Water Budgets and Precipitation Efficiencies of Tropical Cyclones: Results from Typhoons Nari (2001) and Morakot (2009)

Ming-Jen Yang
Dept. of Atmos. Sci. & Inst. of Hydrological and Oceanic Sci.
National Central University, Taiwan

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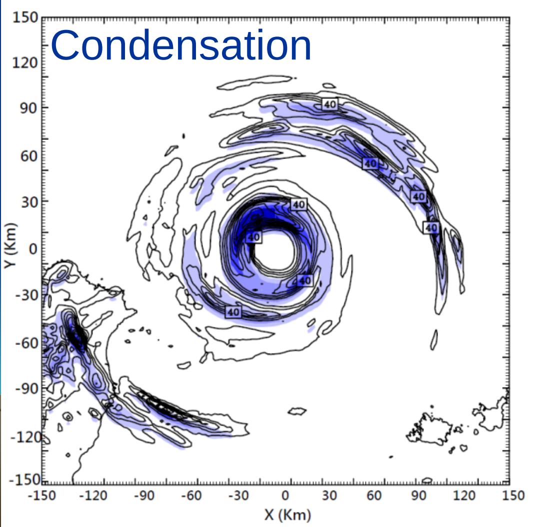
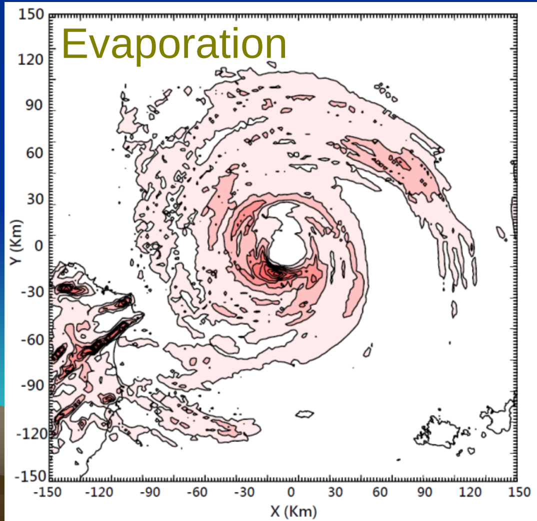
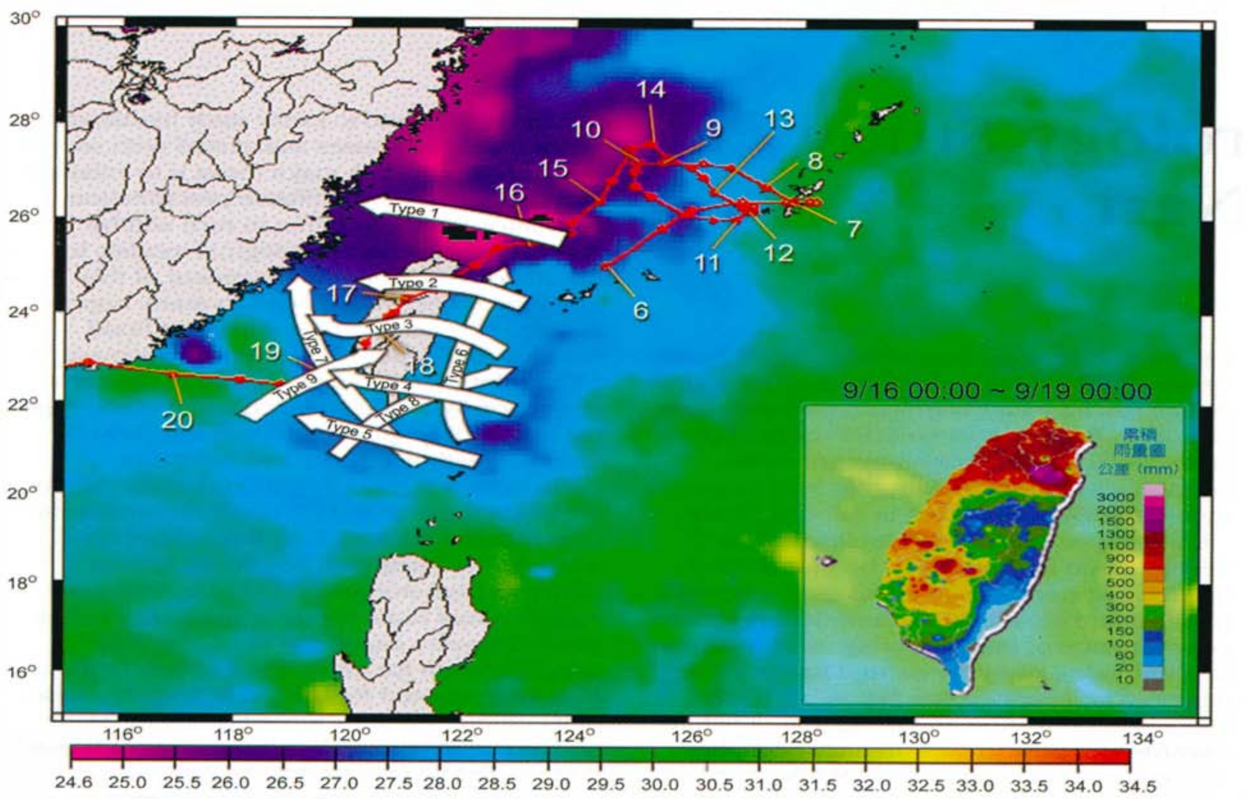




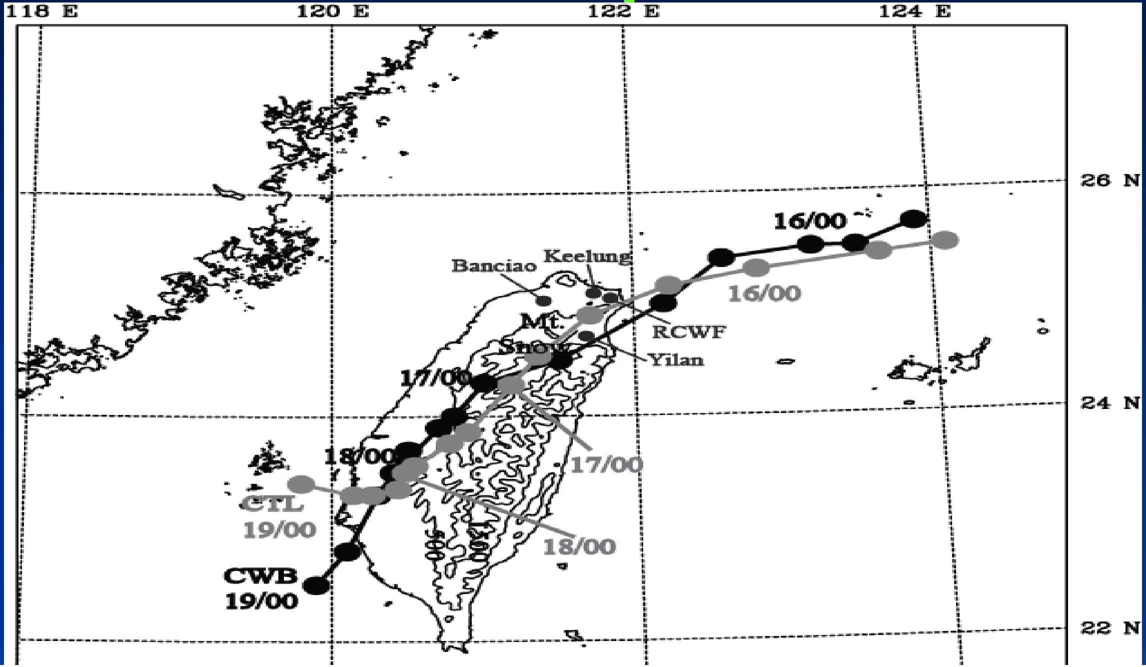
Typhoon Nari (2001)

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



Sui et al. (2002) EOS article

Track Comparison

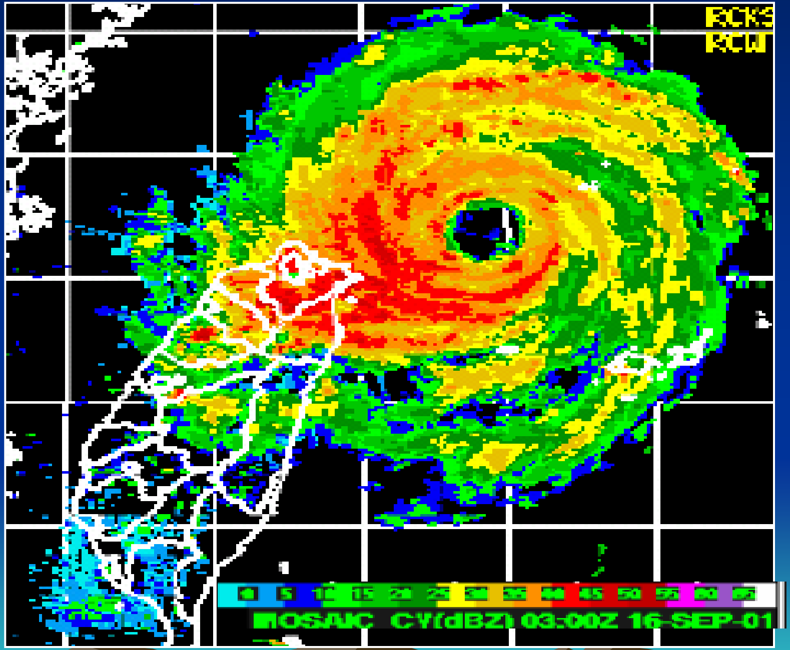


Yang et al. (2008; JAS)

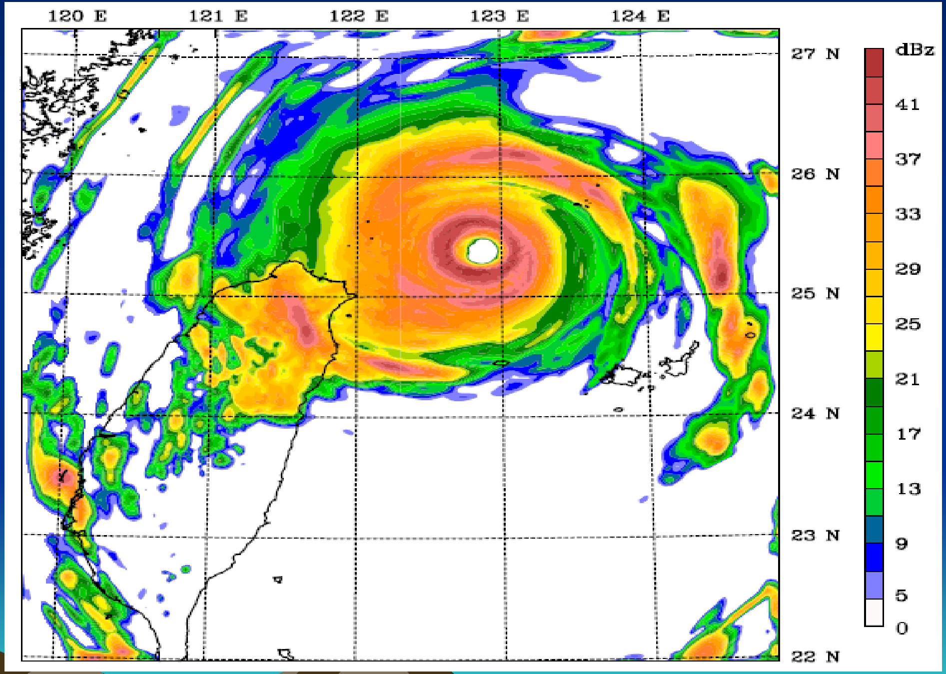
Simulation time (hr)	12	24	36	48	60	72	84
Track error (km)	43.3	61.2	26.8	13.4	12	8.5	104.8

Radar Composite Before Landfall

OBS



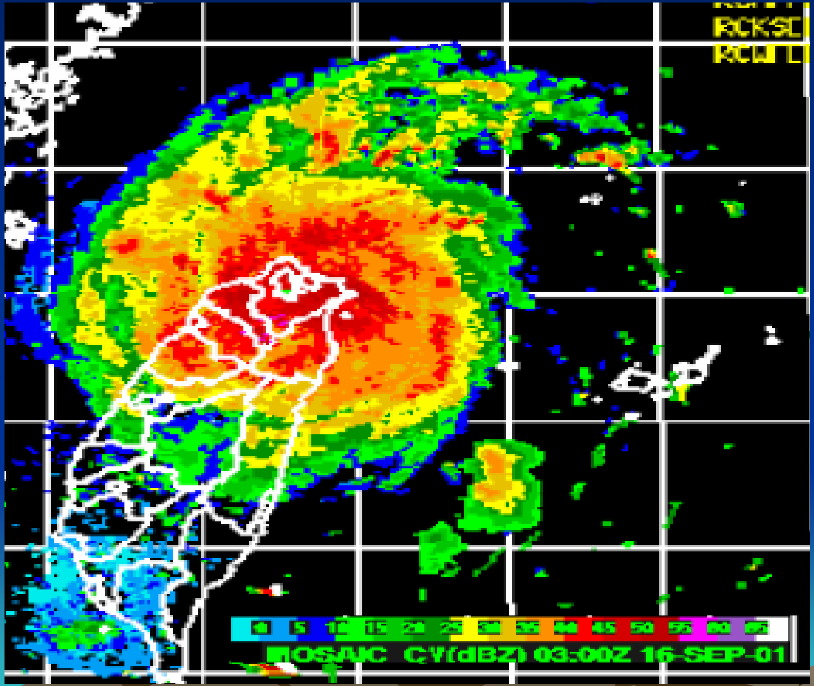
2-km MM5



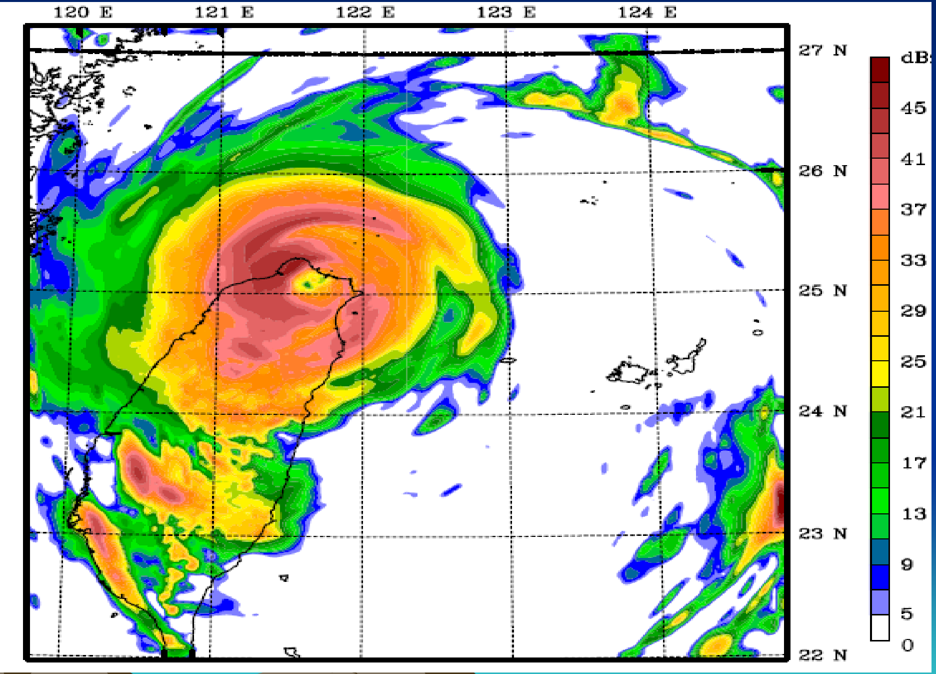
Yang et al. (2008; JAS)

Radar Composite After Landfall

OBS



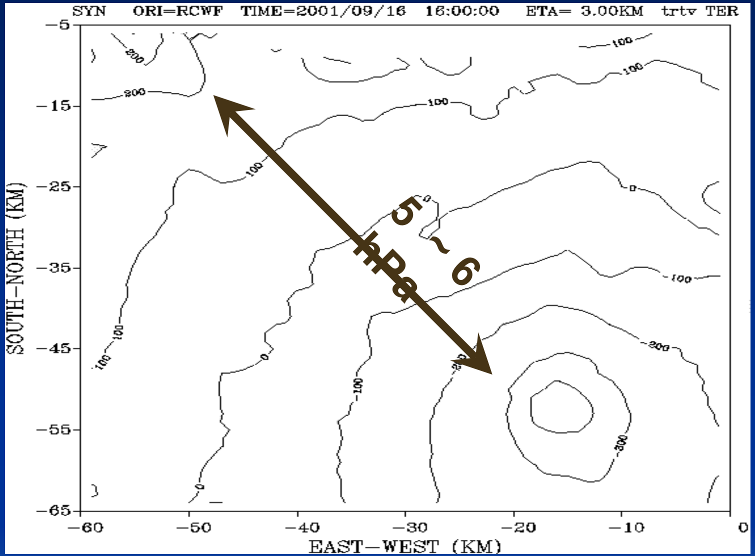
2-km MM5

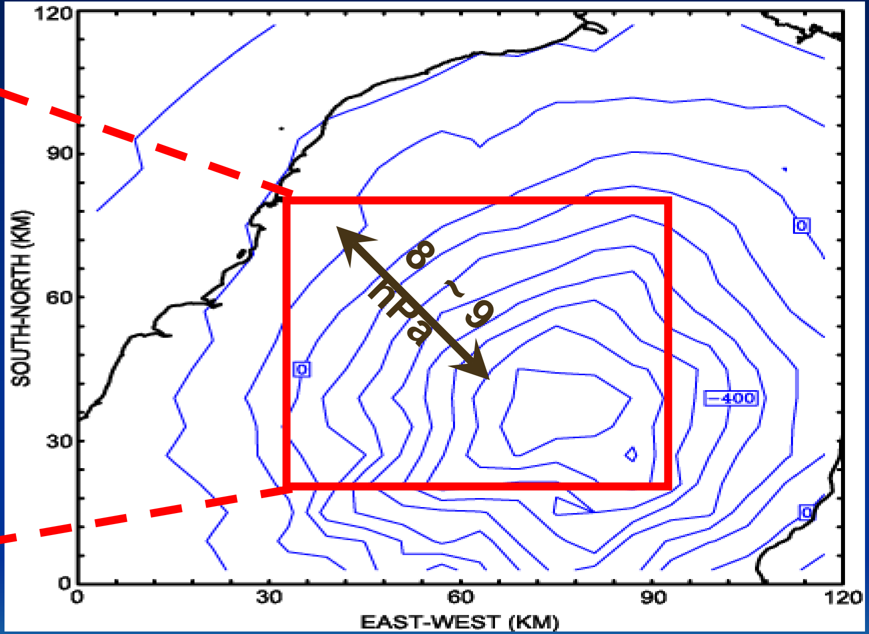


Yang et al. (2008; JAS)

Horizontal Cross Section of Pressure Perturbation

0916_1400 UTC





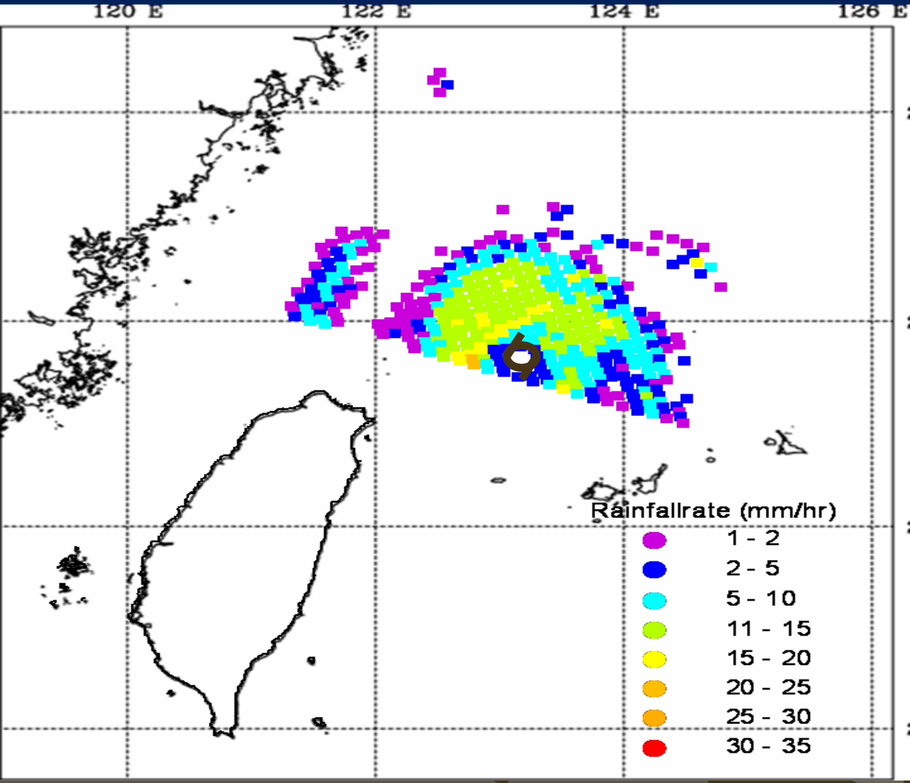
Radar Retrieval (wrt. a Station Sounding)

MM5 Simulation (wrt. a Horizontal Area Mean)

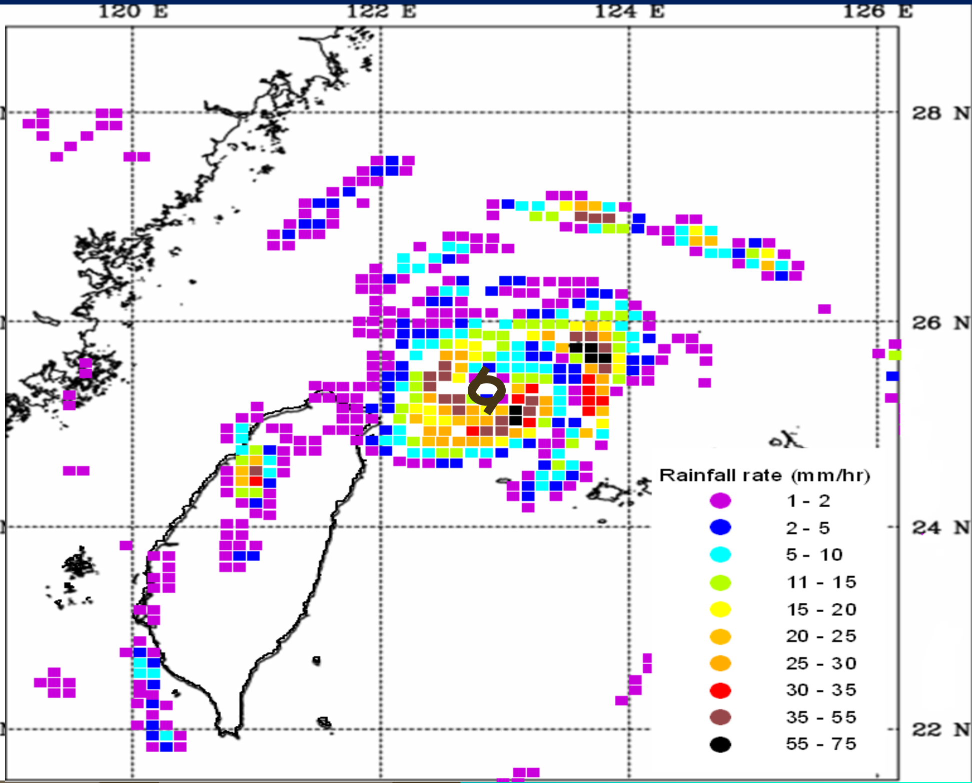
Courtesy of Y.-C. Liou and T.-C. Chen Wang

TRMM Rainrate Comparison

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



MM5: 0915/2100 UTC (6 km grid)



Courtesy of W.-J. Chen

Reference

- Braun, S. A., 2006: High-resolution simulation of Hurricane Bonnie (1998). Part II: Water budget. *J. Atmos. Soc.*, **63**, 43–64.
- 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;

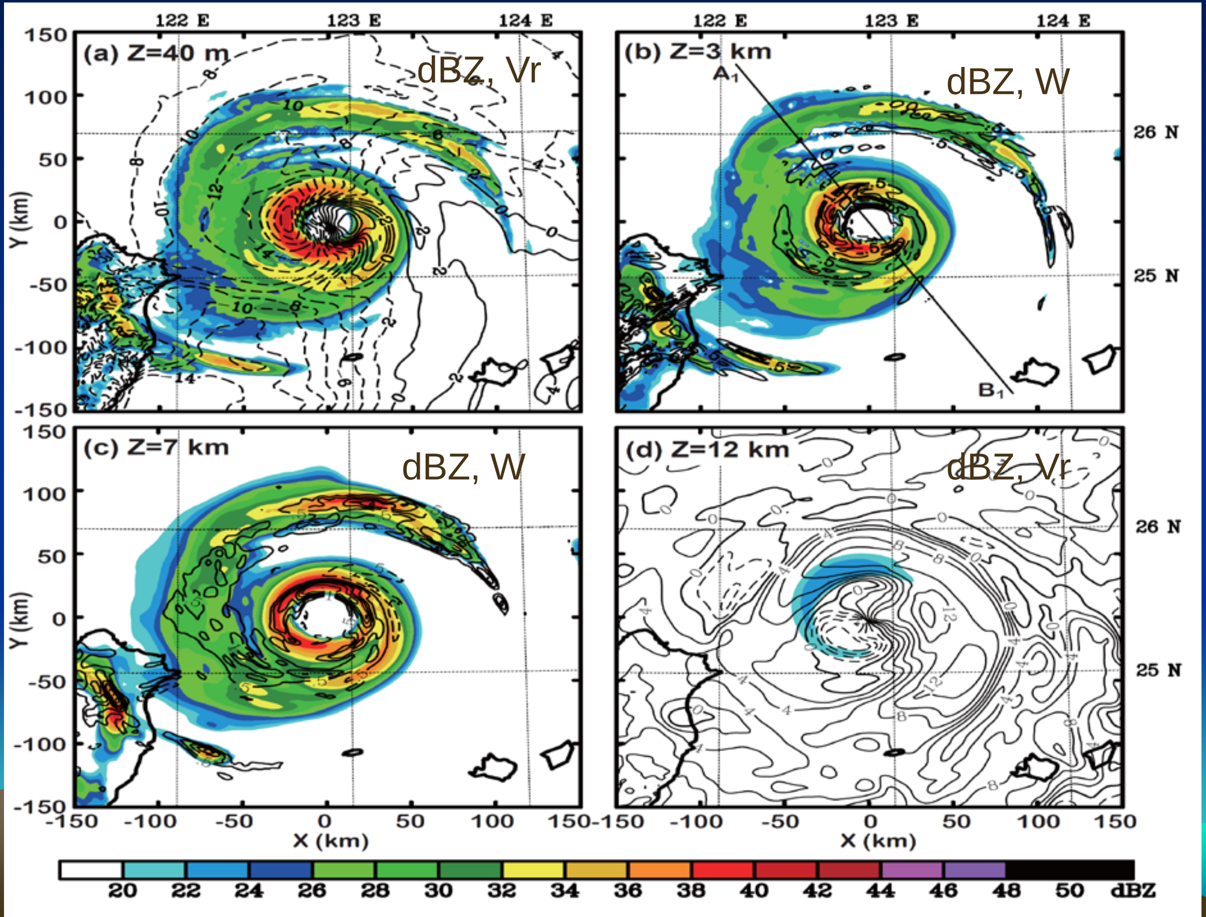
Q_{p-} is the microphysical sink term;

D_p is the numerical diffusion term for precipitation;

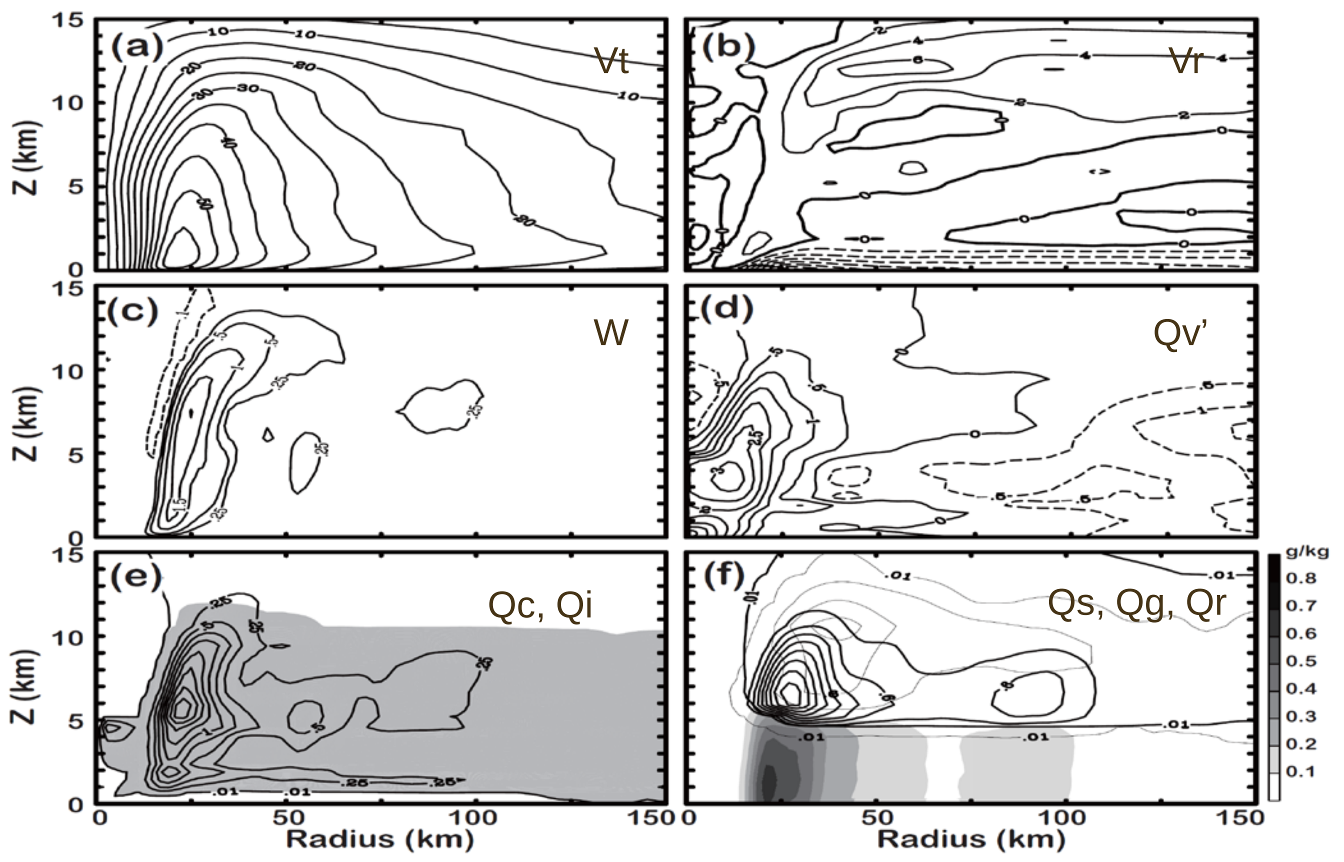
$Resd_p$ is the residual term for precipitation;

V_T is the hydrometeor terminal velocity

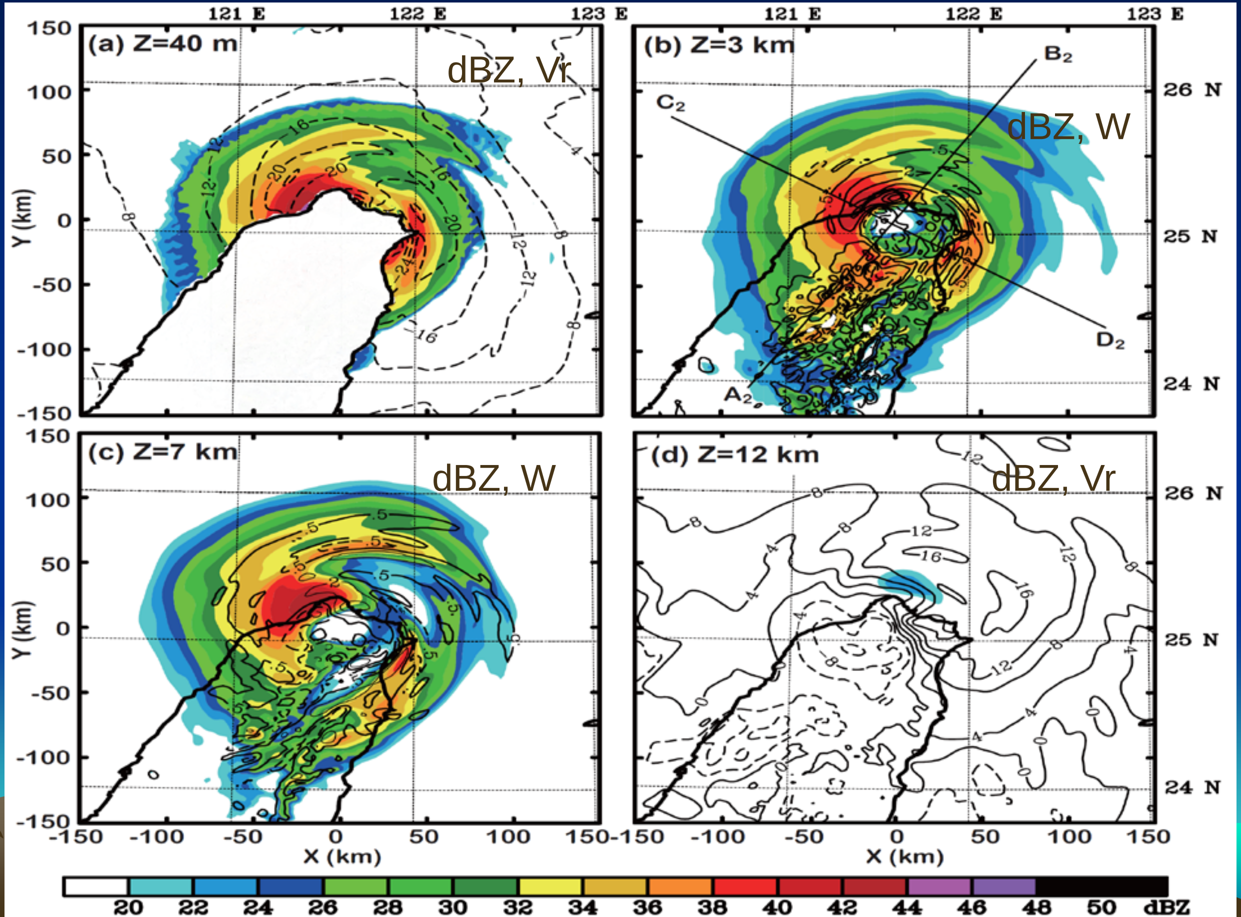
Typhoon Nari over the Ocean



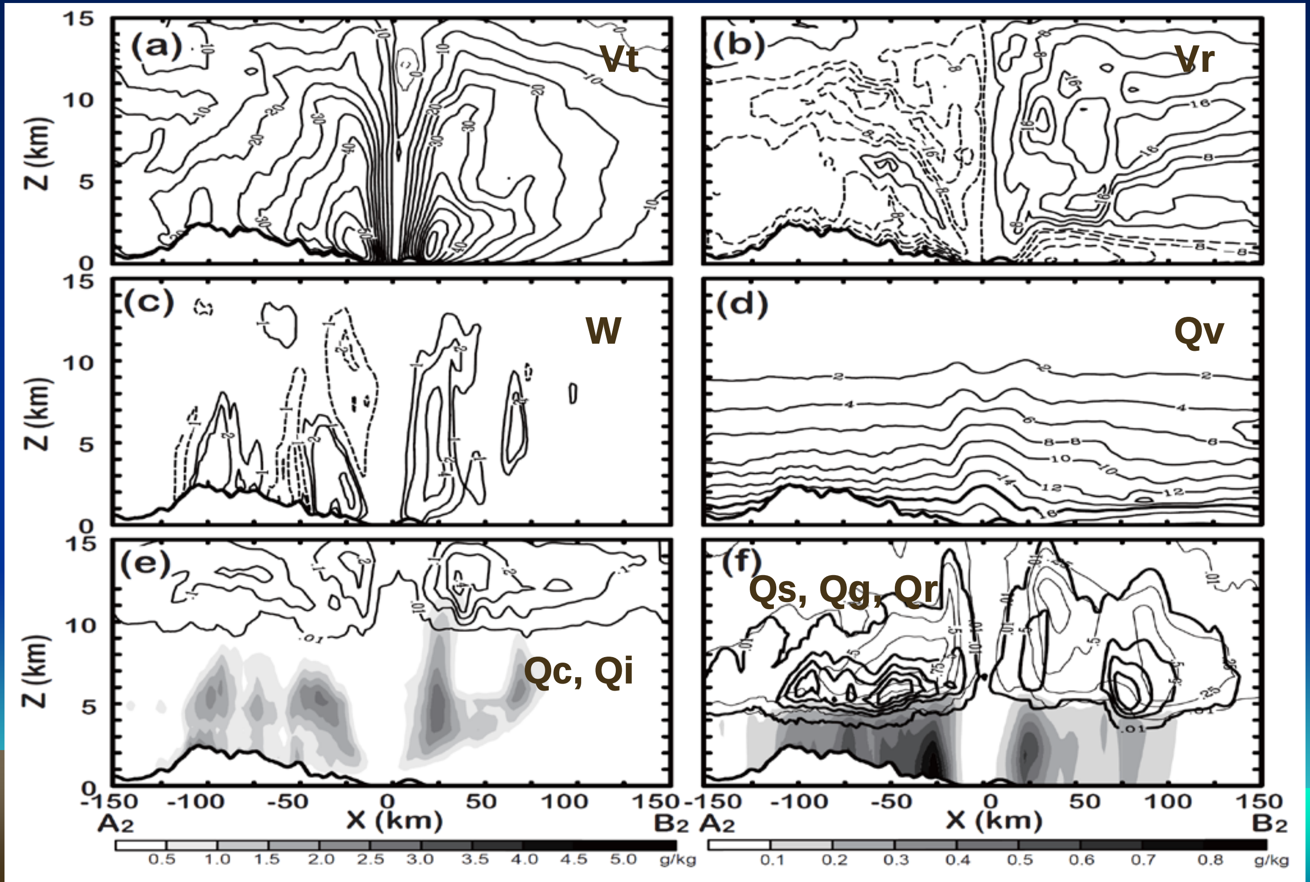
Axis-symmetric Structure of Nari over Ocean



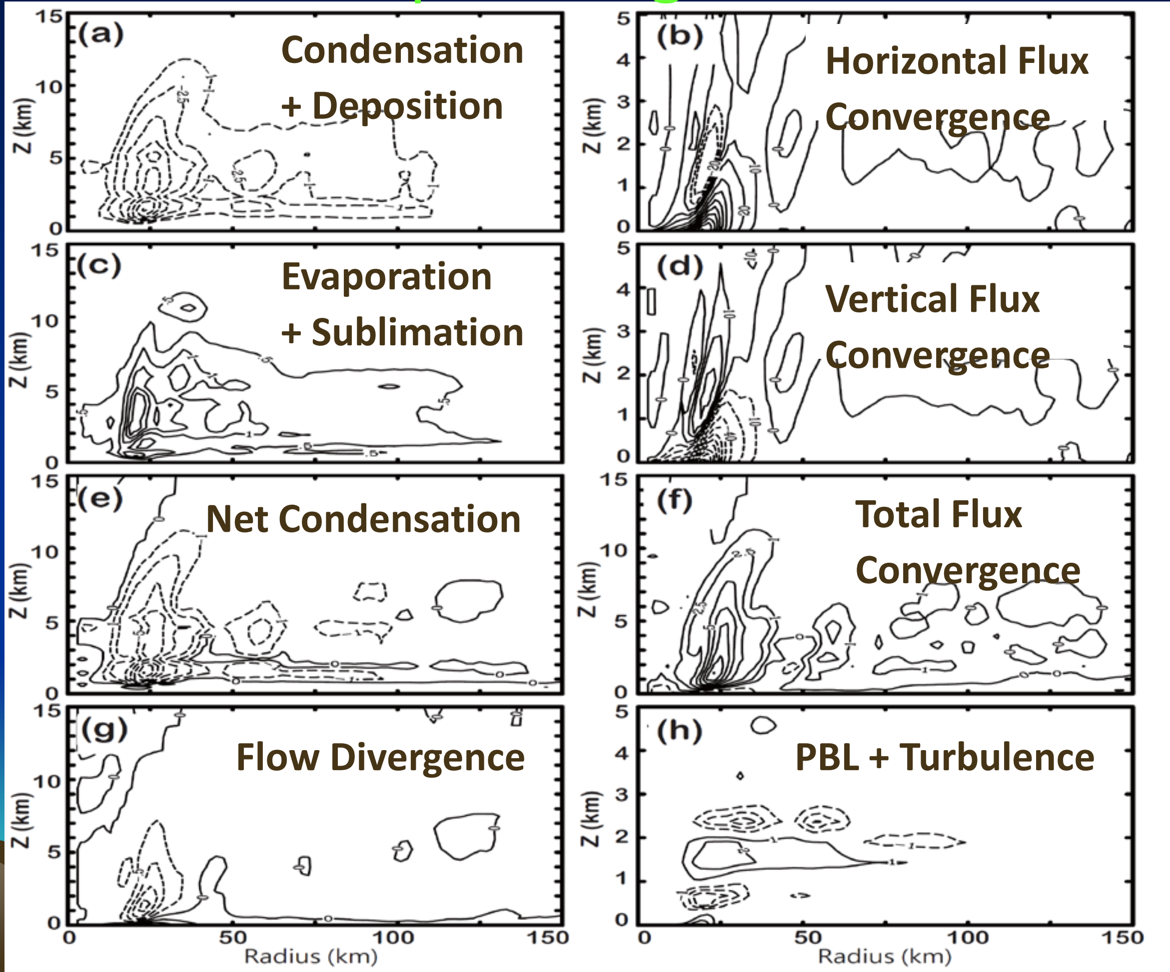
Typhoon Nari at the Landfall Stage



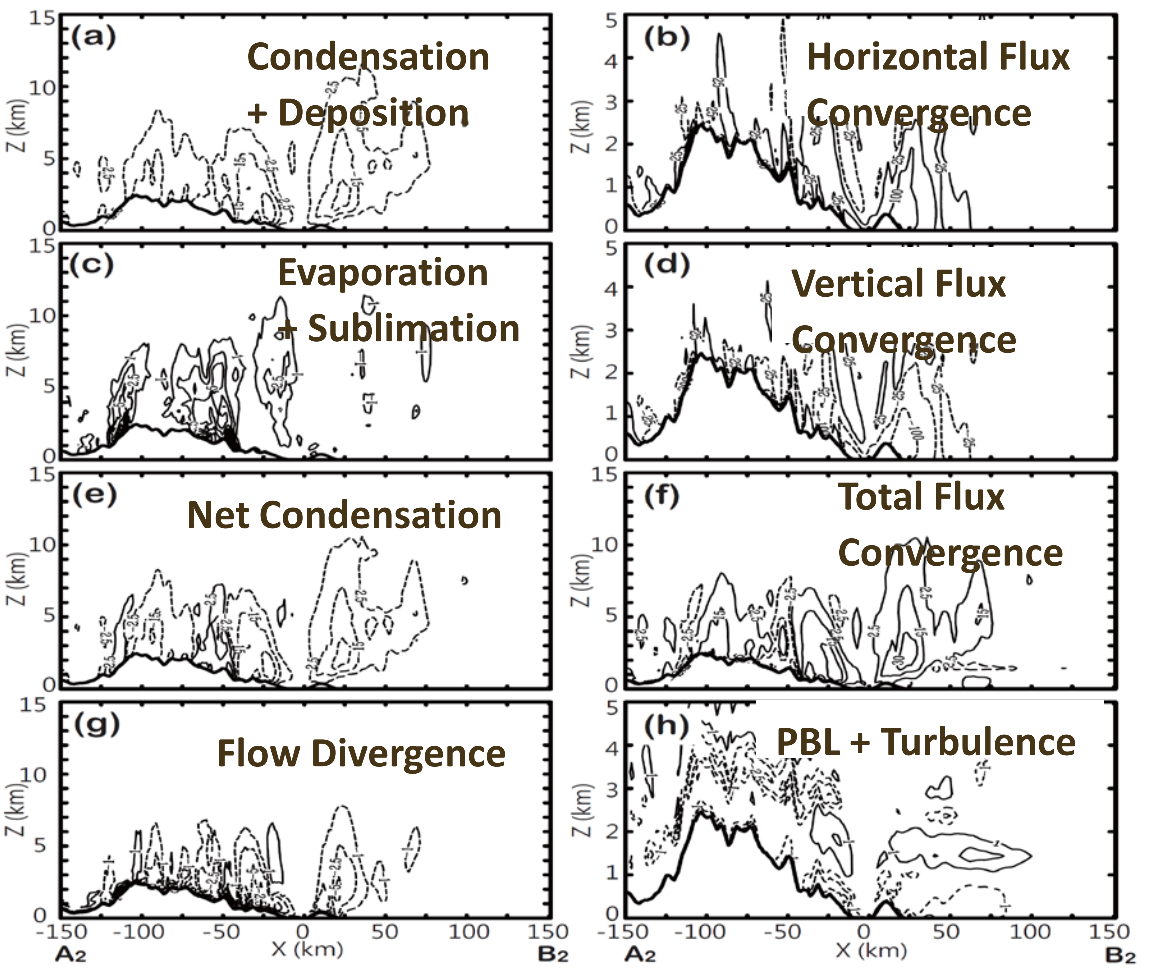
Nari Structure over Land in along-track direction



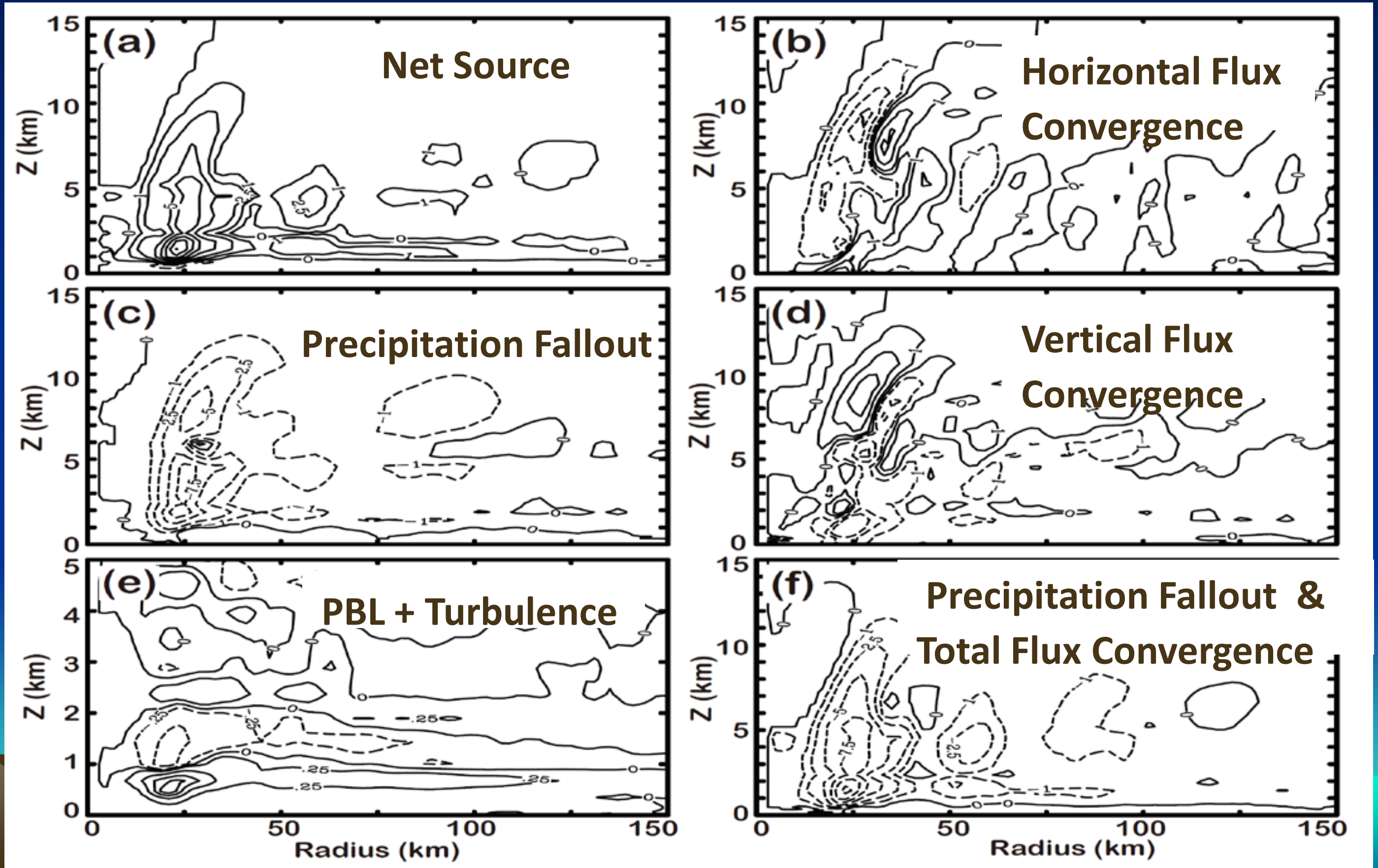
Axis-symmetric Water-Vapor Budget Terms for Oceanic Nari



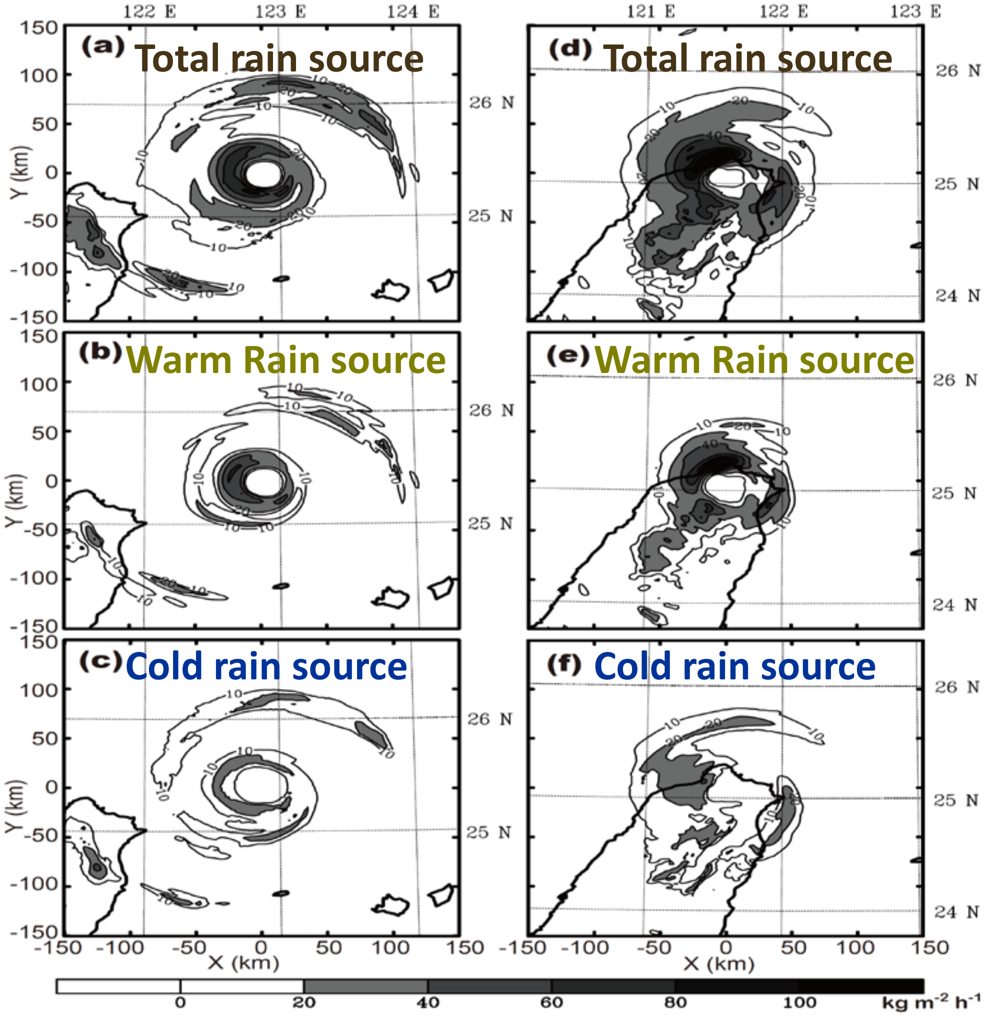
Water-Vapor Budget Terms for Landfall Nari in across-track direction



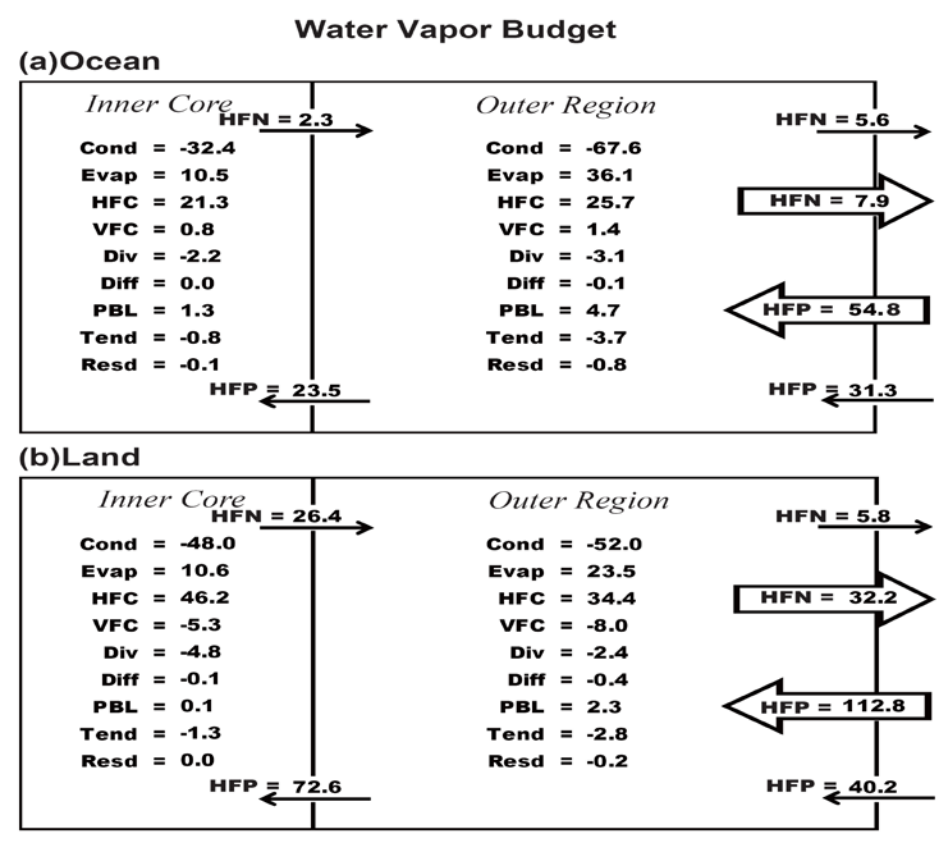
Axis-symmetric Liquid/Ice Water Budget Terms for Oceanic Nari



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

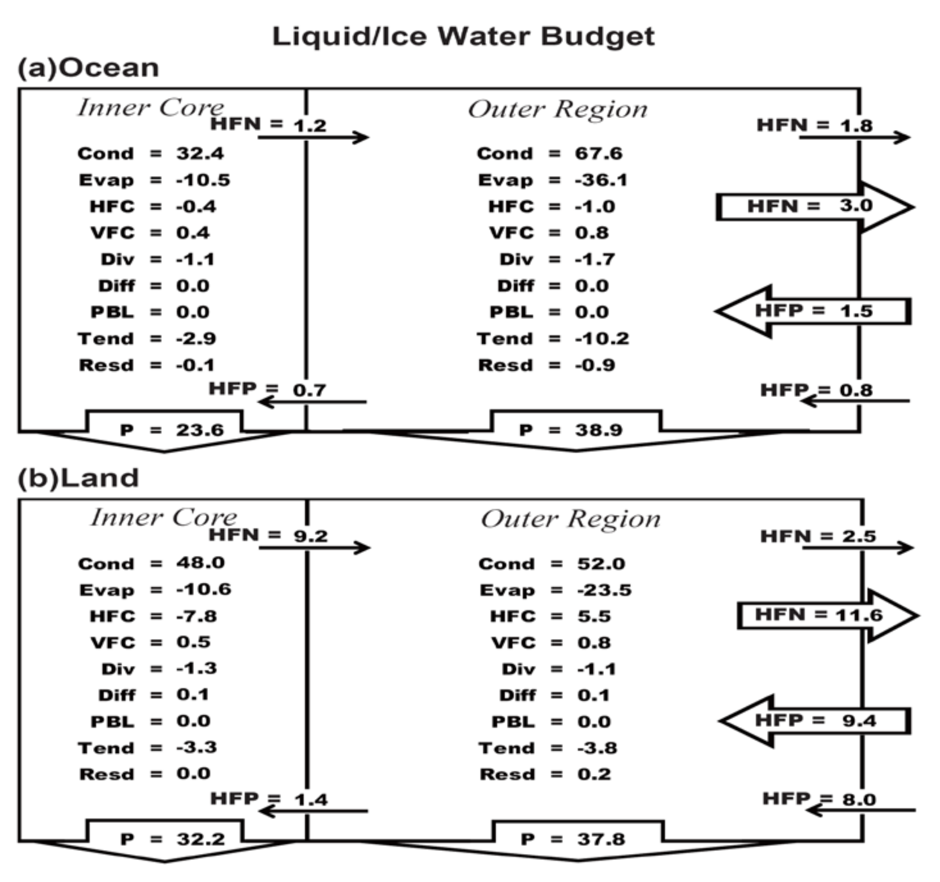


Water Vapor Budgets during the Oceainc and Landfall Stages



Yang et al. (2011; MWR)

Liquid/Ice Water Budgets during the Oceainc and Landfall Stages

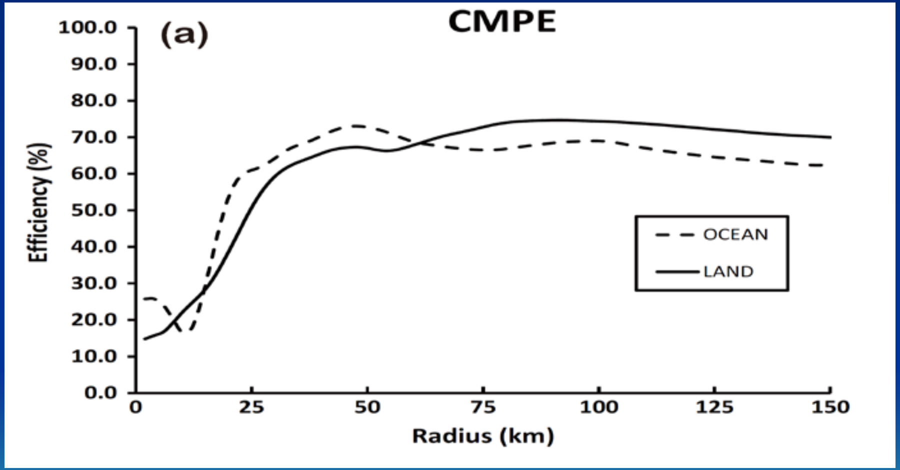


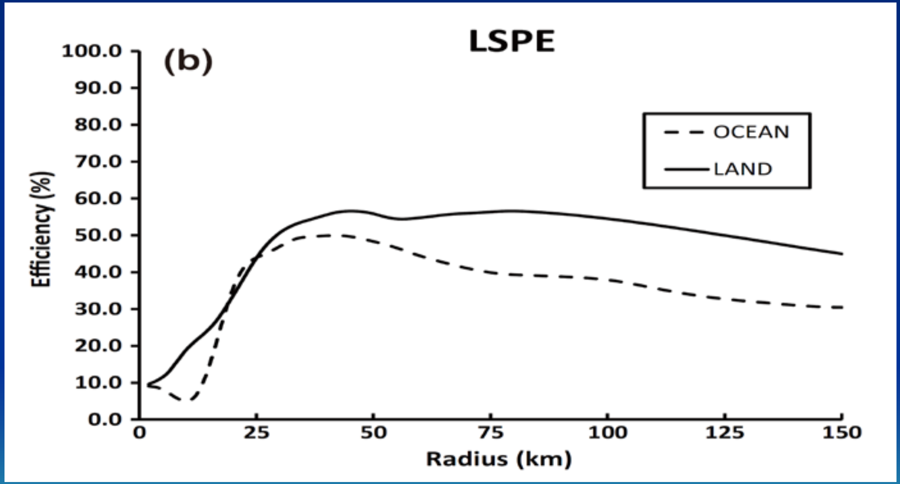
Yang et al. (2011; MWR)

Precipitation Efficiency as a Function of Storm Radius

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

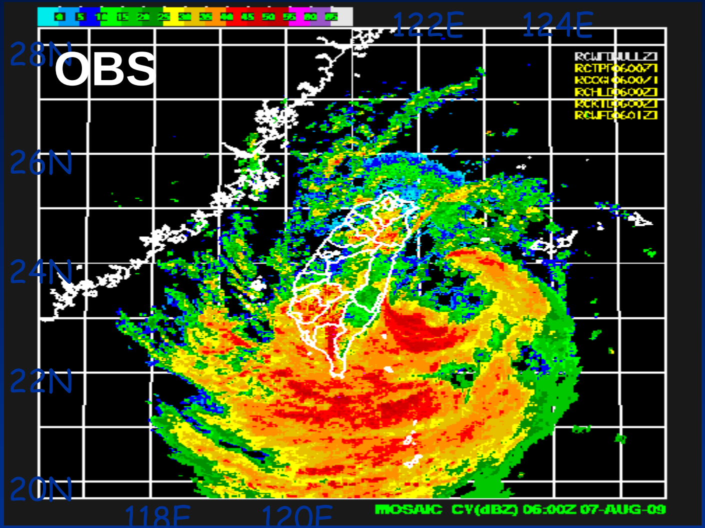
$$\mathrm{LSPE} = \frac{\mathrm{P}}{\mathrm{HFP} + \mathrm{VFP}}$$

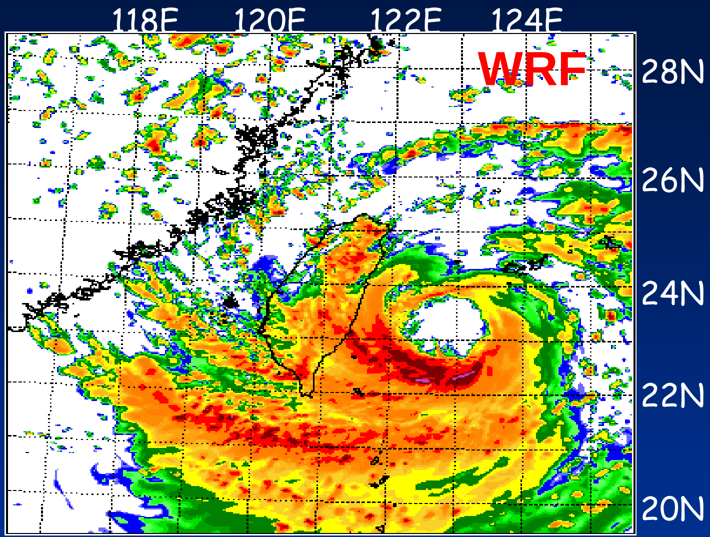


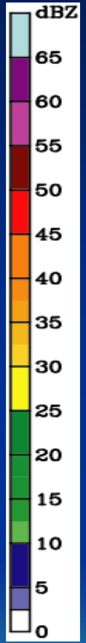


Yang et al. (2011; MWR)

0807/06 Z

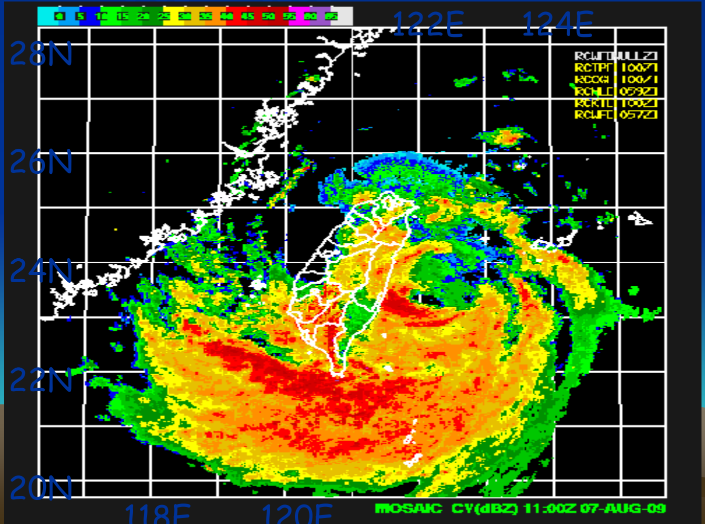


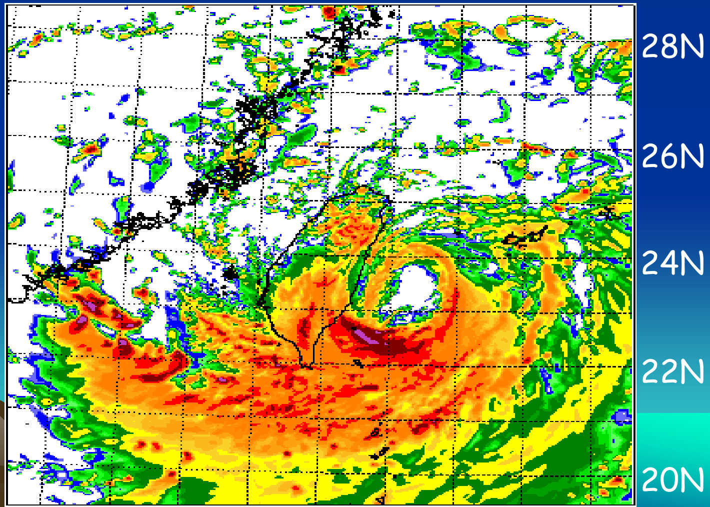




Morakot (2009)

0807/11 Z

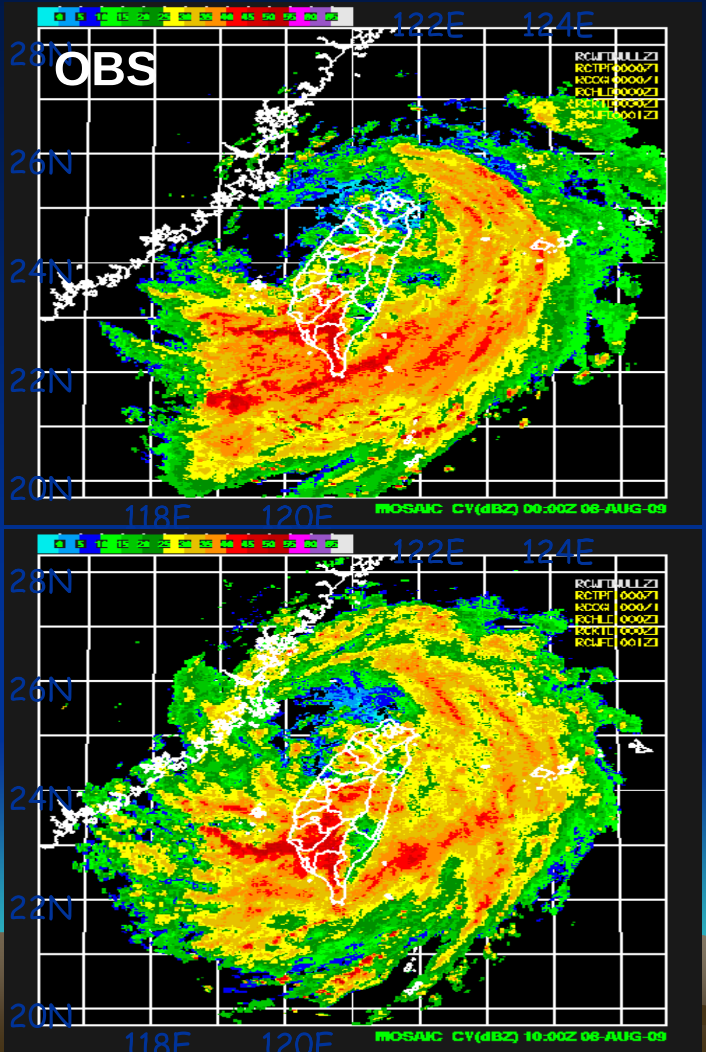


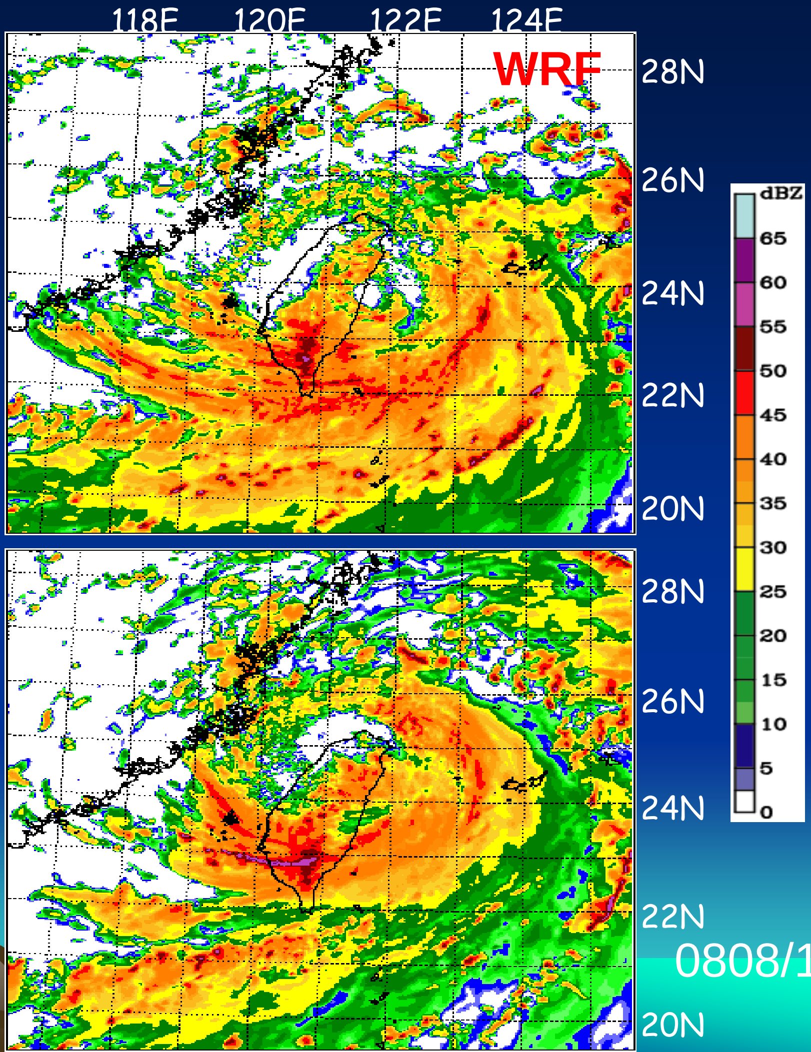


0808/00 Z

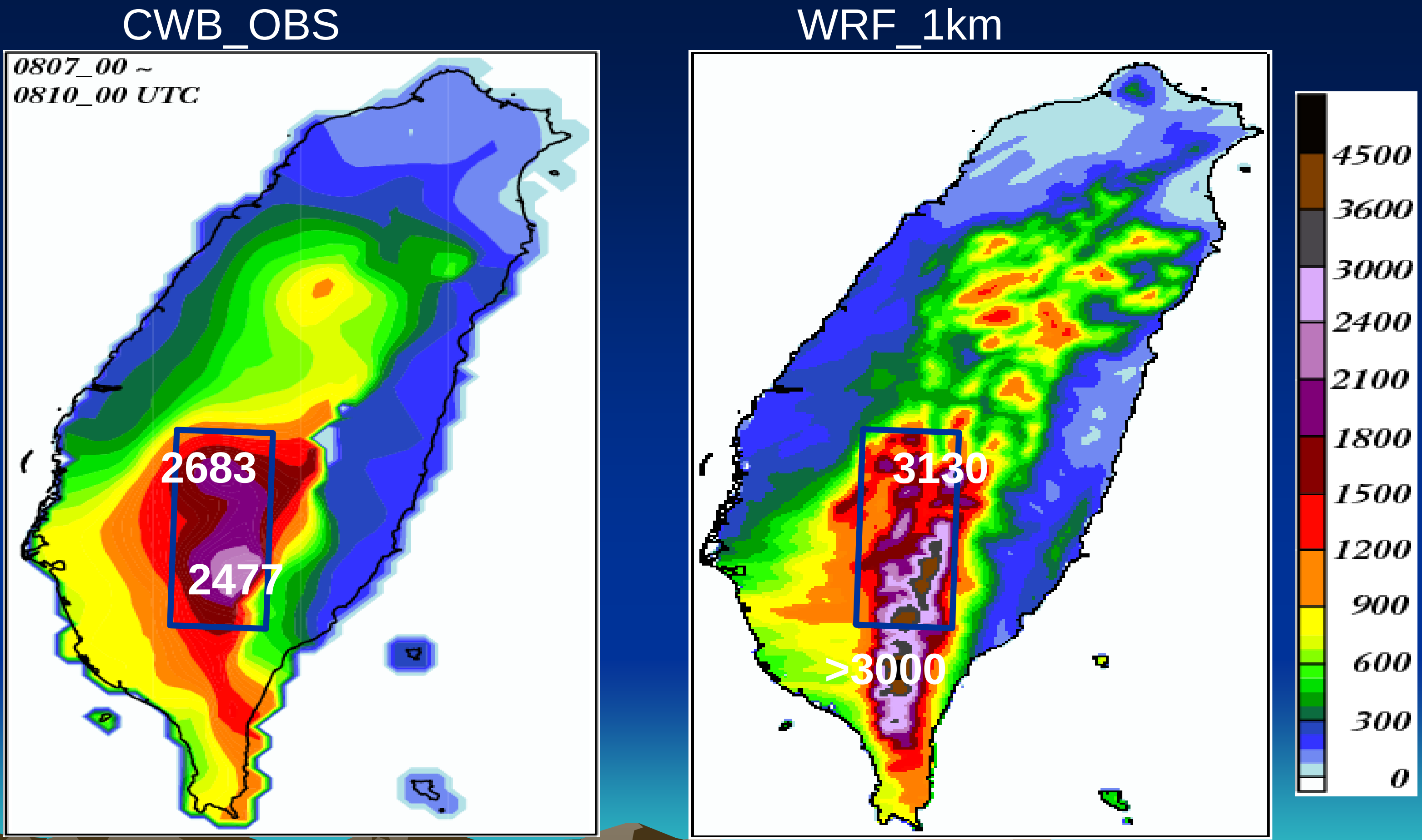
Morakot (2009)

0808/10 Z





0808/11 Z


CWB_OBS
WRF_1km
0807_00 ~
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2683
2477
3130
>3000
4500
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2100
1800
1500
1200
900
600
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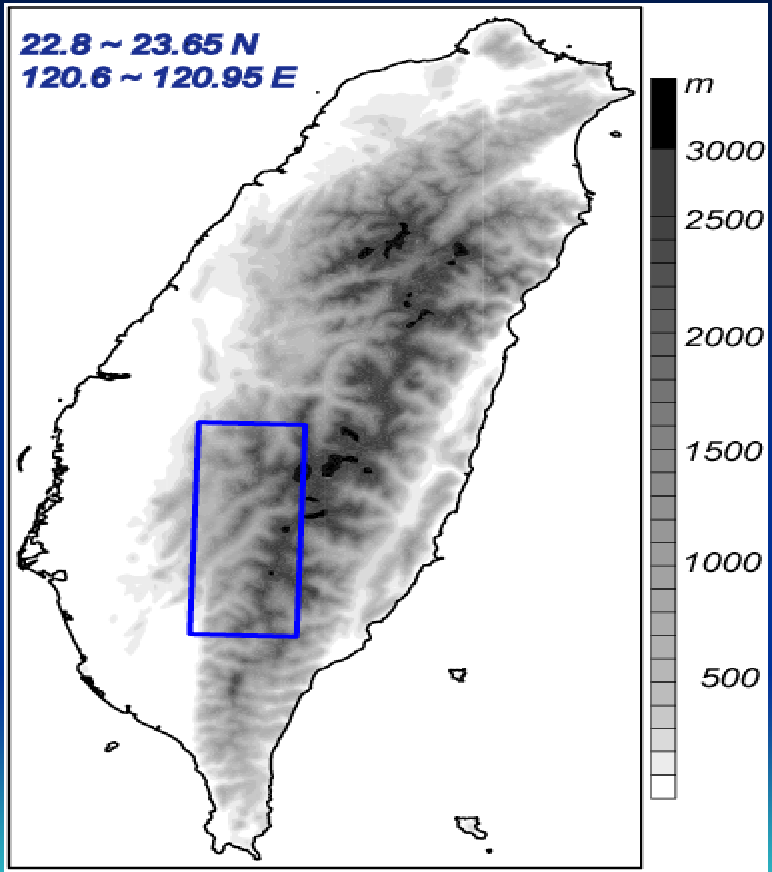
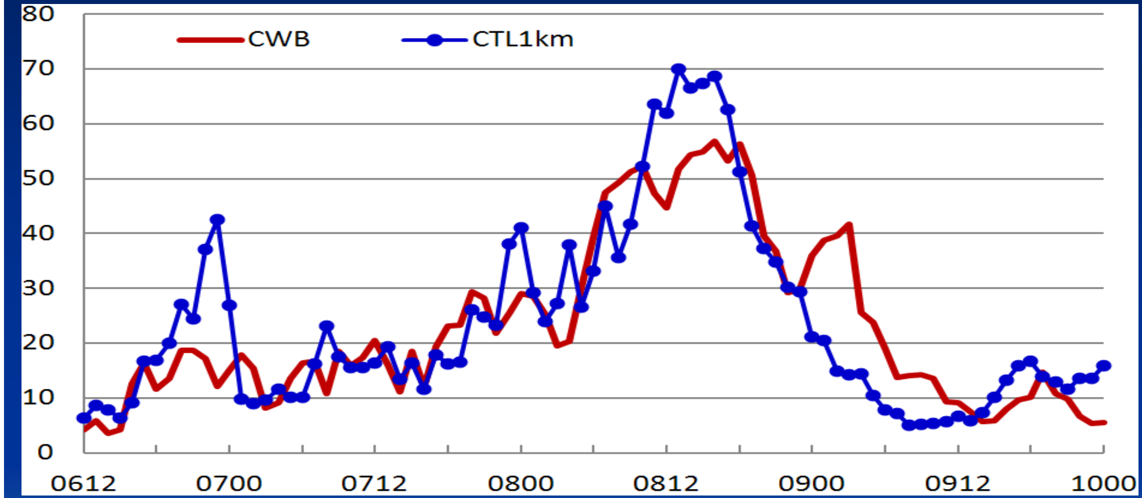
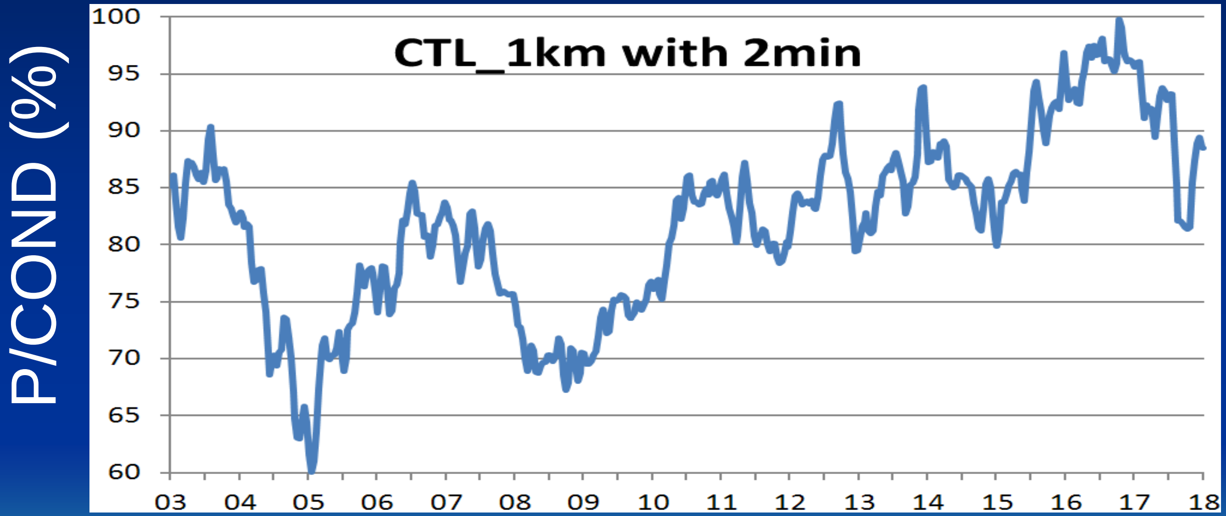
0

Hit Area Rainfall Time Series (mm/h)

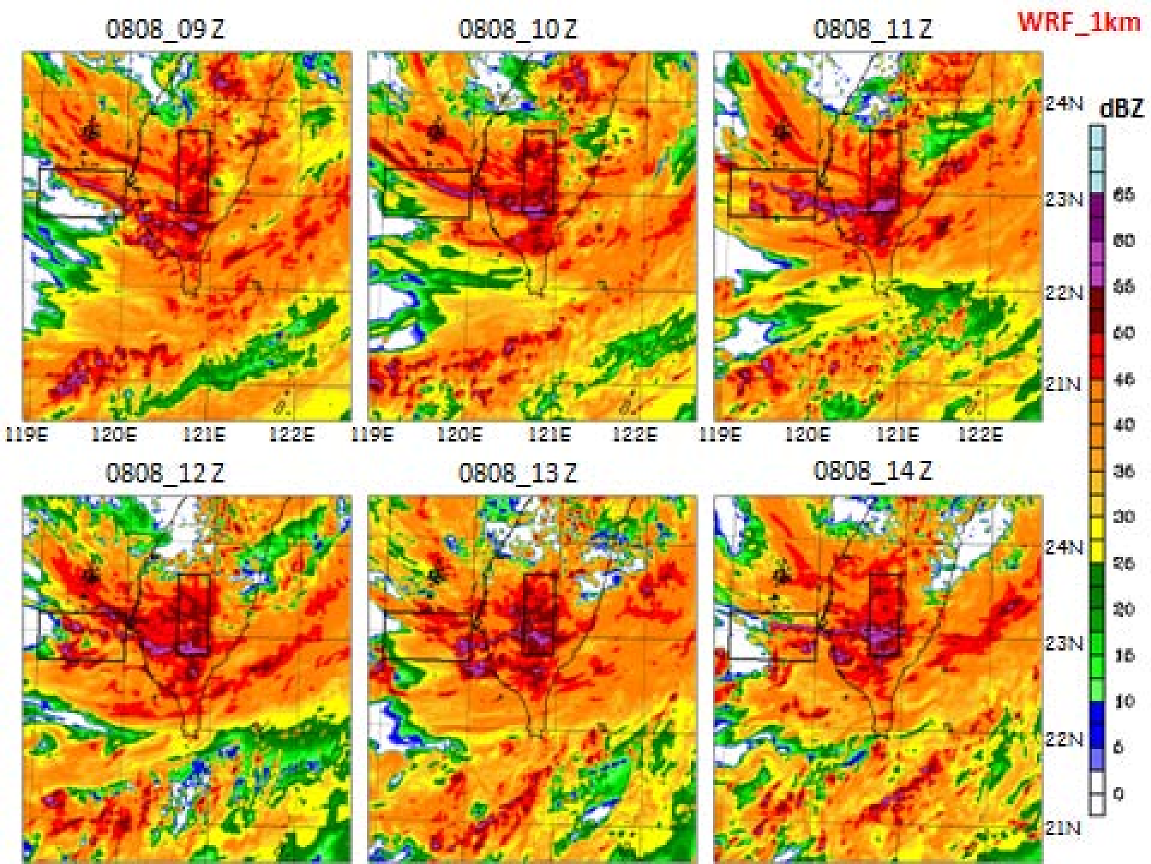




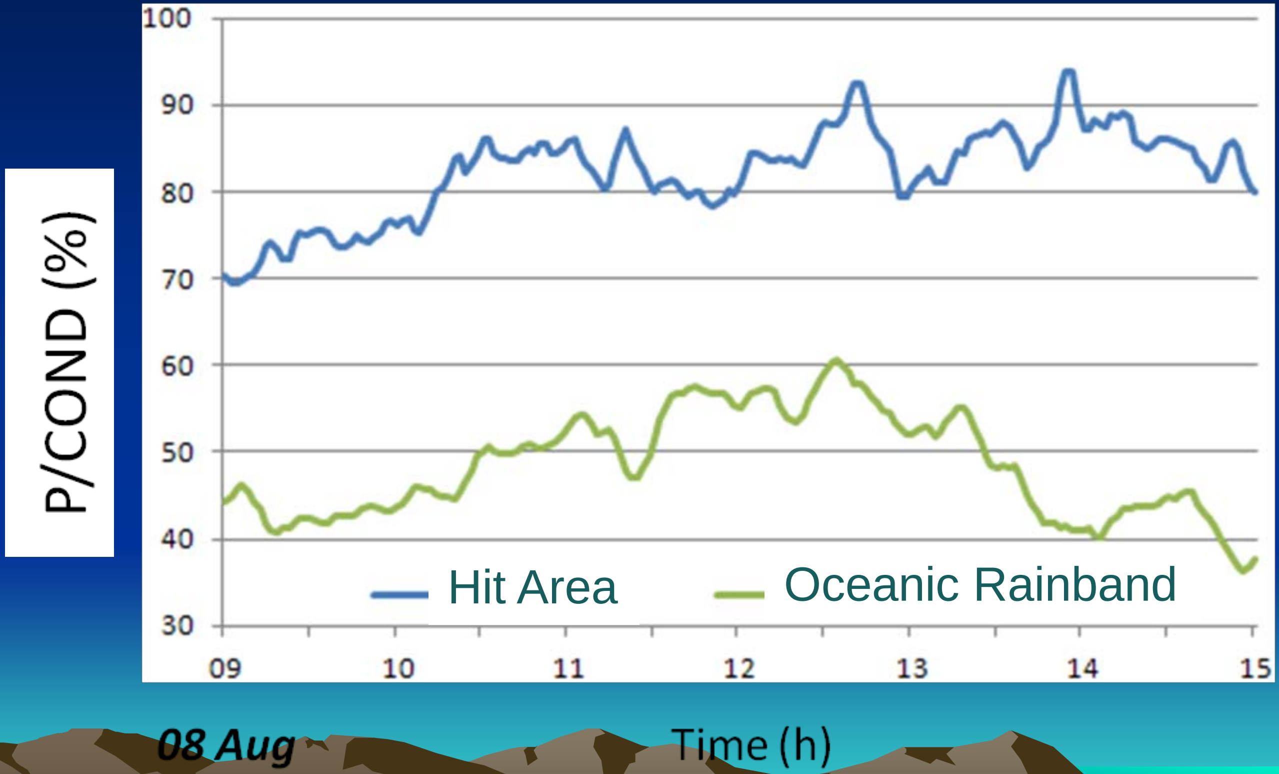
Hit Area CMPE Time Series (mm/h)



Typhoon Morakot (2009)



CMPE of Typhoon Morakot (2009)



Conclusions

- Taiwan's steep terrain enhances Typhoon 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, thus precipitation particles are falling out as quickly as they are produced.

- Precipitation efficiency (PE) of Nari, defined by either the large-scale or microphysics prospective, is increased 10–20% over the outer-rainband region after landfall.

- After landfall, the PE of Morakot reached 95-100% over southern Taiwan, but only 40-50% for the oceanic rainbands. This extremely high PE may explain why Morakot produced the almost-world record of accumulated rainfall on Taiwan (about 3 m in 3 days) and caused the landslide over the entire village of Shiaolin, leaving 700 people dead or missing.

-THE END-

Thanks for your attention!