What have we learned from Typhoon Nari (2001)?

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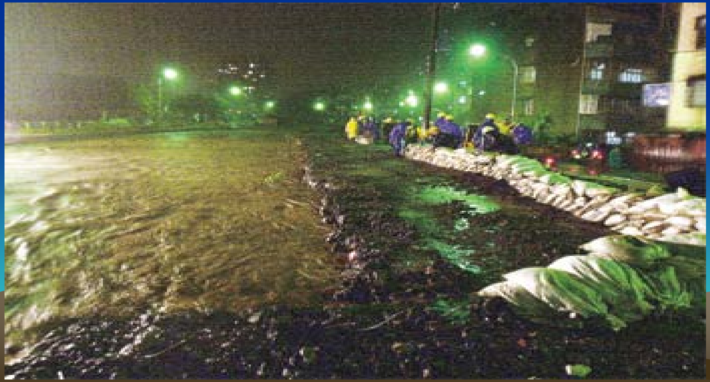
A series of papers on Typhoon Nari (2001)

- Yang, M.-J.*, D.-L. Zhang, and H.-L. Huang, 2008: A modeling study of Typhoon Nari (2001) at landfall. Part I: Topographic effects. *J. Atmos. Sci.*, **65**, 3095–3115.
- Yang, M.-J.*, D.-L. Zhang, X.-D. Tang, and Y. Zhang, 2011: A modeling study of Typhoon Nari (2001) at landfall. Part II: Structural changes and terrain-induced asymmetries. *J. Geophys. Res.*, **116**, D09112, doi:10.1029/2010JD015445.
- Yang, M.-J.*, T.-C. Chen Wang, Y. Zhang, and C.-Y. Weng, 2011: Momentum budget evolution of Typhoon Nari (2001) during the landfall process. *Terr., Atmos., and Oceanic Sci.*, **22**, 595–612, doi:10.3319/TAO.2011.05.31.01(TM).
- Yang, M.-J.*, S. A. Braun, and D.-S. Chen, 2011: Water budget of Typhoon Nari (2001). *Mon. Wea. Rev.*, **139**, 3809–3828.
- Zhang, D.-L.*****, L. Tian, and M.-J. Yang, 2011: Genesis of Typhoon Nari (2001) from a mesoscale convective system, *J. Geophys. Res.*, doi:10.1029/2011JD016640.
- Tang, X.-D.***,** M.-J. Yang, and Z.-M. Tan, 2012: A modeling study of orographic convection and mountain waves in the landfalling *typhoon Nari* (2001), *Quart. J. Roy. Meteor. Soc.*, **138**, 419–438, doi: 10.1002/qj.933.
- Lin P.-S., and M.-J. Yang, 2012: Potential vorticity budget of Typhoon Nari (2001), *Atmospheric Sciences,* in press (in Chinese with English abstract).

Heavy rainfalls induced severe flooding and societal damage !

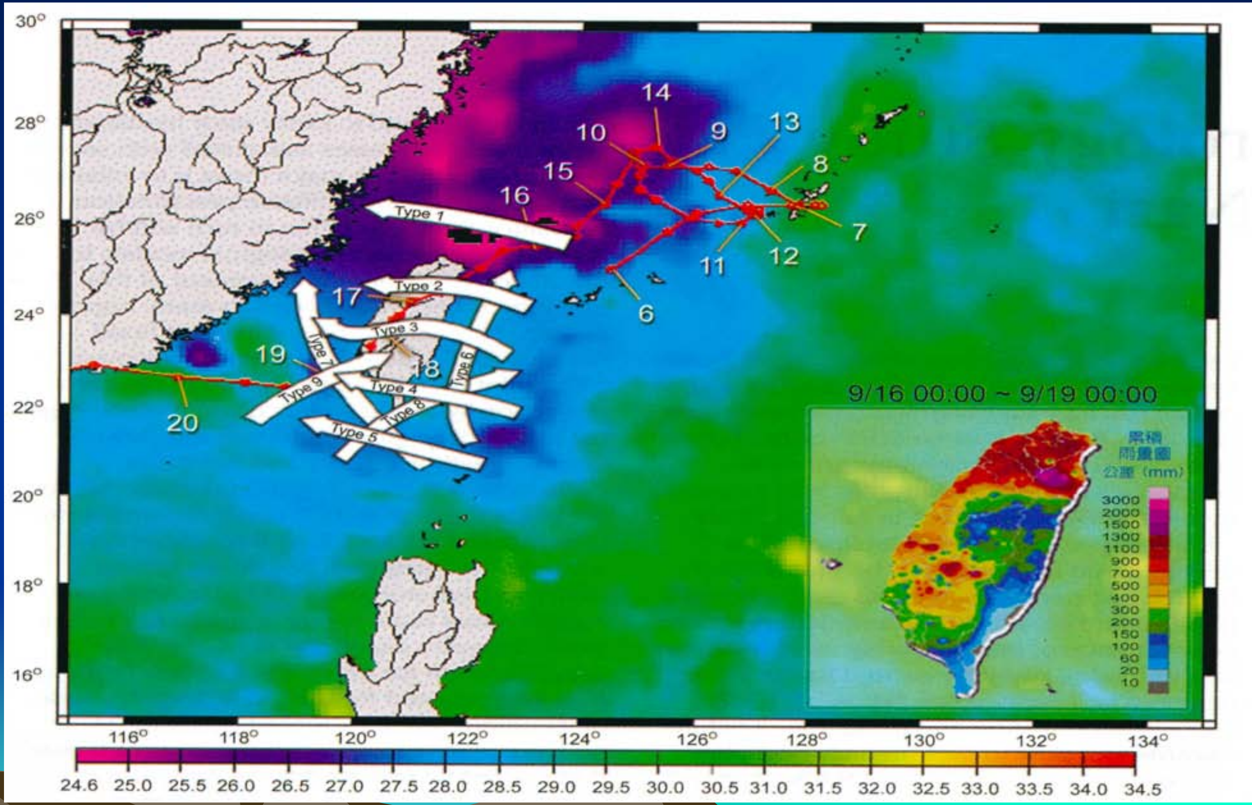
At the time of heavy rainfall,
even Budda cannot save you!

Water World !



Why studied Typhoon Nari (2001)?

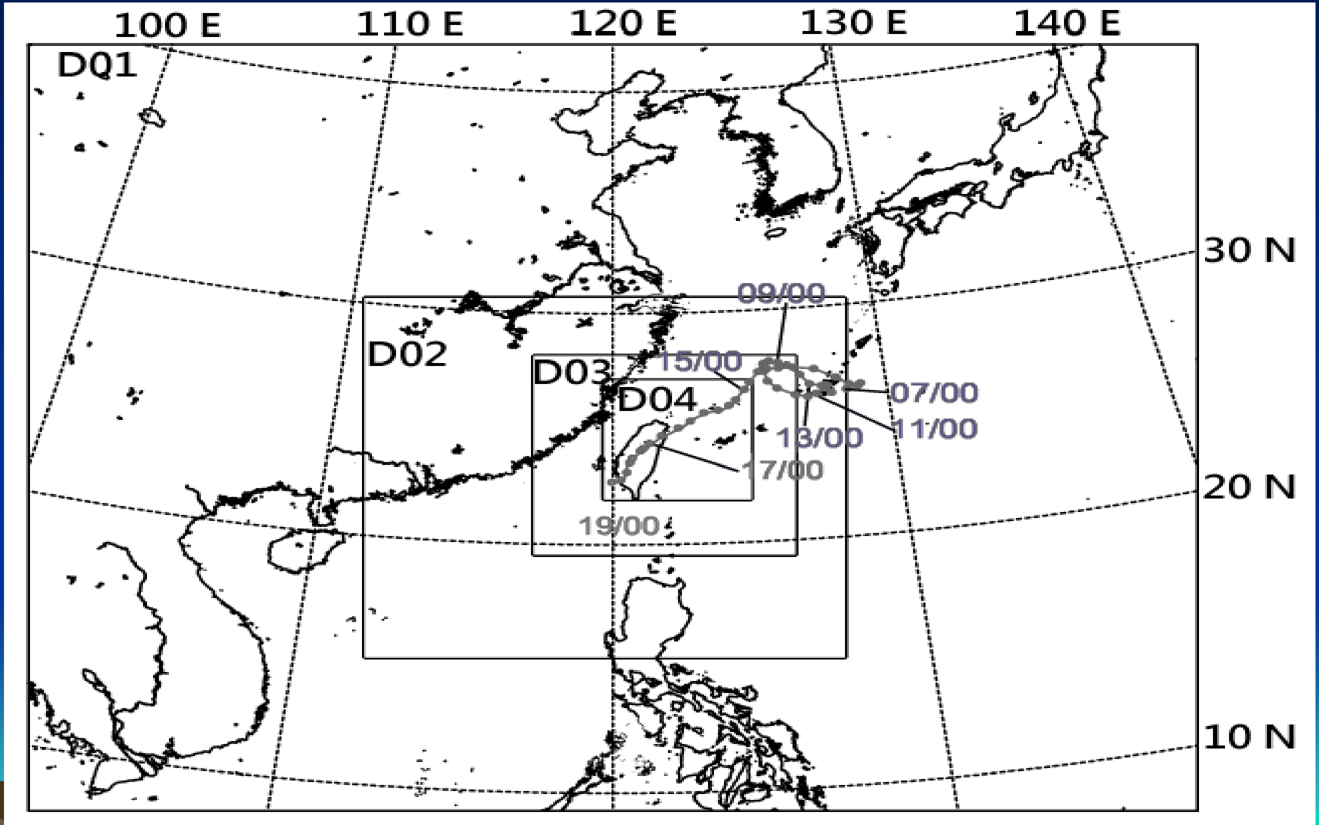
- Unique track
- Slowly moving
- Long duration
- Warm ocean
- Heavy rainfall
- Severe flooding



Sui et al. (2002) EOS article

Part I: Terrain's impacts on track, intensity, and storm structure

- Yang, M.-J.*, D.-L. Zhang, and H.-L. Huang, 2008: A modeling study of Typhoon Nari (2001) at landfall. Part I: Topographic effects. *J. Atmos. Sci.*, **65**, 3095–3115.



MM5 Domains

D1: 54 km

D2: 18 km

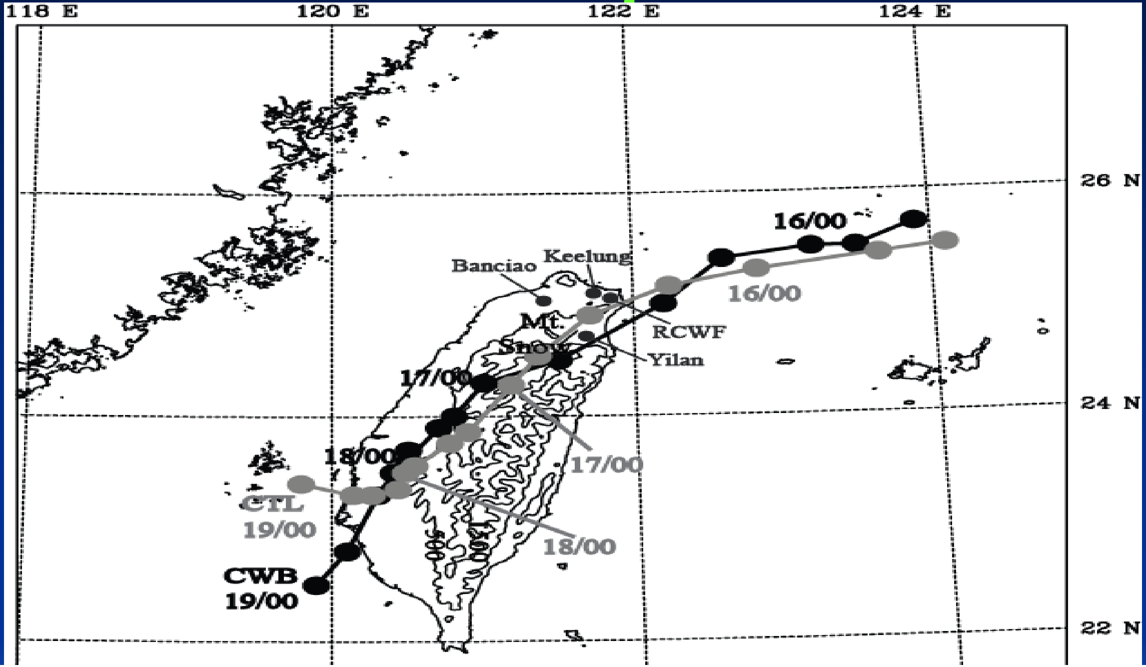
D3: 6 km

D4: 2 km

31 levels

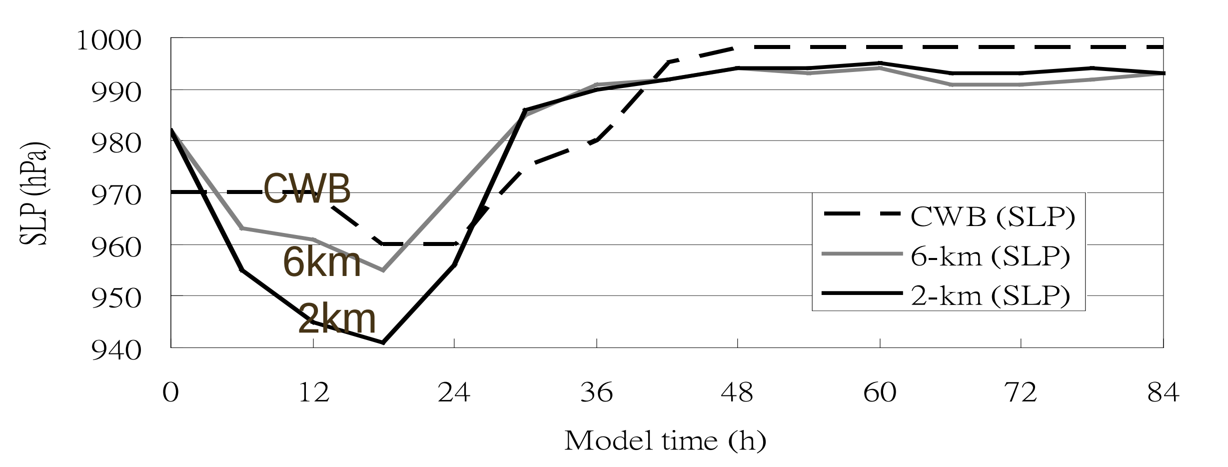
In vertical

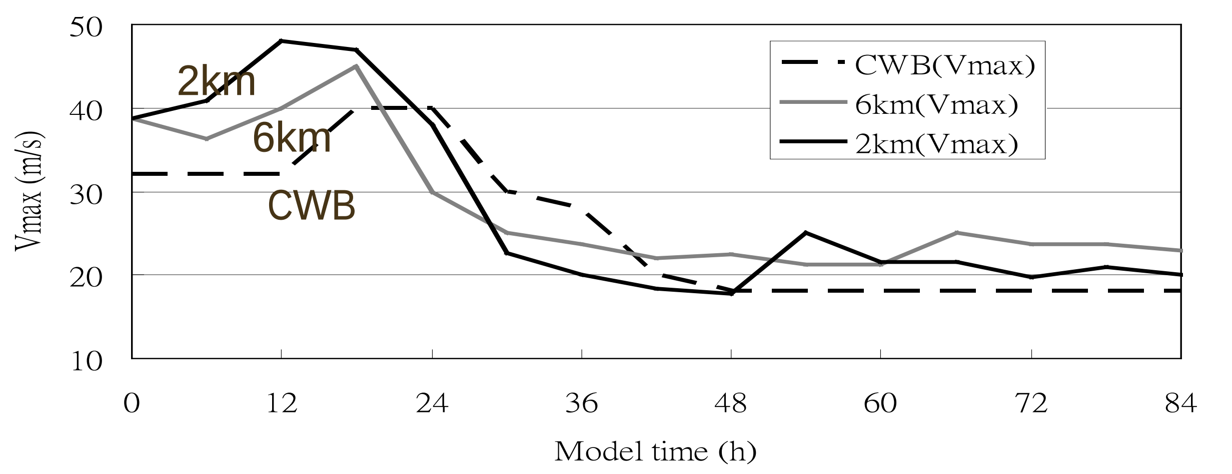
Track Comparison



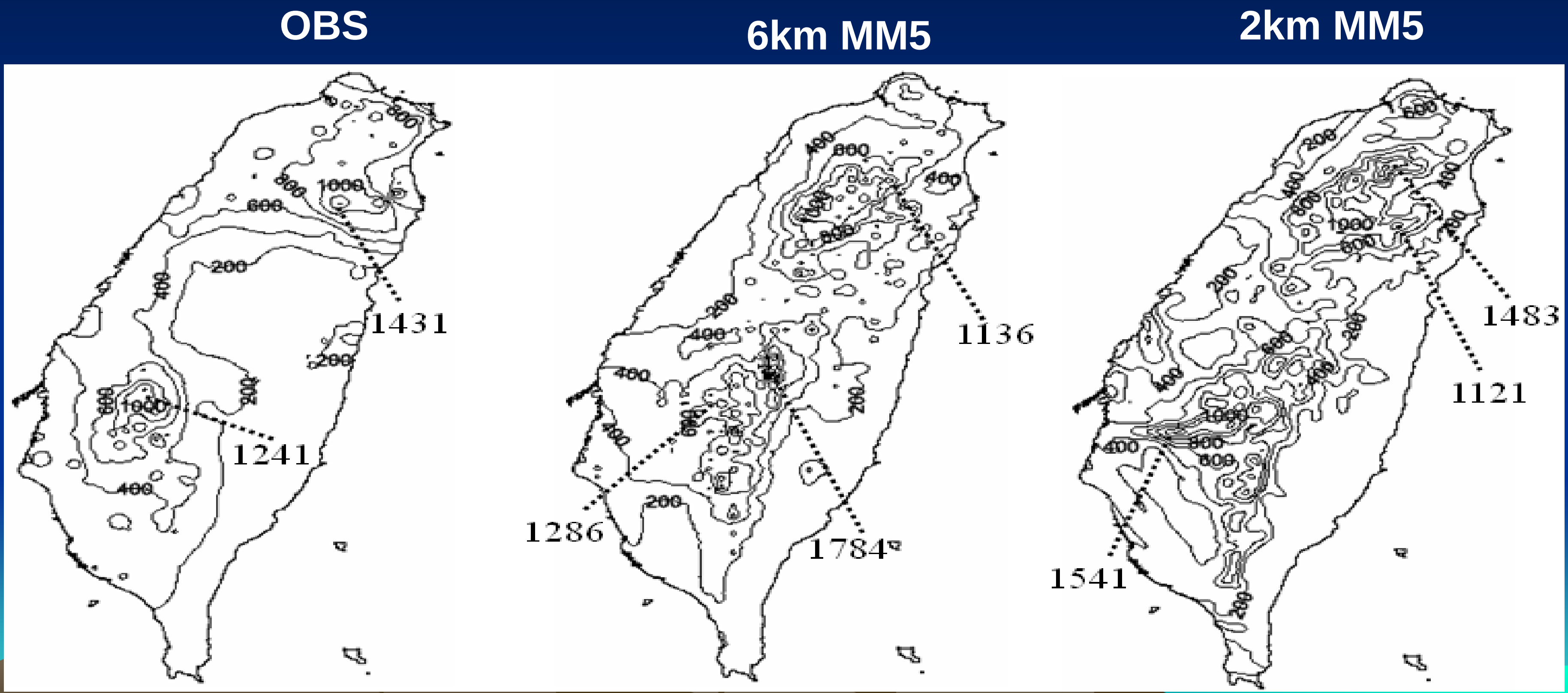
Simulation time (hr)	12	24	36	48	60	72	84
Track error (km)	43.3	61.2	26.8	13.4	12	8.5	104.8

Time Series of SLP and Vmax

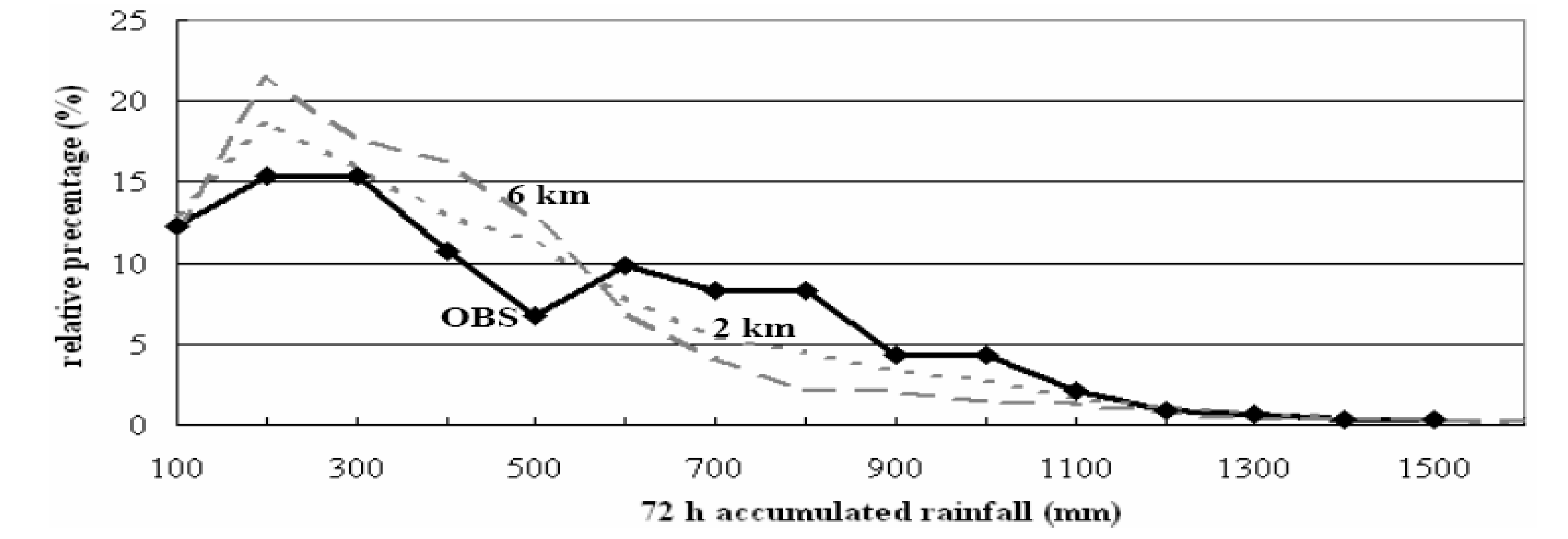




3-day rainfall on 09/16~09/18



Relative Percentage of 3-Day Rainfall



→MM5 overforecasts weak TC rainfall (<550mm/3day) but underestimates heavy TC rainfall (>550mm/3day)

(consistent with Yang et al. 2004)

→As model resolution increases, the simulated rainfall spectrum approaches the observed (consistent with Wu et al. 2002)

Average Rainfall on Taiwan

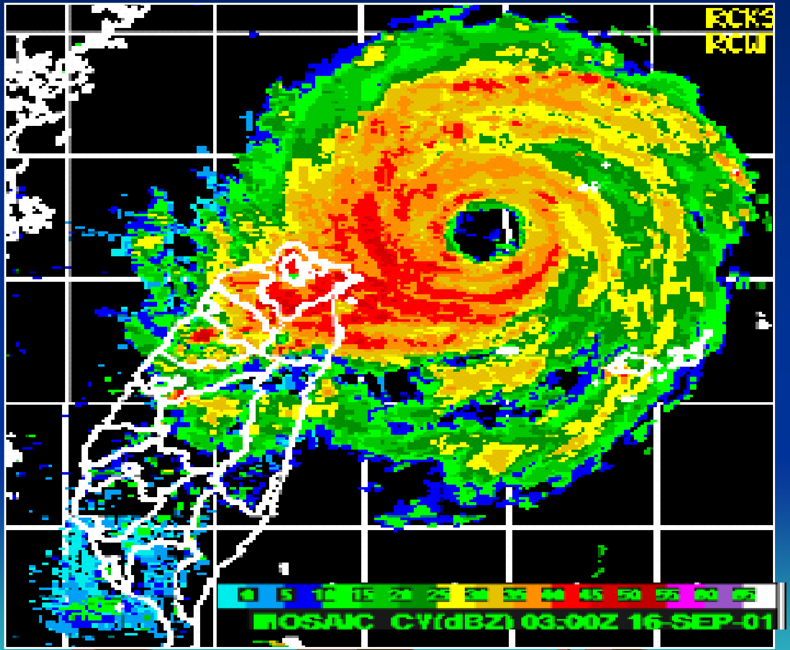
Item	N	09/16	09/17	09/18	3-Day Total
OBS (in mm)	325	132	206	97	435
6km MM5	1073	159	104	75	348
2km MM5	9602	175	133	84	383

Percentage wrt Rain Gauge OBS

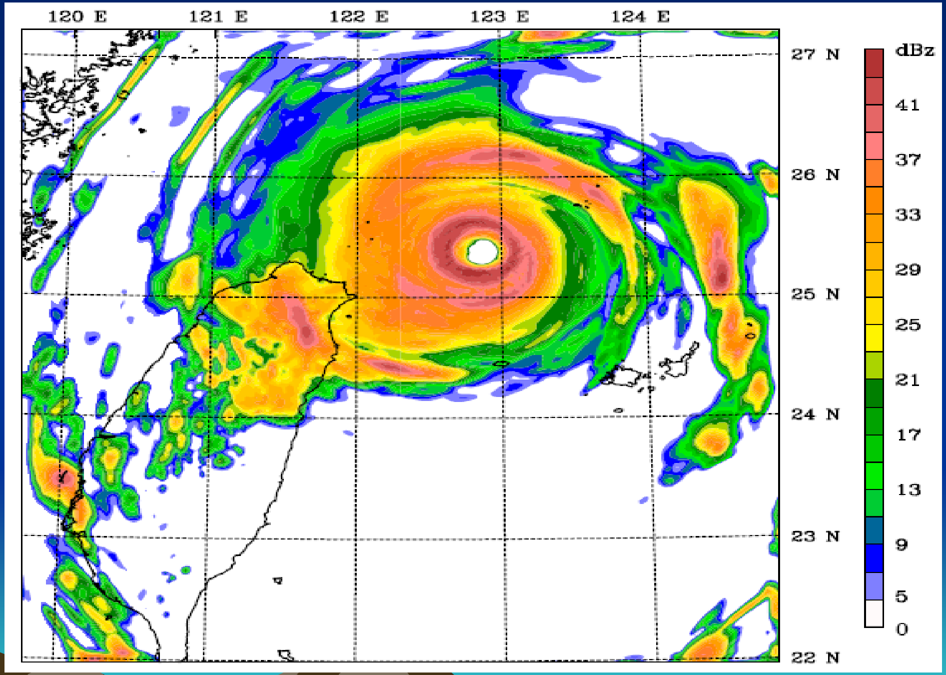
MM5/OBS	09/16	09/17	09/18	3-Day Total
6km MM5	121 %	51 %	78 %	80 %
2km MM5	133 %	65 %	87 %	88 %

Radar Composite Before Landfall

OBS

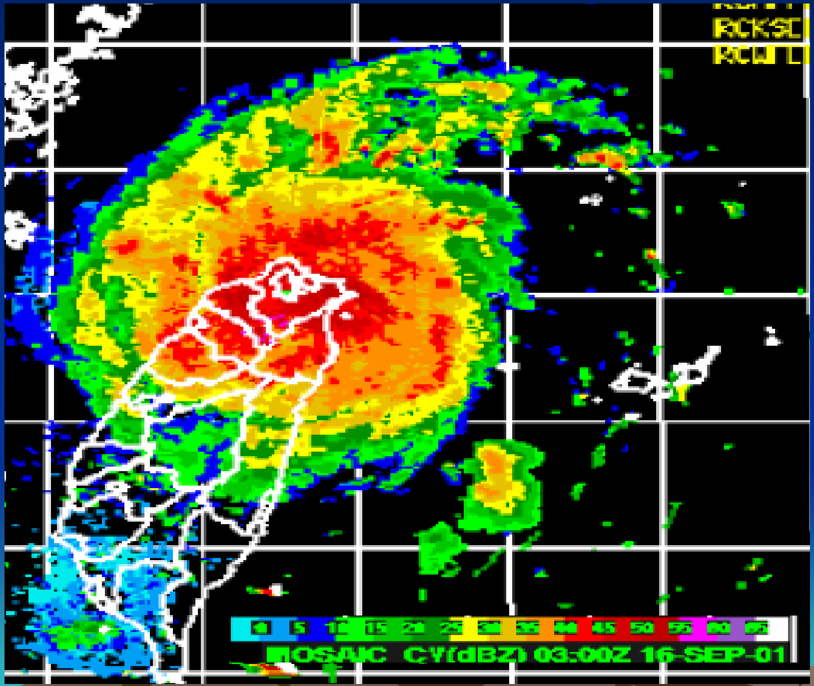


2-km MM5

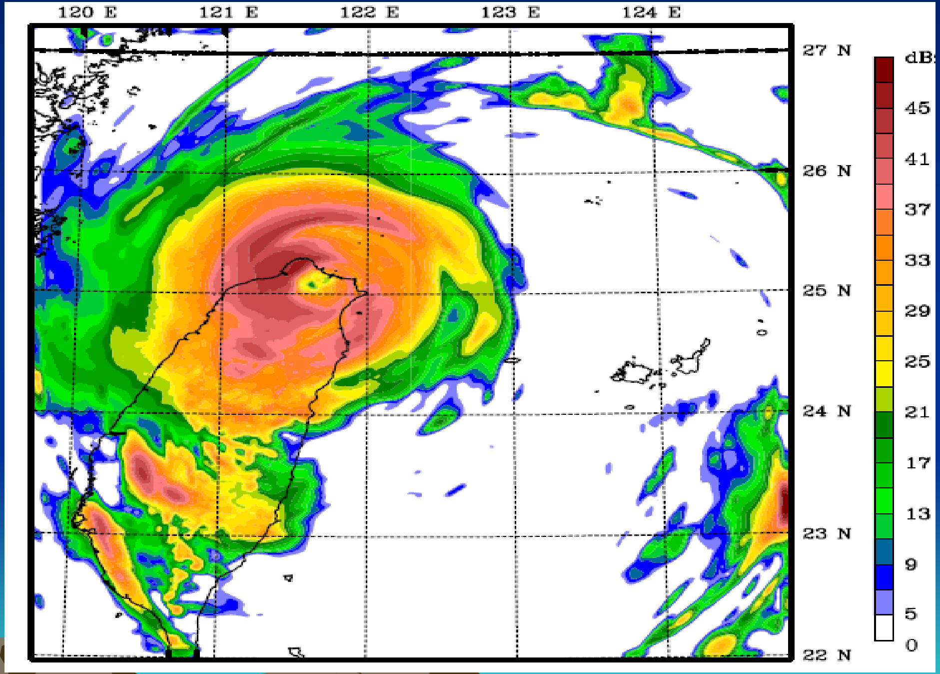


Radar Composite After Landfall

OBS

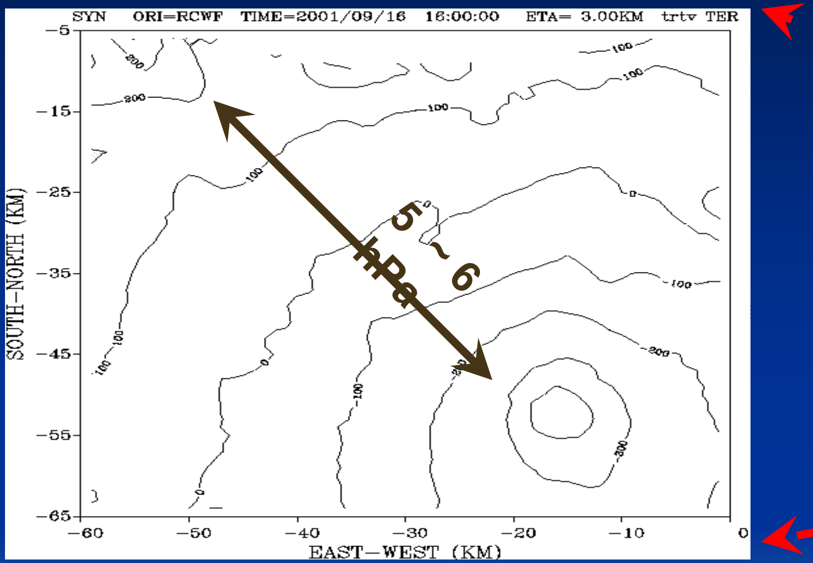


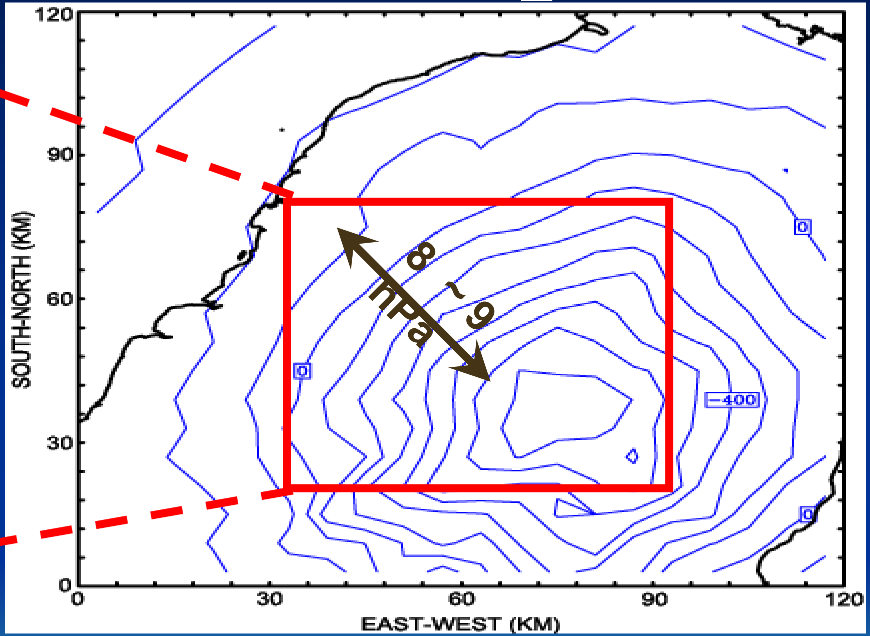
2-km MM5



Horizontal Cross Section of Pressure Perturbation

0916_1400 UTC





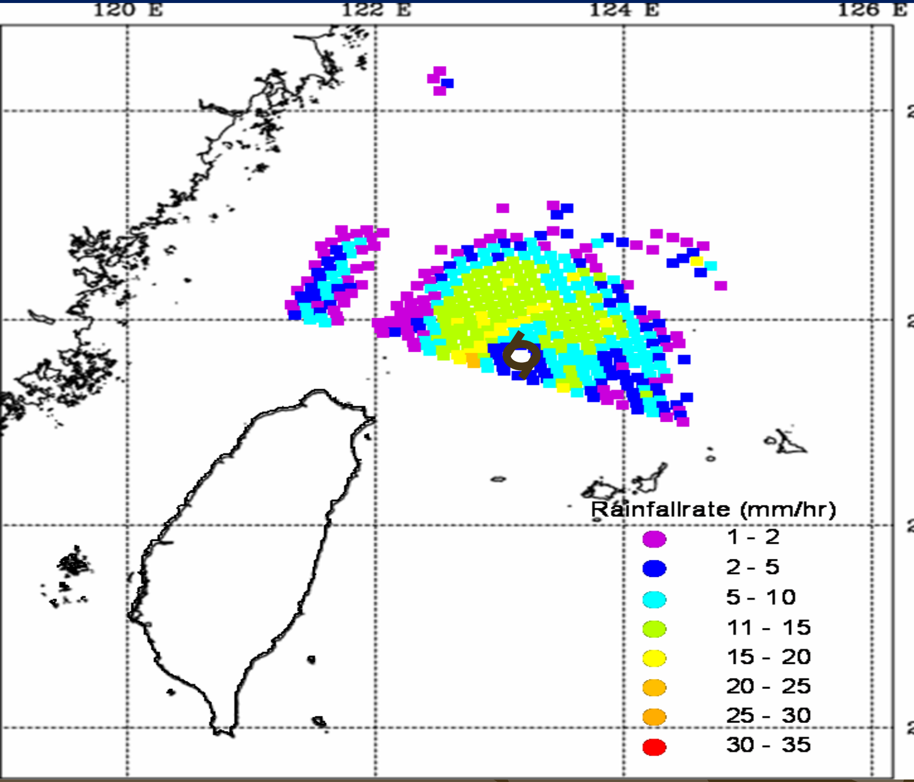
Radar Retrieval (wrt. a Station Sounding)

MM5 Simulation (wrt. a Horizontal Area Mean)

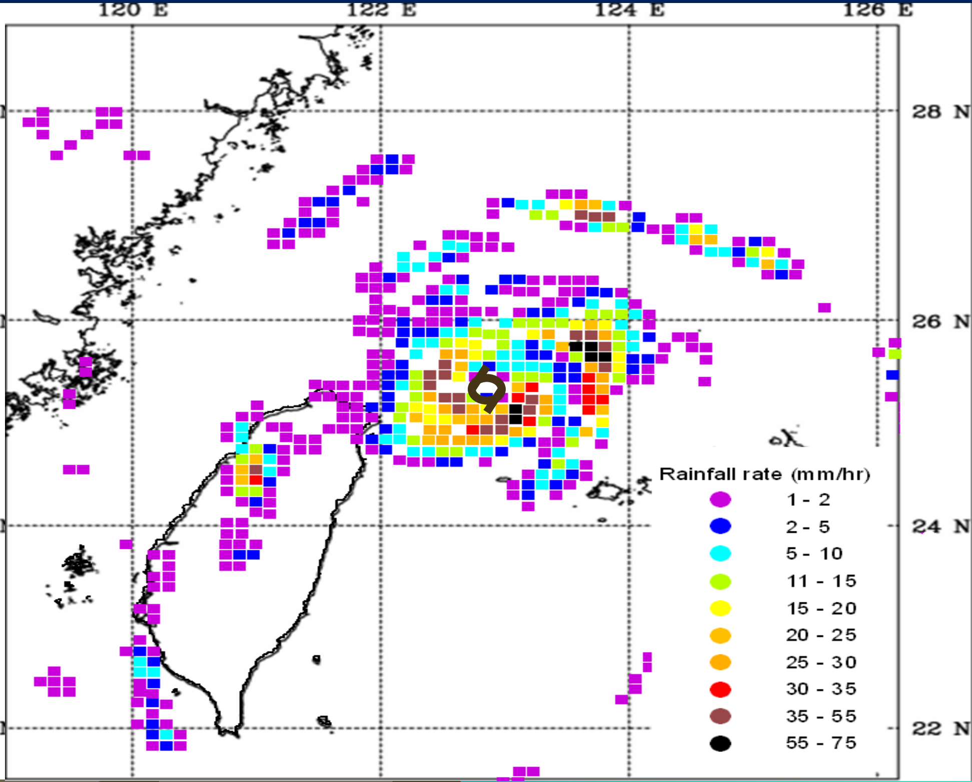
Courtesy of T.-C. Chen and Y.-C. Liou

TRMM Rainrate Comparison

TRMM/PR: 0915/2328 UTC (10 km pixel)



MM5: 0915/2100 UTC (6 km grid)

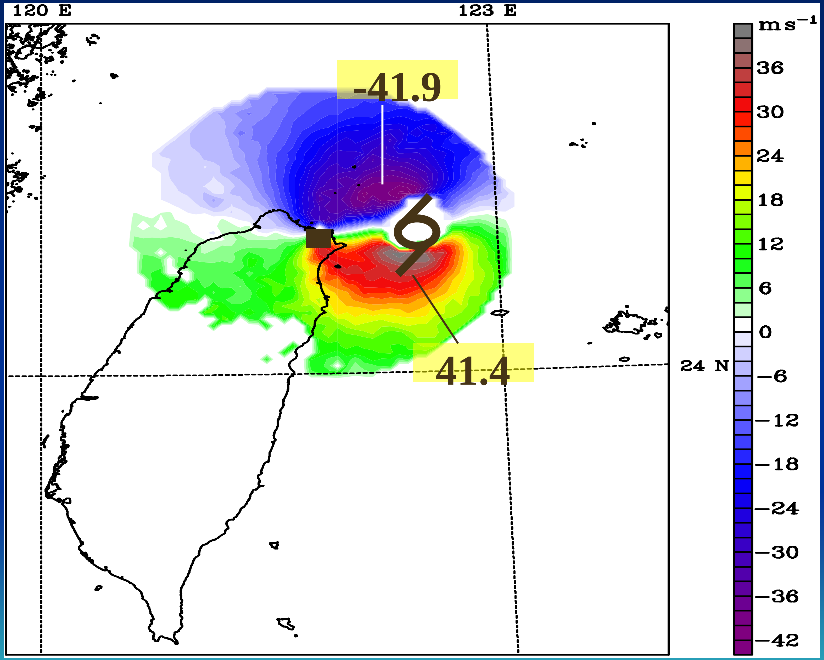


Courtesy of W.-J. Chen

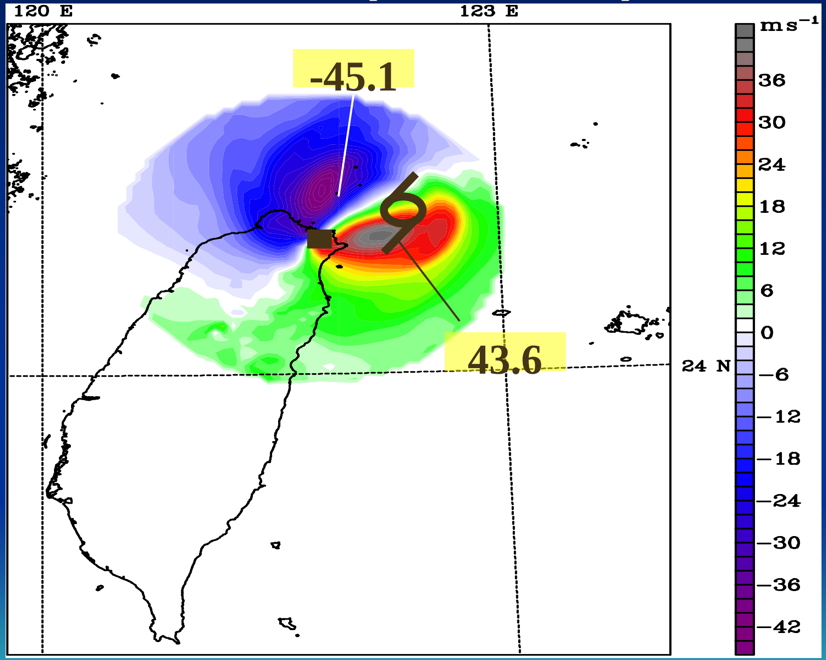
Radial Wind wrt RCWF Radar

@ 3 km Height

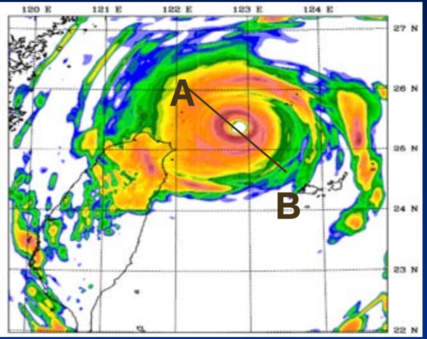
Obs Vr (6 km pixel)

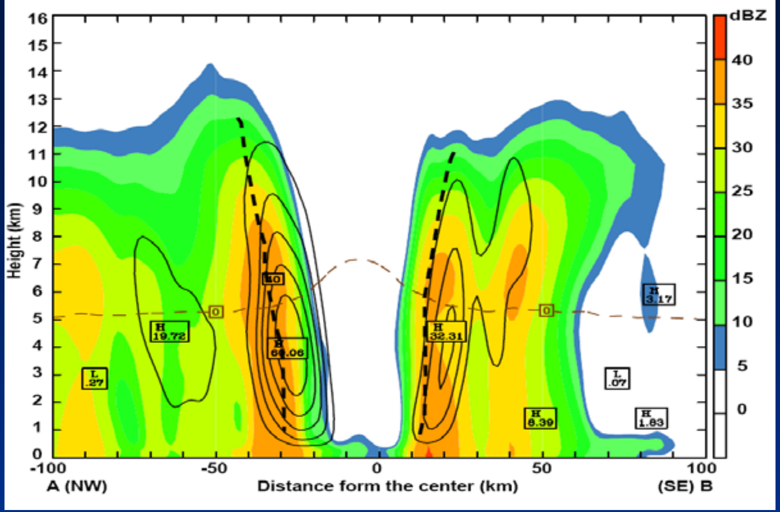


MM5 Vr (dx = 6 km)



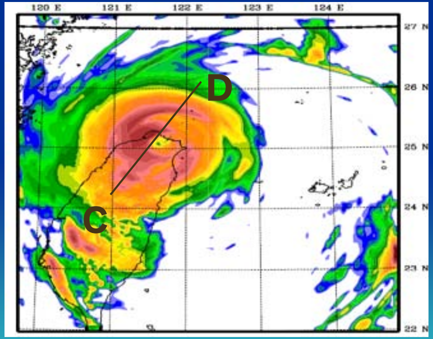
Courtesy of T.-C. Chen and Y.-C. Liou

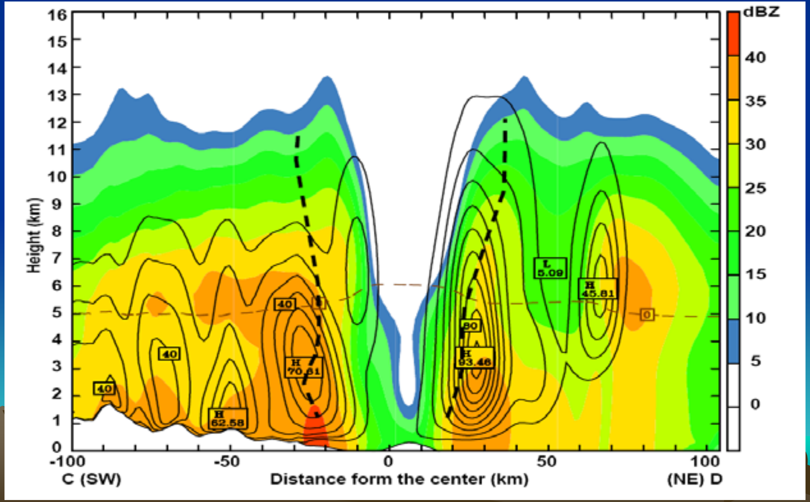




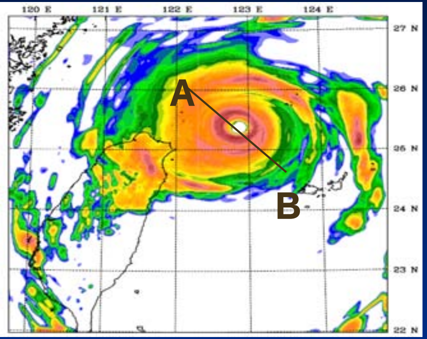
Before Landfall

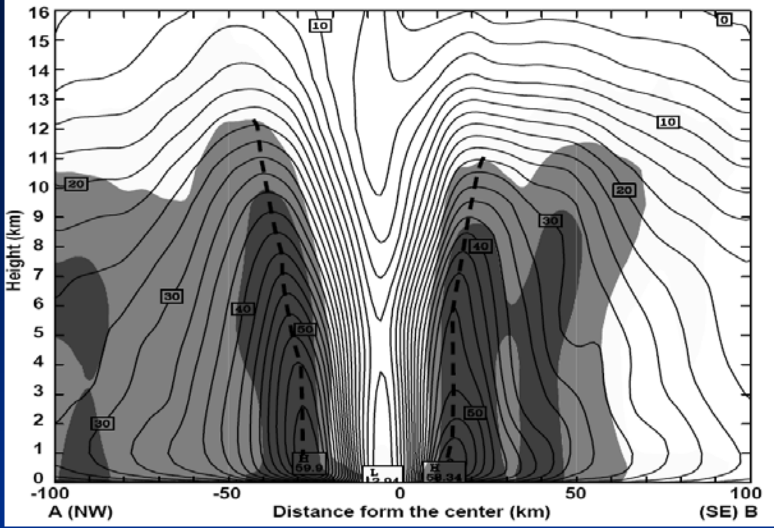
Radar Echo (color)
Condensational Heating (contour)





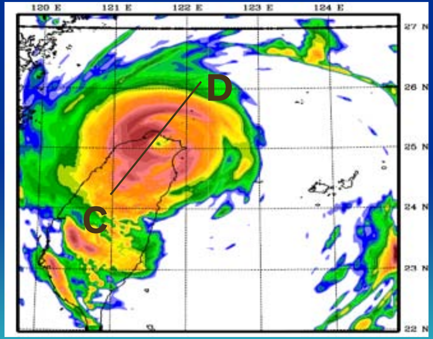
After Landfall

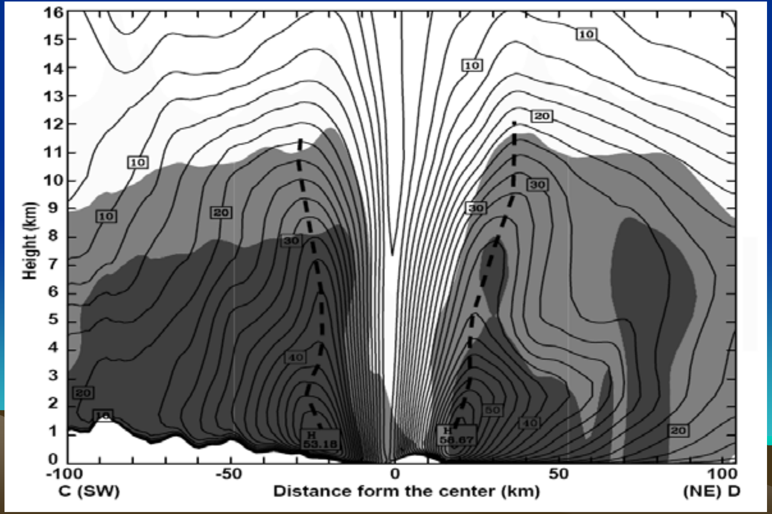




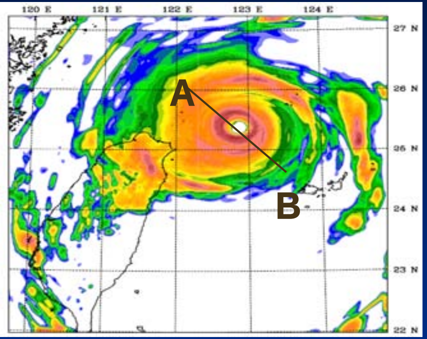
Before Landfall

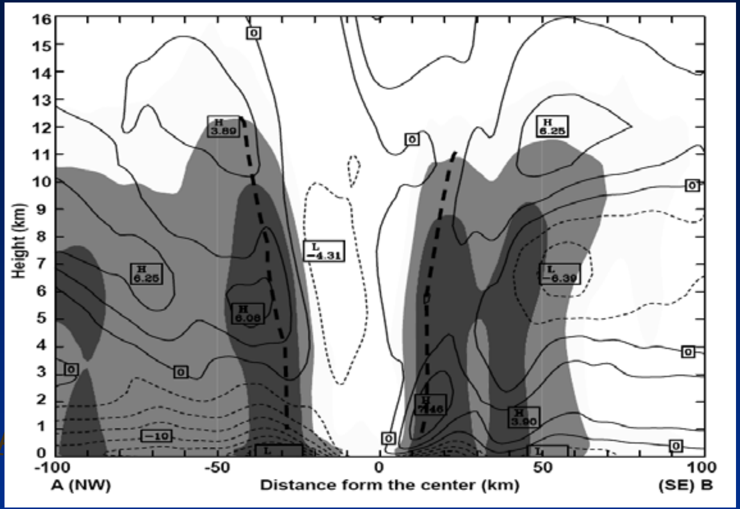
Radar Echo (shading)
Tangential Wind (contour)





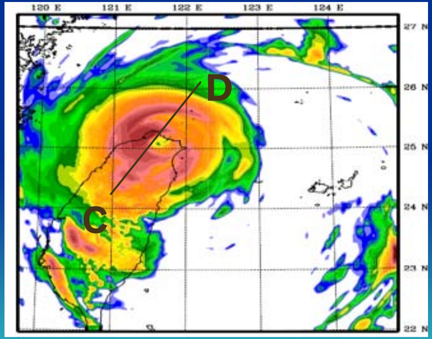
After Landfall

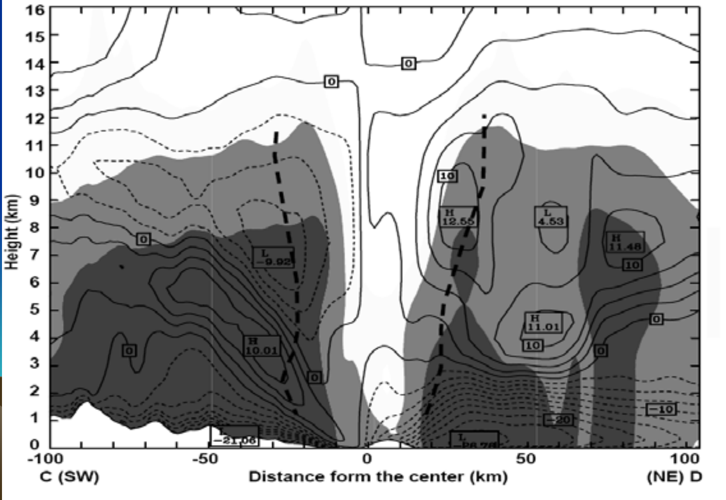




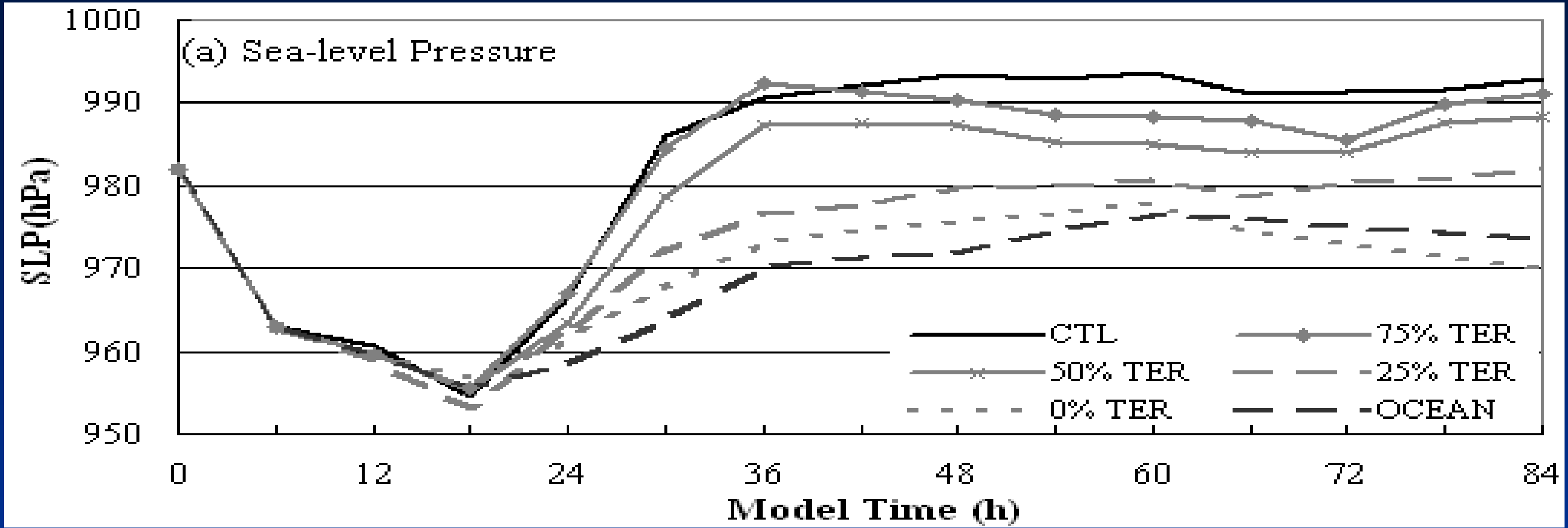
Before Landfall

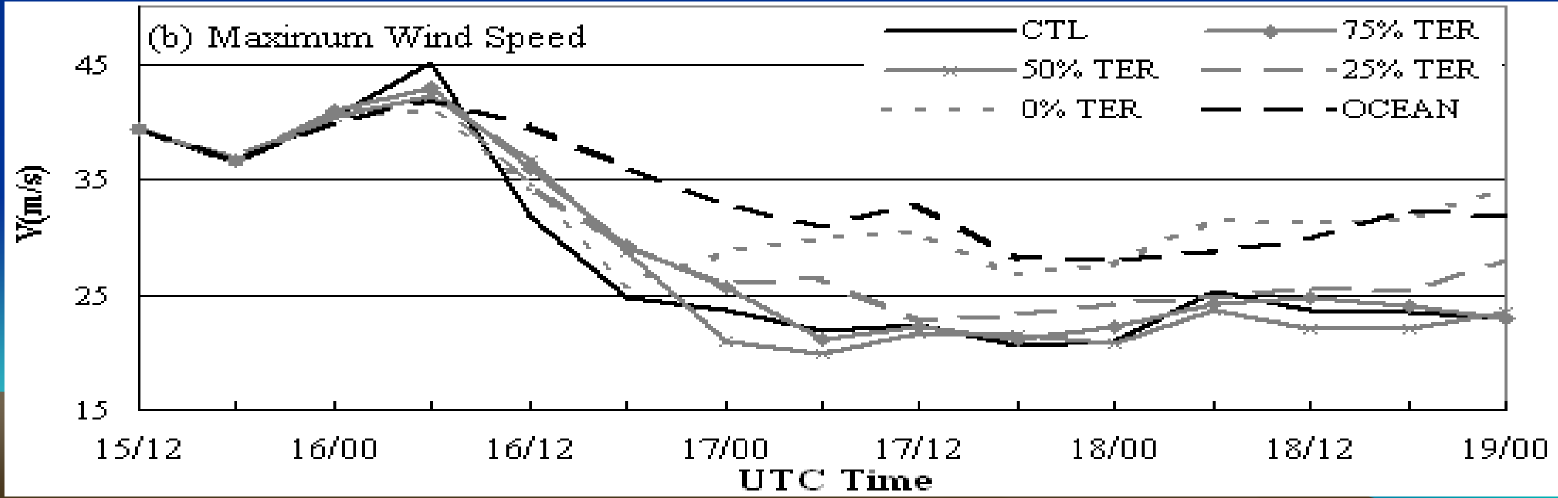
Radar Echo (shading)
Radial Wind (contour)



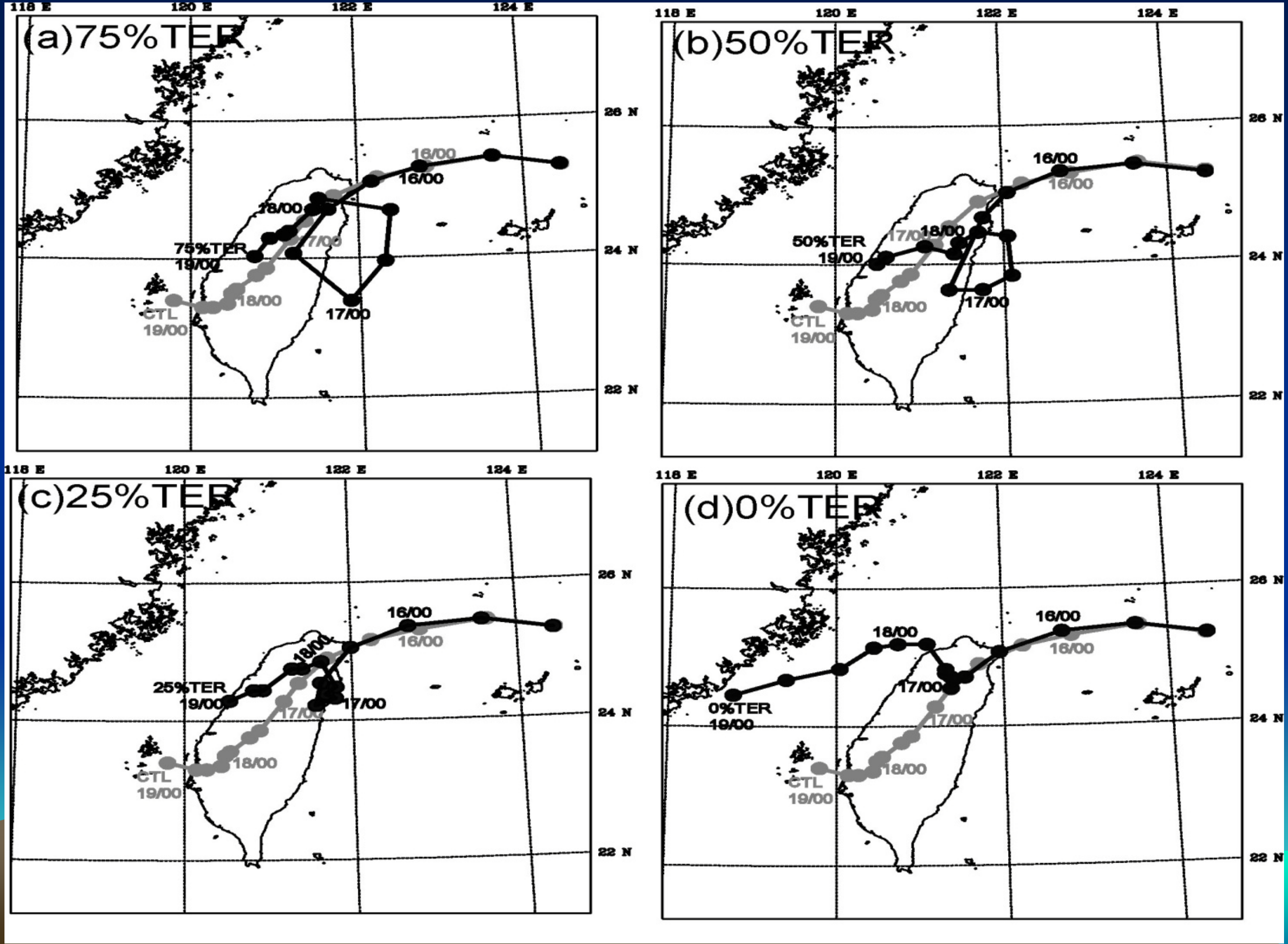


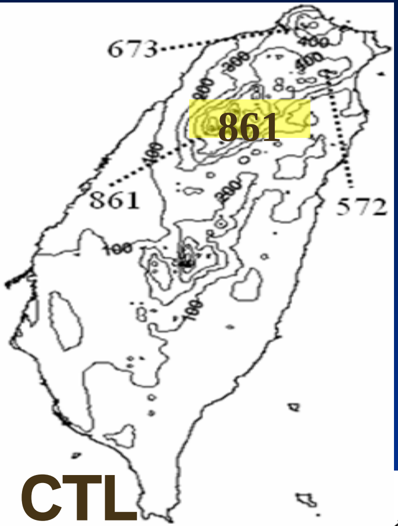
After Landfall


(a) Sea-level Pressure
SLP(hPa)
1000
990
980
970
960
950
0
12
24
36
48
60
72
84
Model Time (h)
CTL
75% TER
50% TER
25% TER
0% TER
OCEAN

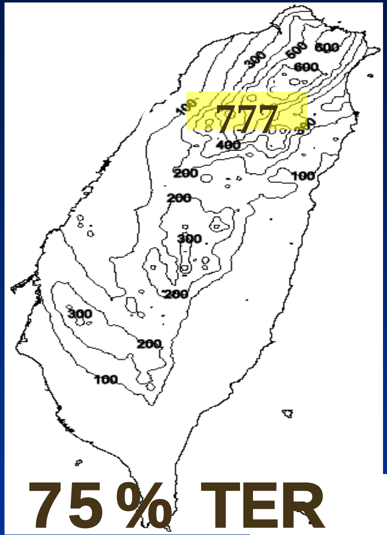

(b) Maximum Wind Speed
V(m/s)
45
35
25
15
15/12
16/00
16/12
17/00
17/12
18/00
18/12
19/00
UTC Time
CTL
75% TER
50% TER
25% TER
0% TER
OCEAN

Simulated Tracks of Terrain Experiments

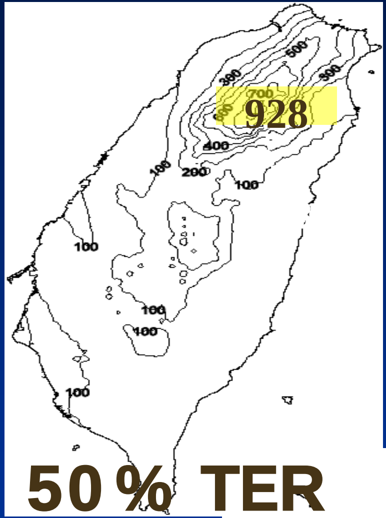




CTL

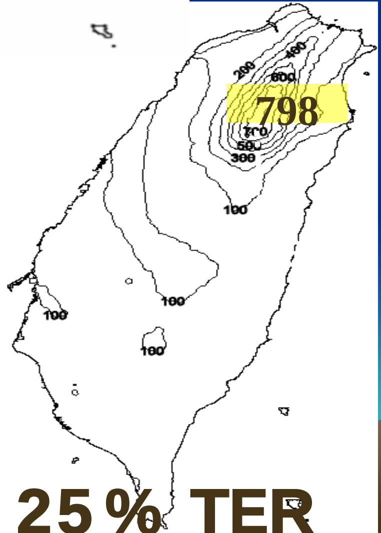


75% TER

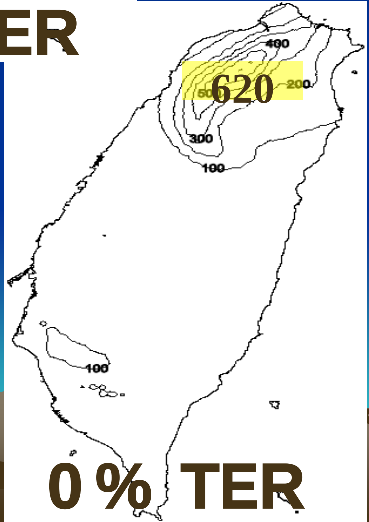


50% TER

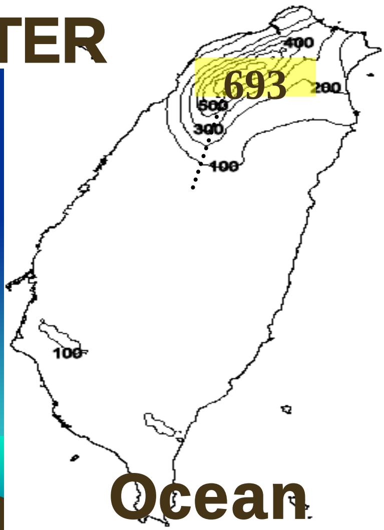
Rainfall @ 09/16 (Day 1)



25% TER



0% TER



Ocean

Conclusions

* The terrain impact on Nari's intensity is quite linear, i.e., higher terrain producing a weaker typhoon.

* However, terrain effects on Nari's track and the accumulated rainfall on Taiwan are nonlinear.

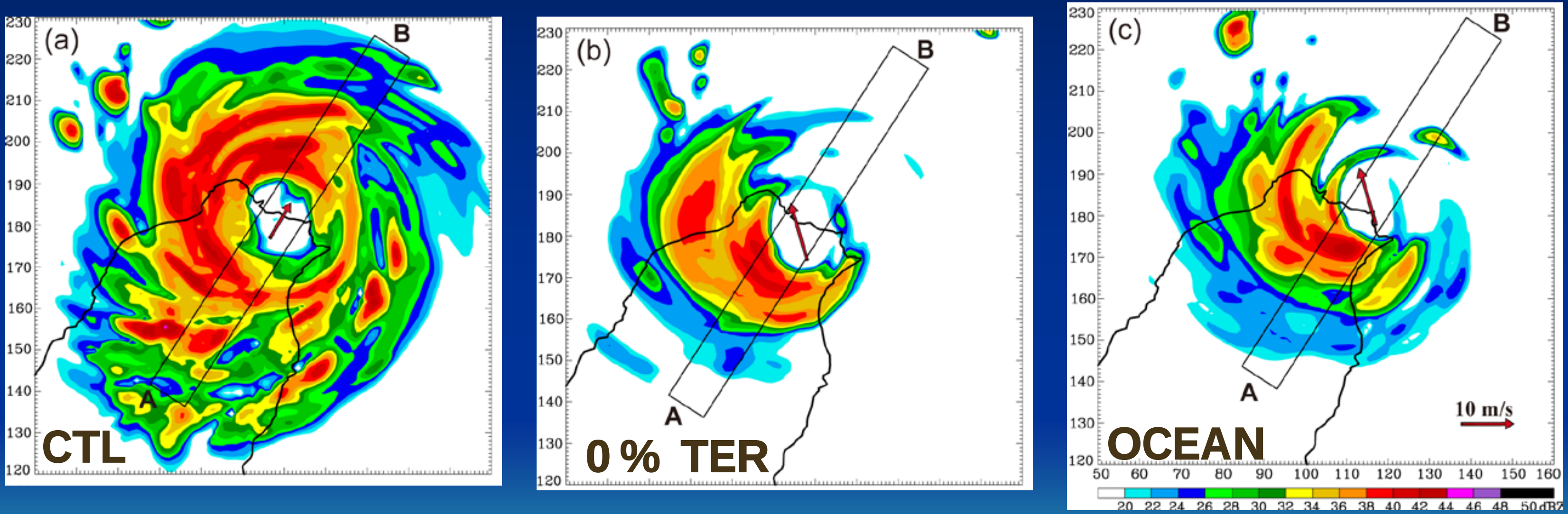
* Stronger storms of reduced terrain experience more a deeper steering layer, compared to the weaker storms over higher terrain.

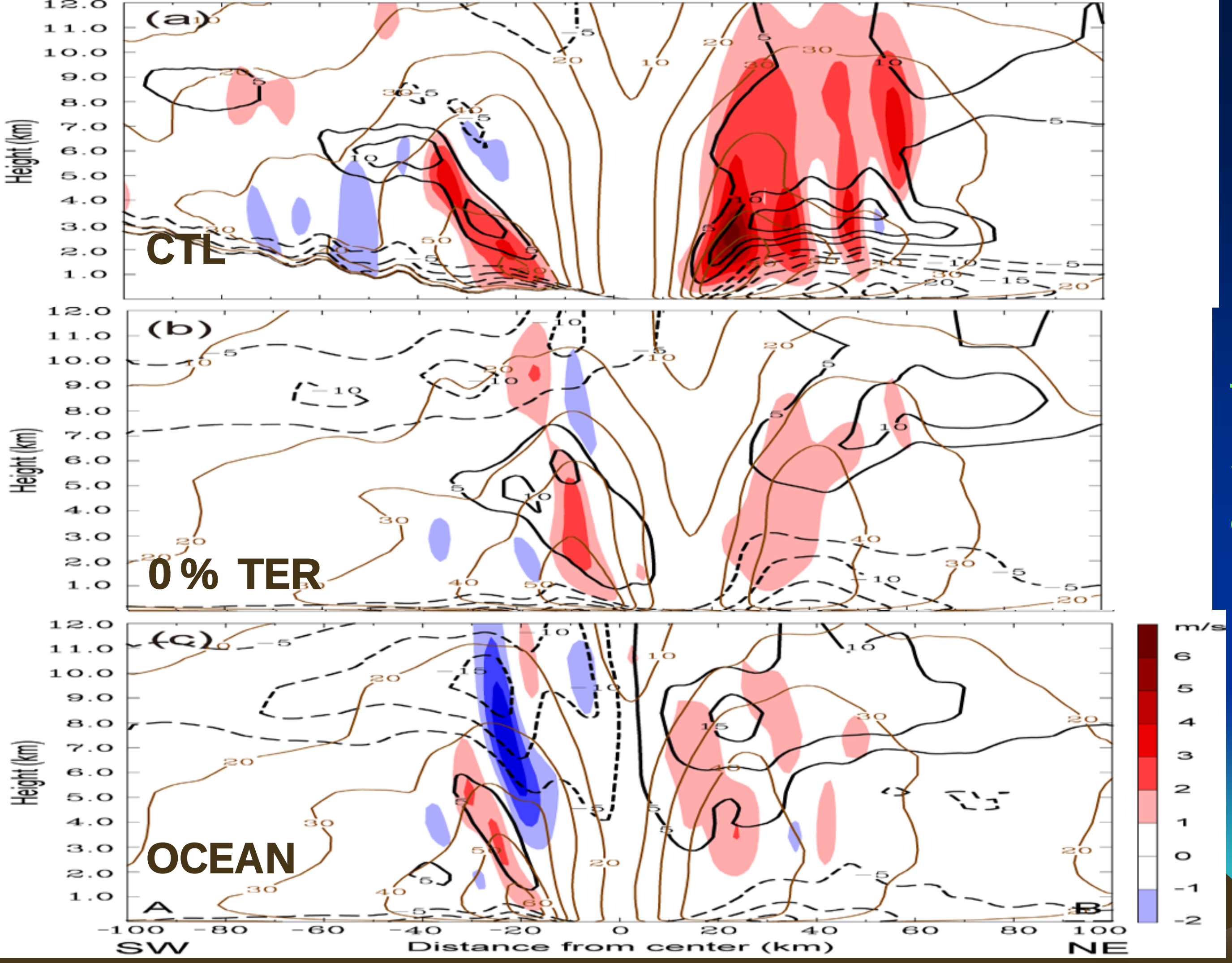
* For Day 1, the environmental wind shear determines the max. rainfall location (downshear left). For Day 2 and Day 3, the rainfall distribution is mainly decided by Taiwan's CMR.

Part II: Terrain-induced storm asymmetry and eyewall breakdown

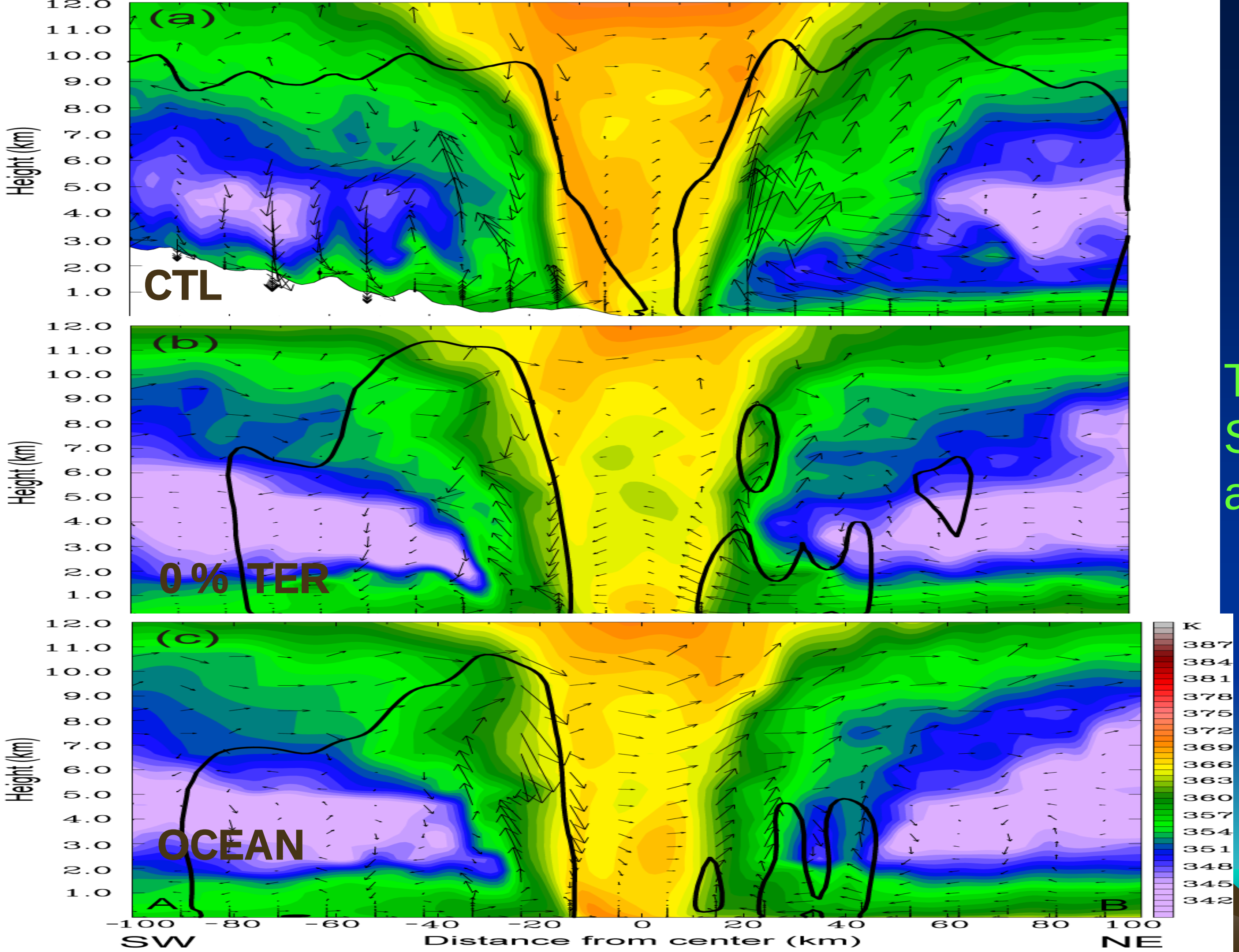
- Yang, M.-J.*, D.-L. Zhang, X.-D. Tang, and Y. Zhang, 2011: A modeling study of Typhoon Nari (2001) at landfall. Part II: Structural changes and terrain-induced asymmetries. *J. Geophys. Res.*, **116**, D09112, doi:10.1029/2010JD015445.

Radar reflectivity and wind shear vector at the time of landfall





Tangential wind & Secondary circulation at the time of landfall

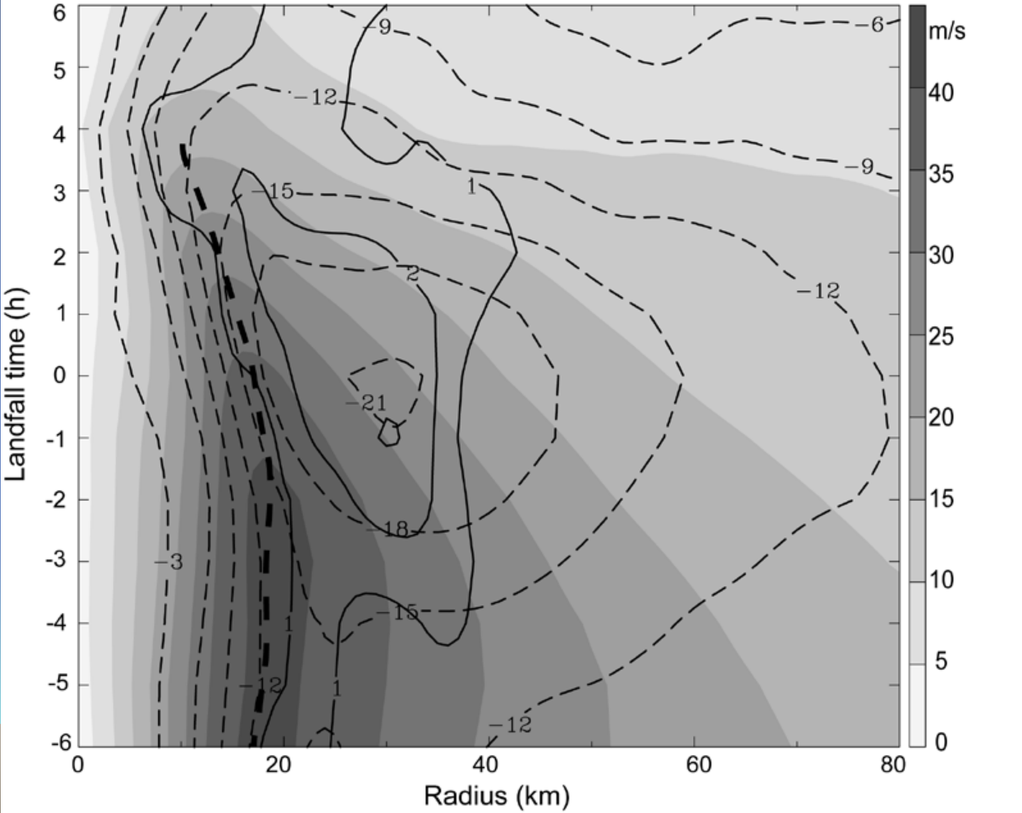


Theta-E & Secondary Cir. Vector at the time of landfall

Contraction of inner-core circulation during landfall

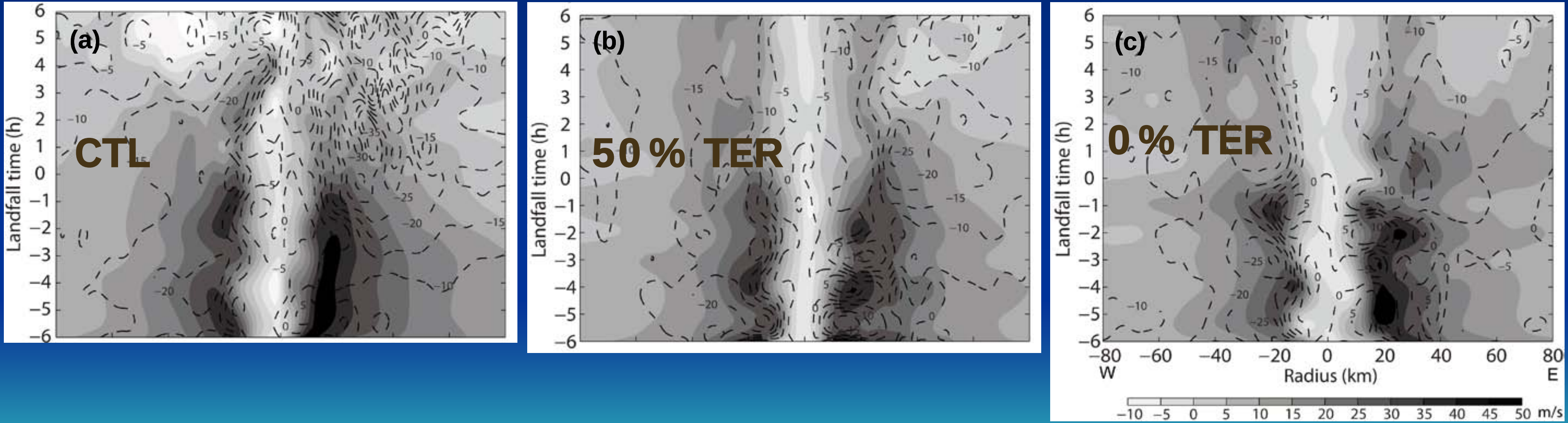
Evolution of
Axis-symmetric
Circulation:

Sfc Vt (shading)
Sfc Vr (dashed)
700-hPa W(contour)
RMW (heavy dashed)

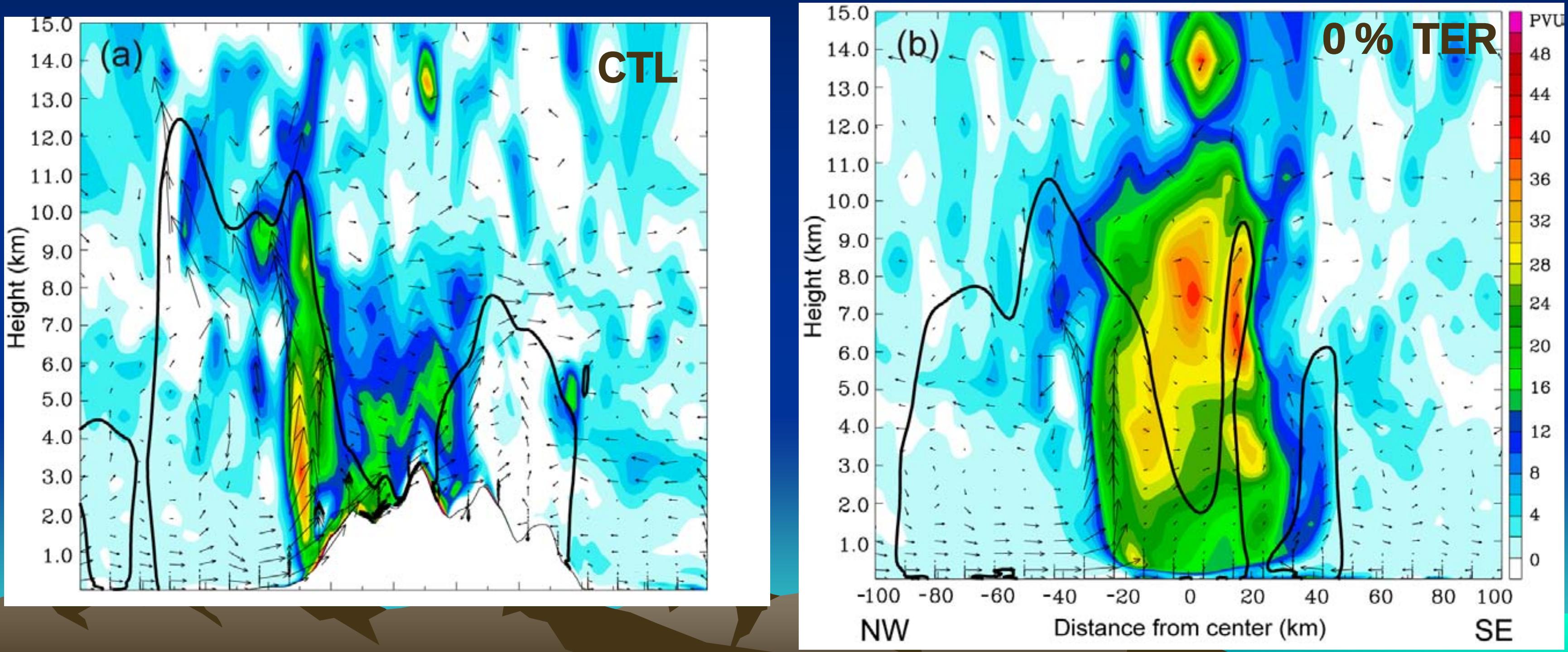


Contraction of inner-core circulation during landfall among terrain sensitivity experiments

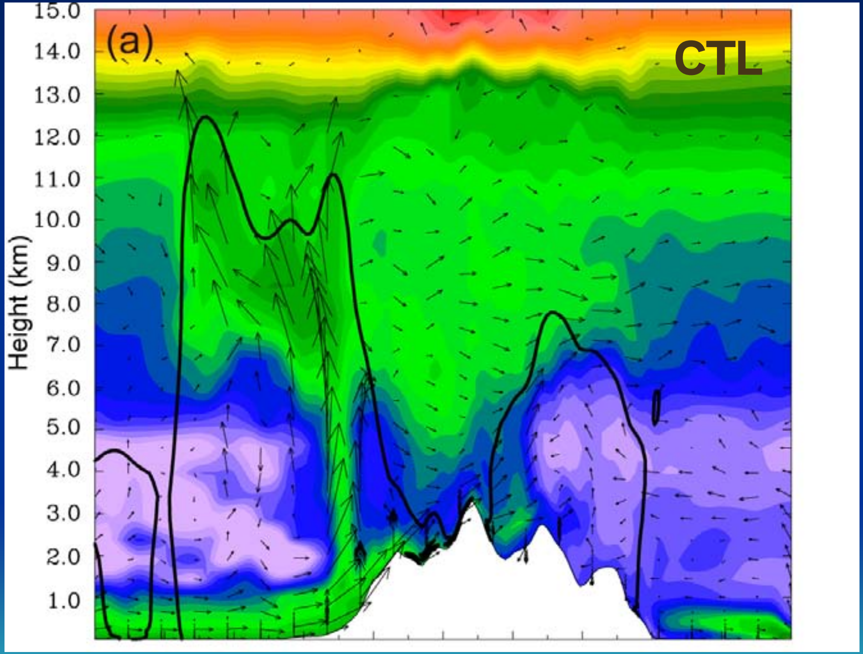
- Evolution of Sfc Vt and Vr in cross-track direction

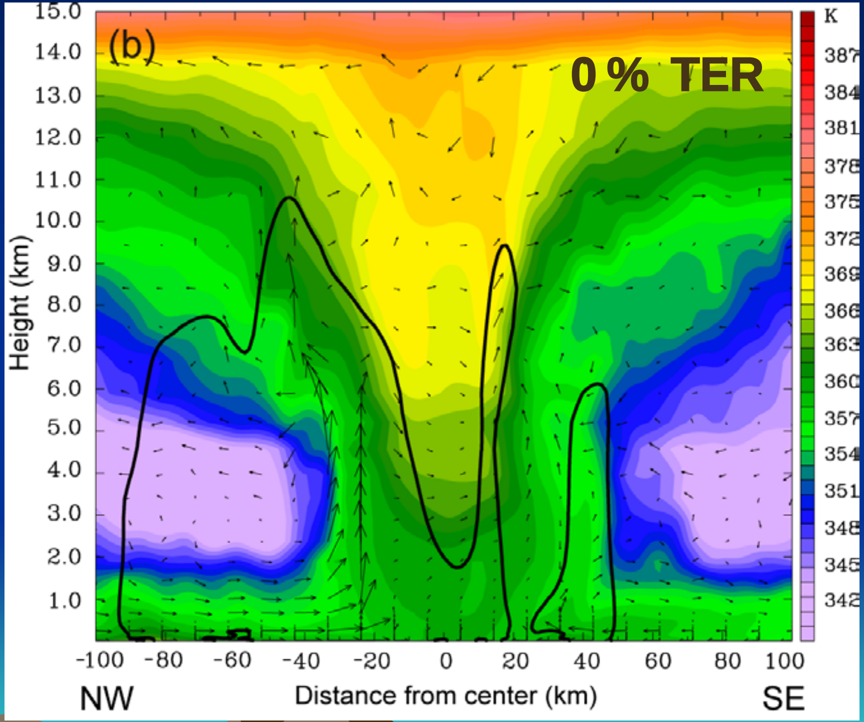


PV (colored) and in-plane flow vectors

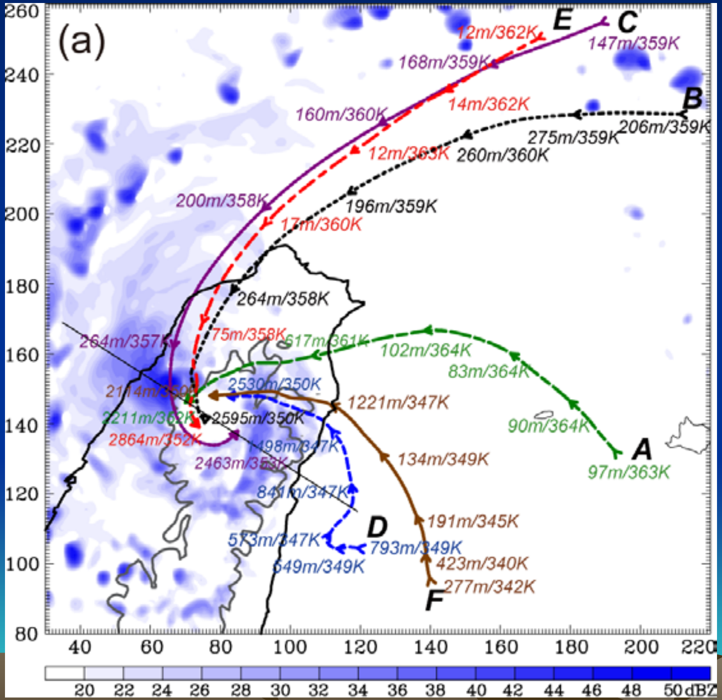


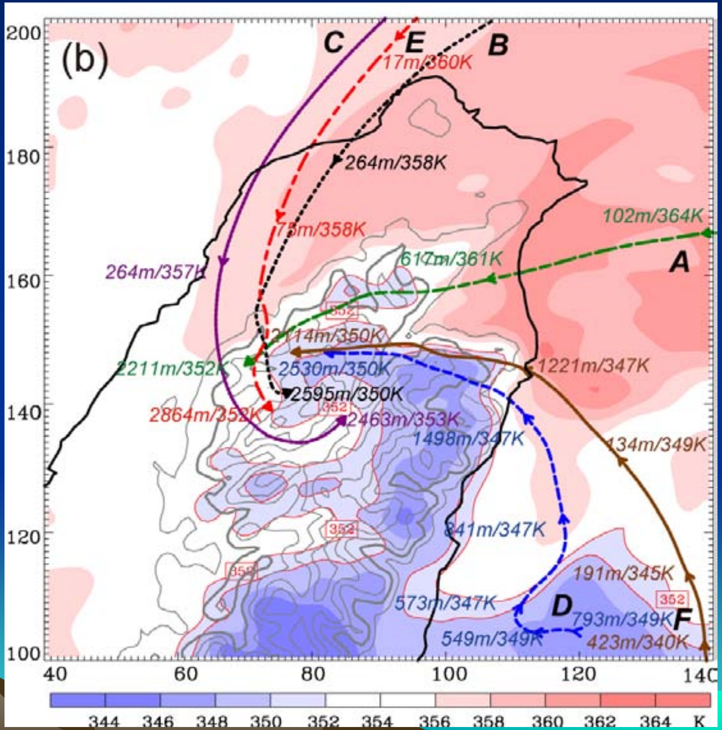
Theta-E (colored) and in-plane flow vectors





Backward air-parcel trajectory analysis to trace the source of low theta-E air





Conclusions

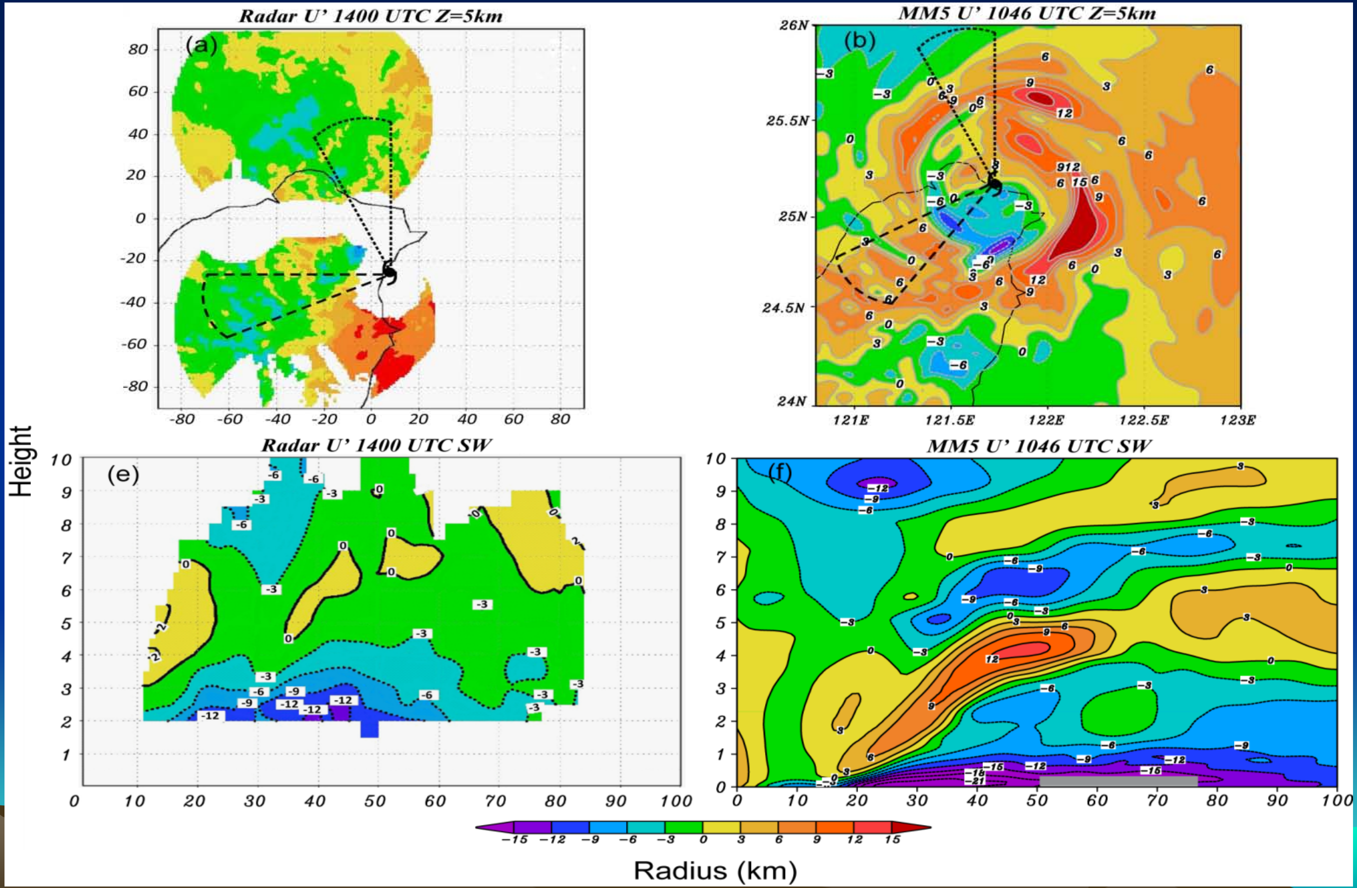
- After landfall, the tangential flow is weakened but the low-level inflow and radial outflow above the terrain are strengthened, due to the increased terrain blocking and surface friction.
- The mid-level radial outflow in the eyewall tilts more outward after landfall, as the dynamic response of Nari’s tangential circulation to the CMR.
- The radii of the near-surface maximum wind and the midlevel eyewall updraft could continue to contract even after landfall due to the continued rapid release of latent heat.
- Because of its high elevation, the CMR allows Nari’s vortex circulation to access the midlevel low theta-e air.
- The intrusion of low theta-e air into the inner-core region causes the breakdown of the eyewall and dilution of the high theta-e air in the eye’s boundary layer.

Part III: Momentum Budget

- Yang, M.-J.*, T.-C. Chen Wang, Y. Zhang, and C.-Y. Weng, 2011: Momentum budget evolution of Typhoon Nari (2001) during the landfall process. *Terr., Atmos., and Oceanic Sci.*, **22**, 595–612, doi:10.3319/TAO.2011.05.31.01(TM).

SMR's terrain impact on Nari's radial-wind structure

Radar Observation | MM5 Simulation



Radial Momentum Budget

- Following Zhang et al. (2001), the governing equation for the radial momentum can be written as

$$\frac{dU}{dt} = -\frac{1}{\rho}\frac{\partial p}{\partial r} + \frac{V^2}{r} + fV - 2\Omega \cos\phi W \cos\lambda + U_D$$

- where

$$\frac{d}{dt} = \frac{\delta}{\delta t} + U'\frac{\partial}{\partial r} + \frac{V'}{r}\frac{\partial}{\partial \lambda} + W\frac{\partial}{\partial z}$$

- and *W*, *U*, and *V* are the vertical, radial and tangential winds; *U'* and *V'* are the horizontal wind components relative to the storm.

Absolute Angular Momentum (AAM) Budget

- The governing equation for the tangential wind (*V*) can be written as

$$\frac{dV}{dt} = \frac{1}{\rho}\frac{\partial p}{r\partial\lambda} - \frac{UV}{r} - fU + 2\Omega\cos\phi W\sin\lambda + V_D$$

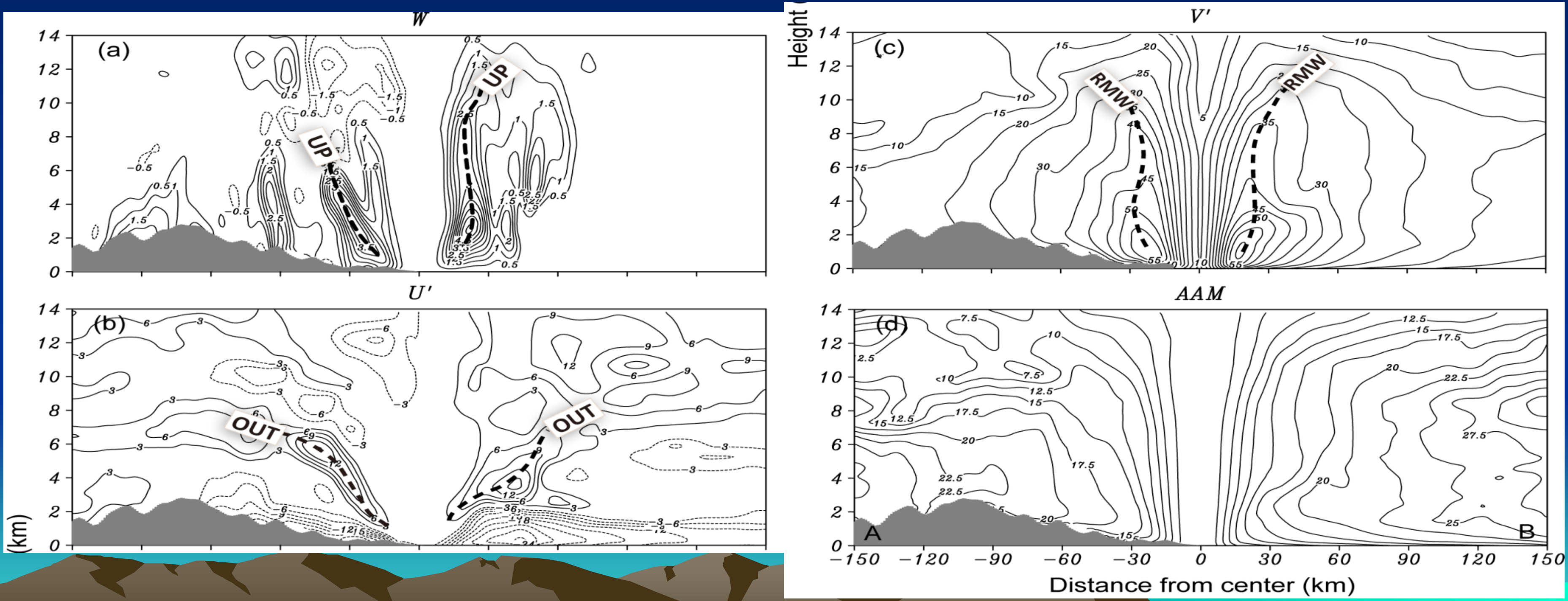
- Using the definition of AAM (or *M*),

$$M = r(V + \frac{fr}{2})$$

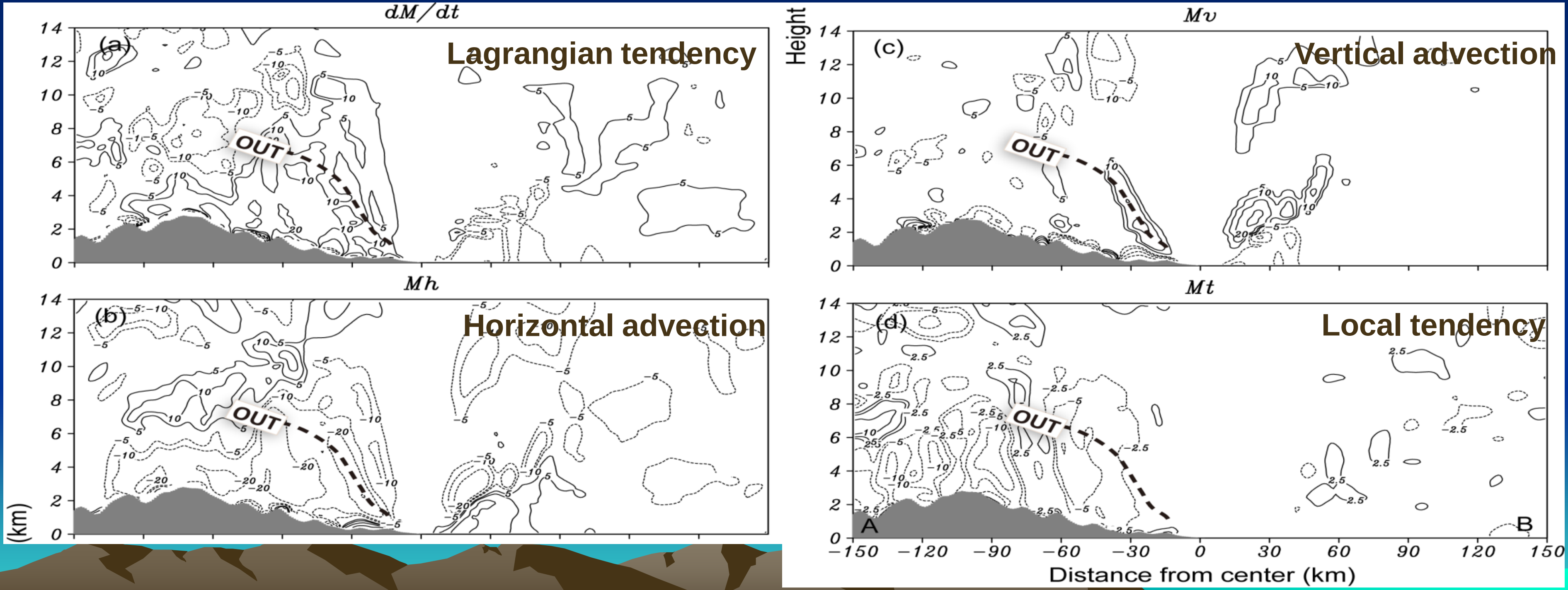
- the above equation can be rewritten as

$$\frac{dM}{dt} = -\frac{1}{\rho}\frac{\partial p}{\partial\lambda} - 2r\Omega\cos\phi W\sin\lambda + \frac{r^2}{2}v_m\beta + rV_D$$

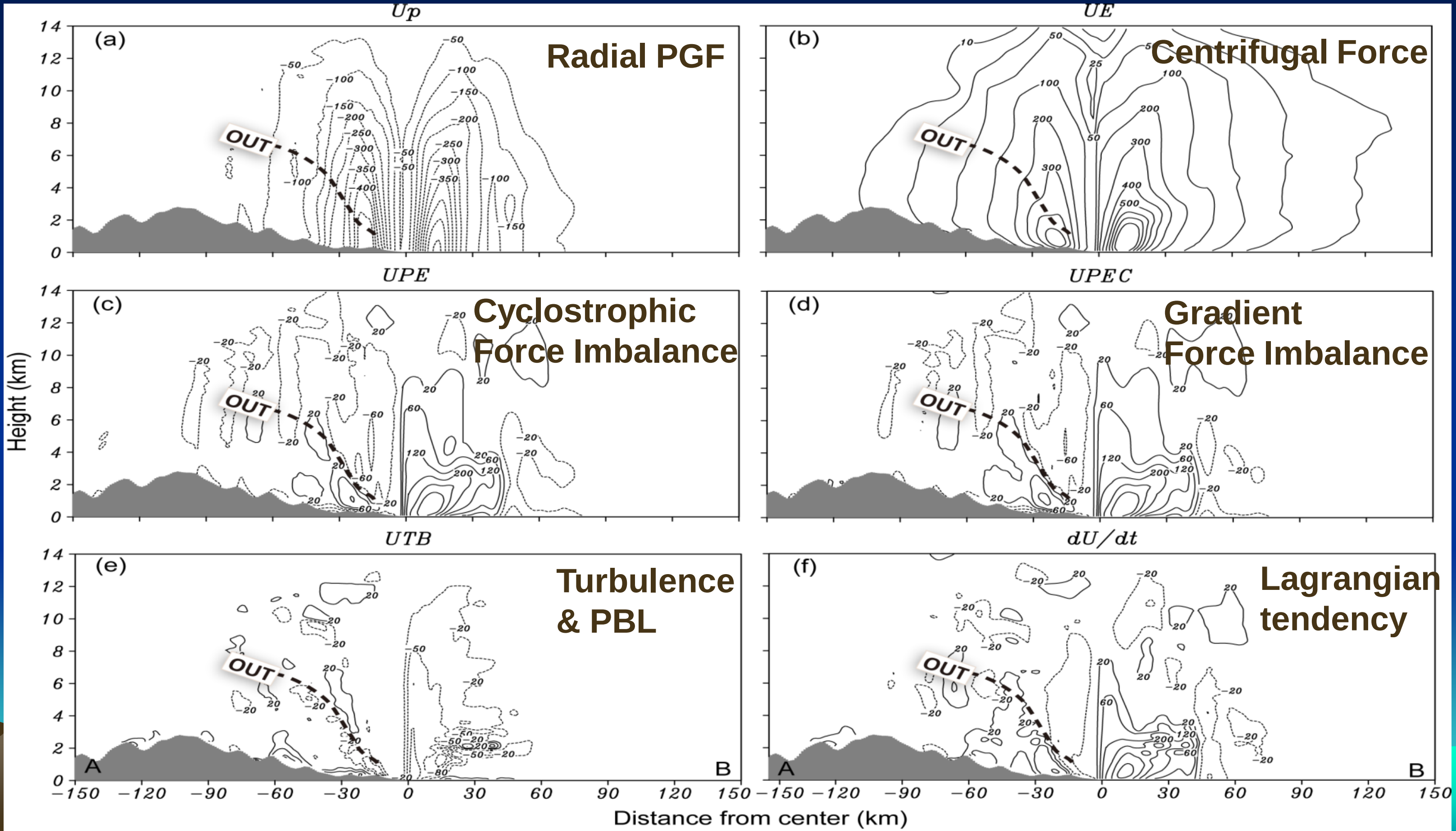
Along-track vertical cross sections of vertical velocity (*W*), radial winds (*U'*), tangential winds (*V'*), and AAM after landfall



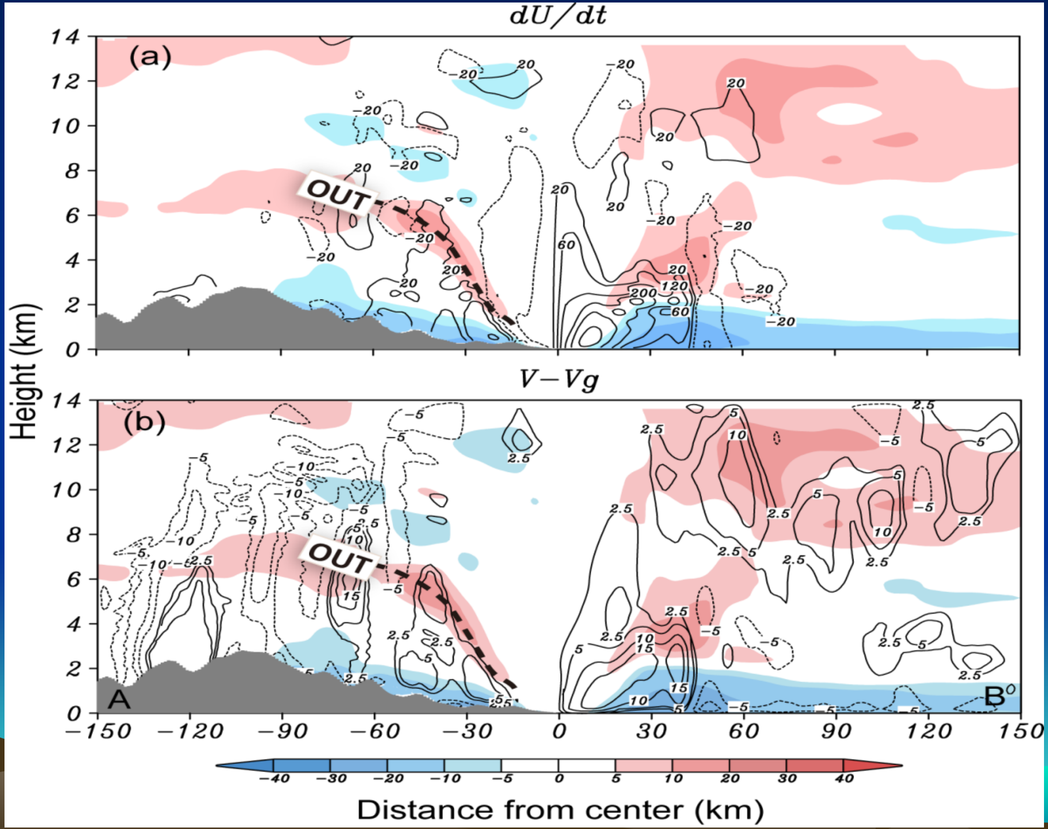
The hourly-averaged AAM budget of Typhoon Nari after landfall



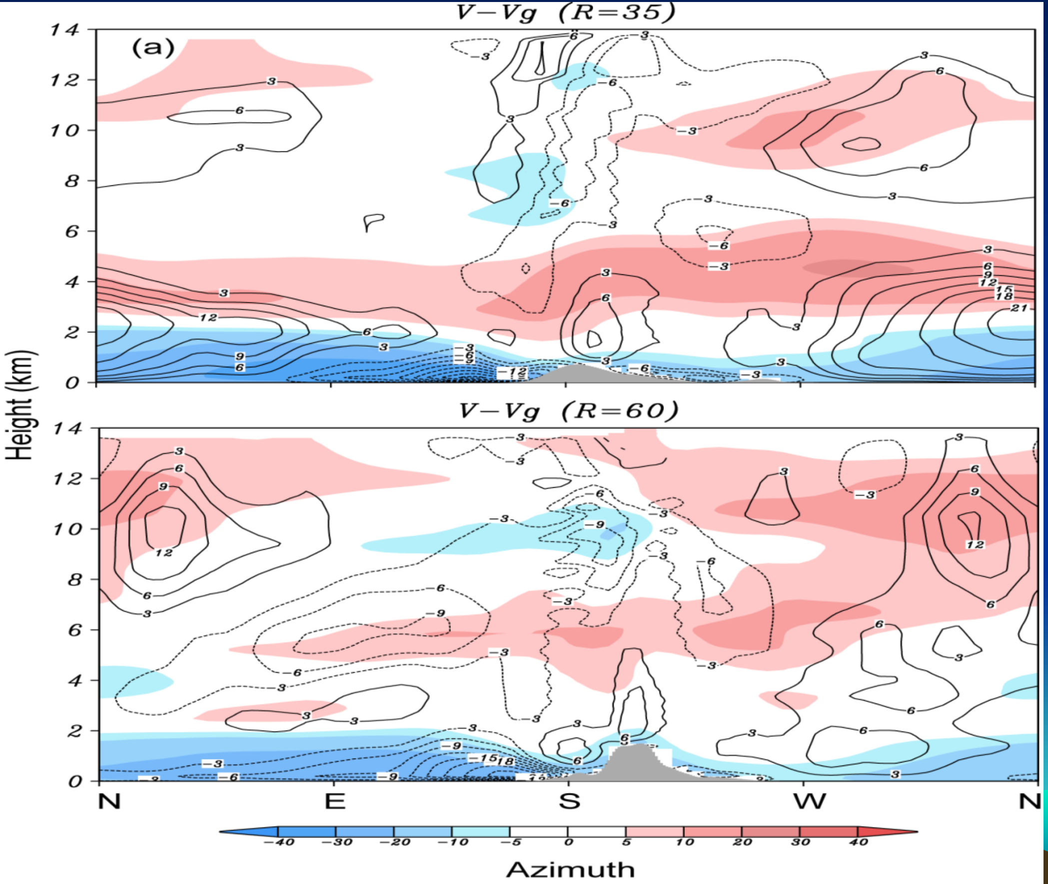
The hourly-averaged radial-momentum budget after landfall



Along-track vertical cross section of Lagrangian tendency (*dU/dt*) Agradient wind (*V–Vg*), *and Radial wind (U; colored)* after landfall



Vertical cross sections of Agradient Tangential Wind (*V–Vg*) and Radial Wind (*U*; colored) for the circles of *r* = 35 km, 60 km



Conclusions

- After Nari's landfall on Taiwan, both the radar observation and model simulation indicate that the radial inflows at lower levels become thicker and stronger over land, and the sloping radial outflow jet is maximized at the midlevel above the rugged topography.
- Centrifugal and Coriolis forces overcompensate the pressure-gradient force, resulting in supergradient accelerations above the SMR.
- The vertical transport of supergradient accelerations by strong updrafts inside the eyewall above terrain produces the sloping midlevel radial outflows.

Part IV: Water budget

- Yang, M.-J.*, S. A. Braun, and D.-S. Chen, 2011: Water budget of Typhoon Nari (2001). *Mon. Wea. Rev.*, **139**, 3809–3828.

Budget Equations

- Water vapor budget: q_v

$$\frac{\partial q_v}{\partial t} = -\nabla \cdot (q_v \mathbf{V}') - \frac{\partial (q_v w)}{\partial z} + q_v \left(\nabla \cdot \mathbf{V}' + \frac{\partial w}{\partial z} \right) - C + E + B_v + D_v + Resd_v$$

- where $\mathbf{V}'$ is the storm-relative horizontal air motion;

  w is the vertical air motion;

  C is the condensation and deposition;

  E is the evaporation and sublimation;

  B_v is contribution by PBL and turbulence;

  D_v is the numerical diffusion term for vapor

  $Resd_v$ is the residual term for vapor.

Budget Equations

- Cloud budget: $q_c = q_w + q_i$

$$\frac{\partial q_c}{\partial t} = -\nabla \cdot (q_c \mathbf{V}') - \frac{\partial (q_c w)}{\partial z} + q_c \left(\nabla \cdot \mathbf{V}' + \frac{\partial w}{\partial z} \right) + Q_{c+} - Q_{c-} + B_c + D_c + Resd_c$$

- where

Q_{c+} is the microphysical source term;

Q_{c-} is the microphysical sink term;

B_c is the contribution by the PBL and turbulence;

D_c is the numerical diffusion term for clouds;

$Resd_c$ is the residual term for clouds

Budget Equations

- Precipitation budget: $q_p = q_r + q_s + q_g$

$$\frac{\partial q_p}{\partial t} = -\nabla \cdot (q_p \mathbf{V}') - \frac{\partial (q_p w)}{\partial z} + q_p\left(\nabla \cdot \mathbf{V}' + \frac{\partial w}{\partial z}\right) + \frac{1}{\rho}\frac{\partial (\rho q_p V_T)}{\partial z} + Q_{p+} - Q_{p-} + D_p + Resd_p$$

$$C - E = Q_{c+} - Q_{c-} + Q_{p+} - Q_{p-}$$

where

Q_{p+} is the microphysical source term;

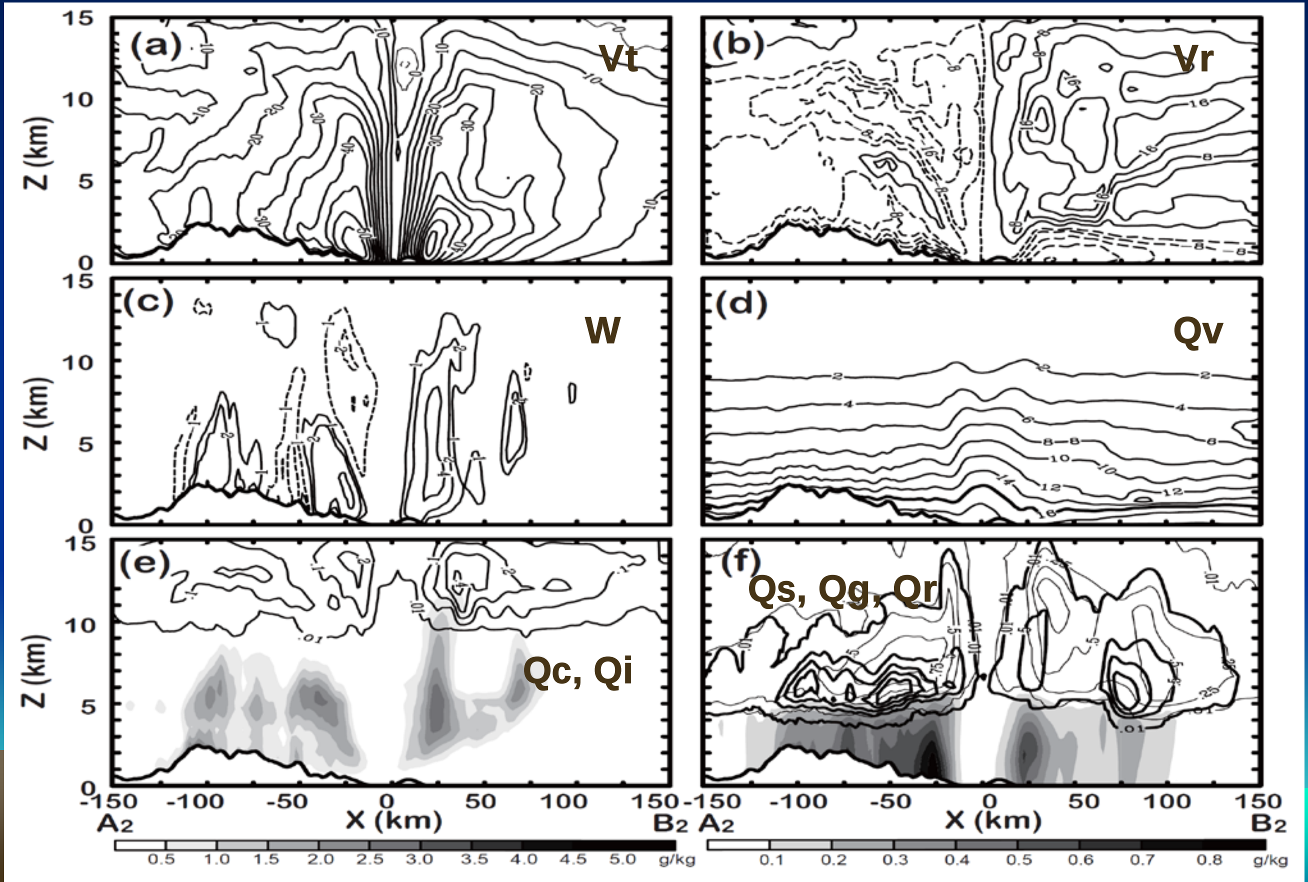
Q_{p-} is the microphysical sink term;

D_p is the numerical diffusion term for precipitation;

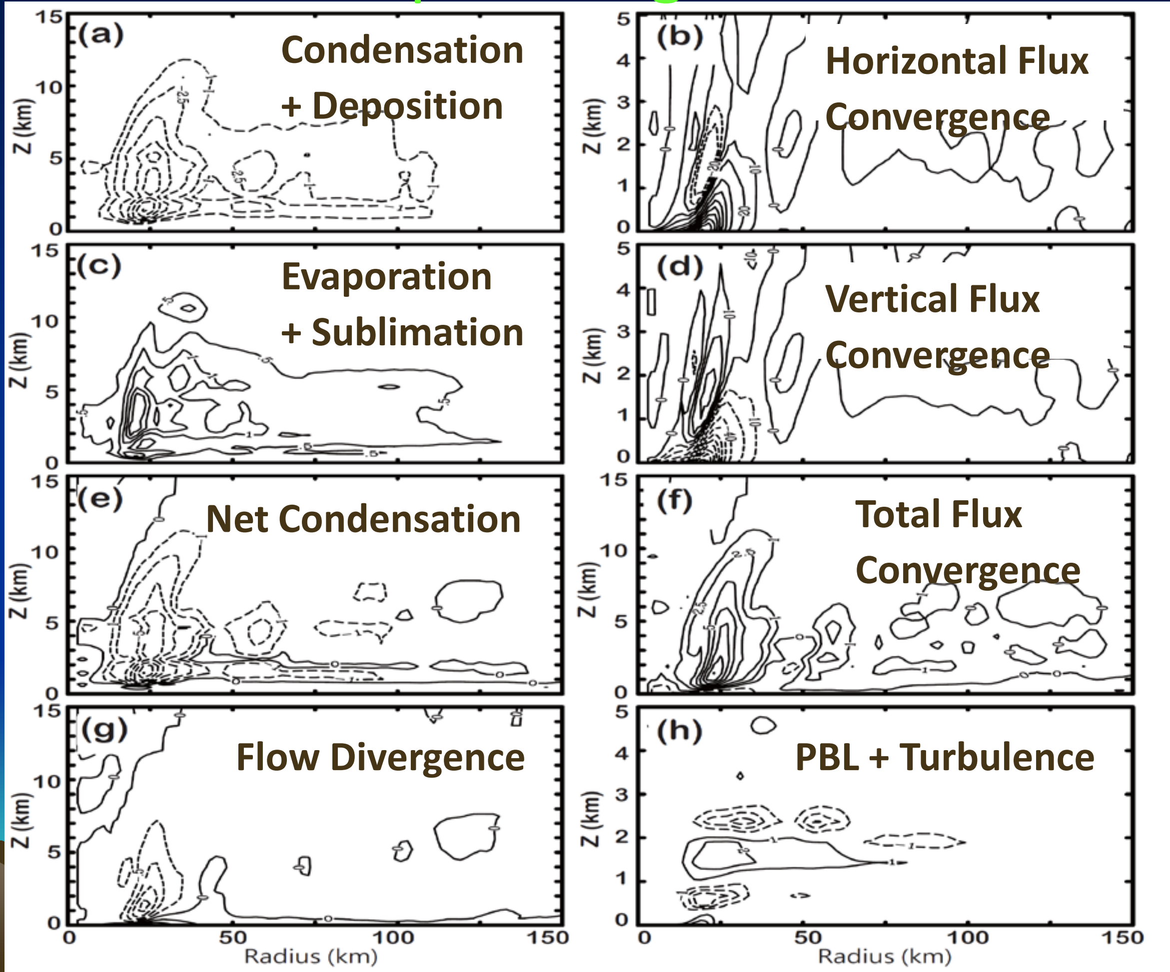
$Resd_p$ is the residual term for precipitation;

V_T is the hydrometeor terminal velocity

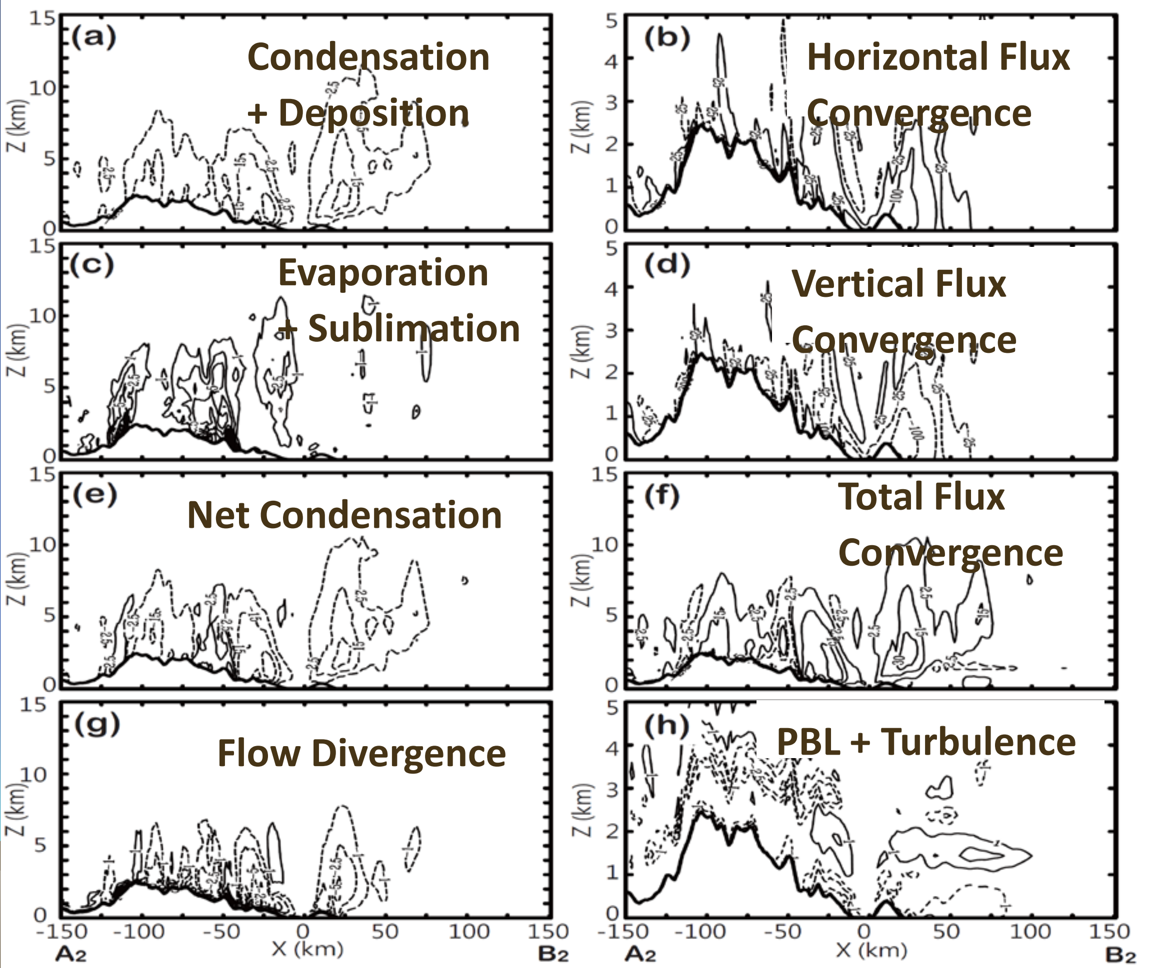
Nari Structure over Land in along-track direction



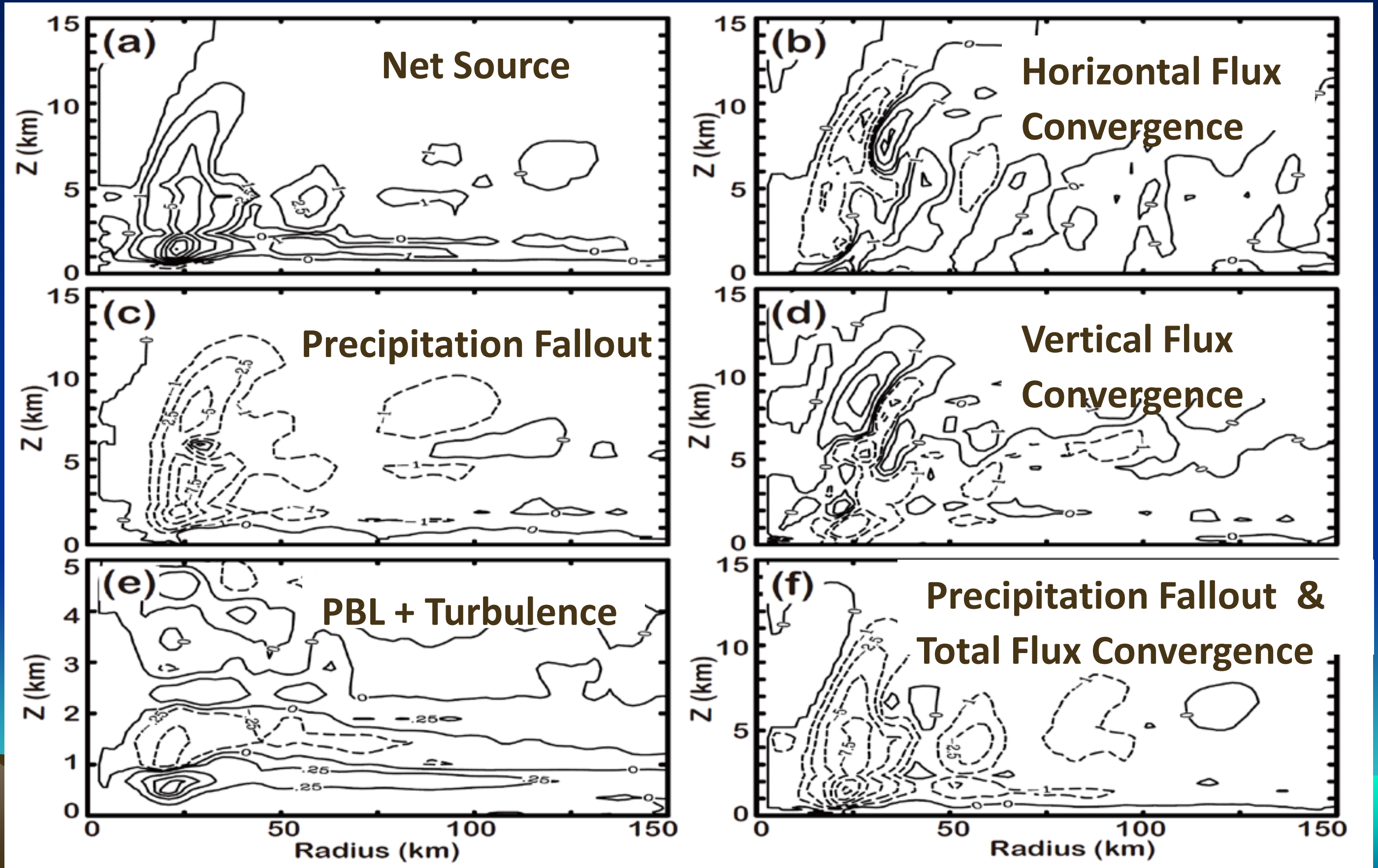
Axis-symmetric Water-Vapor Budget Terms for Oceanic Nari



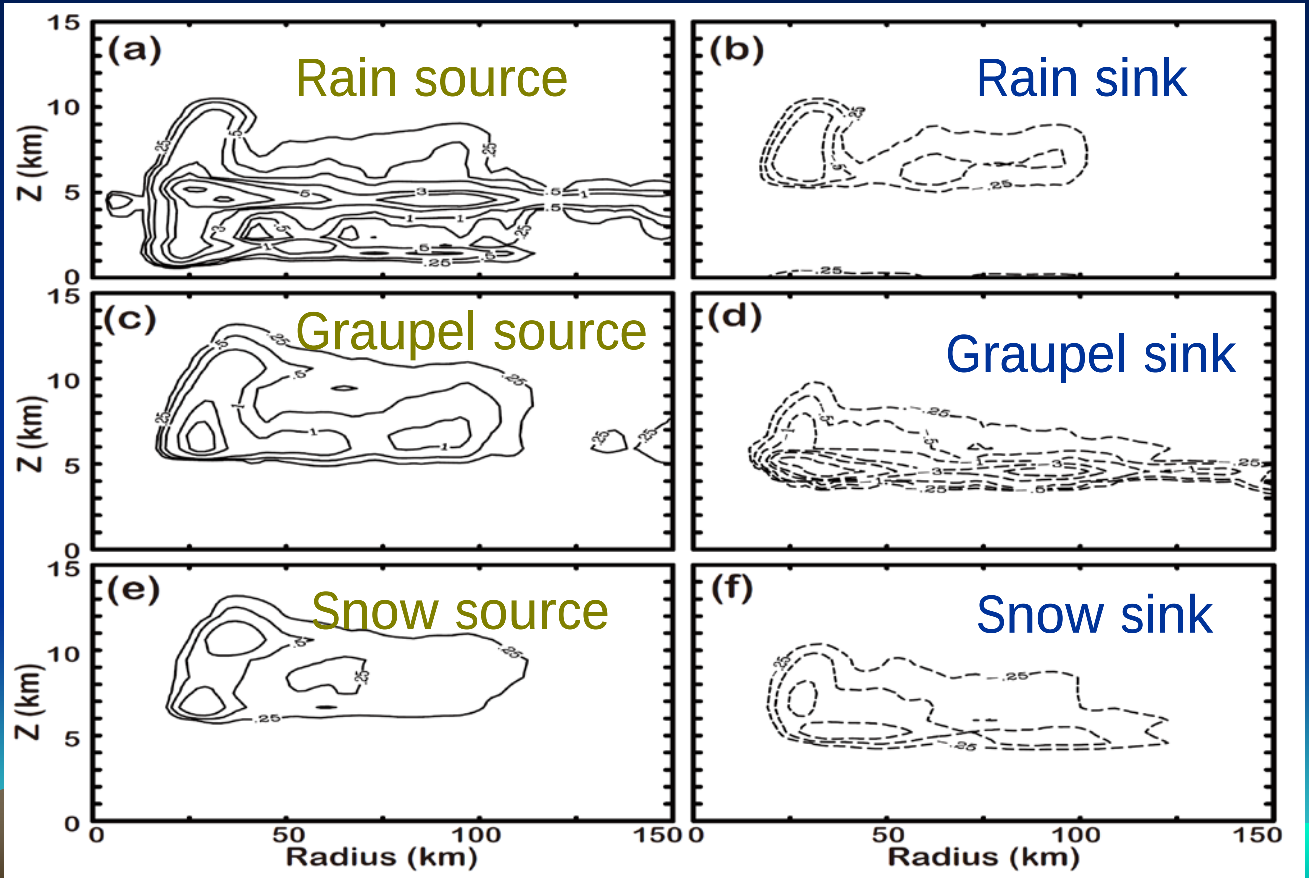
Water-Vapor Budget Terms for Landfall Nari in across-track direction



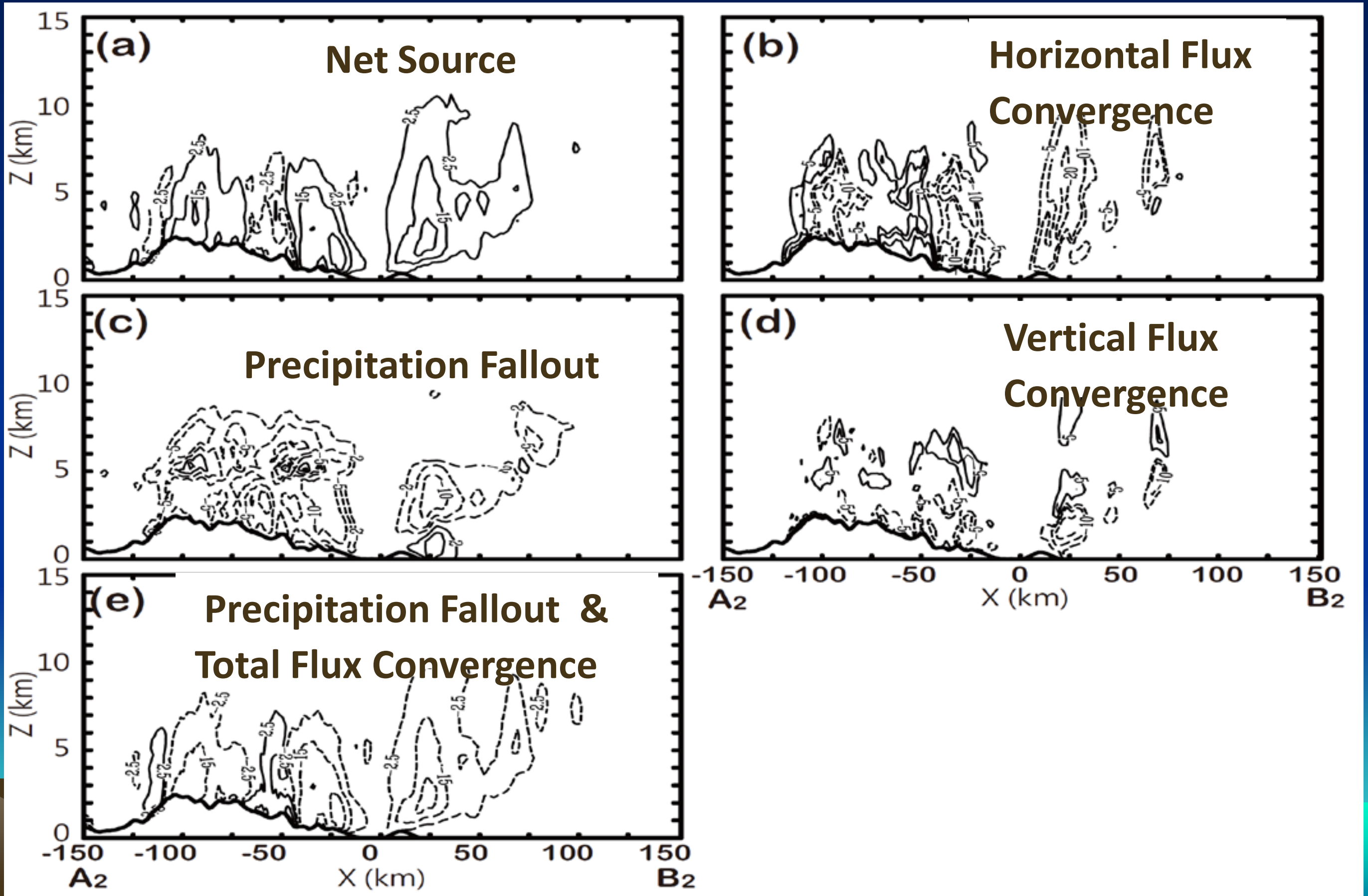
Axis-symmetric Liquid/Ice Water Budget Terms for Oceanic Nari



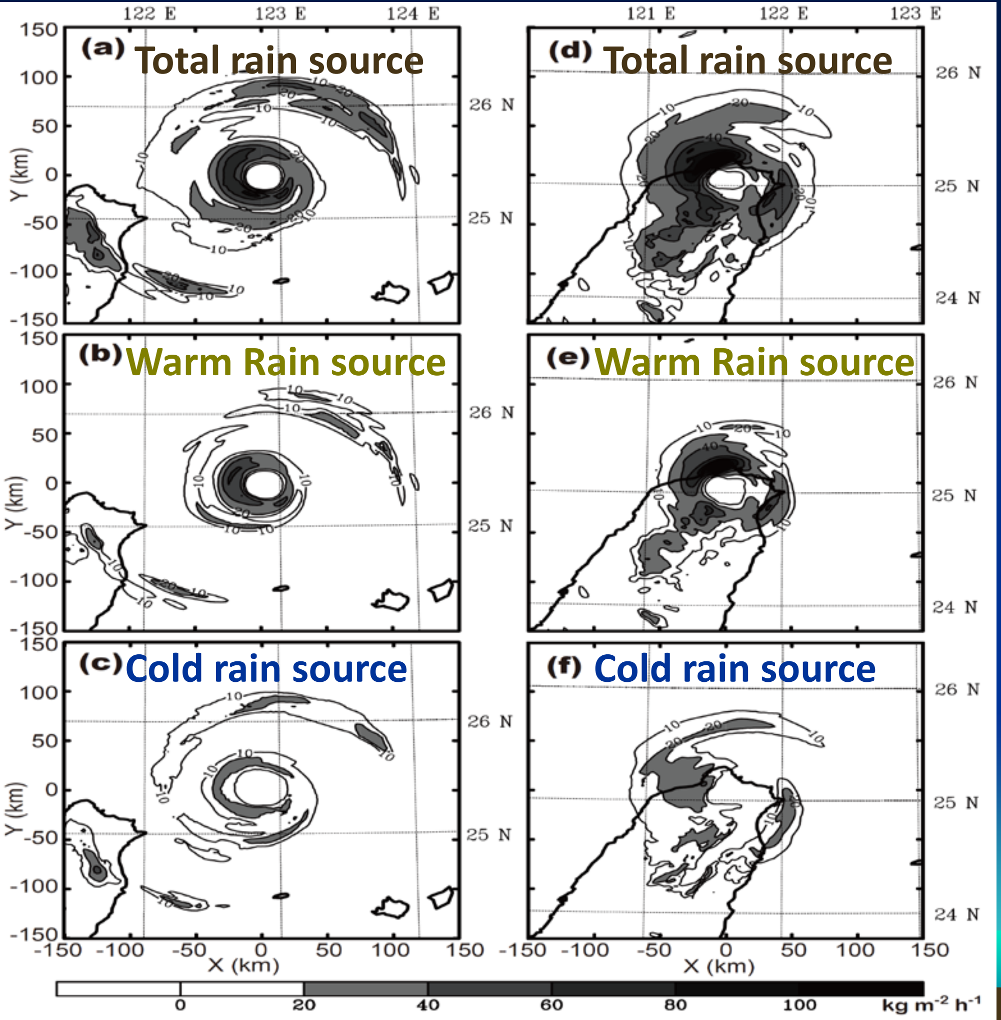
Axis-symmetric Hydrometeor Source/Sink Terms for Oceanic Nari



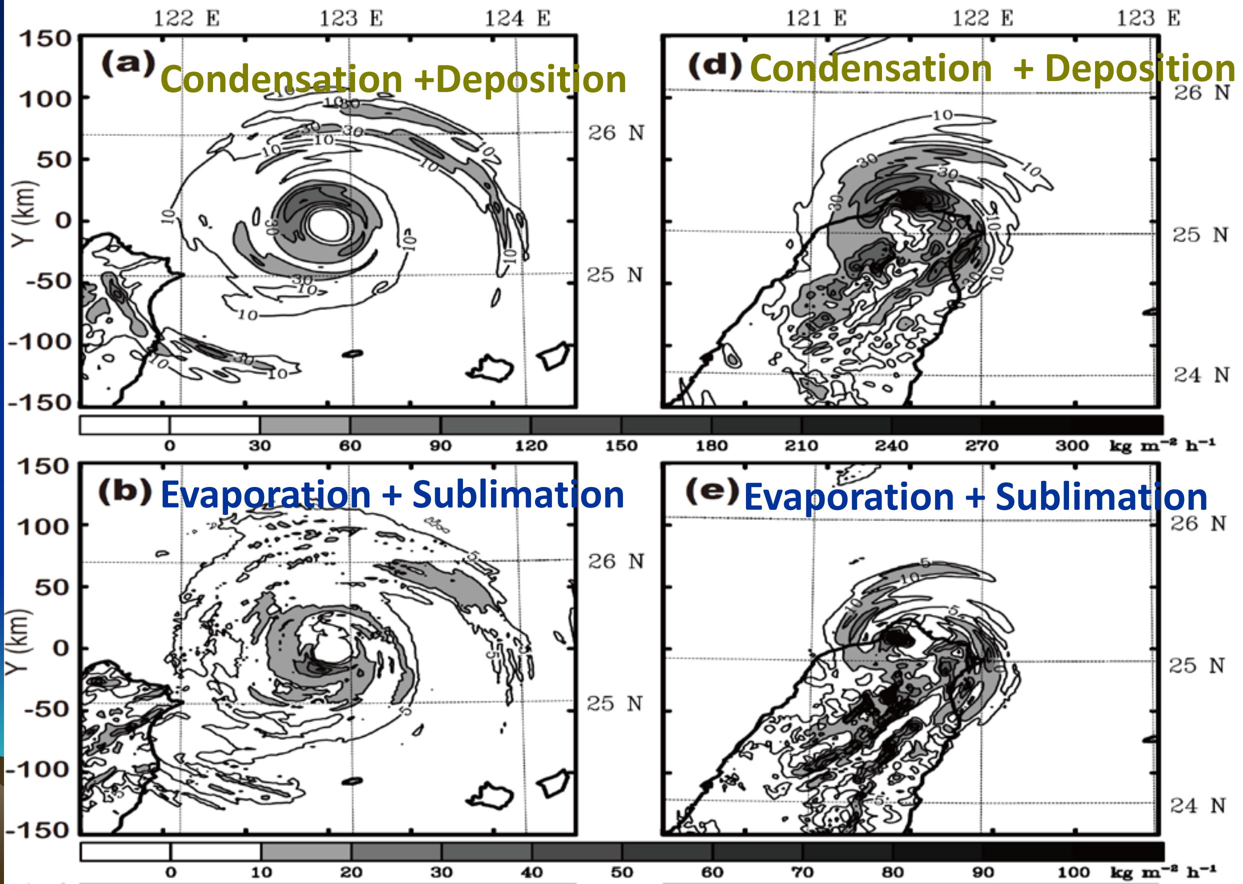
Liquid/Ice Water Budget Terms for Landfall Nari in along-track direction



Time-averaged & Vertically-integrated Amount of Rain Source/Sink



Time-averaged and vertically-integrated amount of microphysical sources and sinks



$$\overline{[\hat{\ }]} = \frac{1}{2\pi(T_2 - T_1)} \int_{T_1}^{T_2} \int_{Z_B}^{Z_T} \int_0^{2\pi} \rho [\ ] \partial\lambda \partial z \partial t$$

Budget Equations

- Water vapor budget equation can be written as:

$$\mathrm{Tend} = \mathrm{HFC} + \mathrm{VFC} + \mathrm{Div} + \mathrm{Cond} + \mathrm{Evap} + \mathrm{PBL} + \mathrm{Diff} + \mathrm{Resd}$$

Note that

$$\frac{\partial q_v}{\partial t} = -\nabla \cdot (q_v \mathbf{V}') - \frac{\partial (q_v w)}{\partial z} + q_v \left(\nabla \cdot \mathbf{V}' + \frac{\partial w}{\partial z} \right) - C + E + B_v + D_v + Resd_v$$

- Liquid/Ice water budget equation can be written as:

$$\mathrm{Tend} = \mathrm{HFC} + \mathrm{VFC} + \mathrm{Div} + \mathrm{P} + \mathrm{Cond} + \mathrm{Evap} + \mathrm{PBL} + \mathrm{Diff} + \mathrm{Resd}$$

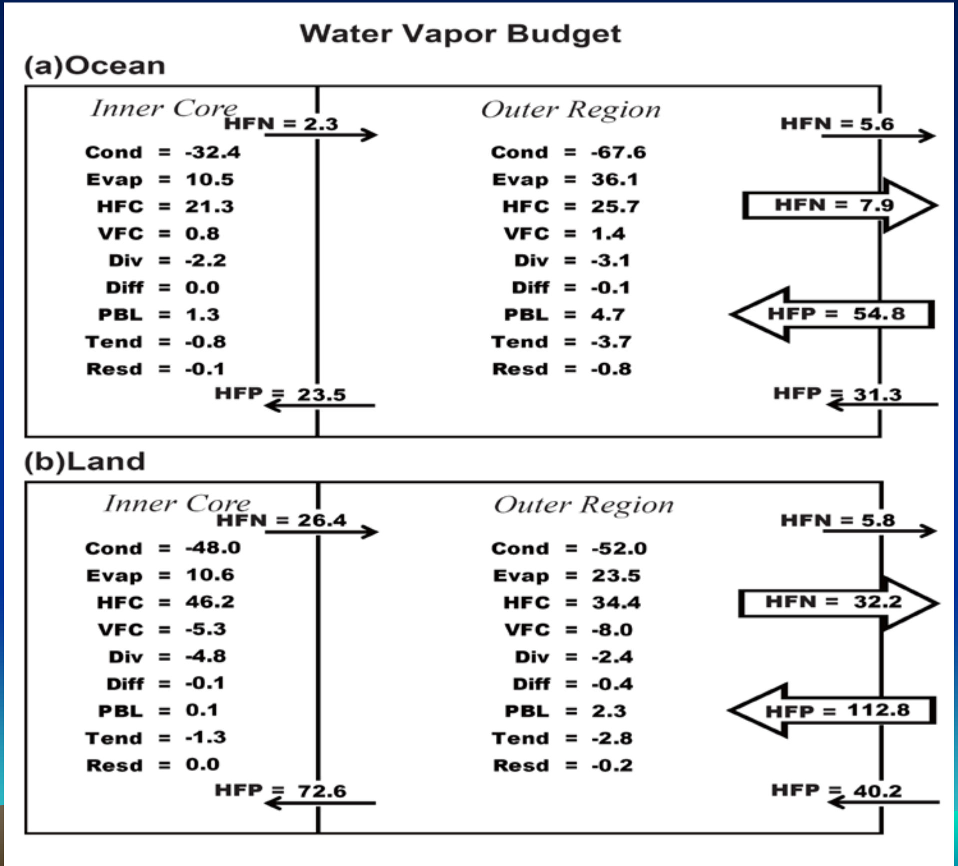
Note that

$$\frac{\partial q_p}{\partial t} = -\nabla \cdot (q_p \mathbf{V}') - \frac{\partial (q_p w)}{\partial z} + q_p \left(\nabla \cdot \mathbf{V}' + \frac{\partial w}{\partial z} \right) + \frac{1}{\rho} \frac{\partial (\rho q_p V_T)}{\partial z} + Q_{p+} - Q_{p-} + D_p + Resd_p$$

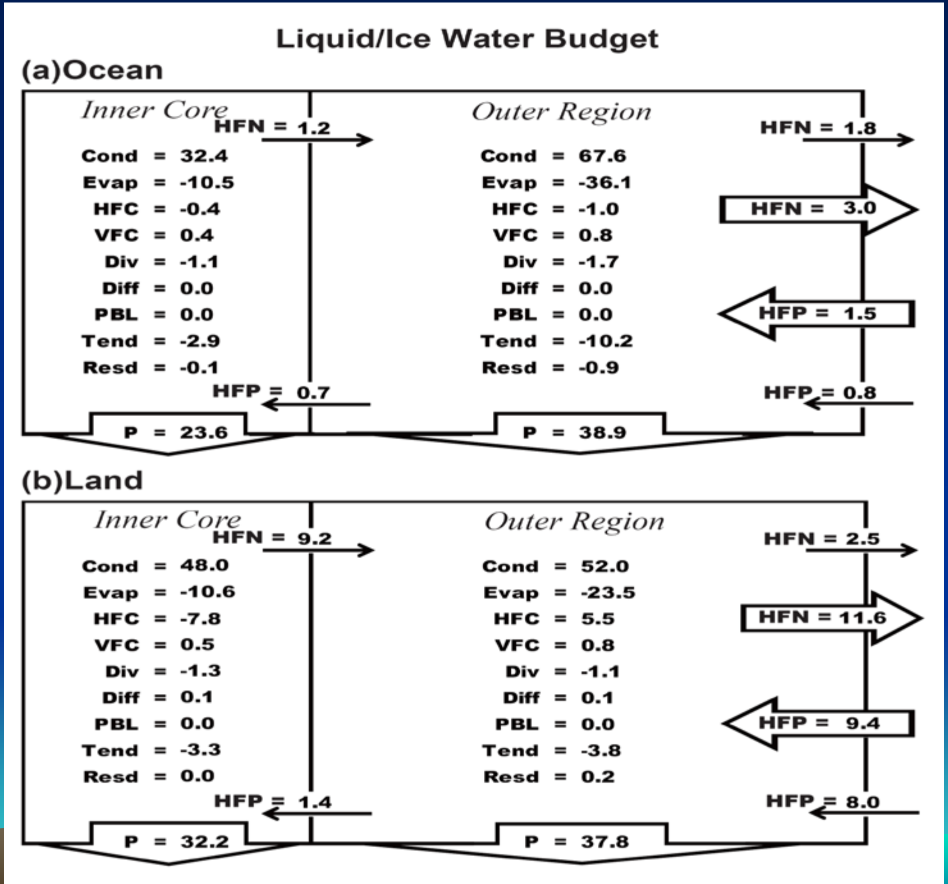
$$\frac{\partial q_c}{\partial t} = -\nabla \cdot (q_c \mathbf{V}') - \frac{\partial (q_c w)}{\partial z} + q_c \left(\nabla \cdot \mathbf{V}' + \frac{\partial w}{\partial z} \right) + Q_{c+} - Q_{c-} + B_c + D_c + Resd_c$$

$$C - E = Q_{c+} - Q_{c-} + Q_{p+} - Q_{p-}$$

Water Vapor Budgets during the Oceainc and Landfall Stages



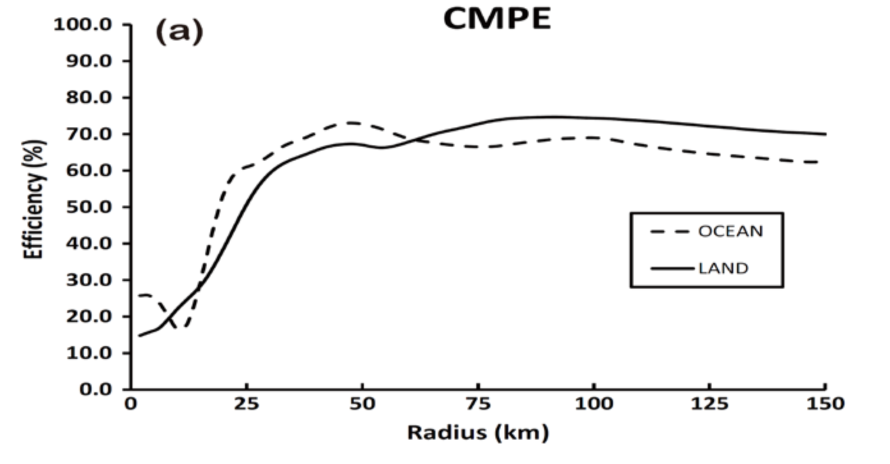
Liquid/Ice Water Budgets during the Oceainc and Landfall Stages

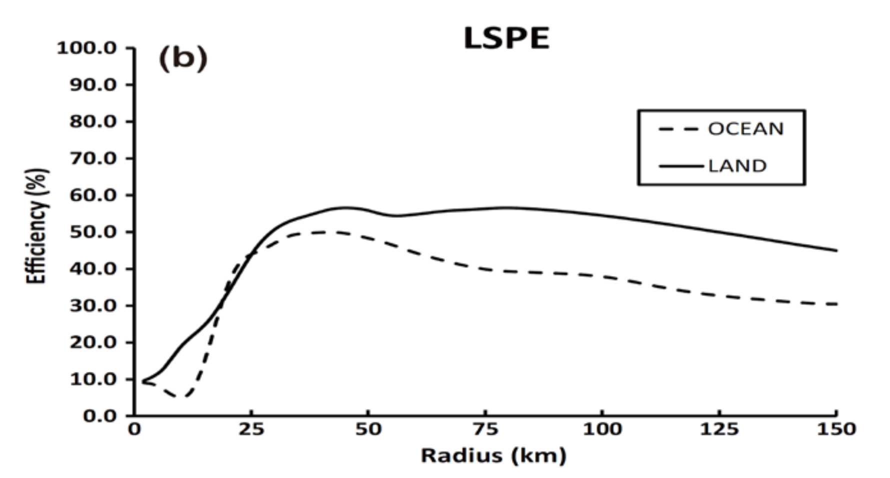


Precipitation Efficiency as a Function of Storm Radius

$$\mathrm{CMPE} = \frac{\mathrm{P}}{\mathrm{Cond}}$$

$$\mathrm{LSPE} = \frac{\mathrm{P}}{\mathrm{HFP} + \mathrm{VFP}}$$





Conclusions

- For the vapor budget, while Nari is over the ocean, evaporation from the ocean surface is 11% of the inward horizontal vapor transport within the 150-km radius from the storm center, and the net horizontal vapor convergence into the storm is 88% of the net condensation.

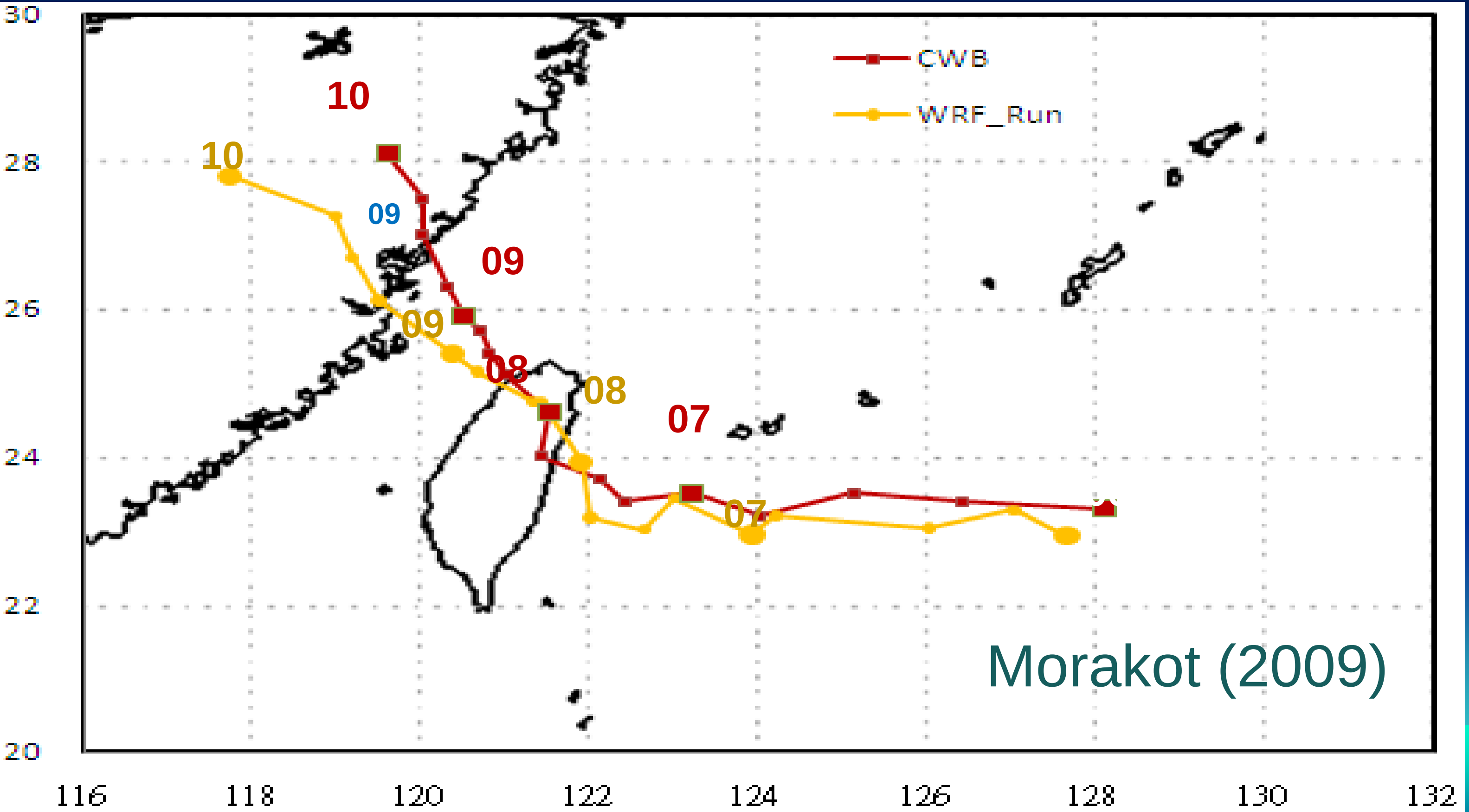
- After landfall, Taiwan’s steep terrain enhances Nari’s secondary circulation significantly; the net horizontal vapor convergence into the storm within 150 km is increased to 122% of the net condensation after landfall.

- For the condensed water budget, summation of precipitation fallout and total flux convergence is largely out of phase with the net microphysical source term, indicating that precipitation particles are falling out as quickly as they are produced.

Conclusions

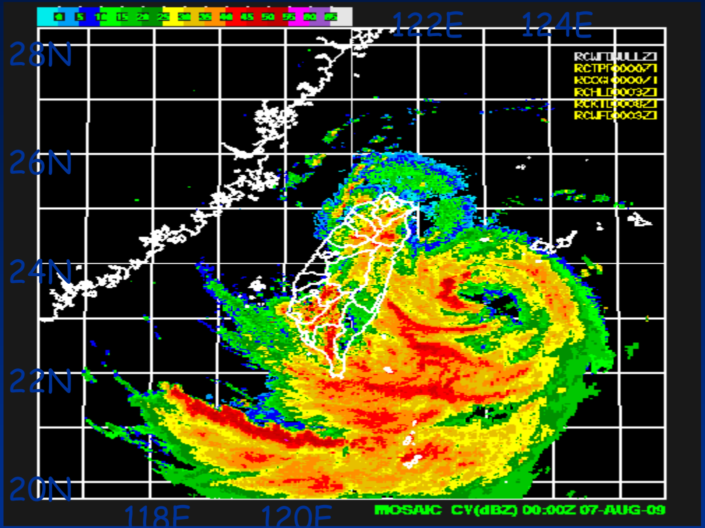
- Warm rain processes dominate in the eyewall region, while the cold rain processes are comparable to warm rain processes outside of the eyewall.
- After landfall, cold rain processes are further enhanced above the Taiwan terrain and the storm-total condensation within 150 km from the center is increased by 22%.
- Precipitation efficiency, defined by either the large-scale or microphysics prospective, is increased 10–20% over the outer-rainband region after landfall, in agreement with the enhanced surface rainfall over terrain.
- At radii greater than 60 km, the cloud microphysics precipitation efficiency remains a constant value of 67% for the oceanic stage of Nari and 73% for the landfall stage.

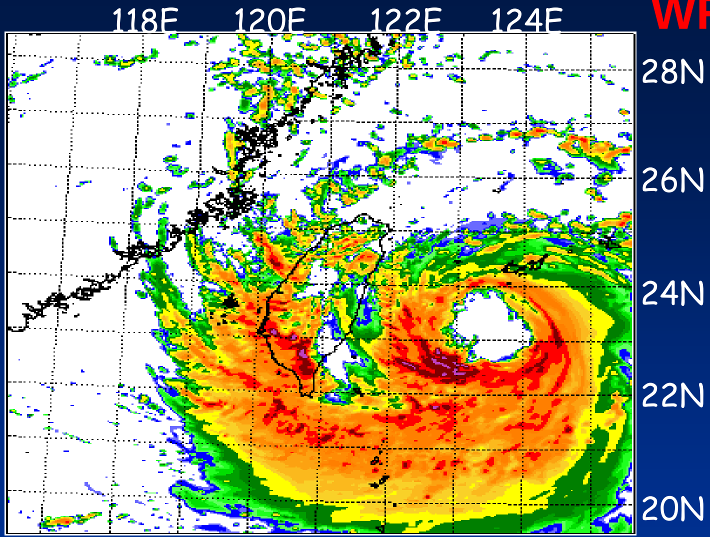
Track of CWB and WRF Run



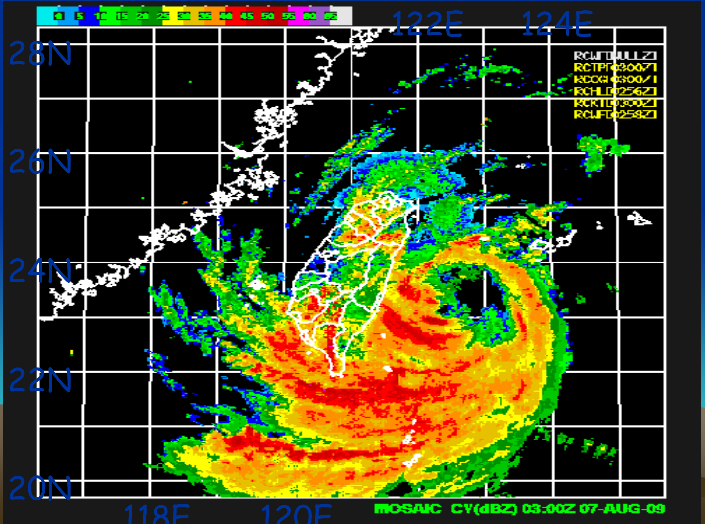
WRF_3km

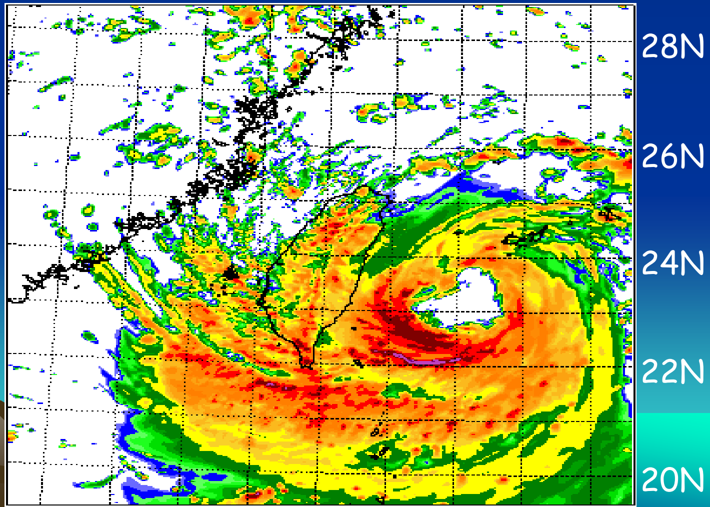
0807/00Z

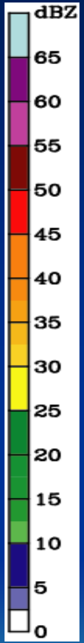




0807/03Z

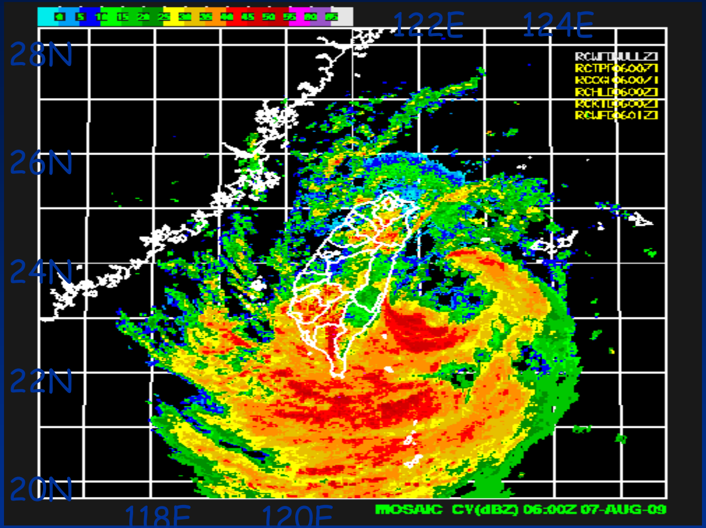




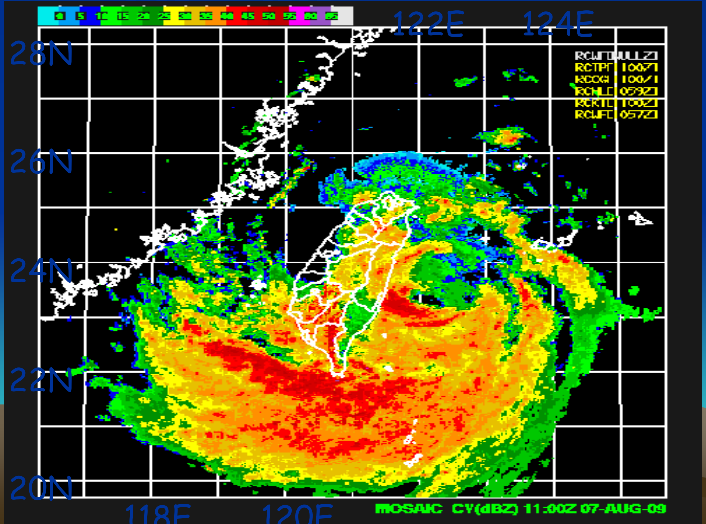


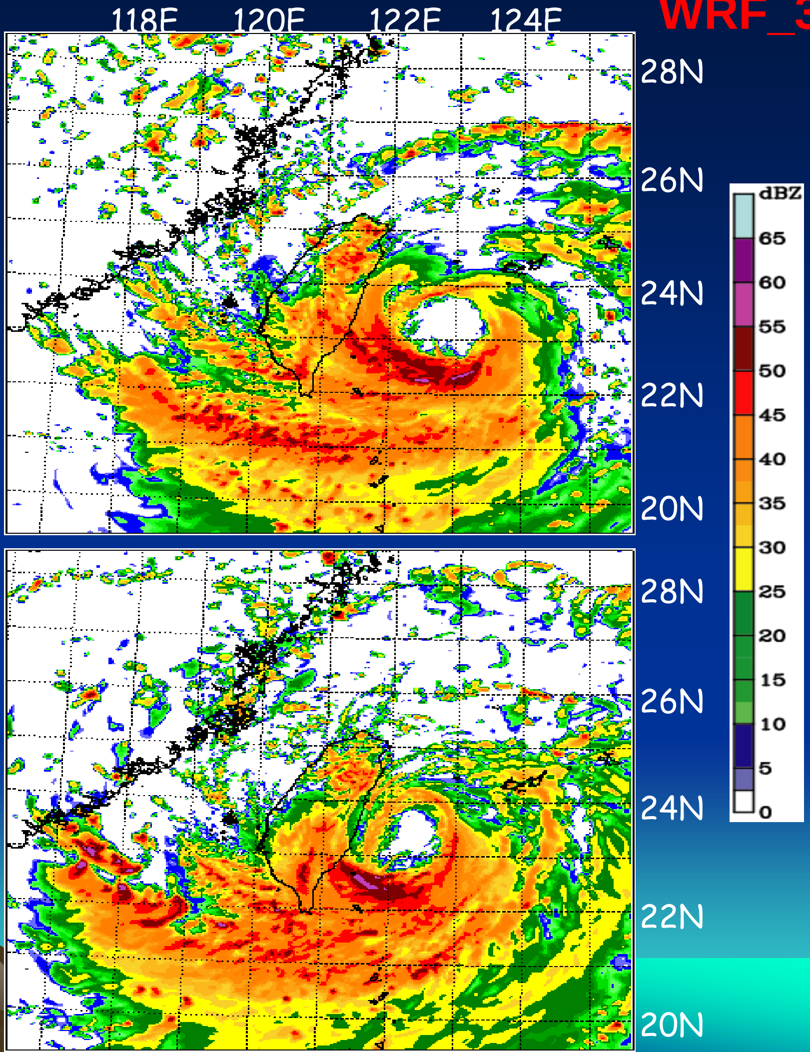
WRF_3km

0807/06 Z



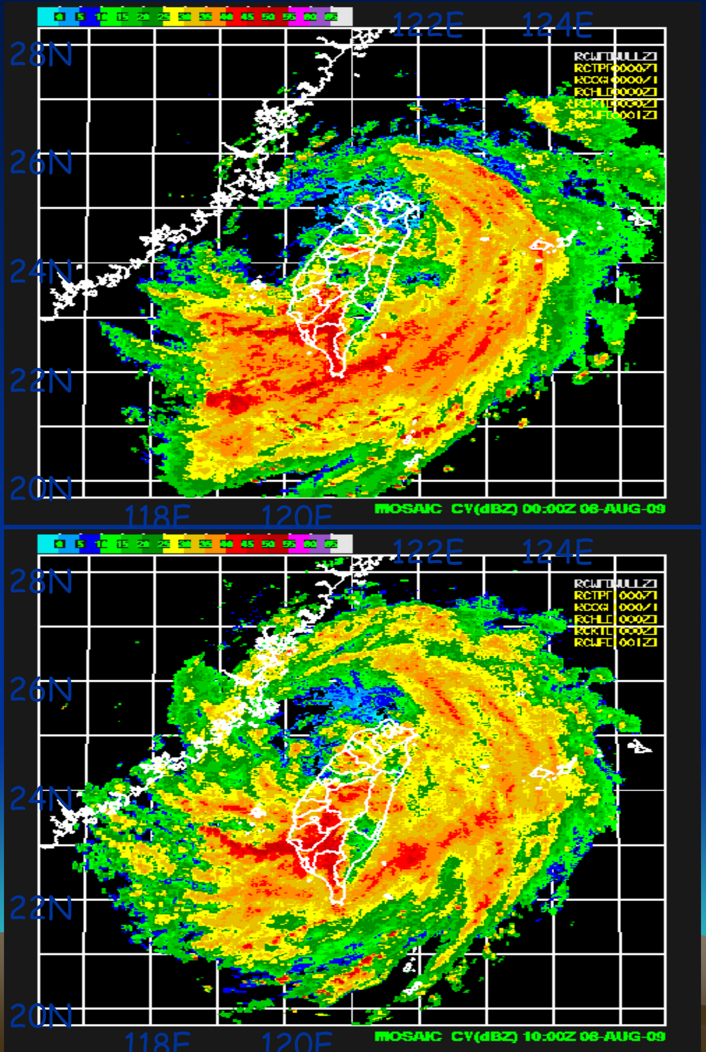
0807/11 Z



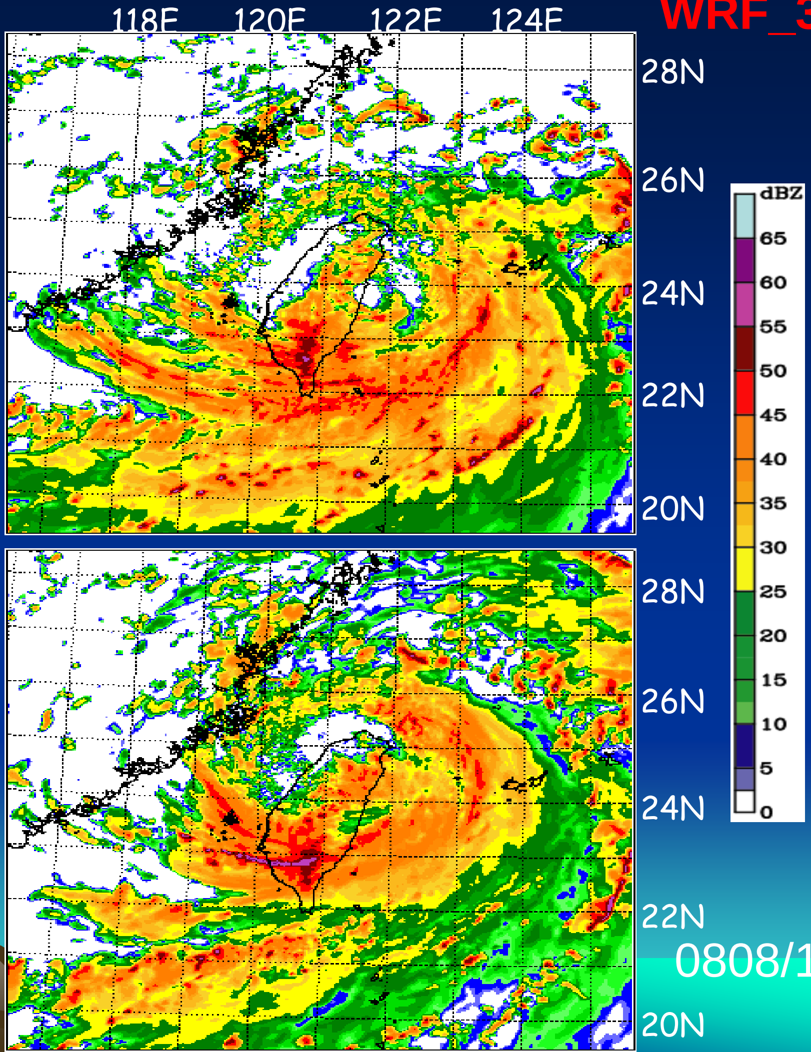


0808/00 Z

0808/10 Z

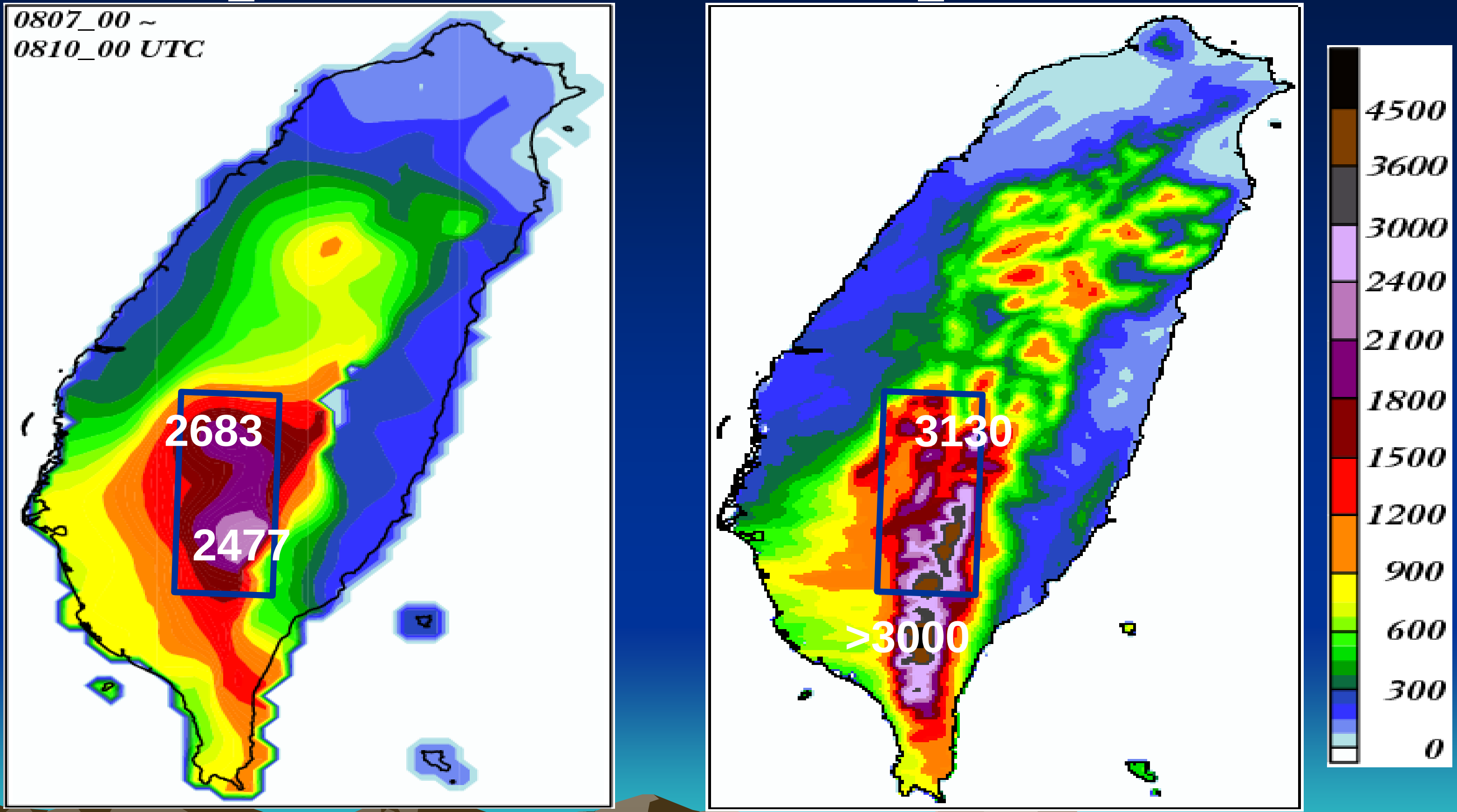


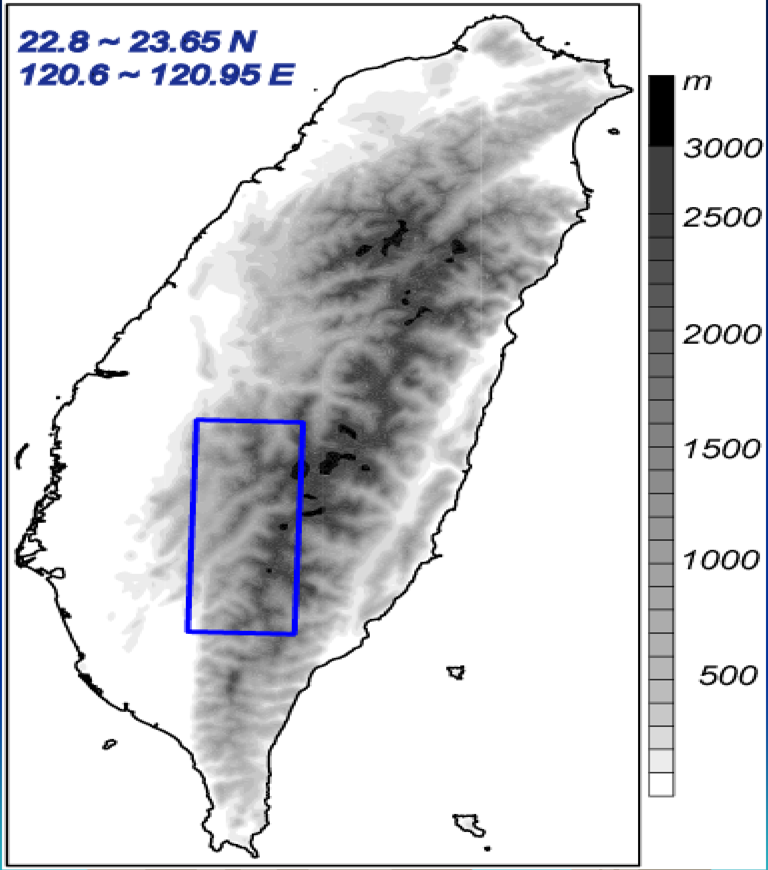
WRF_3km



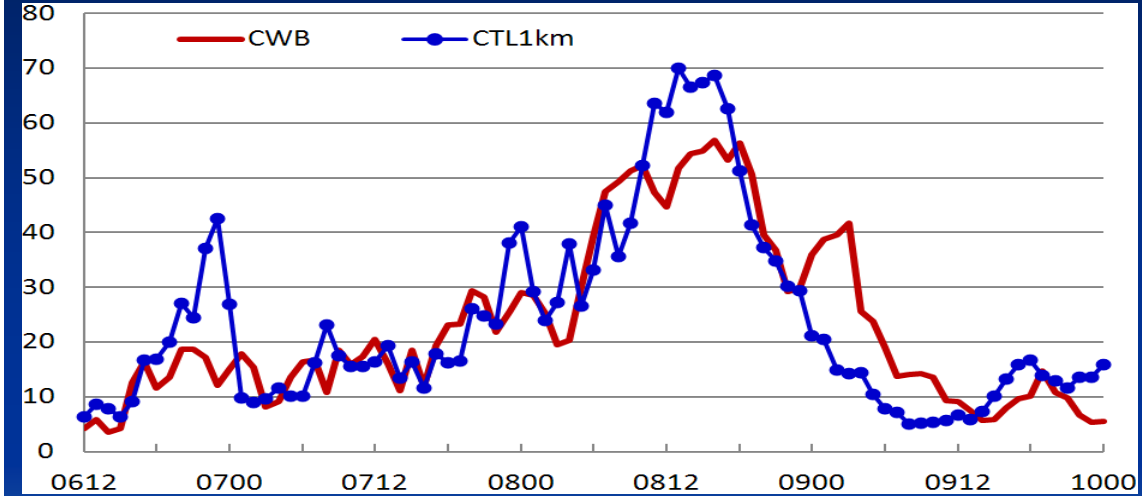
0808/11 Z

CWB_OBS WRF_1km



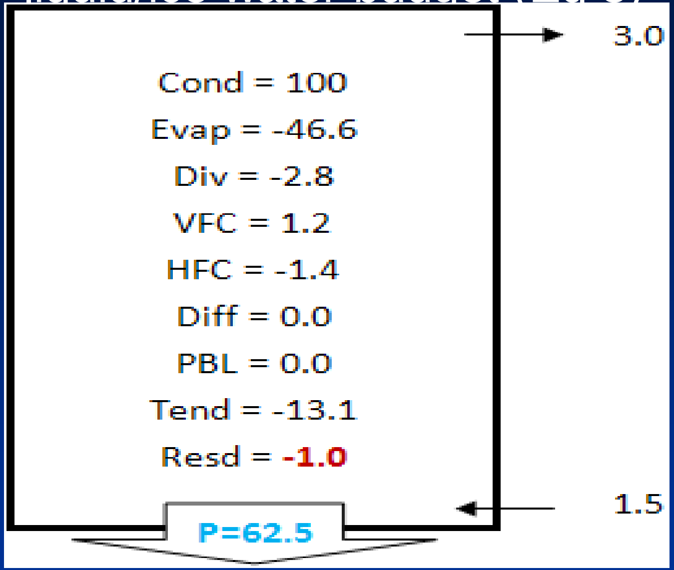


Hit Area Rainfall Time Series (mm/h)

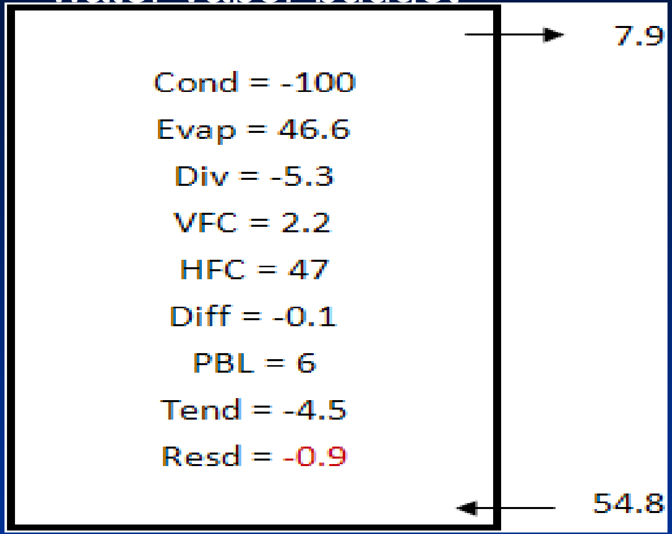


MM5_2km

liquid/ice water budget (Eq 8)



water vapor budget



Nari R=150 km (Yang et al. 2011)

$$\text{Tend} = \text{Cond} + \text{Evap} + \text{HFC} + \text{VFC} + \text{Div} + \text{Diff} + \text{PBL} + \text{Resd}. \quad (7)$$

$$\text{Tend} = \text{Cond} + \text{Evap} + \text{HFC} + \text{VFC} + \text{Div} + \text{Diff} + \text{PBL} + P + \text{Resd}. \quad (8)$$

WRF_3km

liquid/ice water budget (Eq 8)

→ 2.74

Cond = 100
Evap = -53.39
Div = 29.75
VFC = 23.91
HFC = -1.97
Diff = -0.008
PBL = 0.018
Tend = 19.72
Resd = **-4.59**

← 0.76

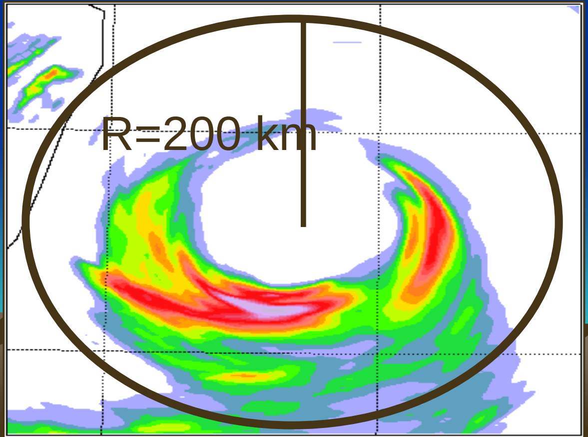
P=74

water vapor budget

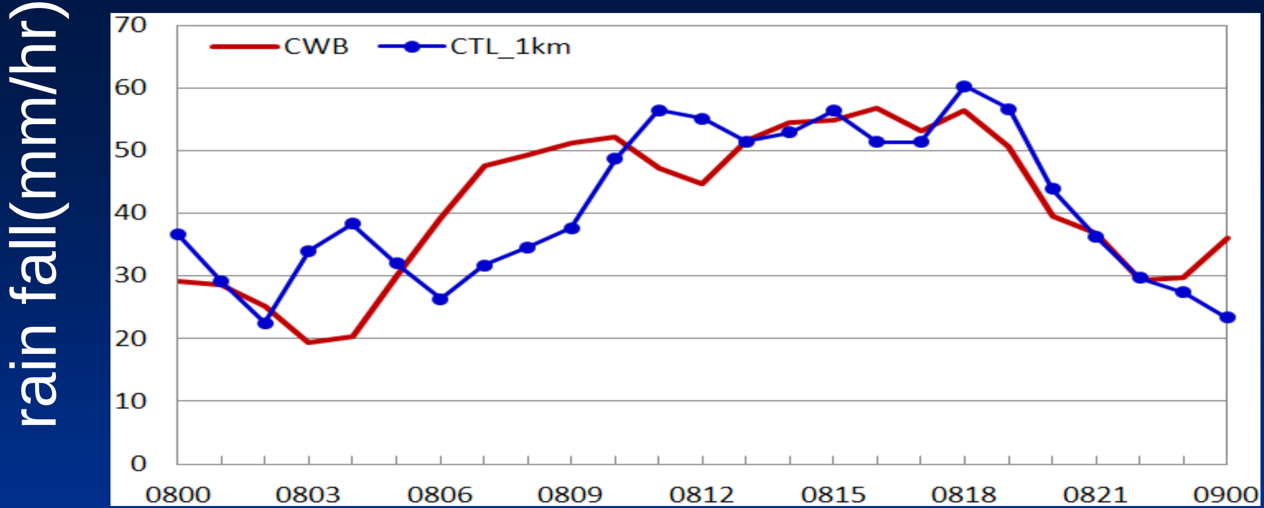
→ 7.13

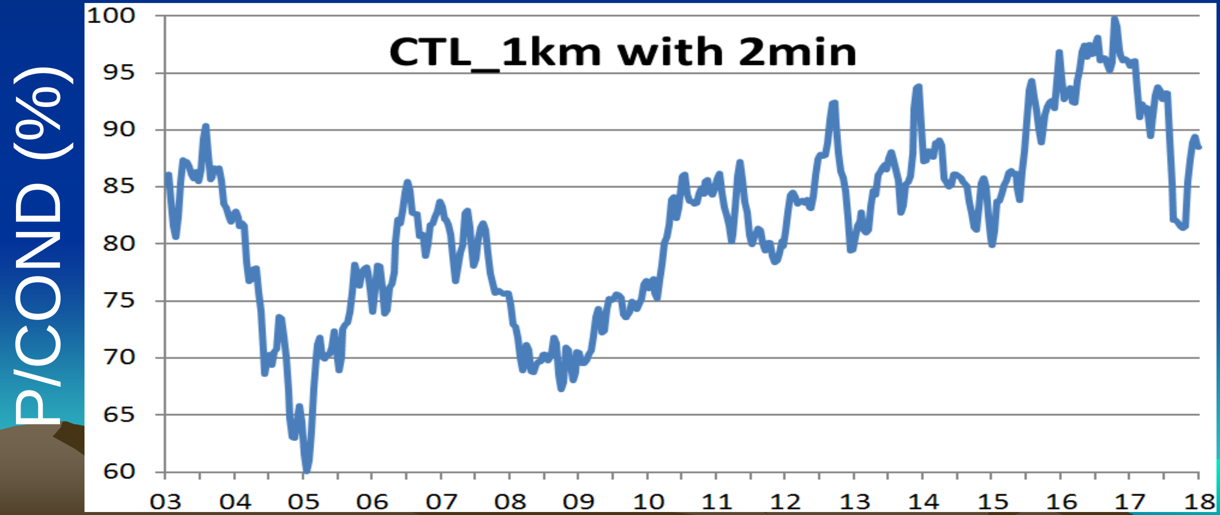
Cond = -100
Evap = 53.39
Div = 28.21
VFC = 22.07
HFC = 13.09
Diff = -0.013
PBL = 2.741
Tend = 24.89
Resd = 5.41

← 20.22

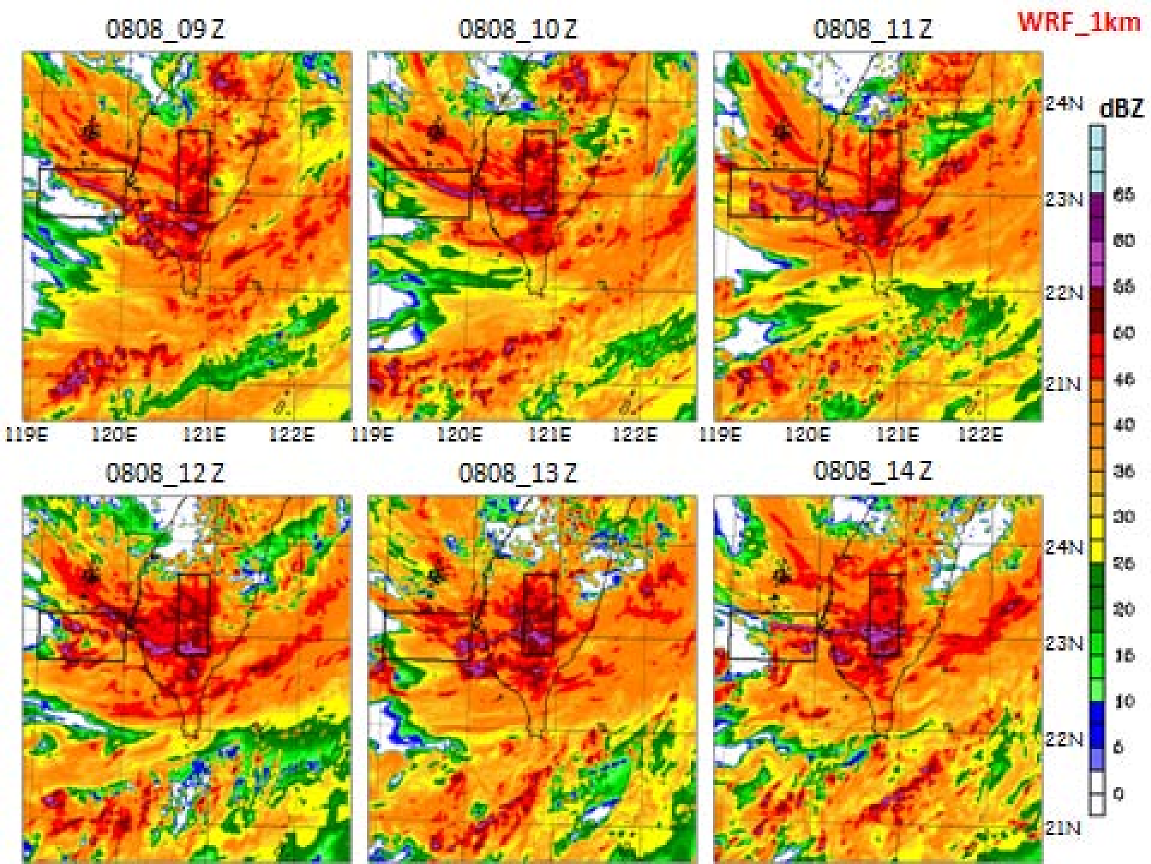


Morakot circle area

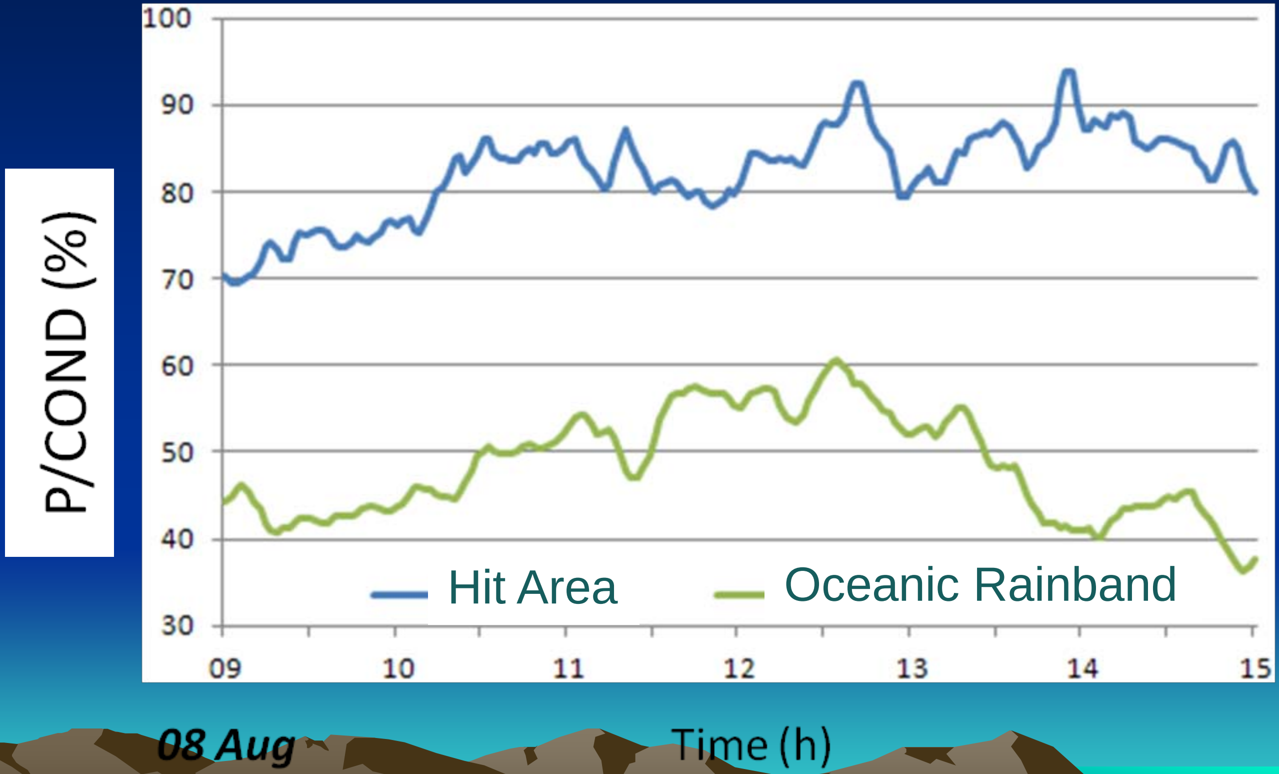

rain fall(mm/hr)
CWB
CTL_1km
70
60
50
40
30
20
10
0
0800
0803
0806
0809
0812
0815
0818
0821
0900


P/COND (%)
CTL_1km with 2min
100
95
90
85
80
75
70
65
60
03
04
05
06
07
08
09
10
11
12
13
14
15
16
17
18

Typhoon Morakot (2009)



CMPE of Typhoon Morakot (2009)



-THE END-

Thanks for your attention!