The Potential Vorticity Budget of 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*., in press, 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.
- Tang, X.-D.*****, and M.-J. Yang, and Z.-M. Tan, 2011: A modeling study of orographic convection and mountain waves in the landfalling Typhoon Nari (2001), *Quart. J. Roy. Meteor. Soc*., DOI:10.1002/qj.933.
- 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.

Introduction

- Hoskins, McIntyre, and Robertson (1985) first introduced the advantage of using potential vorticity (PV) in the analysis of synoptic- and large-scale motions at mid-latitude.
- Schubert and Alworth (1987) further applied the concept of potential vorticity (PV) in the study of tropical cyclone (TC).
- Wu and Emannuel (1995) used the PV inversion technique to determine the influences of different synoptic-scale weather systems on TC's steering flow.
- Wu and Kurihara (1996) used the GFDL hurricane model to perform PV budget calculation of Hurricane Bob (1991), and found that the contribution on PV by latent heating was much larger than that by radiation and surface friction.

Introduction

- Wu and Wang (2000; 2001) examined the impact of asymmetric PV generated by diabtic heating on the steering flows of TCs.

- Wu (2001) examined PV budget of Typhoon Gladys (1994), and found that the primary PV contribution was from latent heating, and the effect of surface friction became significant only after TC's landfall.

- Wu et al. (2009) further conducted PV budget calculation of Typhoon Zeb (1998) and found that the surface fluxes of sensible heat and moisture from ocean had substantial impacts on the evolution of Zeb's eyewall and storm intensity, and in particular:
  - Deep conviction within the eyewall weakened after Zeb's landfall on the Luzon Island, and the intense radial inflow in PBL enhanced the mixing of PV between the eye and eyewall, resulting in a monopole PV.

Objectives

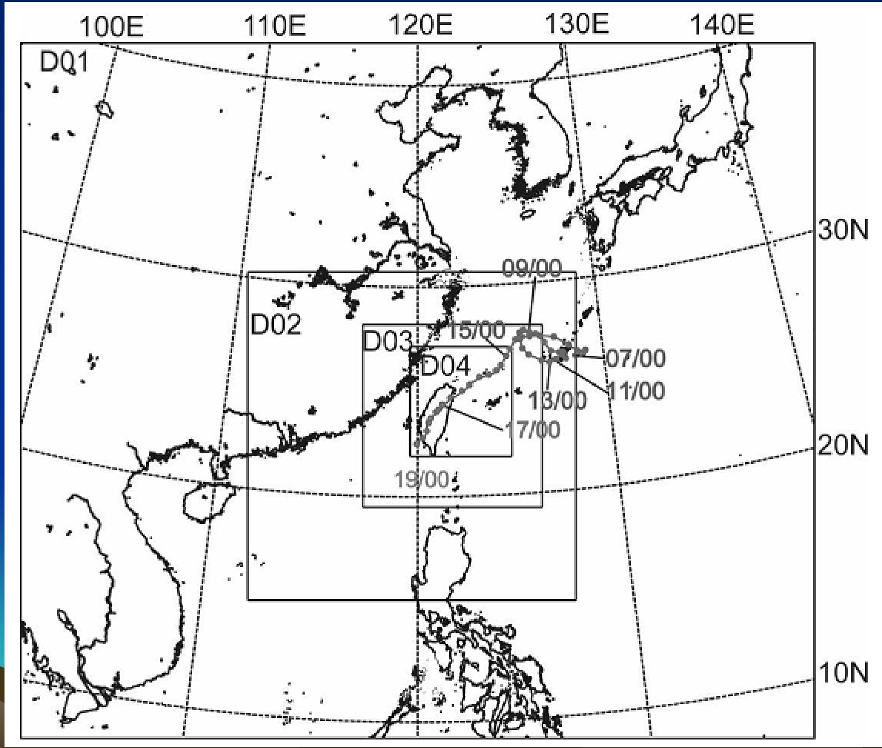
- Although there are many studies on PV in TCs, only few studies has conducted PV budget calculations with high spatial and temporal resolutions (with 2-km horizontal grid size and 2-min time interval).

Three Objectives are:

- 1) To examine how the nonhydrostatic balanced dynamics, surface friction, and turbulence mixing influence TC's PV distribution and intensity.
- 2) To understand the evolution of dynamical and thermodynamical processes of Typhoon Nari (2001) during its landfall on Taiwan through the PV budget calculation.
- 3) To investigate Taiwan's topography effect on Nari's PV evolution.

Model Domains

- Four nested grids using the MM5 v3.5 (Yang et al. 2008;JAS)



Model Configuration

Domain	D01	D02	D03	D04
Horizontal Grid Size (km)	54	18	6	2
Grid Number	81×71	100×100	166×166	271×301
Time Step	90	30	10	3.3
Integration Period	0-84hr			
IC & BC	ECMWF $1.125^{o} \times 1.125^{o}$			From D03
PBL	MRF			
Microphysics	Reisner 2 (with graupel)			
Cumulus	Grell		Not used	
Radiation	Dudhia			
Vertical σ-level：32 levels				

Numerical Experiments

Experiment	Control (CNTL)	No Terrain (NT)	Ocean (OC)
Terrain change	No	Remove terrain by flat surface on Taiwan	Replace by ocean
Landuse change	No	No	Replace by ocean
SST change	No	No	Creat SST by linear interpolation

PV budget equation

- Ertel's PV：

$$P = \frac{1}{\rho}\vec{\eta}\cdot\nabla\theta_v$$

- Virtual Potential Temperature:

$$\theta_v = T_v\left(\frac{p_0}{p}\right)^{R_d/C_p}$$

$\vec{\eta}$：absolute vorticity vector

θ_v: virtual potential temperature

T_v: virtual temperature

$\vec{V}_h$: horizontal wind vector

∇_h: horizontal gradient

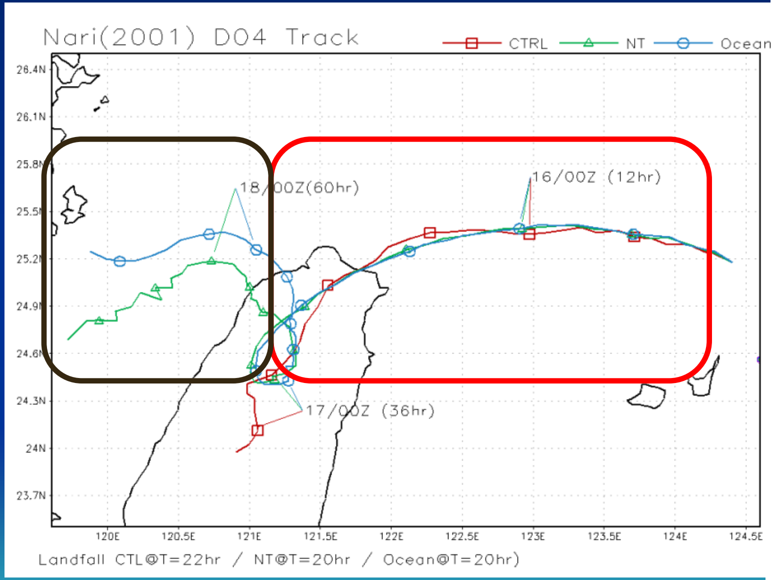
ρ：air density

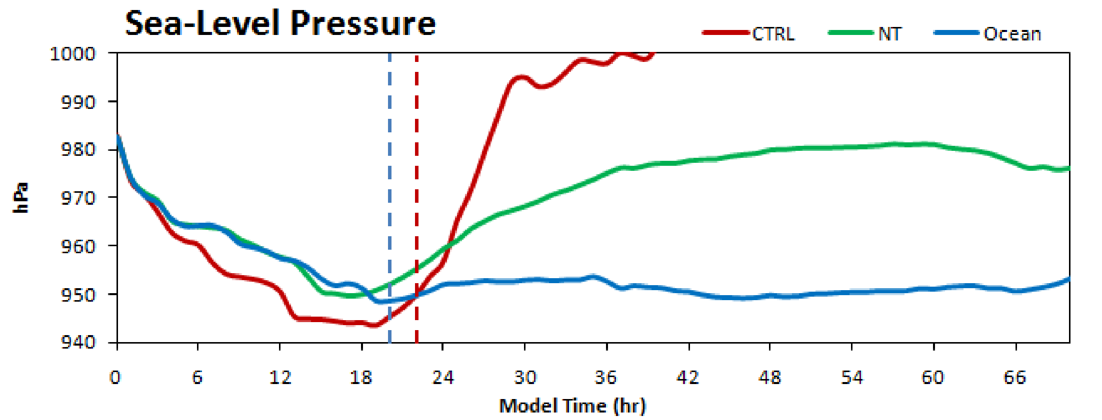
- Following Pedlosky (1987) and Schubert et al.(2001), we can derive the nonhydrostatic moist PV equation as:

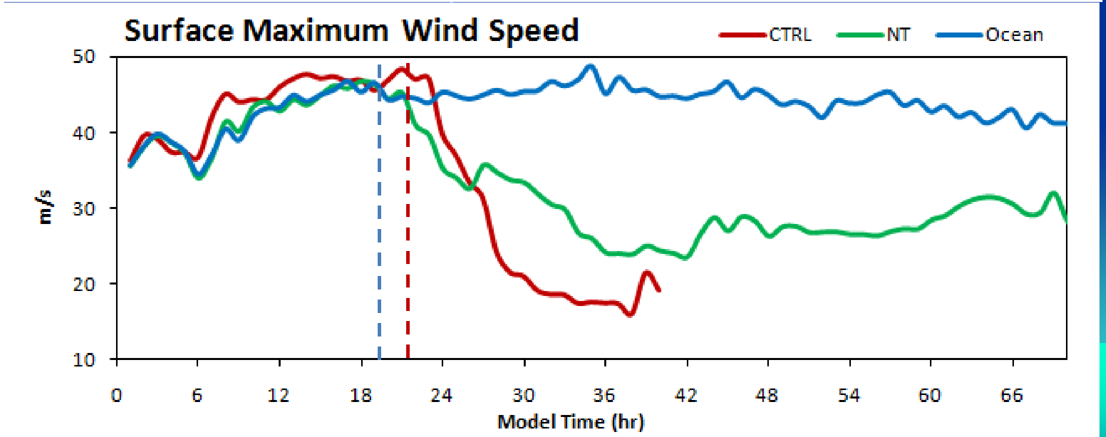
$$\frac{\partial P}{\partial t} = -\vec{V}_h\cdot\nabla_h P - w\frac{\partial P}{\partial z} + \frac{\vec{\eta}}{\rho}\cdot\nabla\frac{d\theta_v}{dt} + \frac{1}{\rho}\nabla\theta_v\cdot\left(\nabla\times\vec{F}_r\right)$$

H./V. Adv. Diabtic Heating Friction

Nari’s track and intensity

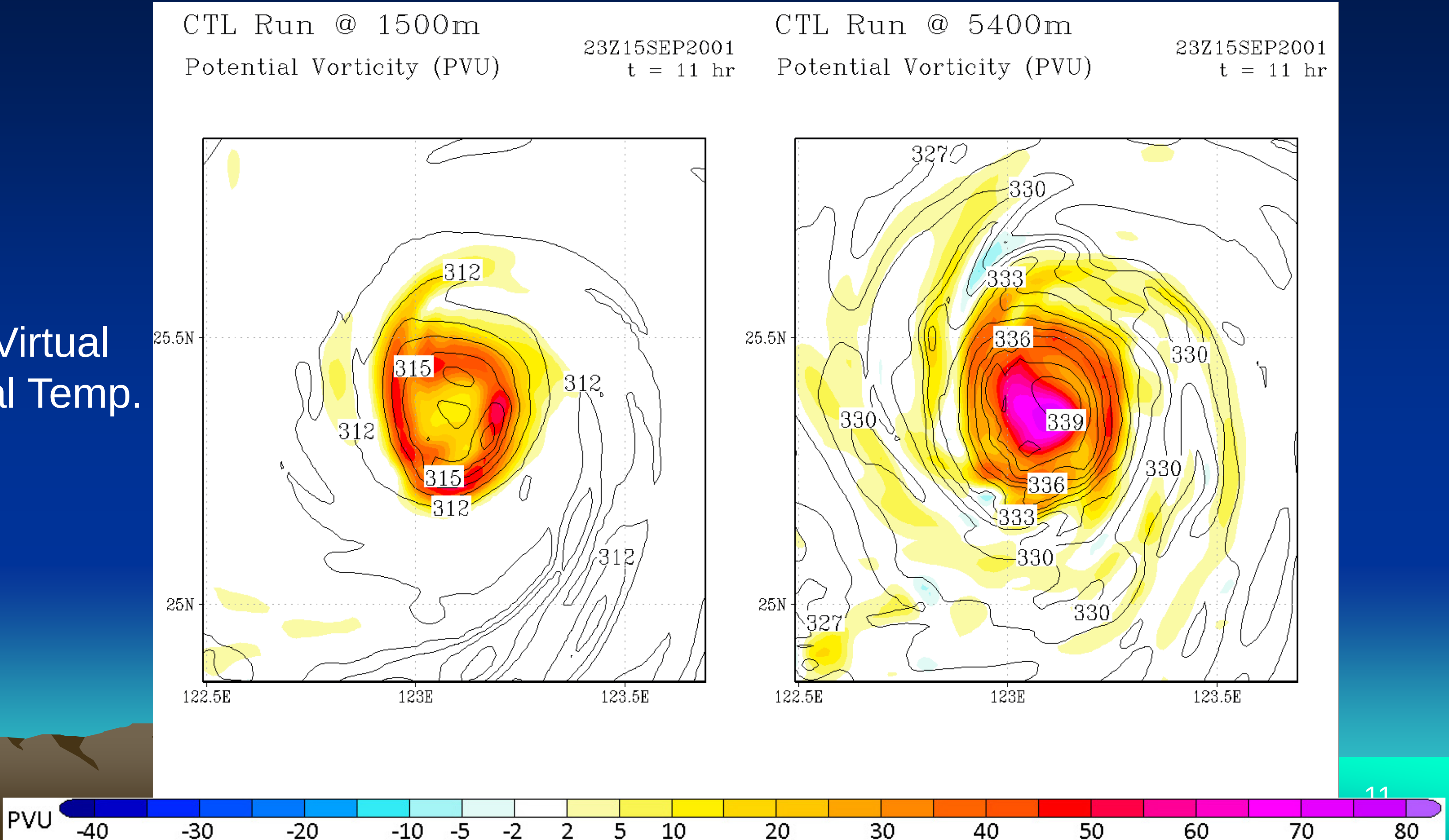






Looping of PV Horizontal Distribution (CTRL)

Color: PV
Contour: Virtual
Potential Temp.



Evolution of PV's Vertical Cross Section

Warm Core

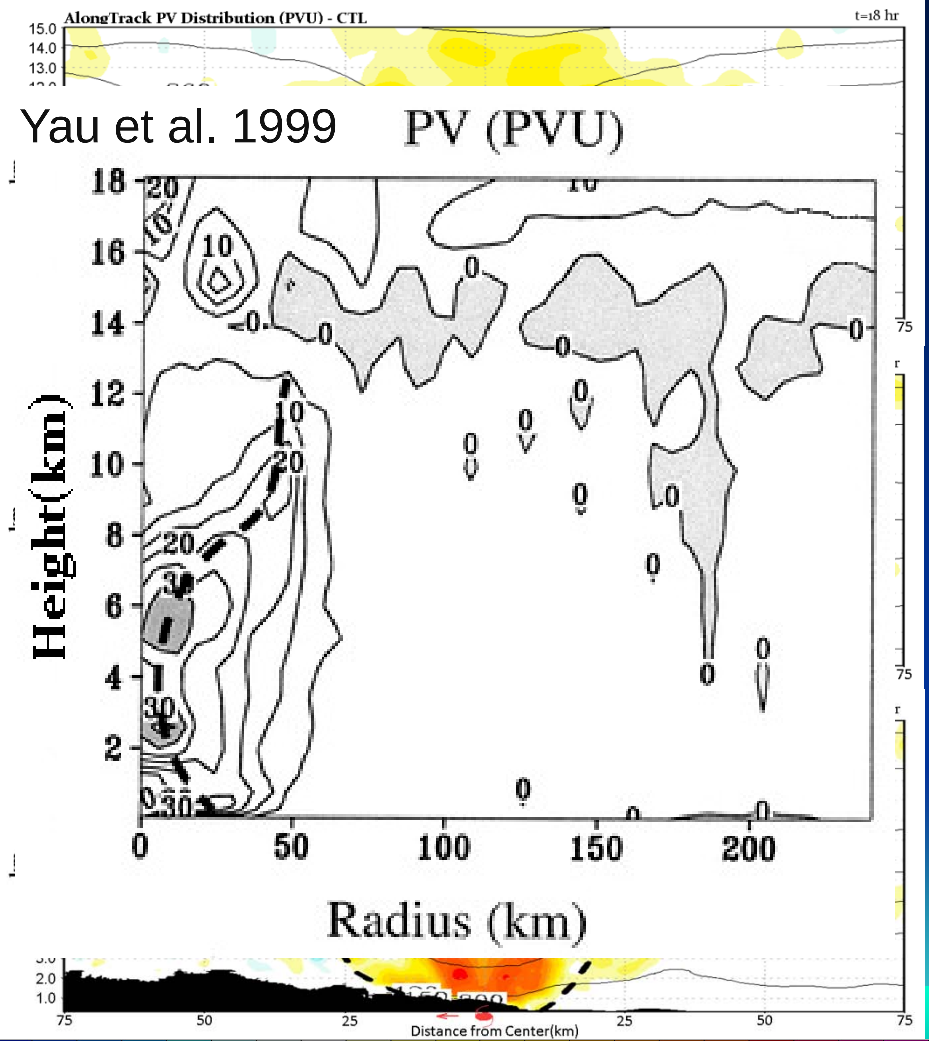
✚

Eyewall

॥

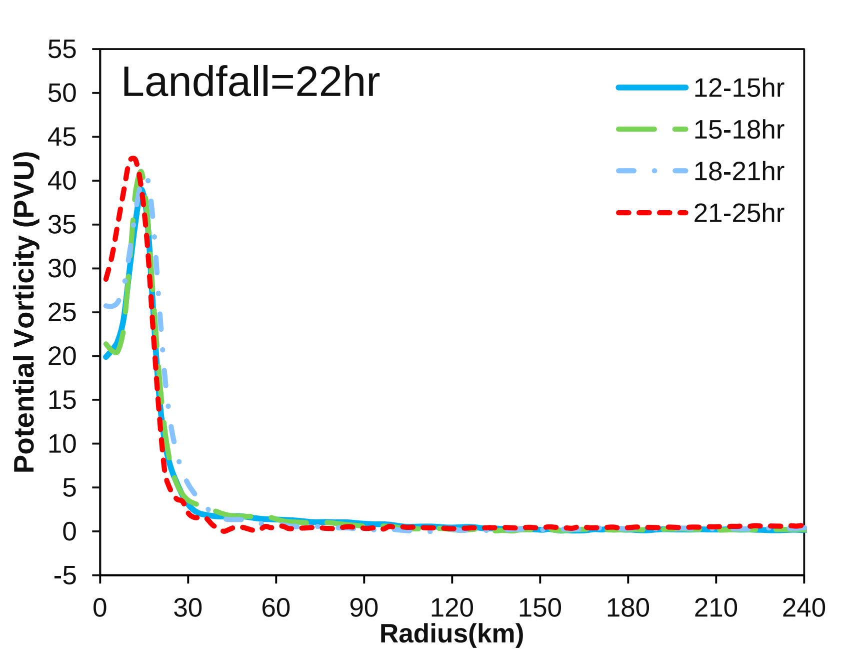
H-Shape distribution
(Yau et al. 1999)

- PV intensified at the time of landfall, and later shrank and weakened due to terrain's friction effect

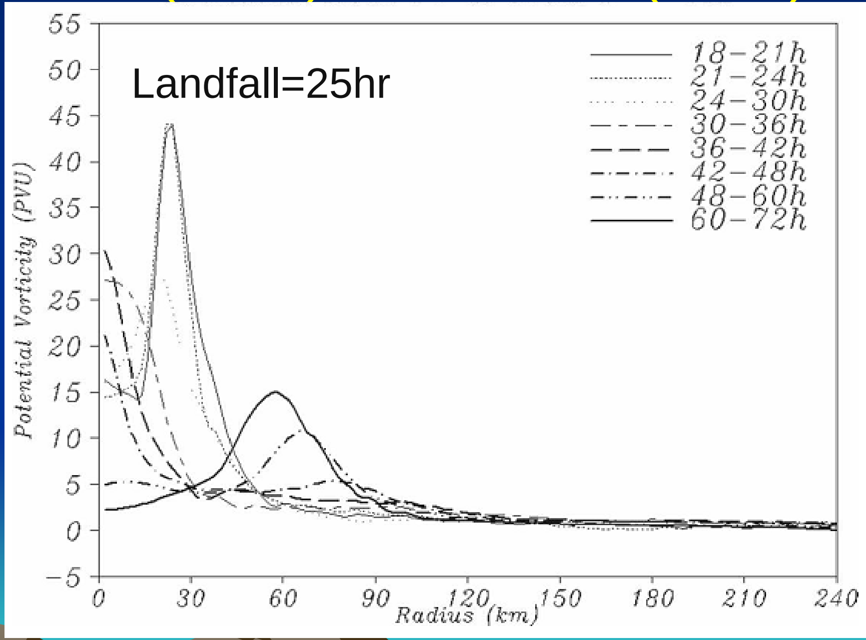


Azimuthally-Averaged PV at 875h Pa

Nari (2001) – This Study

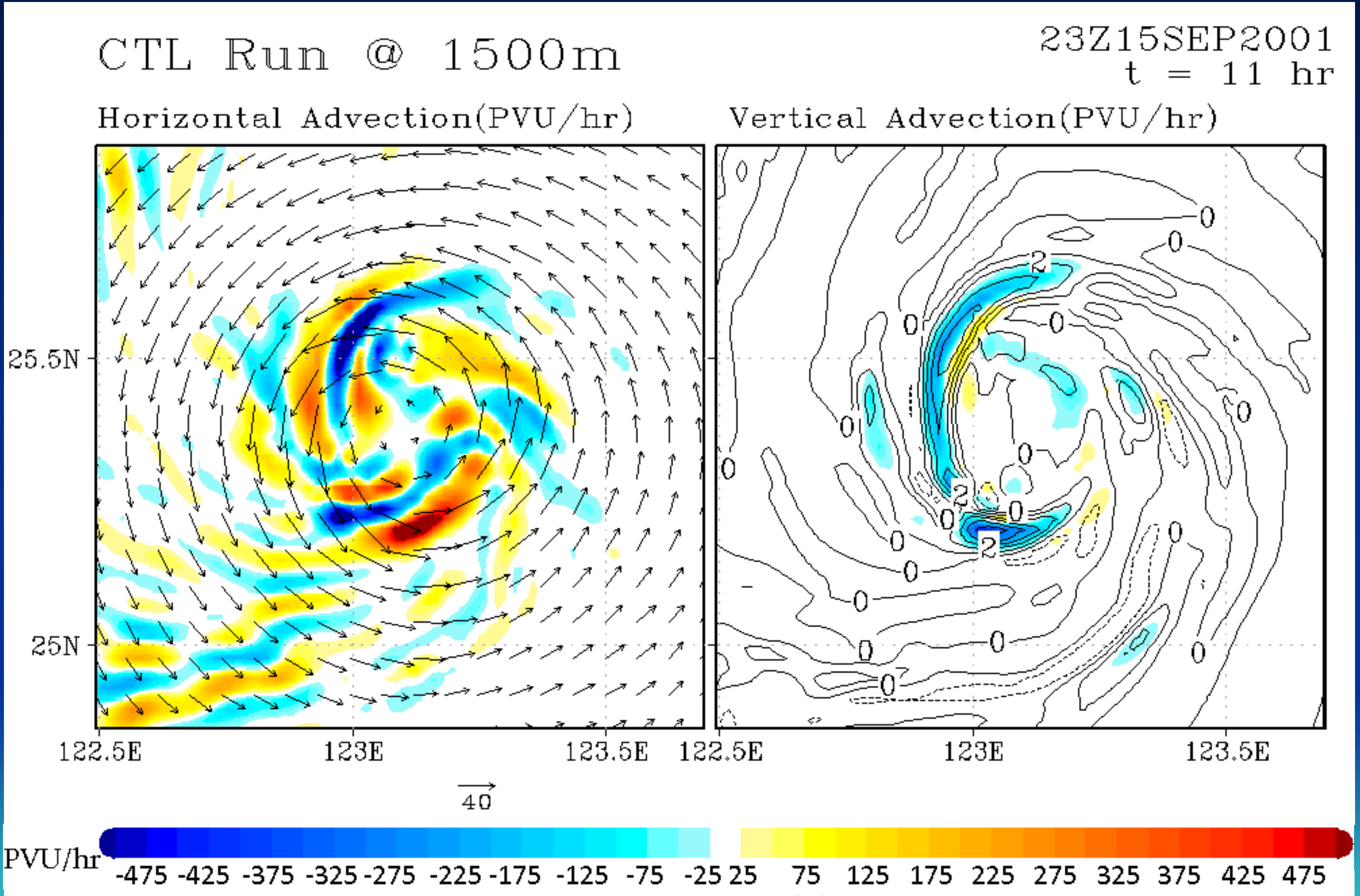


Zeb (1998) – Wu et al. (2009)



Looping of PV Advection

- Horizontal Advection
  - distributes PV cyclonically by the tangential flow
  - transports PV inward and induces mixing by the radial flow
- Vertical Advection
  - transports PV upward by the intense updrafts in eyewall and rainbands

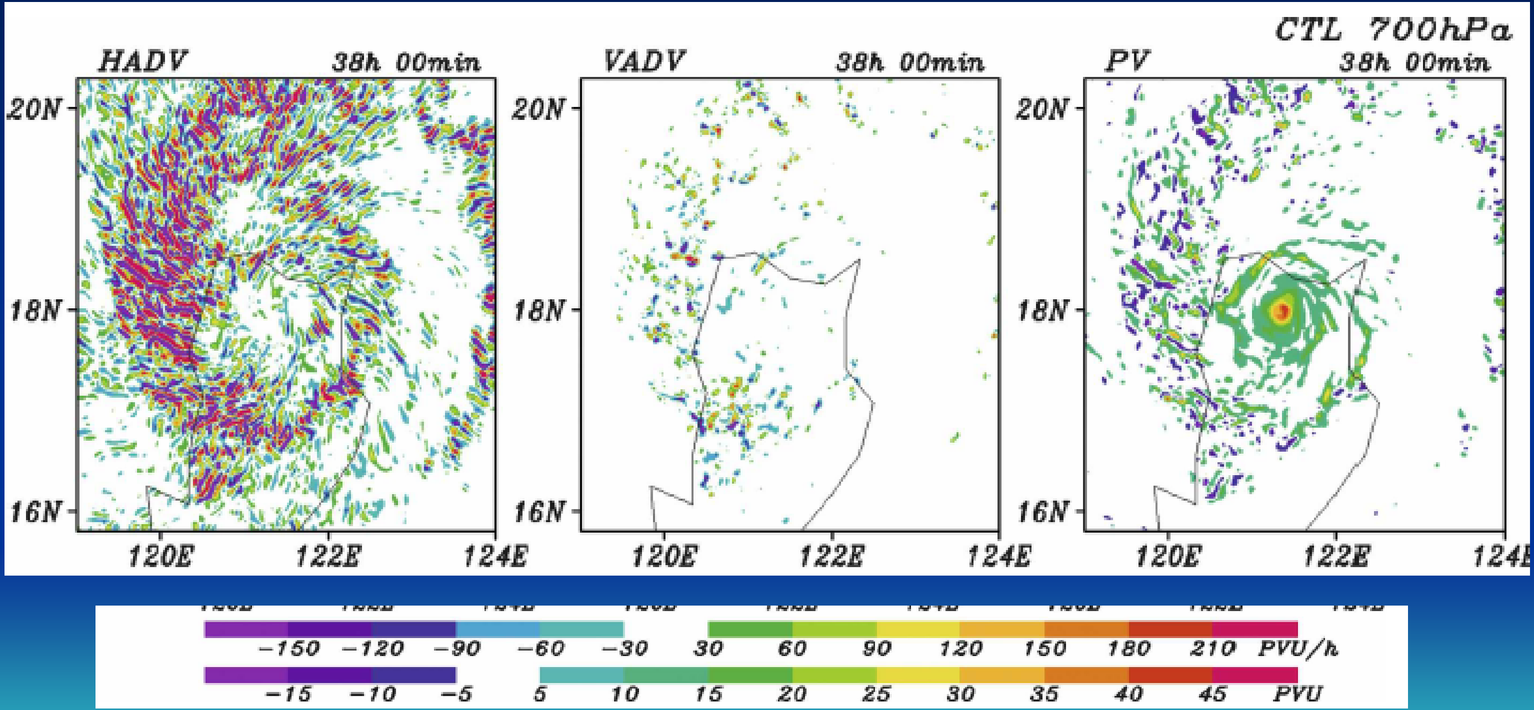


- Advection can only redistribute but cannot generate PV.

$$\frac{\partial P_m}{\partial t} = -\vec{V}_h \cdot \nabla_h P - w\frac{\partial P}{\partial z} + \frac{\vec{\eta}}{\rho} \cdot \nabla \frac{d\theta_v}{dt} + \frac{1}{\rho}\nabla\theta_v \cdot \left(\nabla \times \vec{F}_r\right)$$

PV & Advection terms for Zeb (1998)

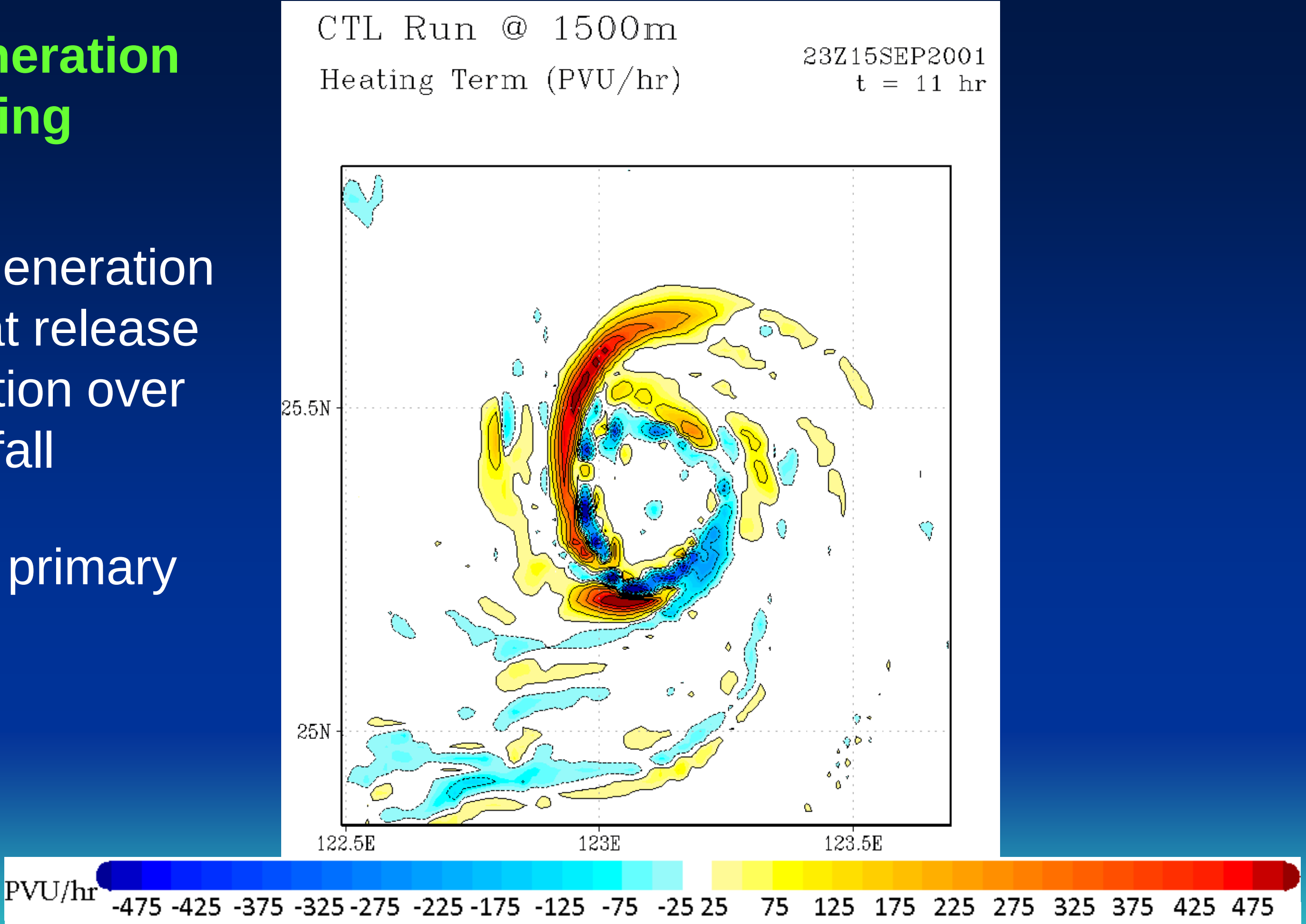
Wu et al. (2009)



Looping of PV generation by latent heating

- Large low-level PV generation by intense latent heat release of enhanced convection over terrain at Nari's landfall

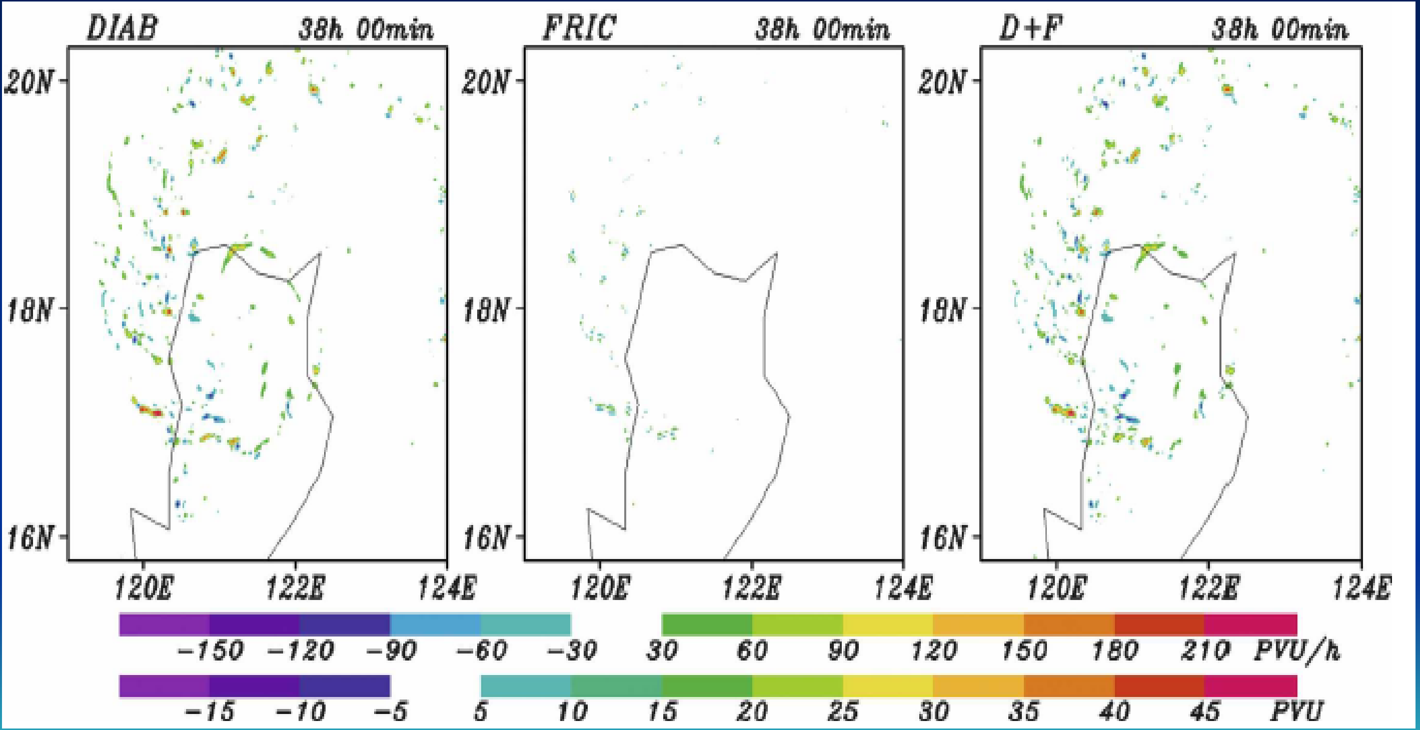
- Latent heating is the primary PV generation term



$$\frac{\partial P_m}{\partial t} = -\vec{V}_h \cdot \nabla_h P - w\frac{\partial P}{\partial z} + \frac{\vec{\eta}}{\rho}.\nabla\frac{d\theta_v}{dt} + \frac{1}{\rho}\nabla\theta_v \cdot (\nabla \times \vec{F}_r)$$

Diabatic and Frictional terms for Zeb (1998)

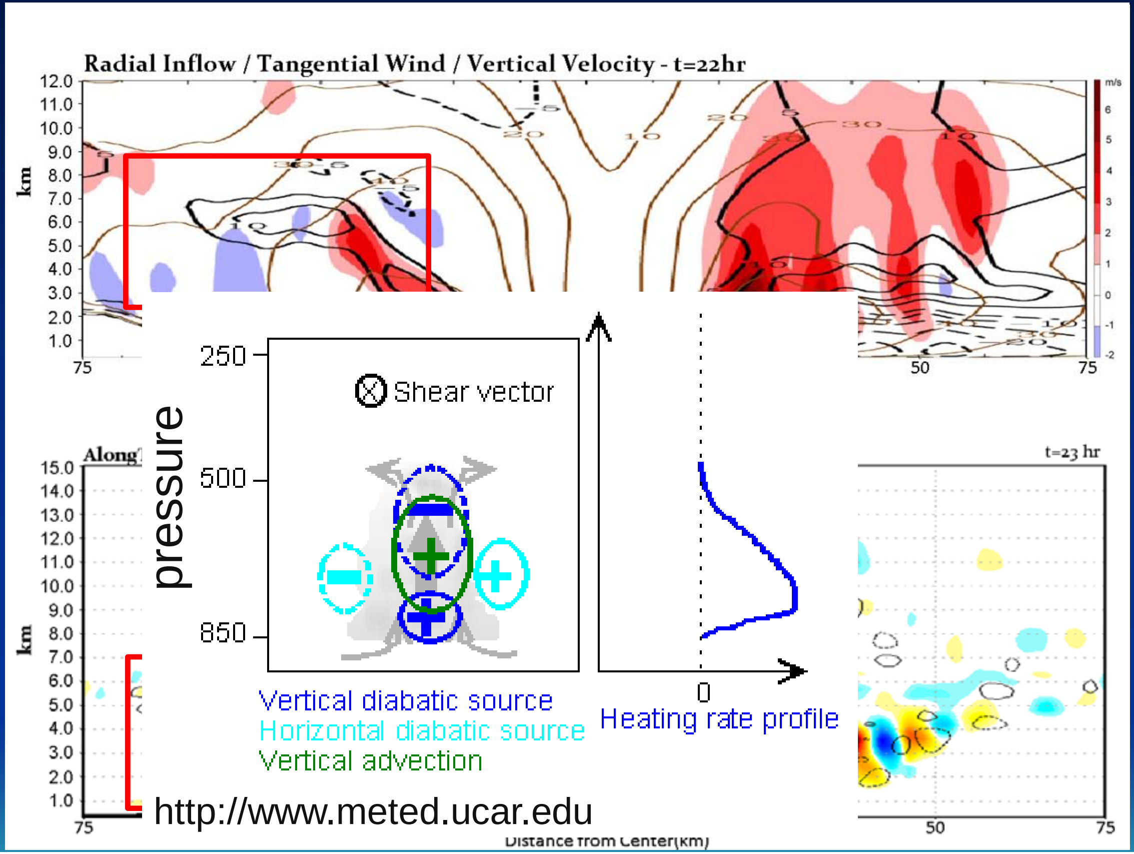
Wu et al. (2009)



Vertical Cross Section of Latent-Heating PV Generation Term

- Effect of Latent heating/cooling on PV generation/loss:
    - Negative PV generation above the max. heating, and positive PV generation below the max. heating
    - Upward transport of positive PV by intense updrafts in eyewall

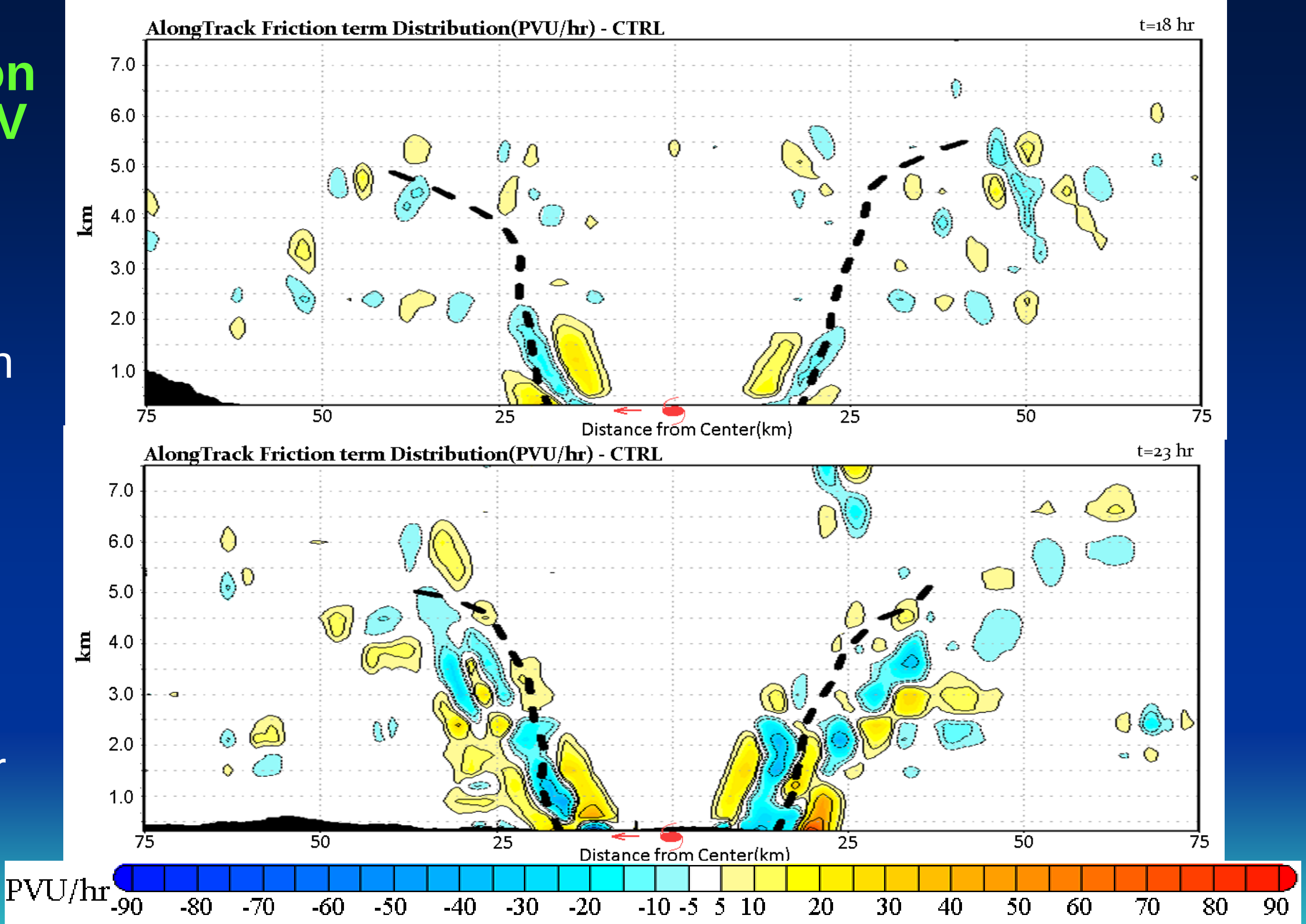
- Outward transport of hydrometeors by the sloping radial outflow, expanding the surface rainfall area above terrain. (Yang et al. 2011; JGR)



$$\frac{\partial P_m}{\partial t} = -\vec{V}_h \cdot \nabla_h P - w\frac{\partial P}{\partial z} + \frac{\vec{\eta}}{\rho}.\nabla\frac{d\theta_v}{dt} + \frac{1}{\rho}\nabla\theta_v \cdot \left(\nabla \times \vec{F}_r\right)$$

Vertical Cross Section of friction-induced PV generation/lose term

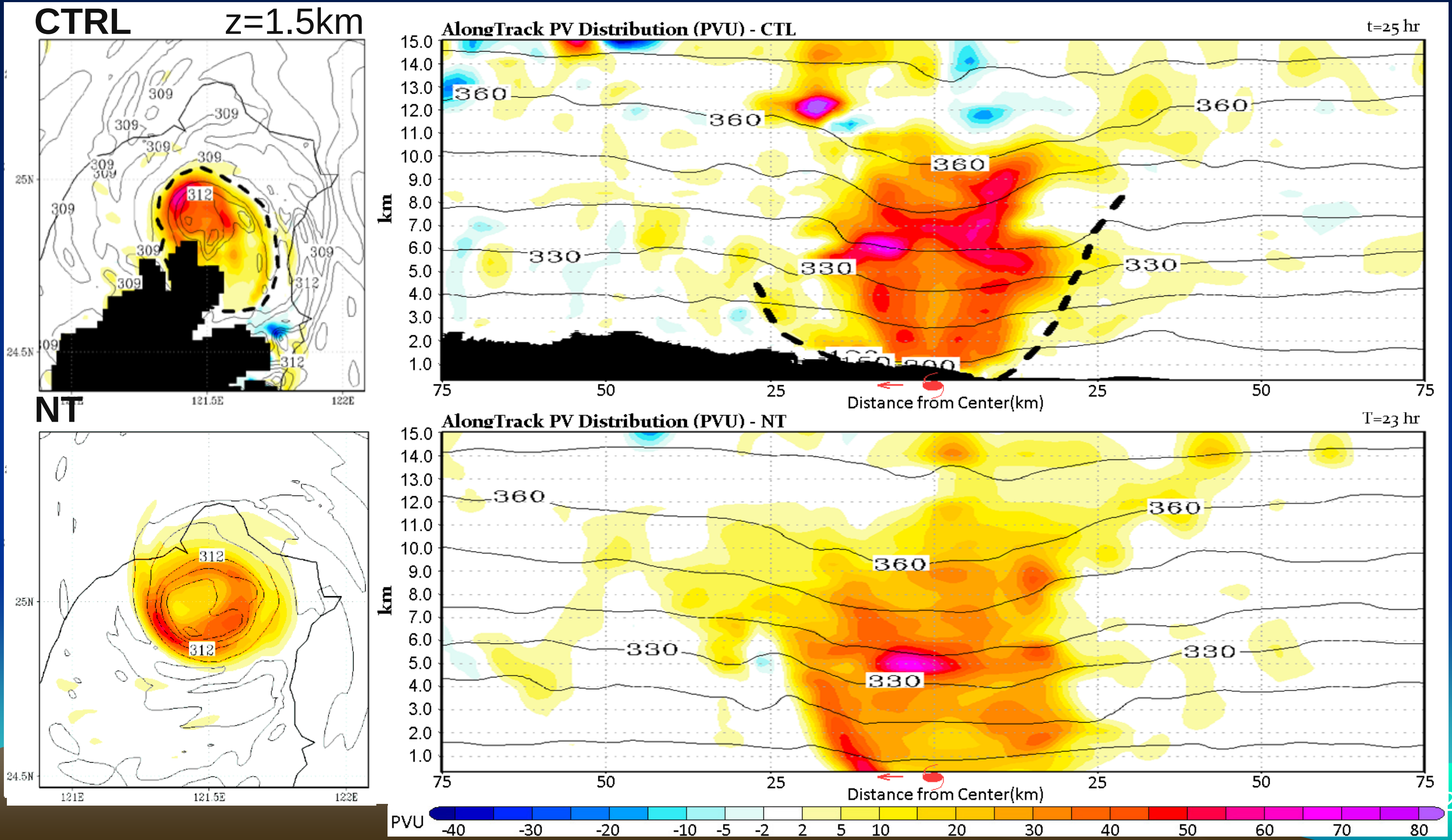
- The friction term includes surface friction and turbulent mixing
- Enhanced mixing after landfall tranports both positive and negative PV upward
- Surface friction becomes stronger after landfall



$$\frac{\partial P_m}{\partial t} = -\vec{V}_h \cdot \nabla_h P - w\frac{\partial P}{\partial z} + \frac{\vec{\eta}}{\rho} . \nabla \frac{d\theta_v}{dt} + \frac{1}{\rho}\nabla \theta_v \cdot \left(\nabla \times \vec{F}_r\right)$$

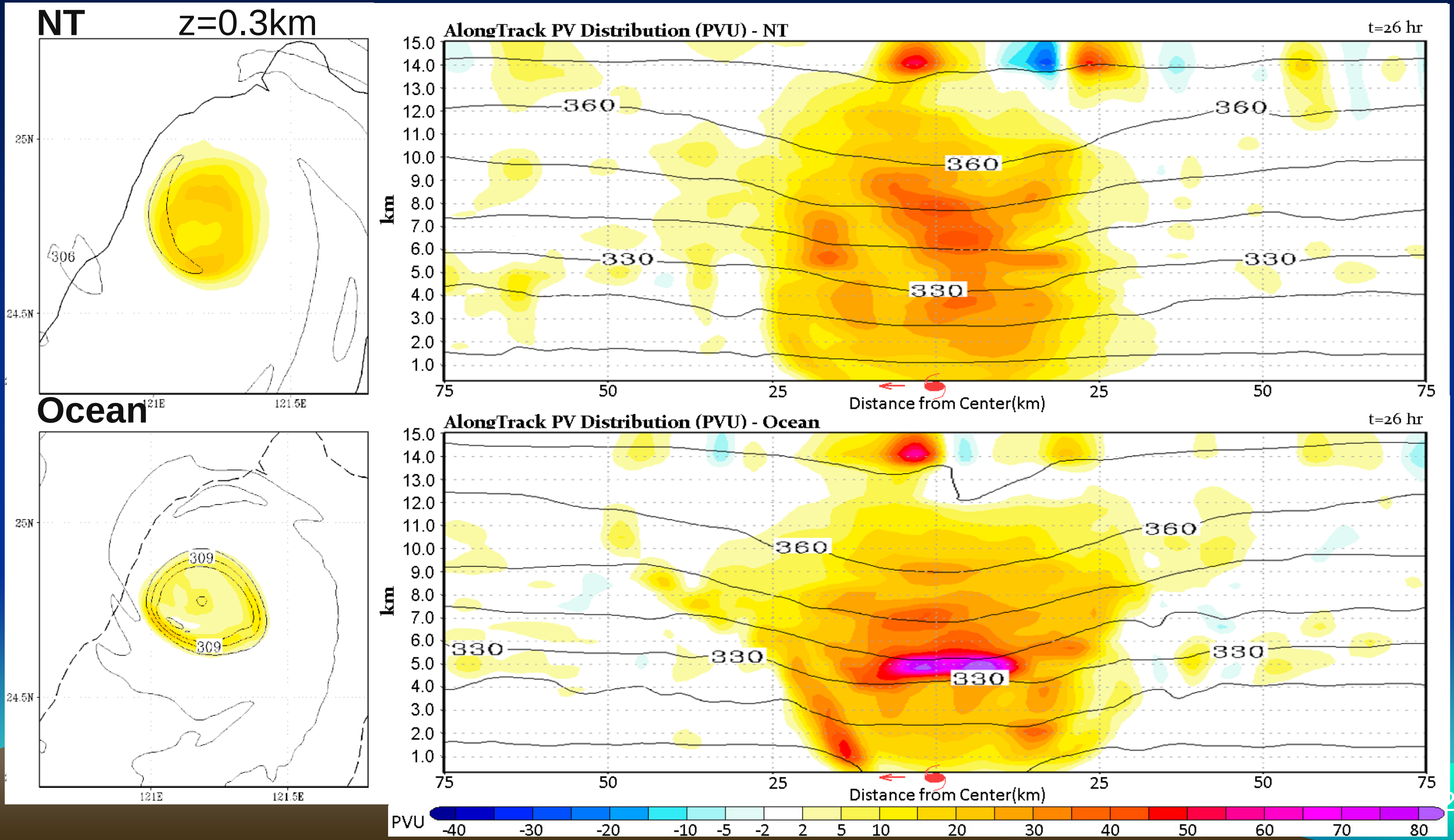
PV Evolution (CTRL vs. NT)

Landfall +4hr

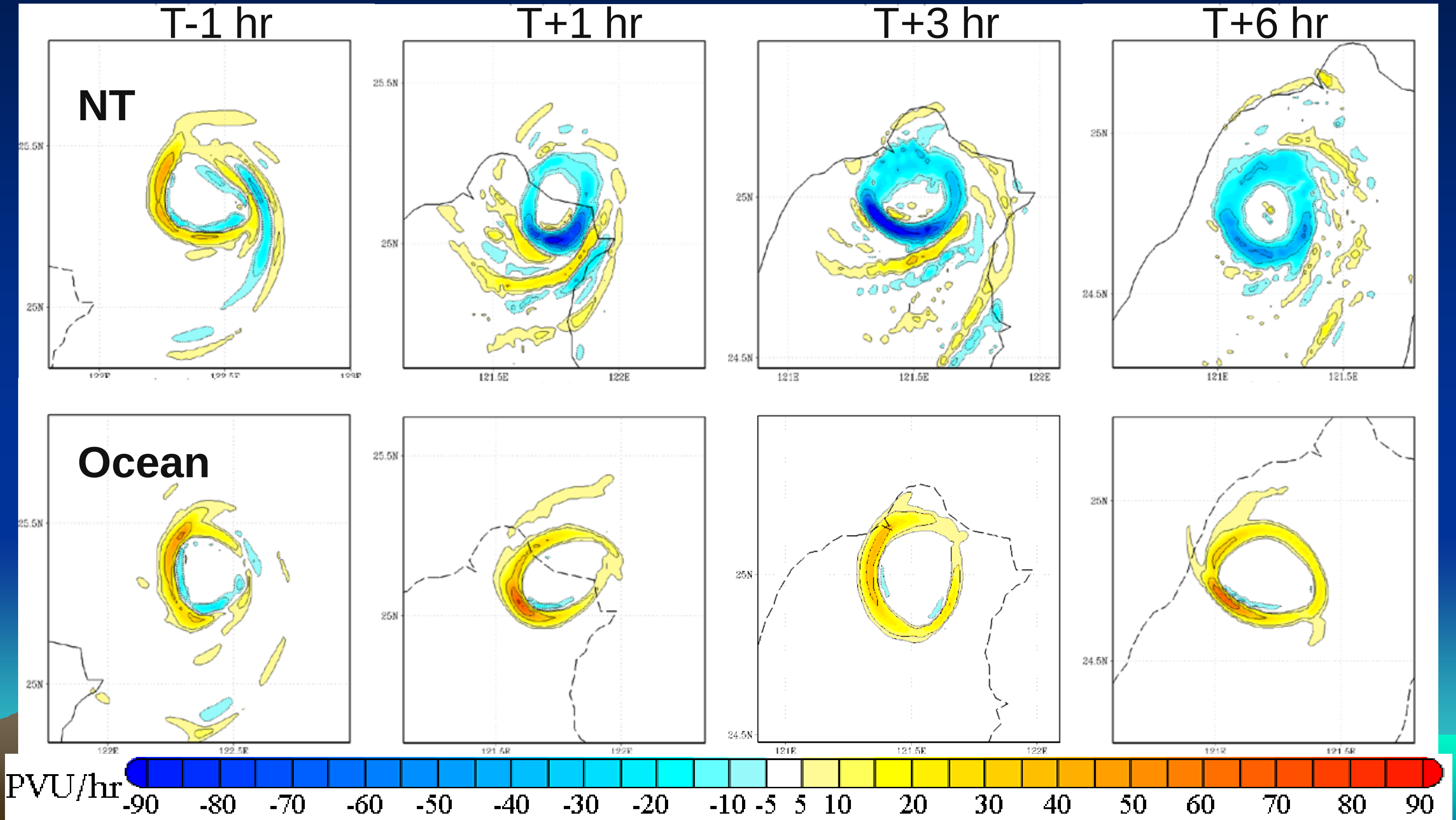


PV Evolution (NT vs. Ocean)

Landfall +4hr

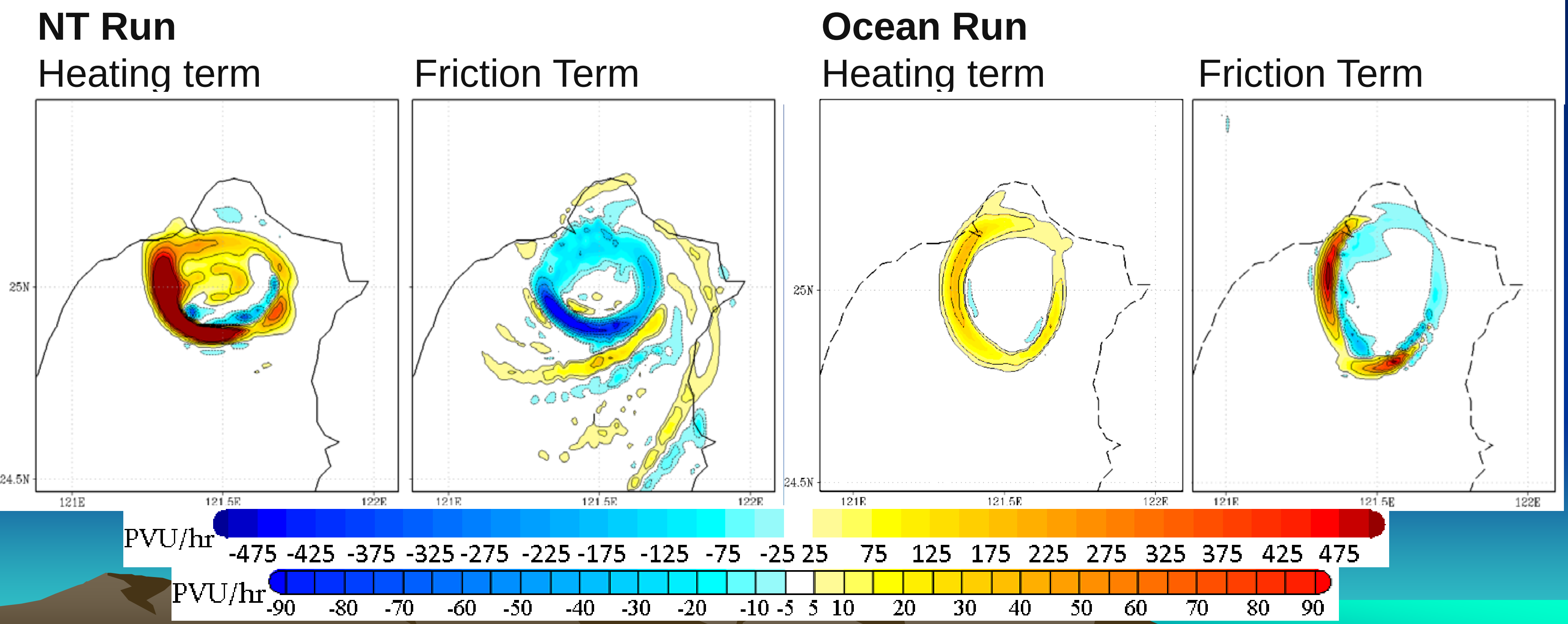


Friction term (NT vs. Ocean) @ z=0.3km



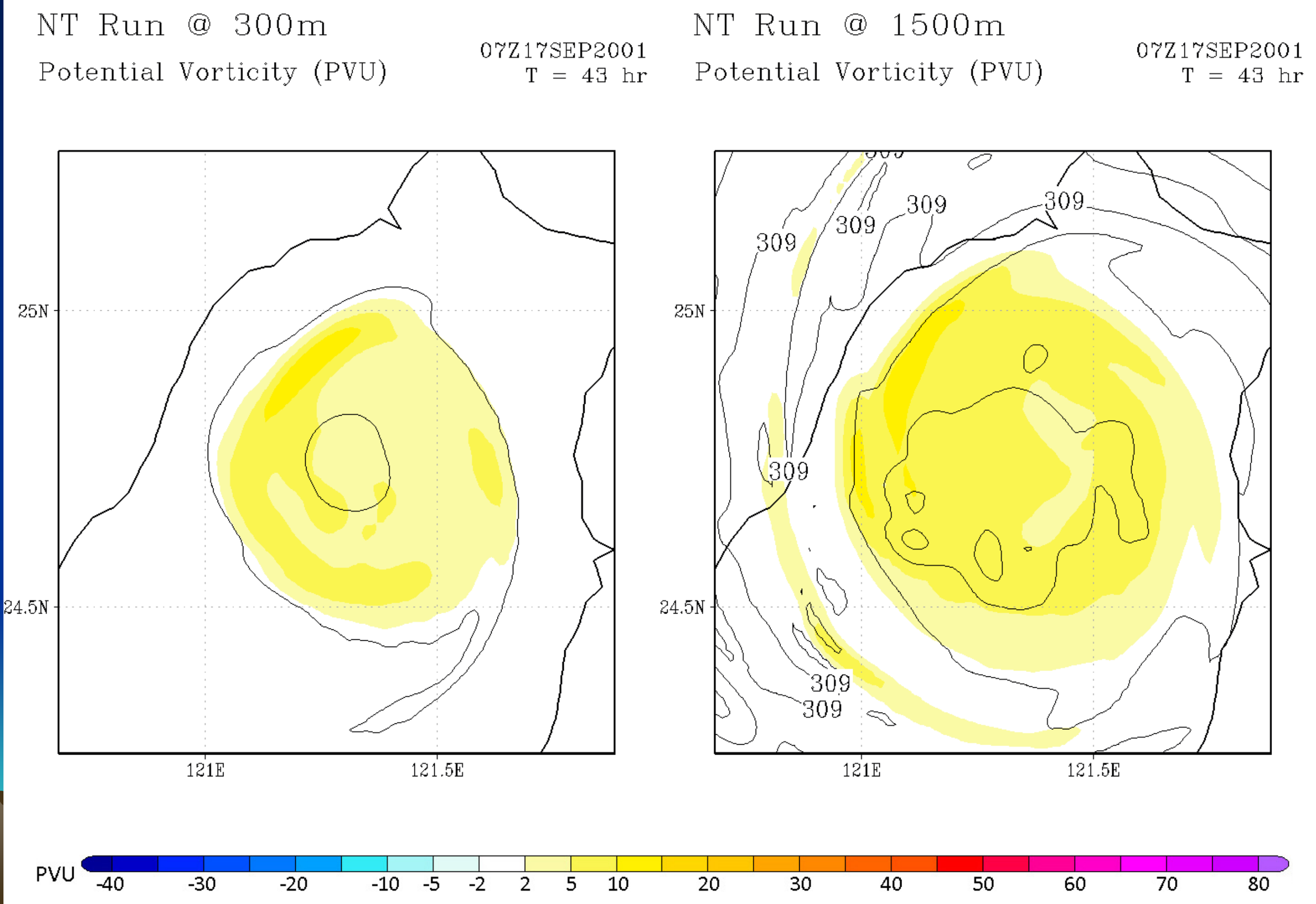
Heating vs. Friction @ z = 0.3km

NT Run | **Ocean Run**

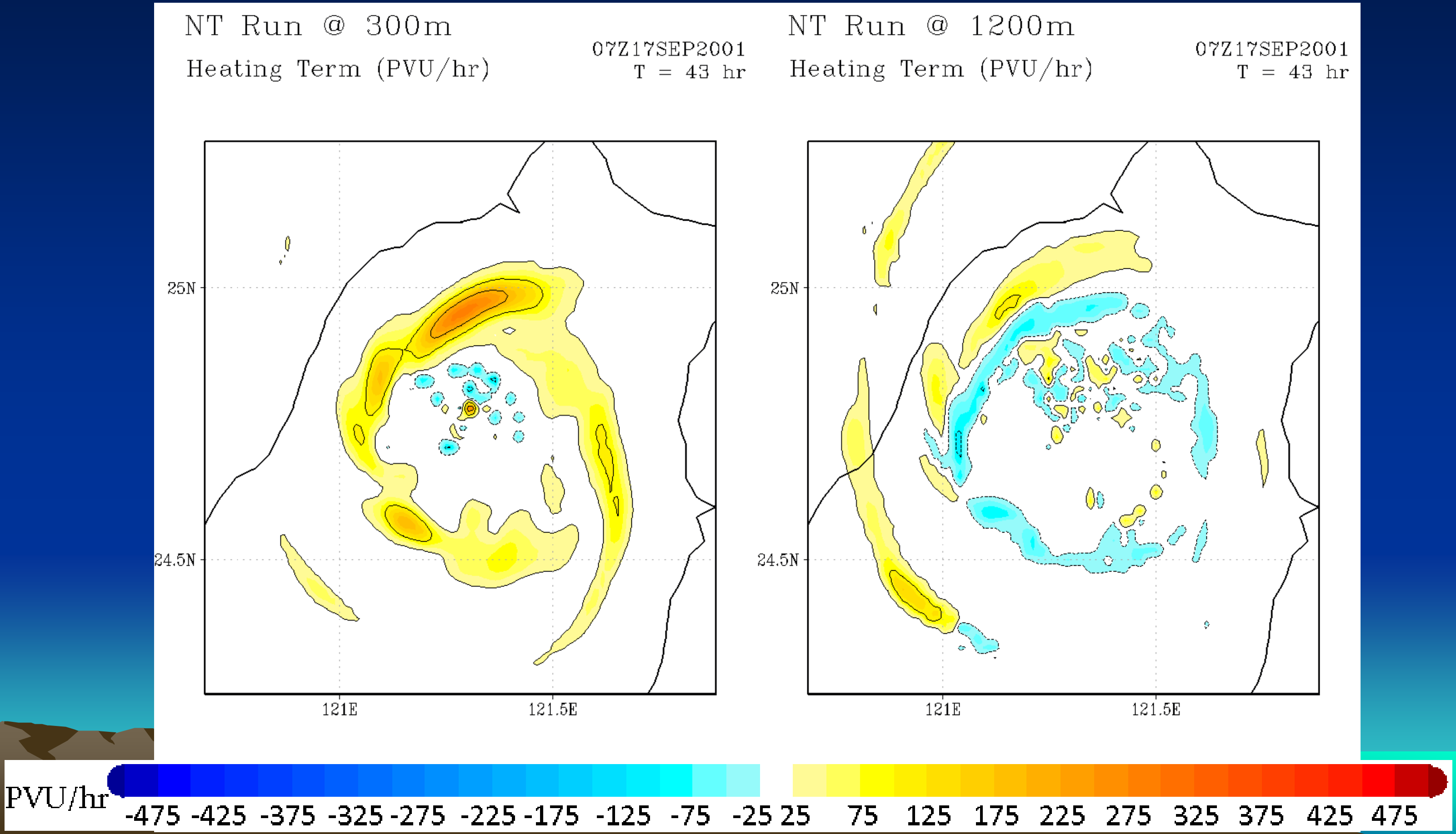


Reorganization of the PV Ring over the Taiwan Strait

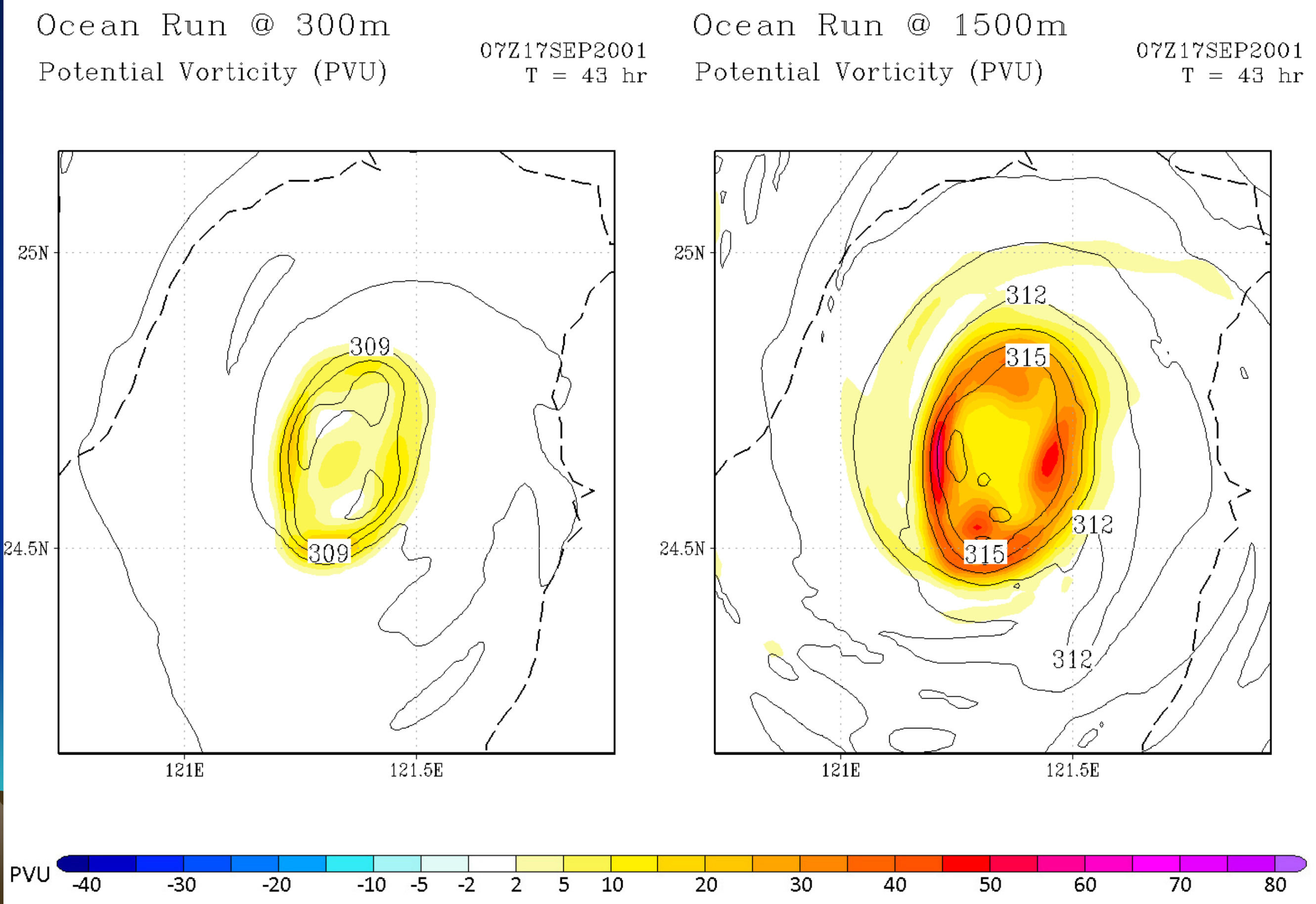
PV Evolution of NT Run @ t = 43-67 hr



PV Latent-Heating term of NT Run @ t = 43-67 hr

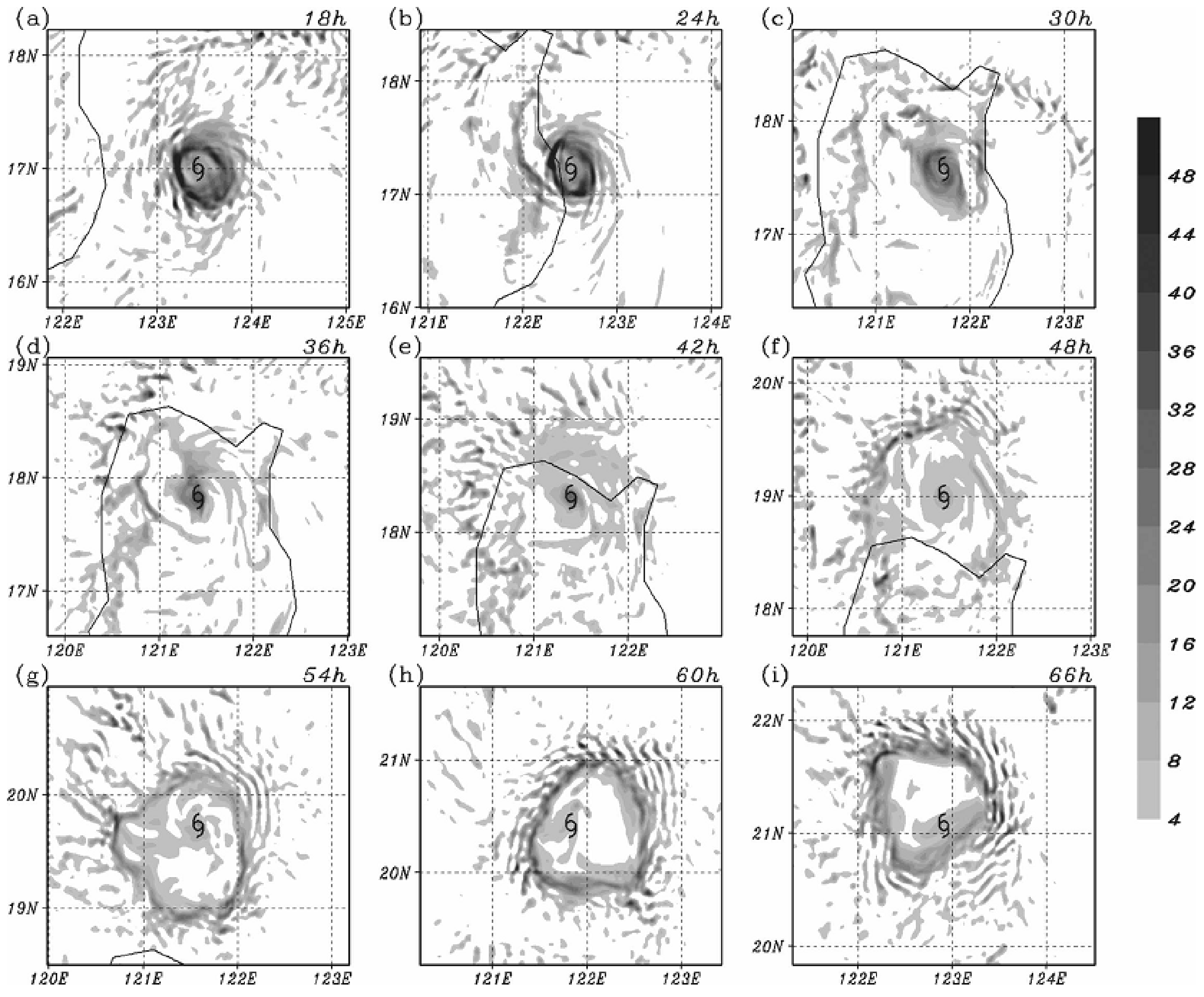


PV Evolution of Ocean Run @ t = 43-67 hr

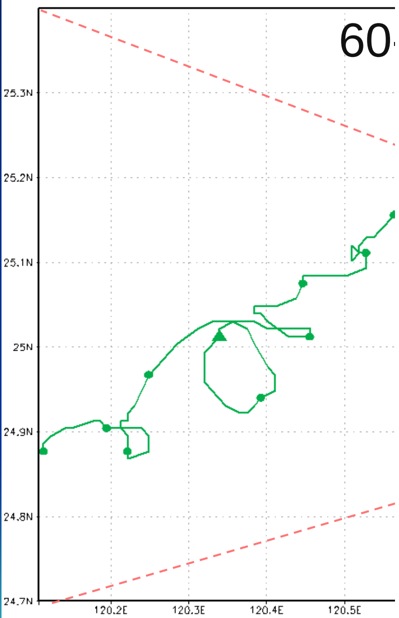


PV Evolution of Zeb (1998)

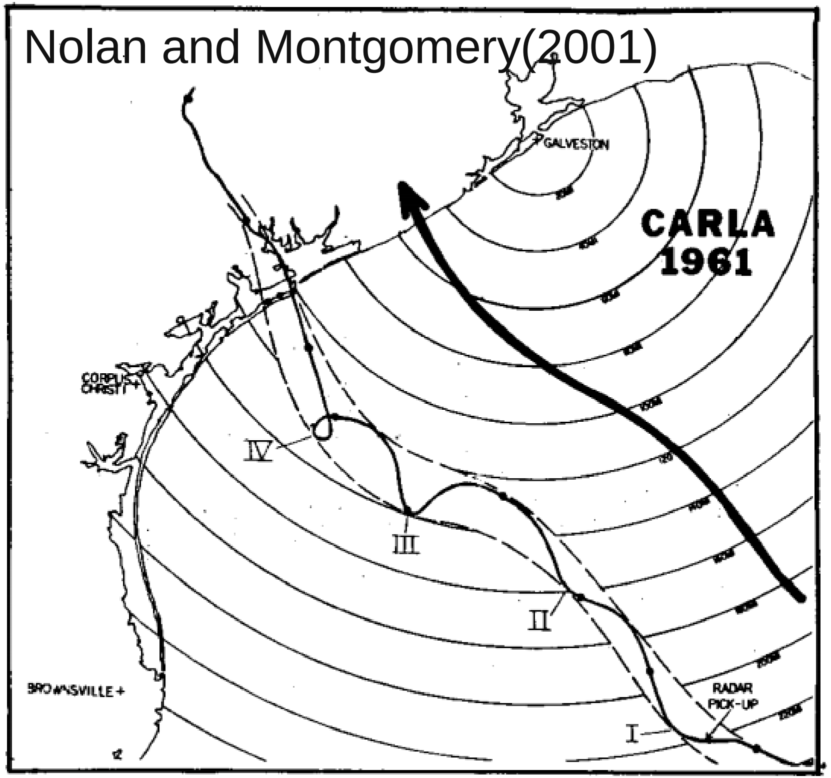
Wu et al. (2009)



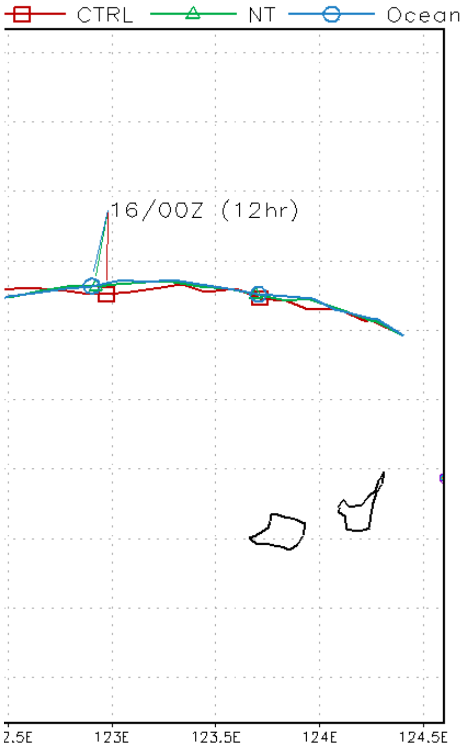
Trochoidal Motion of TC Center



Nolan and Montgomery(2001)



Reanalyzed by Jarvinen et al. (1984)



Landfall CTL@T=22hr / NT@T=20hr / Ocean@T=20hr

Differences from Wu et al. (2009)

- Use nonhydrostatic moist PV with virtual potential temperature as the thermodynamical variable.
- One possible reason for the latent-heating PV generation term in this study is twice of that in Wu et al. (2009) is because of the stronger latent-heat release of Nari (2001) in September, compared to less latent-heat release of Zeb (1998) in October, despite the fact that Nari was only a tropical storm after landfall but Zeb was a Category 2-3 TC at landfall.
- Another reason is that Taiwan Island has a steeper topography (Mount Snow is peaked at 3886 m with half width of 60 km), and the Luzon Island has a relatively gentle mountain slope (Cordillera Central is peaked at 2125 m with half width of 60 km).
- Thus, although Nari was a much weaker TC compared to Zeb, the intense latent-heat release associated with heavy rainfall in Nari could still produce a TC with PV as strong as Zeb.

Conclusions

- PV budget indicates that the PV generation by latent heating is much stronger than that by surface friction and turbulent mixing, as shown in Wu et al. (2009).
- Negative PV generation by latent heating occurs above the maximum heating, and positive PV generation occurs below the heating.
- PV ring in the Nari eyewall contracted after landfall over northern Taiwan; through PV budget calculation, the blocking by Taiwan terrain enhanced convection and increased PV at time of landfall, later enhanced mixing and resulted in a monpole PV distribution.
- Friction and eddy mixing does not always induce negative PV; the Taiwan terrain could increase mixing and transport PV upward.
- The asymmetric latent heating in NT run favors the reorganization of PV ring over the ocean, resulting in the trochoidal motion of TC center.

-THE END-

Thanks for your attention!

Wu et al. (2009)

PV is a quantity useful for understanding many aspects of inner core dynamics of TCs (e.g., Wang 2002a,b). Ertel's PV is approximated (ignoring the horizontal gradient of the vertical velocity in the definition of horizontal vorticity; Wu et al. 2003b, 2004) as

$$q = -\frac{g\kappa\pi}{p}\left(\eta\frac{\partial\theta}{\partial\pi} - \frac{1}{a\cos\varphi}\frac{\partial v}{\partial\pi}\frac{\partial\theta}{\partial\lambda} + \frac{1}{a}\frac{\partial u}{\partial\pi}\frac{\partial\theta}{\partial\varphi}\right),$$

where $\kappa = R_d/C_p$; u and v are the storm-relative radial and tangential winds, respectively; η denotes the vertical component of the absolute vorticity; the vertical

$$\frac{\partial q}{\partial t} = -v_h \cdot \nabla q - \omega^* \frac{\partial q}{\partial \pi} - \frac{g\kappa\pi}{p}\left[\eta \cdot \nabla\left(\frac{d\theta}{dt}\right) + \nabla\theta \cdot \nabla \times F\right]$$

(as in Wu and Kurihara 1996), is governed by the horizontal and vertical advection of PV (where $\omega^* = d\pi/dt$), diabatic heating ($d\theta/dt$, including the condensational and radiative heating), and friction.

Wu and Wang (2000)

$$P = -\frac{g}{p_s}\left[(\zeta + f)\frac{\partial\theta}{\partial\sigma} + \frac{\partial u}{\partial\sigma}\frac{\partial\theta}{\partial y} - \frac{\partial v}{\partial\sigma}\frac{\partial\theta}{\partial x}\right], \quad \text{(B2)}$$

where p, p_s, ζ, and f are the pressure, surface pressure, relative vorticity, and the Coriolis parameter, respectively.

$$\frac{\partial\phi}{\partial\sigma} = -c_p\theta\frac{\partial\pi}{\partial\sigma}, \quad \text{(B6)}$$

$$\frac{\partial P}{\partial t} = -\mathbf{V}\cdot\nabla P - \dot{\sigma}\frac{\partial P}{\partial\sigma} - \frac{g}{p_s}\nabla_3\cdot\left(-\frac{Q}{C_p\pi}\mathbf{q} + \nabla\theta\times\mathbf{F}\right), \quad \text{(B13)}$$

where $\dot{\sigma}$ is the vertical velocity in the σ coordinates, $\mathbf{q}$ is the three-dimensional vorticity vector, and ∇_3 denotes the three-dimensional gradient operator.

where ϕ, F_x, F_y, and Q are the geopotential height, friction component in the x and y directions, and diabatic heating rate, respectively. From Eqs. (B3) and (B4), the