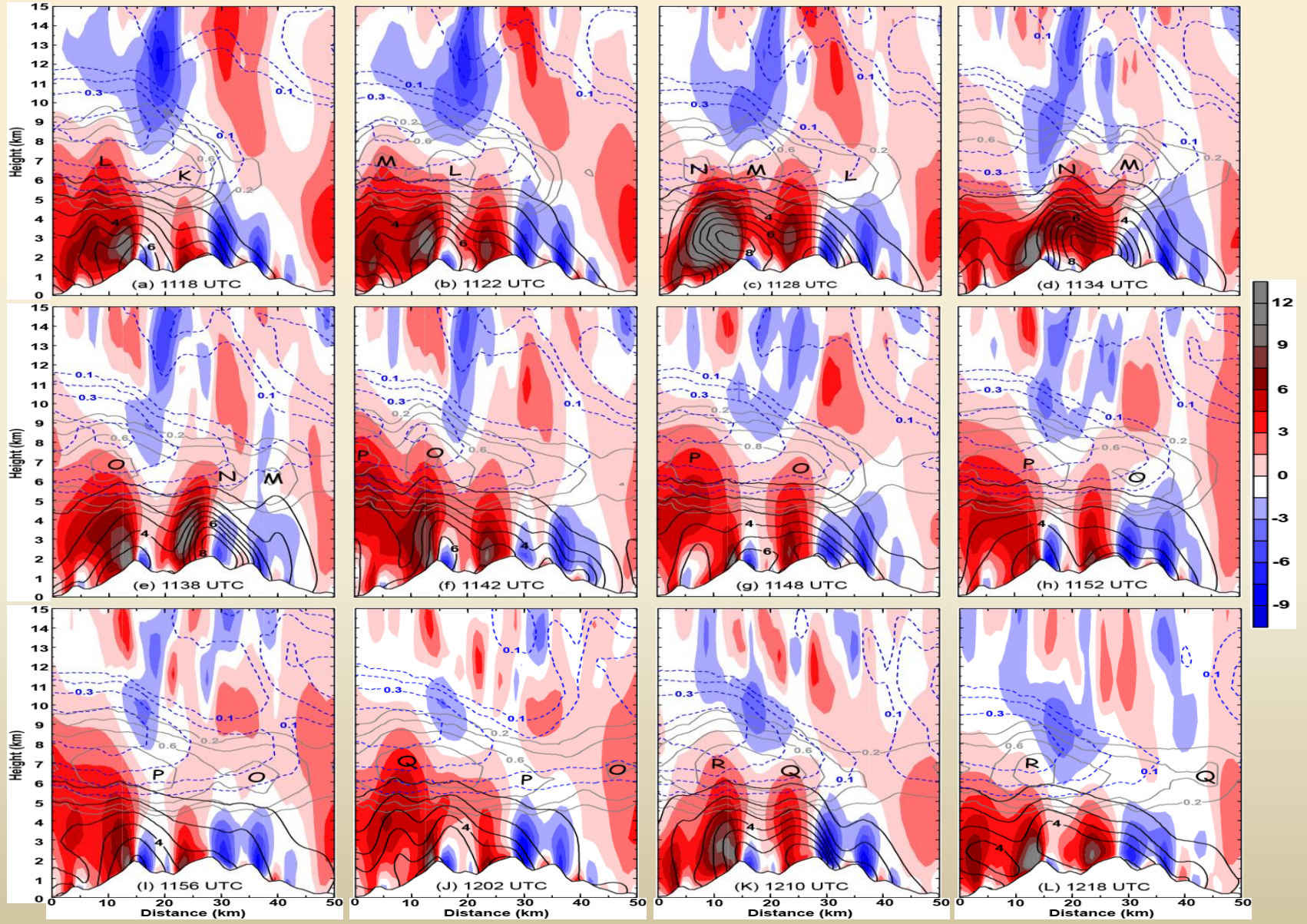
Cell A



Cell B

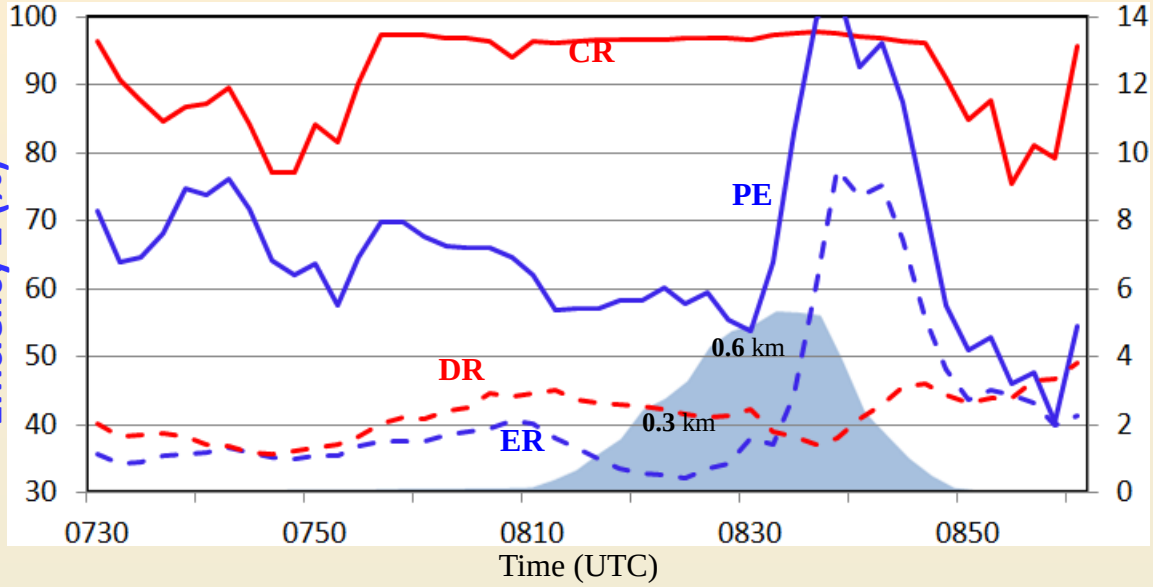


Gravity Waves on the Lee Side (vertical velocity, colored; hydrometeor mixing ratio, contoured)

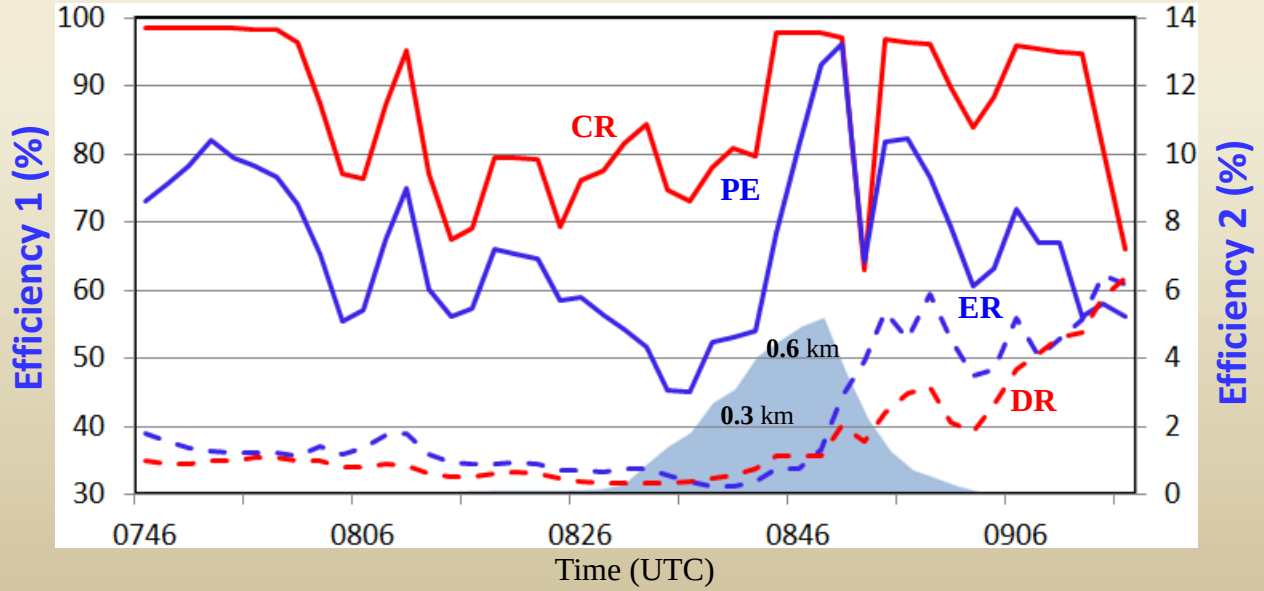


Lagrangian evolution of microphysical parameters

Cell C

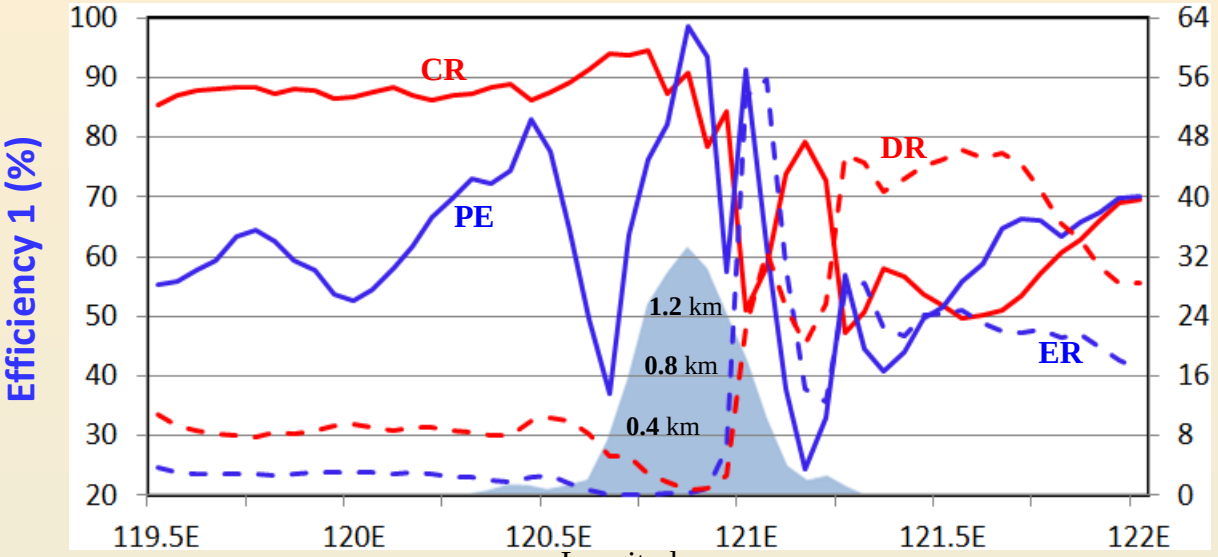


Cell D

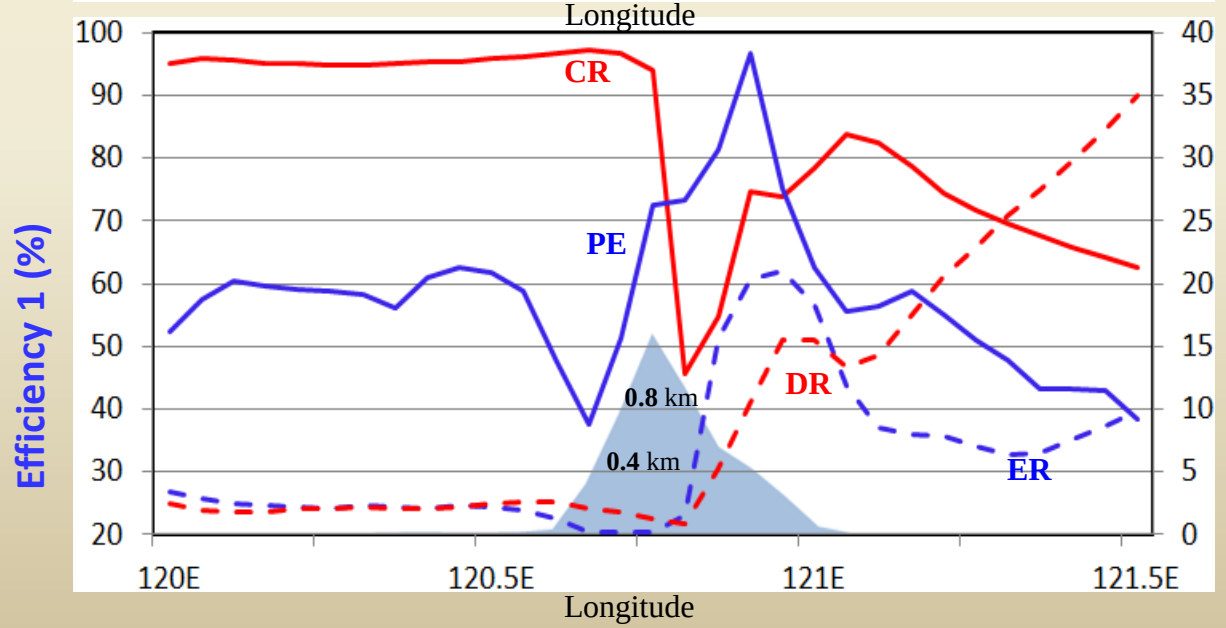


Eulerian evolution of microphysical parameters In two time-and-space-averaged cross sections

Cross Section A



Cross Section B



Are the Morakot results universal?

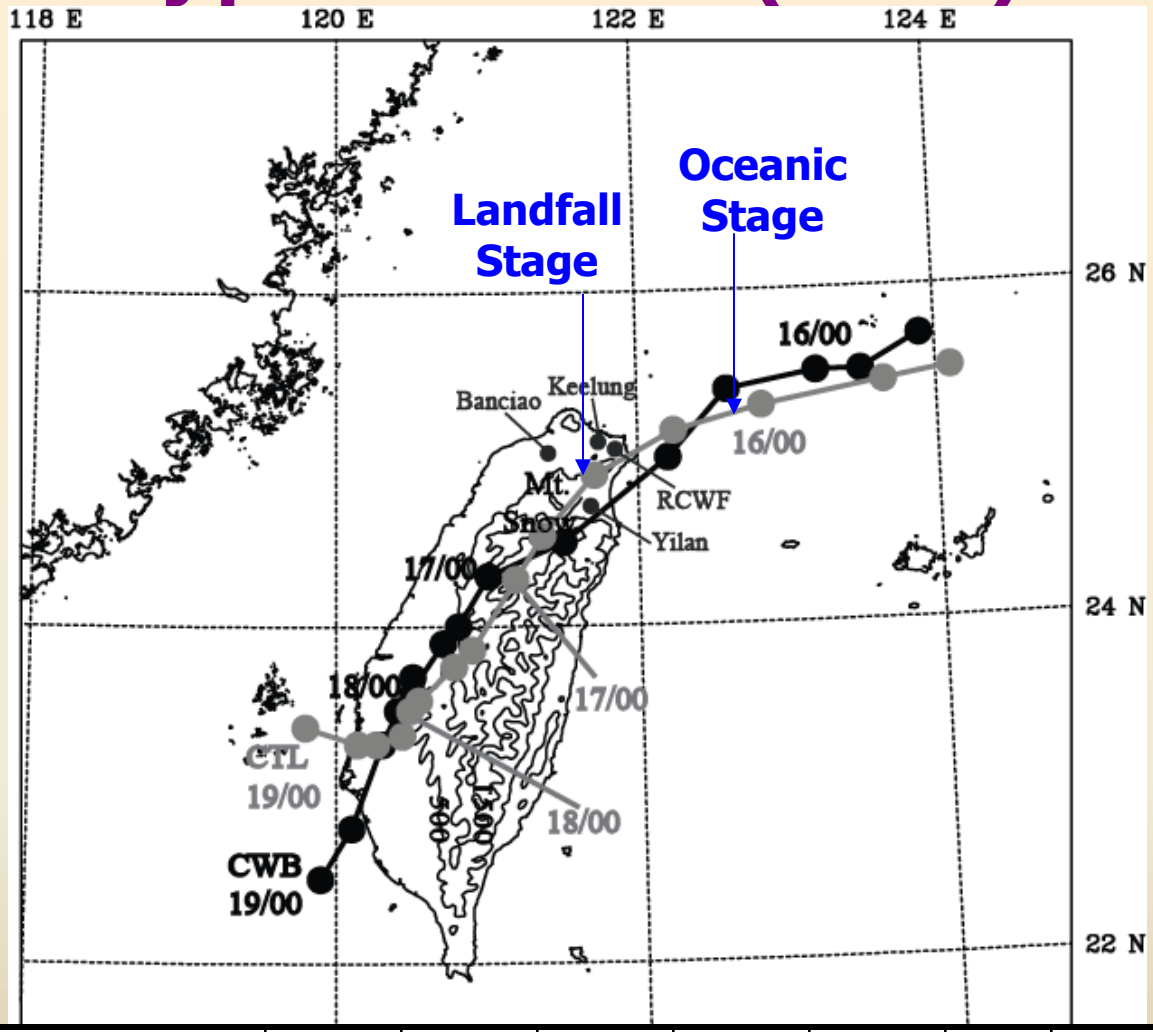
$\Rightarrow$ Another **typhoon case for Nari (2001)**

Heavy rainfall associated with Typhoon Nari (2001)

Water World !

Even Budda cannot save you!

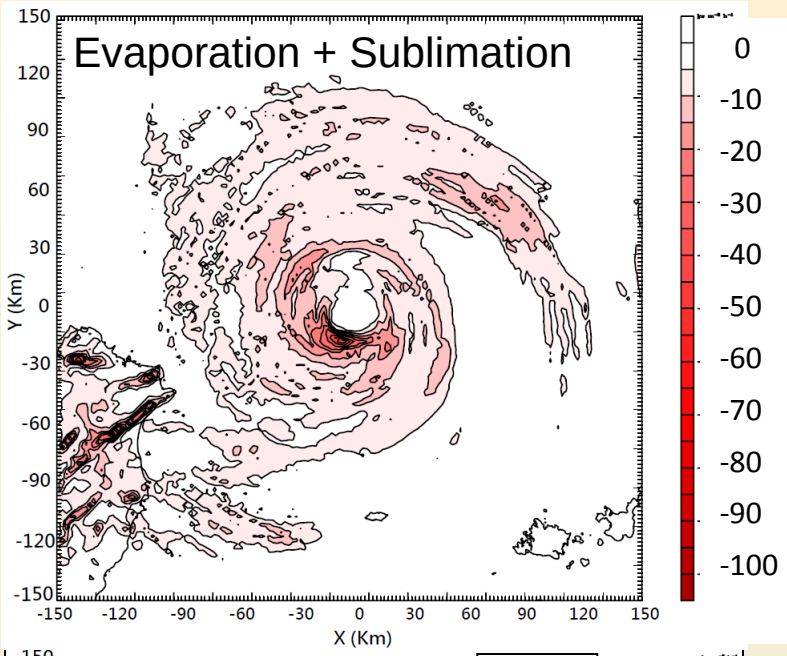
Typhoon Nari (2001)

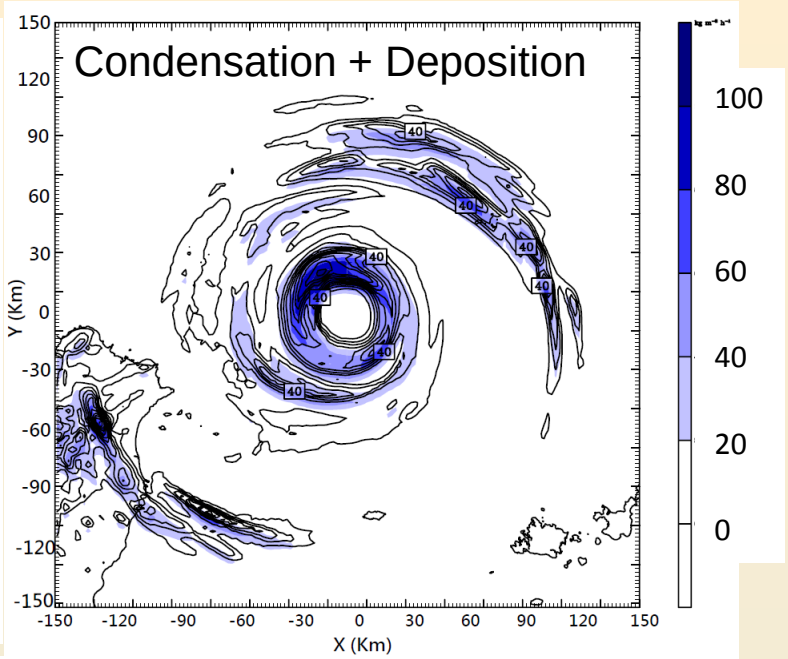


Yang, Zhang, and Huang (2008; JAS)

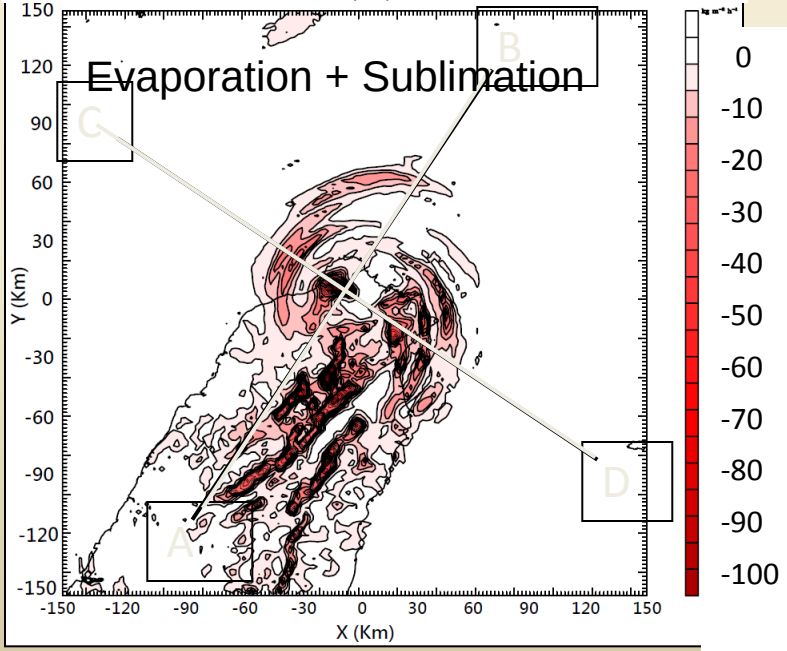
Simulation time (hr)	12	24	36	48	60	72	84
Track error (km)	43.3	61.2	26.8	13.4	12	8.5	104.8

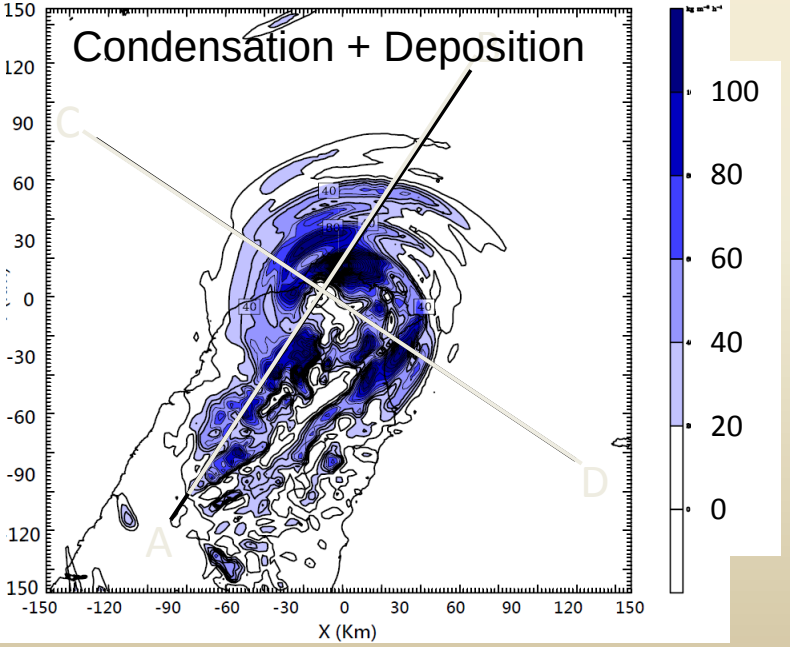
Oceanic Stage





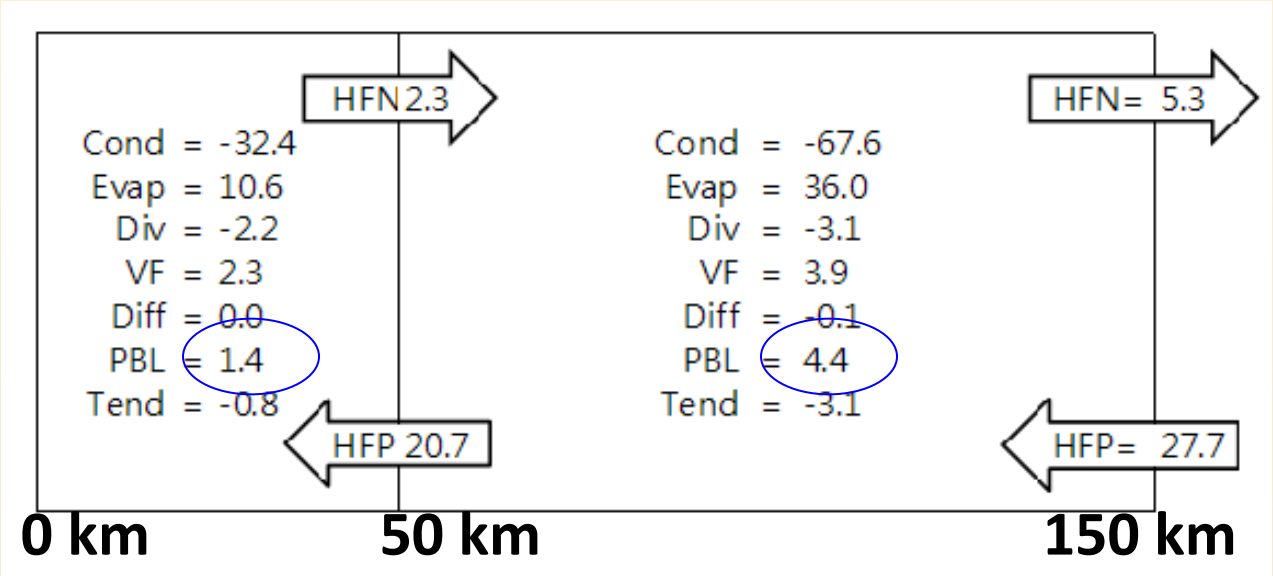
Landfall Stage



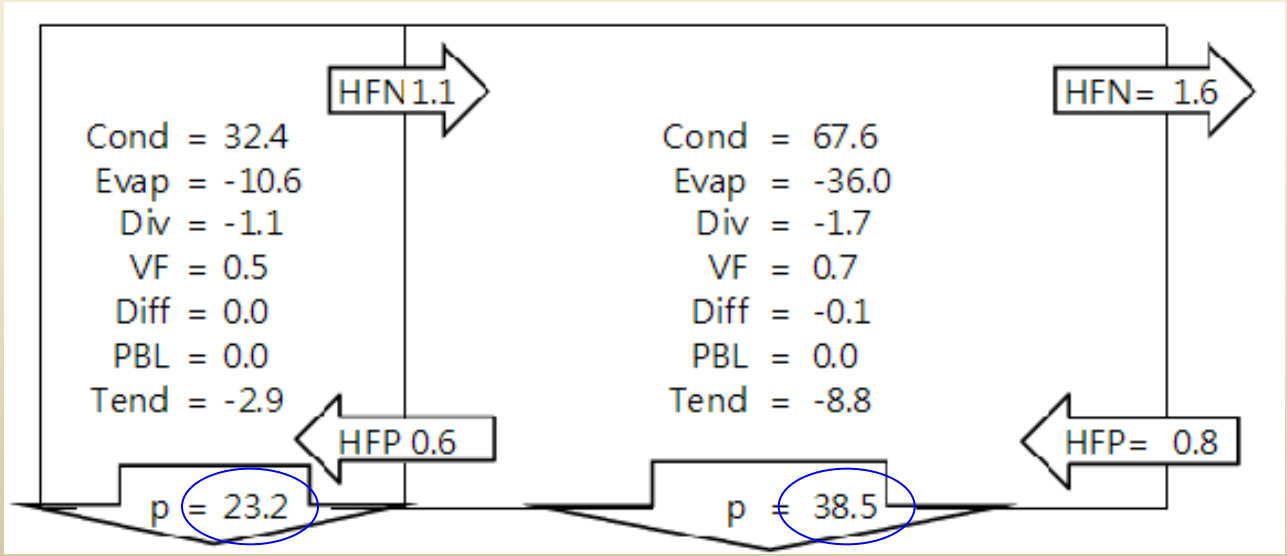


Oceanic Stage

Vapor Budget

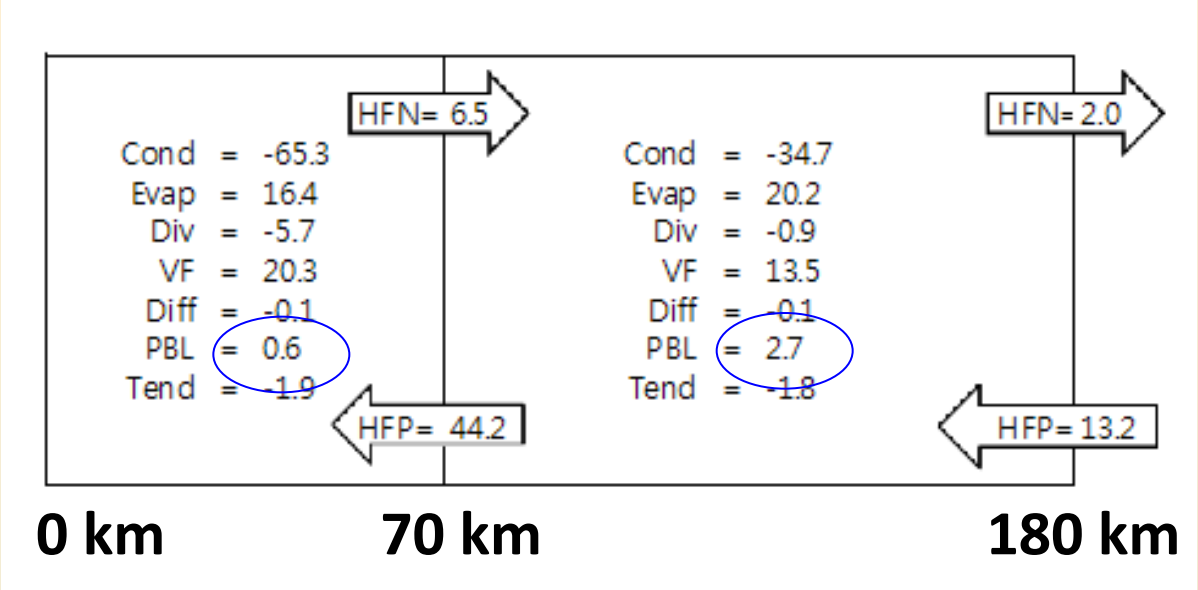


Liquid/Ice Water Budget

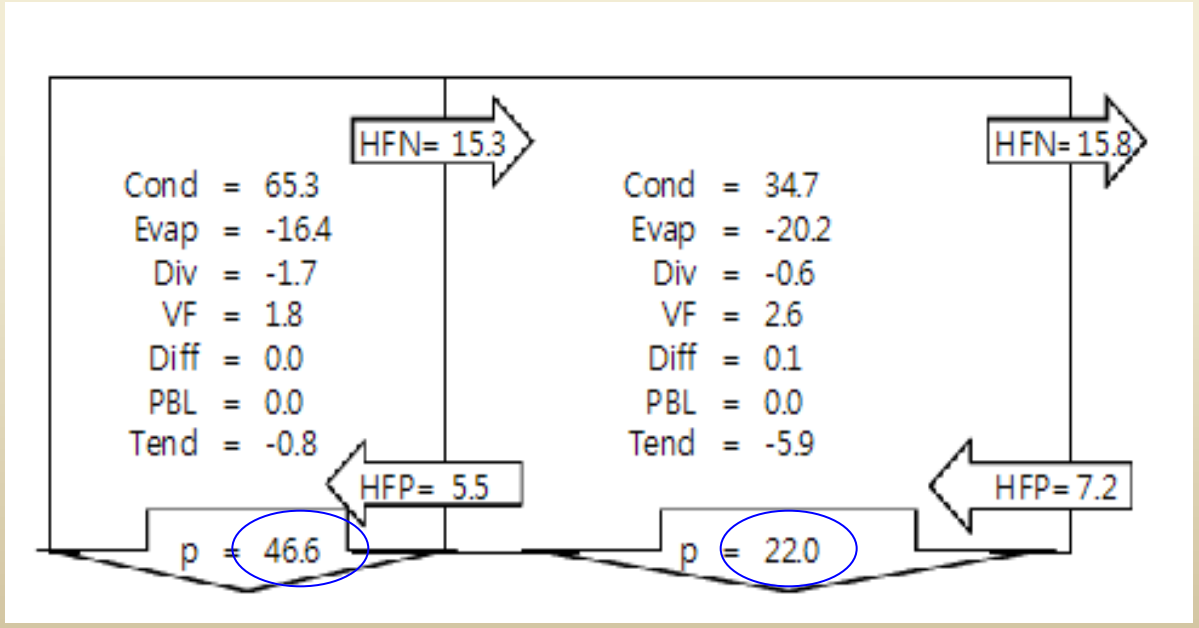


Landfall Stage

Vapor Budget



Liquid/Ice Water Budget



Microphysics Precipitation Efficiency

- Oceanic stage (13-14h)

  Inner core (R=0-50 km): PE=P/Cond=23.2/32.4 ≈ 72 %

  Outer region (R=50-150 km): PE=P/Cond=38.5/67.6 ≈ 57%

- Landfall stage (23-24h)

  Inner core (R=0-70 km): PE=P/Cond=46.6/65.3 ≈ 71%

  Outer region (R=70-180 km): PE=P/Cond=22.0/34.7 ≈ 63%

Conclusions

- The **1-km WRF simulation** reproduced resonably well **the Morakot track, the organization, the sizes of eye and eyewall, major convective cells on outer rainbands, and rainfall maxima** on southwest Taiwan.
- **The surface rainrate (36-54 mm/h) and PE (75-100%)** over southwest Taiwan are **highly correlated**.
- The surface rainrate of the no-terrain run are **50% of the full-terrain run**; and the PE of no-terrain run are **15-20% less than the full-terrain run**.
- By following the movement of major convective cells, **PEs are 60-75% over ocean and > 95% above terrain**, which may account for the record-breaking heavy rainfall over Taiwan.
- The Lagrangian evolution of major cells shows that **PE and CR are increased on the windward slope but decreased on the lee side; the reverse trend is found for the DR and ER**.
- The **Lagrangian evolution** is confirmed by the changes of microphysical parameters across the mountains in two time-and-space-averaged cross sections in an **Eulerian framework**.

Reference:
Yang, M.-J.*, S. A. Braun, and D.-S. Chen, 2011: Water budget of Typhoon Nari (2001). *Mon. Wea. Rev.*, **139**, 3809–3828.
Huang, H.-L., **M.-J. Yang*,** and C.-H. Sui, 2014: Water budget and precipitation efficiency of Typhoon Morakot (2009). *J. Atmos. Sci.*, **71**, 112–129


Thank you