Observation and Simulation on the Genesis and Track of Tropical Cyclones in the Tropical Western Pacific

（熱帯における台風の発生と進路に関する観測と数値実験）

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With special thanks to:
Tomoe Nasuno, Wataru Yanase, Masaki Satoh,
Kunio Yoneyama, and Ryuichi Shirooka

Topics of This Lecture

08:30 — 10:15 am

Observational and numerical studies on the Tropical Cyclogenesis in the Tropical Western Pacific

-- a new TC-genesis scenario based on a case study of Typhoon Fengshen (2008) using PALAU field experiment and NICAM simulations --

10:30 — 11:20 am

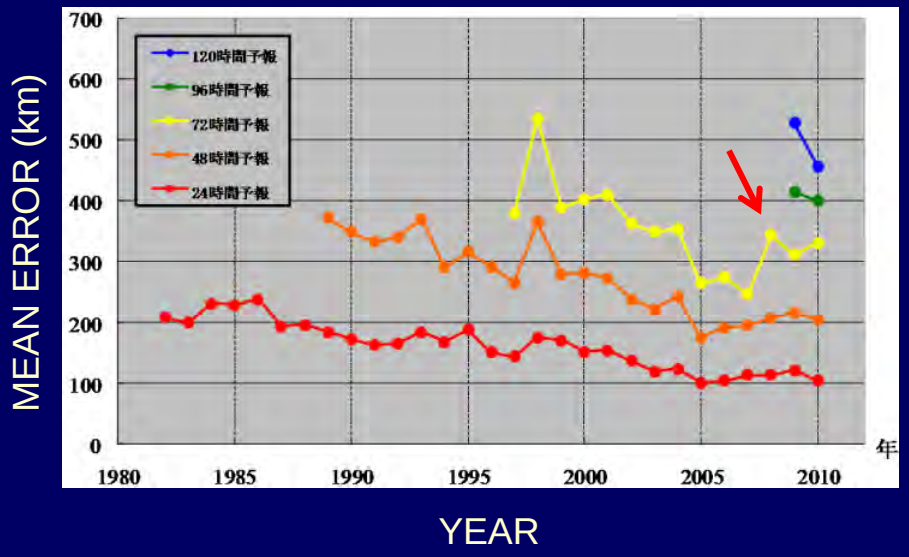
Cloud-resolving simulations of Tropical Cyclone Track in the western Pacific

-- dynamics of westward "propagating" typhoons ---

Background

- Gradual improvement of TC track forecast in 30 years
  (< 1000 km / 72 hours)
- Little improvement in the past several years
- Inclusion of "bad cases" (with large forecast error)

JMA TC track forecast error (from JMA website)

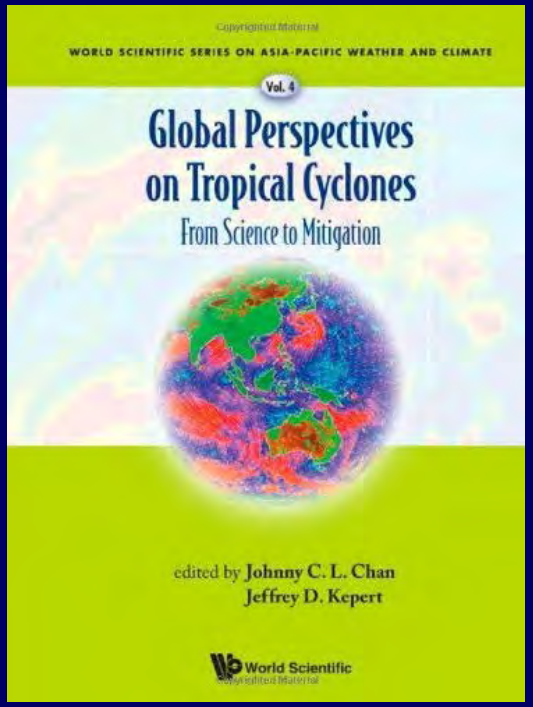


- There are 4 % population of bad cases to total TCs
  (Yamaguchi et al. 2012, GRL)
- Has limitation of TC track predictability reached?

Processes Governing TC Motion

(from a recent textbook by Chan and Kepert, 2010)

- Barotropic effects
  - steering
  - the Beta effect
- Binary Interaction (Fujiwara effect)
- The Gamma effect
- Baroclinic effects
  - vertical wind shear
  - diabatic heating

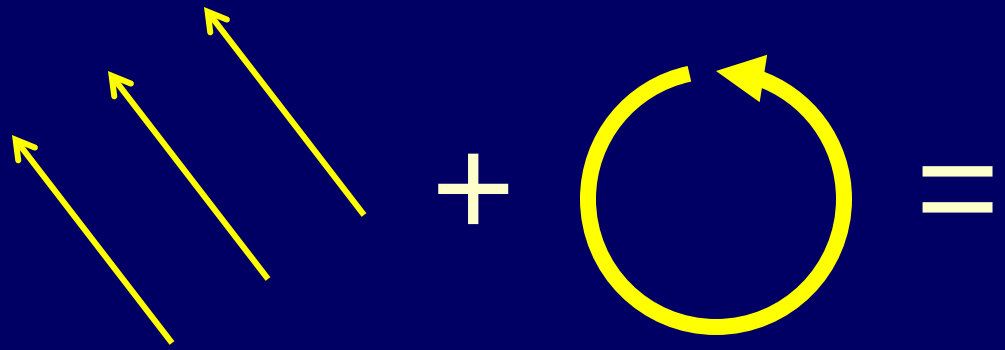


Steering Effects

Vorticity equation in barotropic flow:

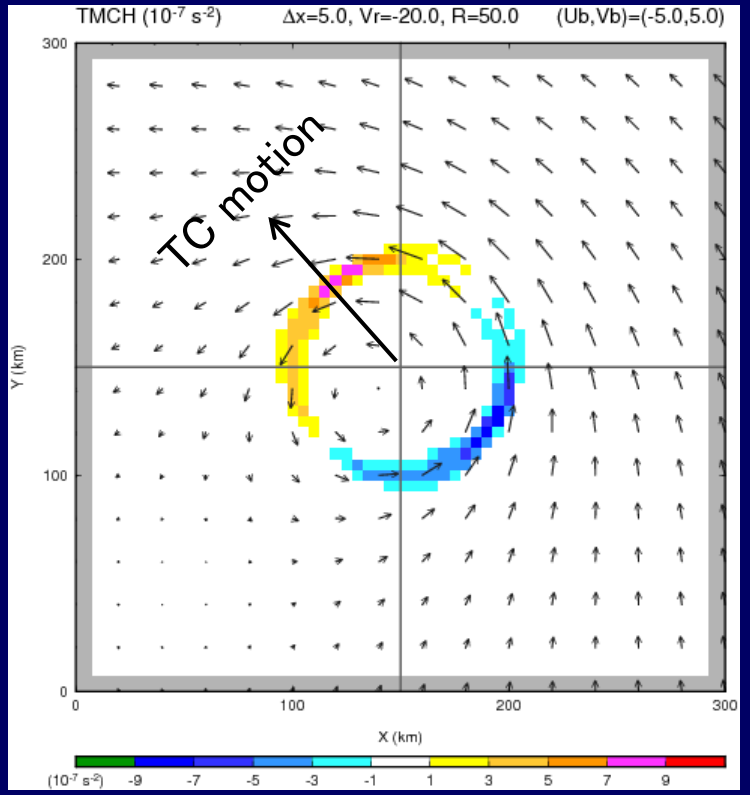
$$\frac{\partial(\zeta + f)}{\partial t} = -(u\frac{\partial \zeta}{\partial x} + v\frac{\partial \zeta}{\partial y}) - v\frac{\partial f}{\partial y}$$

Advection term
(steering)



steering flow vortex

Total Tendency

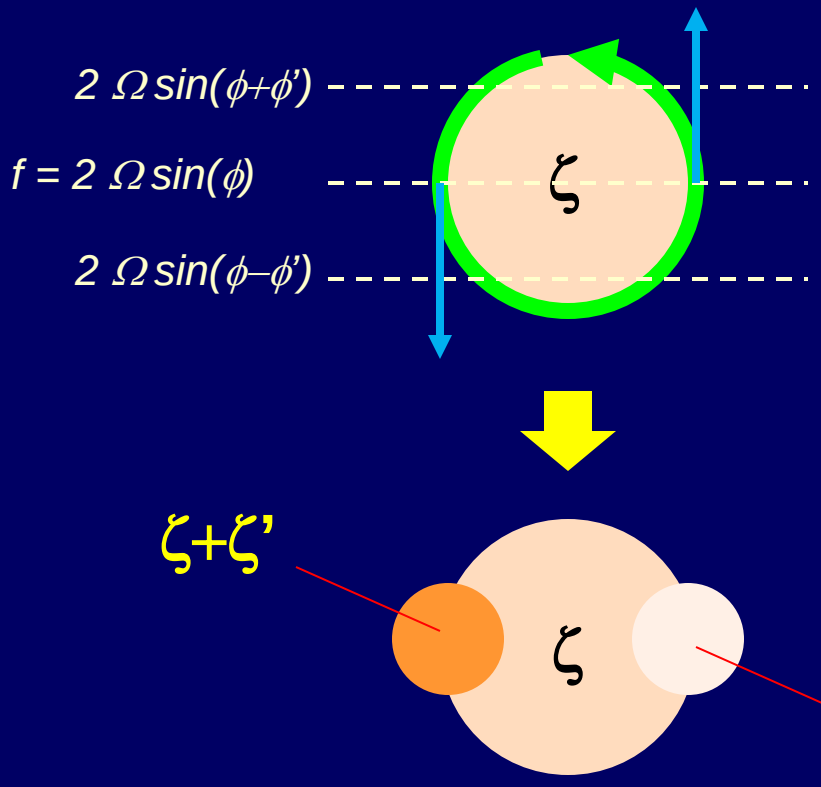


The Beta Effect

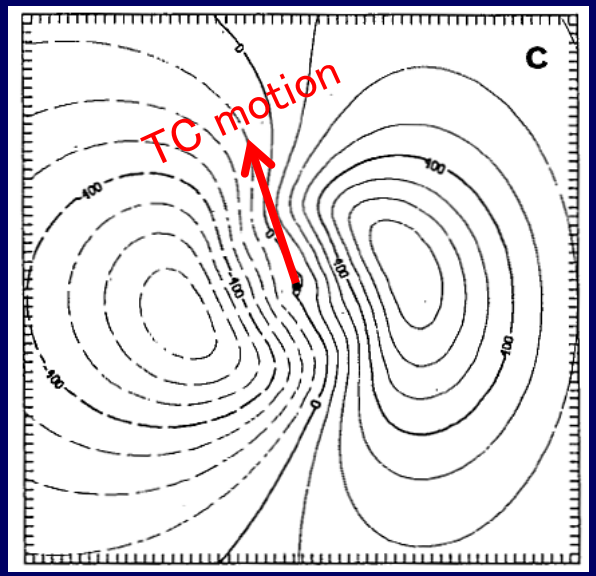
Vorticity equation in barotropic flow:

$$\frac{\partial(\zeta + f)}{\partial t} = -(u\frac{\partial \zeta}{\partial x} + v\frac{\partial \zeta}{\partial y}) - v\frac{\partial f}{\partial y}$$

Meridional advection of absolute vorticity (Beta effect)



Streamfunction



Fiorino and Elsberry (1989)

Baroclinic Effects

Wu and Wang (2000):

- TC is treated as a positive PV anomaly from environmental flows
- TC moves to the region where the azimuthal wavenumber-1 component of the PV tendency reaches a maximum
- Contributions of the vertical shear and diabatic heating can be diagnosed from the wavenumber-1 PV tendency equation:

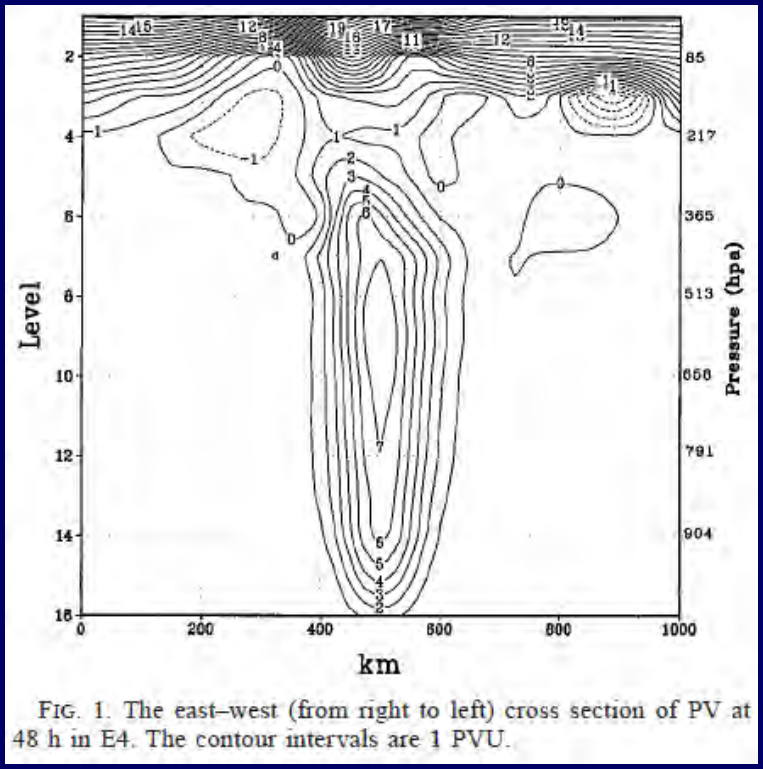


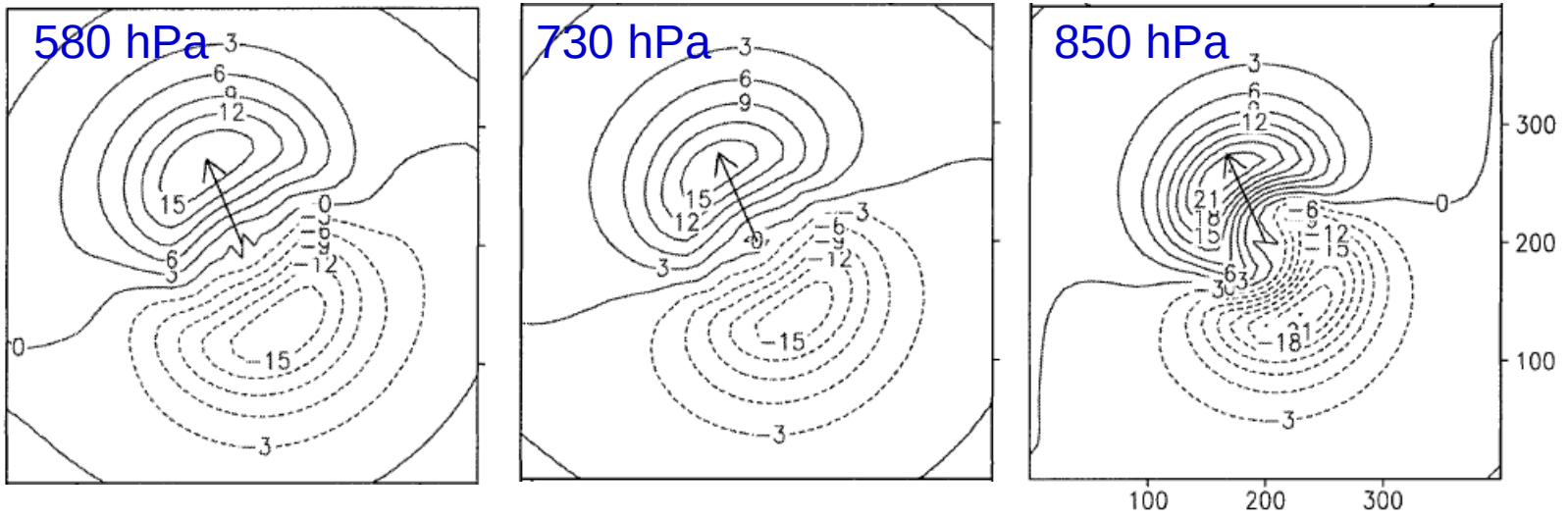
FIG. 1. The east–west (from right to left) cross section of PV at 48 h in E4. The contour intervals are 1 PVU.

$$\left(\frac{\partial P}{\partial t}\right)_1 = \Lambda_1\left\{-\mathbf{V}\cdot\nabla P - \dot{\sigma}\frac{\partial P}{\partial \sigma} - \frac{g}{p_s}\nabla_3\cdot\left(-\frac{Q}{C_p\pi}\mathbf{q} + \nabla\theta\times\mathbf{F}\right)\right\}$$

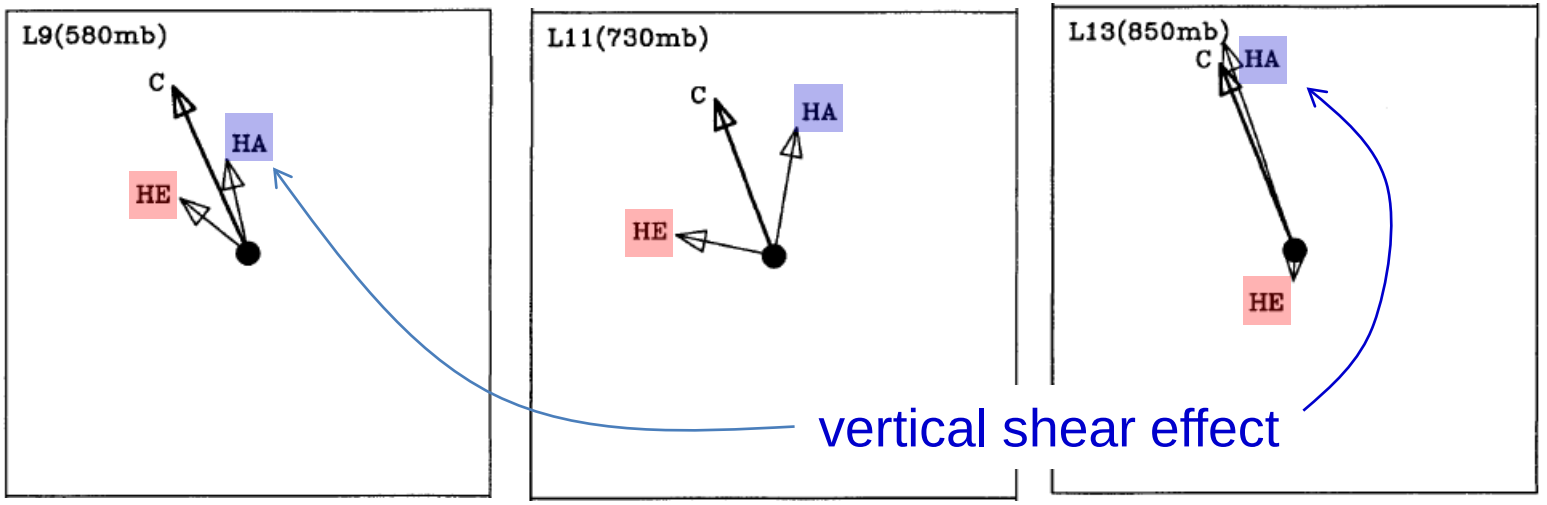
Advection | Diabatic heating | Friction

Baroclinic Effects

Total tendency

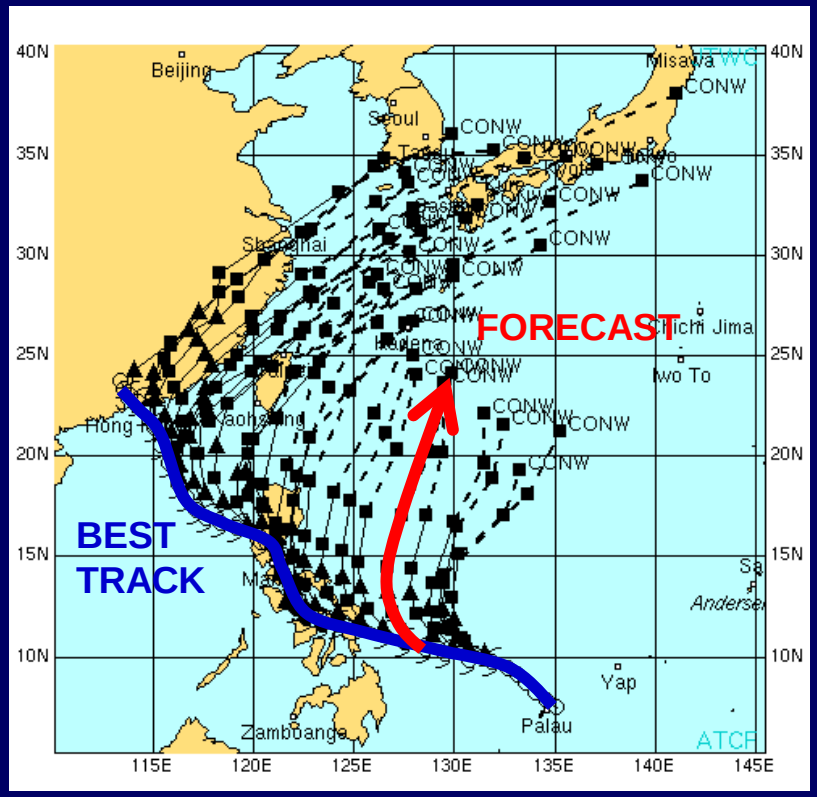


Contributions of the horizontal advection (HA) and heating (HE)



The Recent Worst Case: Fengshen (2008)

JTWC Model Consensus Forecasts



Flood in Panay Isand, Philippines

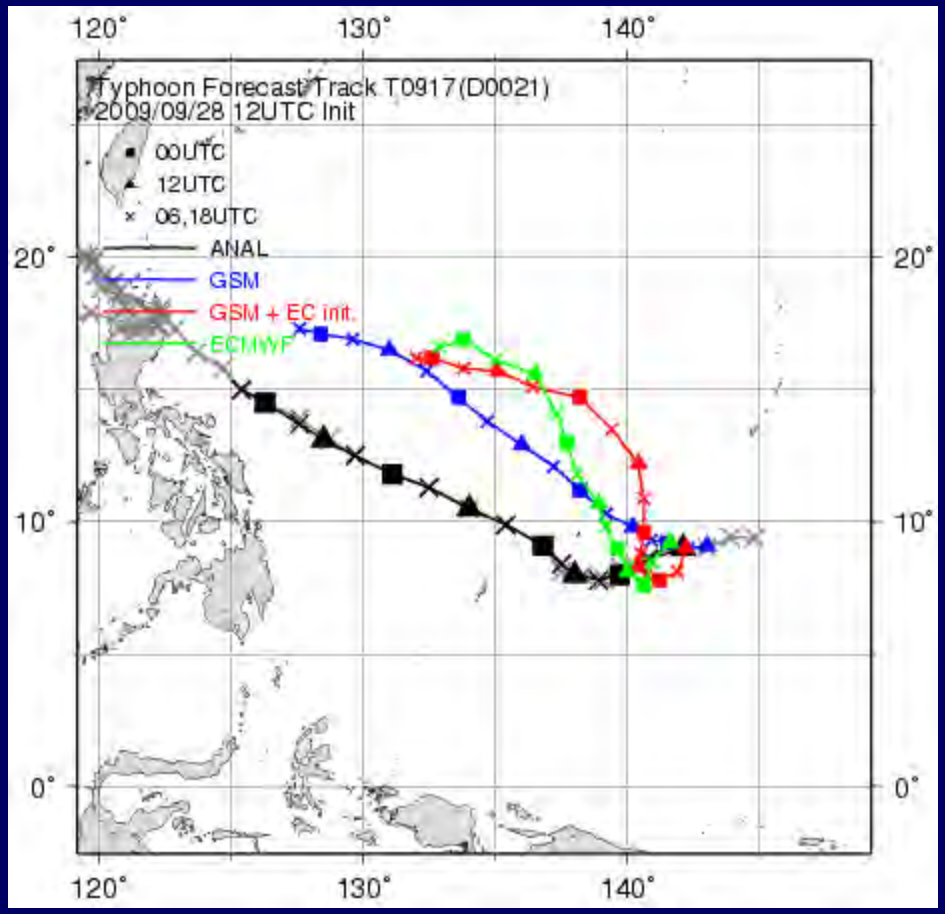
(image downloaded from Wikipedia)

- Erroneous northward track by all operational models (JTWC, JMA, etc.)
- Disasters with death of more than 1,300 people in Philippines
- *"Immediate evaluation is necessary to determine the root causes of the unreliability of the dynamic models in this case"*
  (JTWC annual TC report in 2008)

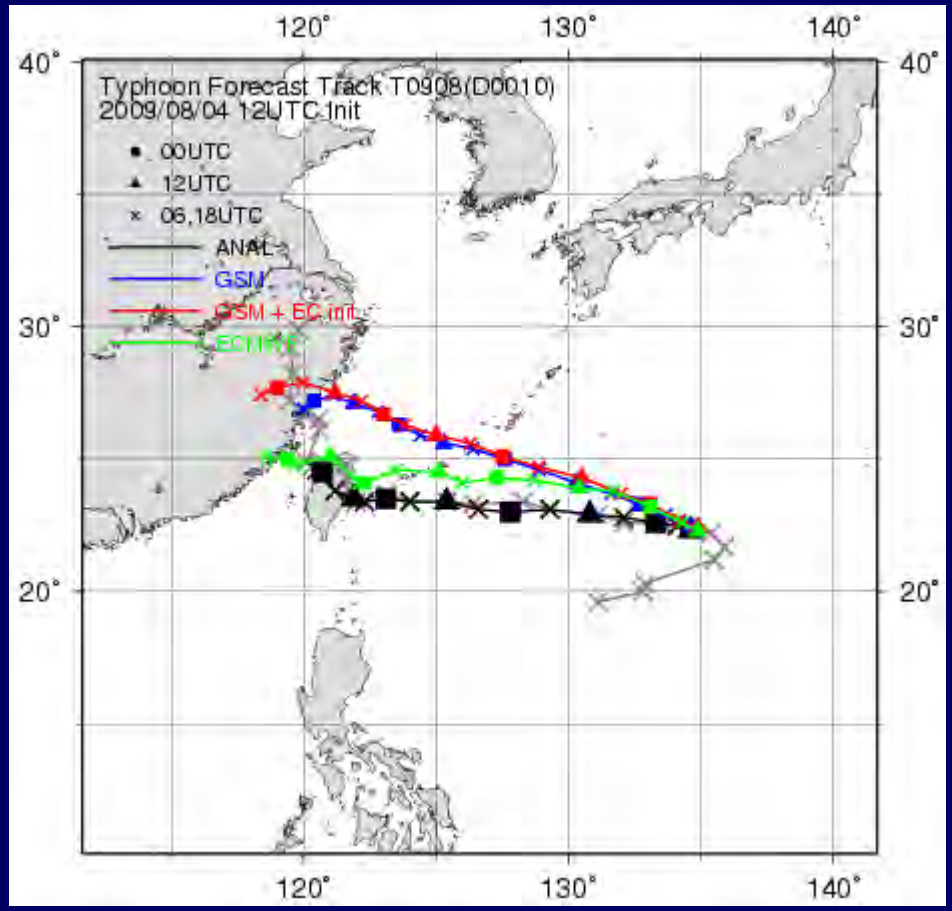
Other Bad Cases

Yamaguchi et al. (2012, GRL)

Parma (2009)



Morakot (2009)

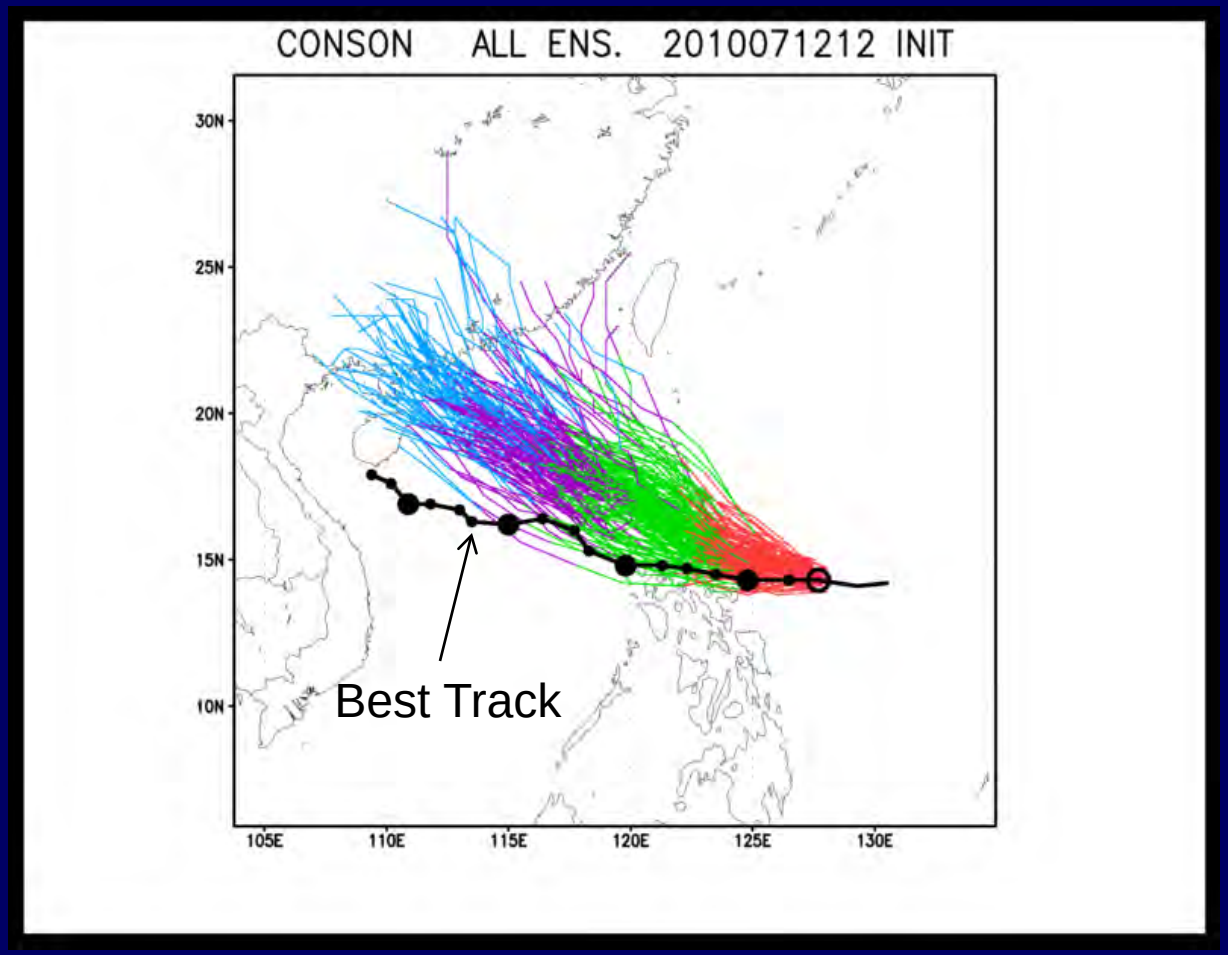


Northward bias is sometimes significant
in westward-moving typhoons

Biased Ensemble Results

Courtesy of Dr. Hoshino (MRI/JMA)

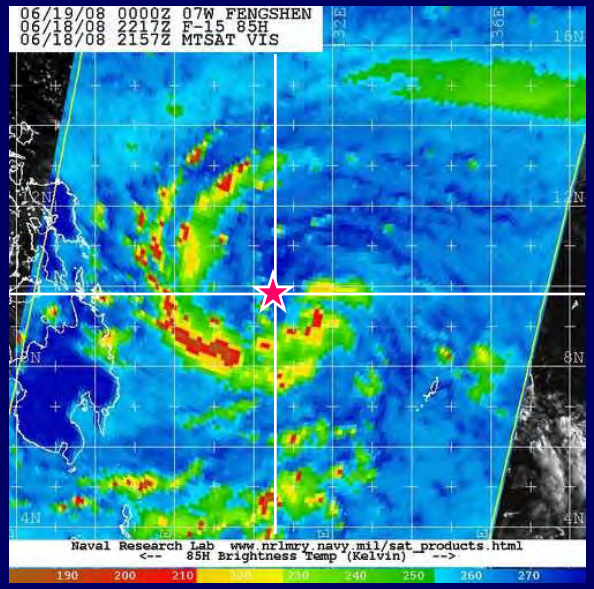
Conson (2010)



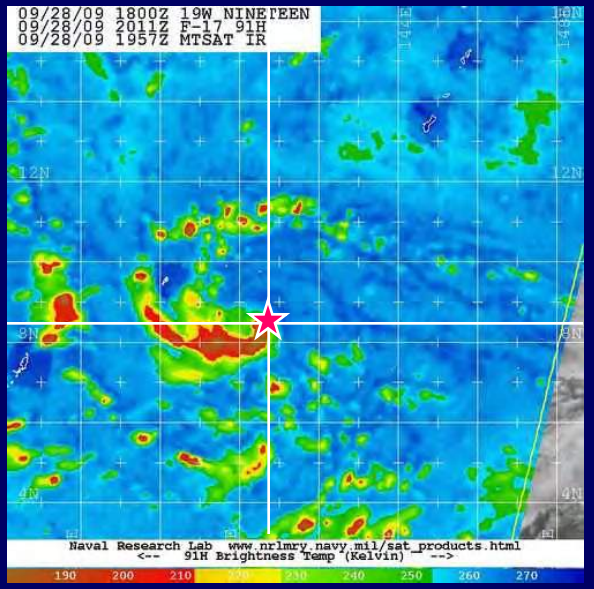
Northward bias is not always relieved by ensemble framework

Consensus among Bad Cases: Asymmetry

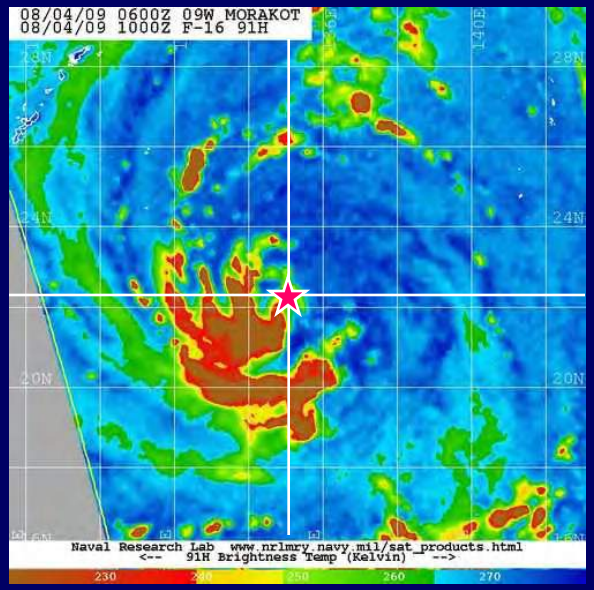
Fengshen (2008)



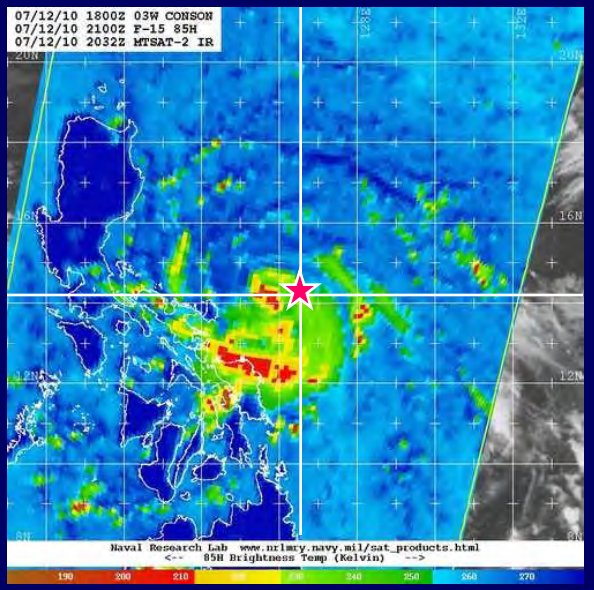
Parma (2009)



Morakot (2009)



Conson (2010)



Rainfall maximum in the southwest quadrant

Question & Motivation

- TC motion is mostly due to the steering and the beta effect and their nonlinear interaction in a barotropic atmosphere, and is explained by PV tendency in a baroclinic framework (Chan 2011).
- This knowledge is based on research activity in the 1980s and early 1990s, using simple numerical models with coarse resolution.
- Any other effects associated with mesoscale processes?

  ex) asymmetry of eyewall and spiral rainbands

  vortex-induced Rossby waves

  inhomogeneous moisture and SST distributions
- Necessity of examining TC motion using nonhydrostatic cloud-resolving framework.

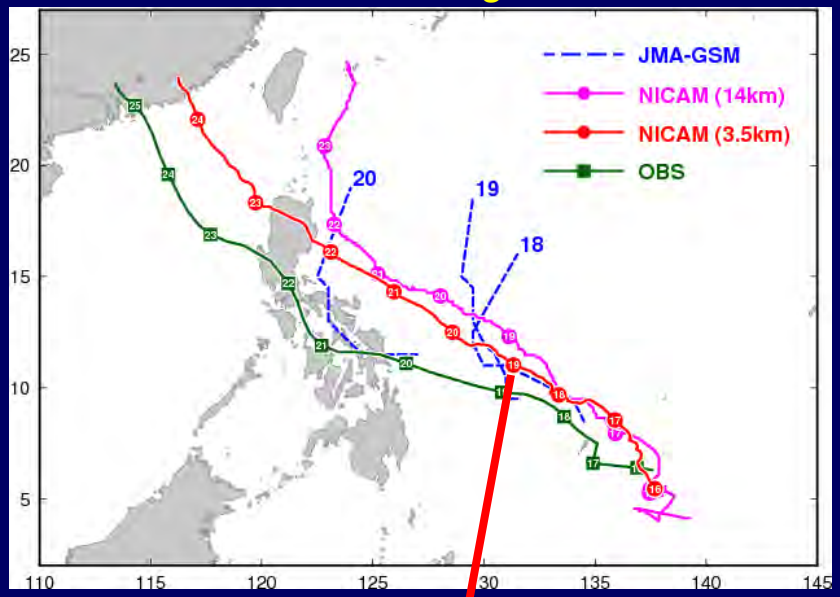
Objective & Method

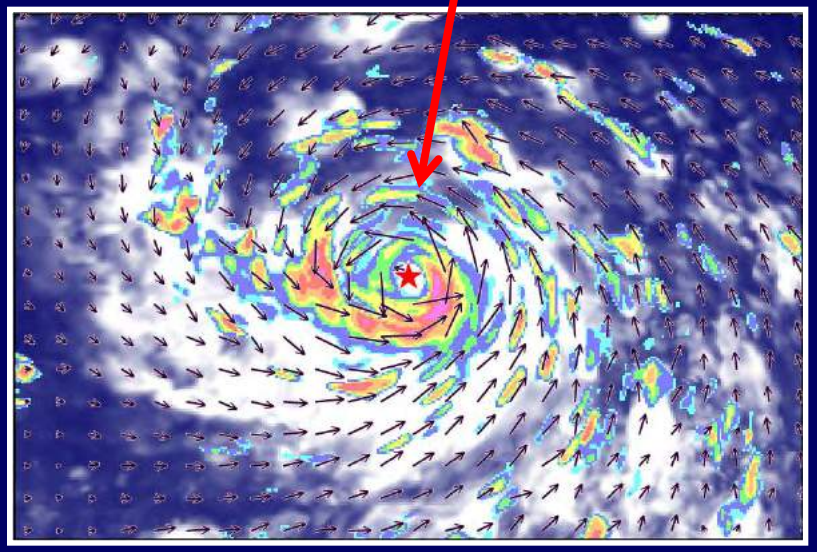
- Objective:
  To understand causes of track error of a bad case, TY Fengshen (2008), by nonhydrostatic numerical simulation

- Two models:
  JMA-GSM (hydrostatic, bad track)
  NICAM-3.5km (nonhydrostatic, better track, but not perfect)

- Method:
  Decomposing factors contributing TC track, using model results and vorticity tendency equation

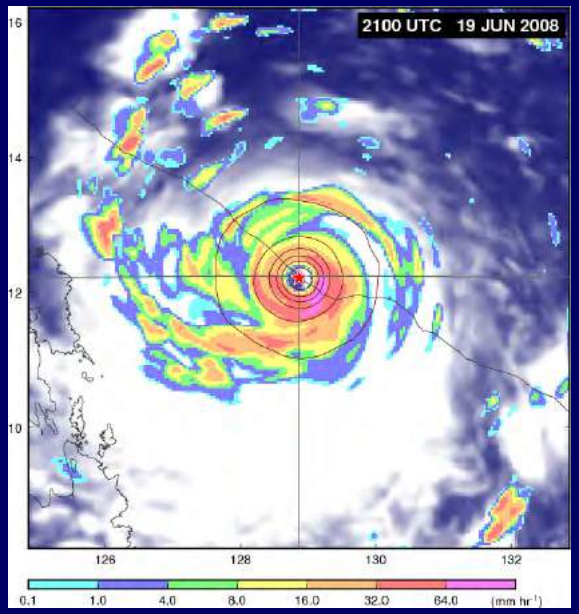
Track of Fengshen



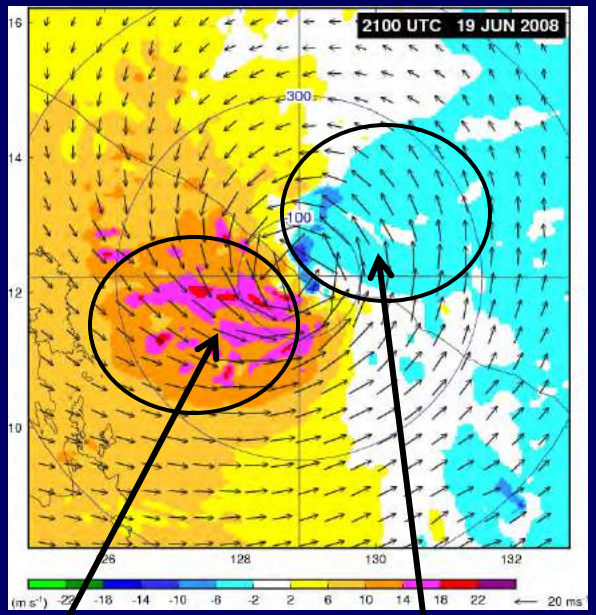


Asymmetric Structure in NICAM

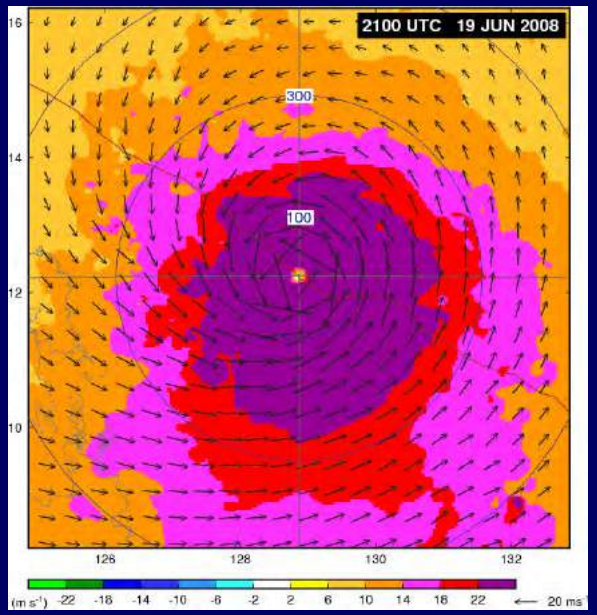
RAIN, SLP



-Vr (0-3 km)



Vt (0-3 km)

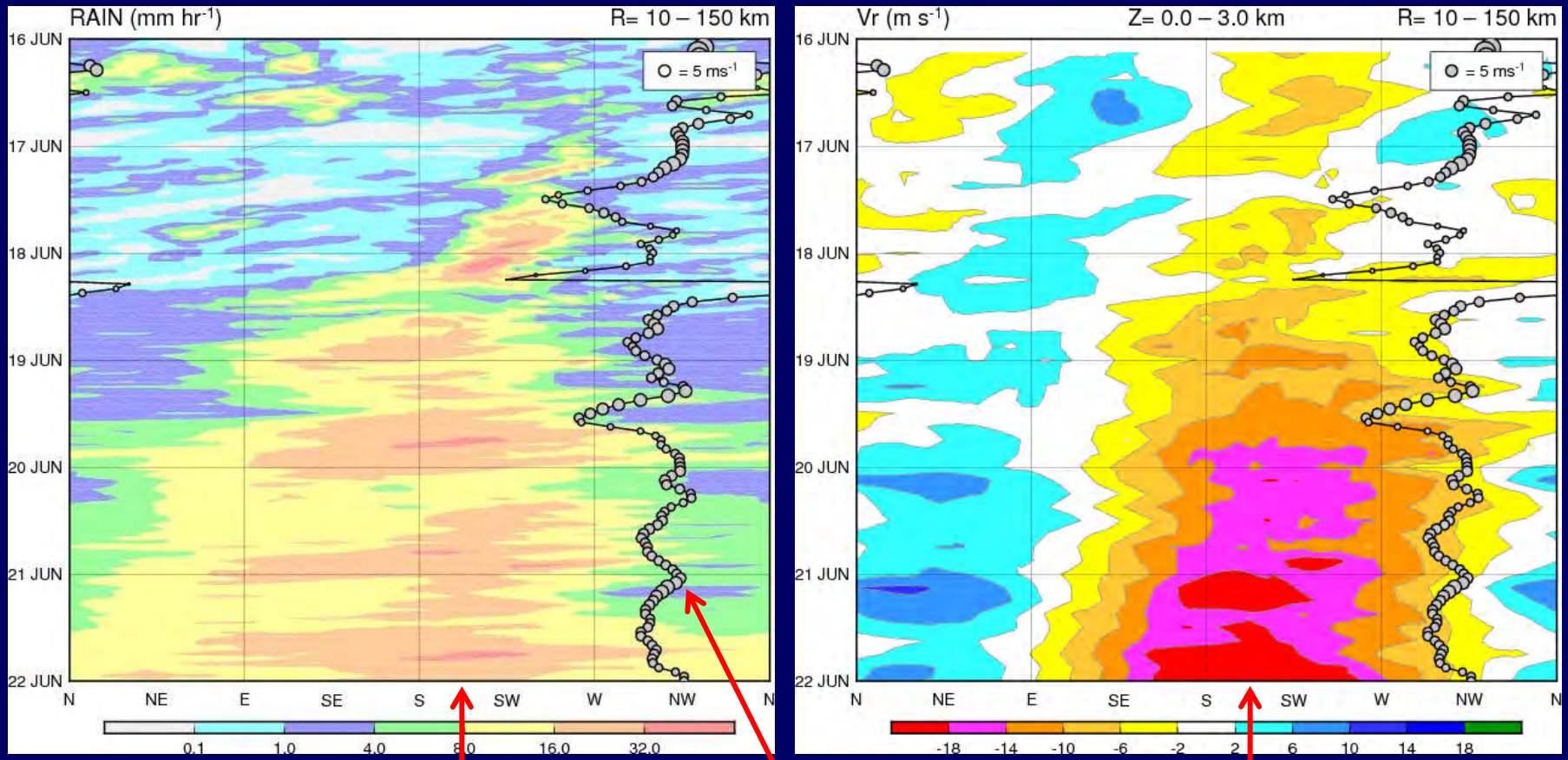


Vr<0
(convergence)

Vr>0
(divergence)

- Asymmetry with rainfall maximum in the SW quadrant was reproduced by NICAM
- Rain asymmetry corresponds to Vr asymmetry

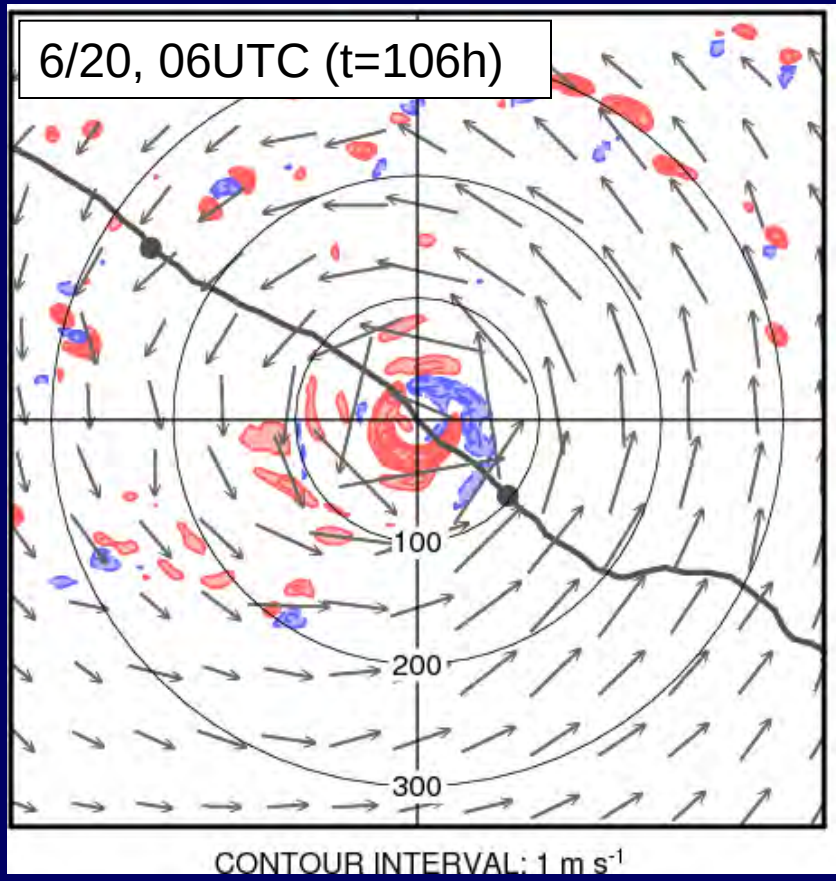
Asymmetric Structure in NICAM



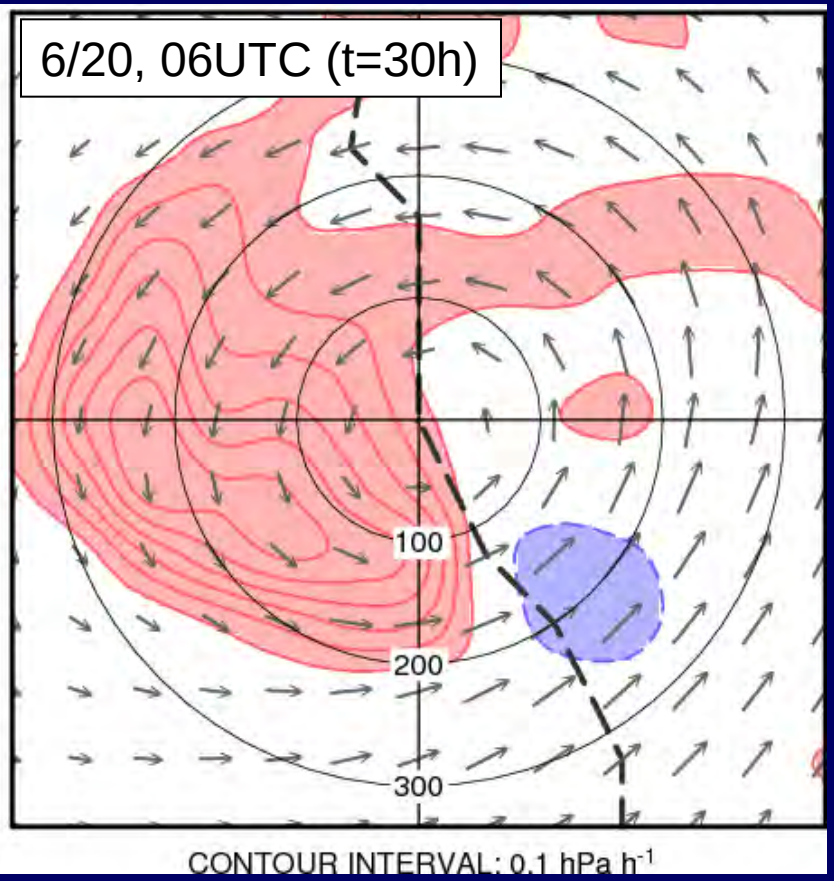
- Sustained asymmetric structure with convergence and rainfall maximum in the southwestern quadrant

Flow Structure

NICAM (Z=3.2km)



JMA-GSM (700 hPa)



- Difference in the horizontal scale of updrafts, according to the model grid spacing
- But, there is a consensus in asymmetric distribution

Vorticity Equation

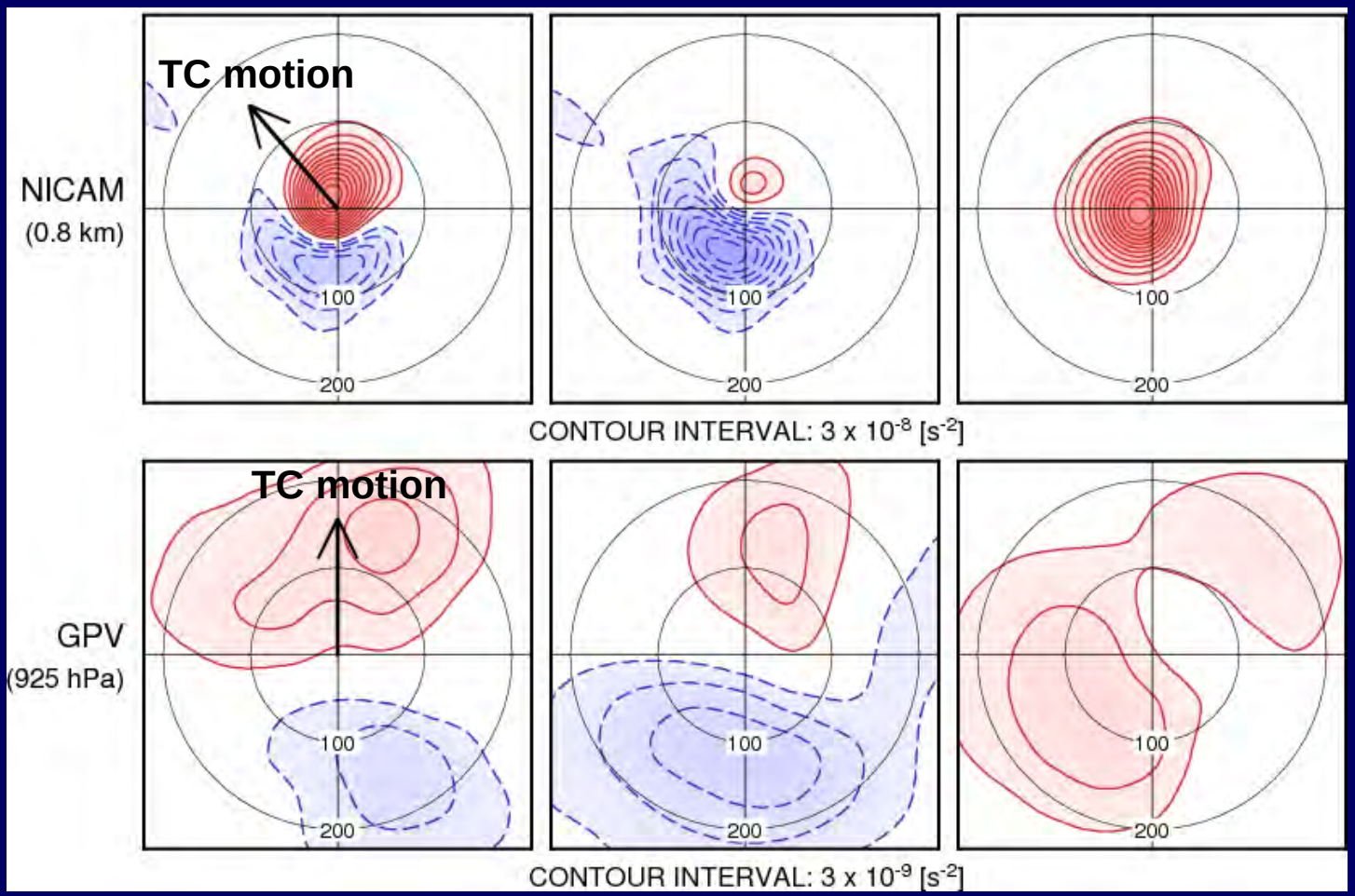
$$\frac{\partial(\zeta+f)}{\partial t} = -(u\frac{\partial \zeta}{\partial x} + v\frac{\partial \zeta}{\partial y} + w\frac{\partial \zeta}{\partial z}) - v\frac{\partial f}{\partial y} - (\zeta+f)(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}) - (\frac{\partial w}{\partial x}\frac{\partial v}{\partial z} - \frac{\partial w}{\partial y}\frac{\partial u}{\partial z})$$

-HADV -VADV -COR -STR -TILT

- Total tendency (left-hand side) is obtained as a residual of right-hand side
- Evaluate the contribution of each term

Primary terms:	HADV	(horizontal advection)
	STR	(stretching)
Secondary terms:	VADV	(vertical advection)
	TILT	(tilting)
Negligible:	COR	(Coriolis effect)

Vorticity Budget Analysis



Similarity: advection northward, stretching westward

Difference: weak stretcing in GSM, causing northward bias of TC motion

Discussion: cause of asymmetric stretching

- Beta effect

  Negligible contribution of Coriolis term
  Beta gyre hardly identified in the asymmetric flow

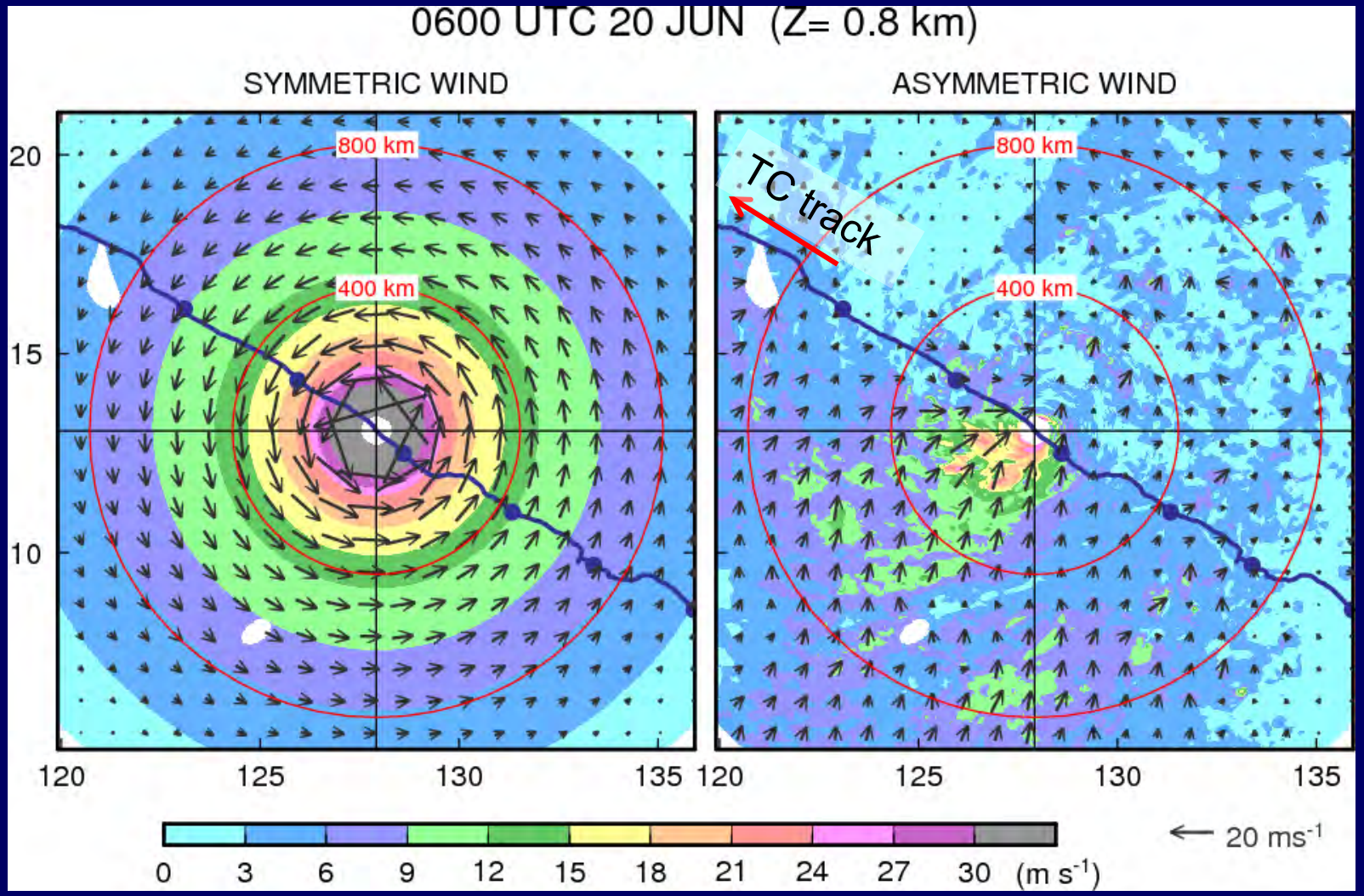
- Monsoon Interaction

  Prevailing southwesterly asymmetric flow to the southwestern part of the TC track

- Coupling of TC vortex with a synoptic-scale disturbance

  Westward-propagating signal of relative vorticity

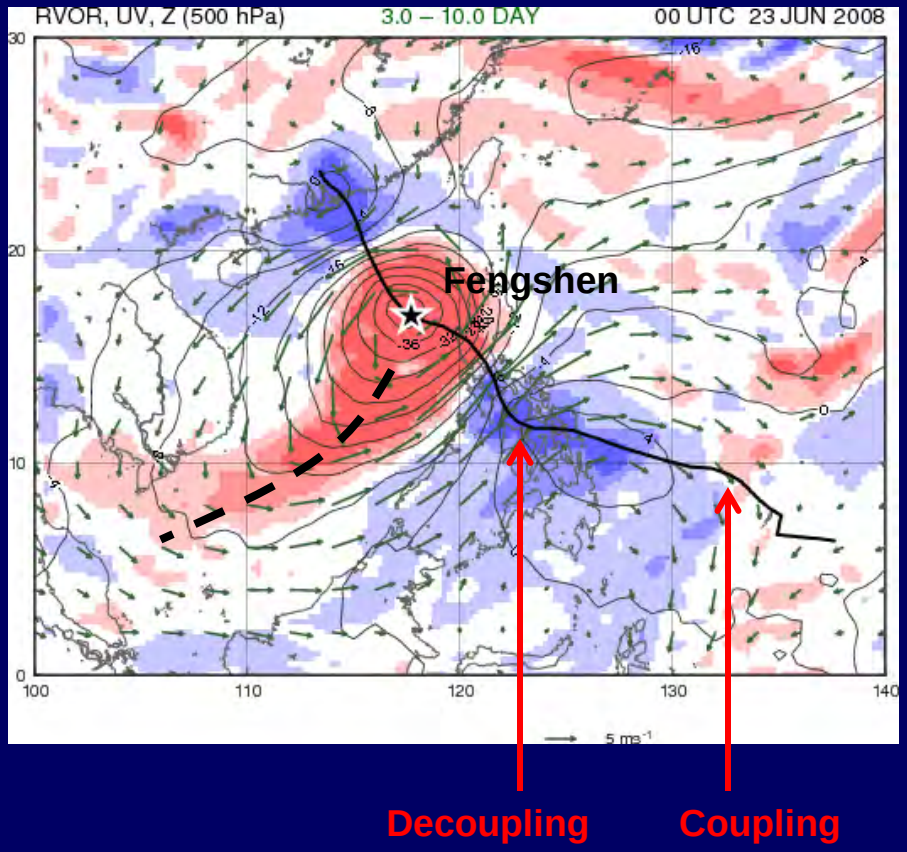
Symmetric and Asymmetric Flows



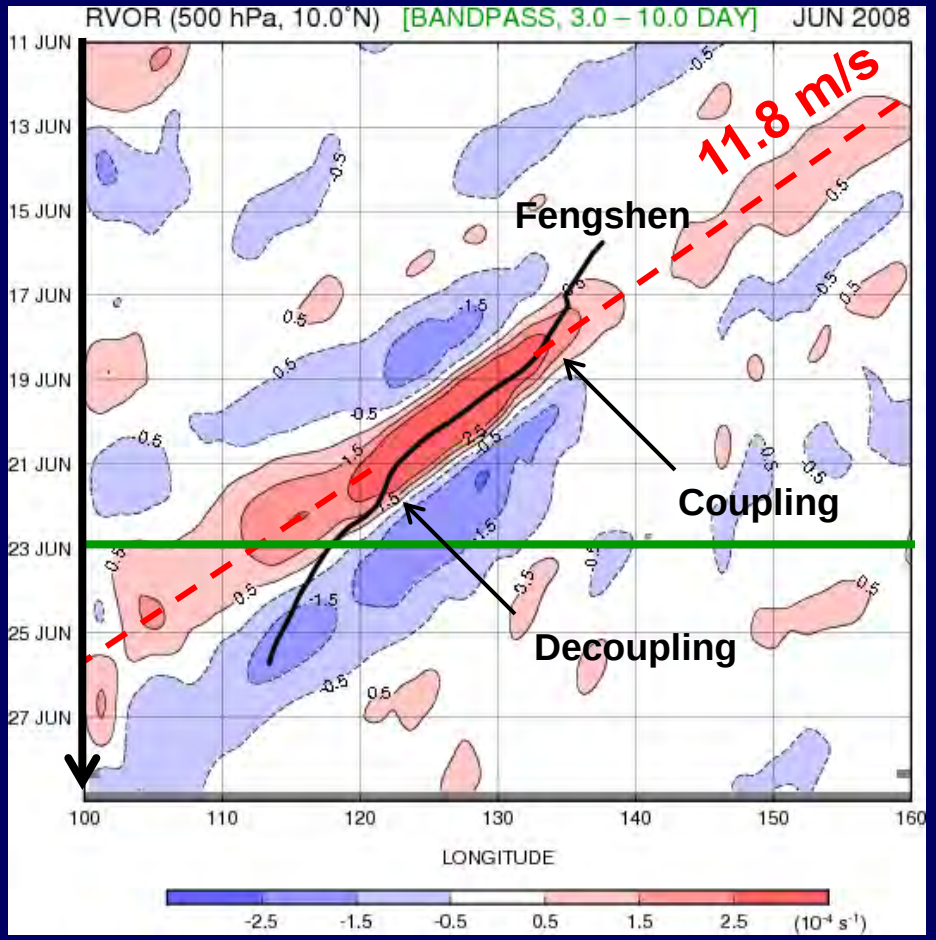
- Predominant southwesterly in the asymmetric component in the southwestern side of the TC track
- Beta gyre hardly identified in asymmetric winds

Discussion: cause of stretching

Relative Vorticity (ζ) at 500 hPa (3-10 day bandpass filtererd)



Hovmöller of ζ500 (3-10 day)

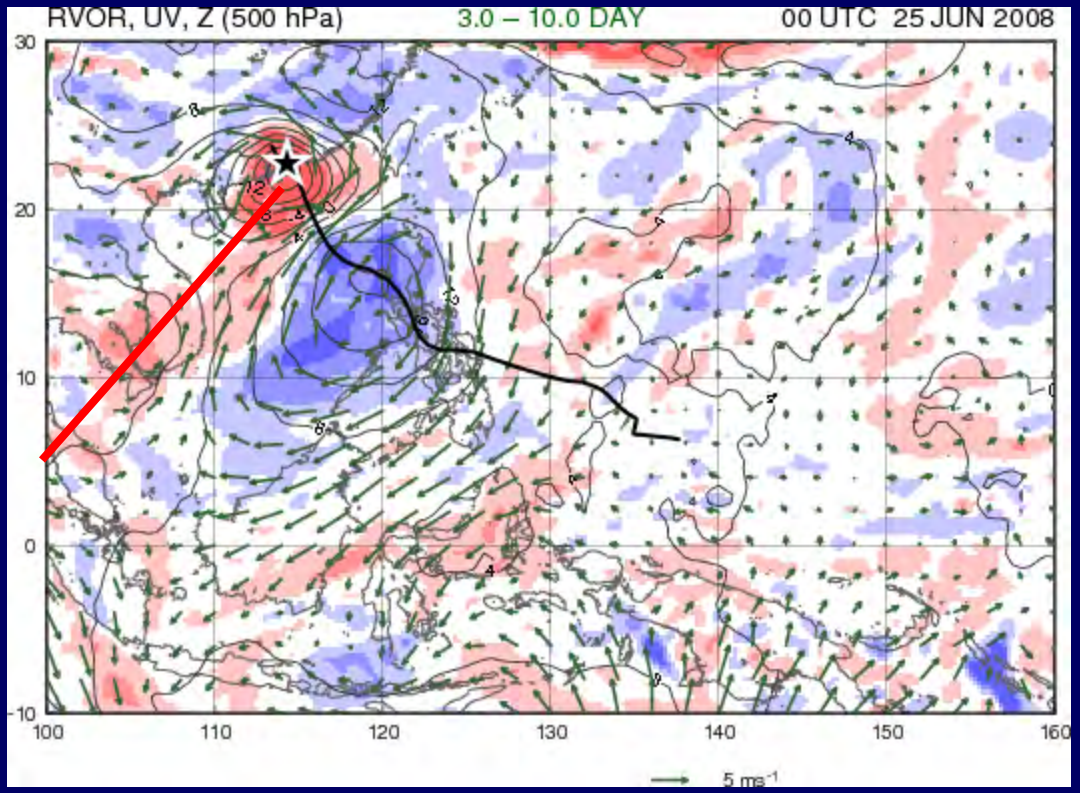


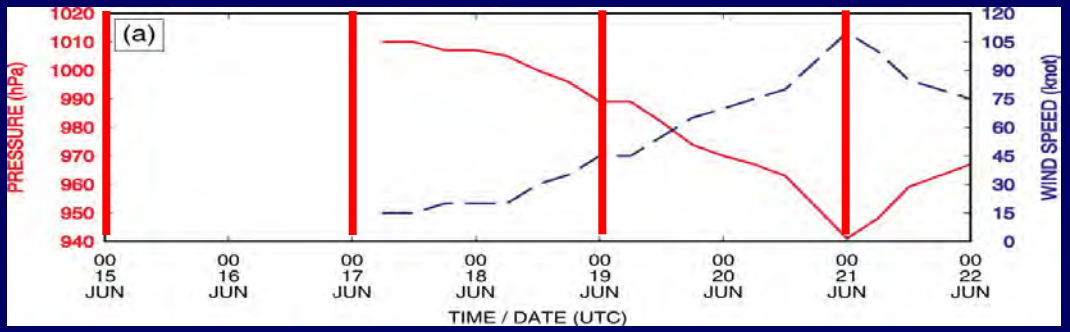
Couple of Fengshen to a westward-propagating wave trough in the period of westward track

Westward-Propagating Disturbance

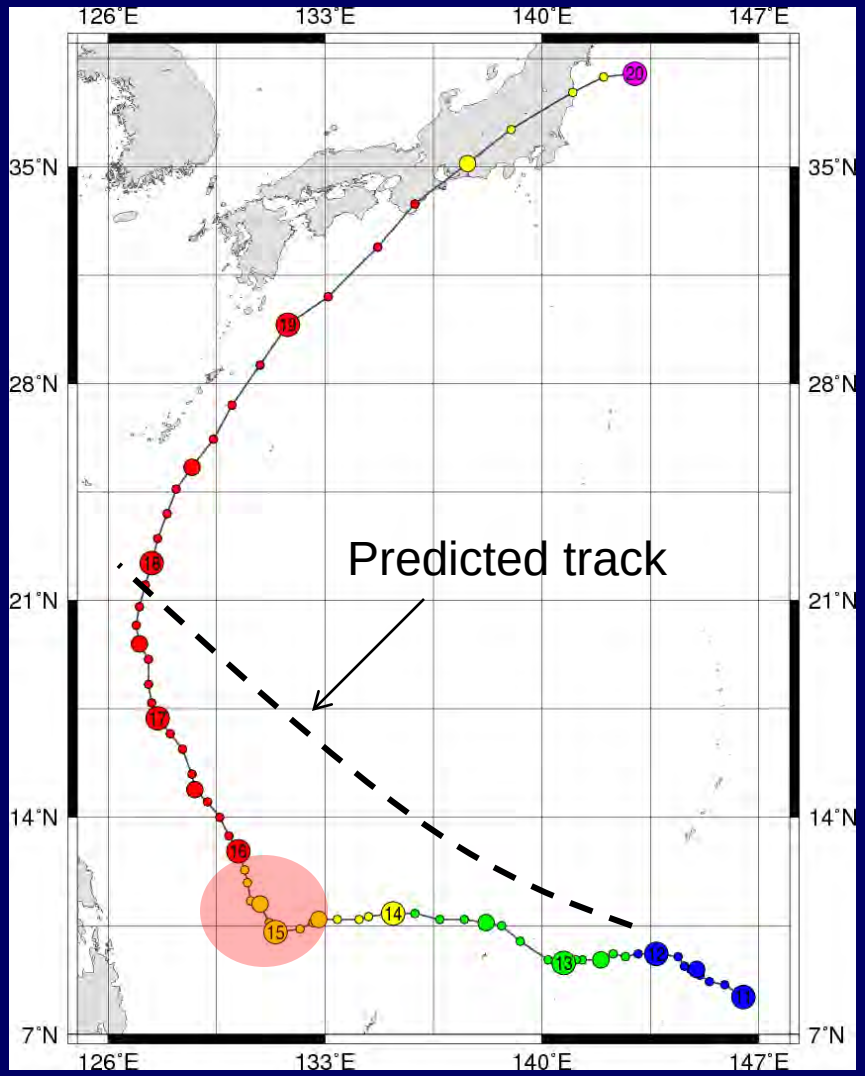
(in the 3-10-day bandpass-filtered relative vorticity)

10°N ⟶

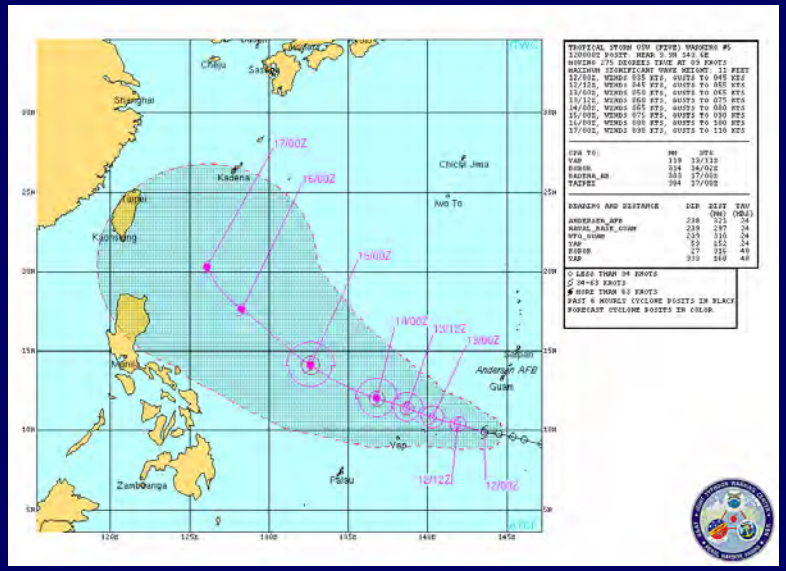




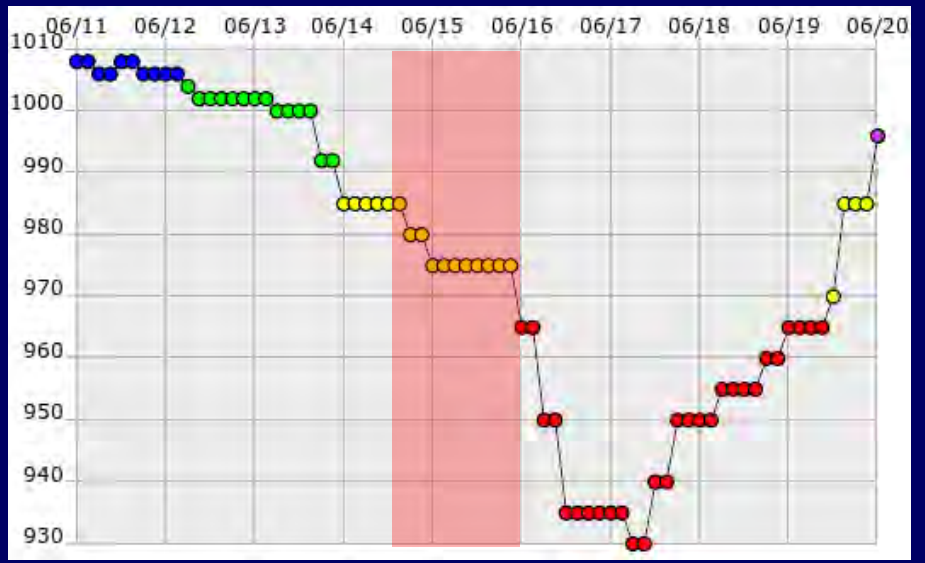
Typhoon Guchol (2012)



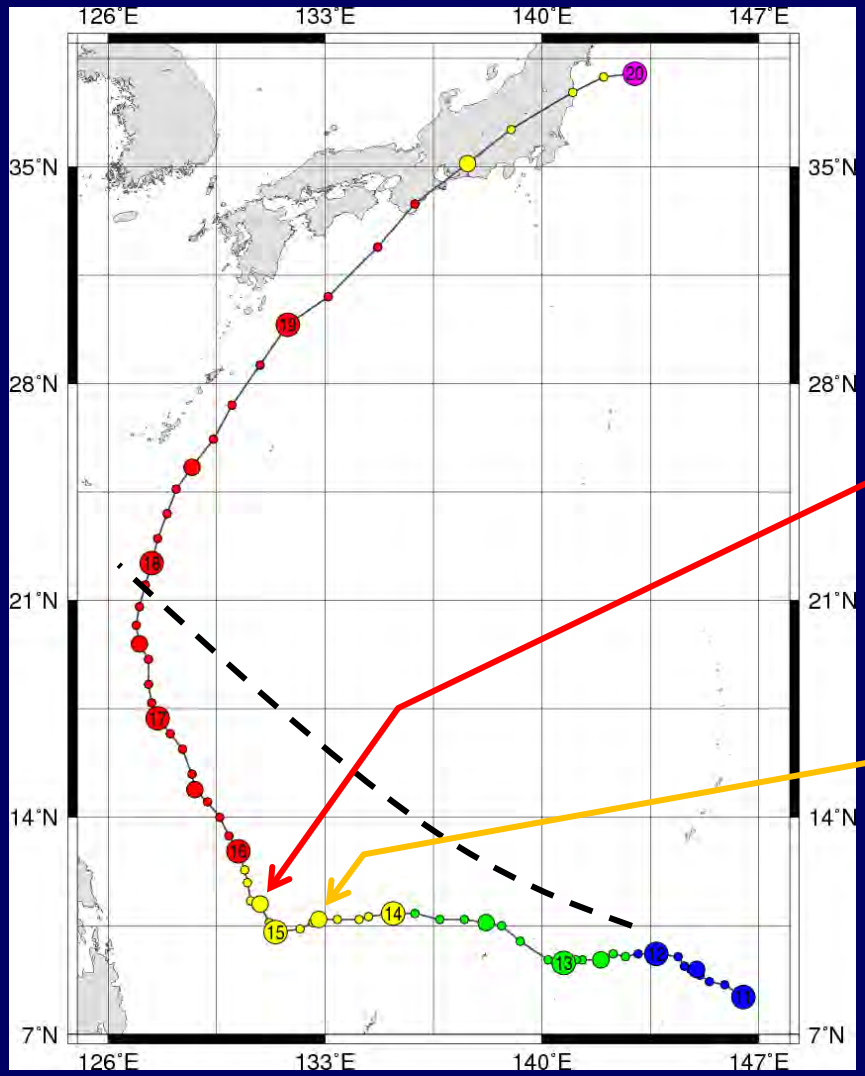
http://agora.ex.nii.ac.jp/digital-typhoon/



http://www.usno.navy.mil/JTWC/



Axisymmetrization during Recurvature



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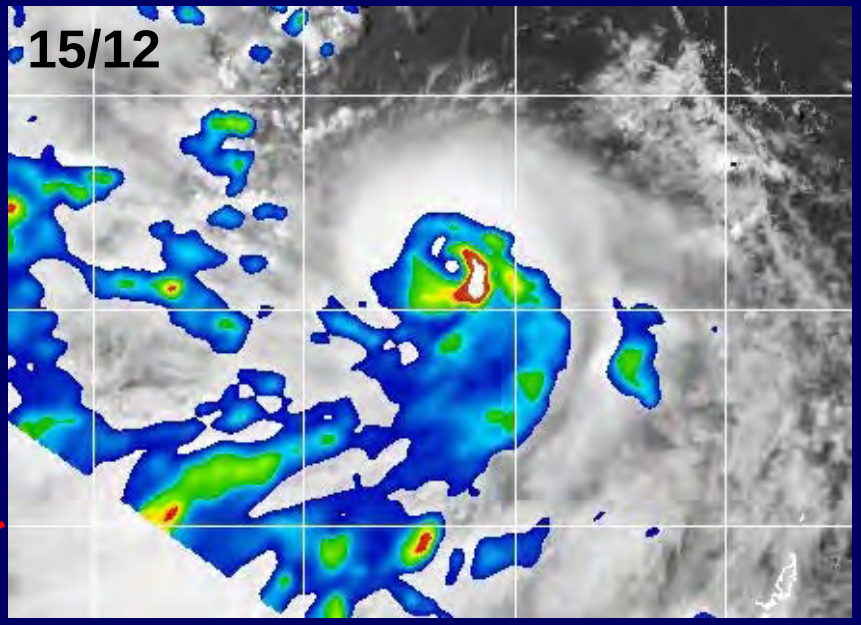
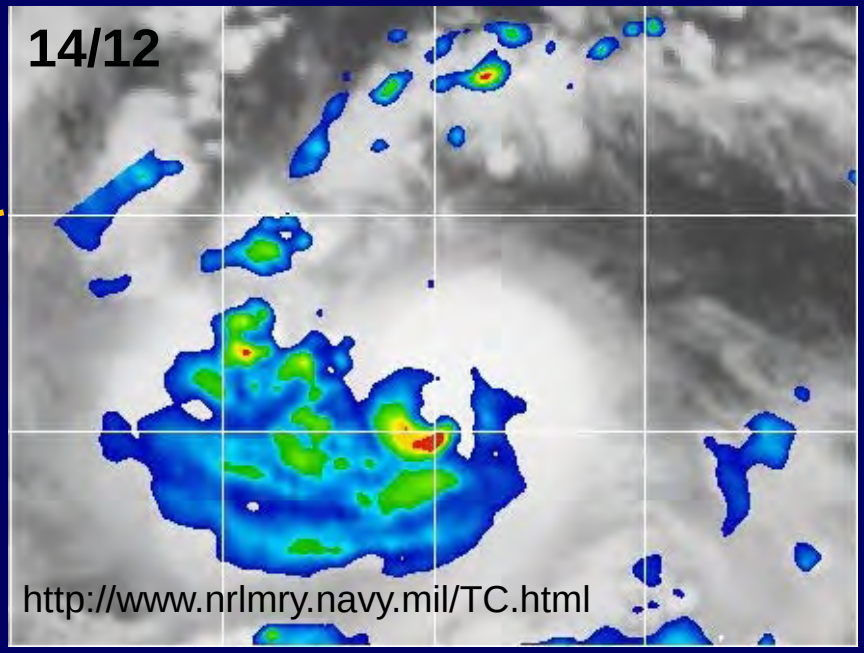
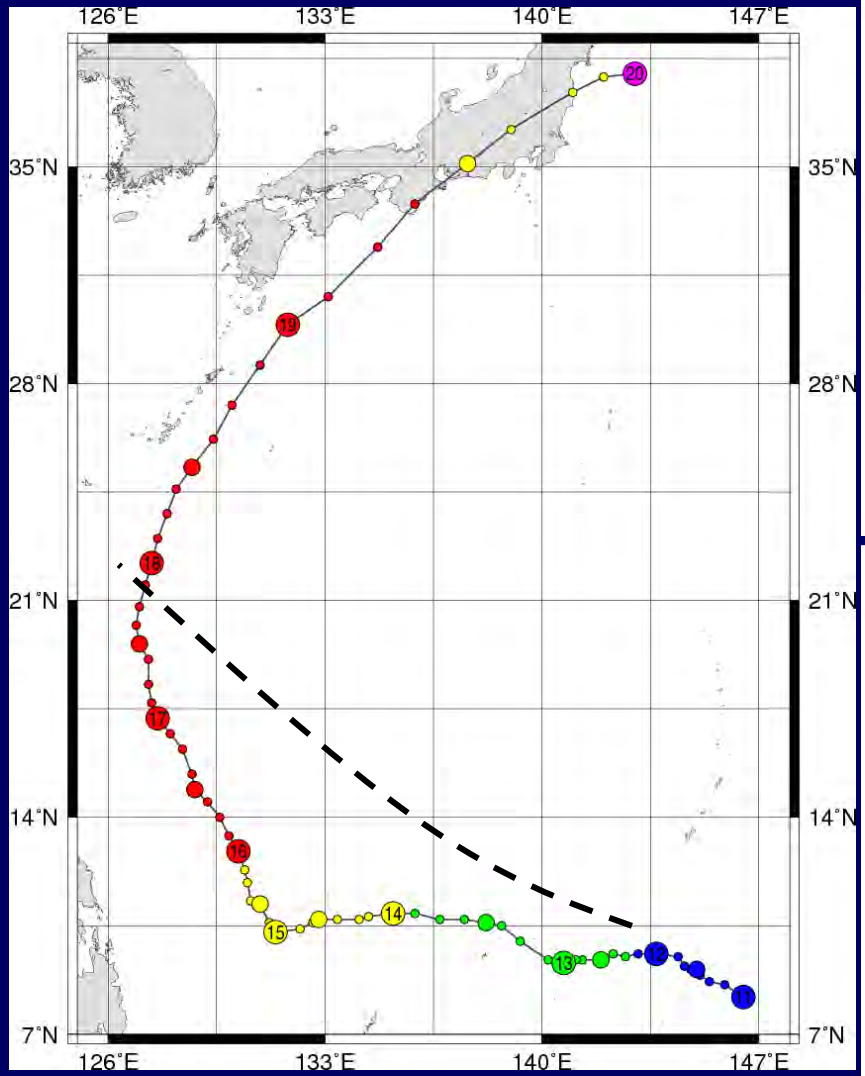




http://www.nrlmry.navy.mil/TC.html

Axisymmetrization during Recurvature



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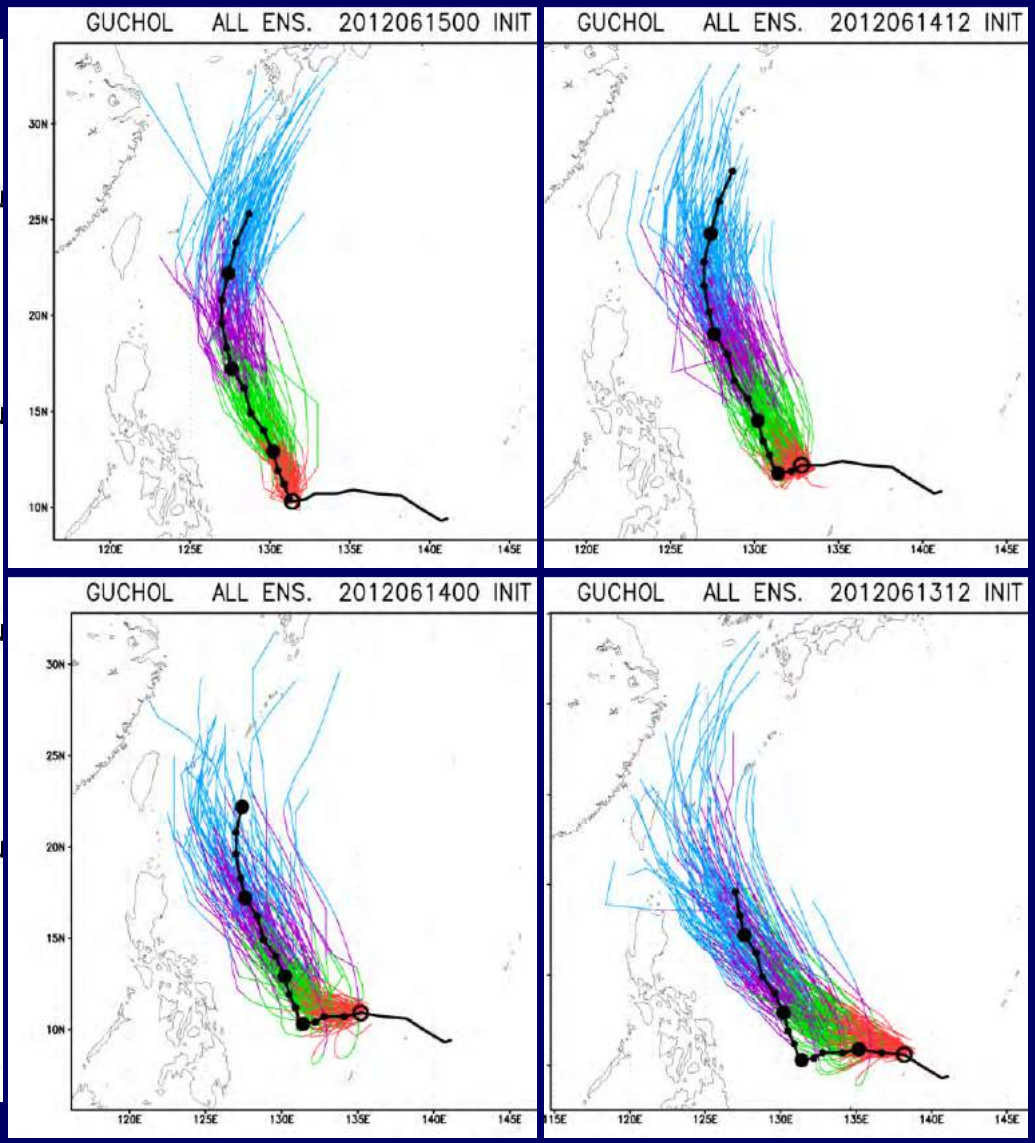

http://tparc.mri-jma.go.jp/cyclone/login.php

Summary

- Factors causing the northwestward track of Typhoon Fengshen (2008) were diagnosed using the outputs of both non-hydrostatic NICAM and hydrostatic JMA-GSM.
- NICAM results show the prevalence of convection-induced lower-tropospheric stretching effect in the western side on the TC track while this effect was relatively weak in JMA-GSM, causing an erroneous northward bias.
- The asymmetric stretching may have been attributed to either of monsoon-TC interaction or the coupling with a synoptic-scale disturbance along 10^{o}N.
- Results showing the westward “propagating” nature of typhoons with northward bias of models, and suggesting an importance of non-hydrostatic, explicit cloud-resolving framework for better track prediction.

References

- Yamaguchi, M., T. Nakazawa, and K. Aonashi, 2012: Tropical cyclone track forecasts using JMA model with ECMWF and JMA initial conditions. *Geophysical Research Letters*, Vol. 39, L09801, doi:10.1029/2012GL051473. [HTML]
- Chan, J. C. L., 2011: Movement of Tropical Cyclones. A chapter of textbook "Global Perspectives on Tropical Cyclones -- From Science to Mitigation", Edited by J. C. L. Chan and J. D. Kepert, World Scientific Series on Asia-Pacific Weather and Climate, Vol. 4. [HTML]