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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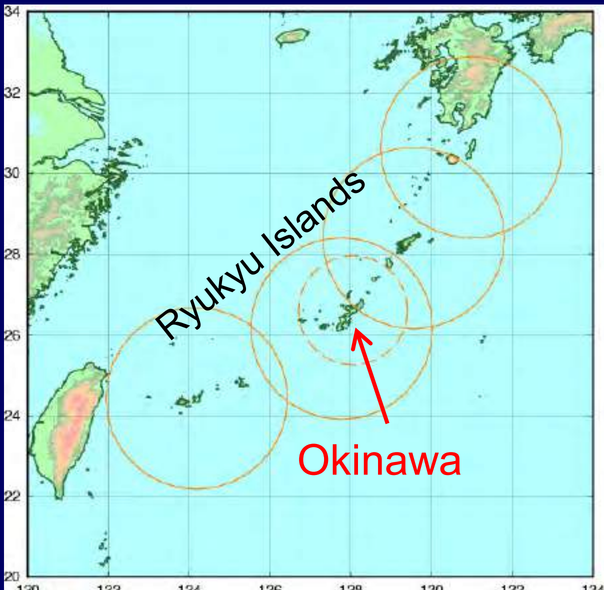
[University of the Ryukyus / JAMSTEC]

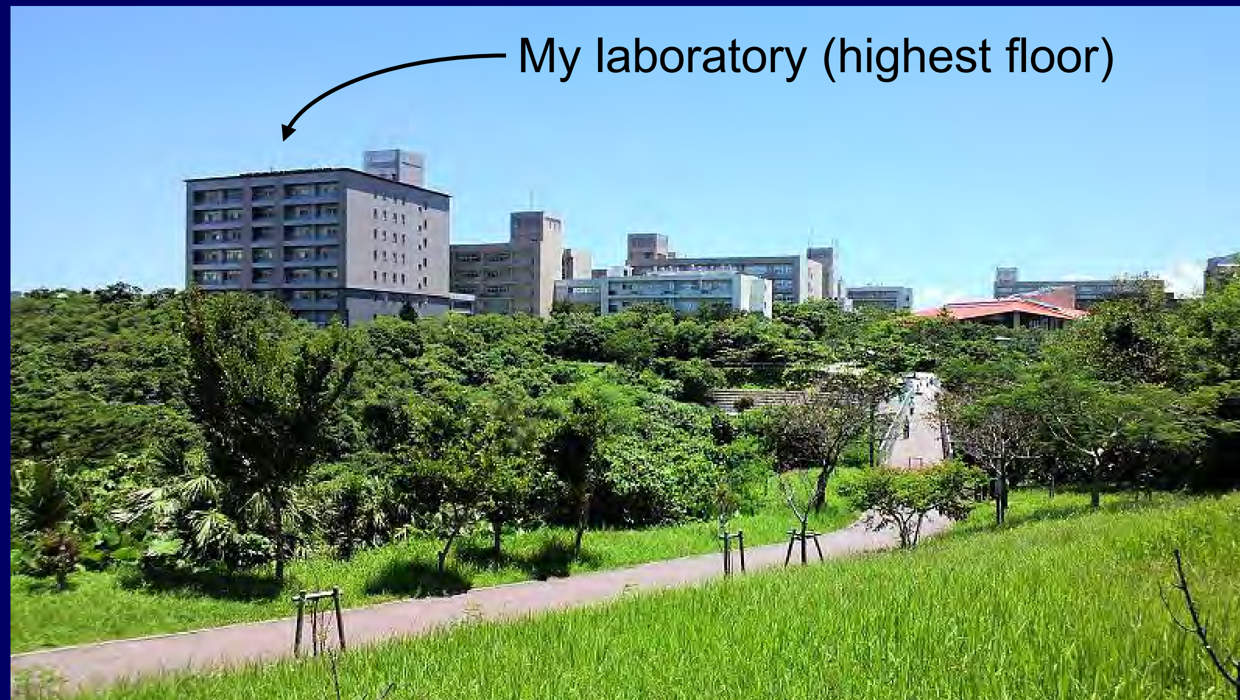
With special thanks to:
Tomoe Nasuno, Wataru Yanase, Masaki Satoh,
Kunio Yoneyama, and Ryuichi Shirooka

JAMSTEC

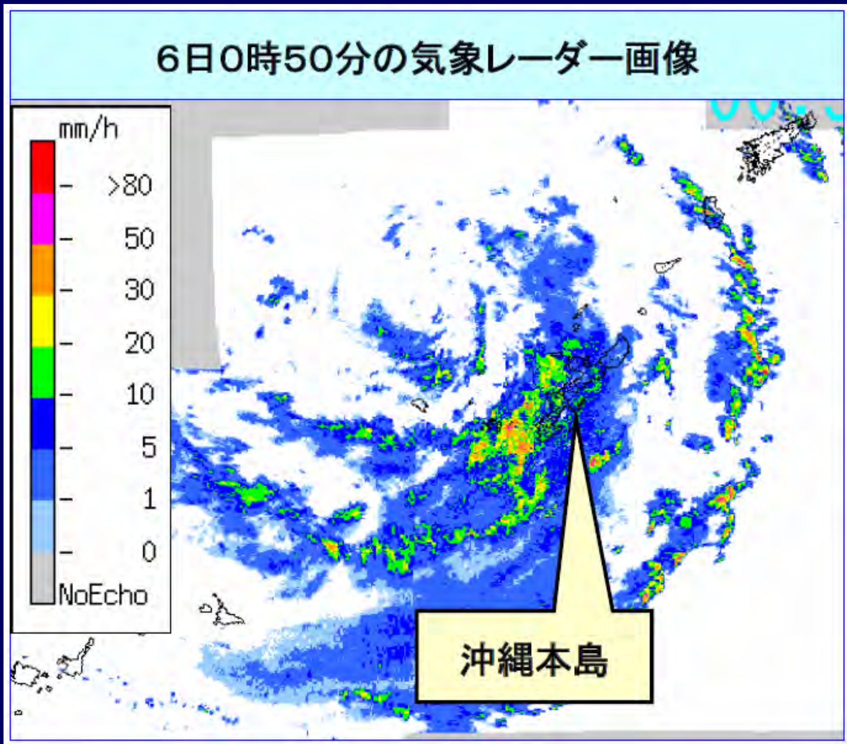
University of the Ryukyus

Arrival at my new post in University of the Ryukyus（琉球大学）

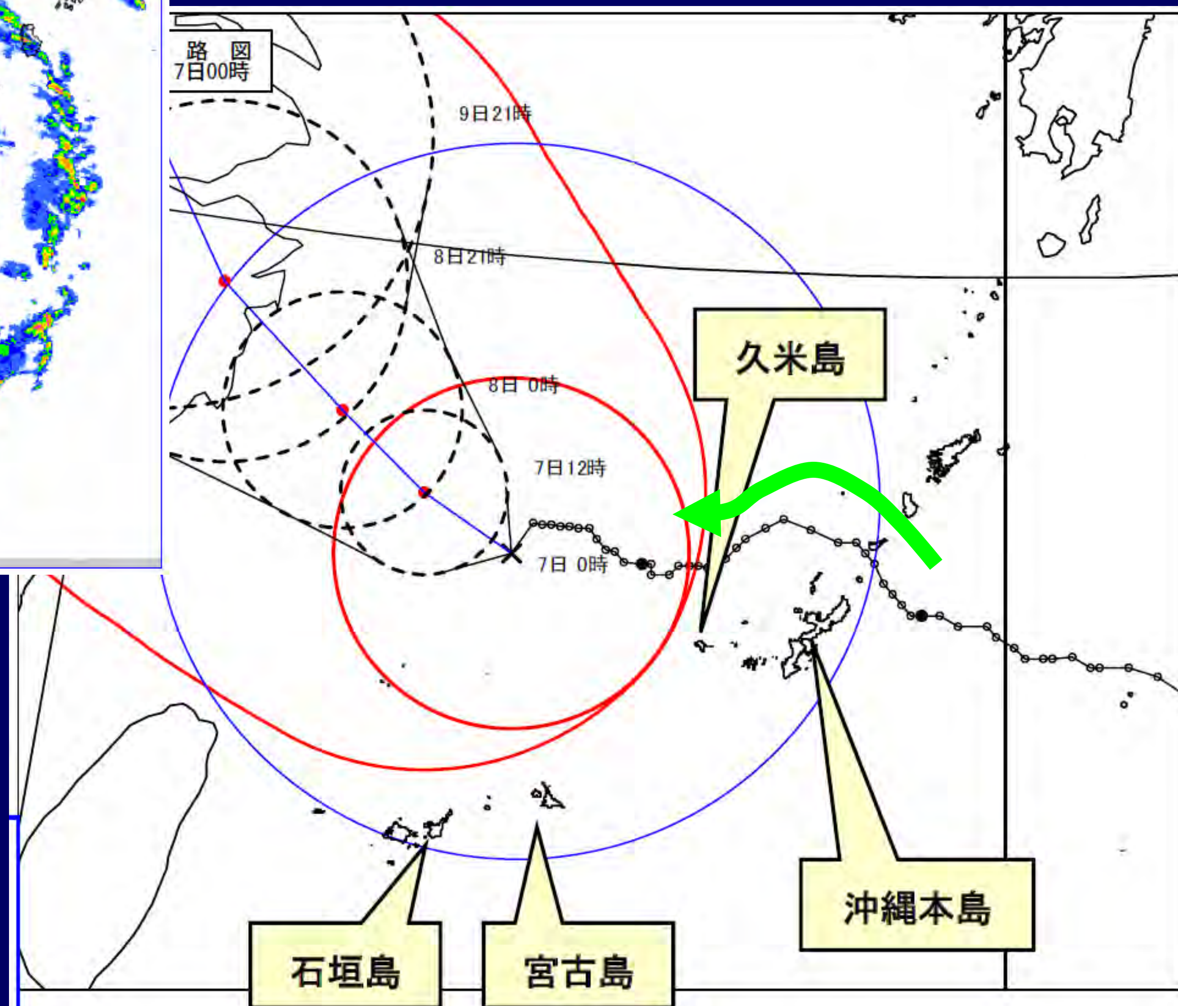




First Case . . . welcomed me, or not?



Typhoon Haikui (12w)

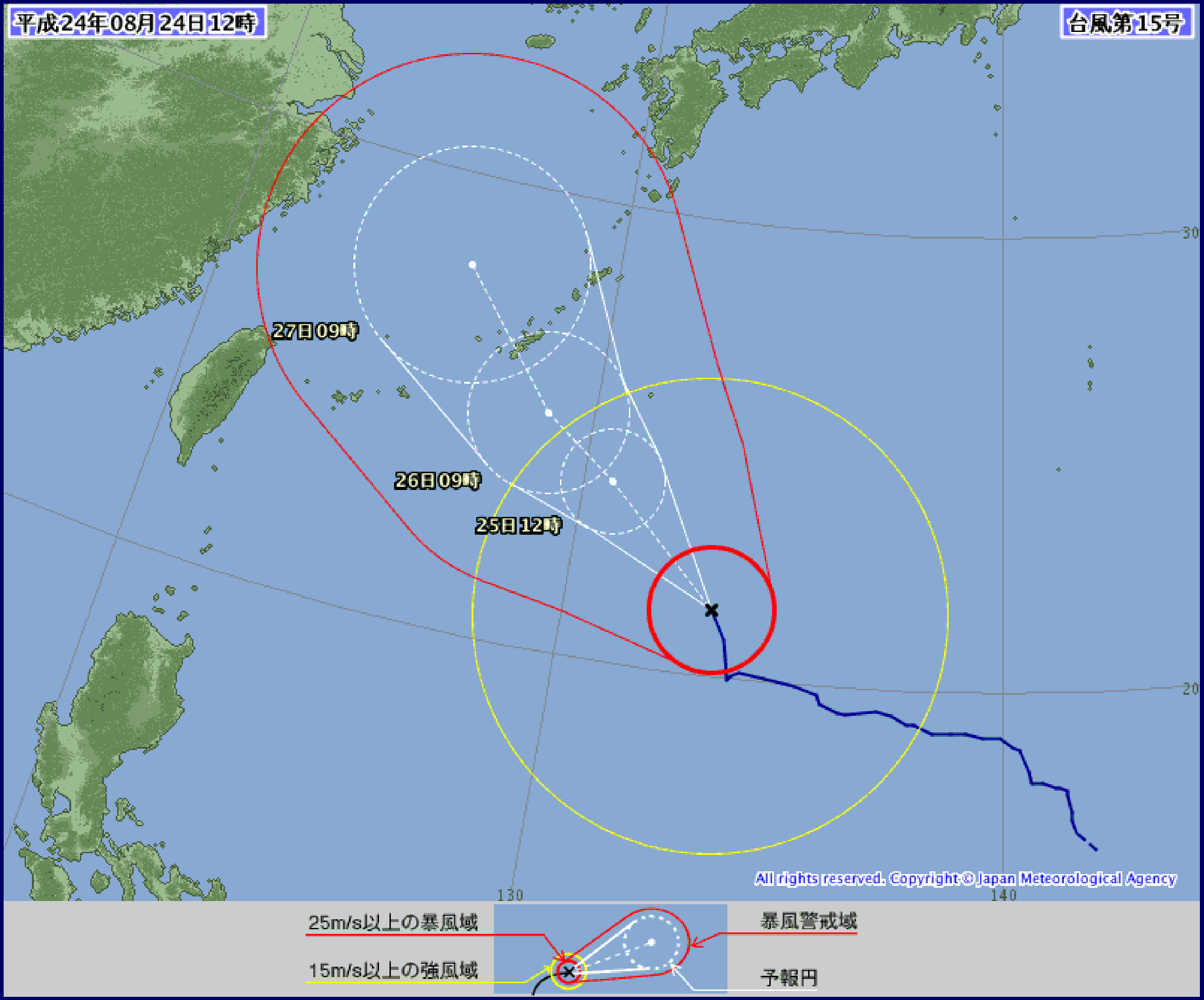


Avoiding Okinawa?

(from the JMA Okinawa observatory)

Second Case . . . , My First Desersion（逃亡）. . .

Typhoon Bolaven



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 ---

What's the problem of Tropical Cyclogenesis?
（台風発生の問題点）

Climatological requirement of tropical cyclogenesis (Gray 1968)

- sea-surface temperature above 26.5-27.0 ^{o}C
- a deep surface-based layer of conditional instability
- enhanced values of cyclonic low-level absolute vorticity
- organized deep convection in an area with large-scale ascent and high mid-level humidity
- weak to moderate vertical wind shear

However, even though all of these conditions are satisfied, tropical cyclogenesis is infrequent at any location.

There must be additional dynamical processes leading to tropical cyclogenesis, although they have not been understood yet.

Definition of Tropical Cyclogenesis
（台風発生の定義）

Based on the definition by Zehr (1992, NOAA Tech. Rep.)

Tropical Cyclogenesis:

Weather systems and their ongoing atmospheric processes during the period before initial designation as a tropical storm (TS).

Intensification:

Time periods after TS designation.

Difference in dynamics:

External processes are hypothesized to be required for cyclogenesis, while they are likely not required for intensification, due to self-sustaining mechanism of TS and TY

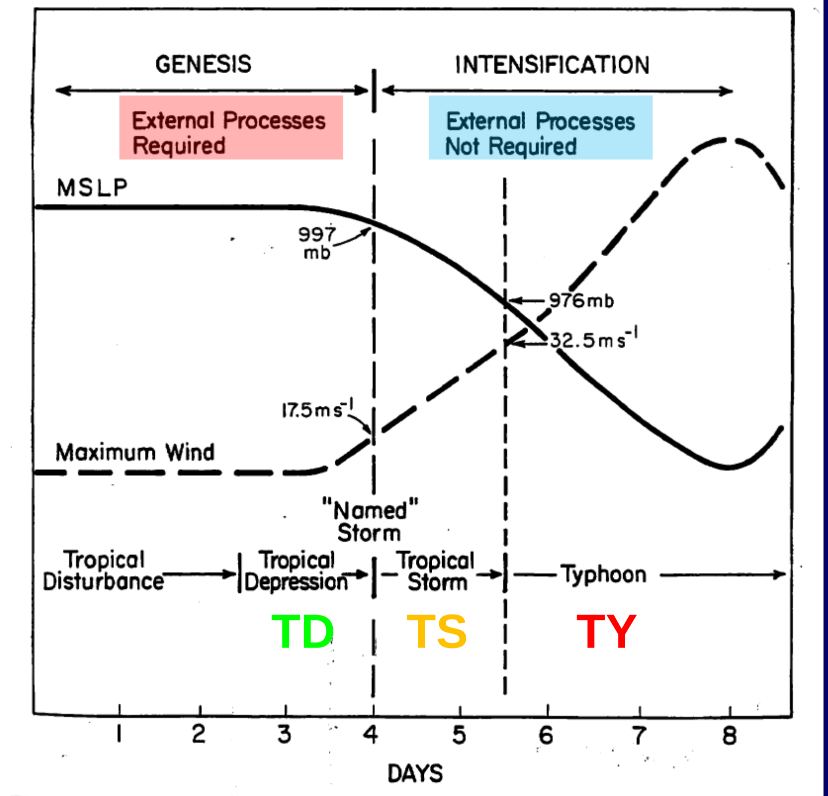


Figure 1.1: Depiction of typical genesis and intensification periods and their associated MSLP and maximum surface wind speed.

External Processes during Genesis Stage
（発生期の外部過程）

Enhancement of an initial disturbance over ITCZ
(e.g., Gray 1998)

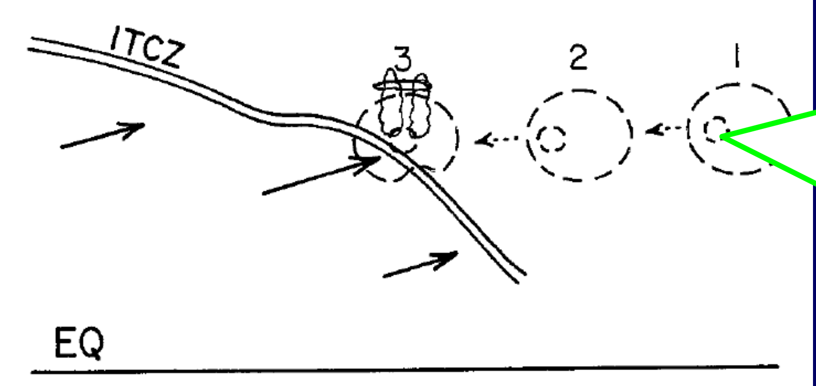


Fig. 14. Illustration of a westward moving cloud cluster (shaded) entering a stationary ITCZ monsoon trough can bring about an effective wind surge on the equatorward side of the trough. Convection becomes rapidly enhanced

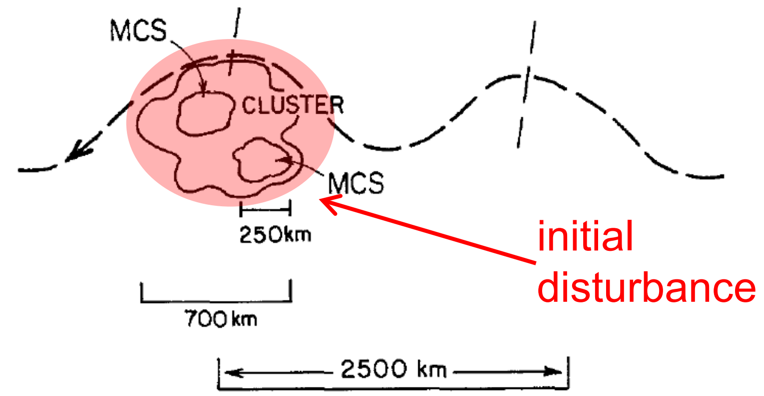
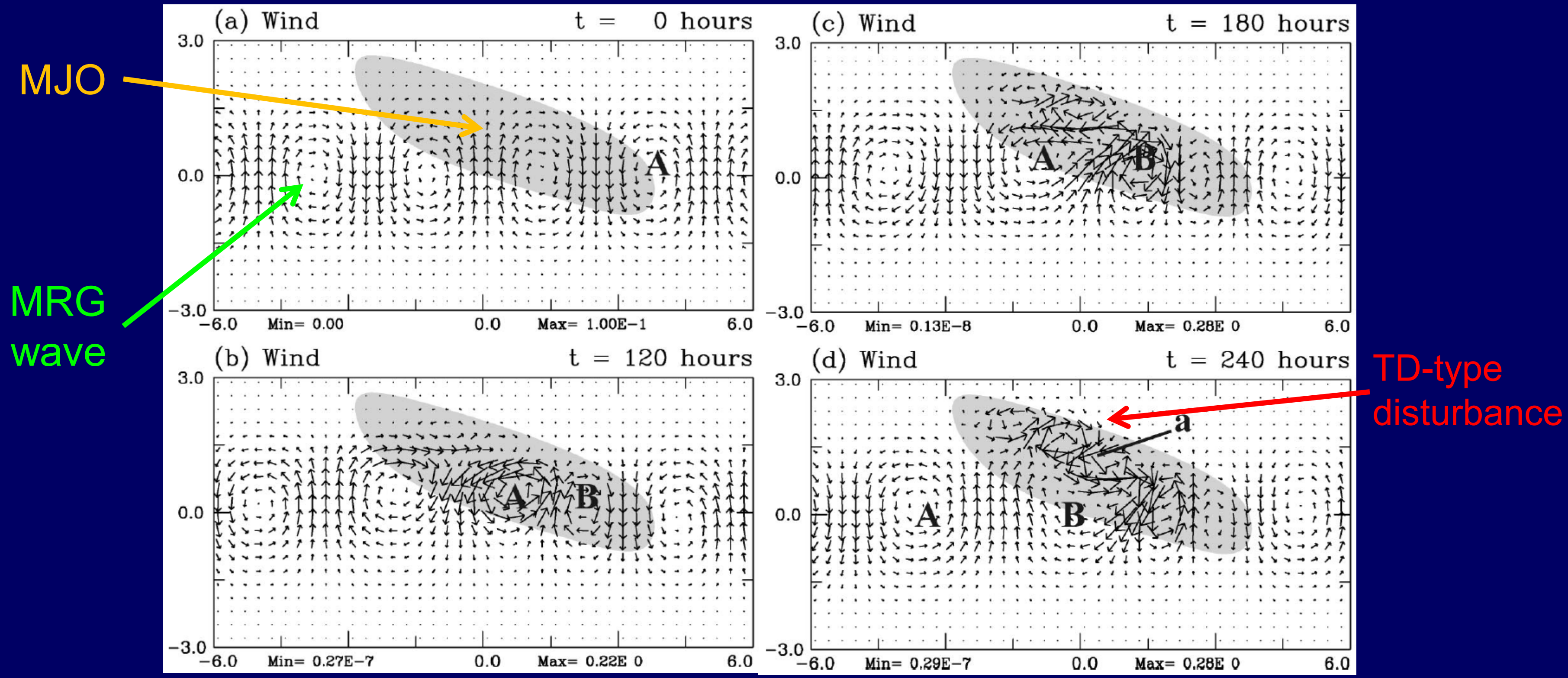


Fig. 2. Illustration of the typical size and flow of an easterly wave (~2500 km) in which a cloud cluster (~700 km) and a MCS (~250 km) are embedded

An initial disrutbance within a trough region of an easterly wave can spin-up over a stationary ITCZ monsoon trough due to enhanced low-level convergence and relative vorticity.

External Processes during Genesis Stage
（発生期の外部過程）

Modification of a mixed Rossby-gravity (MRG) wave
by Madden-Julian Oscillation (MJO)
(Aiyyer and Molinari 2003)



Tropical depression (TD)-type disturbance can be spawned due to the modification of MRG wave under the influence of MJO

Vertical structure of initial disturbances
（初期擾乱の鉛直構造）

Reed and Recker (1971)

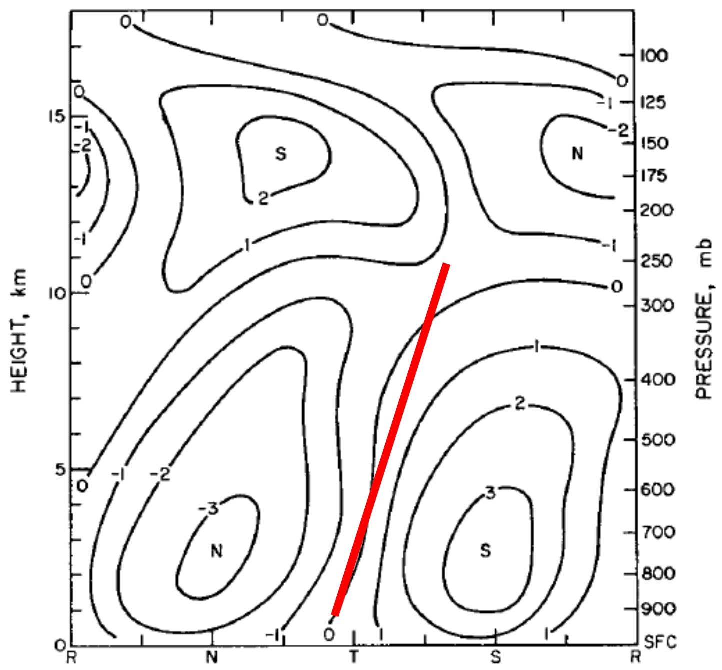


FIG. 4. Composite diagram of meridional wind speed (m sec⁻¹) for KEP. The letters R, N, T and S refer to the ridge, north wind, trough and south wind regions, respectively, of the wave as defined by its structure in the lower troposphere.

Takayabu and Nitta (1993)

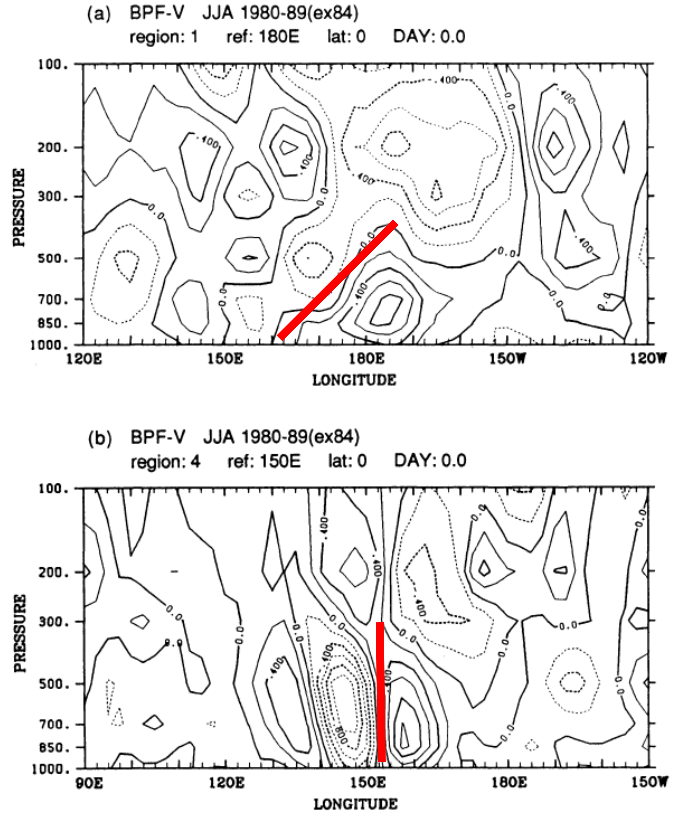
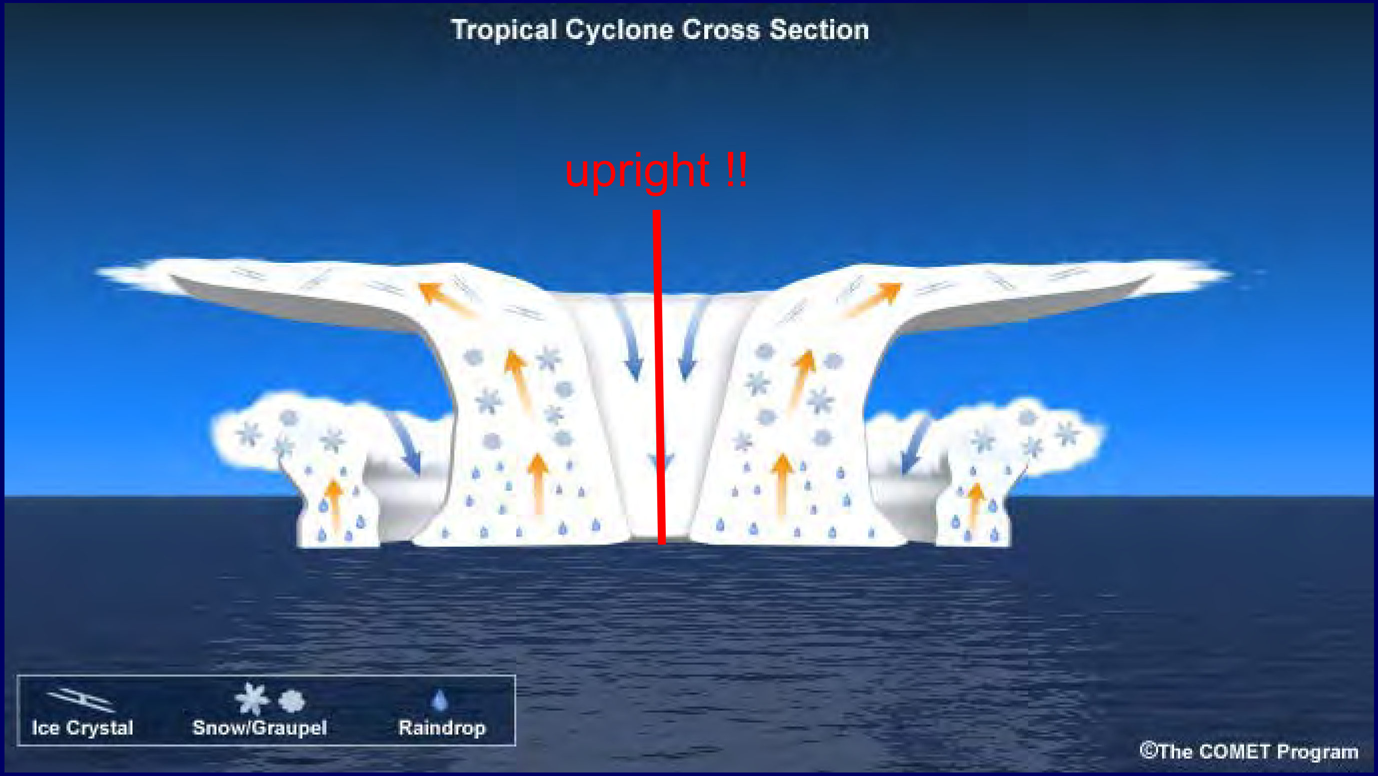


Fig. 11. Vertical cross section of the composite BPF-meridional wind (a) for the dateline composite along the equator and (b) for the 150°E composite along 5°N. The contour interval is 0.2 m/s and negative values are depicted by broken lines.

Structure of disturbances usually tilt eastward with height, and it often becomes upright as they move to the far-western Pacific

Vertical structure of tropical cyclones
（台風の鉛直構造）



from “Introduction of Tropical Meteorology”, Chapter 10 “Troppical Cyclones”
(http://www.meted.ucar.edu/tropical/textbook_2nd_edition/)

Upright vortex structure is one of the characteristics of tropical cyclones with hydrostatic and gradient-wind balance

Taylor-Proudman Theorem
（テイラー・プラウドマンの定理）

Gradient-wind balance (in radial direction):

$$\frac{V_\theta^2}{r} + fV_\theta = \frac{1}{\rho_0}\frac{\partial P}{\partial r} \qquad \text{- - - (1)}$$

Hydrostatic balance (in vertical):

$$\frac{1}{\rho_0}\frac{\partial P}{\partial z} + g = 0 \qquad \text{- - - (2)}$$

The derivative of (1) over z yields,

$$(2\frac{V_\theta}{r} + f)\frac{\partial V_\theta}{\partial z} = \frac{1}{\rho_0}\frac{\partial^2 P}{\partial r \partial z} \qquad \text{- - - (3)}$$

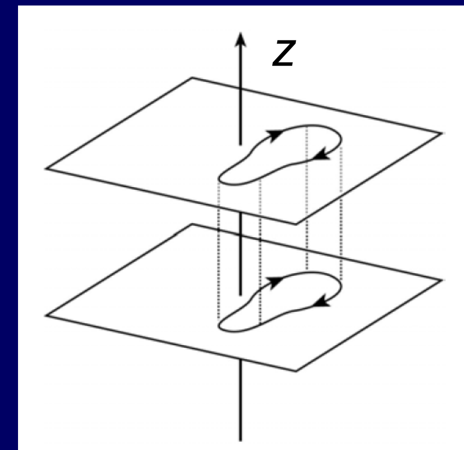
The derivative of (2) over r yields,

$$\frac{1}{\rho_0}\frac{\partial^2 P}{\partial r \partial z} = 0 \qquad \text{- - - (4)}$$

Since we can assume $(2\frac{V_\theta}{r} + f) > 0$ for cyclonic vortex in the northern hemisphere, the substitution of (4) for (3) yields,

$$\frac{\partial V_\theta}{\partial z} = 0$$

vortex with
no vertical shear



傾度風平衡にある定常流は2次元的で、流速は高さによらない
（→傾いた渦では気圧は下がりにくい）

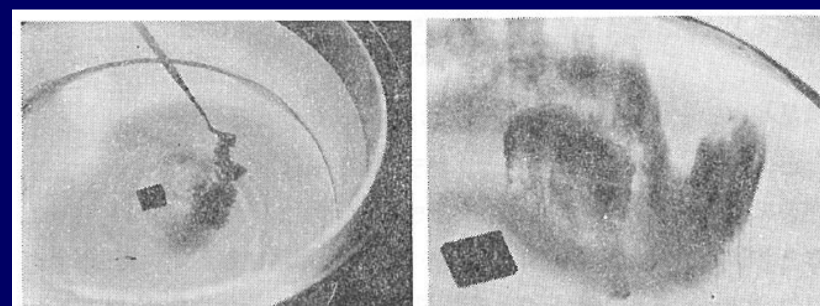
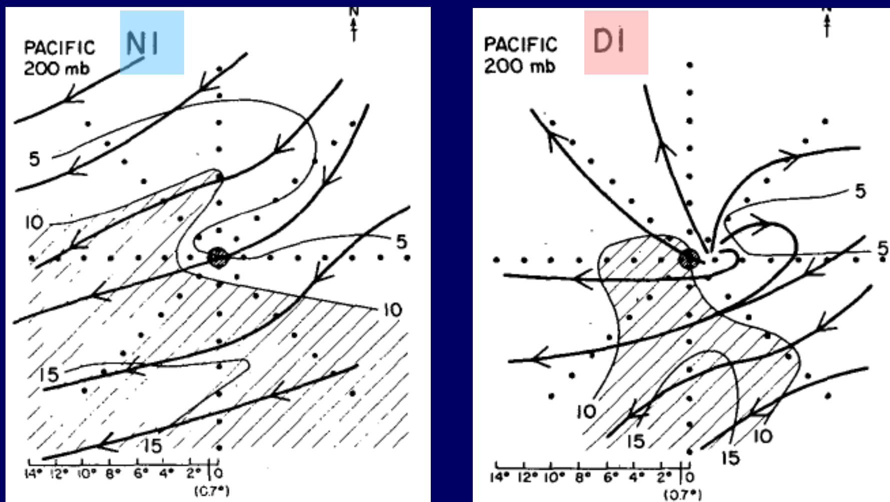


図 3.2 テーラーのインクの壁．左：回転流体にスポイトでインクを注入した直後．右：数分後，流れは二次元的になる．

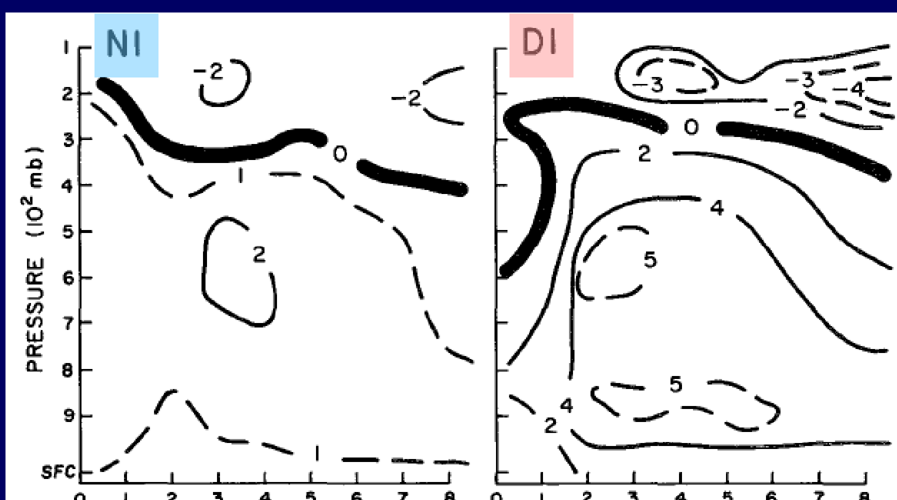
地球流体力学入門（木村著）

Non-developing v.s. developing disturbances
（台風に発達する渦としない渦との違い）

Streamlines at 200hPa



Tangential wind in radial-vertical domain



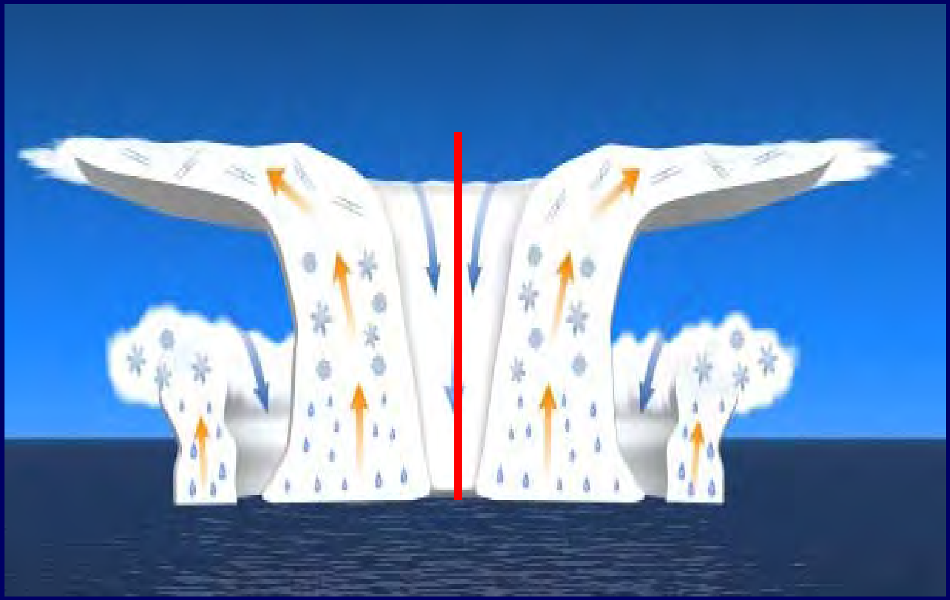
McBride and Zehr (1981, JAS):

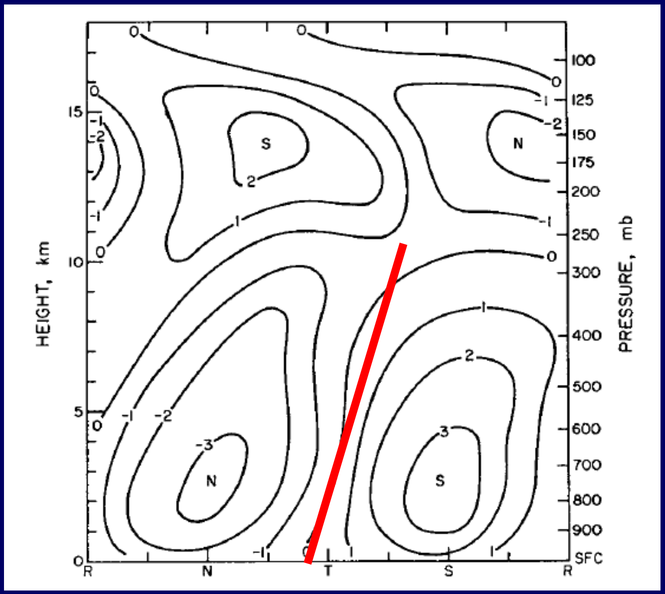
Non-developing disturbances (N1) are characterized by weak tangential wind with upper-tropospheric mono-directional flow

Pre-typhoon disturbances (D1) has stronger tangential winds with upper-level divergent flow

a deep upright vortex is preferable to a shallow (or tilted) one for tropical cyclogenesis

Key issue of tropical cyclogenesis



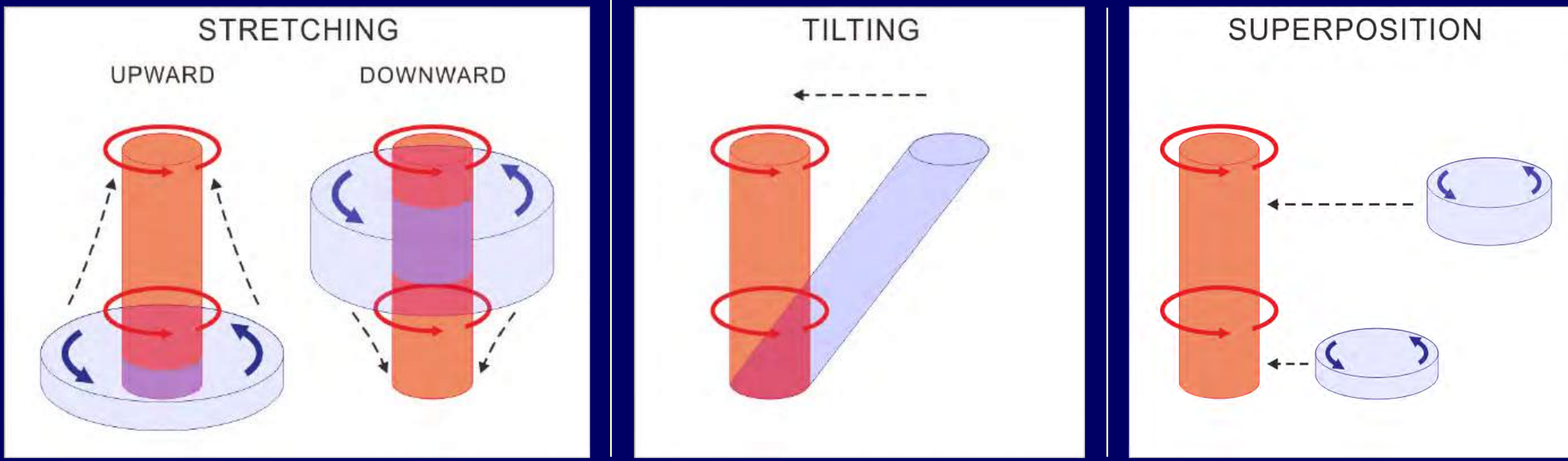


How can a deep upright vortex be spawned from a tilted disturbance ?

Possible Processes of Vortex Transformation

2-dimensional

3-dimensional



Bottom-up? Top-down?

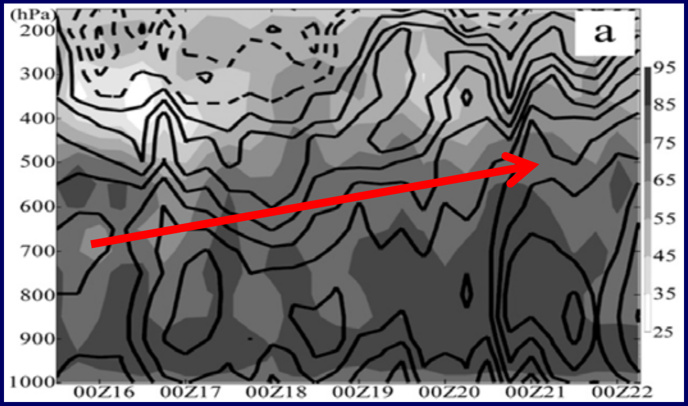
Bottom-up hypothesis

Montgomery et al. (2006):

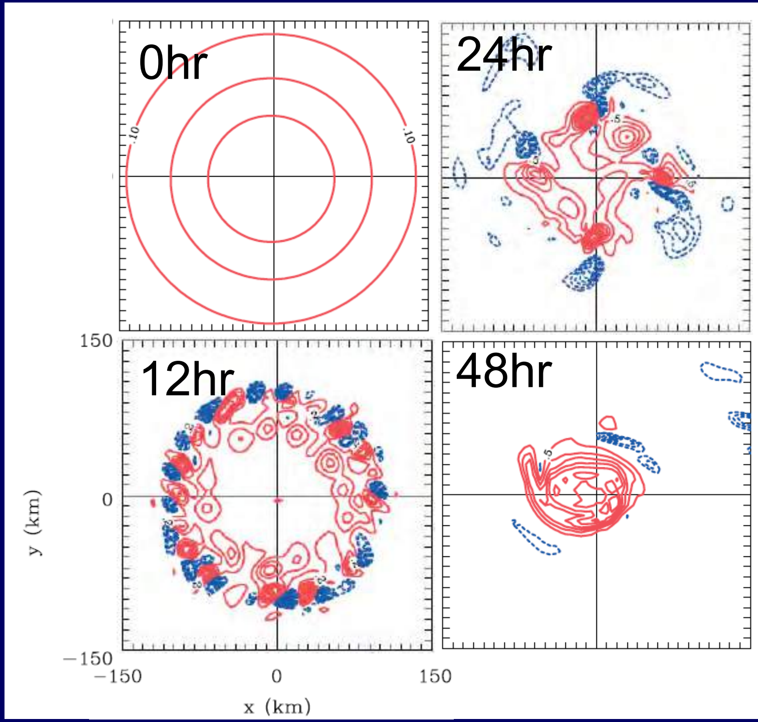
- An initial circulation exists in the lower and/or middle troposphere.
- It can intensify and extend upward due to vorticity stretching induced by convective updrafts (i.e., vortical hot tower: VHT).
- Aggregation of VHTs projects the vorticity into larger scale and lead to the spin-up of the cyclonic circulation.

Support from many recent numerical studies (e.g., Hendricks et al 2004; Tory et al. 2006; Nguyen et al., 2008; Kieu and Zhang, 2008, 2009, 2010; Fang and Zhang 2010, Fudeyasu et al. 2010ab)

Fang and Zhang (2010)



Nguyen et al. (2008)

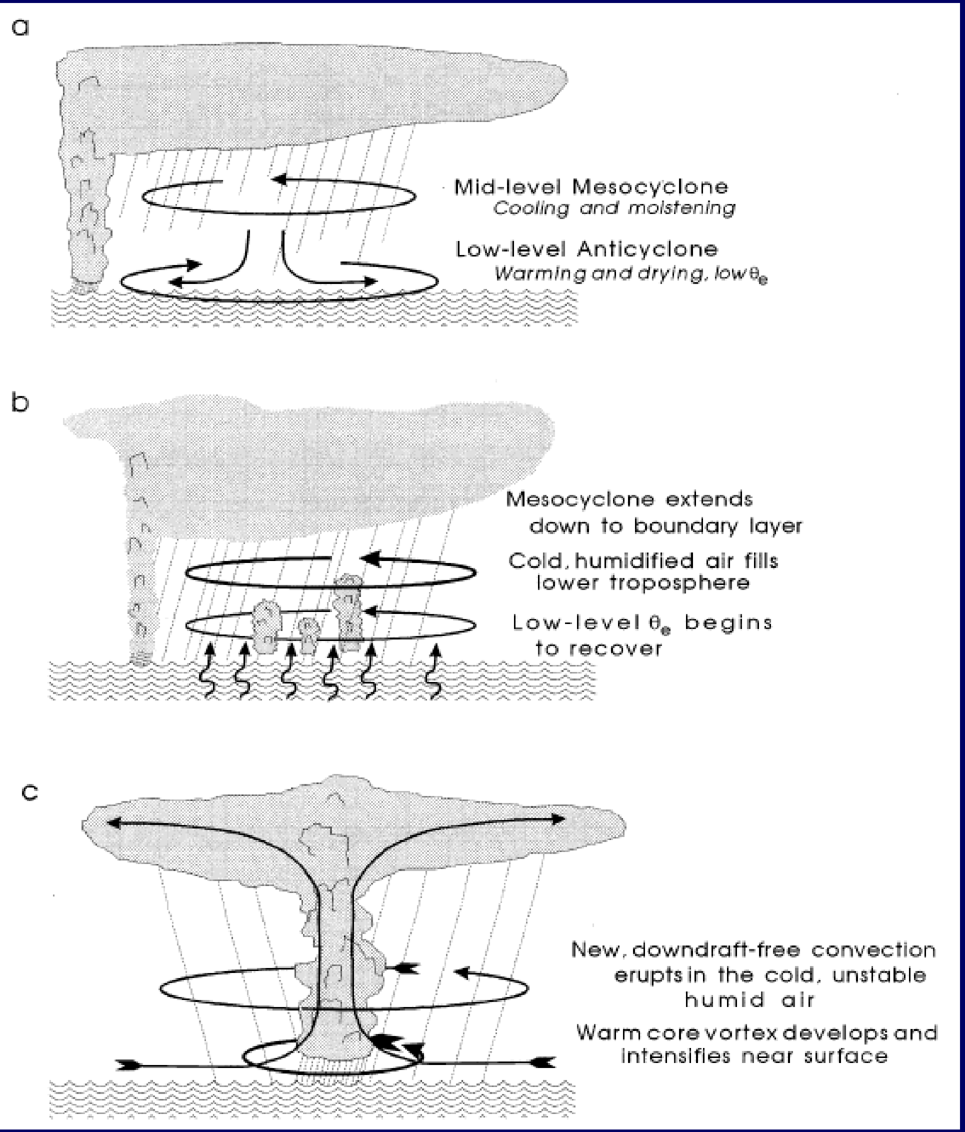


Top-Down (Showerhead) Hypothesis

Bister and Emanuel (1993):

- An initial circulation originates from a mid-tropospheric mesoscale convectively-induced vortex (MCV).
- It can intensify and extend downward under a dynamical balance due to evaporative cooling.
- Surface heat flux can be enhanced by this vortex, and a new convection can create a warm-core vortex.

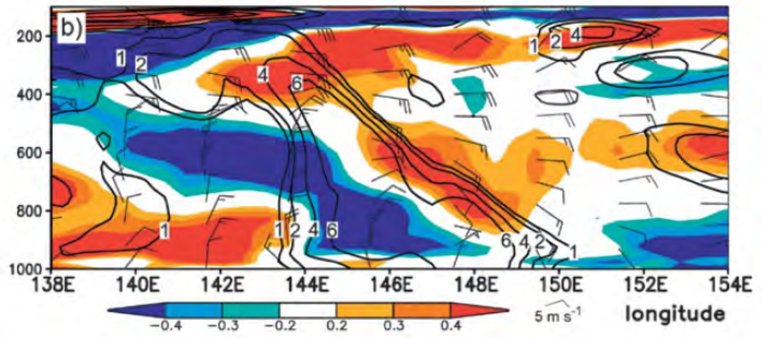
There is little support from later studies.

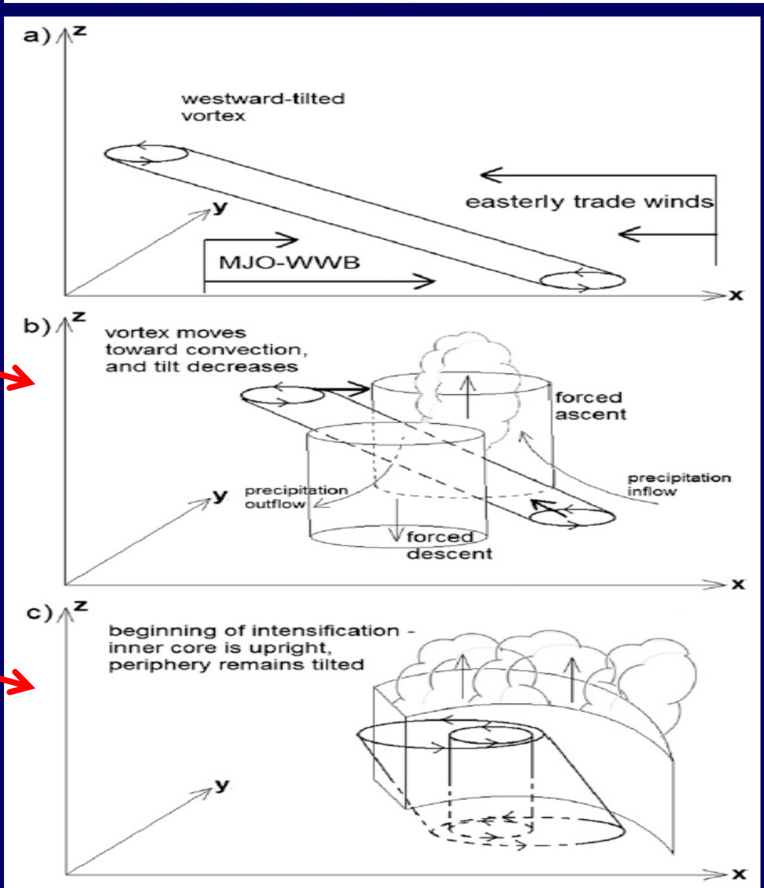


Vortex Uptilting Hypothesis

Hogsett and Zhang (2011):

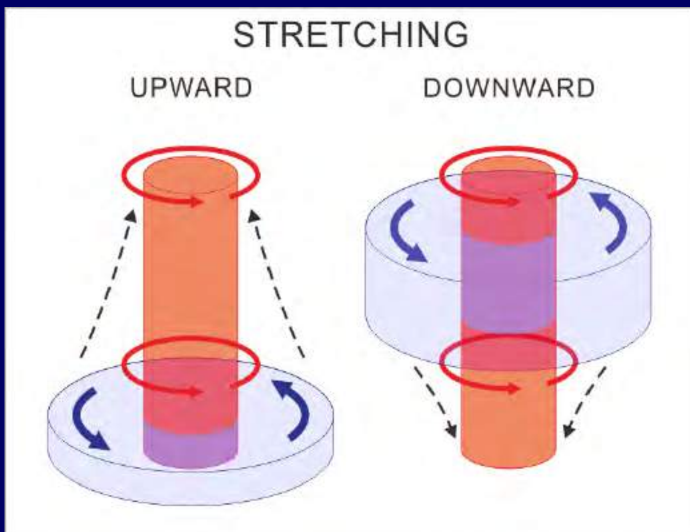
- A case study of Chanchu (2006)
- An initial circulation tilts westward with height under the influences of MJO-related westerly burst and easterly trade winds
- Convection develops in the downtilt-right side, with weak vertical shear and low-level convergence
- Both the convective forcing and the dry dynamical vortex resiliency (復元力) help decrease the vertical tilt of the WWB vortex

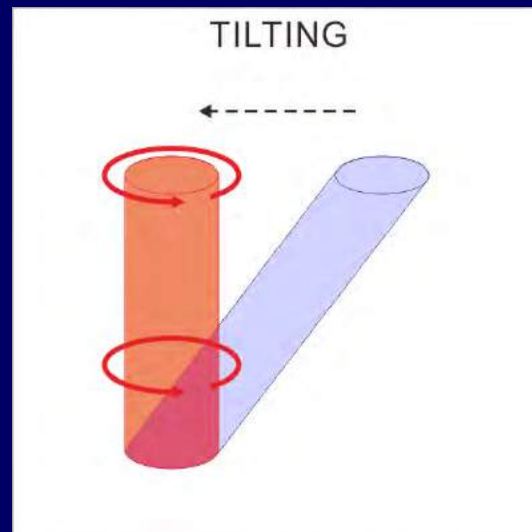


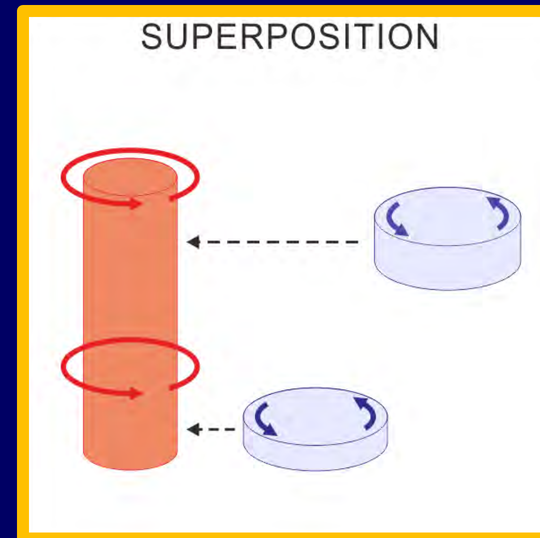


Possible Processes of Vortex Transformation

2-dimensional | **3-dimensional**







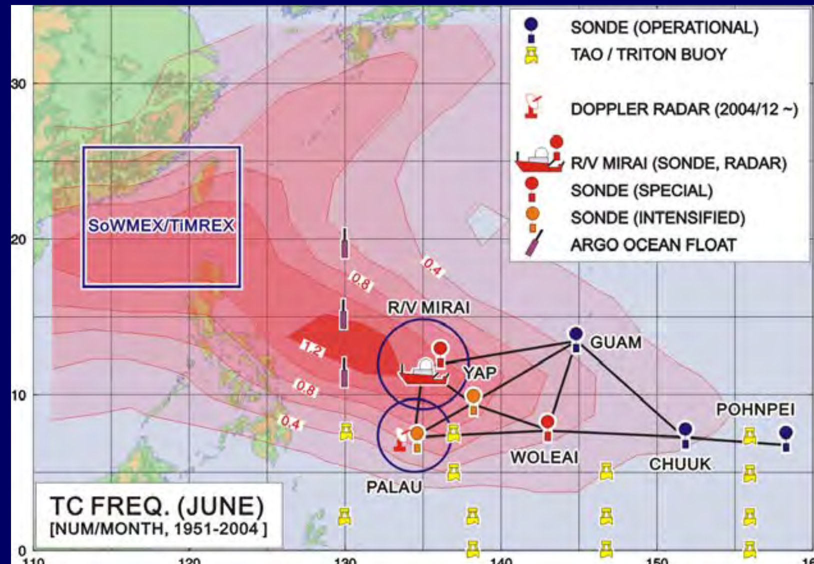
Hendricks et al. (2004)
Montgomery et al. (2006)
Tory et al. (2006)
Nguyen et al. (2008)
Kieu and Zhang (2009)
Fang and Zhang (2010)
Fudeyasu et al. (2010)

Bister and Emanuel (2004)

Hogsett and Zhang (2010)

Focus of this presentation based on a case study in the tropical western Pacific

JAMSTEC's Research on Typhoon Formation



Observation in East Philippine Sea

- PALAU field experiment in early summer season (June-July) of 2005, 2008, and 2010
- Using ground-based and ship-borne Doppler radars, upper-air sounding arrays, oceanic buoys
- To capture the structure and evolution of mesoscale convective systems embedded in a pre-typhoon vortex

Global cloud-resolving simulation

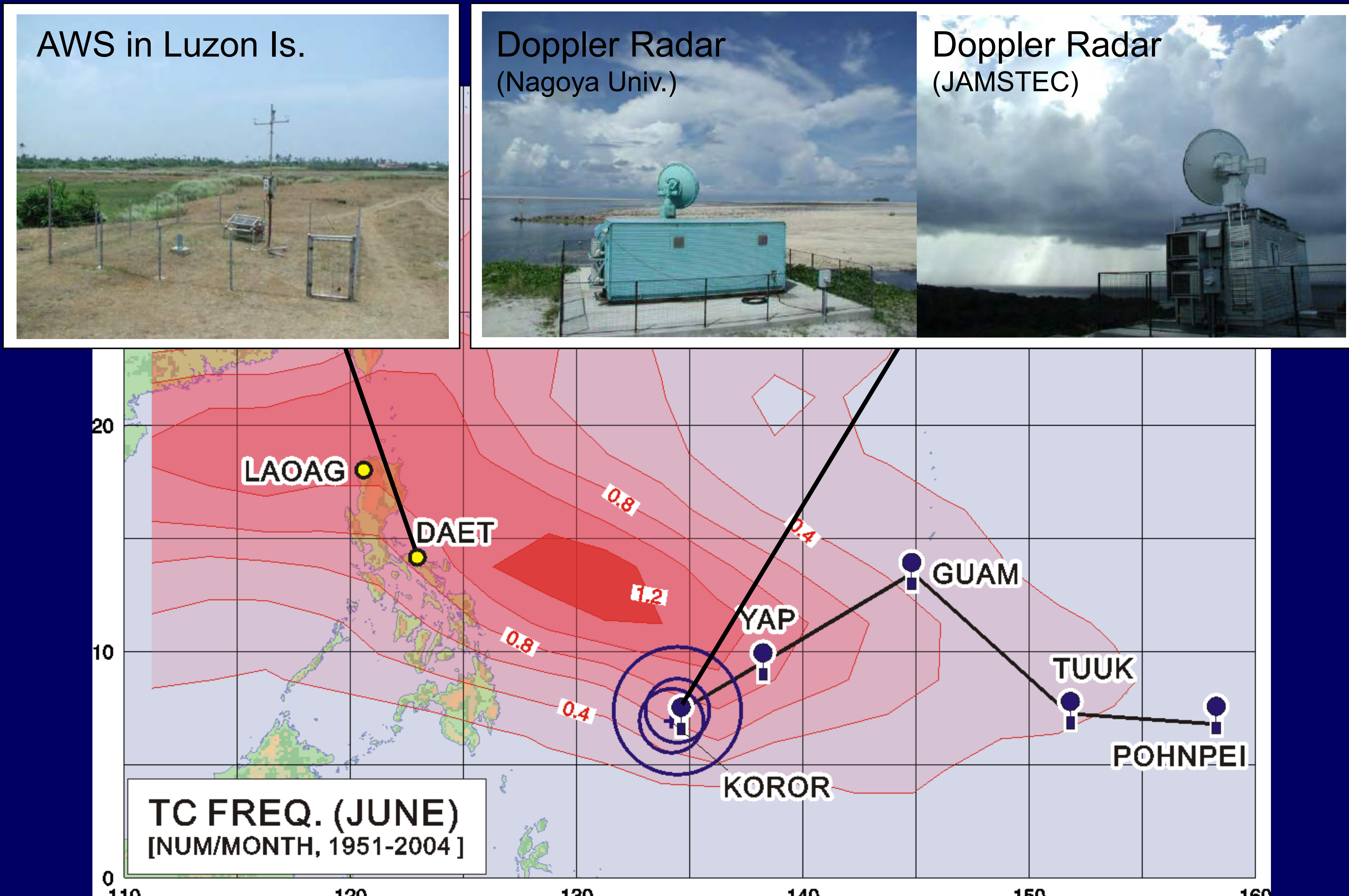
- Using the Nonhydrostatic Icosahedral Atmospheric Model (NICAM), developed at JAMSTEC
- Explicit cloud physics, no cumulus parameterization, with horizontal resolution of 3.5 km
- To understand the key process of typhoon formation, under influences of synoptic- and large-scale waves and disturbances (e.g., MJO)

PALAU-2005 Field Experiment

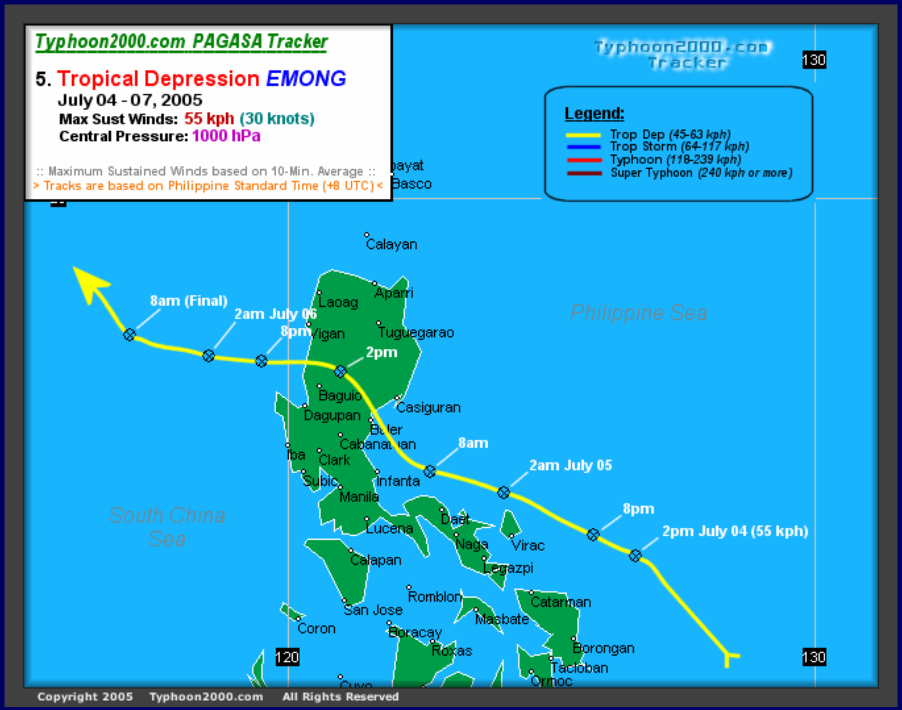
~ A Prologue to TC Genesis Observation ~

PALAU-2005

Pacific Area Long-term Atmospheric observation for Understanding climate change

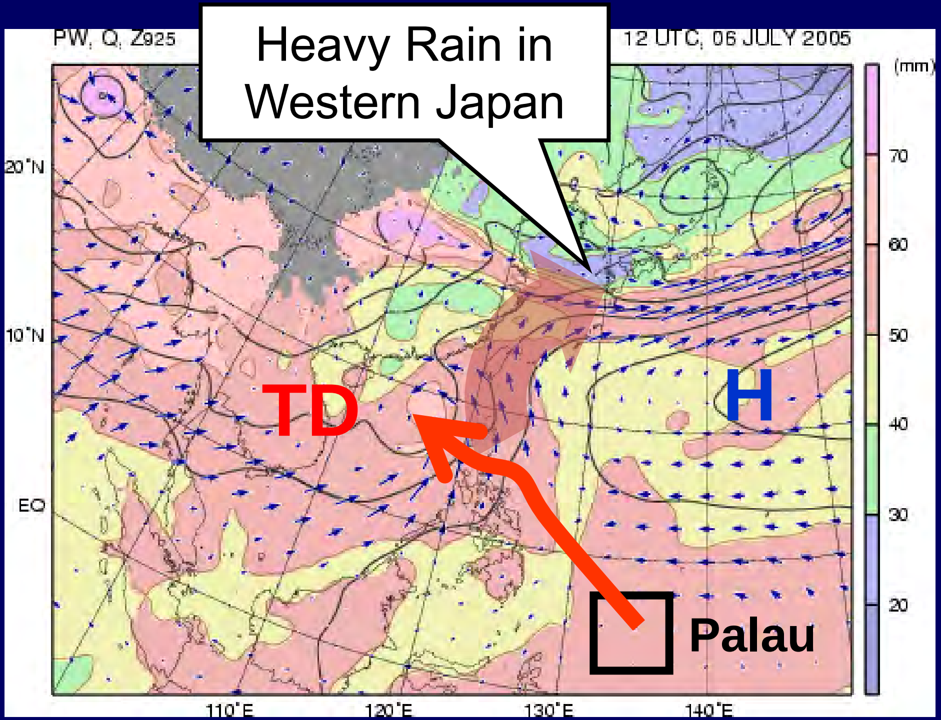


A Tropical Depression during PALAU-2005



Tracking Chart of TD "Emong"

(from http://www.typhoon2000.ph)

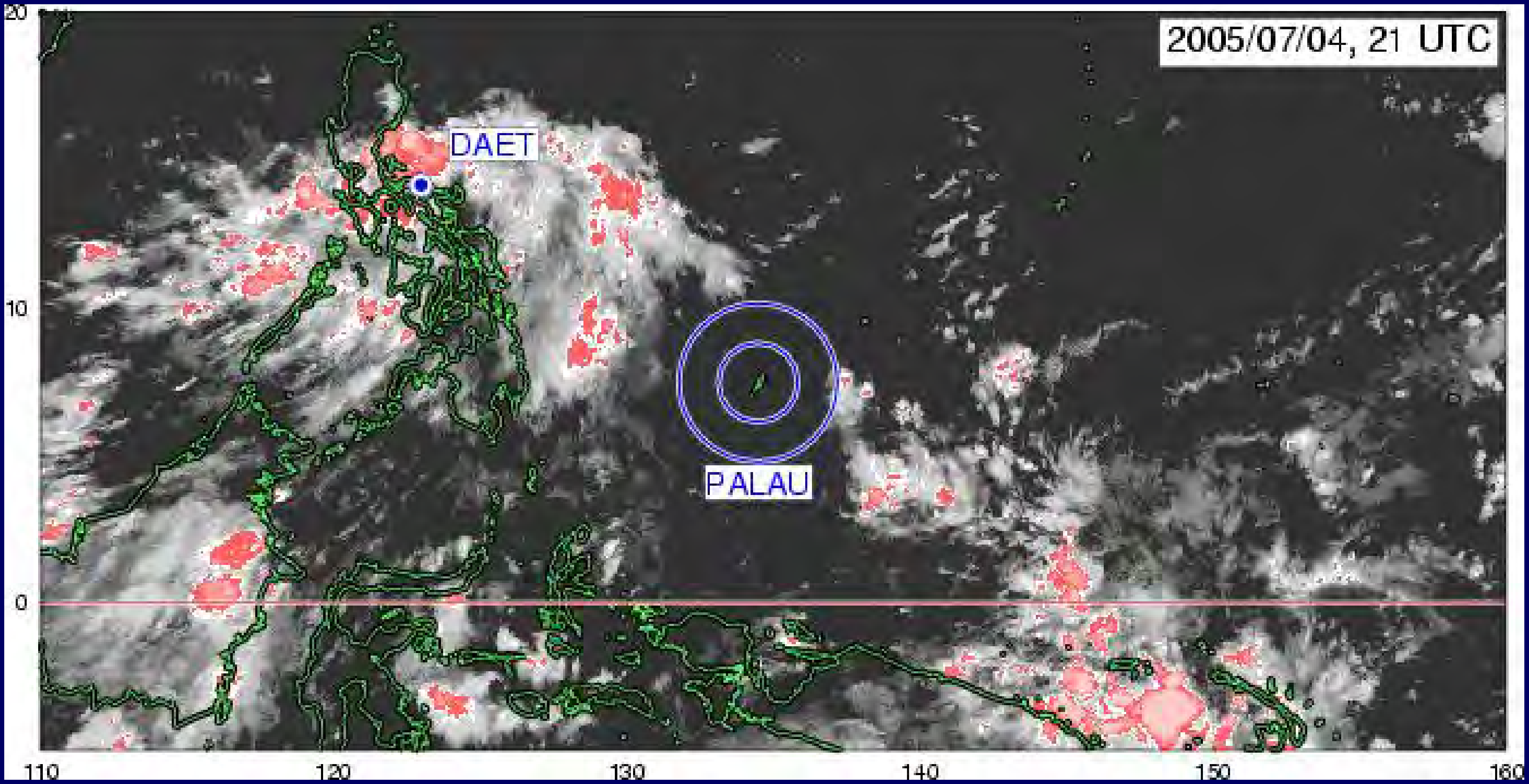


Precipitable Water, Vapor Flux

and Geopotential Height at 925 hPa

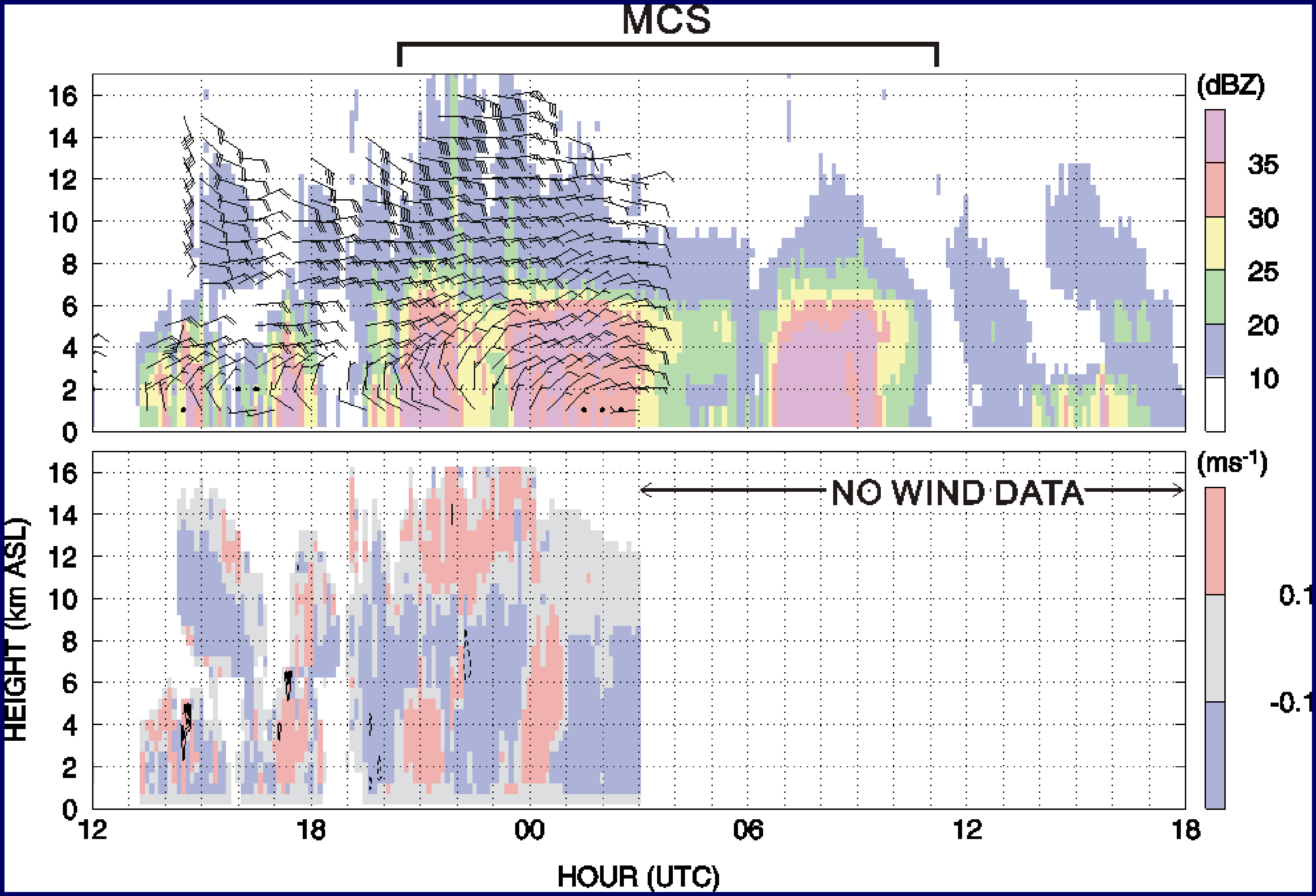
- Emong was a weak tropical depression that started to develop within the PALAU area, but did not intensified into a tropical storm.
- Significant vapor transport to western Japan, associated with this depression, was analyzed before the heavy rain episode in 8-10 July.

Overall Cloud Evolution



- Convective blowout over the PALAU region
- Dissipation and redevelopment near Philippines

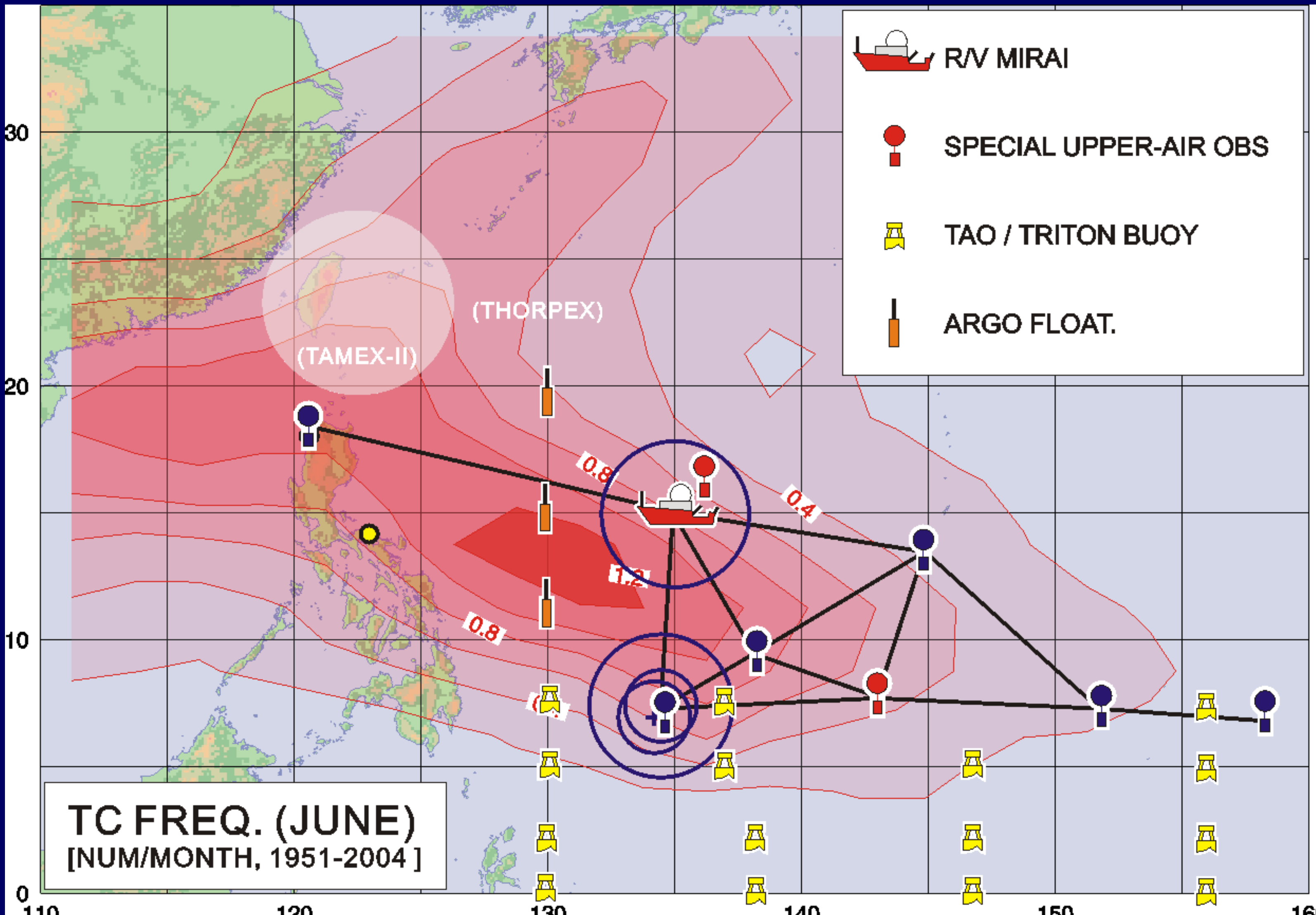
Vertical Structure



- cyclonic wind shift existed only in the lower troposphere
- monodirectional easterly flow in the upper troposphere

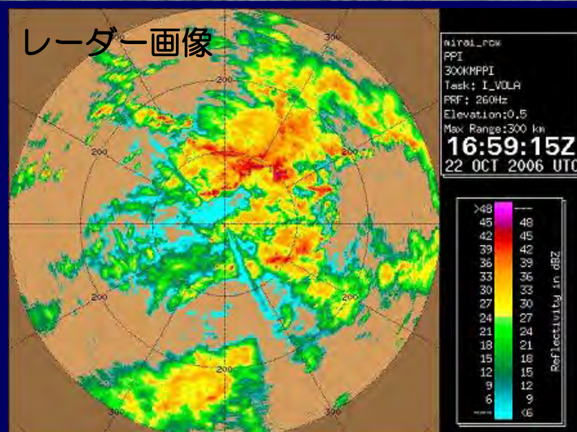
PALAU-2008 Field Experiment

PALAU-2008

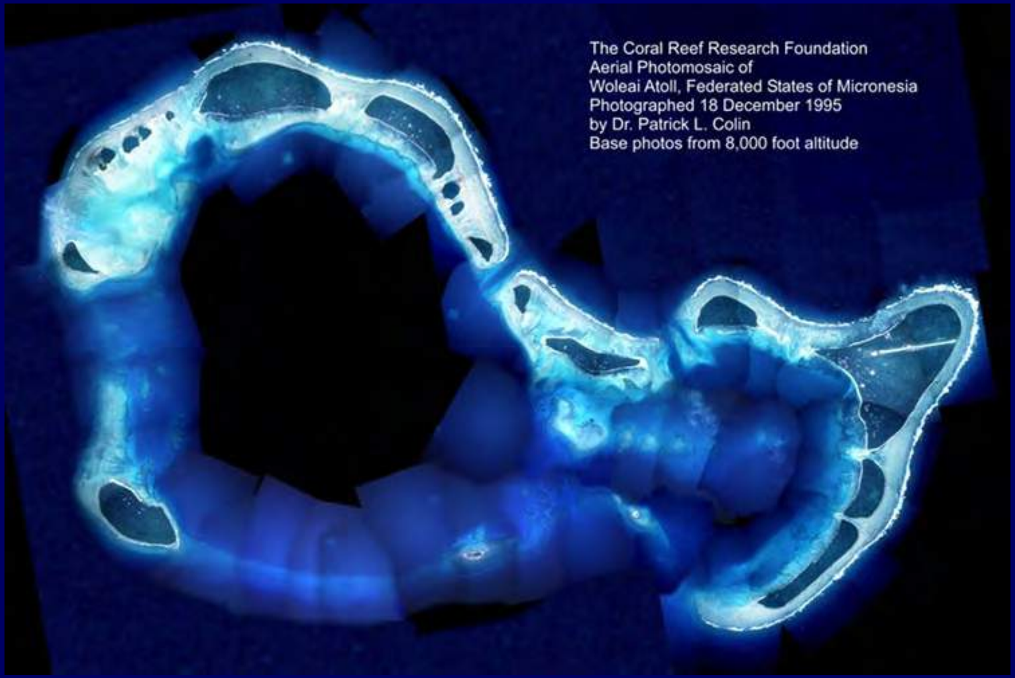


R/V MIRAI
SPECIAL UPPER-AIR OBS
TAO / TRITON BUOY
ARGO FLOAT.
(THORPEX)
(TAMEX-II)
0.8
0.4
1.2
0.8
TC FREQ. (JUNE)
[NUM/MONTH, 1951-2004]
30
20
10
0
110
120
130
140
150
160

PALAU-2008 Field Experiment



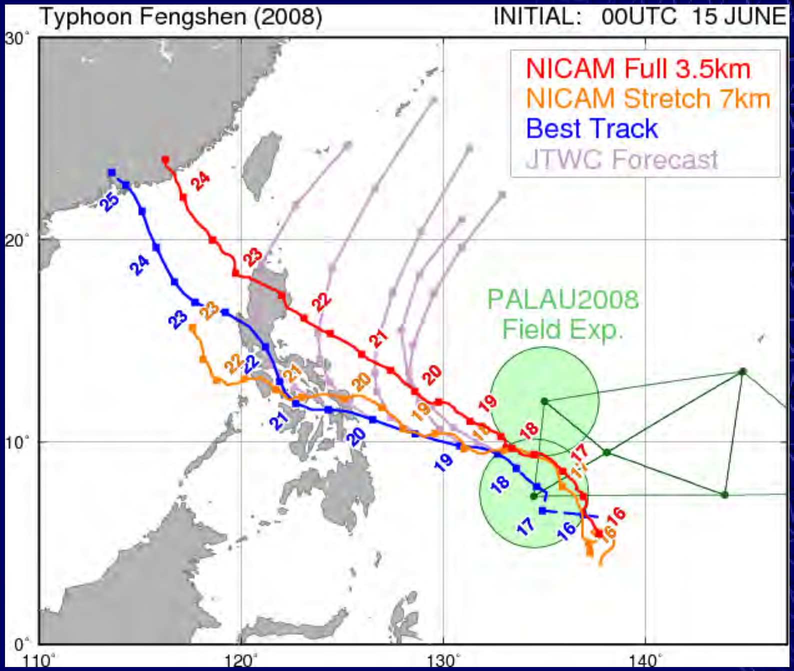
What I did during PALAU-2008 Experiment



Woleai Atoll, Micronesia

Typhoon Fengshen (2008)

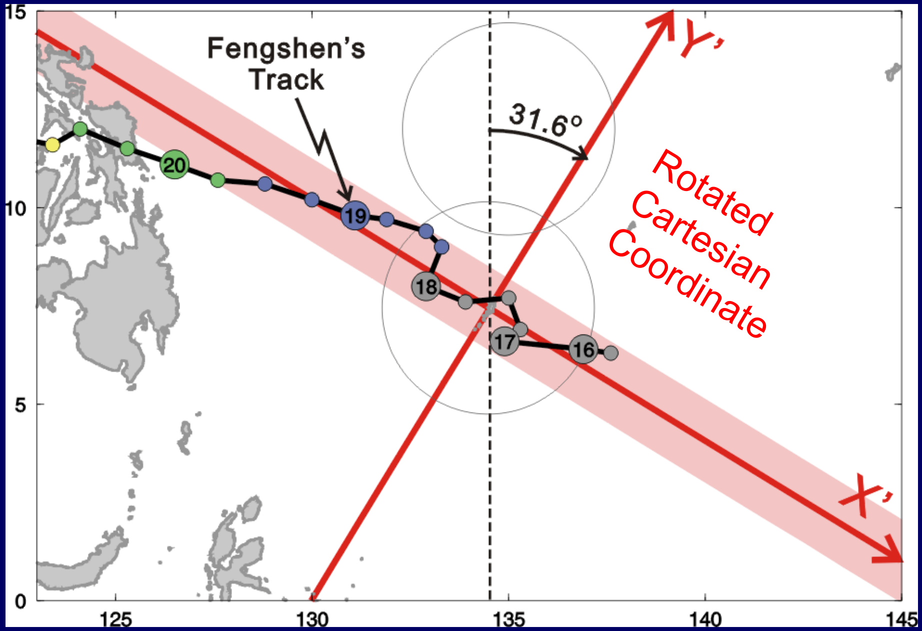
Observed and Simulated Tracks

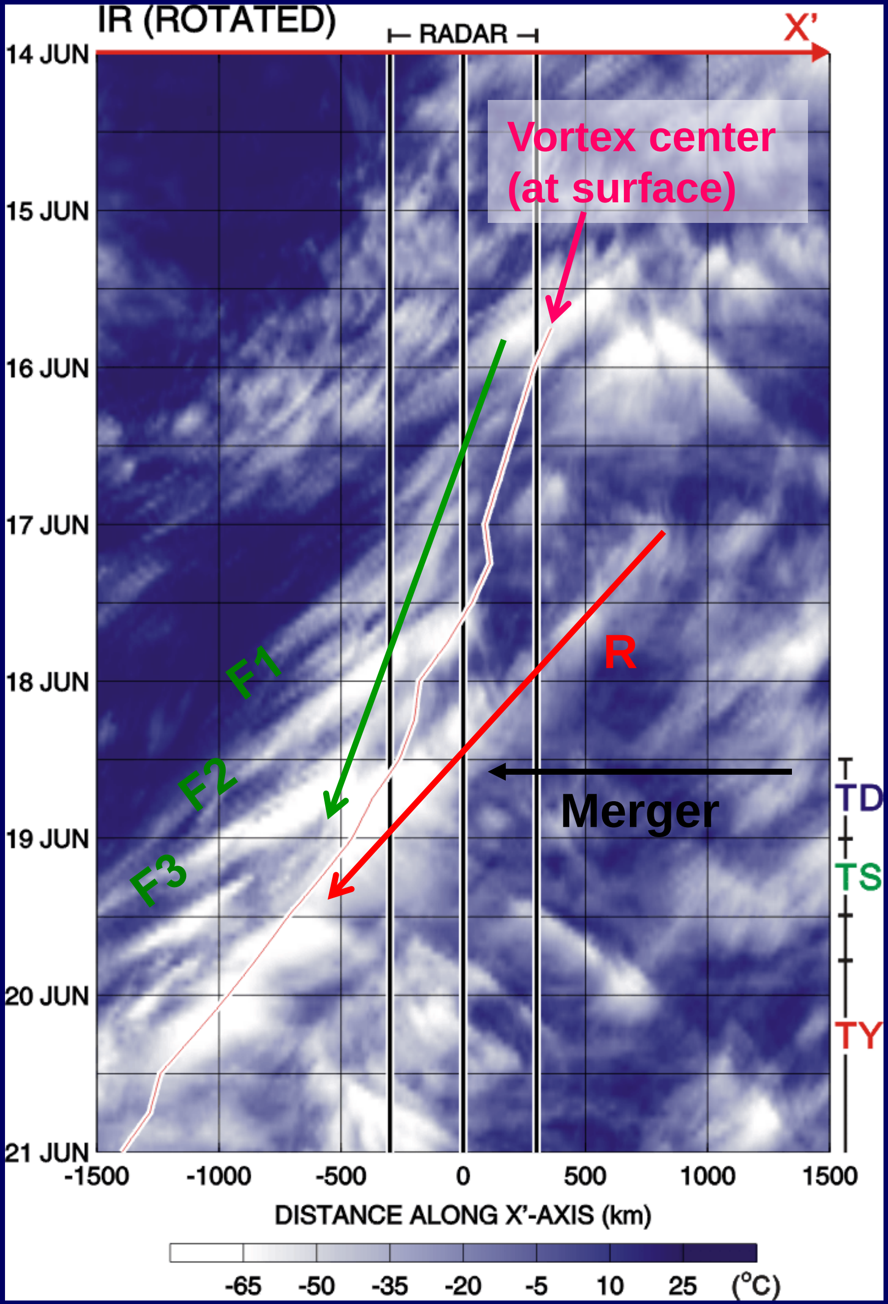


Flood in Panay Is., Philippines at 27 June (image obtained from Wikipedia)

- Category 3 typhoon, formed in the PALAU observation area
- Disasters with death of more than 1,300 people in Philippines
- Erroneous northward track before landfall, predicted by all operational centers (JTWC, JMA, ECMWF etc.)

Merger of Cloud Systems





Merger of clouds system before the Fengshen's upgrade into TS/TY

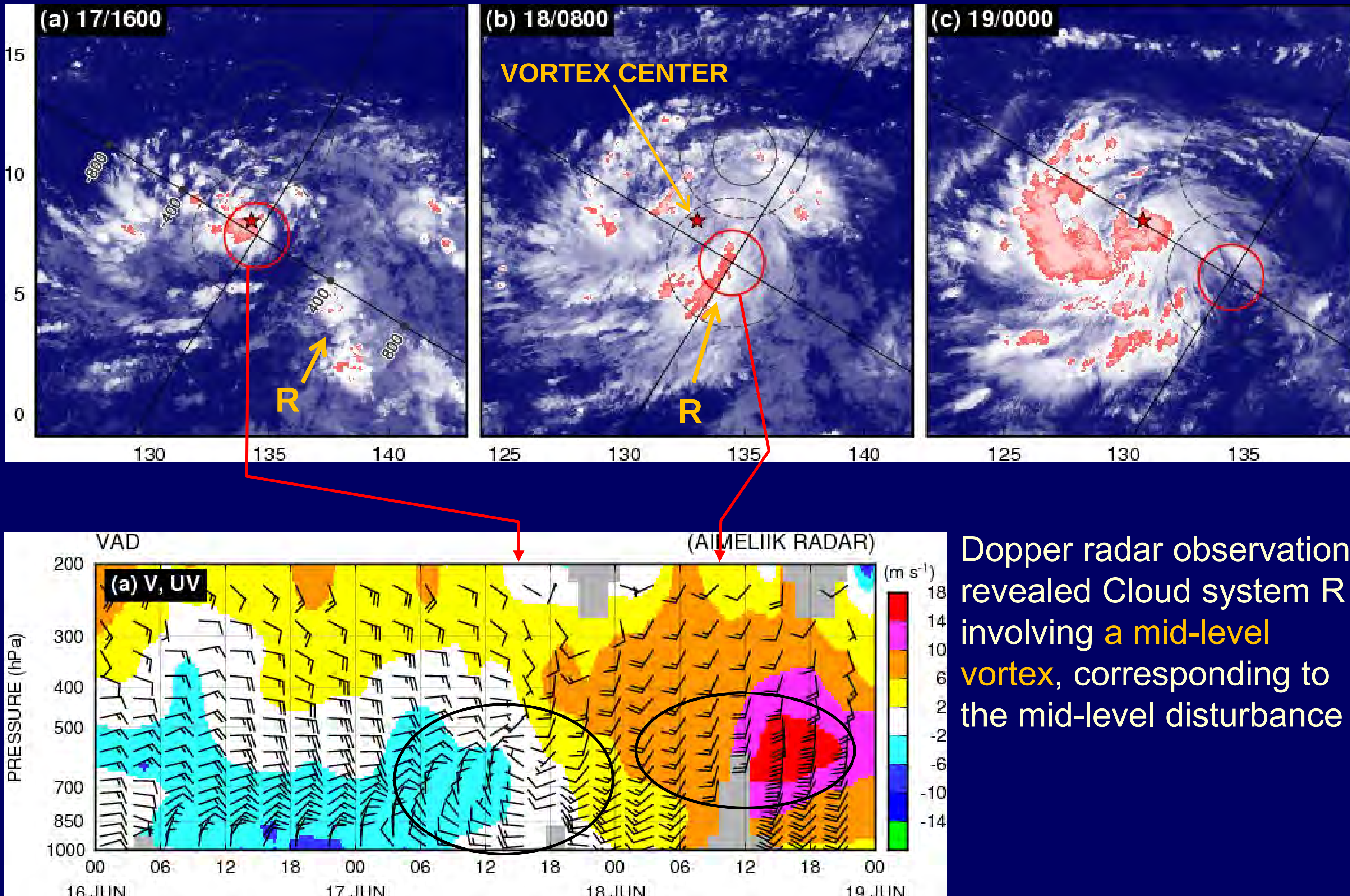
- Cloud systems F1-F3:

  successive development near the slow-moving surface vortex

- Cloud system R:

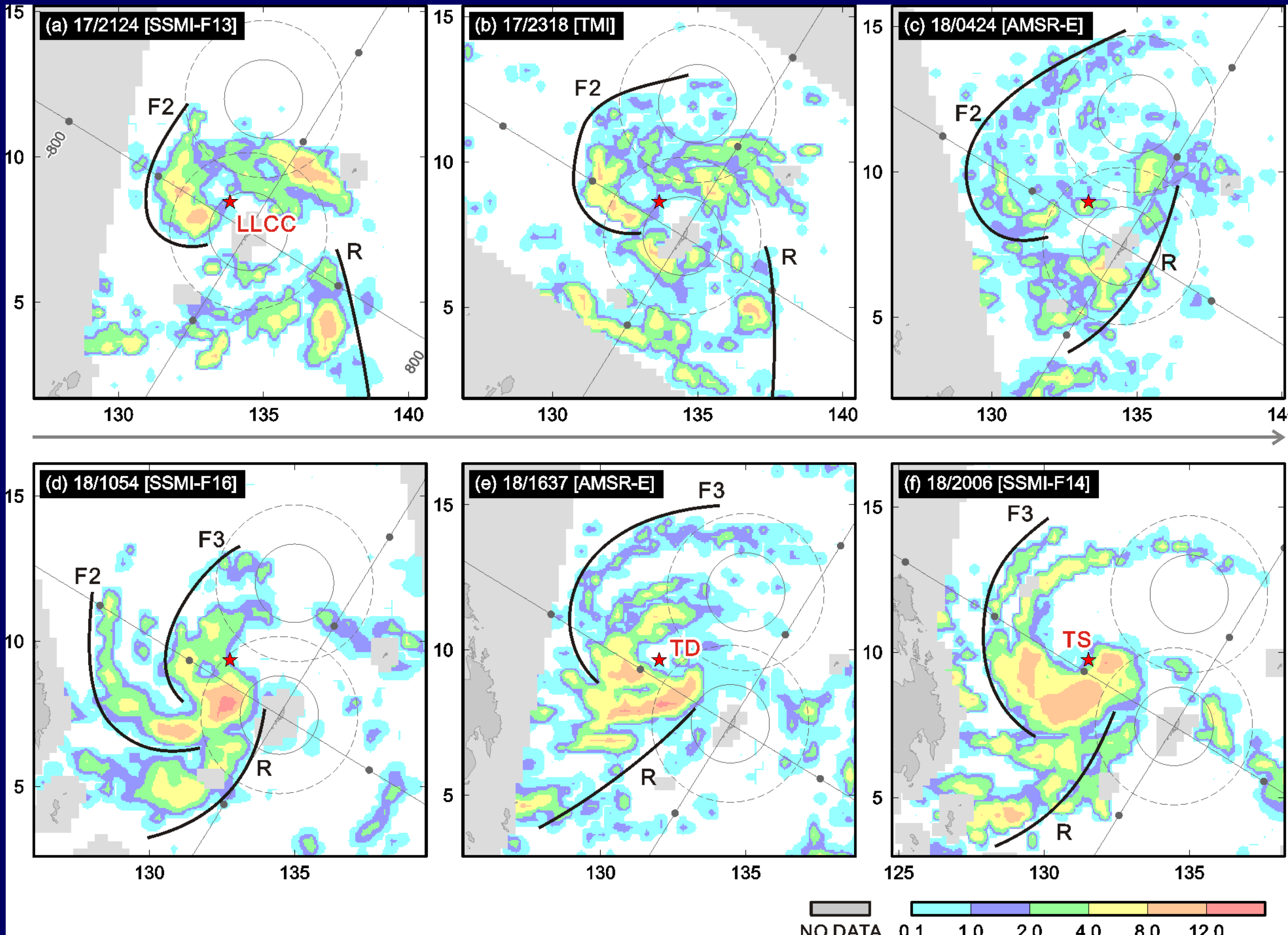
  constant propagation speed (7 m/s) before and after the merger

Cloud Distribution and Vertical Wind Profile



Dopper radar observation revealed Cloud system R involving a mid-level vortex, corresponding to the mid-level disturbance

Rainfall Distributions



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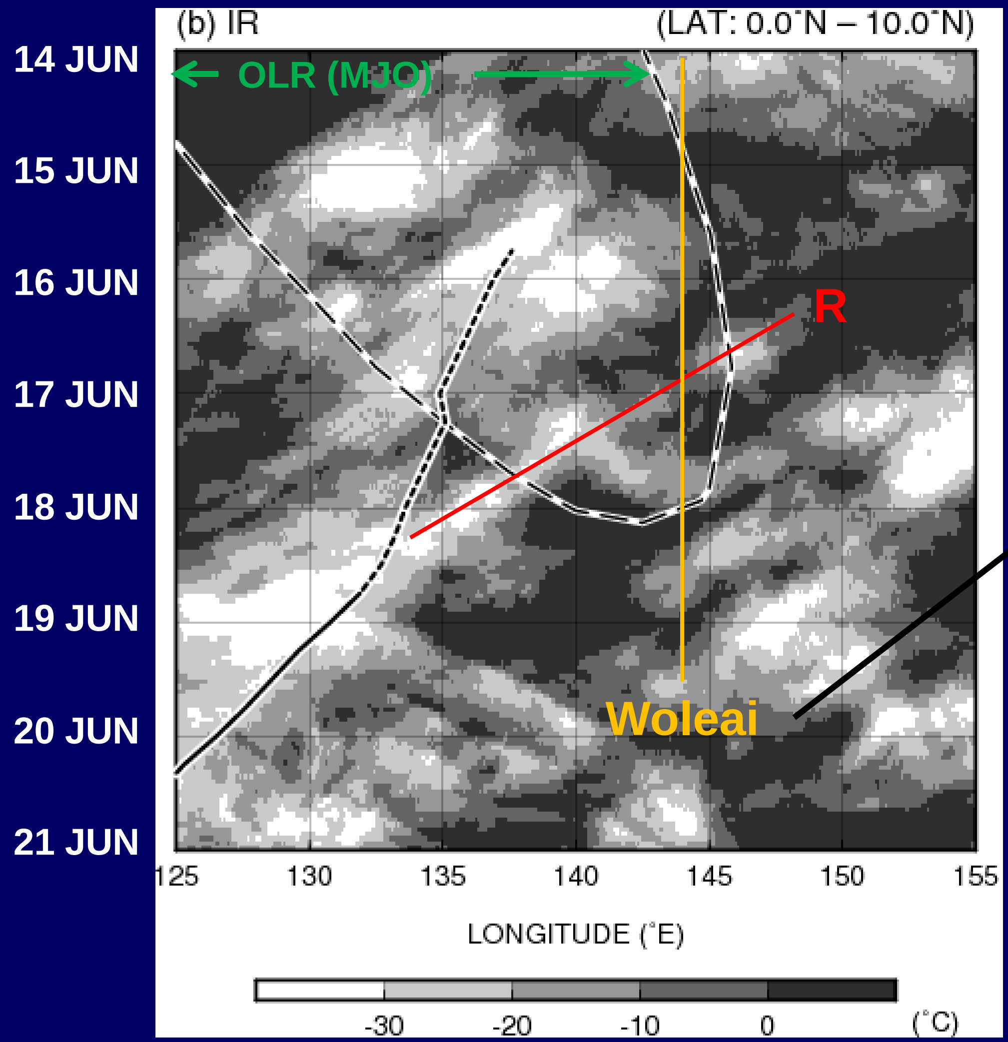
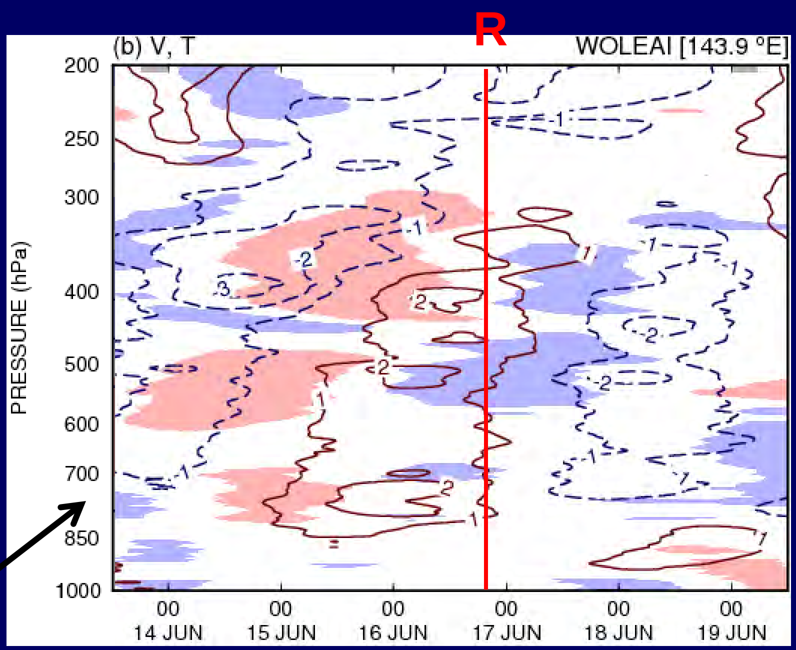


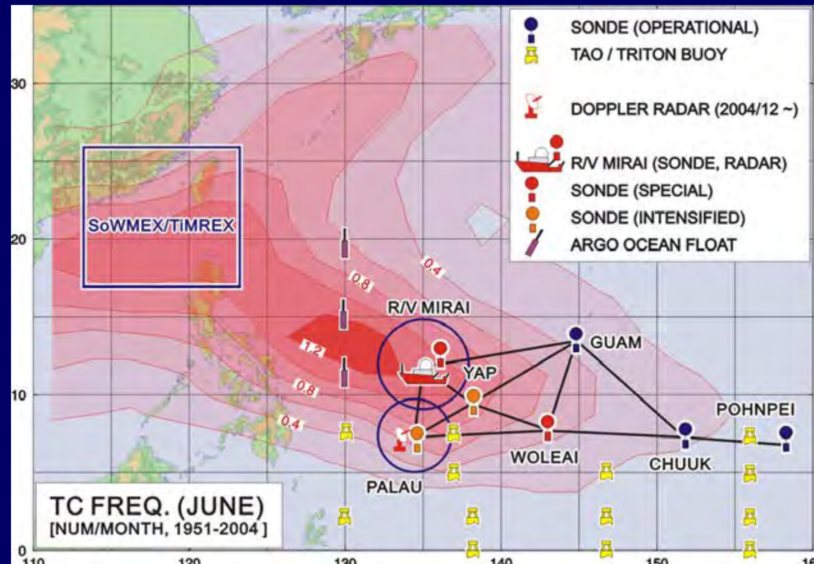


Cloud system R corresponds to a westward-propagating disturbance, developing in the convectively-active area of MJO.

NICAM Simulation of Fengshen

Vortex Superposition,
as a Key Process of TC Genesis

JAMSTEC's Research on Typhoon Formation



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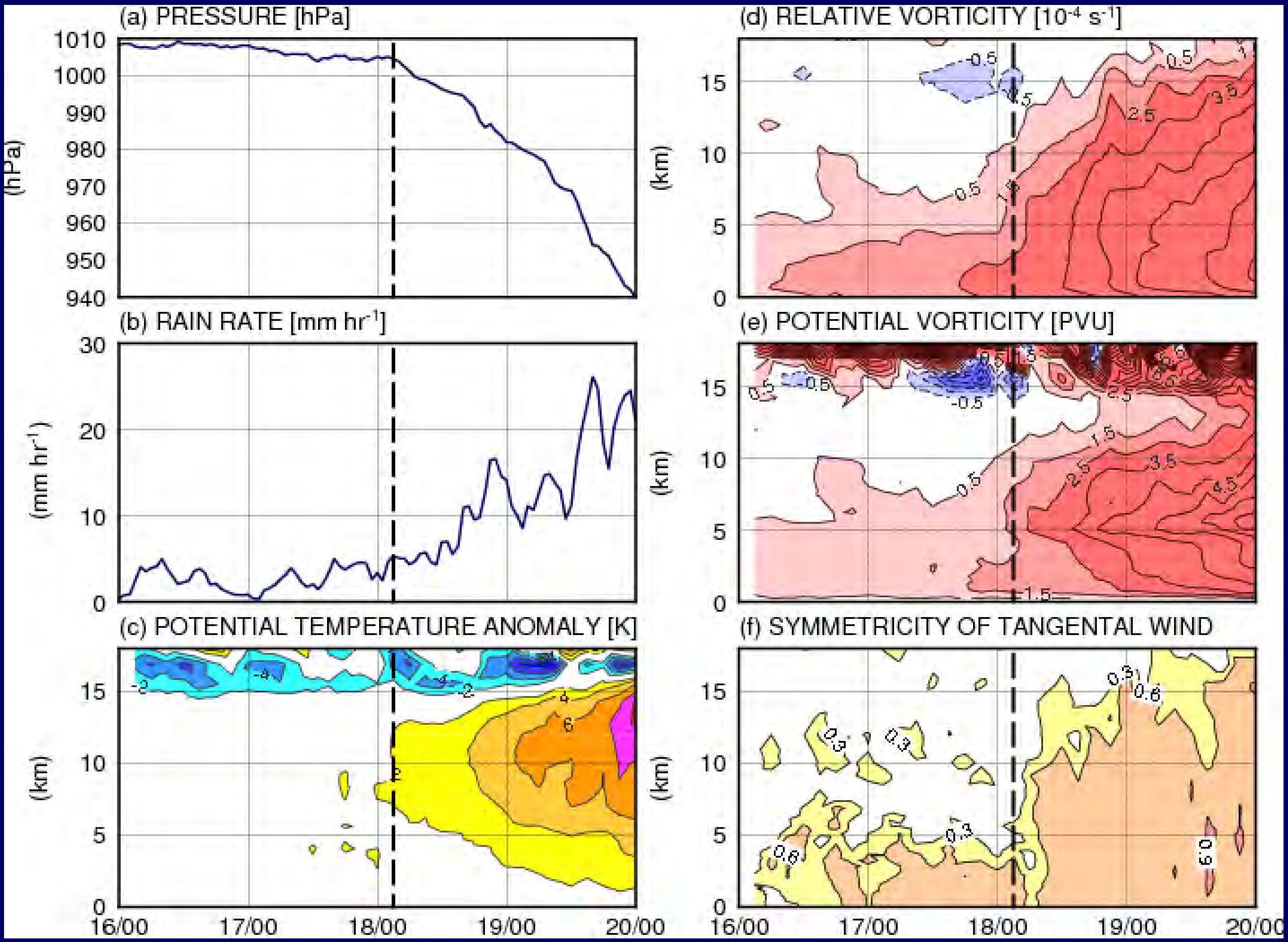
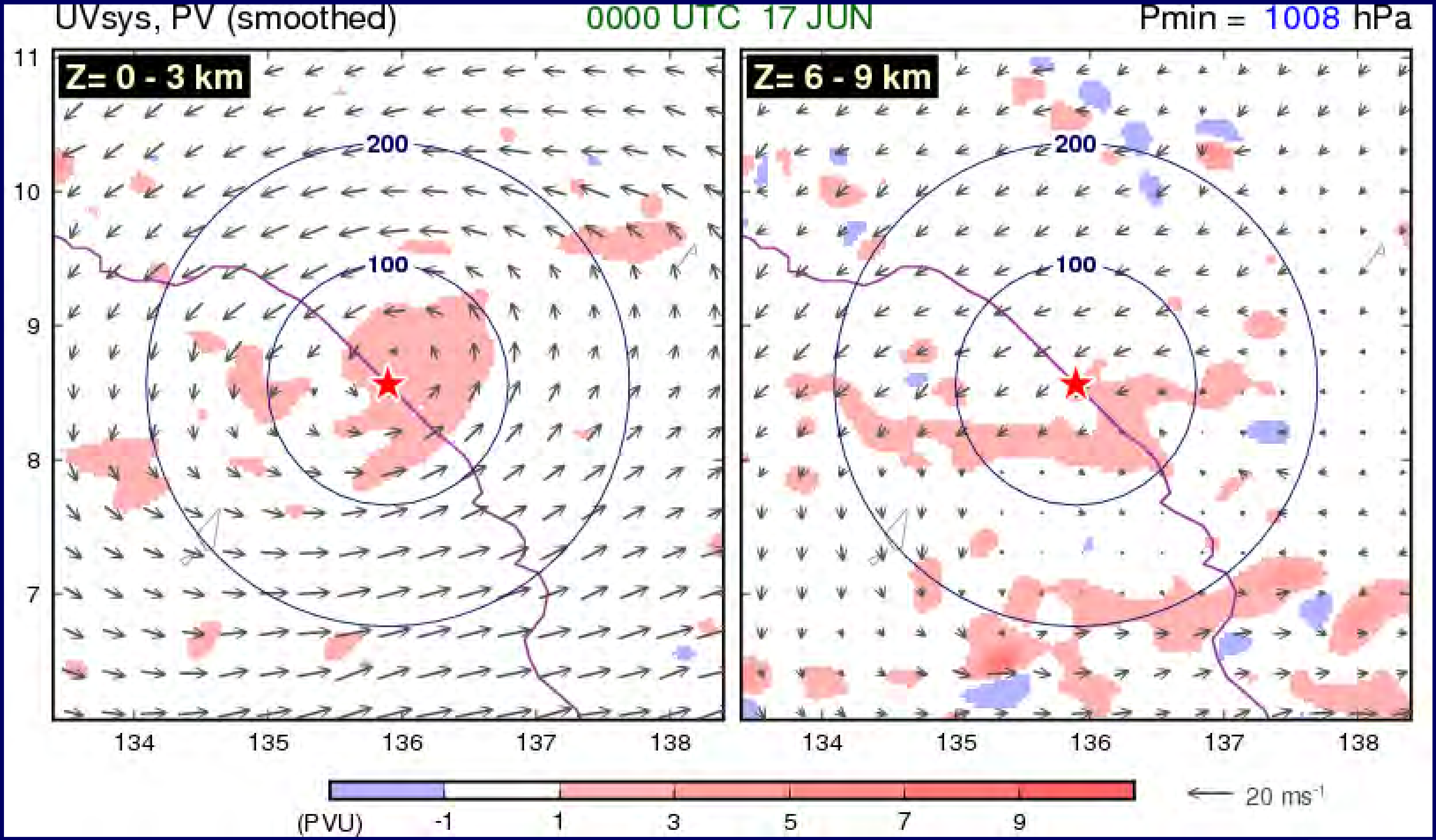
- To understand the key process of typhoon formation, under influences of synoptic- and large-scale waves and disturbances (e.g., MJO)

Simulated Overall Evolution (R<100km)

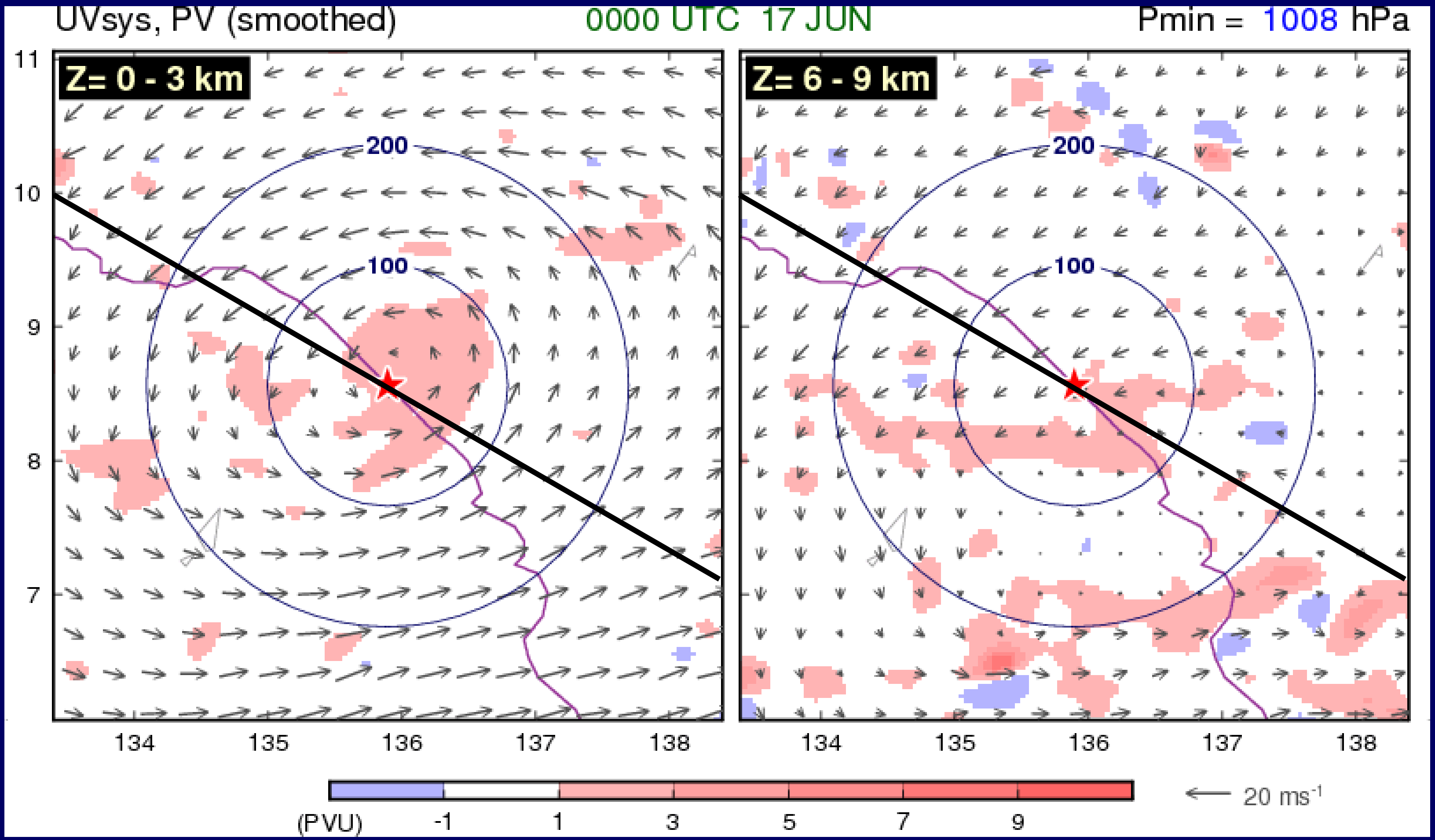


Formation of a deep symmetric vortex with warm core, in concurrence with pressure drop, after 0300 UTC 18 June

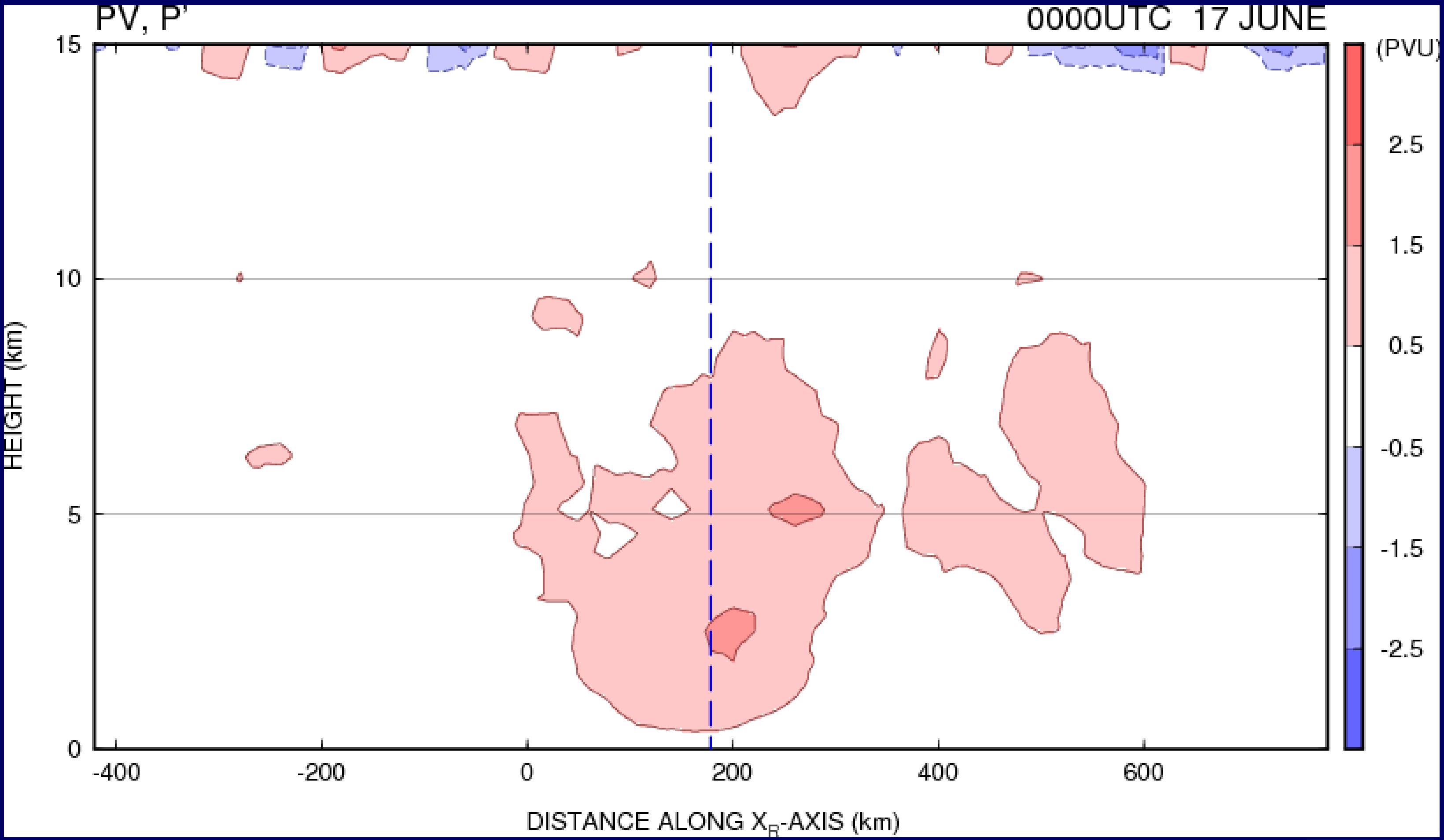
Potential Vorticity (animation)



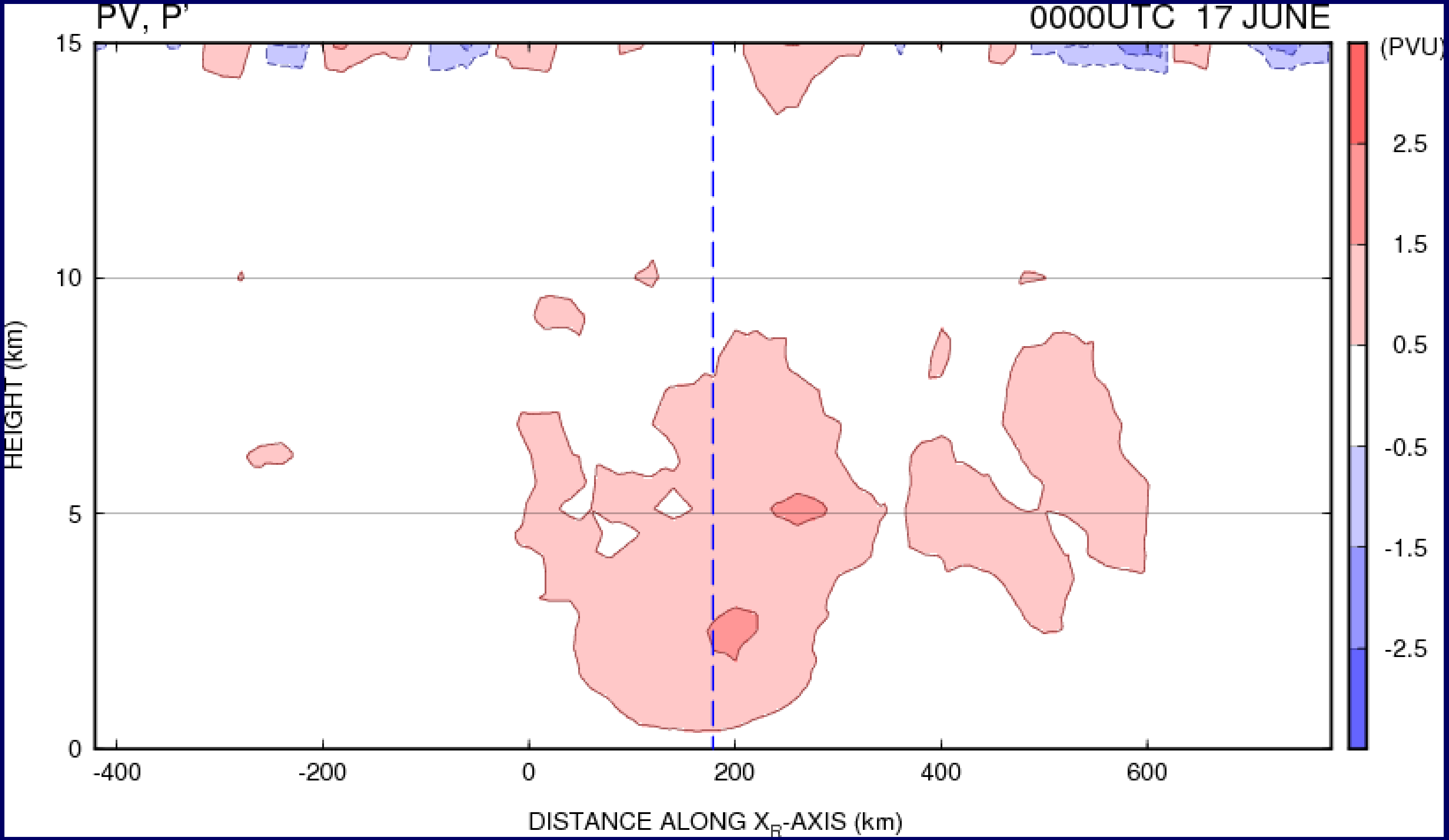
Potential Vorticity (animation)



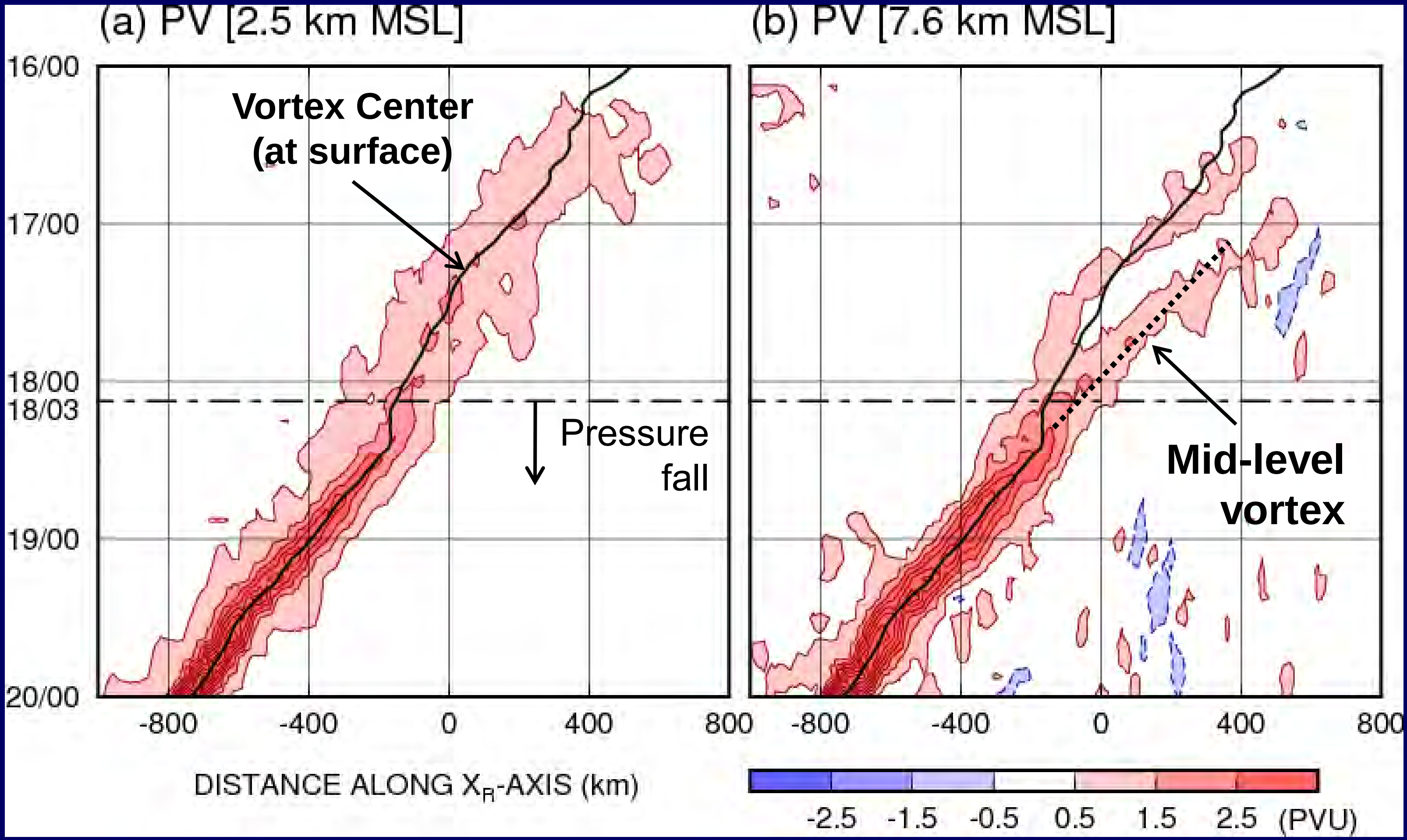
Vertical Distribution of PV and P' (animation)



Vertical Distribution of PV and P' (animation)



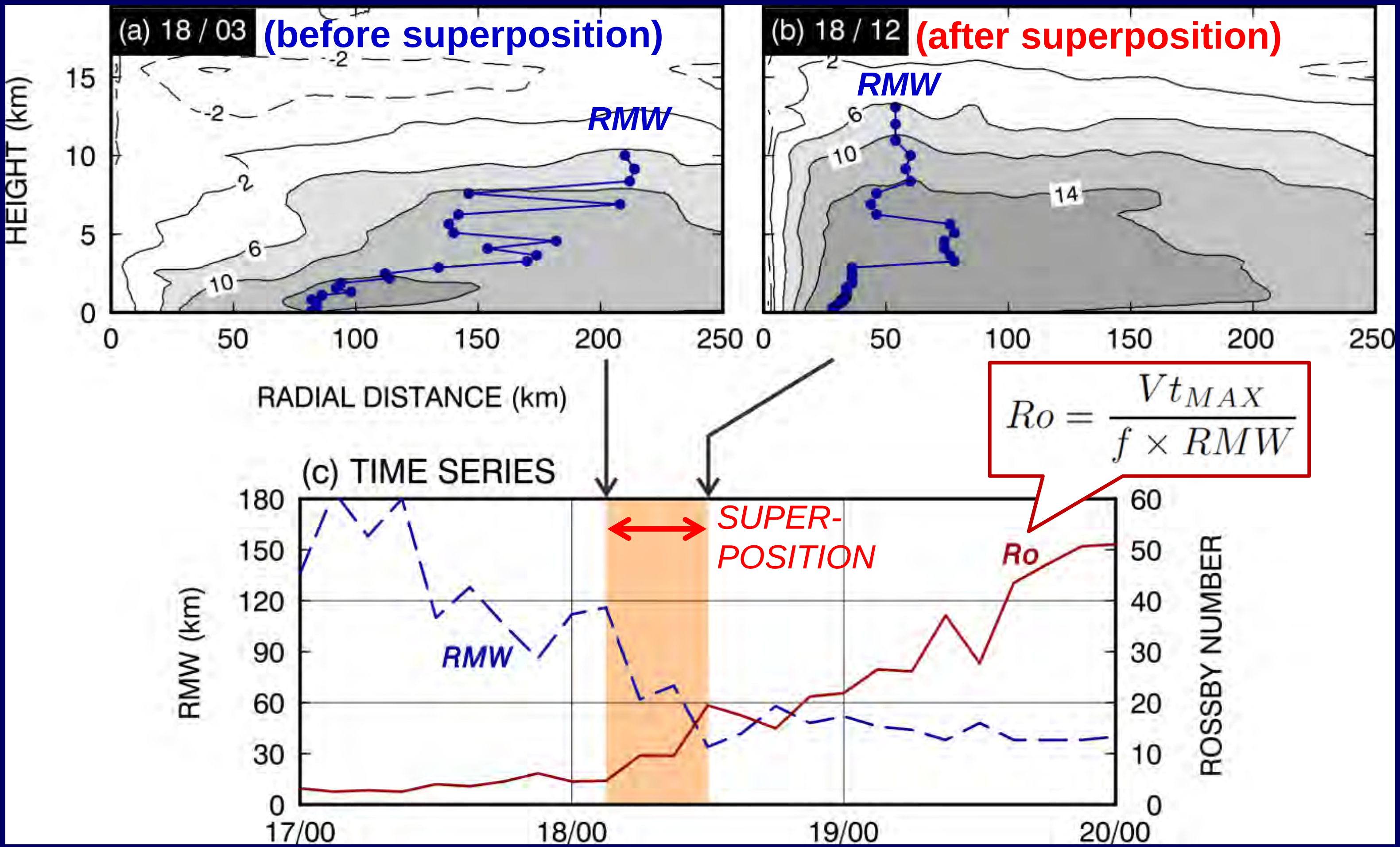
Simulated Vortex Superposition



Pressure began to fall just after a mid-tropospheric positive vorticity area superposed upon the surface initial vortex.

Change in the Vortex Structure

Tangential winds (azimuthally averaged)

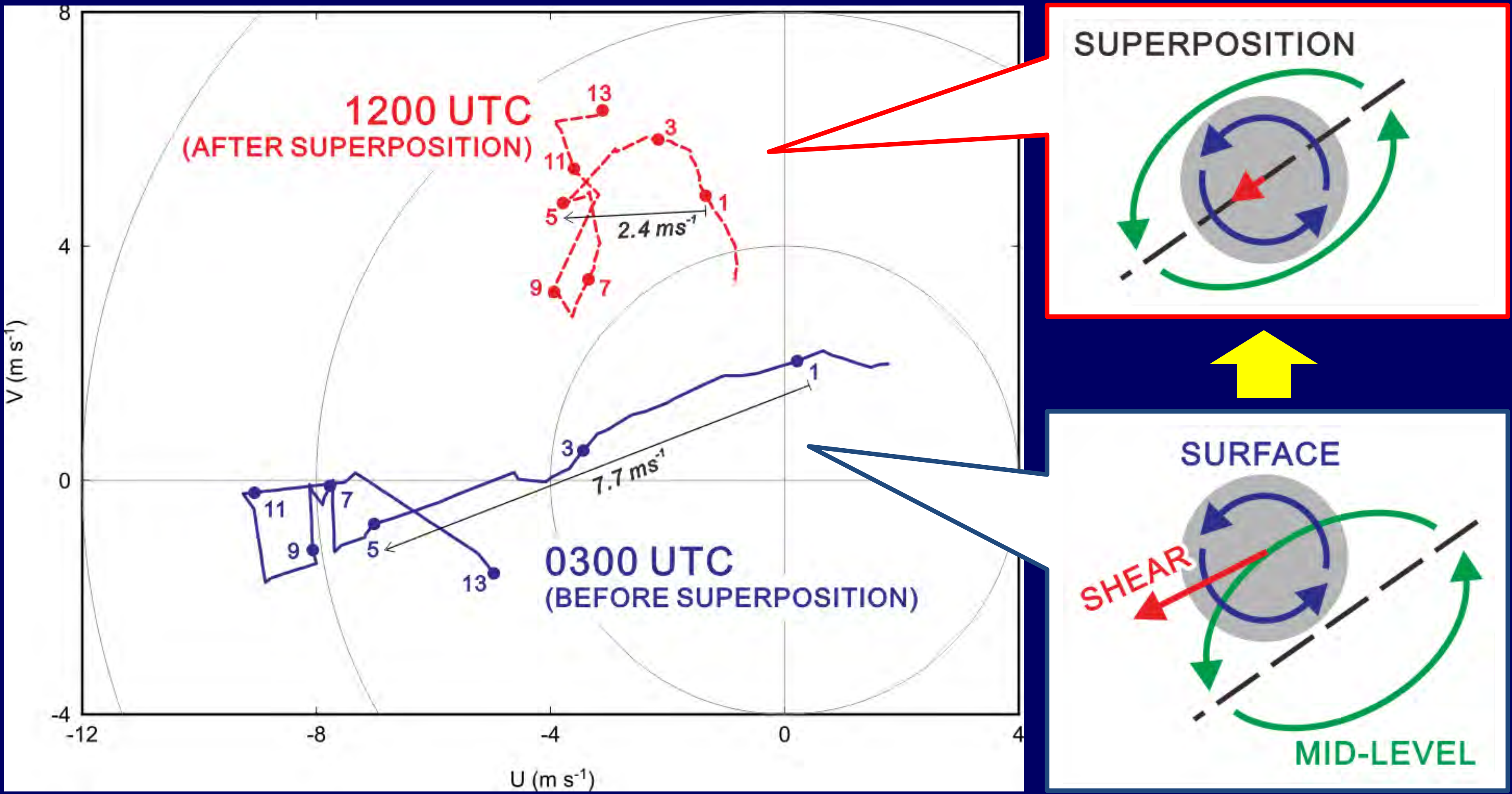


$$Ro = \frac{Vt_{MAX}}{f \times RMW}$$

Dynamical balance of the inner circulation changed from gradient wind (*Ro*~1) to cyclostrophic (*Ro*>>1) after the vortex superposition

Decrease in Vertical Wind Shear

Hodograph of winds (averaged within R<100 km)

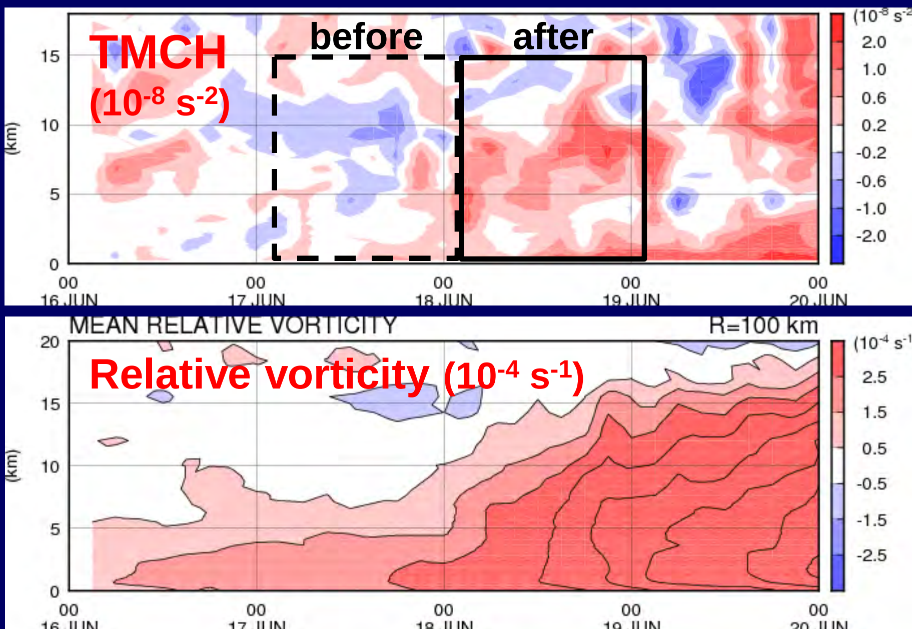


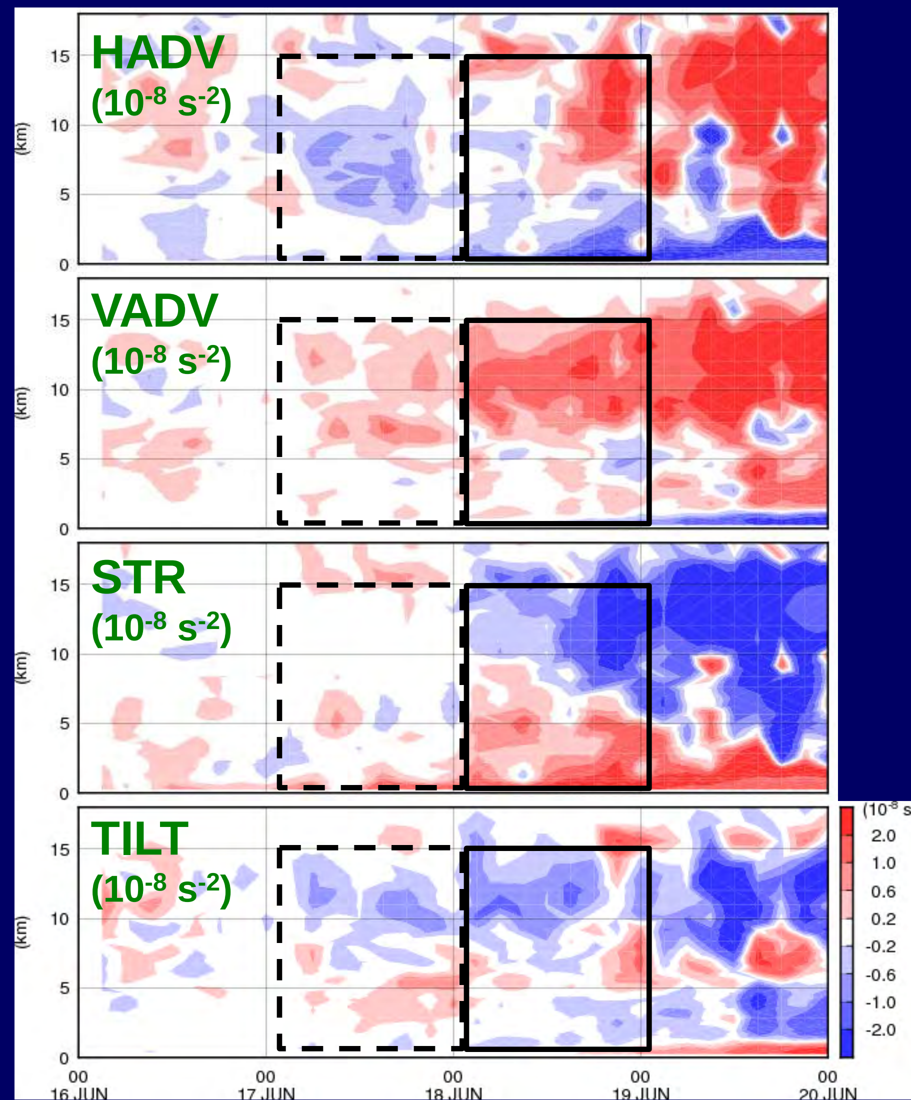
Mean vertical shear above the surface vortex reduced dramatically due to the alignment of surface and mid-level vortices

Vorticity budget analysis

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

TMCH HADV VADV COR STR TILT

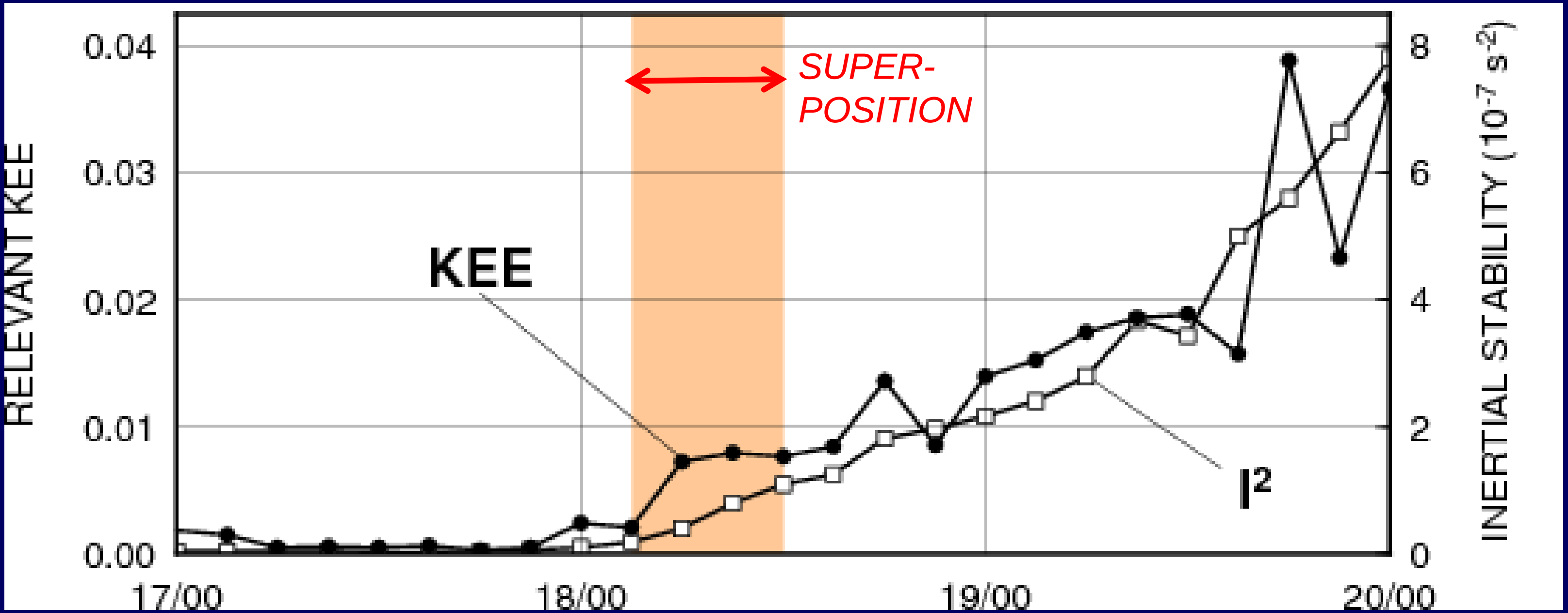




- Negative effect of horizontal advection [HADV] before superposition.
- Elimination of negative HADV and increase in stretching [STR] after superposition (bottom-up building).

Increase in the Kinetic Energy Efficiency (KEE)

Inertial stabitity, KEE
(R<100km, Z:6-9 km)



Volume-Averaged Kinematic energy efficiency (KEE):

$$KEE = \frac{Ks}{Q}$$

Nolan et al. (2007)

$$I^2 = (f + \frac{\partial rv}{r\partial r})(f + \frac{2v}{r})$$

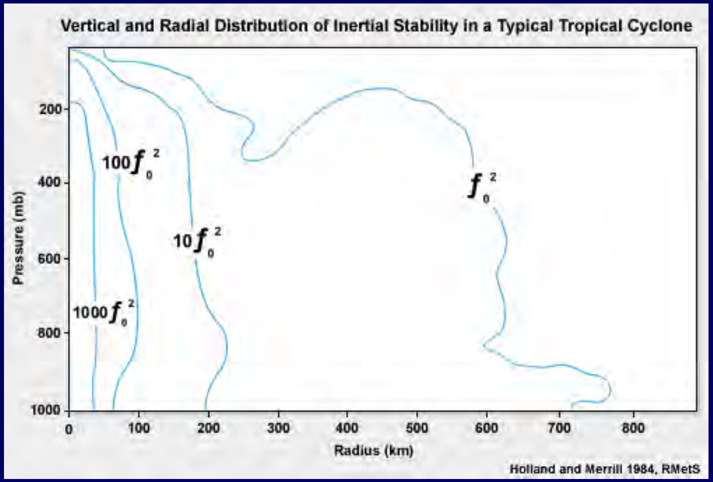
Inertial stability and KEE increased after the upright vortex formed.

Inertial Stability

(Schubert and Hack 1982, JAS)

$$I^2 = (f + \frac{\partial rv}{r\partial r})(f + \frac{2v}{r})$$

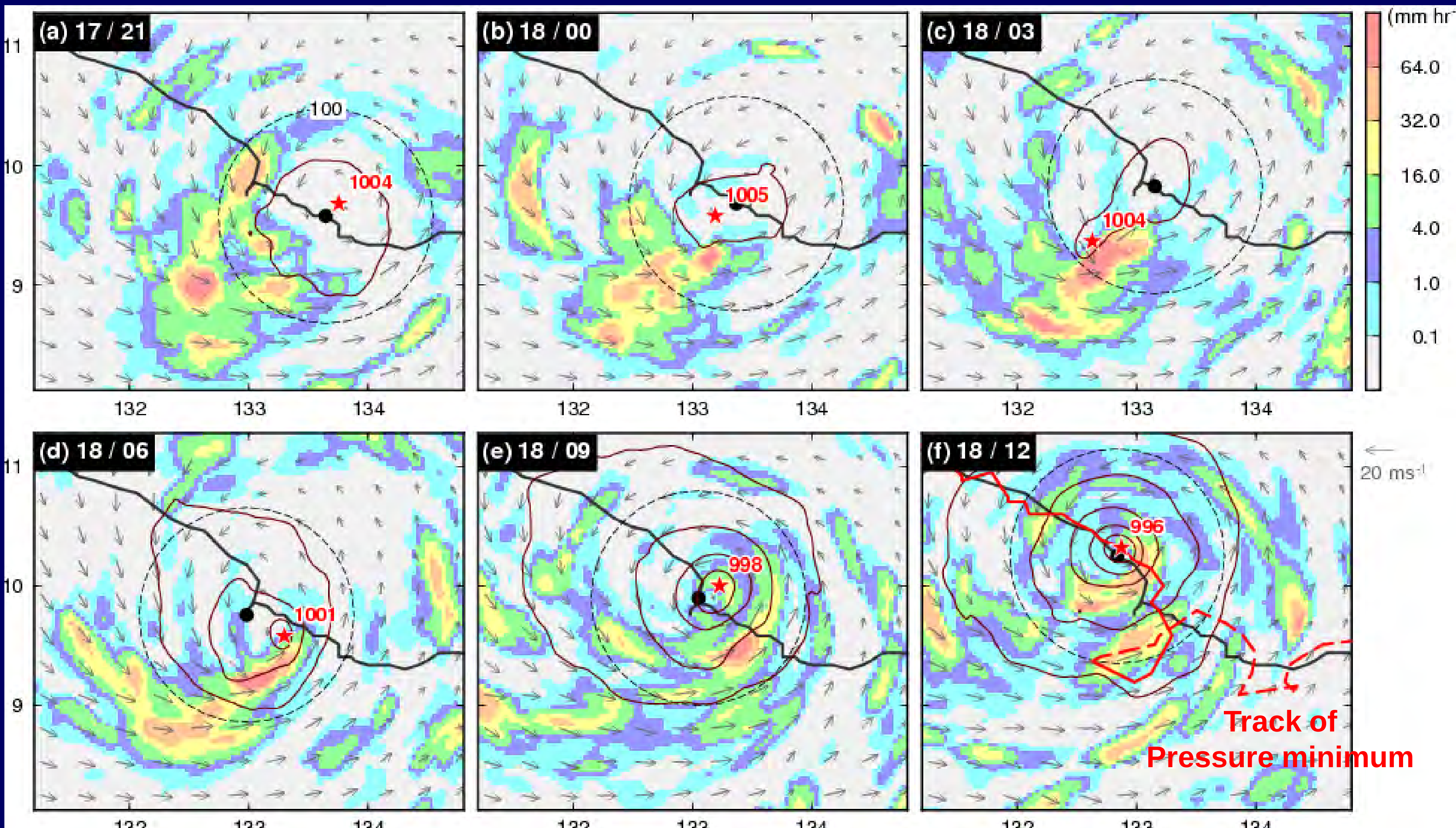
f: Coriolis parameter
r: radial distance
v: tangential wind component



- A measure of the resistance to the movement of air parcels in the radial-vertical (*r, z*) plane
- Increased inertial stability means reduced adiabatic cooling ($N^2 w$) and more efficient diabatic warming of the air due to convection.
- Large value in tropical cyclone, more than [100 * f^2] in the inner core (Holland and Merrill 1984)
- $f^2 = 6.4 * 10^{-10}$ s^{-1} (at 10^{o}N)

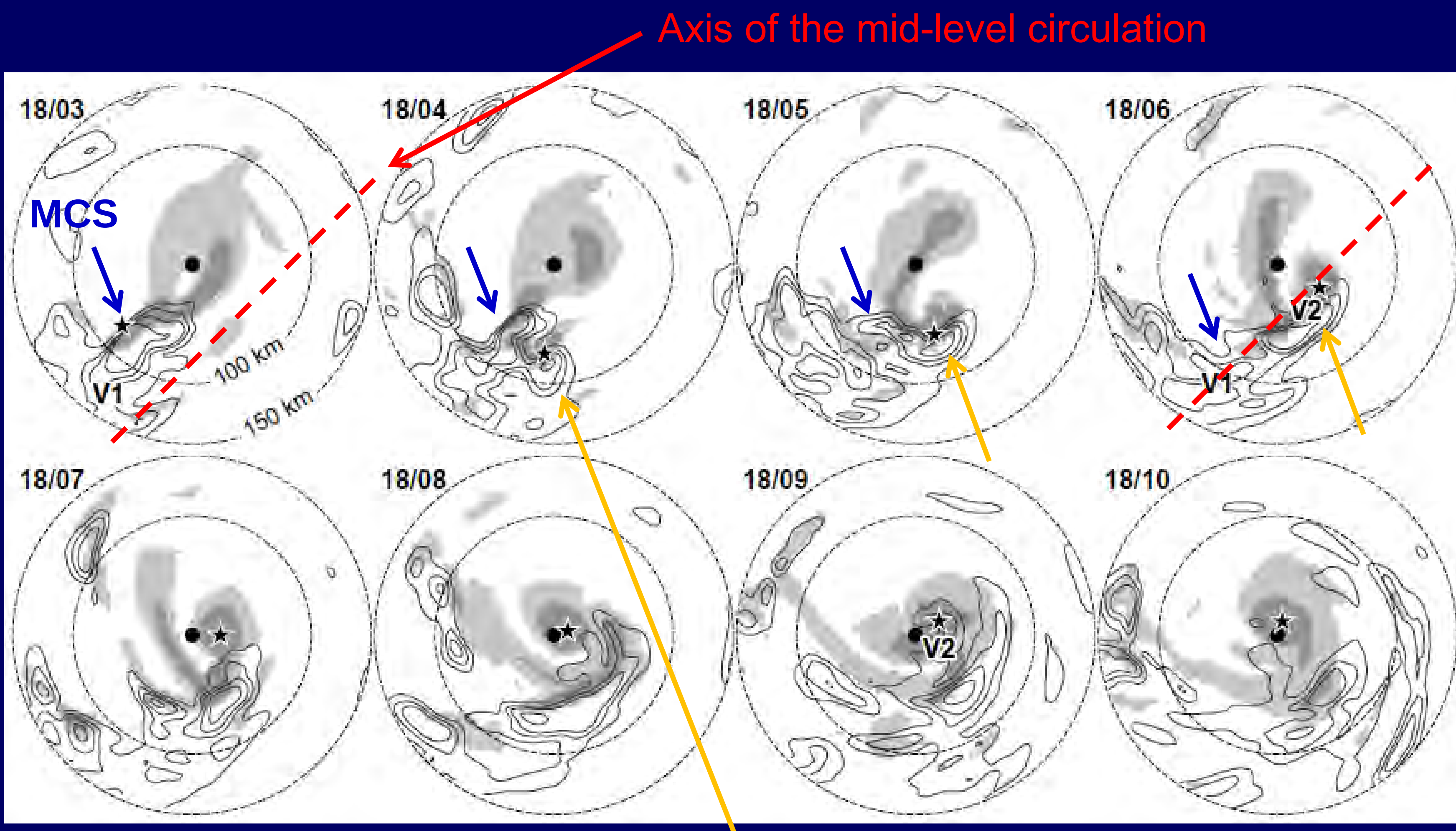
Pressure and Rain Rate at Surface

(in a resting frame)



The pressure drop initially took place near the MCS, and its location moved to the vortex center as the MCS transformed into a partial eyewall.

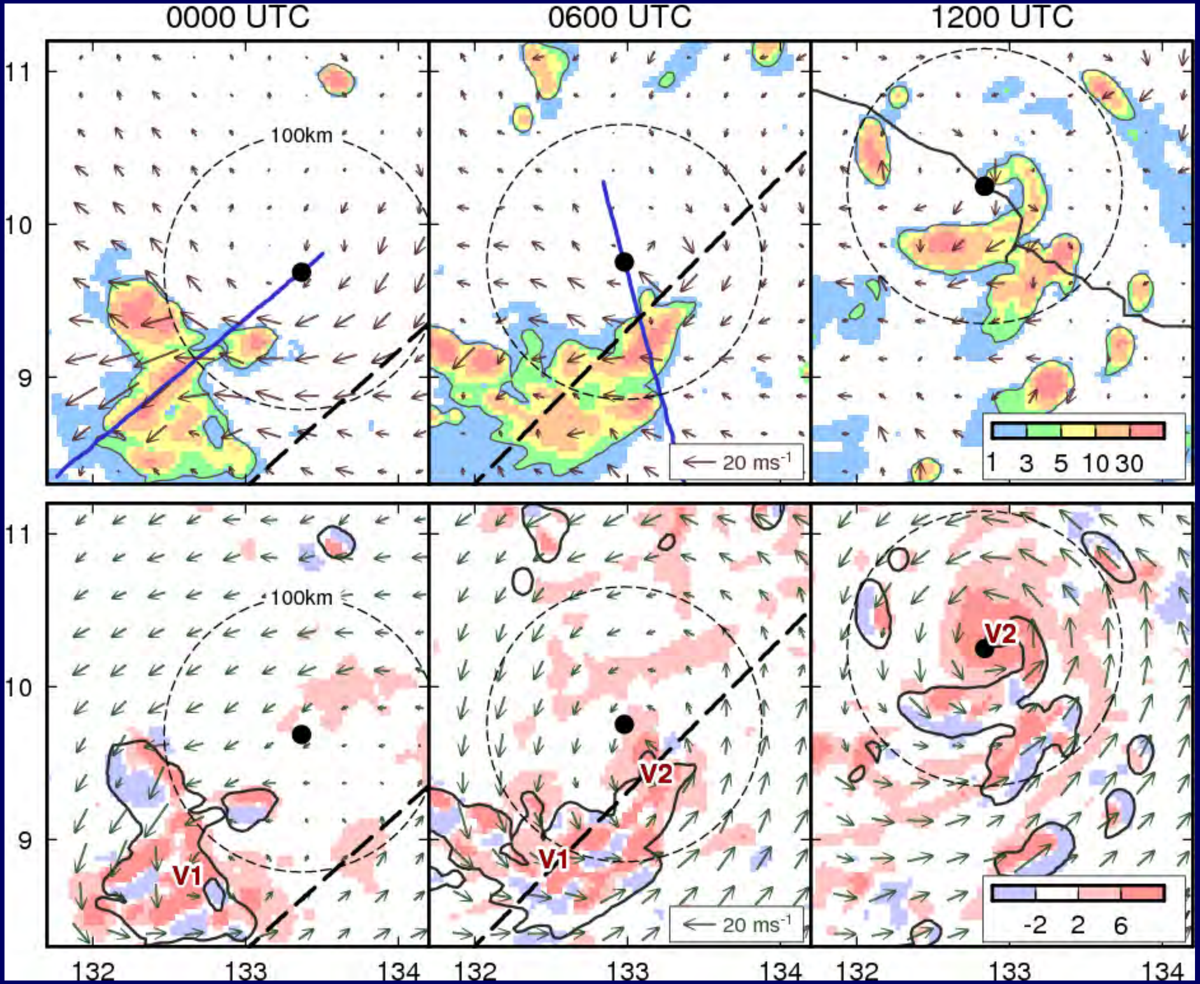
Hourly Distribution (Vorticity, Rainfall)



A new convective element, possessing mesoscale vortex V2, developed in the mid-level synoptic-scale circulation, and subsequently transformed into a partial eyewall.

Aggregation of VHT-induced vorticity patches is hardly identified.

Mesoscale Processes during Superposition



Hydrometeor mixing ratio (7.5 km)

Shear vector (1.5 – 7.5 km)

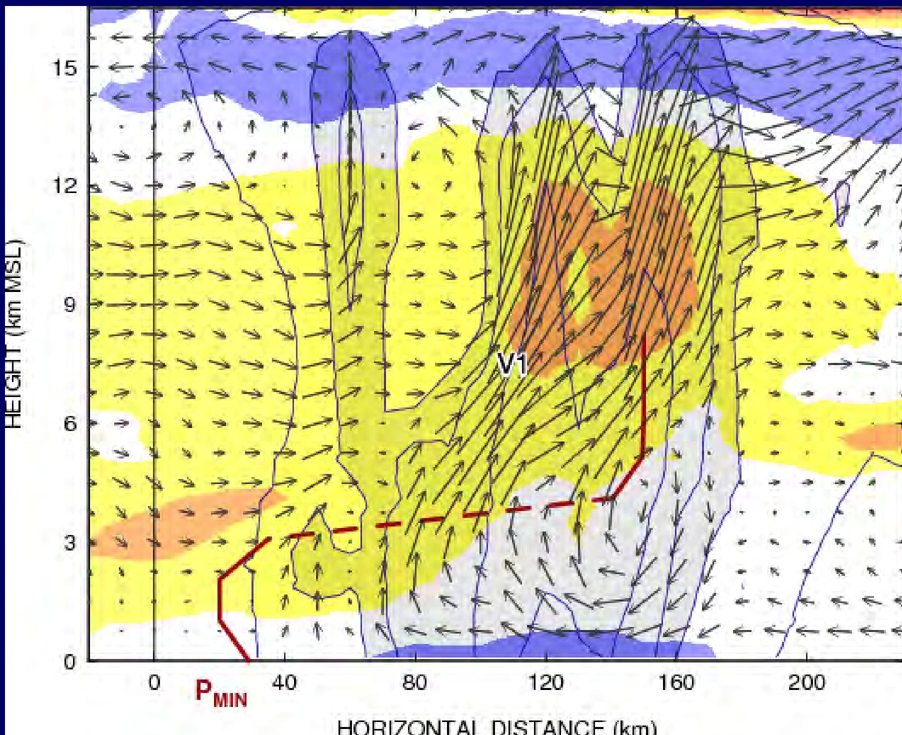
PV (7.5 km)

Relative winds (7.5 km)

- The environment of V1 is characterized by strong vertical shear
- V2 forms in an envoriment with weak vertical shear

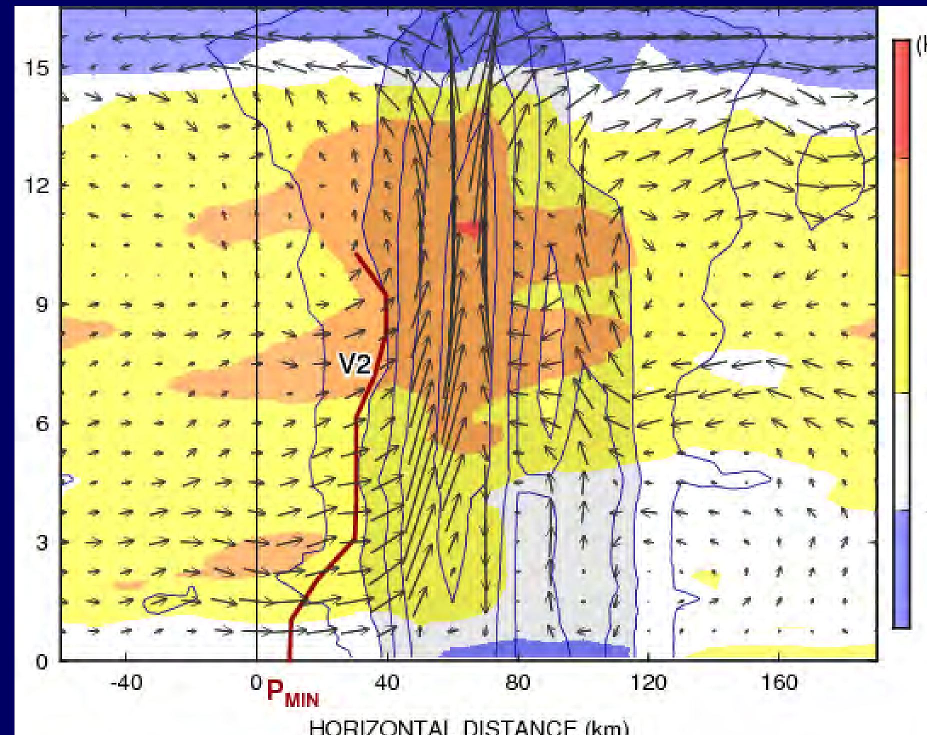
Difference in the Vertical Structure

The Decaying MCS



- Significantly tilted outward with height, due to vertical shear
- Upper-level warm anomaly is more than 100 km apart from the surface vortex center

The Developing Partial Eyewall



- Upright structure
- Pressure minimum with warm anomaly in the rim of convective updraft

→ warm-core development under hydrostatic adjustment

3 Hour Before Superposition (18/00)

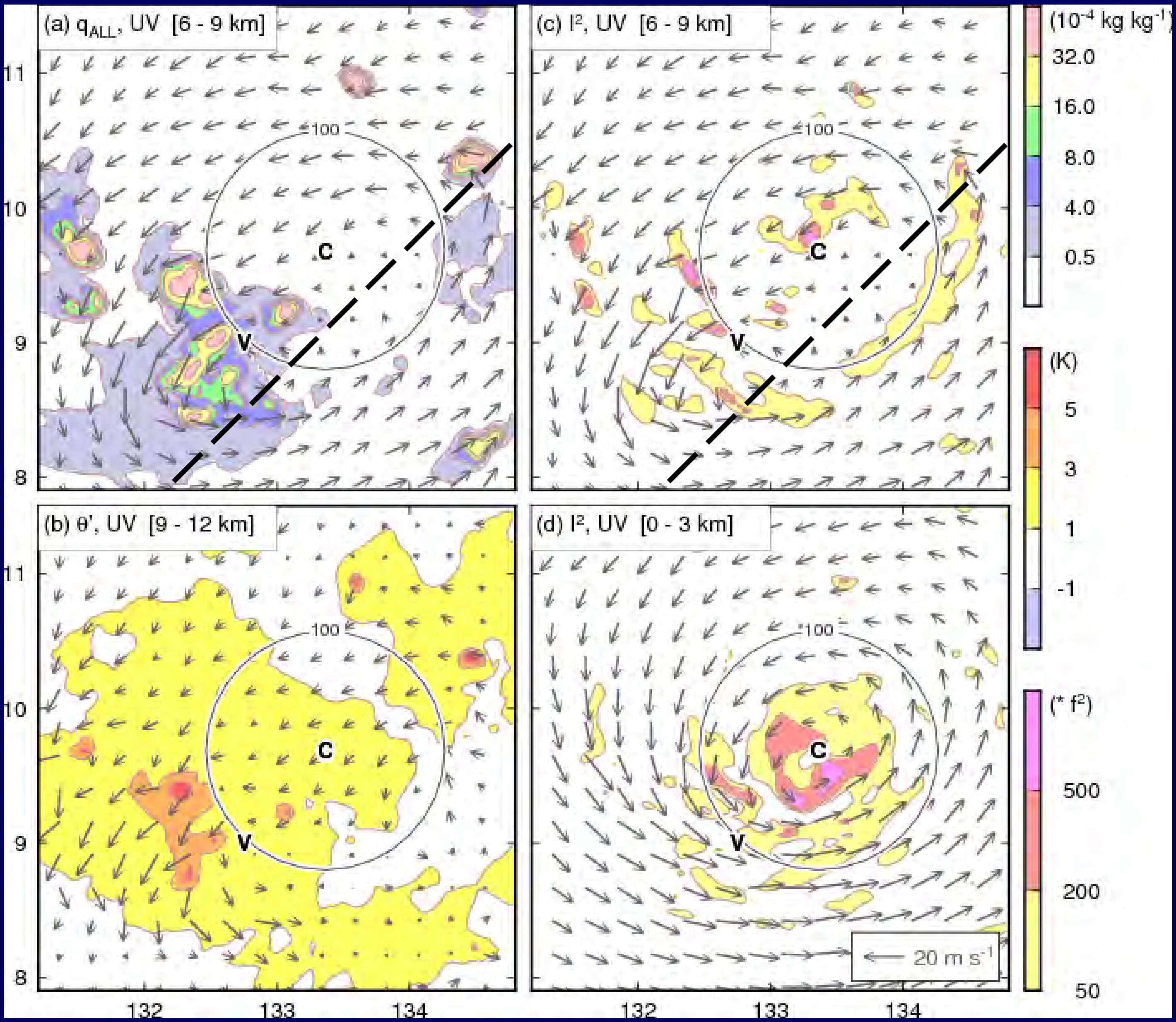
A remaining unidirectional flow

Tilted vortex axis

Weak inertial stability

Outward movement of MCS due to vertical wind shear

Displacement of an MCS-induced warm core (MCV)



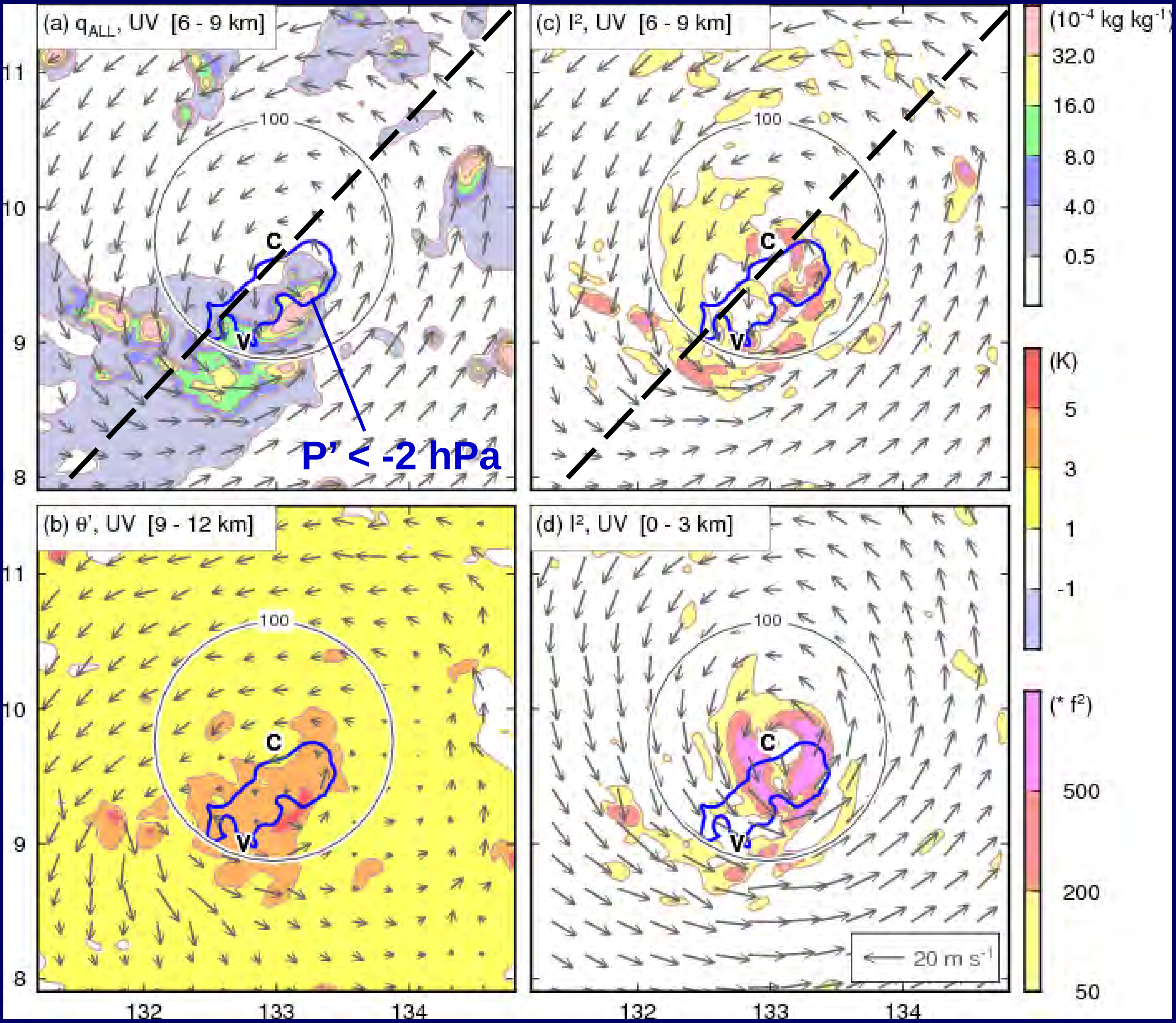
3 Hour After Superposition (18/06)

Upright axis of vortex

Increased inertial stability (> 100 * f^2)

Formation of a protected area

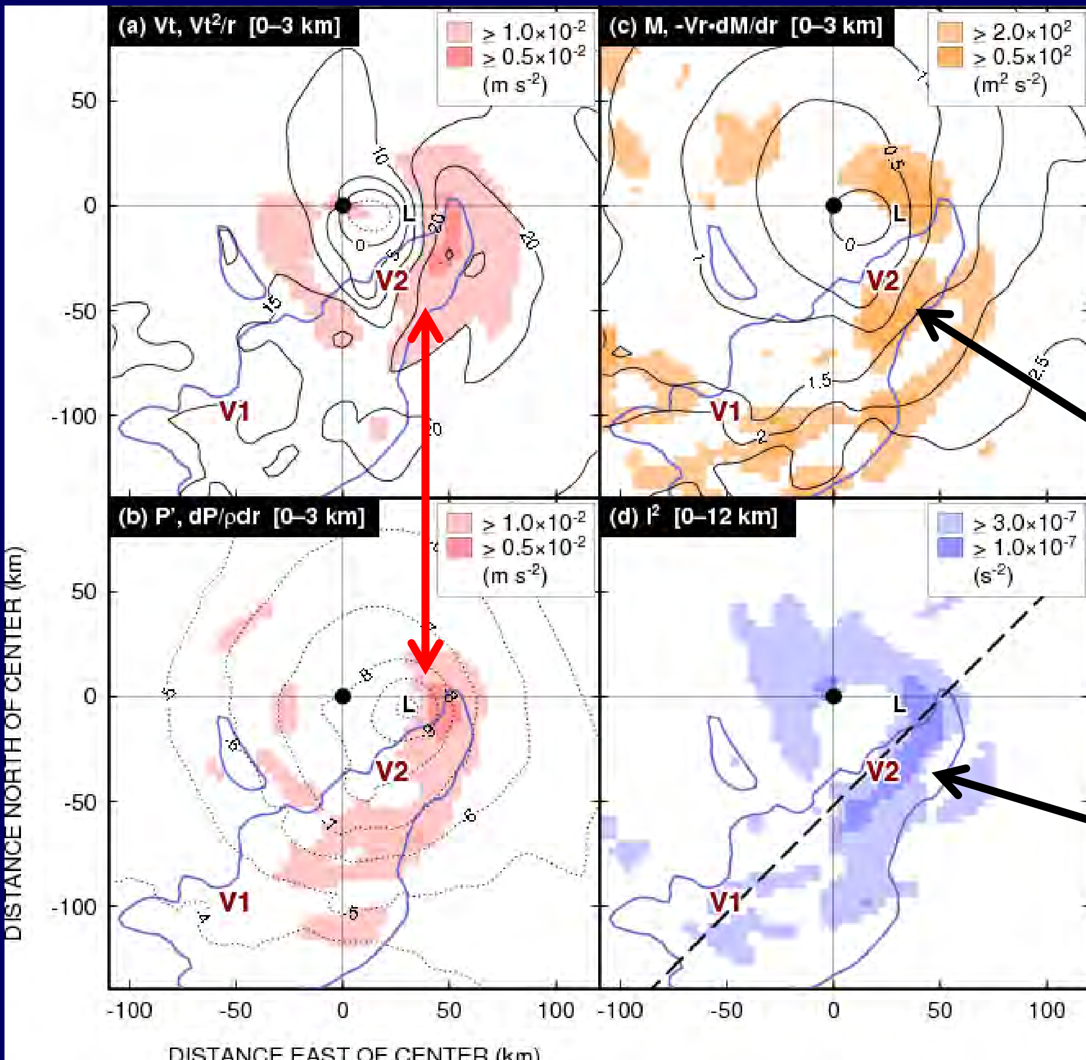
Evolution of a partial eyewall with warm core and low pressure near the surface vortex center



発達する壁雲の力学的特徴

接線風速（コンター） 遠心力（カラー）

絶対角運動量 (コンター) 角運動量の内向き移流 (カラー)



気圧偏差（コンター） 気圧傾度力（カラー）

慣性安定度

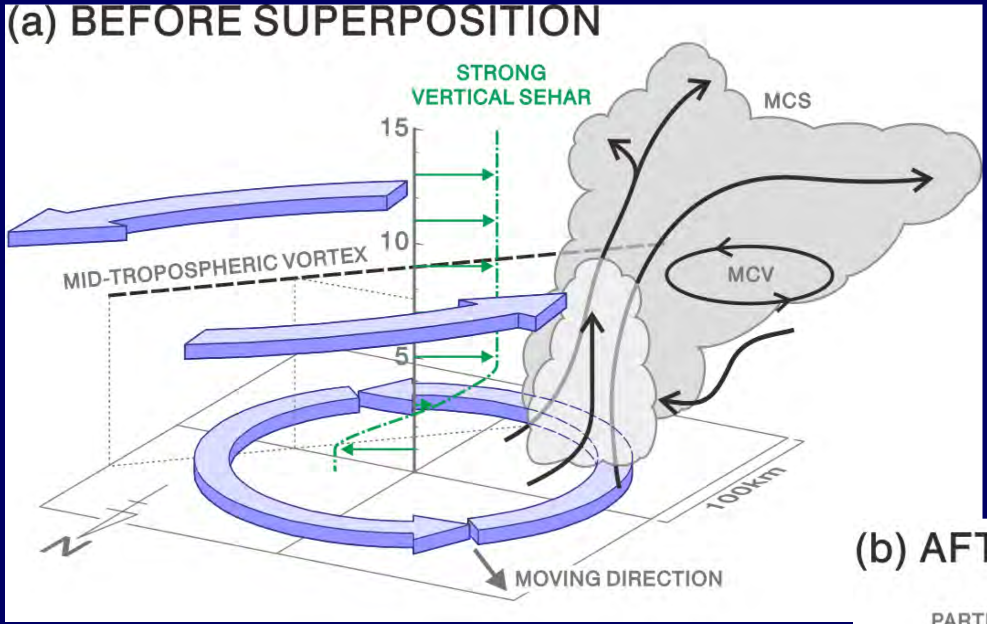
平衡状態:
壁雲のごく近傍で旋衡風平衡

$$\frac{Vt^2}{r} \approx \frac{1}{\rho}\frac{\partial p}{\partial r}$$

スピンアップ過程:
壁雲の下層収束による
角運動量の内向き輸送

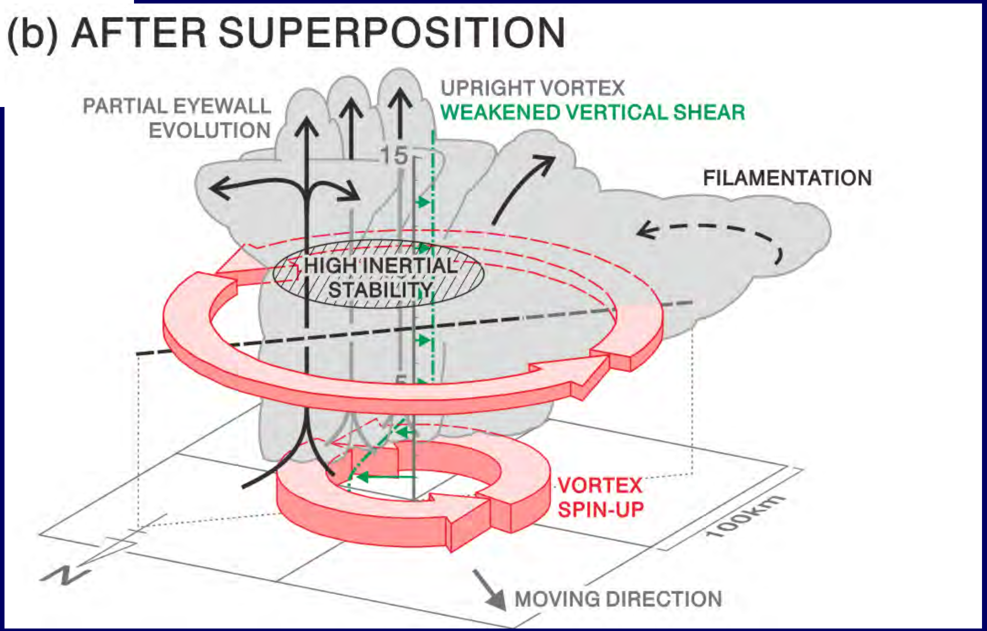
重なり合う中層渦の役割:
慣性安定度の増加
対流加熱から運動エネルギーへの変換効率を増加

Schematic View of The Fengshen's Genesis



Misaligned vortex centers in the lower and middle troposphere, causing vertical wind shear over the surface vortex center

MCS leaving behind the surface vortex due to the vertical shear



Formation of an upright vortex in gradient wind balance

Transformation of MCS into a partial eyewall under the environment with reduced vertical shear and increased inertial stability

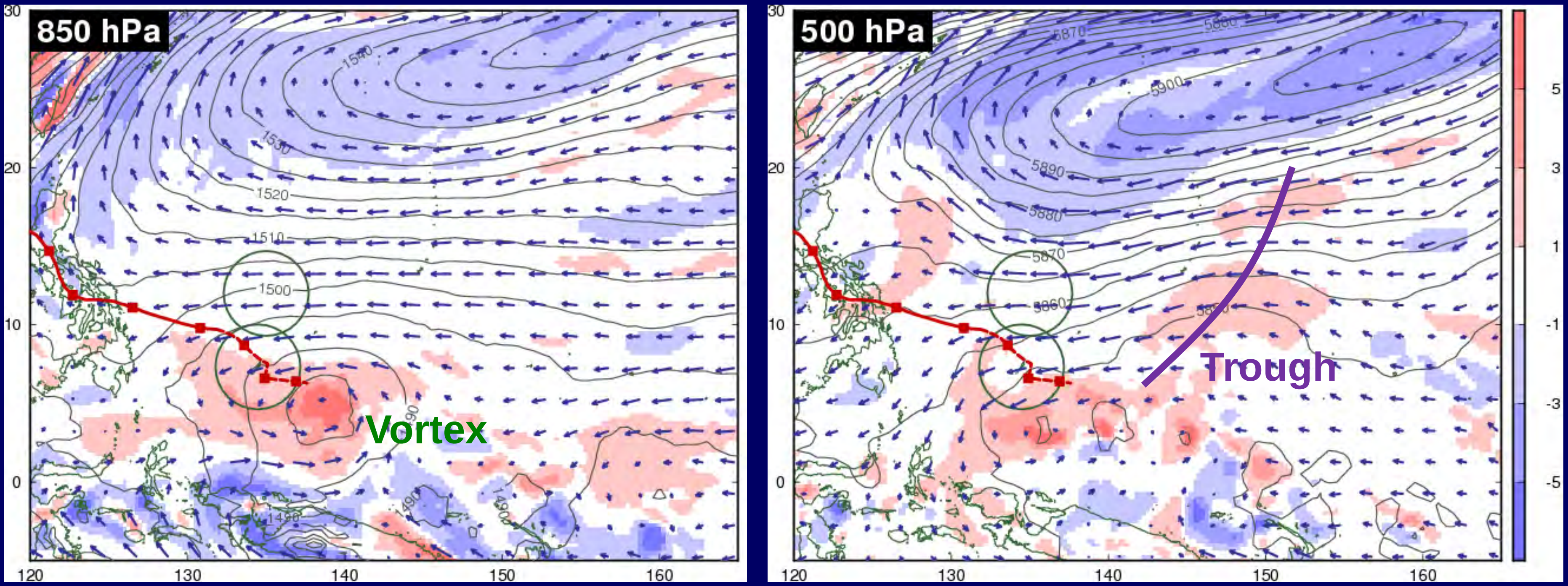
The vortex superposition is the key process in the genesis of Fengshen

Synoptic-Scale Processes

Role of Madden-Julian Oscillation

Synoptic Situation (ECMWF-YOTC analysis)

Height, Wind, Relative Vorticity (15 June, 3 days before genesis)



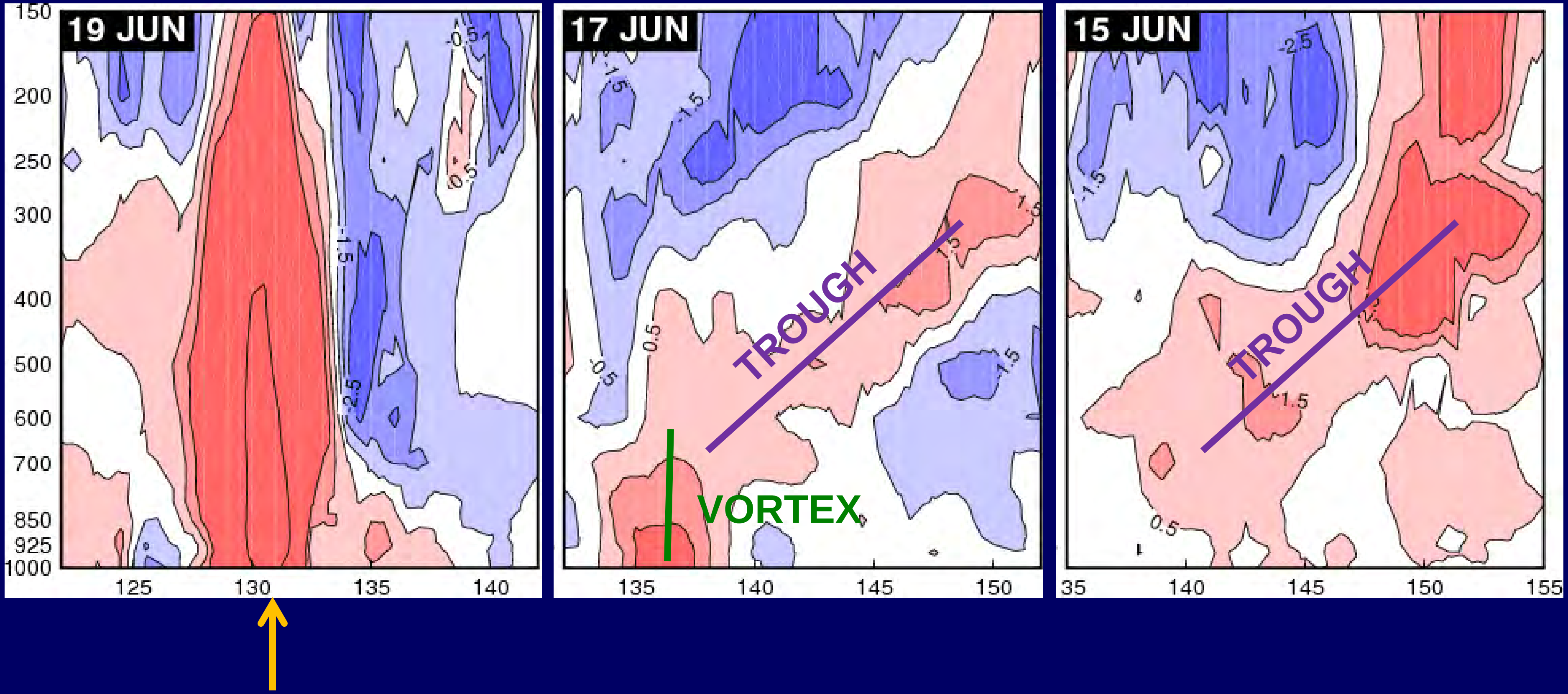
Two synoptic-scale disturbances in different vertical levels:

- **A closed circulation near 5ºN at 850 hPa**
- **A trough in a easterly flow near 15ºN at 500 hPa**

Change in the Vertical Structure

Zonal-vertical sections of relative vorticity (7.5-12.5°N)

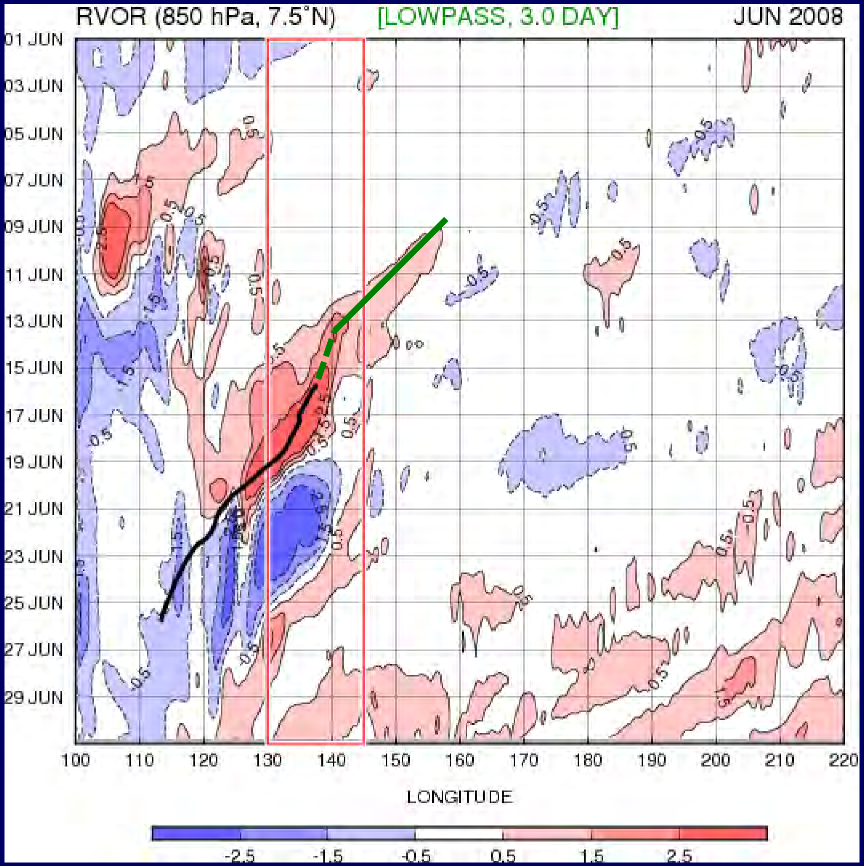
+1 day ← -1 day ← -3 day



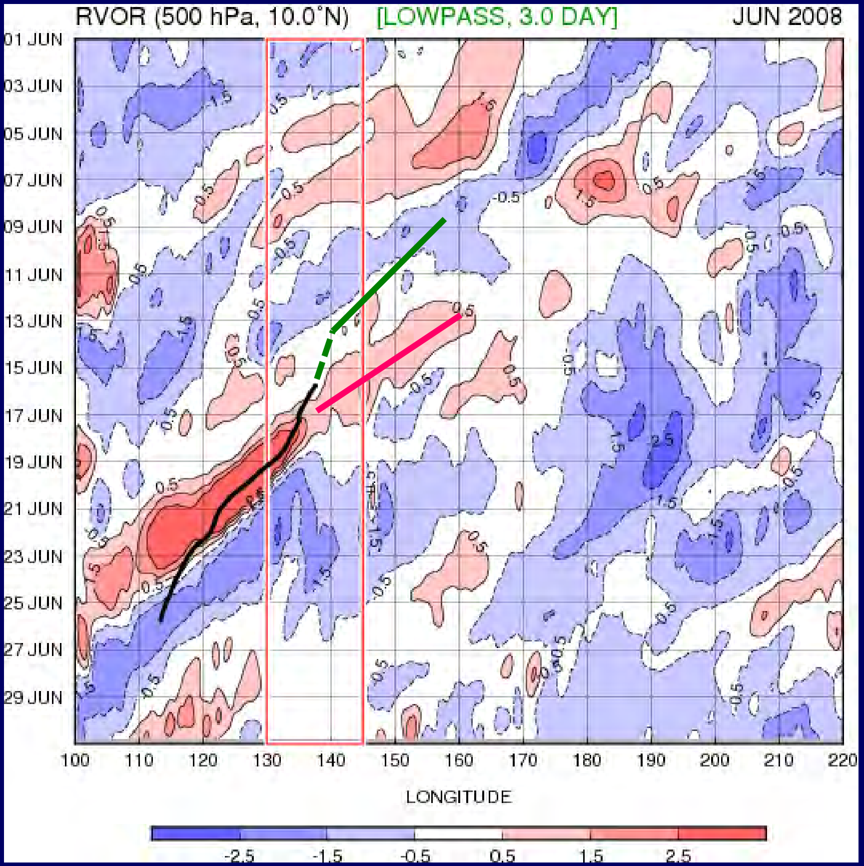
An upright vortex of Typhoon Fengshen was formed from the superposition of the two disturbances.

Hovmöller Diagrams of Relative Vorticity

850hPa, 5-10N



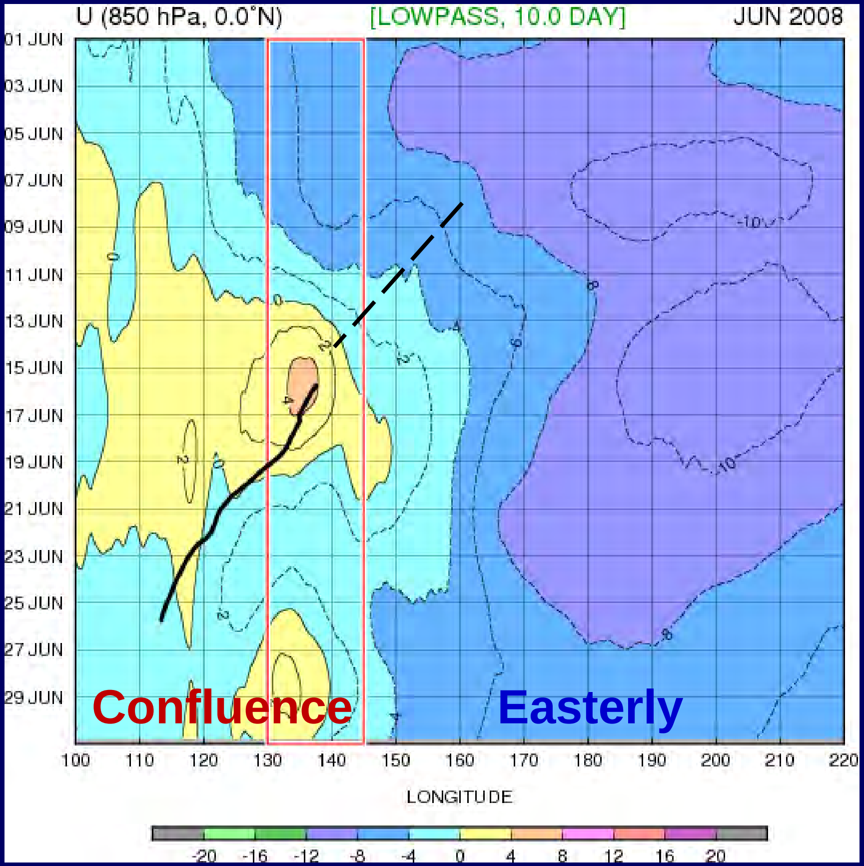
500hPa, 7.5-12.5N



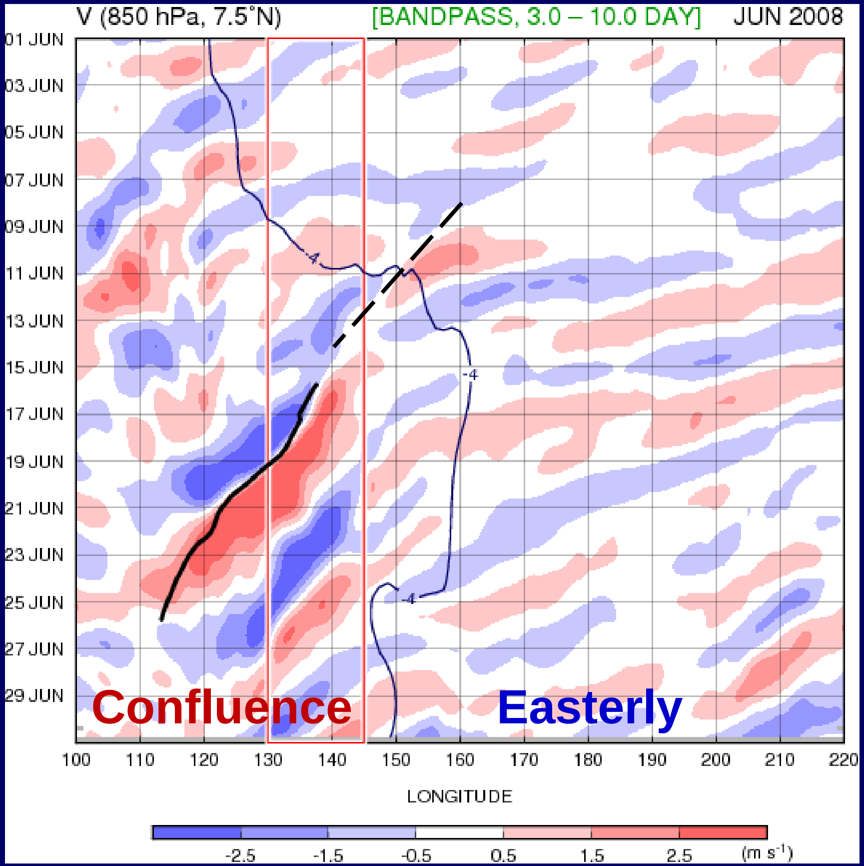
The vortex superposition took place due to the slowdown of the westward propagation in the lower troposphere.

Slowdown Leading to Vortex Superposition

U (10day, 850hPa, 2.5S-2.5N)



V (3-10day, 850hPa, 5-10N)

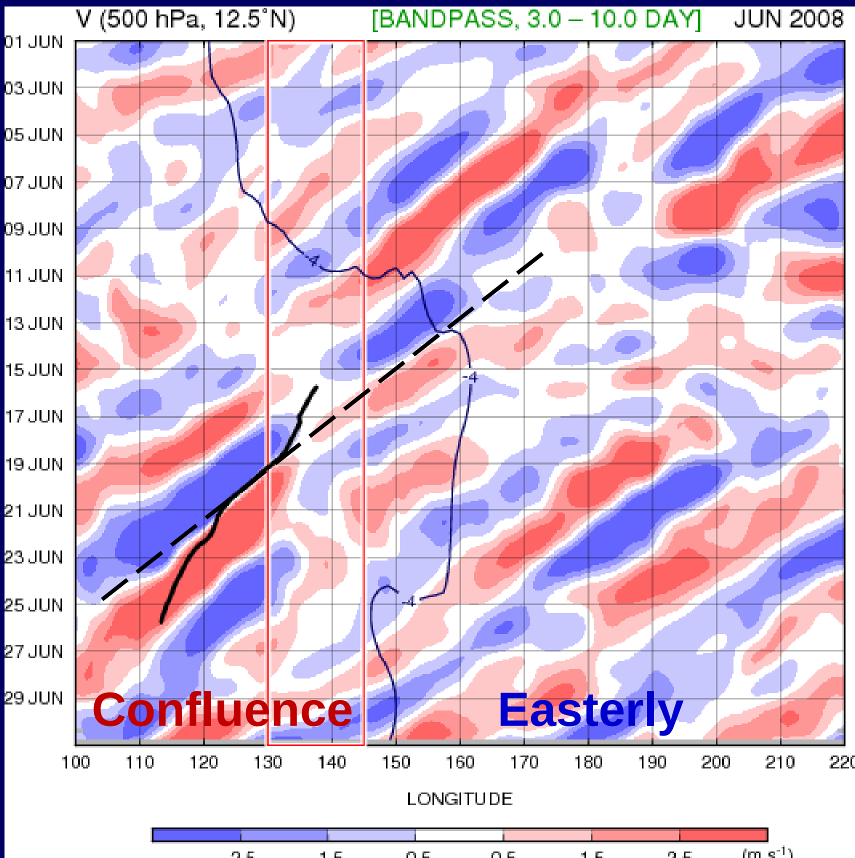


The propagation speed of disturbances was decreased within a zonal confluent region of MJO.

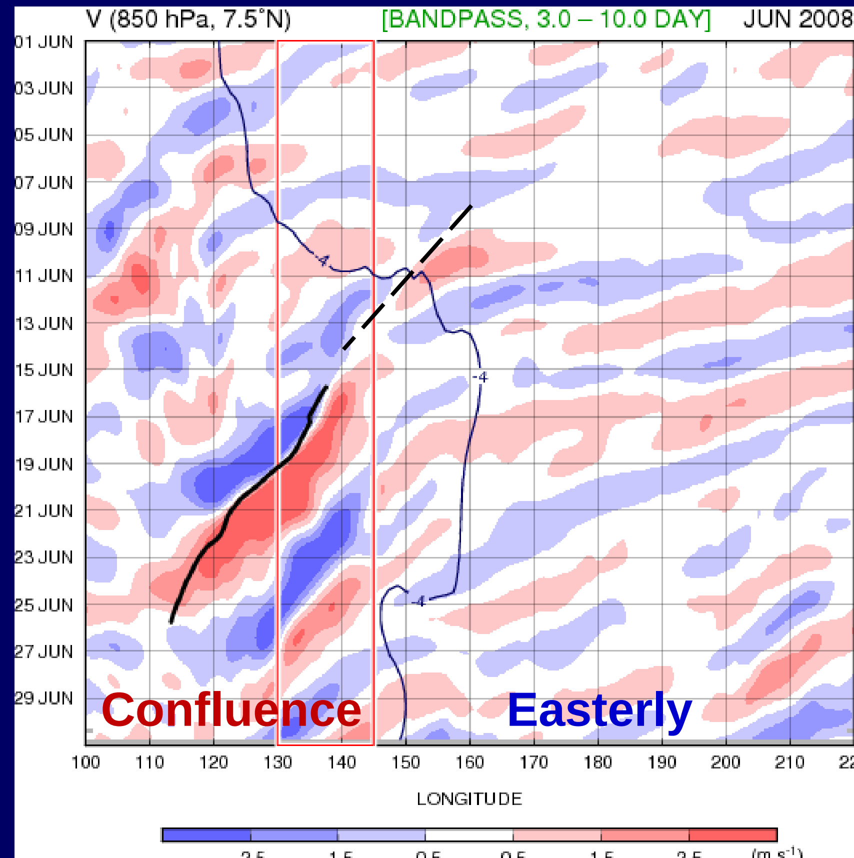
(i.e., wave accumulation, Aiyyer and Molinari 2003, JAS)

Slowdown Leading to Vortex Superposition

V (3-10day, 500hPa, 10-15N)

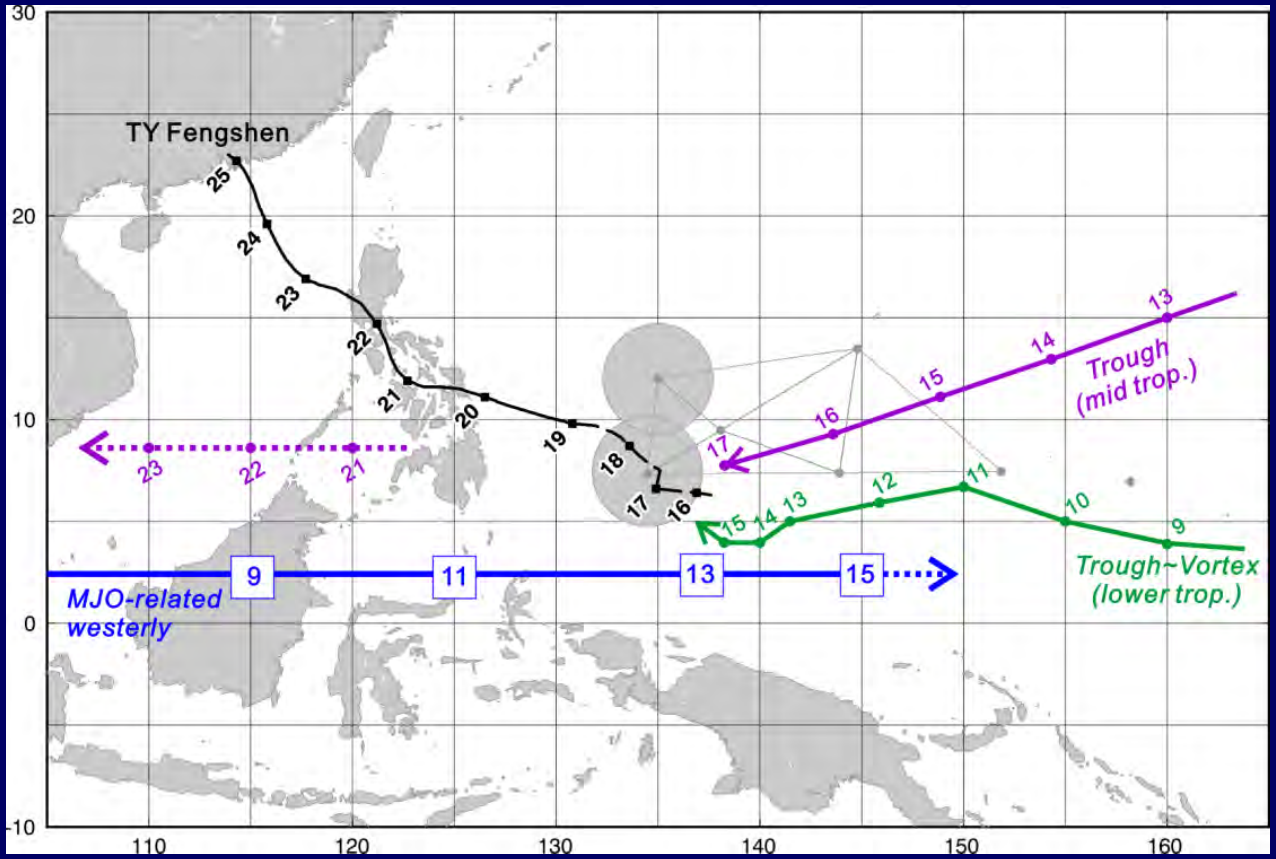


V (3-10day, 850hPa, 5-10N)



The slowdown is not significant in the middle troposphere.

Schematic View of Synoptic-Scale Process



- MJO-related westerly in the lower troposphere caused the slowdown of the low-level vortex, increasing the probability of superposition with the mid-tropospheric vortex.

Summary of Fengshen Study

- Synoptic and mesoscale processes leading to the genesis of Typhoon Fengshen (2008) were investigated based on observations and numerical simulations.
- This typhoon was formed when a mid-tropospheric trough was superposed upon a lower-tropospheric vortex (TD-type disturbance). The presence of two separated vortices before the genesis was supported by the observations.
- The simulation represented the mesoscale process leading to the formation of a partial eyewall ,under the condition of increased inertial stability and reduced vertical shear (due to vortex superposition).
- These results suggests an importance of vortex superposition for tropical cyclogenesis in the tropical western Pacific.
- The results also suggest the importance of correctly reproducing the vertical structure of incipient disturbances for simulating typhoon formation.

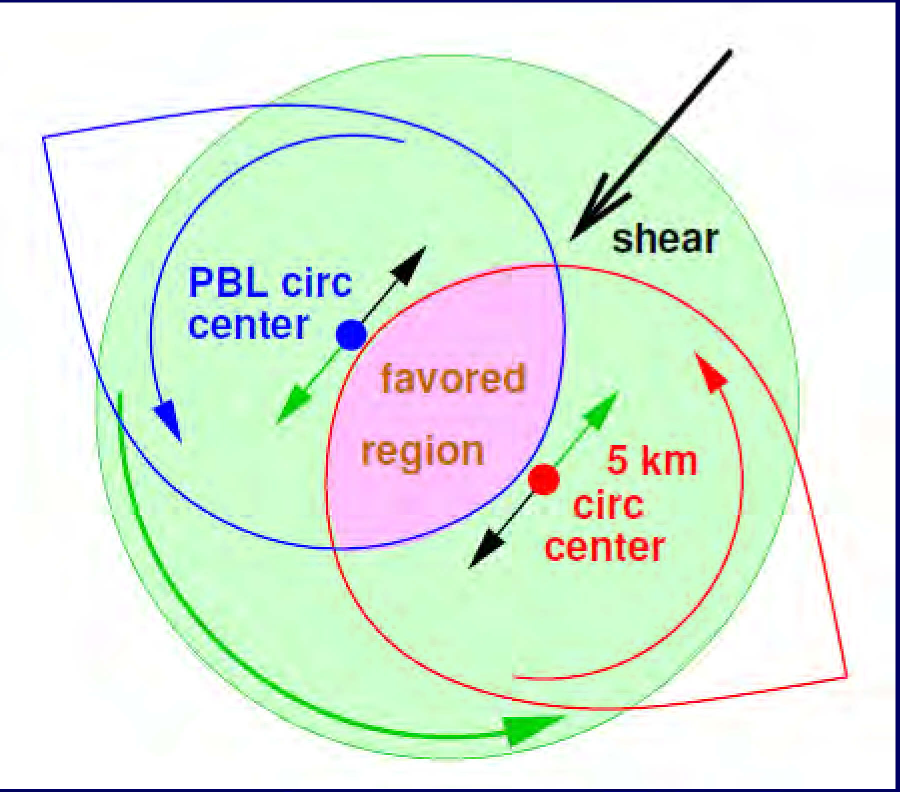
Relation to Other Studies

Importance of Vertical Structure

Typhoon Nuri during TCS-08

Raymond and Lopez (2011):

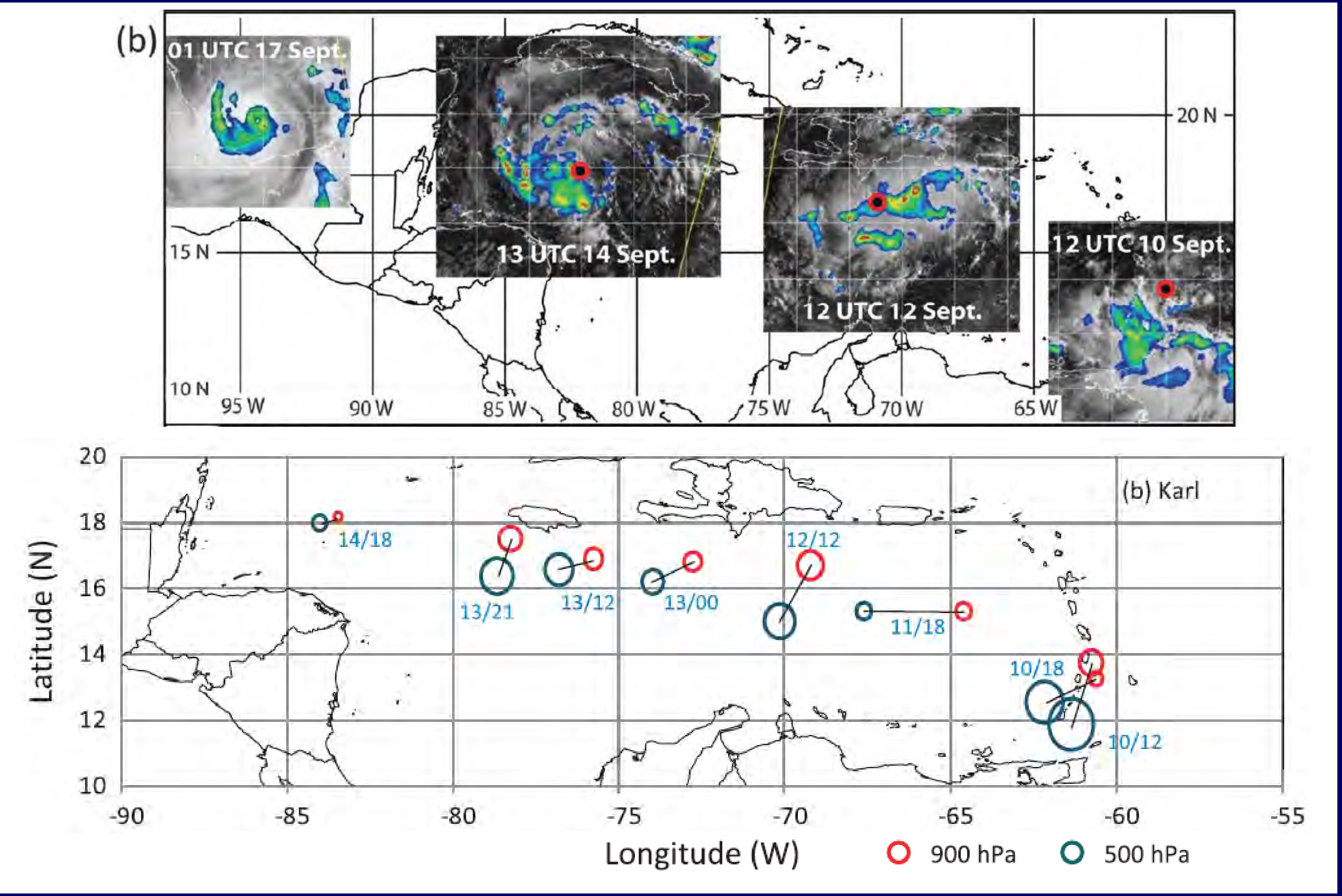
- Dropsonde observation of the pre-Nuri vortex using P-3/C130 aircrafts
- Misalignment of vortices in the lower and middle troposphere was observed
- The area where two vortices overlap is protected from environmental incursions, and is likely to be the area in which the core of the developing tropicalcyclone spins up.



→ Importance of the vertical structure of vortex is consistent with the argument of our study

Hurricane Karl during PREDICT (2010)

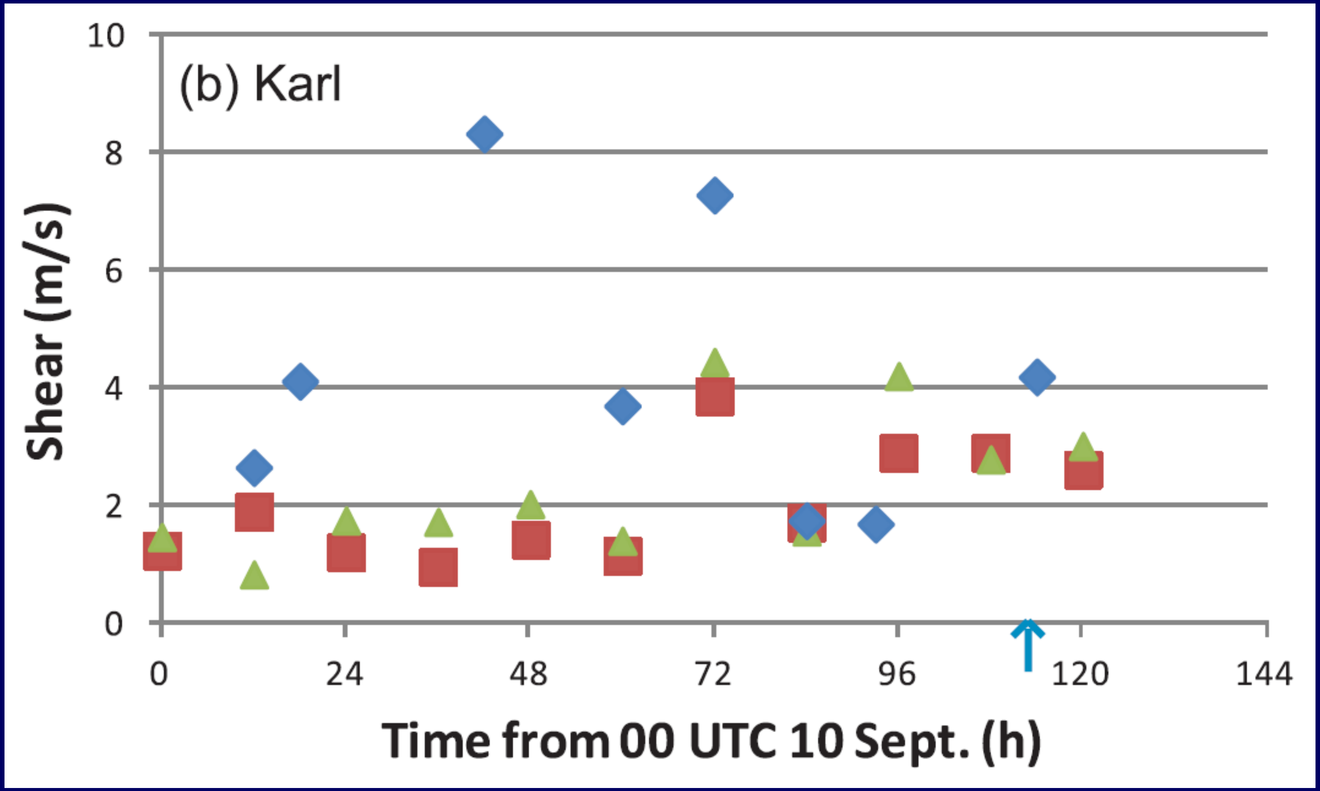
Davis and Ahijevych (2012, JAS)



Misaligned vortices between lower and middle troposphere was realigned until the designation as a tropical storm (18 UTC 14 September).

Hurricane Karl during PREDICT (2010)

Davis and Ahijevych (2012, JAS)



Change in the vertical shear due to vortex misalignment/realignment was represented by dropsonde observation (blue), while GFS (maroon) and ECMWF (red) models poorly reproduce it.