Vortex-Vortex Interaction

-Stimulation to and from Tropical Cyclone (TC) Research-

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Many slides are provided by A. Yamazaki,
K. Yoshida, M. Hayashi, and H. Tsuji.

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 (tropical dynamics, potential vorticity)
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1. Introduction

羅馬之図　Seiho TAKEUCHI (1864-1942)
(Rome)

Revolution of Japanese Painting ← Western Painting

Originally, Shijo school Kano school

TC

other fields

Other fields

vortex-vortex interaction

TC : one of vortices

stimulation to TC research

from TC research

Request from Sawada *san*

・Tropical dynamics (difference from mid-latitude)

・PV thinking

Review of Hoskins et al. (1985) and so on

Its application: indirect effect of TCs on heavy rainfall (Yoshida and Itoh 2012)

2. Basic dynamics

1. Tropics vs. mid- and high-latitudes
2. Rossby radius of deformation
3. Potential vorticity

together

伊藤久徳, 2007 : 熱帯の力学と台風の発生.
月刊海洋, No. 3, 136-144.
H. Itoh, 2007: Tropical dynamics and the genesis of tropical cyclones. Gekkan Kaiyo, No.3, 136-144. (in Japanese)

1. Tropics vs. mid- and high-latitudes

Tropics

Smallness of the Coriolis parameter

$f \sim 10^{-5}$/s at about 5º latitude

→ Large deviation from geostrophic wind

Scale Analysis

$L \sim 1000$km, $U \sim 10$m/s

→ $\delta\Phi \sim U^2 \sim 100$, $\delta z \sim 10$m, $\delta T \sim 0.3$K

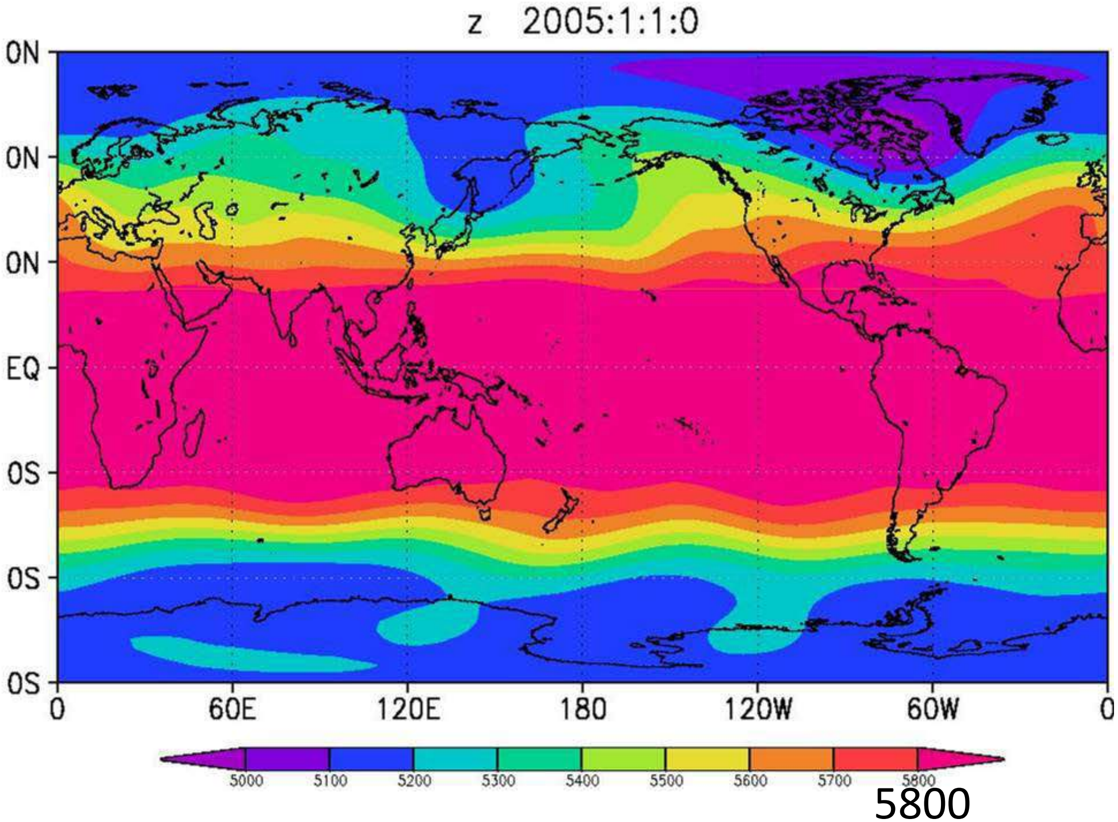
Midlatitude

$\delta\Phi \sim fUL \sim 10^3$, $\delta z \sim 100$m

Φ : geopotential

z : geopotential height

T : temperature

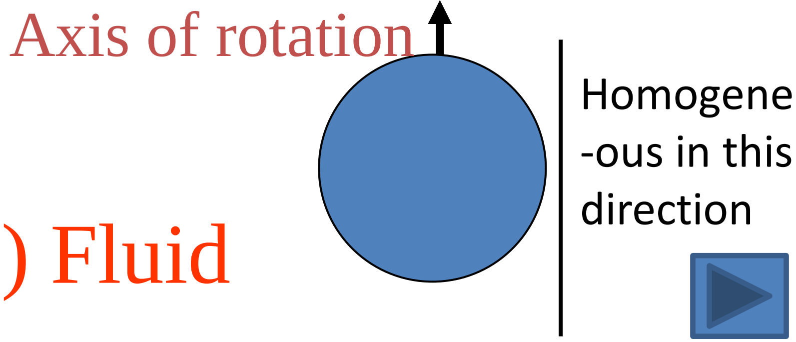


500hPa height

Homogeneity in the horizontal direction

Relatively unknown things Charney (1963)

Small vertical motion, quasi-horizontal flow, decoupling between upper and lower layers



Rotating (f) and stratified (N) Fluid

f (Coriolis parameter)　Homogeneity in the vertical direction

Nondivergent　(Axis of rotation)

N (Brunt-Vaisala frequency)　Homogeneity in the horizontal direction

Zero vertical velocity

β (Rossby parameter)　Homogeneity in the E-W direction　$\beta\frac{\partial \Phi}{\partial x}$

Scale analysis　L～1000 km,　U～10 m/s

D(vertical scale)～3km,　W(vertical velocity)～0.3cm/s

Amplitudes of Height and Temperature　Small

⇒ Weak surface wind

Rotating(f) and Stratified(N) Fluid

When *f* is large $(f \rightarrow \infty)$

Geostrophic wind

$$\frac{\partial \zeta}{\partial t} = -\boldsymbol{v} \cdot \nabla (f + \zeta) - w \frac{\partial \zeta}{\partial z} - (f + \zeta) \nabla \cdot \boldsymbol{v} + \ldots$$

Horizontal div. small imcompressible

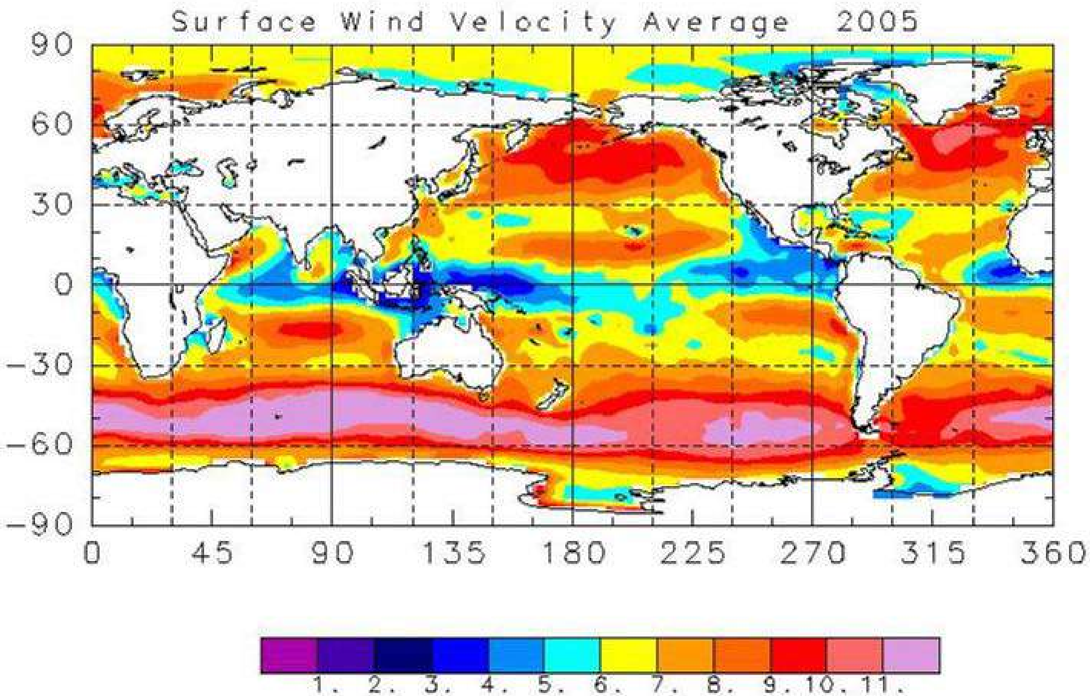
Deep (equivalent barotropic) $\frac{\partial w}{\partial z} \rightarrow 0$

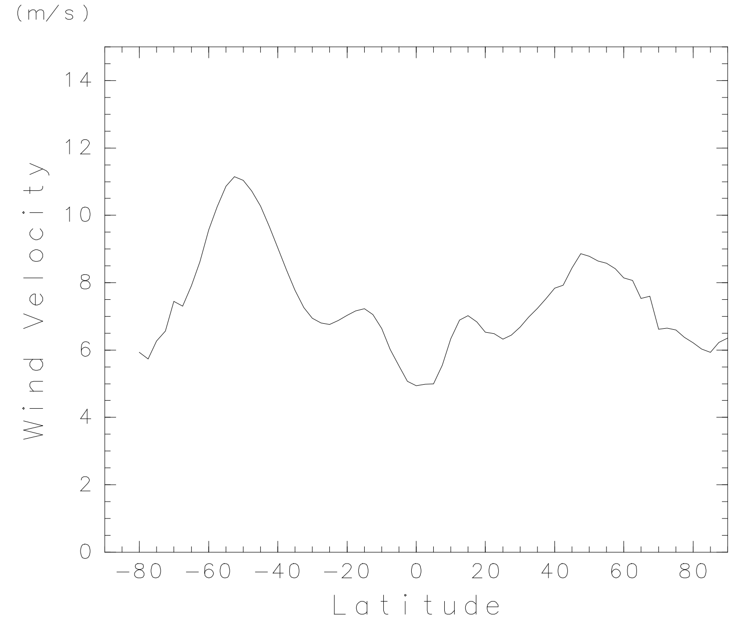
When *N* is large

$$\frac{\partial \theta}{\partial t} = -\boldsymbol{v} \cdot \nabla \theta - w \frac{\partial \theta}{\partial z}$$

$w \rightarrow 0$ quasi-2 dimensional motion

vertical scale is small

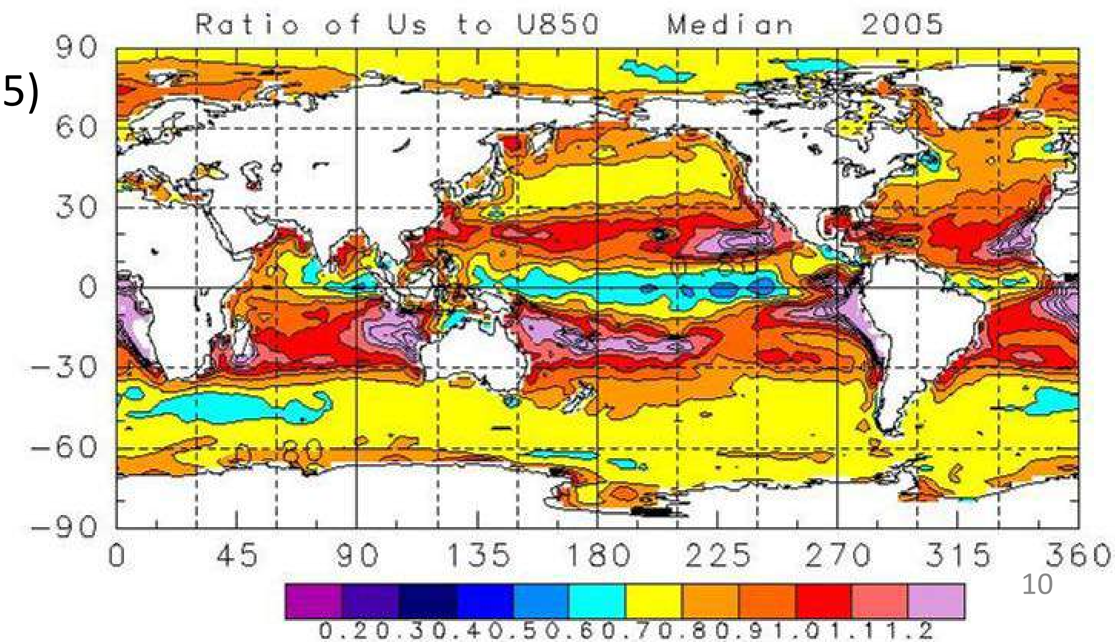




|v| at surface (σ=0.995)
daily mean

Year 2005

Median of
$|v_s|/|v_{850}|$



More generally N and $f \rightarrow I$ large: immediately return

Eq. of vertical displacement

small: can go distantly

$$\frac{d^2 z}{dt} + N^2 z = Q$$

N: measure of static stability

In the horizontal (y direction)

$$\frac{d^2 y}{dt} + I^2 y = F$$

$$I^2 = f(f + \overline{\zeta}) \equiv f(f - \frac{\partial \overline{u}}{\partial y})$$

I: measure of inertial stability

Characteristic in the tropics weak inertial stability

In the cylindrical coordinate (basic : gradient wind balance)

$$\frac{d^2 r}{dt} + I^2 r = F$$

$$I^2 = (f + \zeta)(f + 2u/r)$$

r: radial direction

u: tangential wind

Rossby radius of deformation (baroclinic)

$$\lambda = NH/f \quad (ND/f)$$

Horizontal scale for which geostrophic adjustment (GA) occurs

In the tropics

Time scale of GA (f^{-1}) Large

λ Large

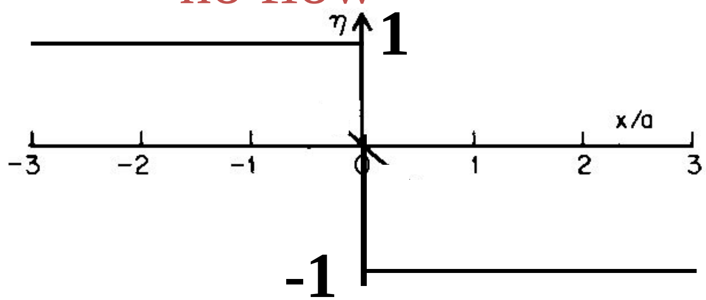
Gravity waves go to long distance before the rotation can be effective

→ Deviation from geostrophic flow Large

However, the above is derived under some assumption

Rossby radius of deformation (RD)

Initial water surface
no flow



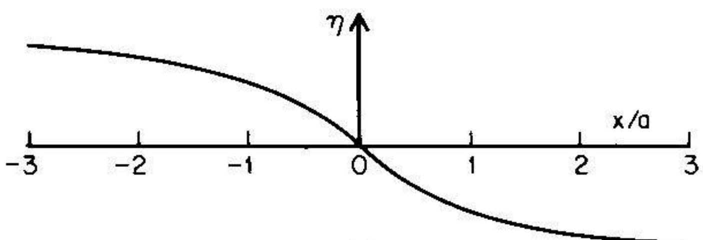
In non-rotating frame
- flat surface
- all initial potential energy is lost

Geostrophic adjustment (GA)

In rotating frame, final state?

$\lambda_R(=a)$: horizontal scale of GA

f^{-1}: time scale of GA

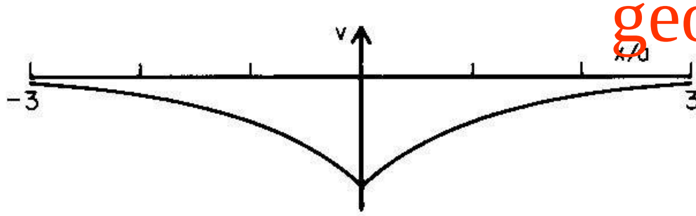


(a)

-1+exp(-1) at x=a

$a = \sqrt{gH}/f$

geostrophic flow



(b)

Phase speed of gravity wave × f^{-1}

No convection, No vortex (as basic field)

Convection

Strong divergence, large vertical motion,
coupling between upper and lower layers
(baroclinic mode)

Amplitude of temperature is still small

Vortex with large vorticity (as basic field)

ζ in $f+\zeta$ is effective.

For instance, a latitude of $f+\zeta=0$ is the “equator” (dynamical equator).

Homogeneous in the vertical direction

Rossby RD   rotational Froude number

$$\lambda_R = ND/I, \qquad F_R = L/\lambda_R = \frac{IL}{ND}$$

Dynamics considerably changes, depending on the magnitude of *I* even in the same tropics.

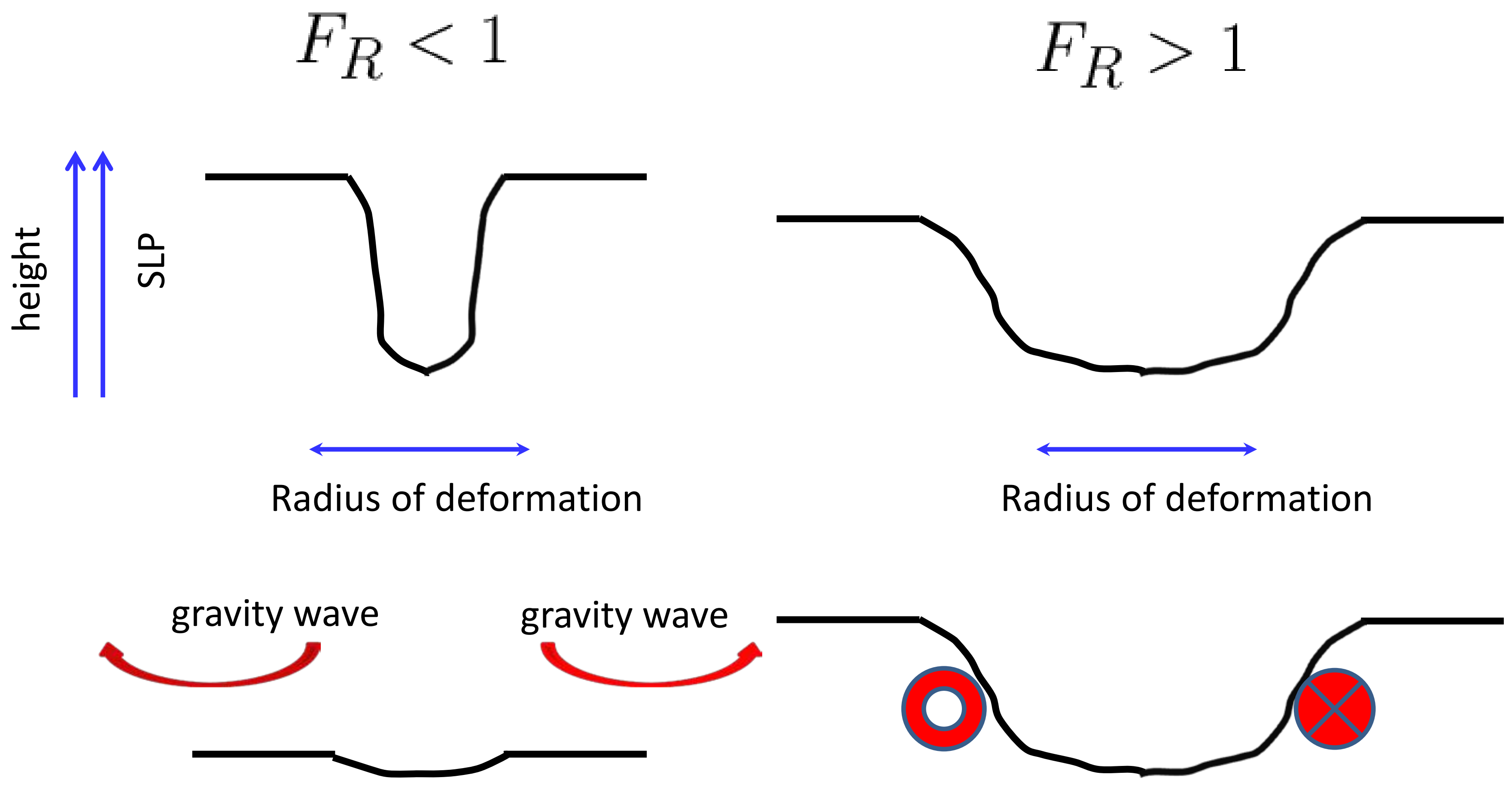
with or without strong vortex

$F_R < 1$ Fluctuation of mass field (by convection)

→ gravity wave

Wind ← Mass (pressure)

$F_R > 1$ Mass (pressure) ← Wind


$F_R < 1$
$F_R > 1$
height
SLP
Radius of deformation
Radius of deformation
gravity wave
gravity wave

Relationship to tropical cyclogenesis

How?

dip of water surface = low pressure area = high temperature area = for instance, area heated by convection

However,

No rotation

Low pressure area cannot be formed, even though the atmosphere is heated.

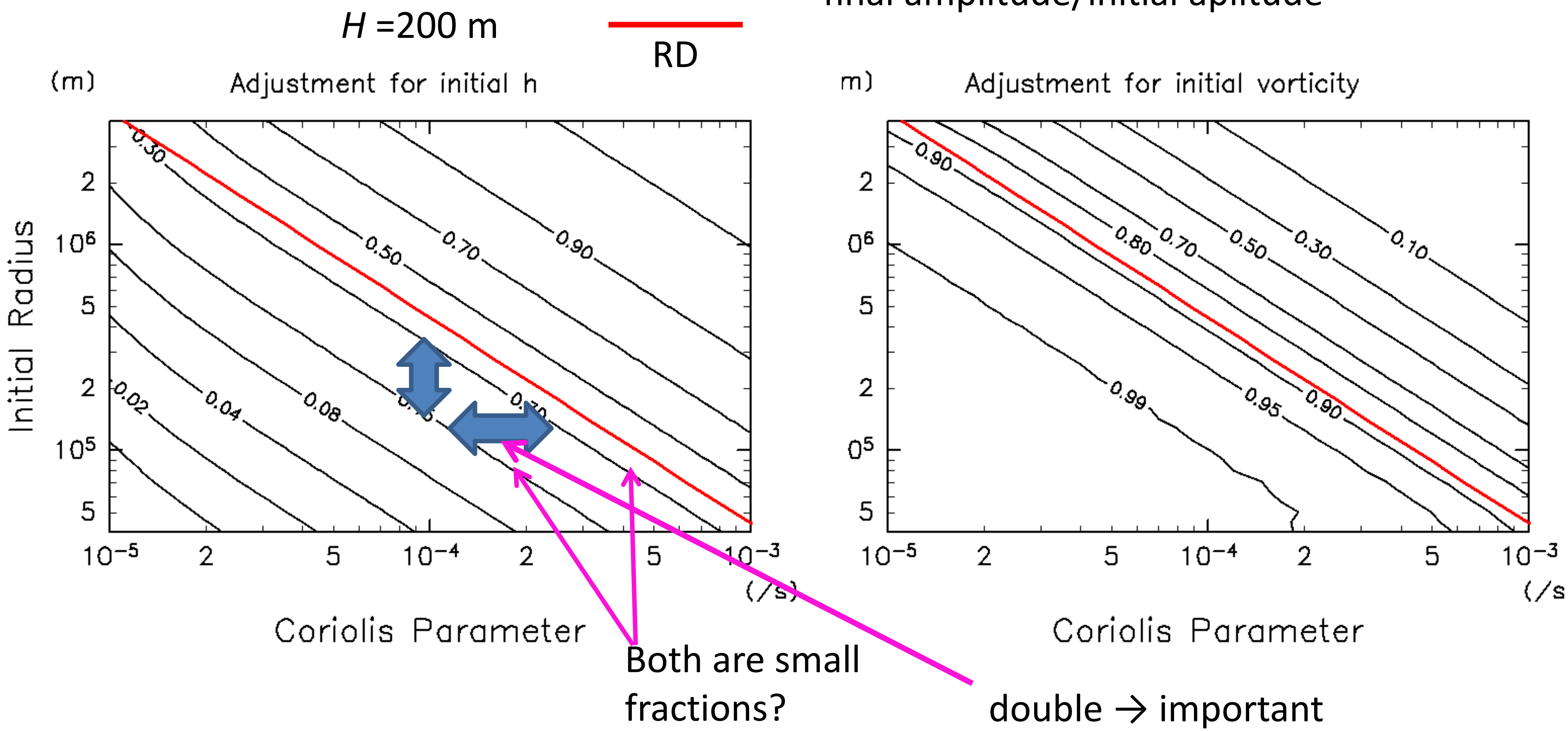
Rotation Low pressure area can be formed.

In particular, it is effective that low pressure is formed in small areas.

Whether the atmosphere heated by convection can form to what extent of low pressure areas is closely related to Rossby RD.

Shallow water model

final amplitude/initial aplitude

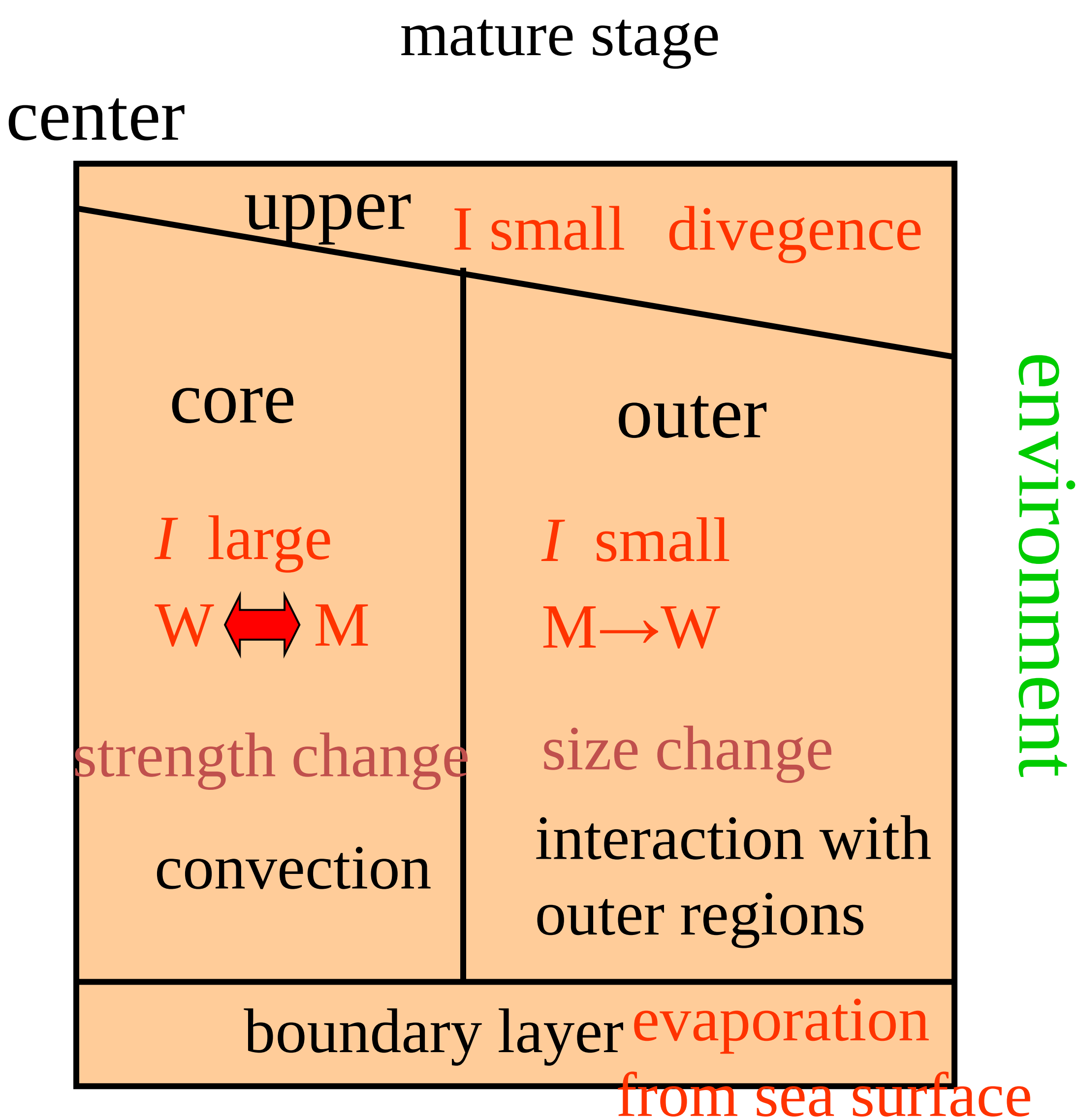


In the genesis of TCs, which is first, Vortex (wind) or Low pressure?

Vortex

Structure and dynamics of TCs

cross section of a TC



Strong vortex：

・retain energy generated by convection, storing it in the interior.

・make boundary-layer wind strong, promoting evaporation from sea surface.

M : mass, W : wind

3. Potential Vorticity (PV)

$$P \equiv (f + \zeta_\theta)/\sigma \qquad \text{where} \qquad \sigma \equiv -\frac{1}{g}\frac{\partial p}{\partial \theta}$$

ErtelのPV

absolute vorticity × static stability

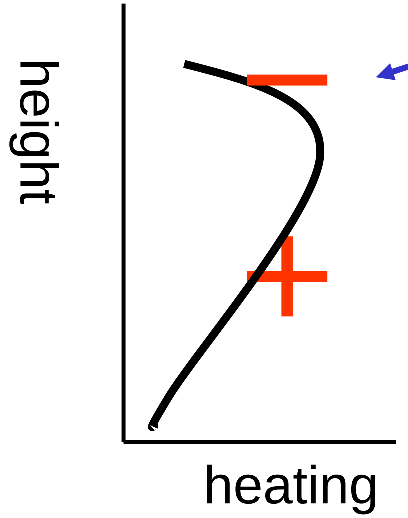
Unit : PV unit (PVU)

$$\mathrm{PVU} = 10^{-6}\ \mathrm{m^2\ s^{-1}\ K\ kg^{-1}}$$

Conserved under adiabatic and inviscid flow

$$\frac{DP}{Dt} \equiv \frac{\partial}{\partial t}P + \mathbf{V}\cdot\nabla_\theta P = \frac{P}{\sigma}\frac{\partial}{\partial \theta}(\sigma\dot{\theta}) + \sigma^{-1}\mathbf{k}\cdot\nabla_\theta \times \left(\mathbf{F}_r - \dot{\theta}\frac{\partial \mathbf{V}}{\partial \theta}\right)$$

stretching tilting



Analogous to vorticity eq.

$\dot{\sigma\theta}$ is larger in the upper than in the lower. → stretching
lower upper shrinking

Stretching which is not in physical space, but is "stretching" departing from isentropic surfaces.

Levels of ＋

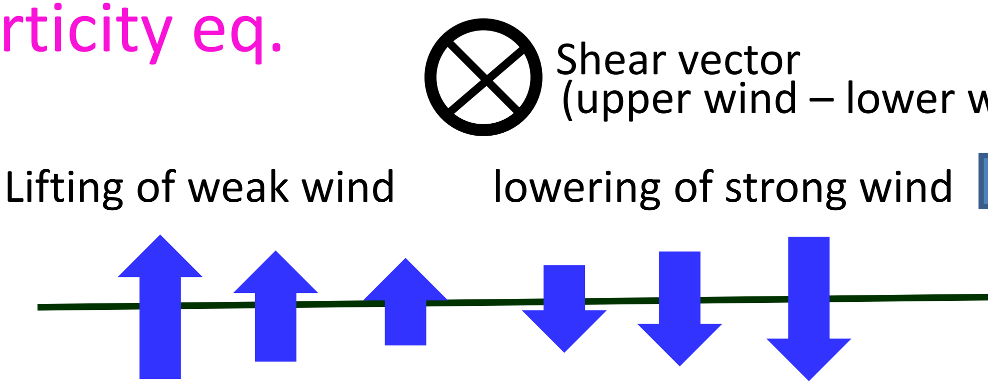
Isentropic surfaces (ISs) lower in the heating level, and the lowering is larger in the upper than in the lower.
→ Distance between two ISs shortens = σ decreases.
In other words, static stability becomes large.

Generated or lost by the vertical difference of diabatic heating

Explanation of Tilting

Vorticity eq.

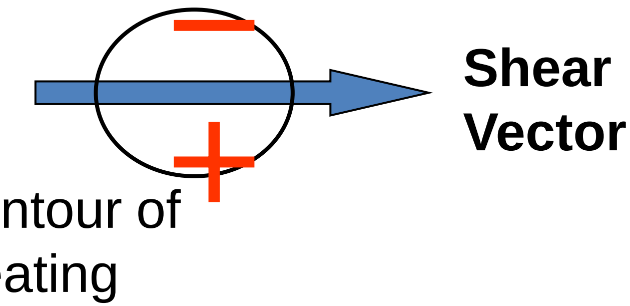
$$\frac{\partial \zeta}{\partial t} = \dots + \boldsymbol{k} \cdot \left(\frac{\partial \boldsymbol{v}}{\partial z} \times \nabla w \right) \dots$$

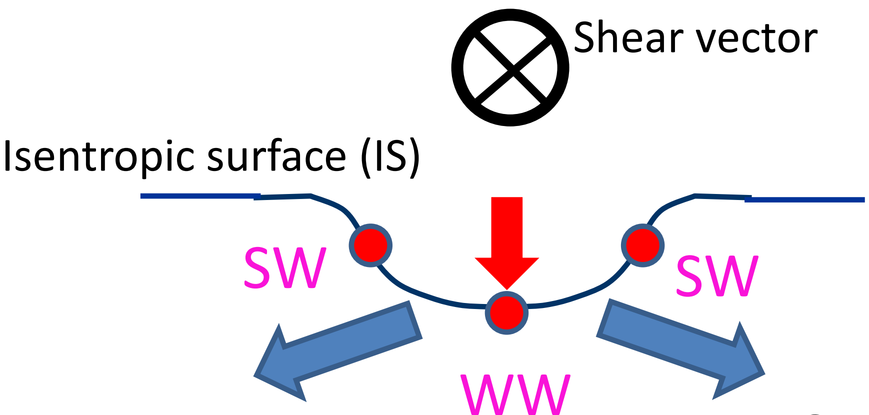


Generation of positive vertical vorticity

PV eq.
+ diabatic heating

$$-\frac{1}{\sigma} \boldsymbol{k} \cdot \nabla_{\theta} \times \left(\dot{\theta} \frac{\partial \boldsymbol{v}}{\partial \theta} \right)$$





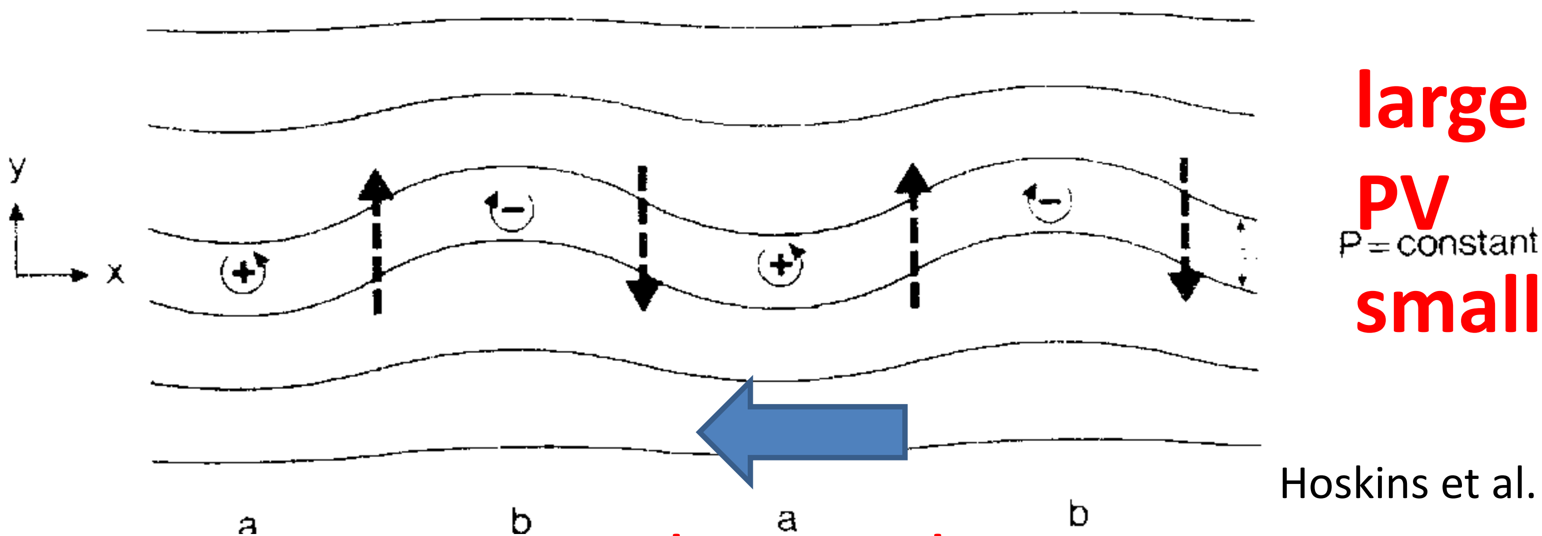
IS is lowered by diabatic heating

SW: strong wind
WW: weak wind

Generation of negative vertical vorticity

Generation of positive vertical vorticity

Restoring force of Rossby wave :
PV gradient of basic field



large PV

small

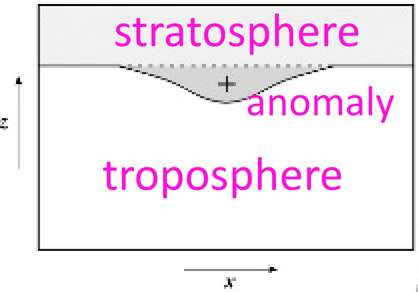
phase velocity

Hoskins et al. (1985)

Reversal of PV gradient ➡ Instability
(necessary condition)

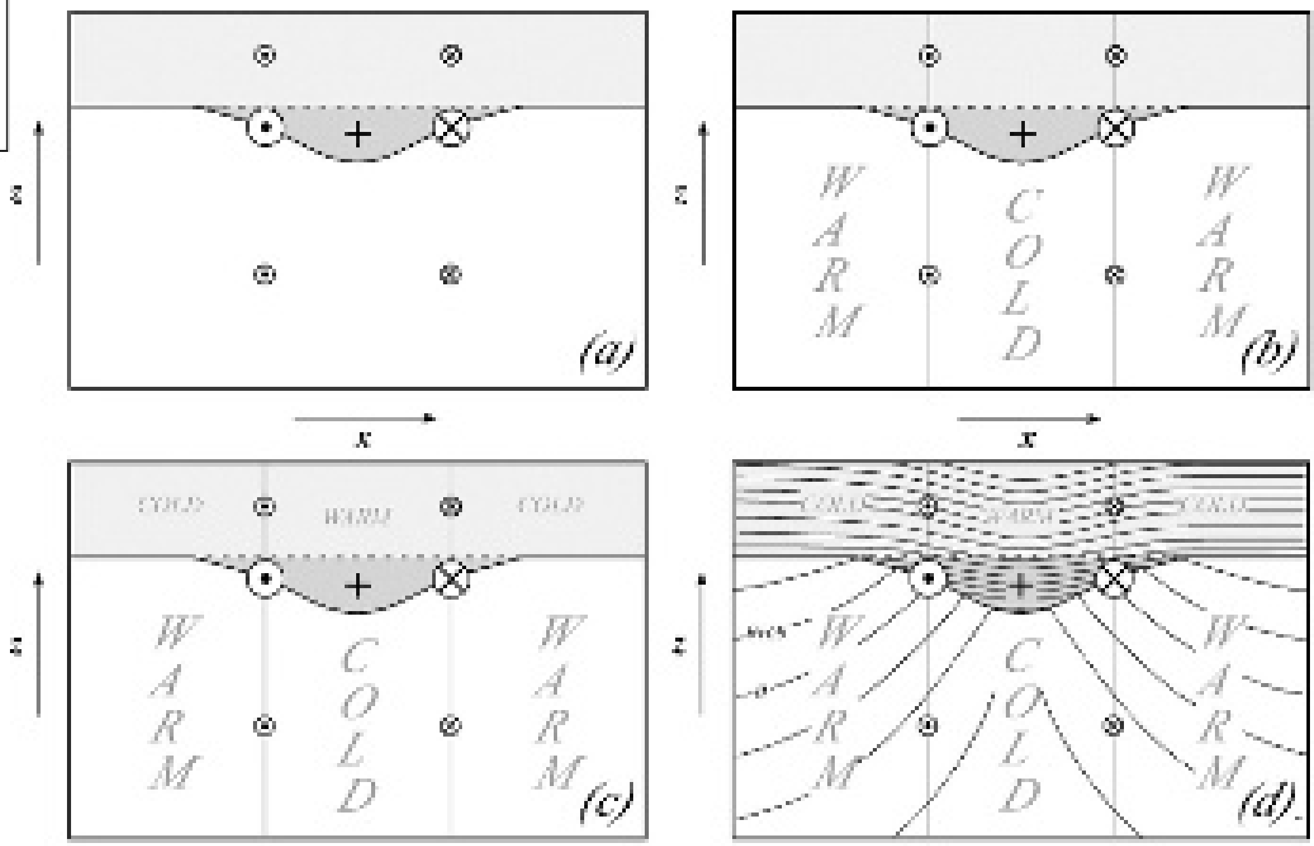
PV thinking

Wind and temperature induced by positive PV at the tropopause.



wind

temperature in
the troposphere



Thermal wind

PV is characterized by vorticity and static stability anomalies of the same sign!

Martin (2006)

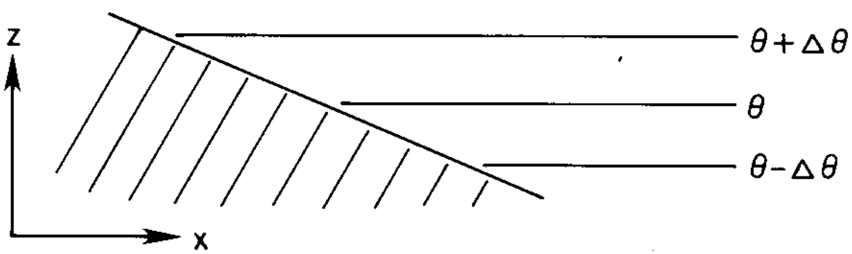
Surface Potential Temperature (ϑ) anomaly = PV anomaly

Positive ϑ anomaly at the lower boundary = Positive PV anomaly
Negative ϑ anomaly at the lower boundary = Negative PV anomaly

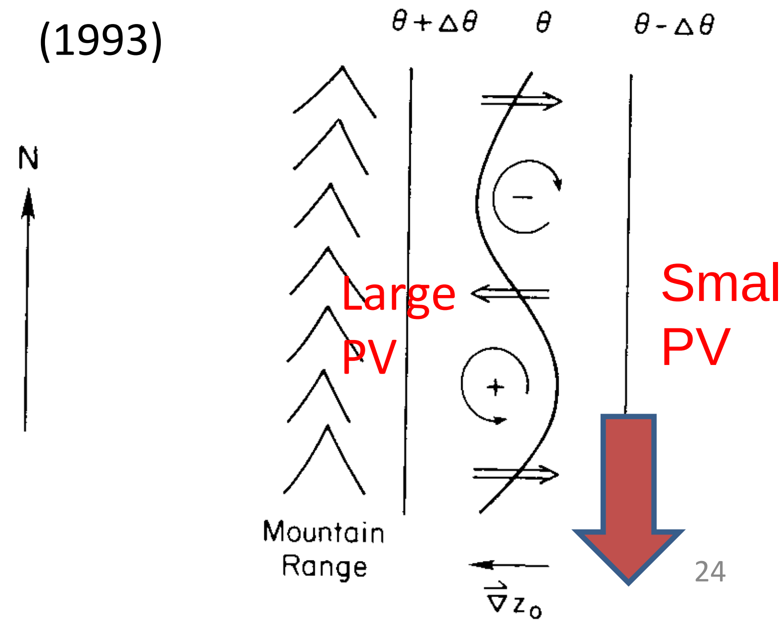
Baroclinic instability ⇐ PV gradient: positive in the atmosphere negative at the surface

TCs : PV gradients both in the atmosphere and at the surface with the radial direction are generally negative. ⇒ stable

Waves around mountains



Bluestein (1993)

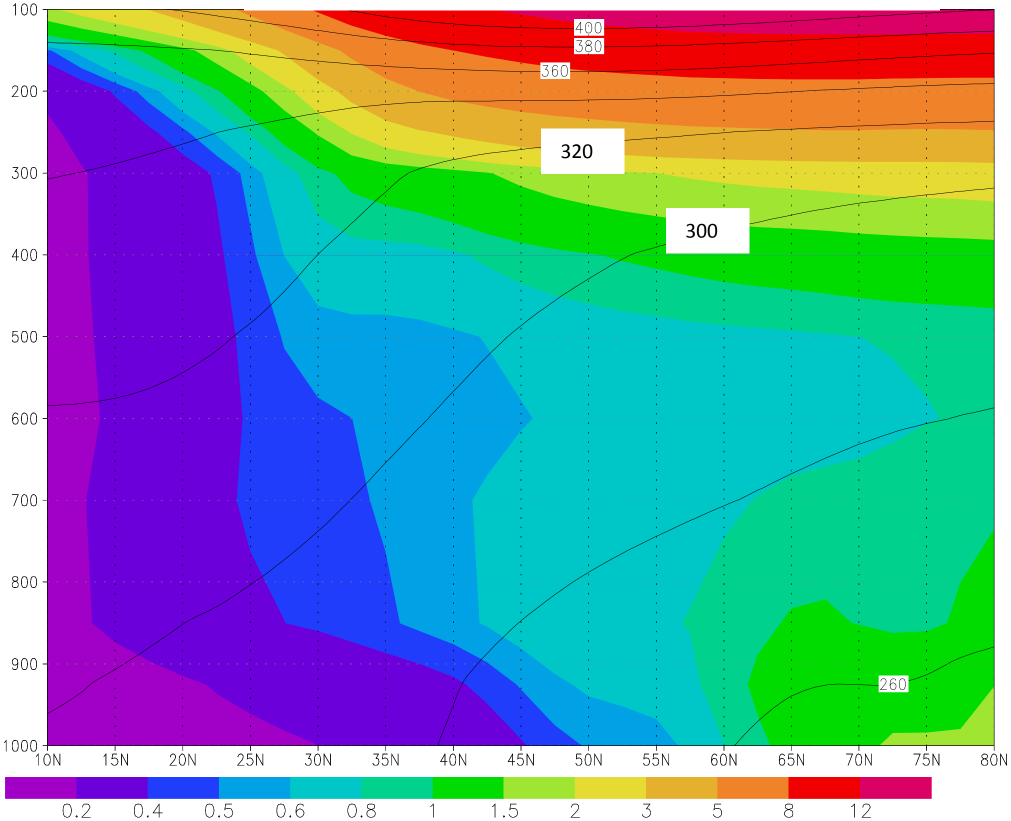


Topographic Rossby wave

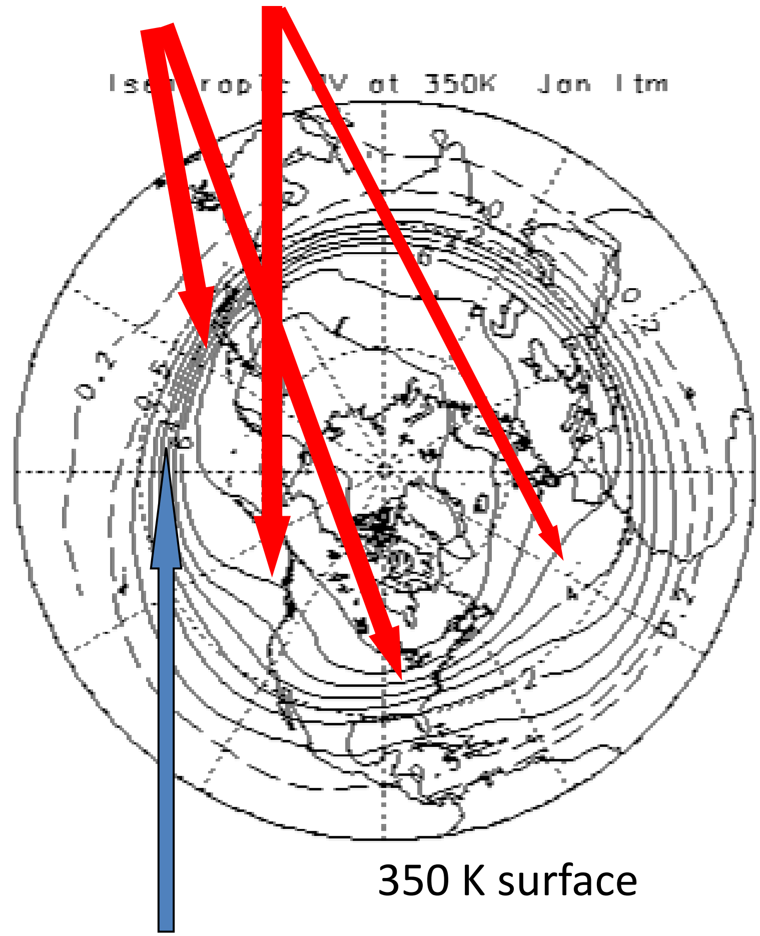
Zonally averaged PV (color) and potential temperature (contour)

Contrast

January long-term average



latitude



350 K surface

Increase with latitude in the lower troposphere

Increase with height in the upper troposphere and stratosphere

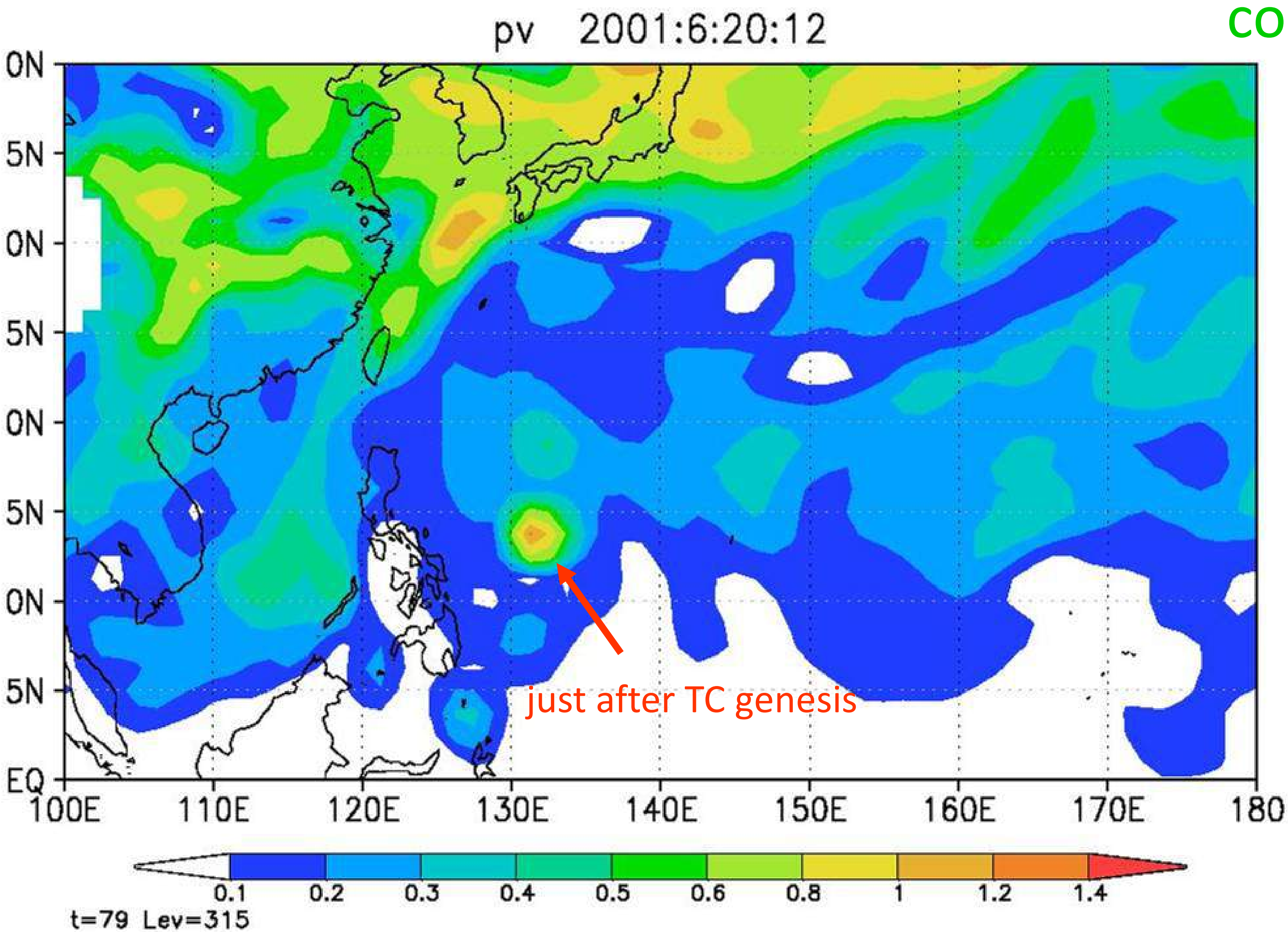
Large gradient at the border of two airmass

Tropics very small PV → TCs large PV

How?

vorticity

convection



PV at 315K surface

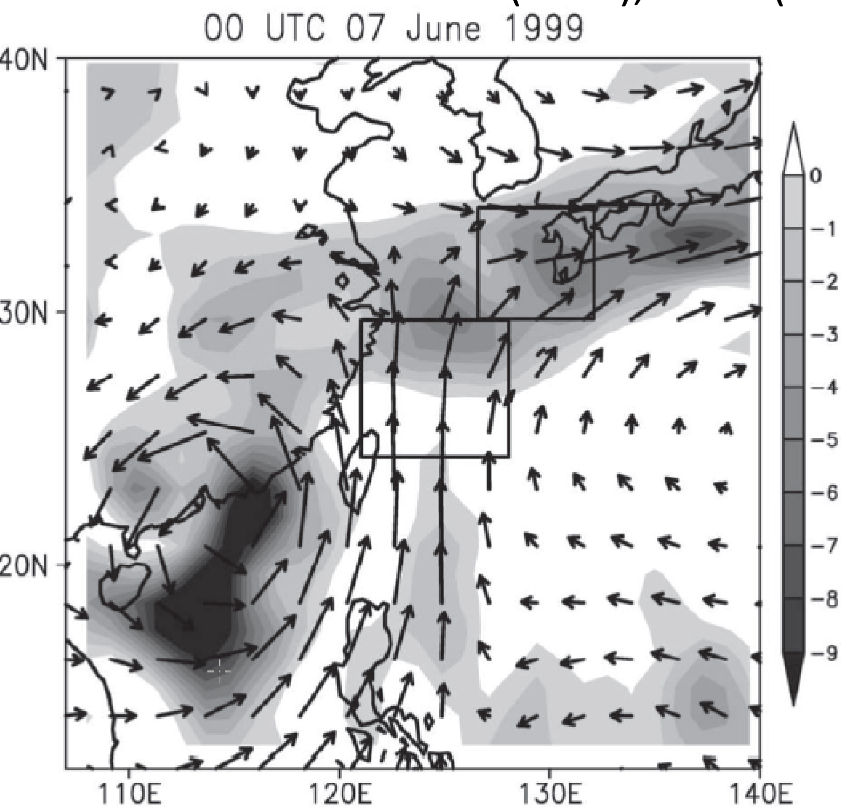
Invertibility Principle

PV → height and wind under the assumption of some balance (←Poisson eq.)

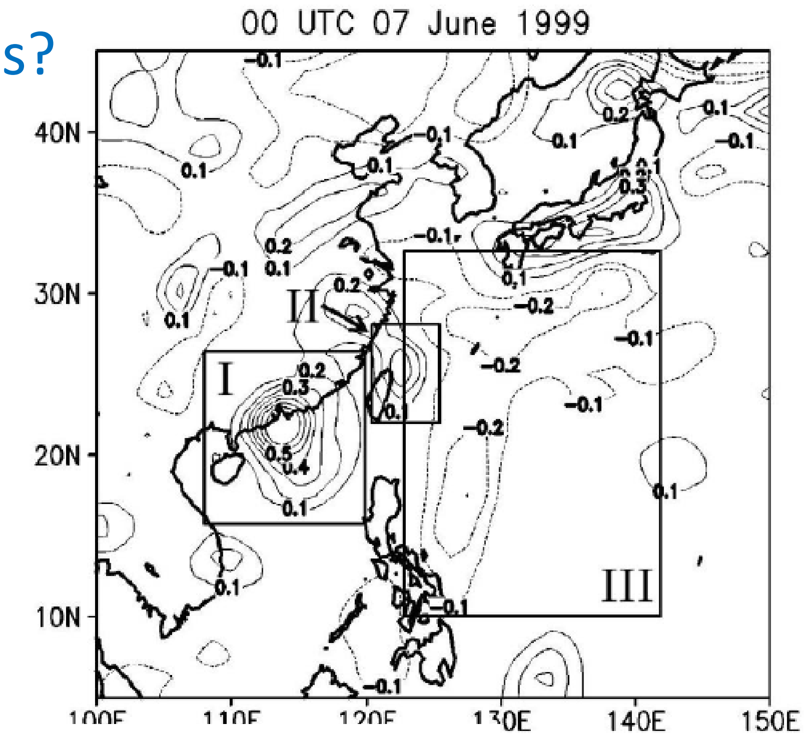
piecewise PV inversion

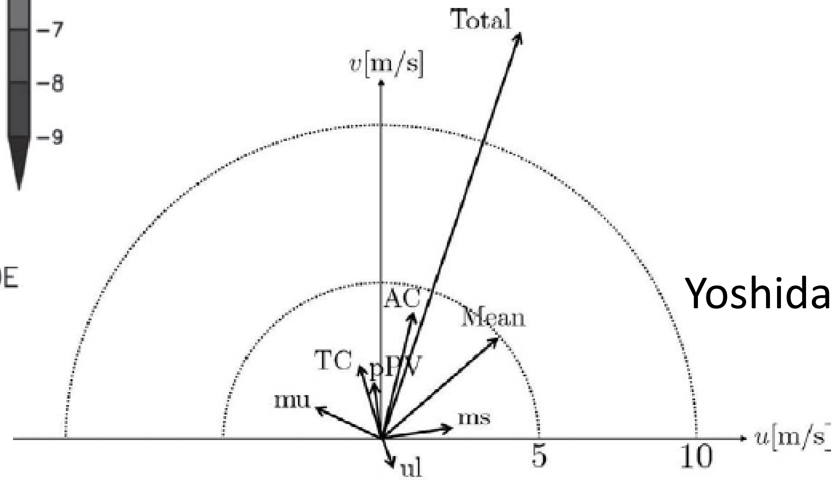
In which area does PV contributes to what extent of height and wind in some areas?

QG → nonlinear balanced inversion
Davis and Emanuel (1991), Davis (1992)



Moisture flux and its convergence



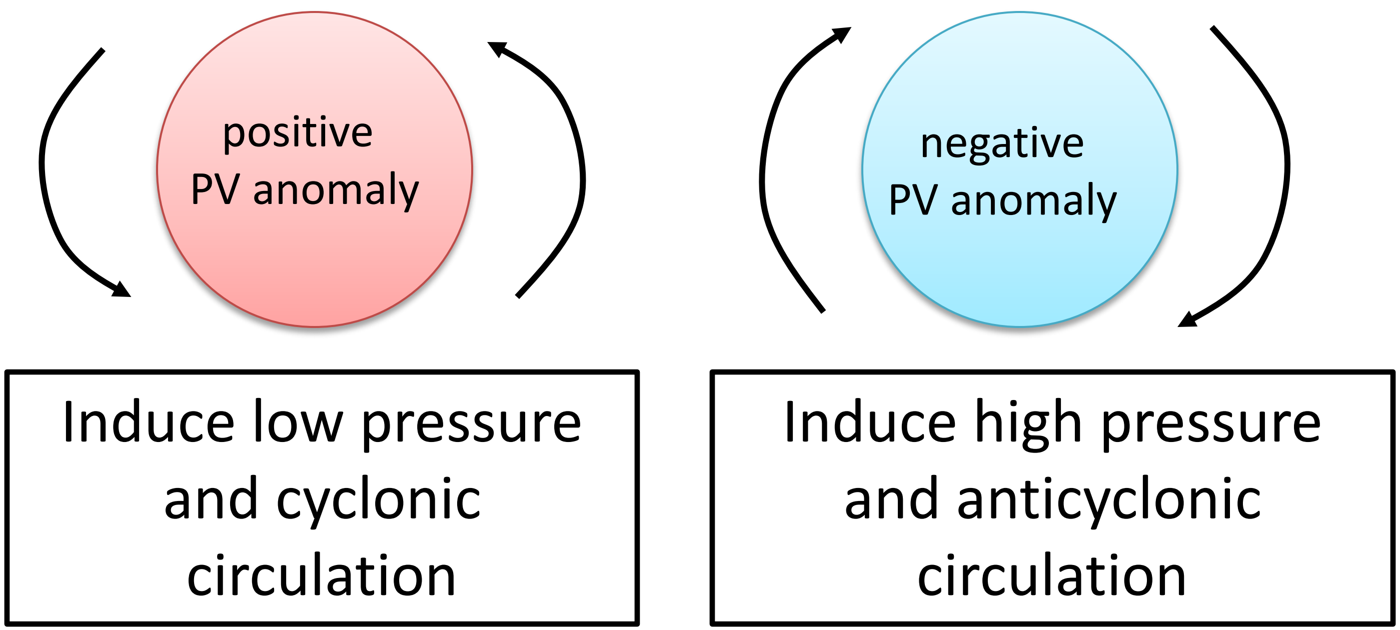


Yoshida and Itoh (2012)

Piecewise Potential Vorticity Inversion

Davis and Emanuel (1991), Davis (1992a,b)

PV anomaly defined as the difference between PV at an arbitrary time and time-averaged PV is partitioned into several regions → Height and wind induced by each PV anomaly



3. Vortex-vortex interaction

3-1 Basic idea

3-2 Vortex-vortex interaction

Blocking

3-3 Small vortex embedded in a large vortex

MJO

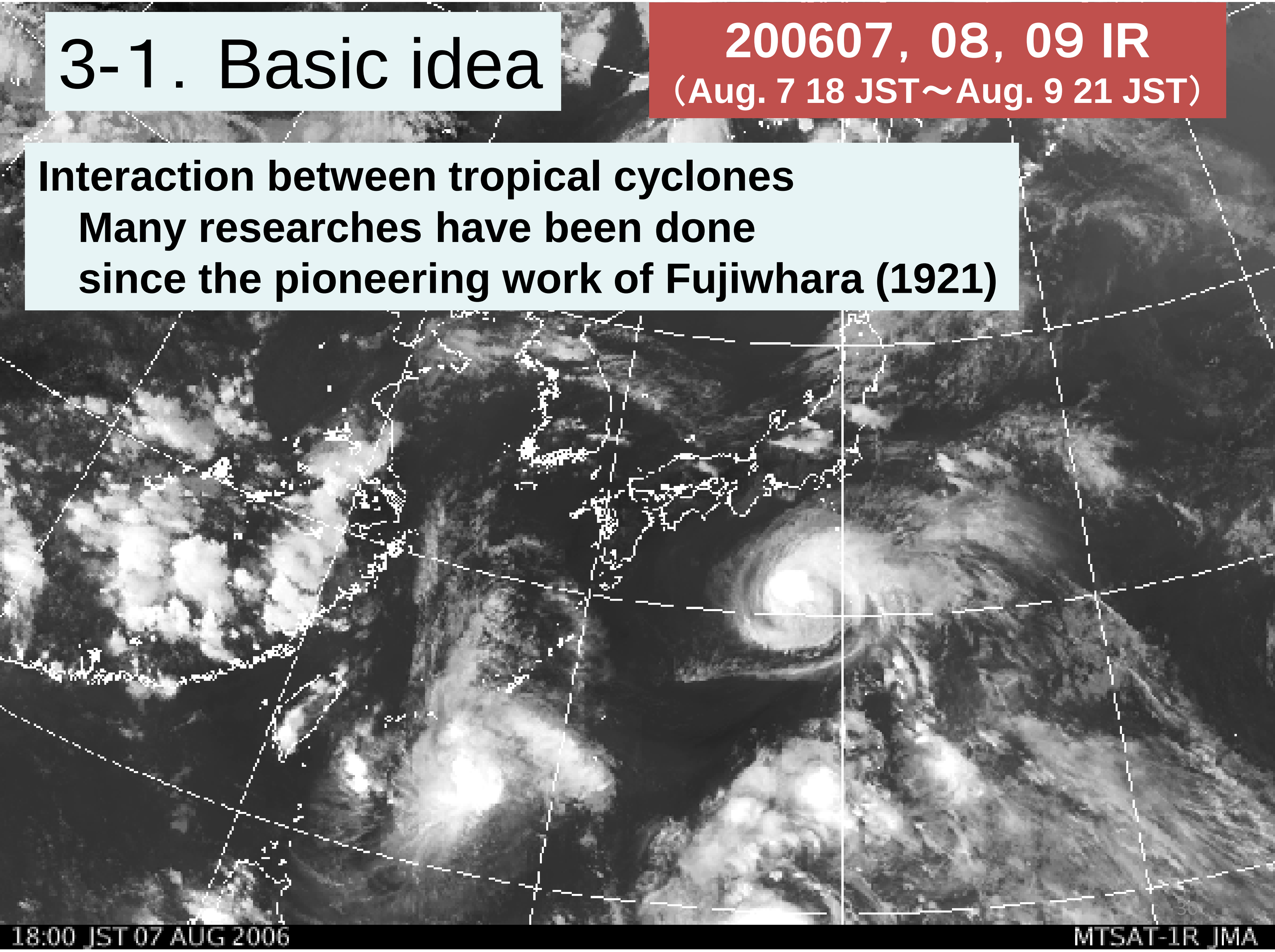
3-4 Size of tropical cyclones

3-1. Basic idea

200607, 08, 09 IR
(Aug. 7 18 JST～Aug. 9 21 JST)

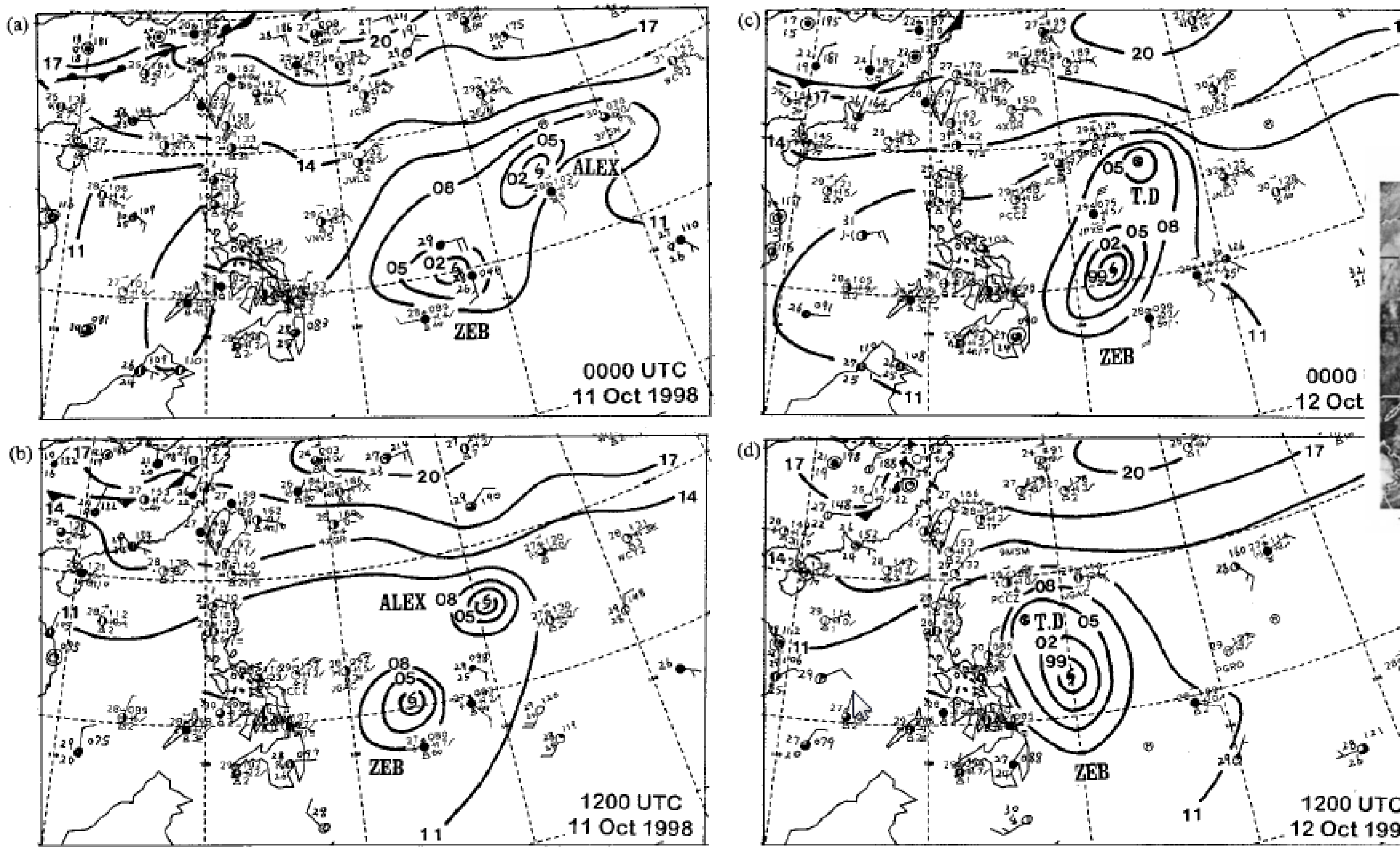
Interaction between tropical cyclones

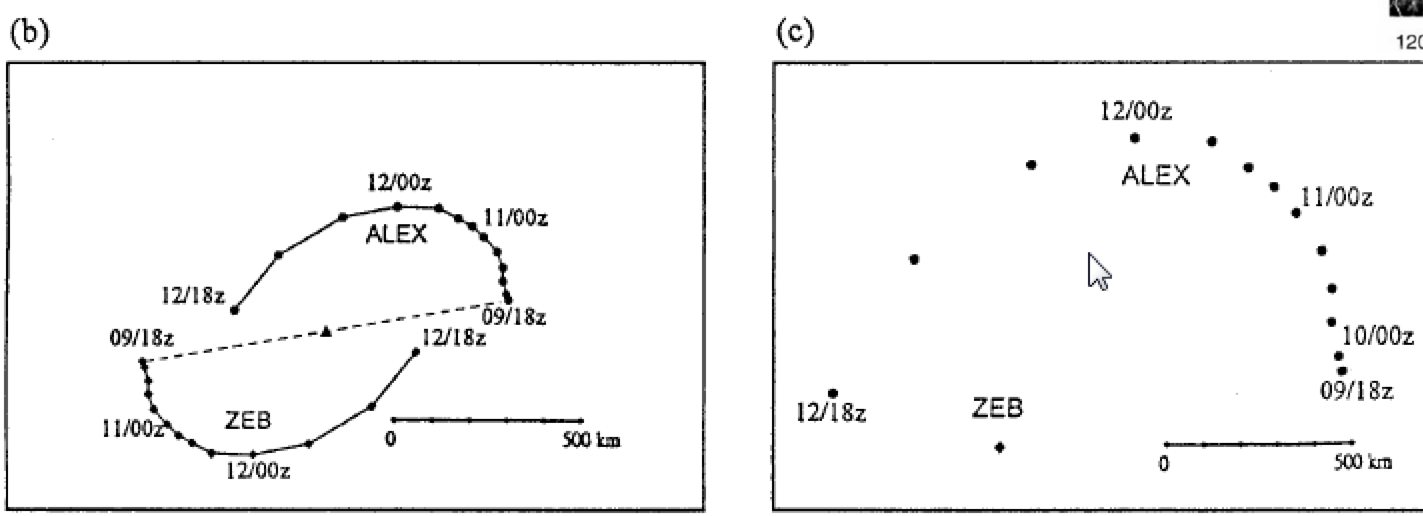
Many researches have been done since the pioneering work of Fujiwhara (1921)

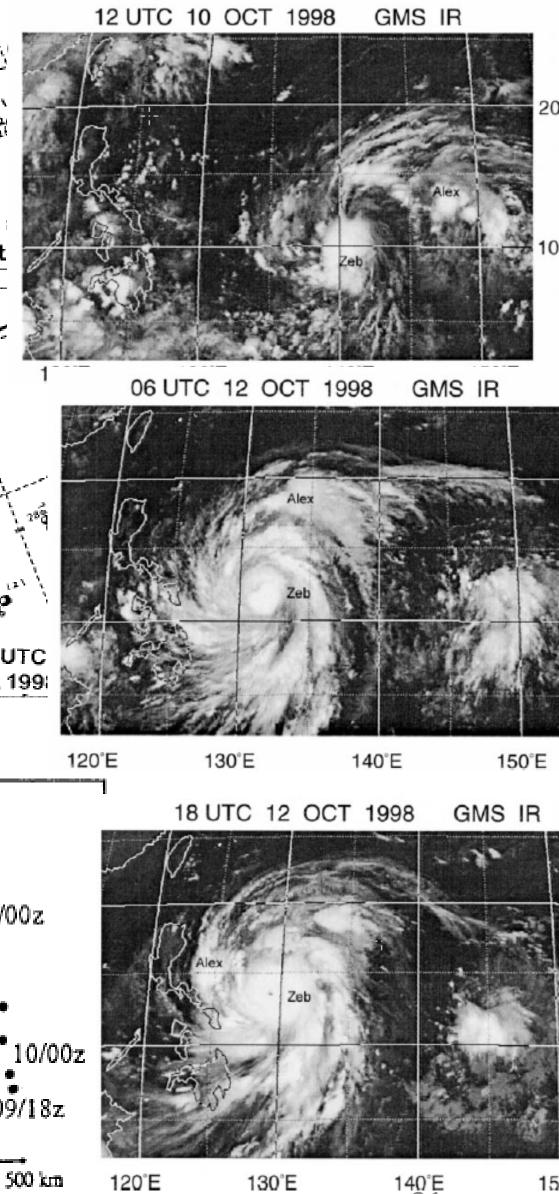


Merger of Zeb and Alex

Kuo et al. (2000)







This is one example of vortex-vortex interaction

However, there are many vortex-vortex interactions in the atmosphere (and oceans)

⇩

We (with many students) have gradually recognized that the idea of vortex-vortex interactions gives wide perspective in the atmospheric sciences.

TC research ⇨ many other research fields

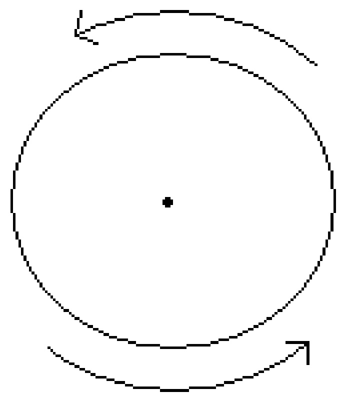
Consider vortex motion as vorticity transport

barotropic , nondivergent (2D)
vorticity：conserved quantity

Case of one vortex（axisymmetric）

Vorticity transport： $v\zeta$

v ：tangential wind velocity
ζ ：vorticity



・net transport is zero

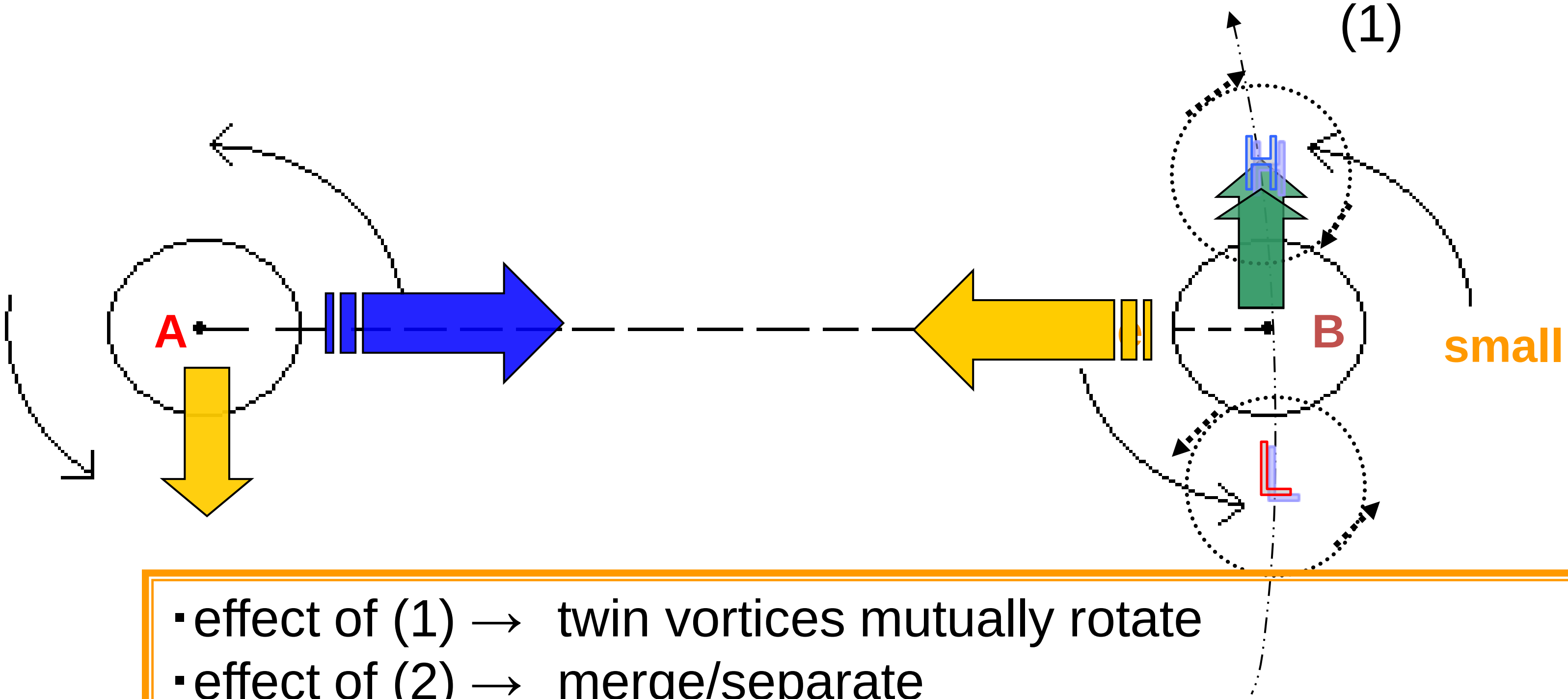
DeMaria and Chan (1984)

Case of twin vortices from the l.h.s. vortex

Vorticity transport:

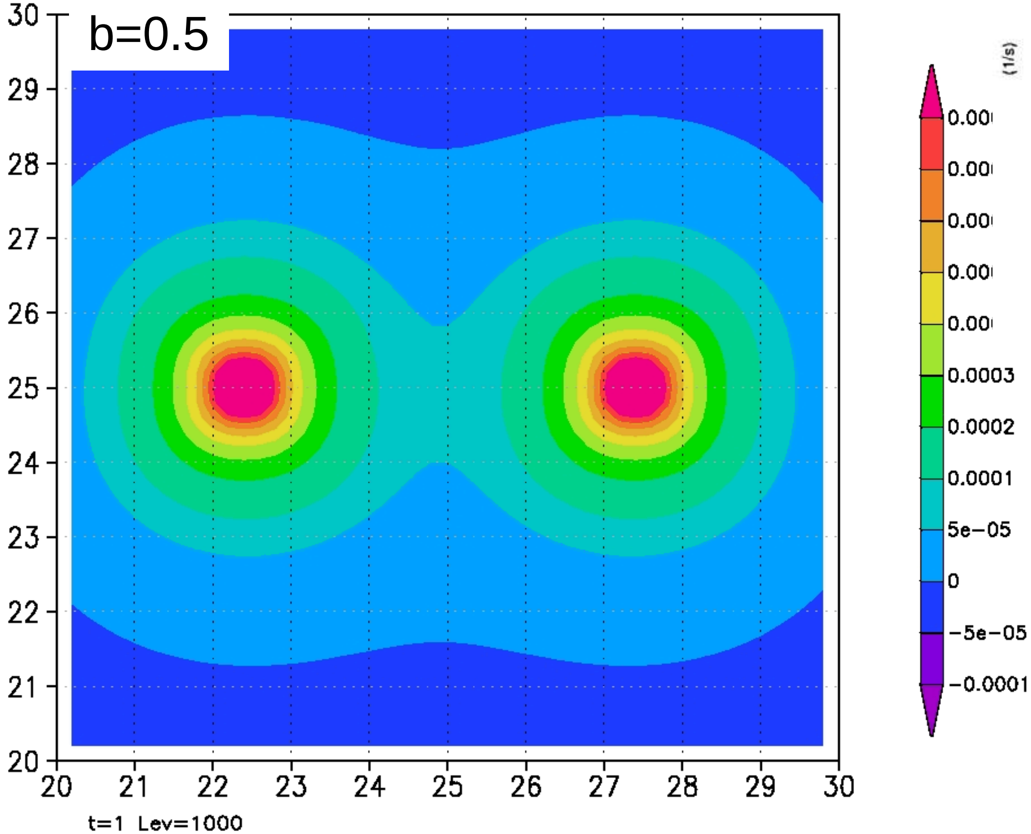
$$(\boldsymbol{v}_a + \boldsymbol{v}_b)(\zeta_a + \zeta_b)$$

$$= \underline{\boldsymbol{v}_a\zeta_a + \boldsymbol{v}_b\zeta_b} + \underbrace{\boldsymbol{v}_a\zeta_b}_{(1)} + \underbrace{\boldsymbol{v}_b\zeta_a}_{(2)}$$

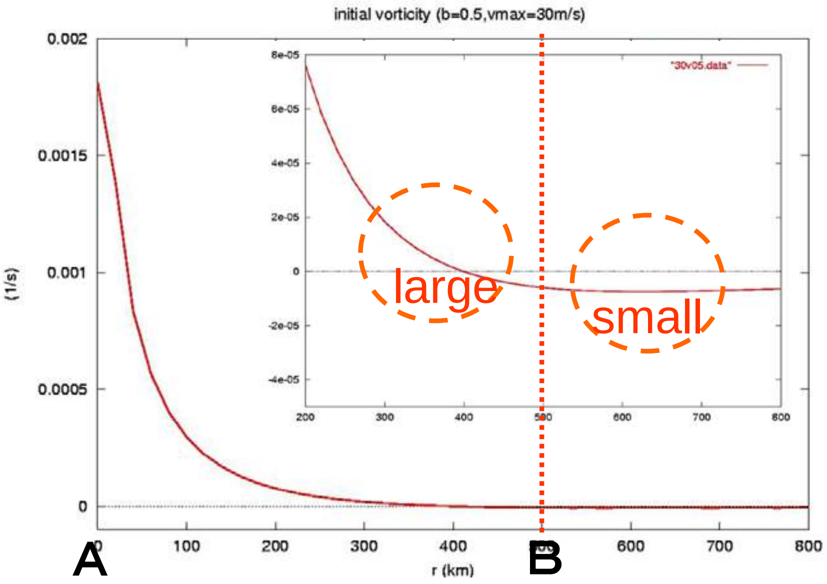


- effect of (1) → twin vortices mutually rotate
- effect of (2) → merge/separate
- effect of (2) → slow down/speed up the rotational velocity by (1)

Interaction of binary vortices with the same polarity



Each 3 hours

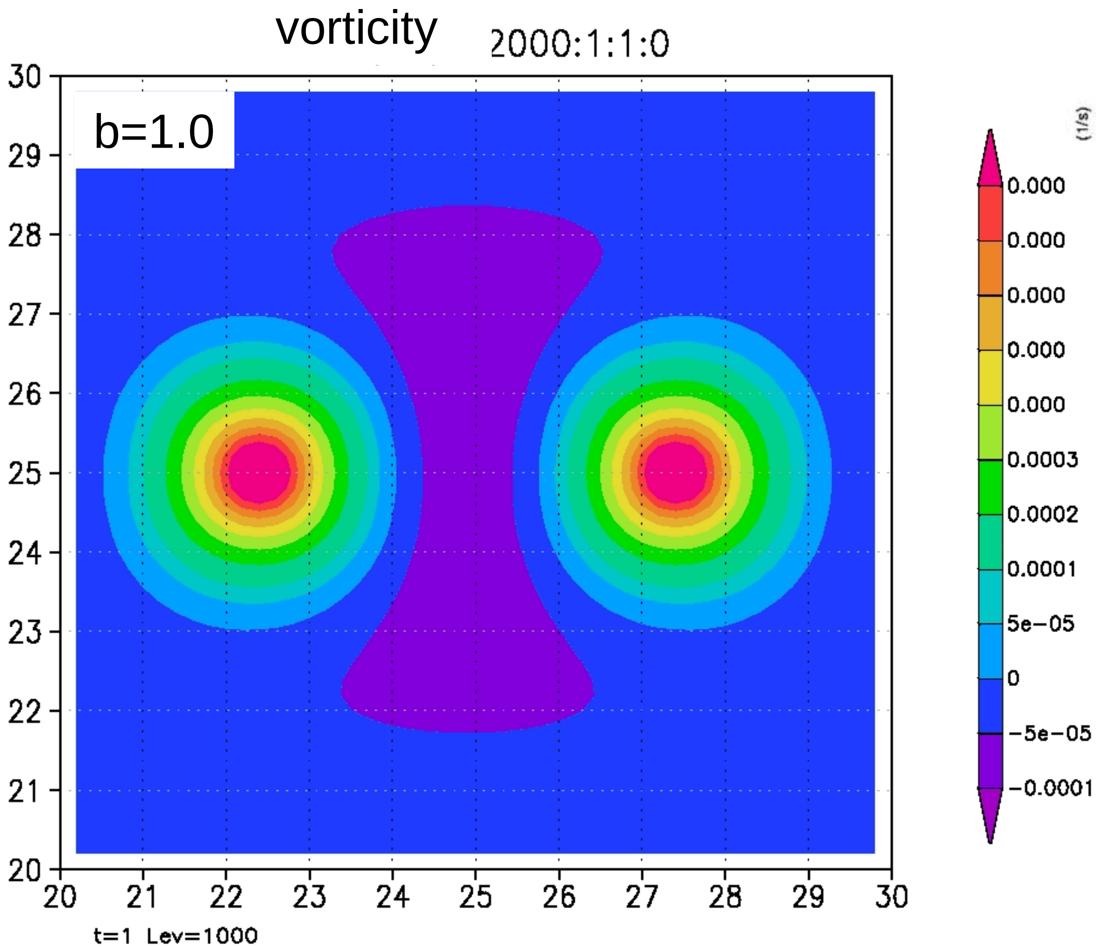


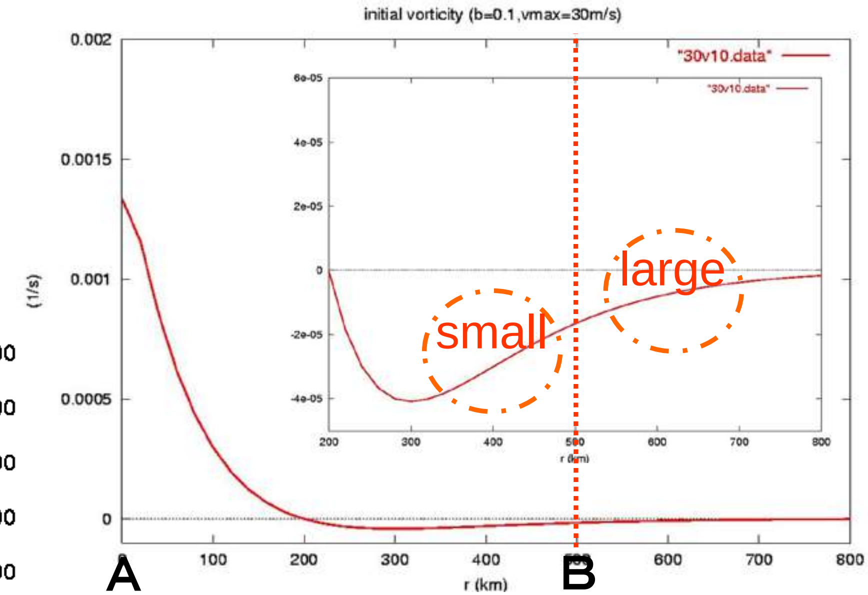
merger

- mutually rotate and merge

←

- Initial vorticity is relatively large in the inner side.





separation

▪separate without one rotation

←

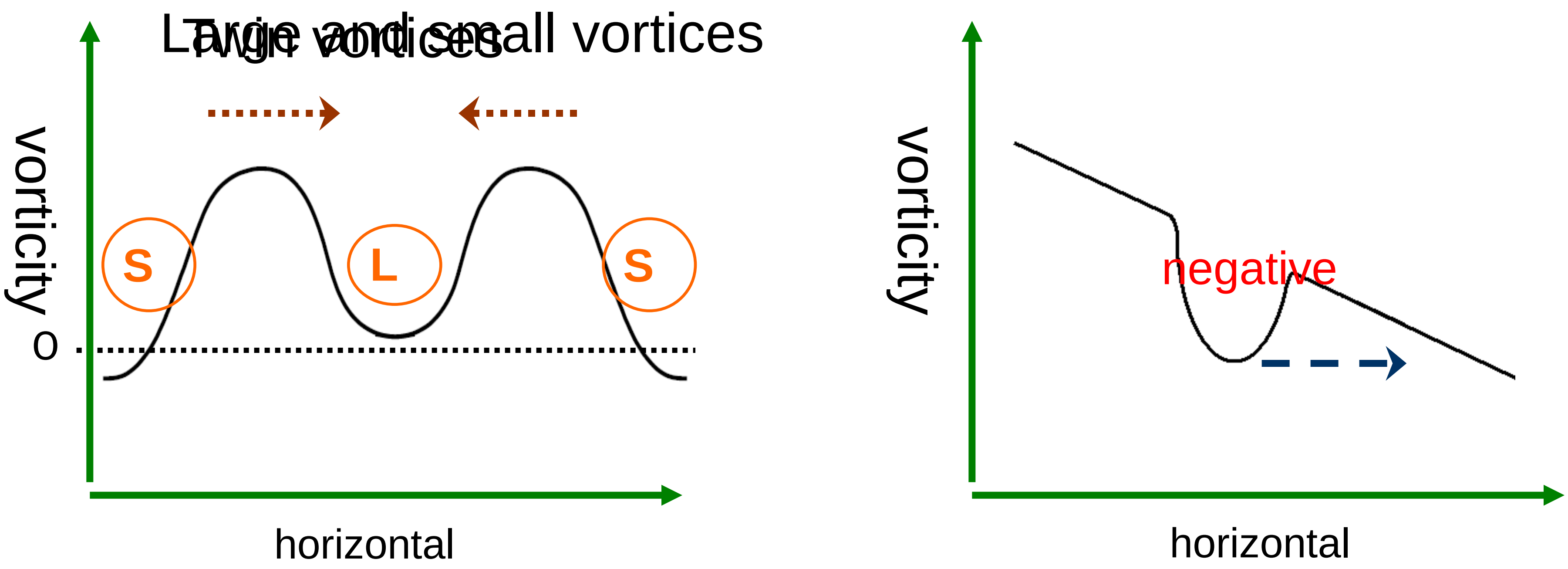
▪Initial vorticity is relatively large negative in the inner side.

Each 3 hours

Merge/separarion of binary vortices can be explained by the initial vorticity distributin.

However, it is not easy to fully understand even this process.
Papers related to this topic are still published.

Generalization



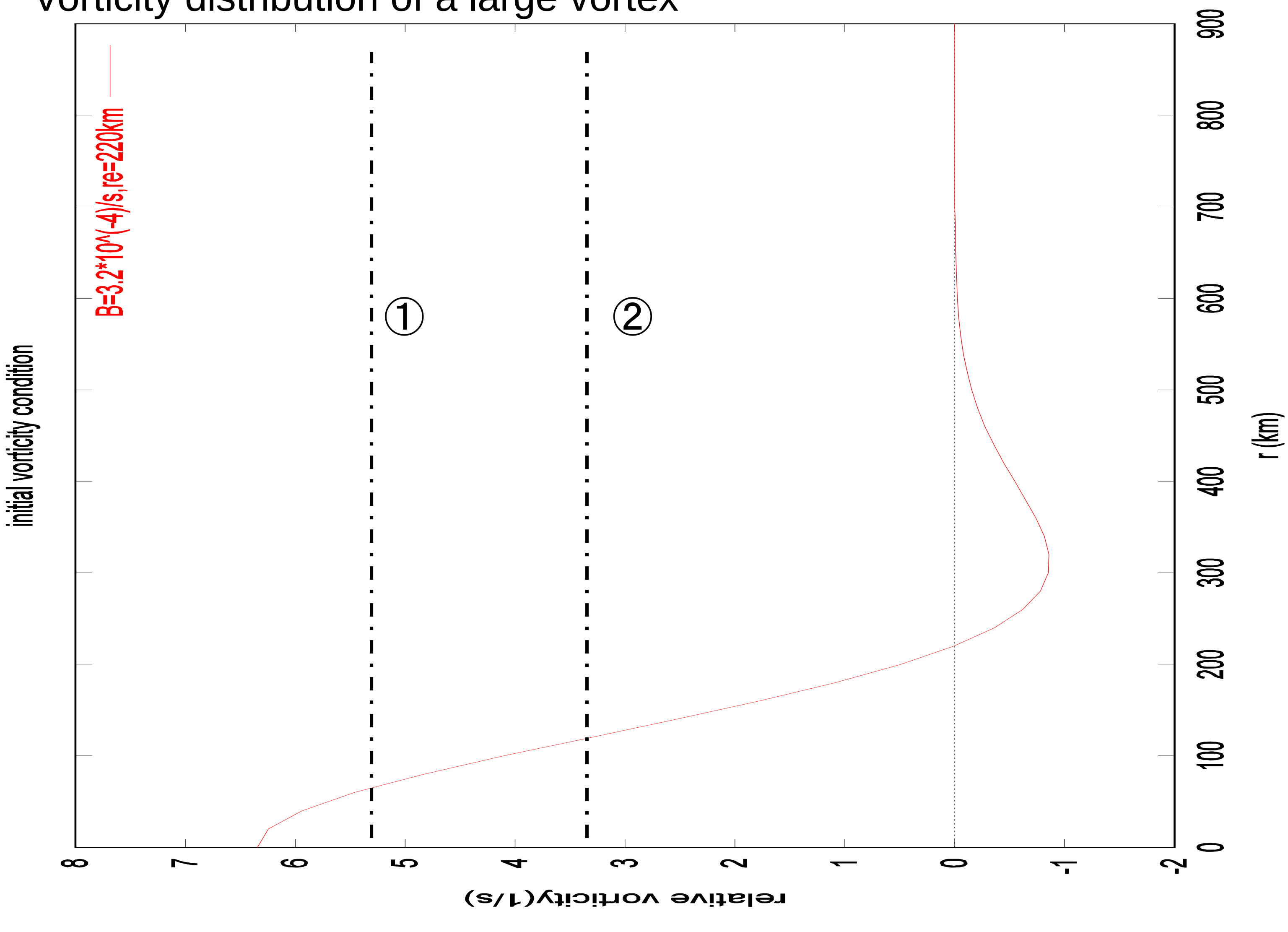
S: small

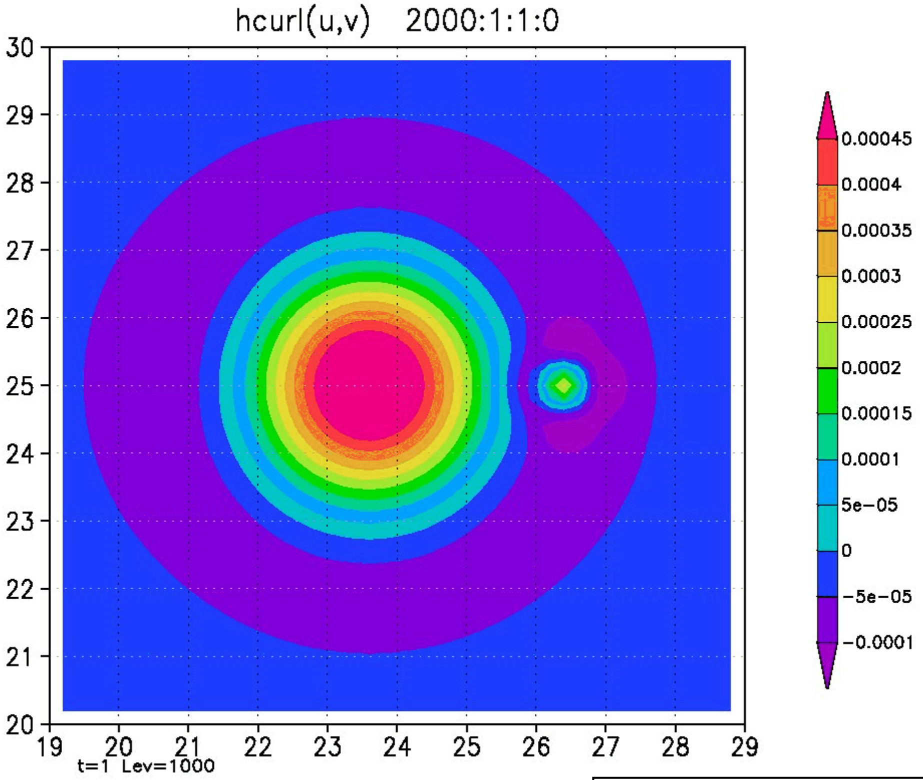
L: large

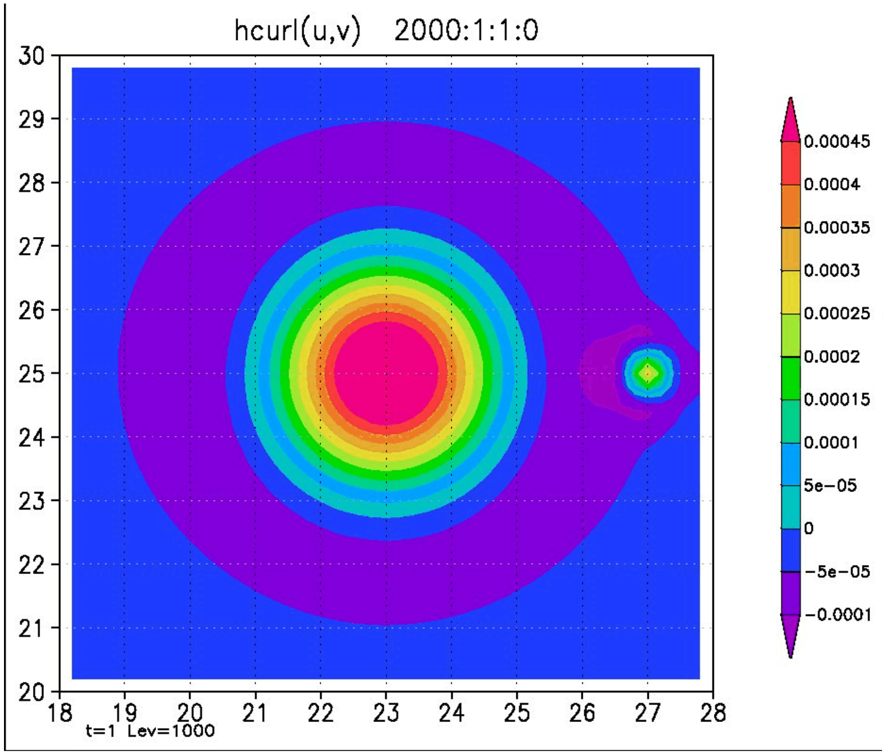
Reversal of vorticity gradient = instability

Relationship between large and small vortices

Vorticity distribution of a large vortex







(1) d = 240 km

Time evolution of vorticity

(2) d = 400 km

Merger/separation is determined by the vorticity gradient of the large vortex.

Earth and TC ← motion of (1)

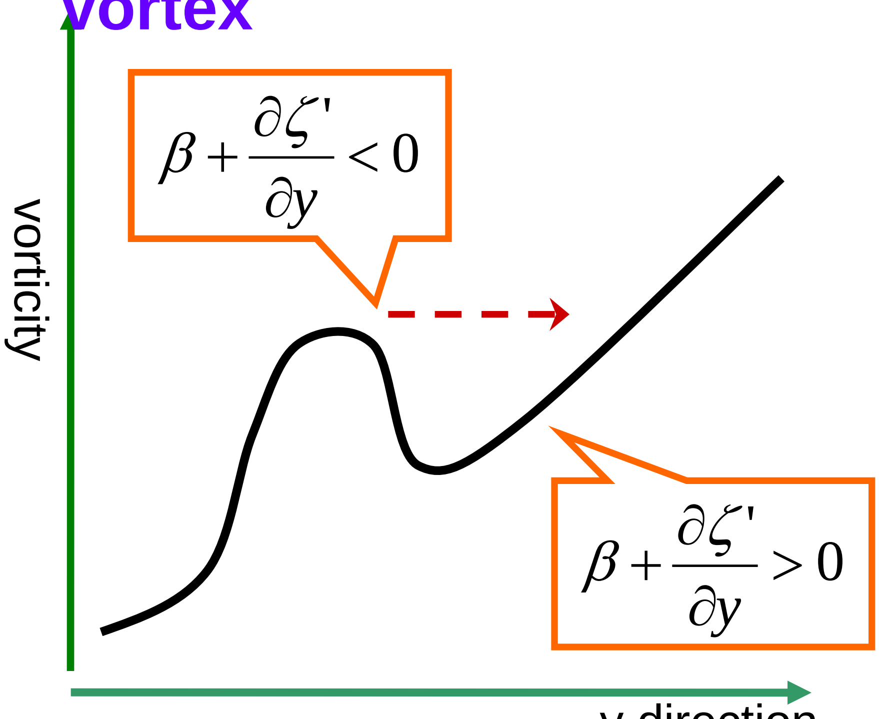
⇒ Small vortex move into the center of a large vortex

⇒ Northwestward movement of TCs

vorticity：conserved quantity

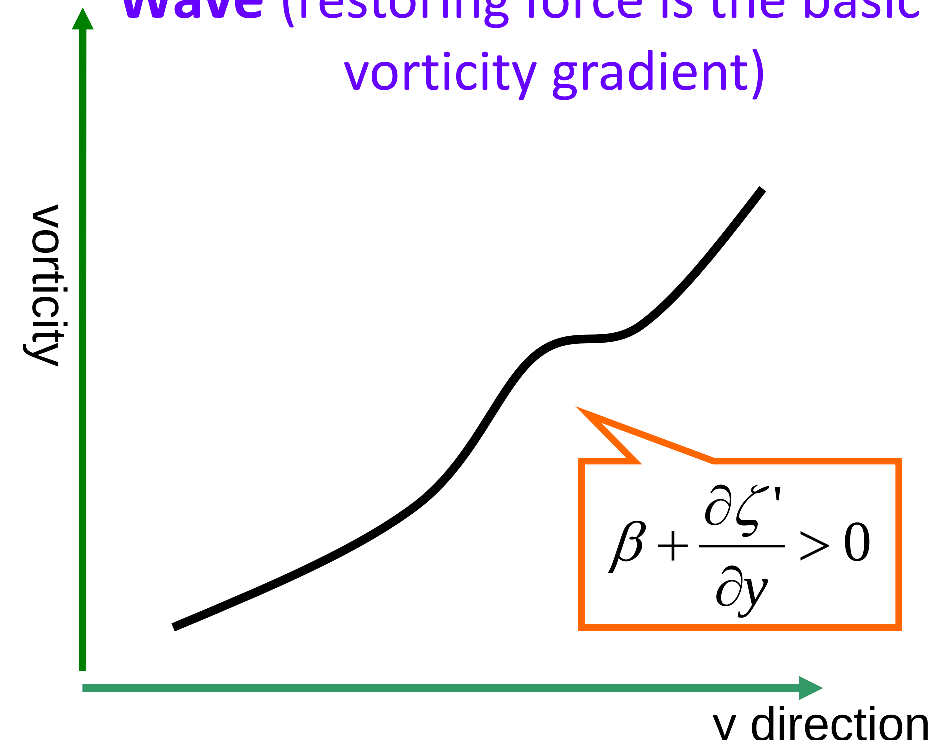
Reversal of vorticity gradient

vortex



No reversal

Wave (restoring force is the basic vorticity gradient)



Equation system； barotropic , nondivergent vorticity equation

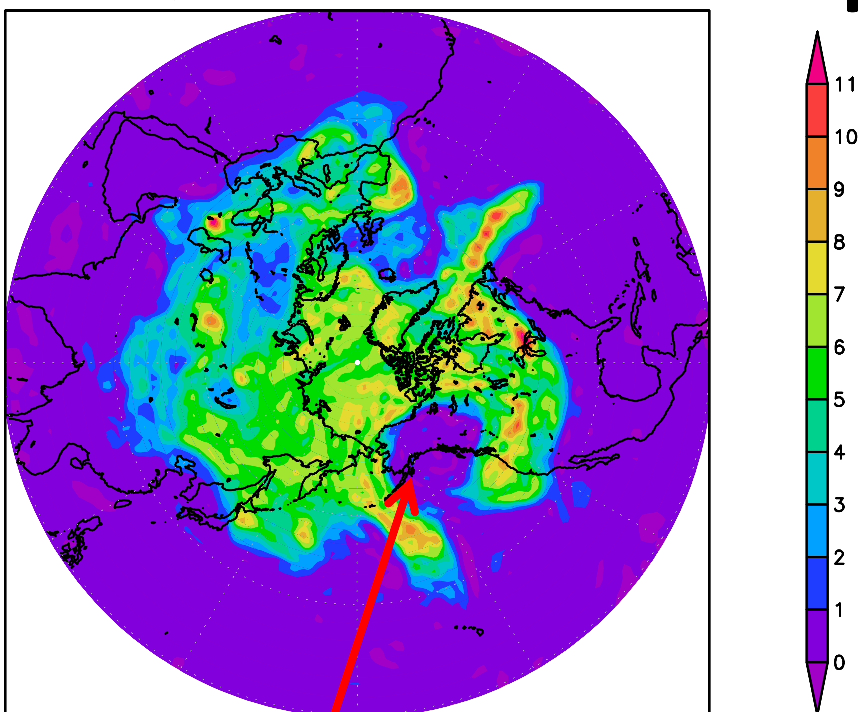
The same is applicable if eqs. have the form of the horizontal advection of conserved quantity

Conserved quantity	vorticity	→ Absolute vorticity	→ PV	Same eq.
field	barotropic	Barotropic β	3D	

PV

Conserved quantity in 3 dimensional fields

Latitudinal gradient : Restoring force of Rossby waves

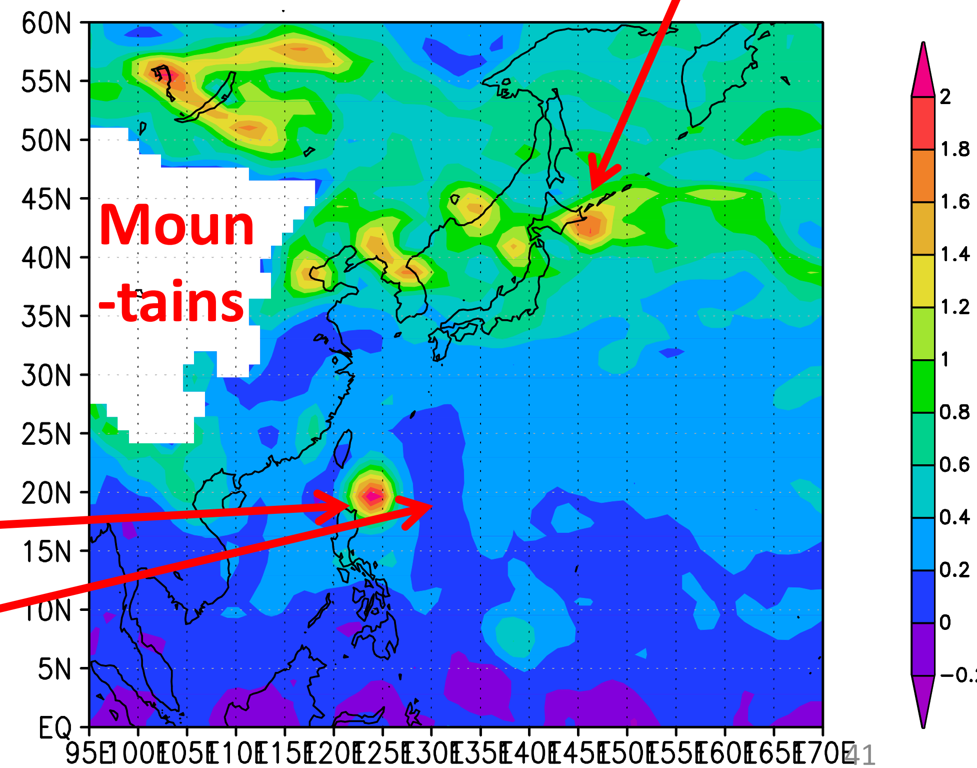


PV at 320 K surface on 28 Feb.1 996

Blocking is an anticyclonic vortex

Baiu front is composed of many vortices

PV at 310 K surface on 18 July 1991



TC

Low PV ← Yoshida and Itoh (2012)

Application to various phenomena

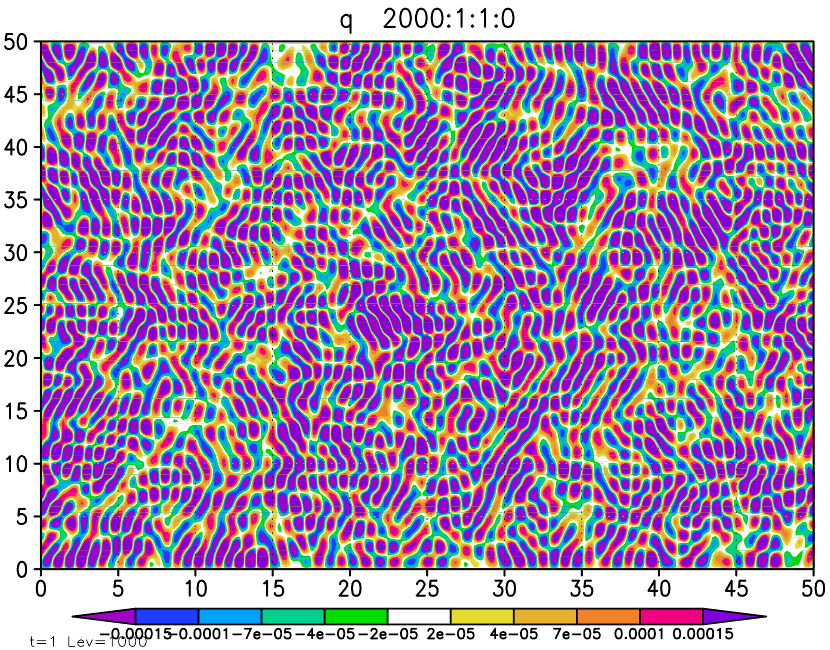
More general vortex -vortex interaction

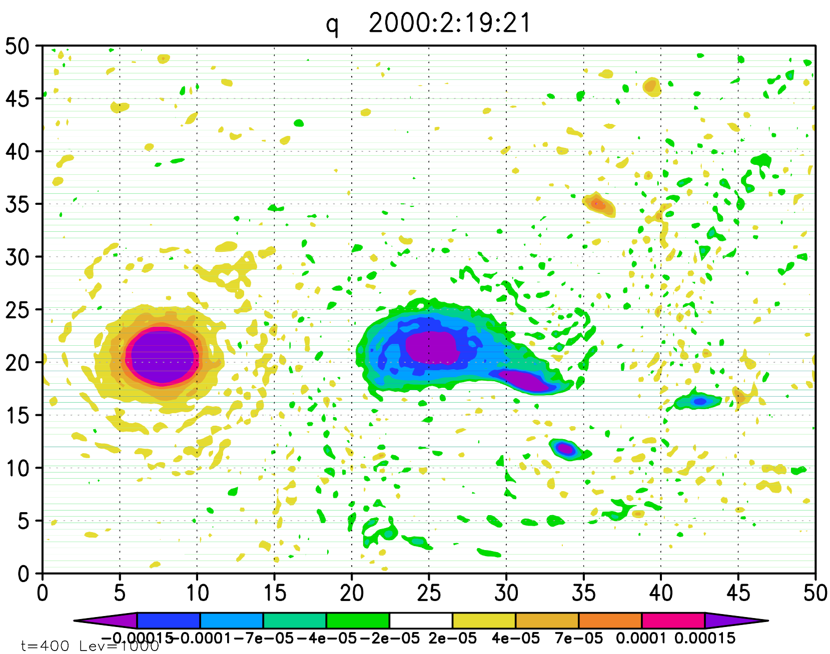
← Binary TCs

・2D turbulence （interaction among many small vortices）
・Tropical cyclogenesis in winter
・Baiu front and TCs
・Baiu front and vortices in it
（cyclonic “vortex” extending zonally and small cyclonic vortices）
・Blocking high and synoptic anticyclones
（large anticyclonic vortex and small anticyclonic vortices）
・Stationary lows and synoptic cyclones
（large cyclonic vortex and small cyclonic vortices）

However, it is important to make settings and contents proper to individual problems.

Two-dimensional turbulence （β=0）





Time evolution of vorticity field

2D turbulence has been considered so far from the standpoint of the wavenumber space

→ Easy to understand physically to consider it from vortex-vortex interaction.

2枚削除

Applications

3-2. Maintenance mechanism of blocking

Vortex-vortex interaction

Yamazaki, A., and H. Itoh, 2012: Vortex--vortex interactions for the maintenance of blocking. Part I: The selective absorption mechanism and a case study. *J. Atmos. Sci*., **70**, 725-742.

Yamazaki, A., and H. Itoh, 2012: Vortex--vortex interactions for the maintenance of blocking. Part II: Numerical experiments. *J. Atmos. Sci*., **70**, 743-766.

3-3. Slow moving speed of the MJO

Vortex within a vortex (Earth)

Hayashi and Itoh 2013: in preparation

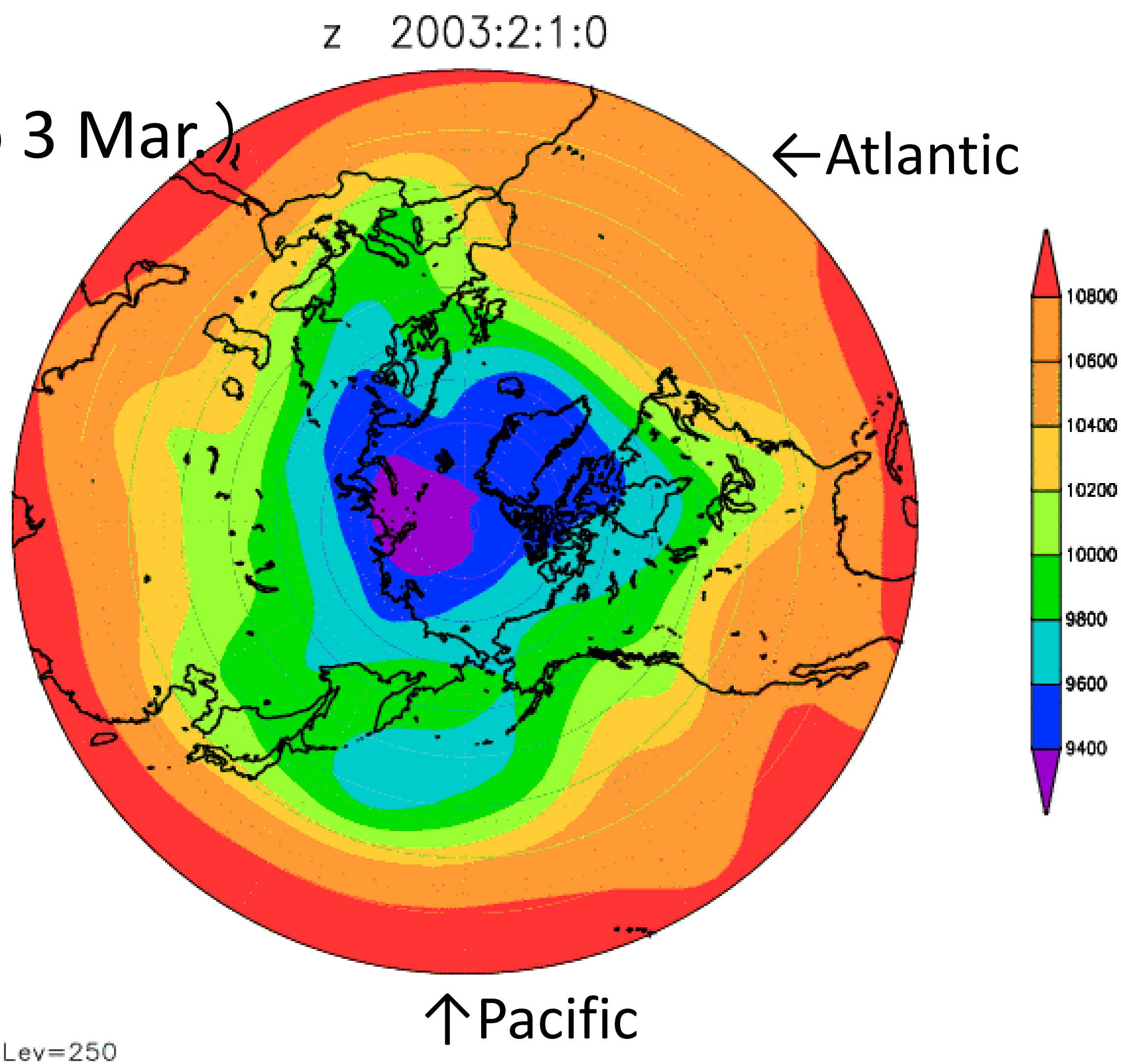
3-4. Size of TCs

Small vortices within a large vortex (TC)

Tsuji and Itoh 2013: in preparation

Blocking

250 hPa height
（each 1 day,
From 1 Feb. to 3 Mar.）



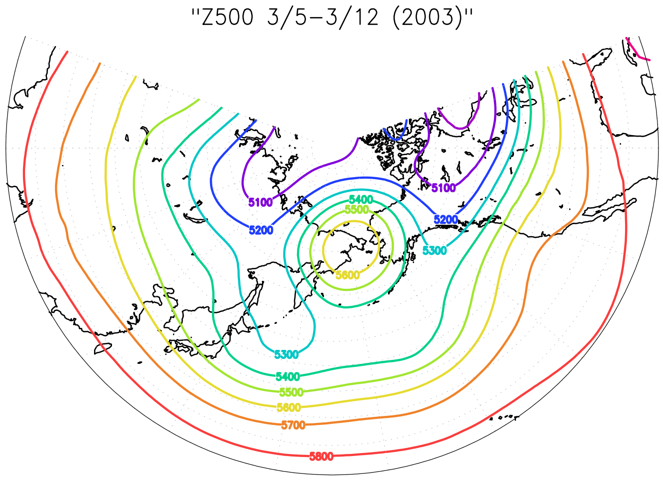
Large anticyclone in high-latitudes (blocking high)

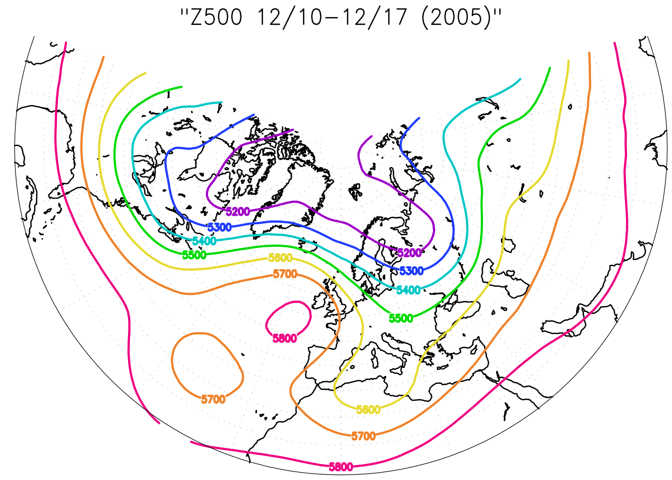
Persists for long periods.

Shapes of blocking

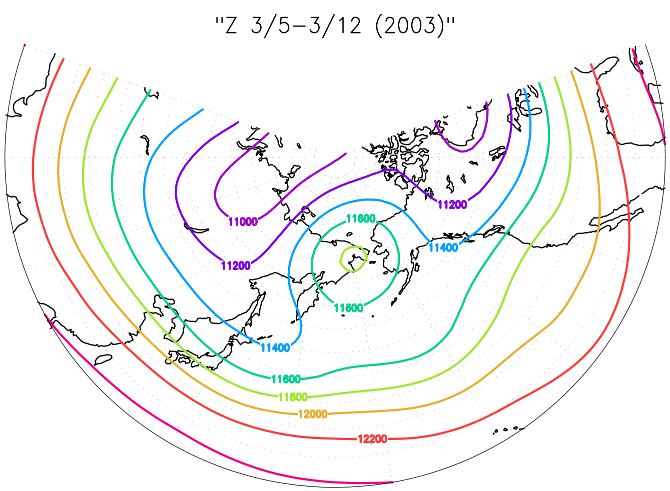
Ω-type

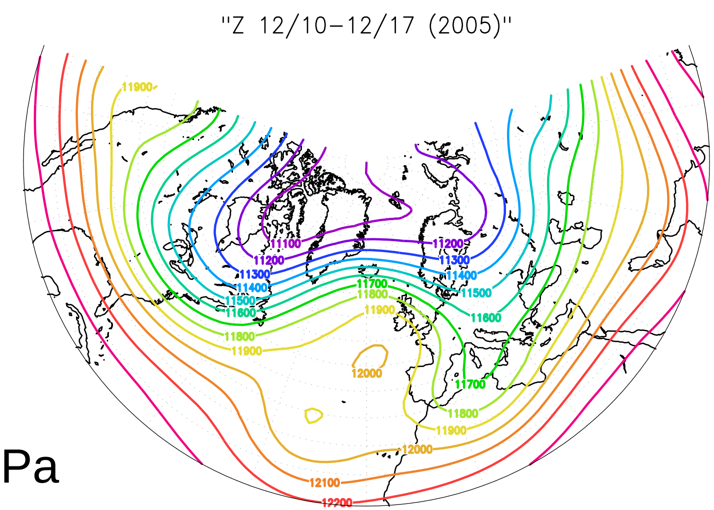
Dipole-type





500 hPa

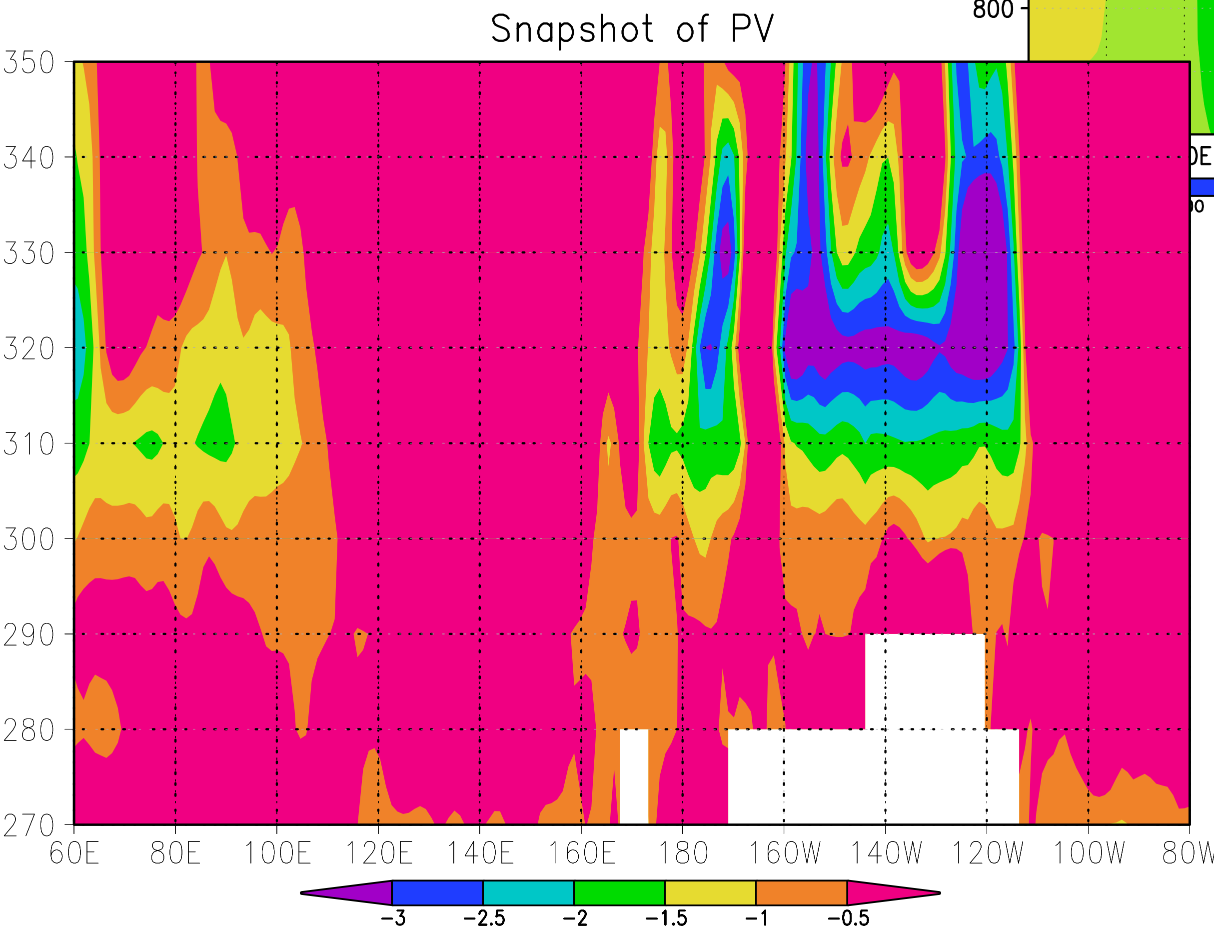


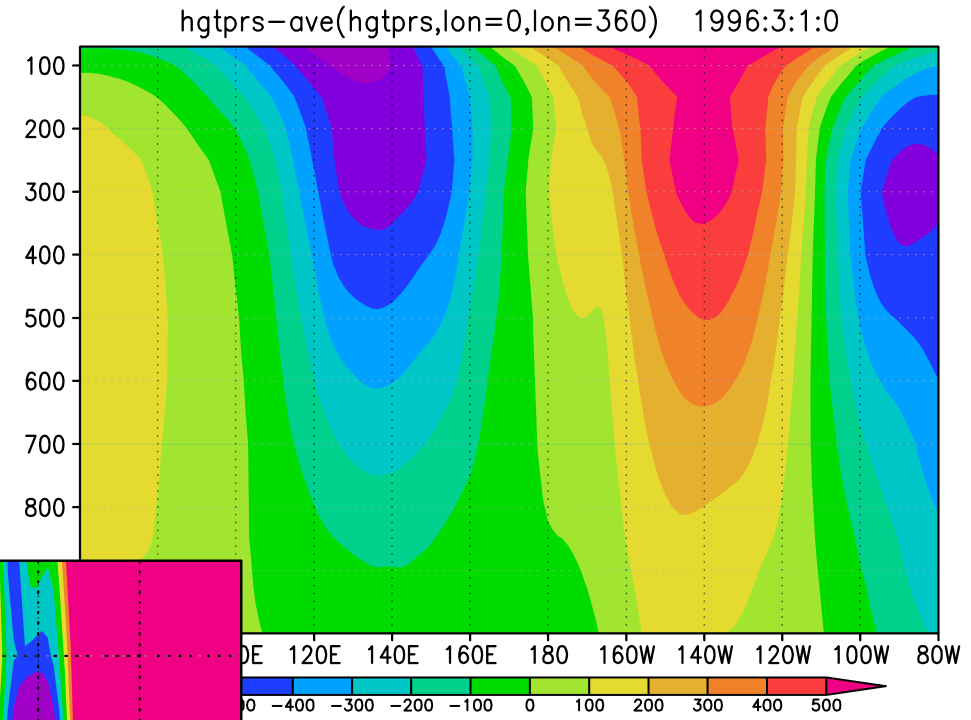


250 hPa

00 UTC 1 Mar. 1996
60°N

PV anomaly





Height anomaly

Equivalent-barotropic structure

Large negative PV anomaly near 320 K surface

Characteristics of blocking

- Long persistency（~10日）
- To “block” synoptic eddies
- Regions of frequent occurrence relation to synoptic eddies
  East sides of the Pacific and Atlantic
  = Downstream of jet streams
- Equivalent-barotropic structure single level
- Close relationship to anomalous weather

Mechanisms of blocking

No established theory

"The last unresolved, difficult problem in the 20th century" (Kimoto 1993)

Here, we tackle the maintenance mechanism, which is different from the formation mechanism, since these two have different time scales.

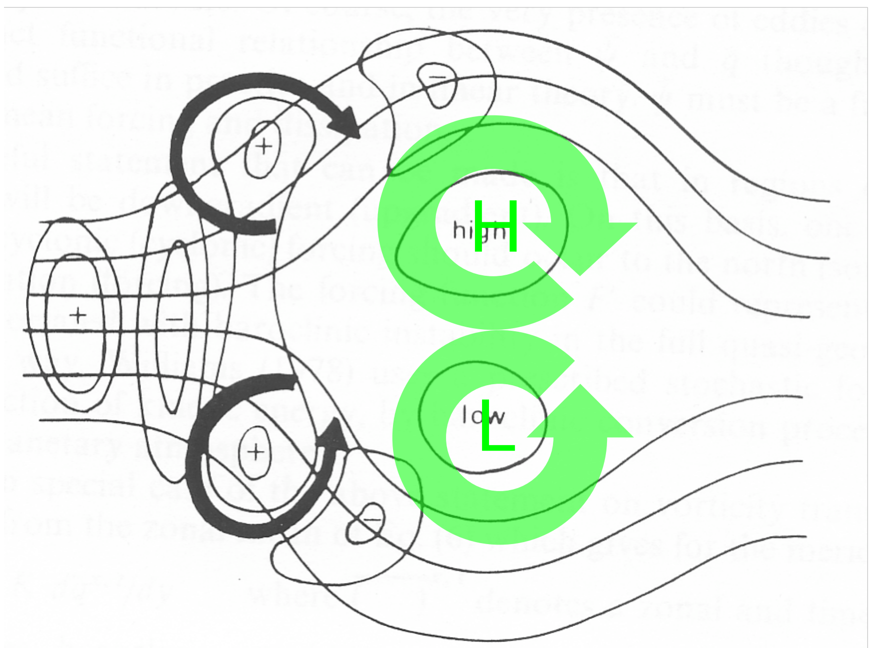
Highly influential hypothesis of block maintenance

Eddy Straining Mechanism (ESM)

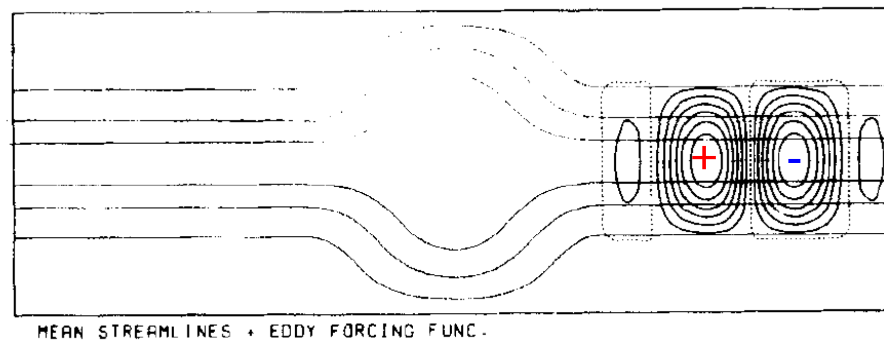
Shutts (1983)

straining of synoptic eddies → upward cascade of energy (maintenance)

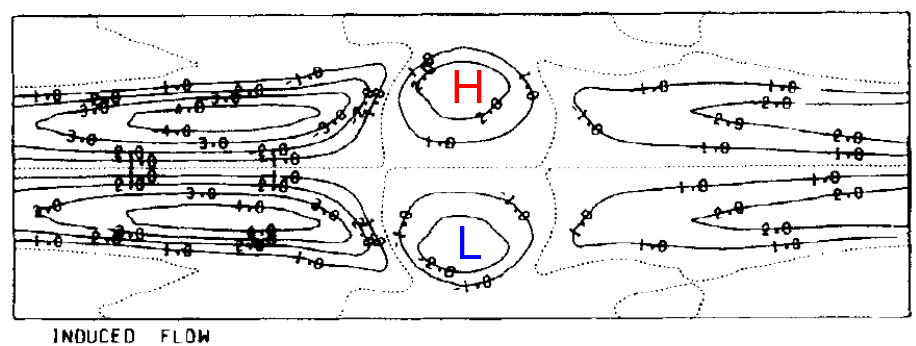
- ❖ wavemaker: artificial forcing to generate synoptic eddies



wavemaker & blocking flow



Second-order induced flow

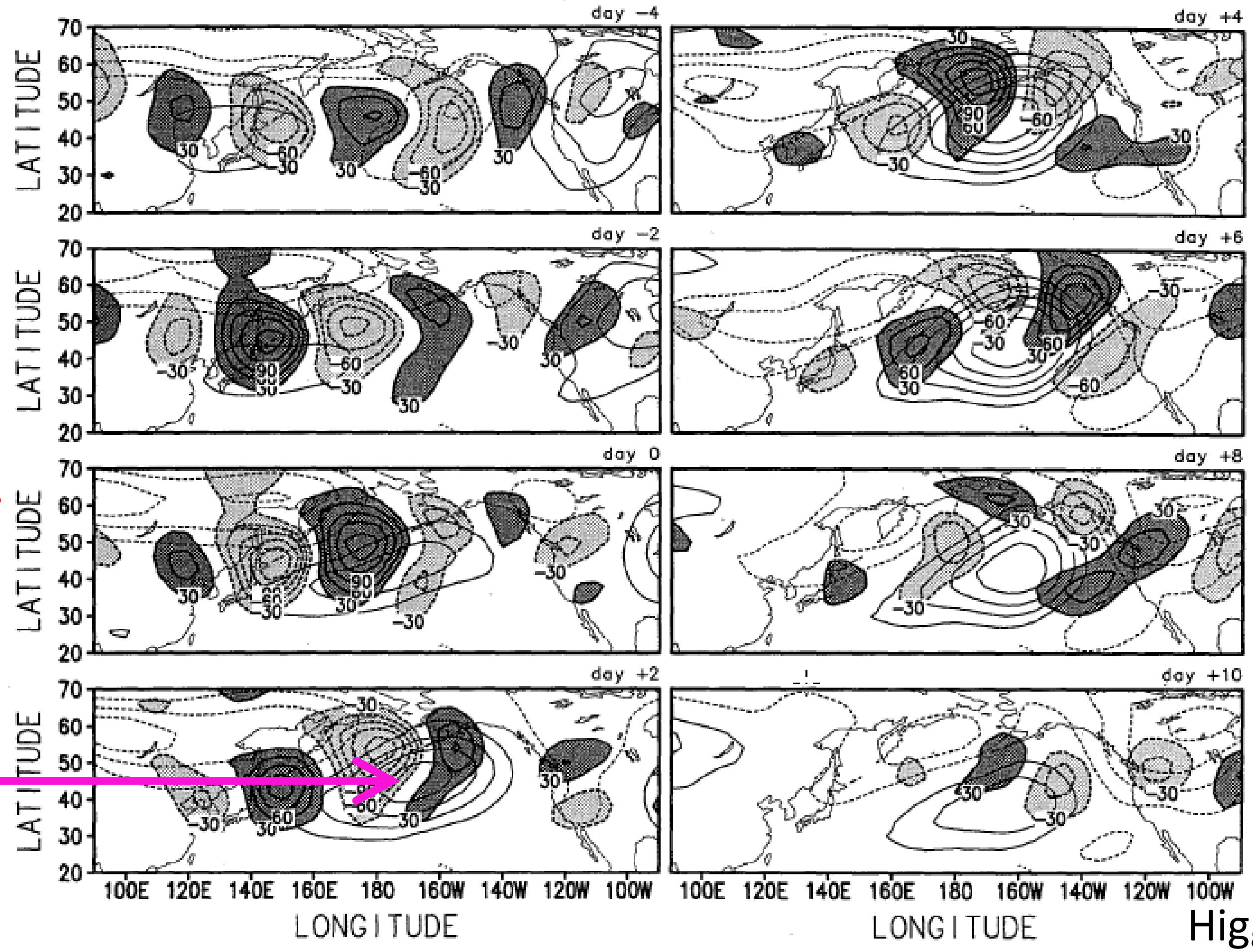


Eddy feedback by eddy straining

Example of analyses of straining

bandpass filtered 500-hPa heights (thick contours, shaded)

Onset of blocking



Higgins and Shubert (1994)

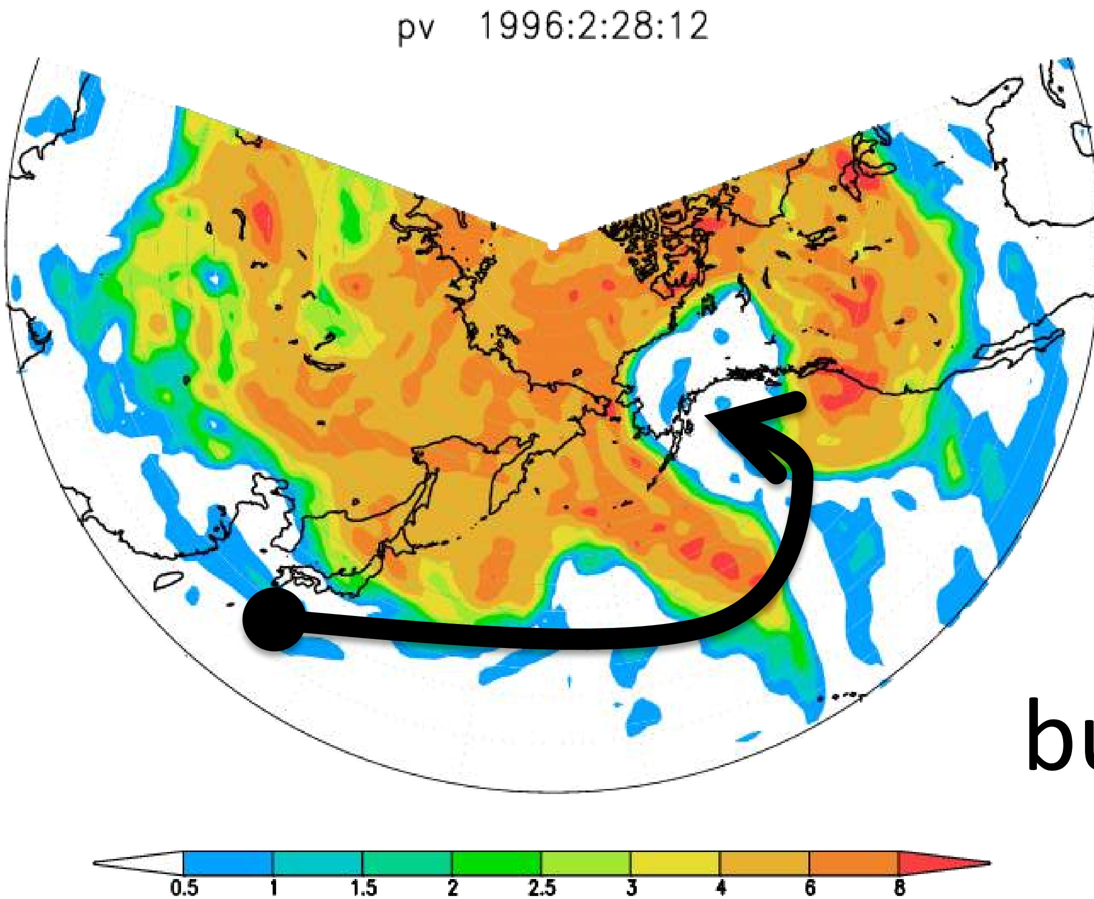
However, recently, many drawbacks have been recognized.

ESM is fragile. e.g., meridional shift of stormtrack

New proposal

Selective Absorption Mechanism (SAM)

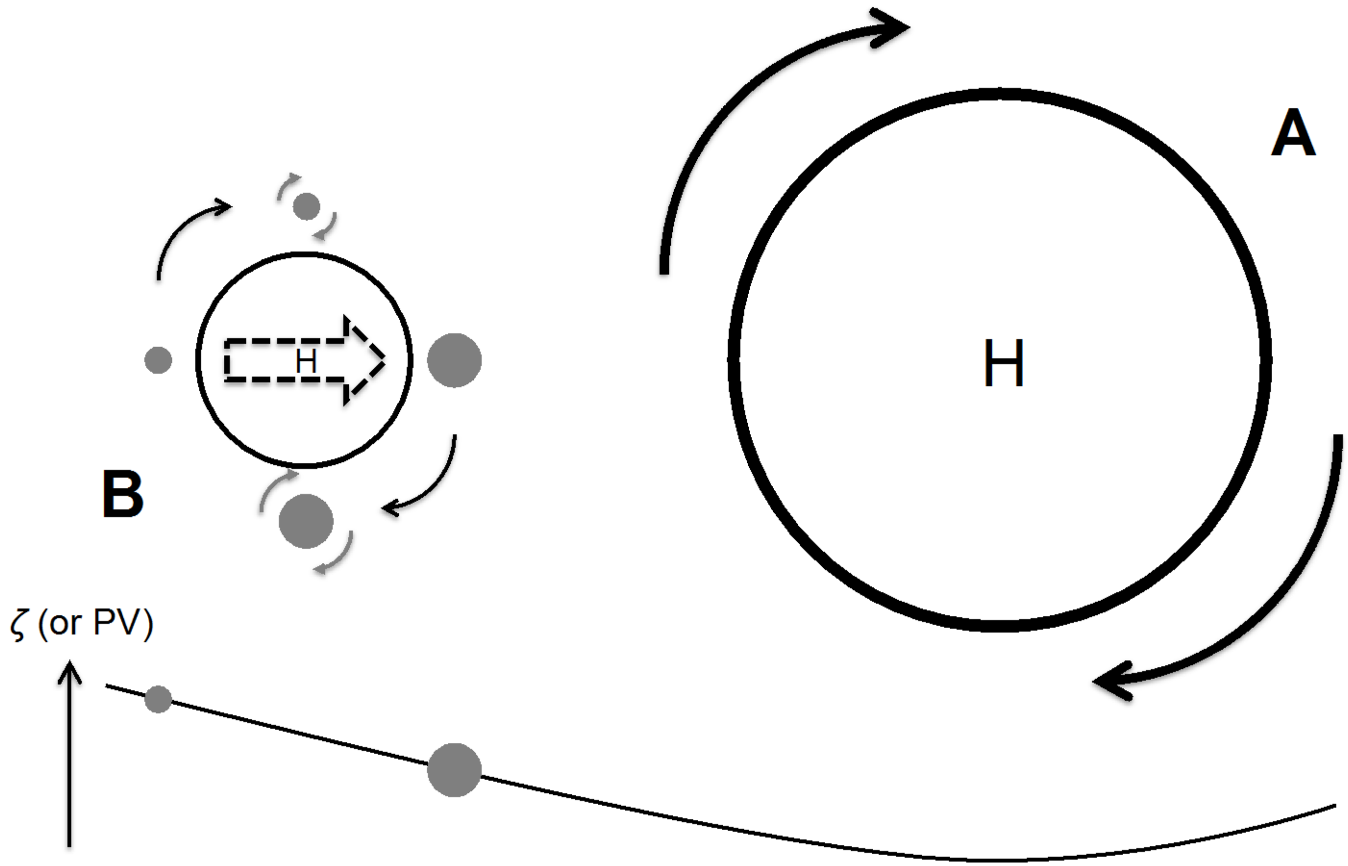
Supply of low PV **(conserved quantity)** from synoptic anticyclones to a blocking high



but how?

Vortex-vortex interaction

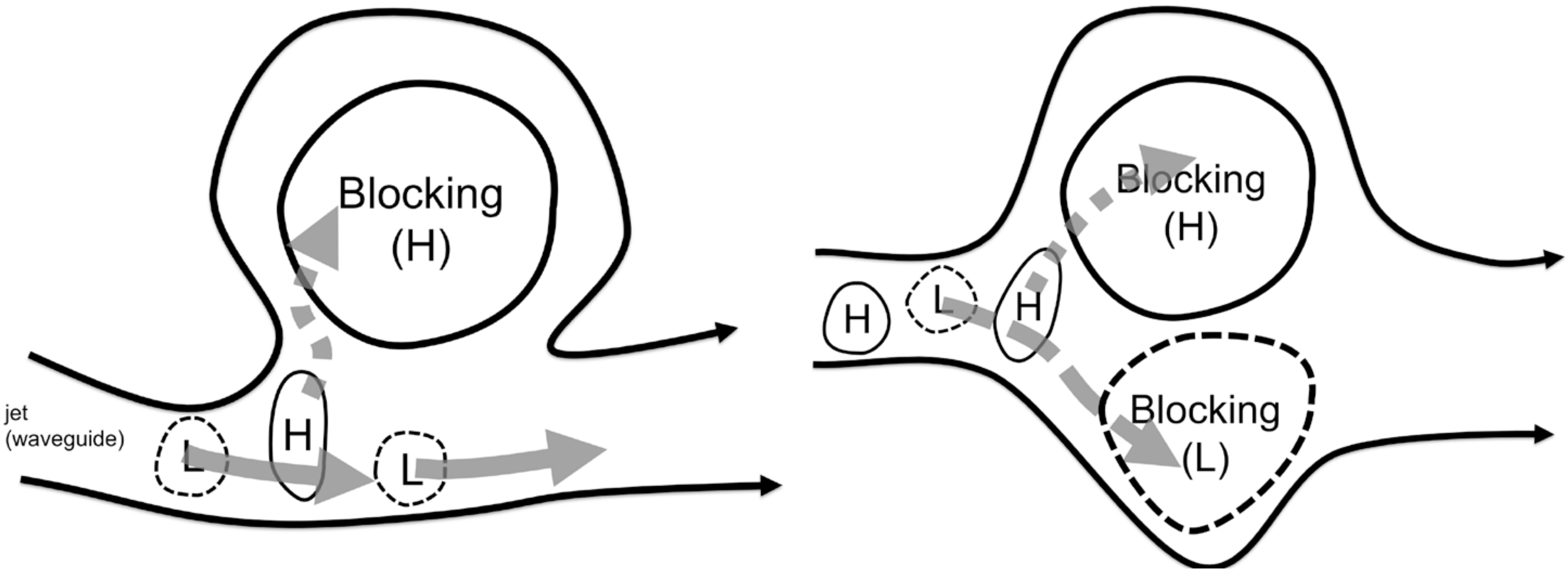
Vortex-vortex interaction (in terms of PV)
= β gyre (e.g., Cushman-Roisin 1994) or Fujiwhara effect



$$\frac{\partial \zeta}{\partial t} = -J(\psi,\zeta) = -J(\psi_A,\zeta_A) - J(\psi_B,\zeta_B) - J(\psi_A,\zeta_B) - J(\psi_B,\zeta_A)$$

Selective Absorption Mechanism (SAM)

Blocking anticyclone selectively absorbs synoptic anticyclones (air parcels with low PV), and can persist against dissipation.



Jet streams effectively transport synoptic eddies near blocking

Eddies: Equivalent-barotropic downstream of jets

Verification of SAM

- Does the selective absorption really occur ?
  →trajectory analyses
- Is it robust absorption to various parameter settings of stormtracks and eddies?
  →numerical experiments

Case studies

- Parcels originating from synoptic anticyclones & cyclones are tracked: **Forward trajectory** analysis

→ to check the selective absorption of synoptic anticyclones.

- Parcels in blocking anticyclones are traced backwardly: **Backward trajectory** analysis

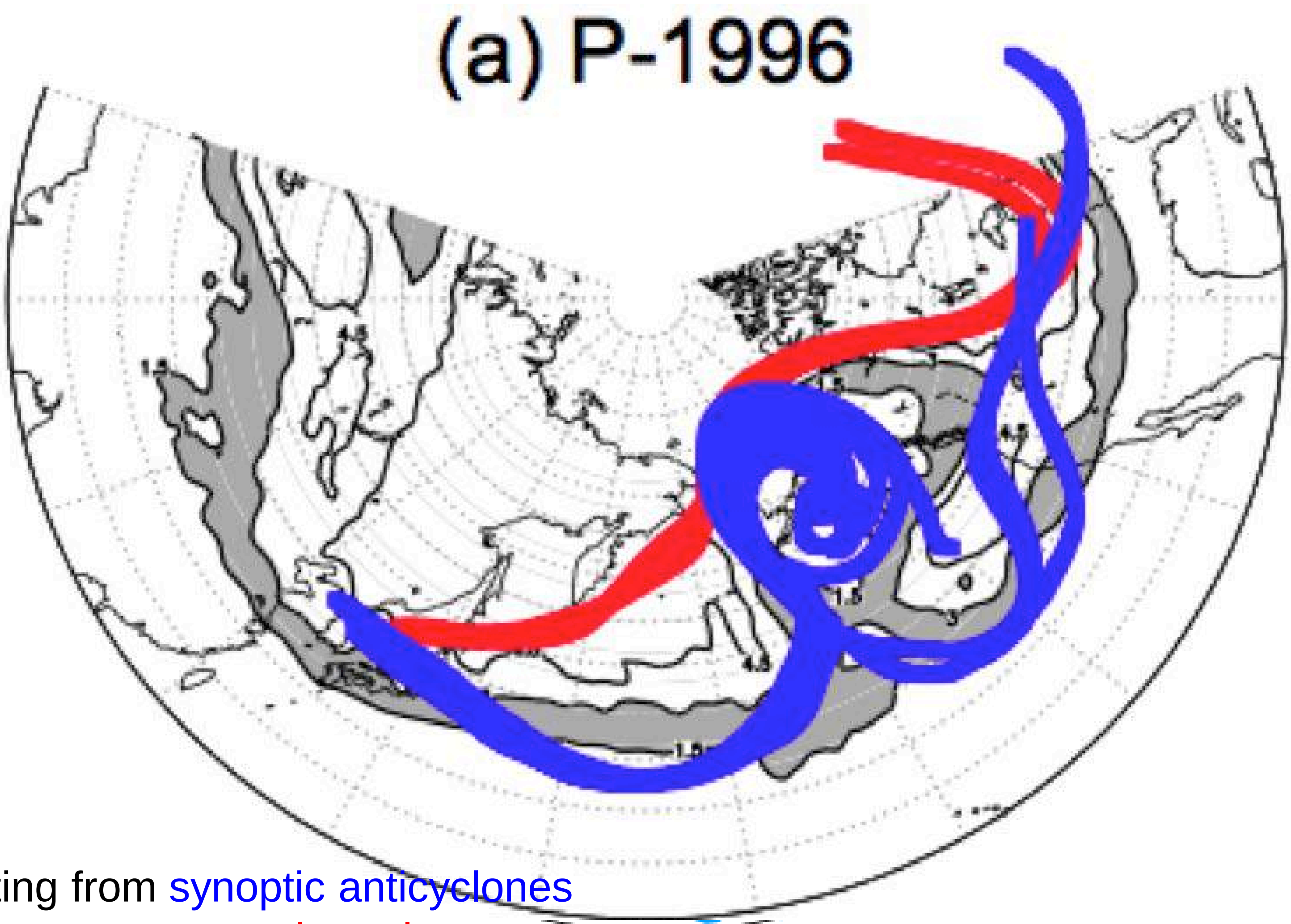
→ to search the main contributor for the low-PV supply.

Data : JRA-25

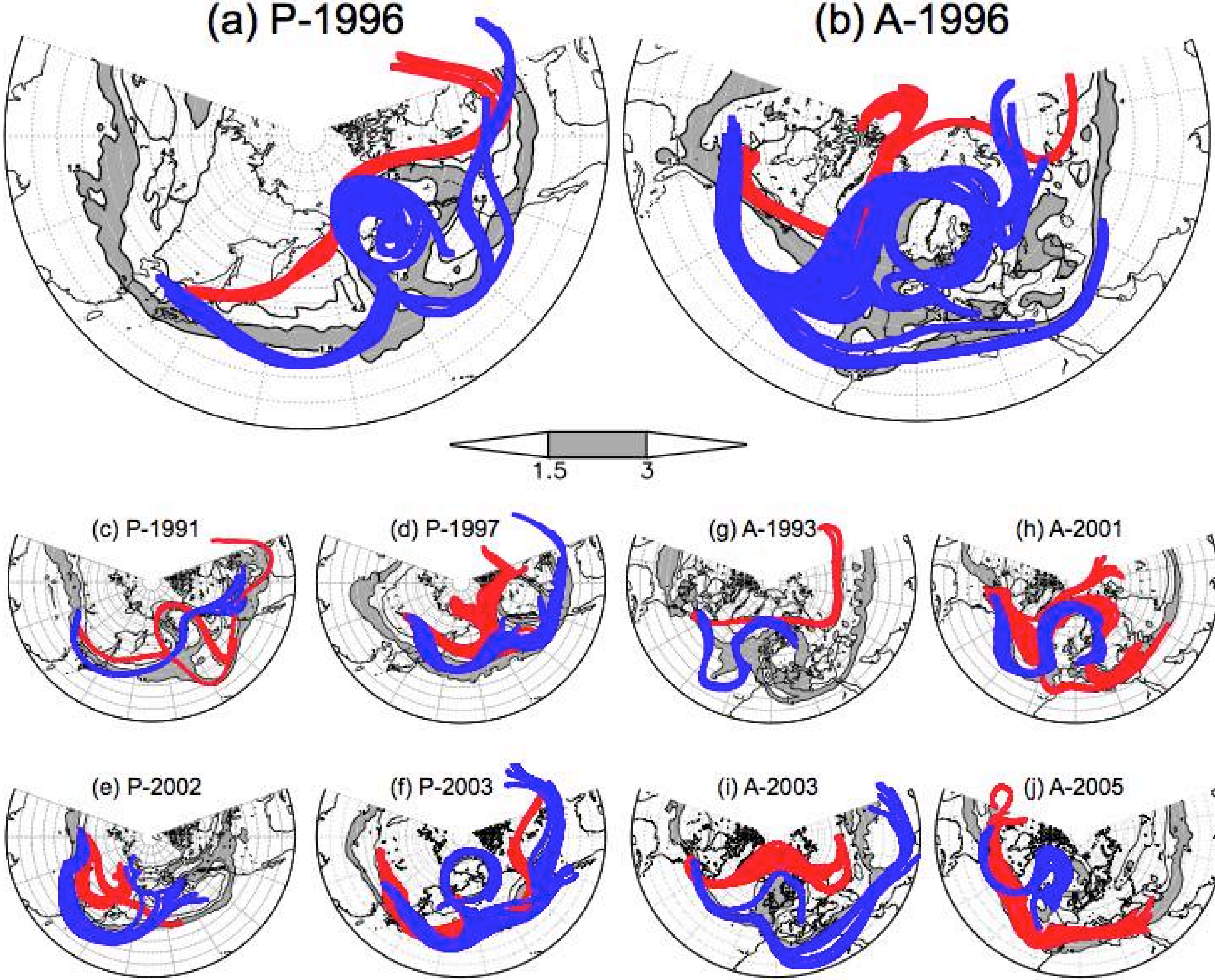
Ertel's PV and wind (320x160 Gaussian grids; 6-hourly) on 320 K

Region	Event name	Period of blocking	Duration (days)
PAC	P-1991	1991/2/25 – 3/4	8
	P-1996	1996/2/27 – 3/12	15
	P-1997	1997/11/9 – 11/16	8
	P-2002	2002/11/3 – 11/11	9
	P-2003	2003/3/3 – 3/17	15
ATL	A-1993	1993/2/4 – 2/18	15
	A-1996	1996/3/6 – 3/27	22
	A-2001	2001/12/9 – 12/17	9
	A-2003	2003/2/6 – 3/5	28
	A-2005	2005/2/14 – 3/7	22

Forward trajectory analysis

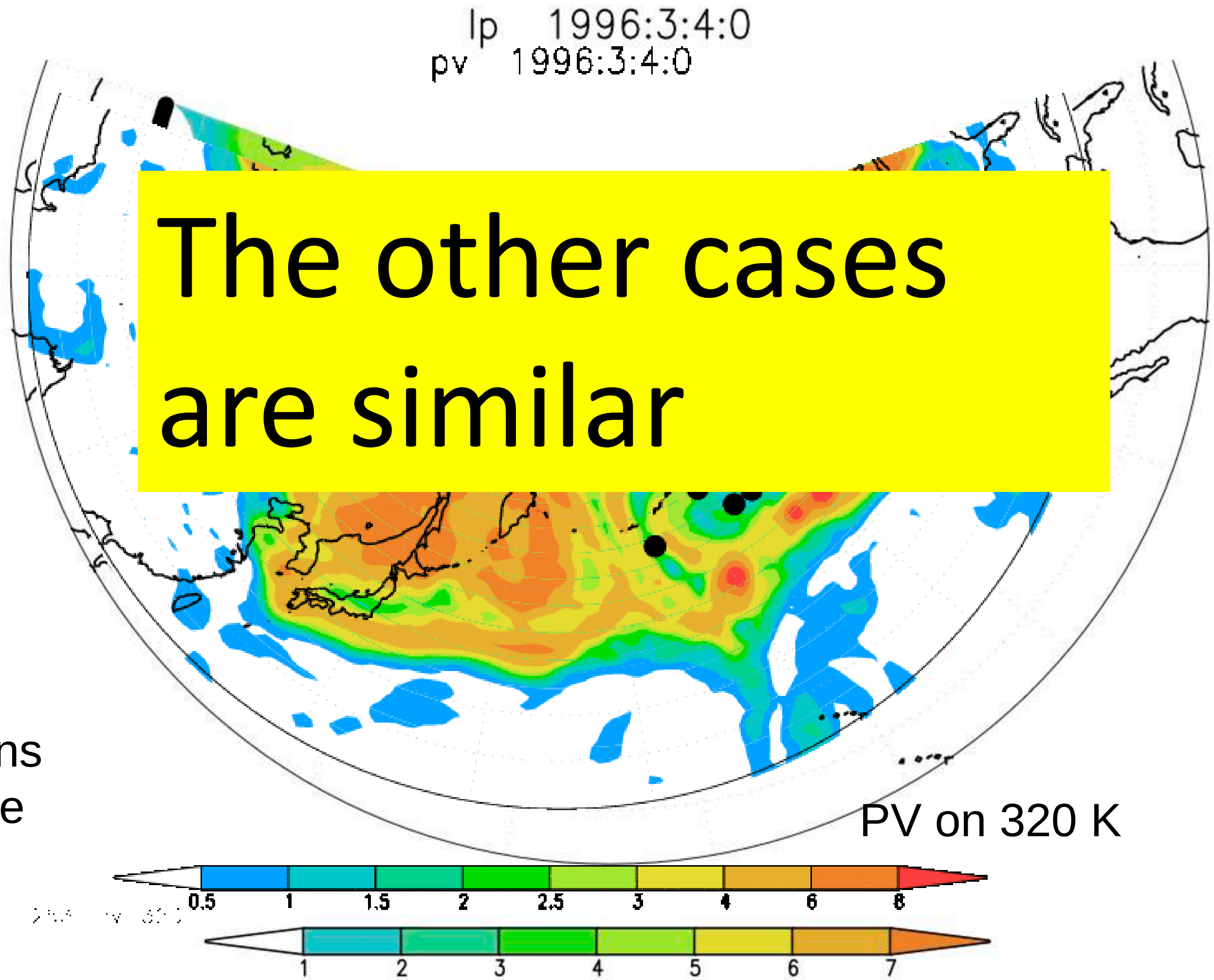


• signs are originating from synoptic anticyclones
■ signs synoptic cyclones



(a) P-1996
(b) A-1996
1.5
3
(c) P-1991
(d) P-1997
(g) A-1993
(h) A-2001
(e) P-2002
(f) P-2003
(i) A-2003
(j) A-2005

Backward trajectory analysis



○: Initial positions

✚: 6 days before

Numerical experiments

Equivalent–barotropic QGPV equations on a β–plane and a sphere with realistic parameters.

Design of numerical experiments

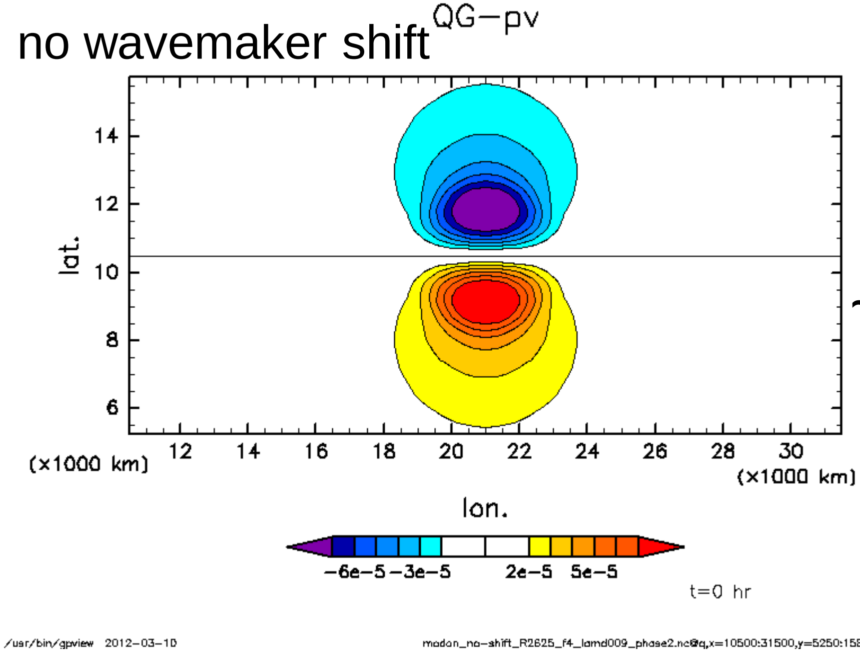
Model	Basic field	Initial blocking pattern	Main purposes
β-plane channel	Uniform westerly	Modon	Basic characteristics of dipole-type BL
			Sensitivity to various characteristics of synoptic eddies
			Sensitivity to WM shifts
		Rider	Basic characteristics of Ω-type BL
			Sensitivity to WM shifts
	Uniform westerly plus a jet	Modon-like	Role of a jet
			Sensitivity to WM shifts
			Wave-breaking pattern
Spherical surface	Solid body rotation	Spherical modon	Role of the sphericity
			Sensitivity to WM shifts
	Real	Real	Characteristics of real blocking

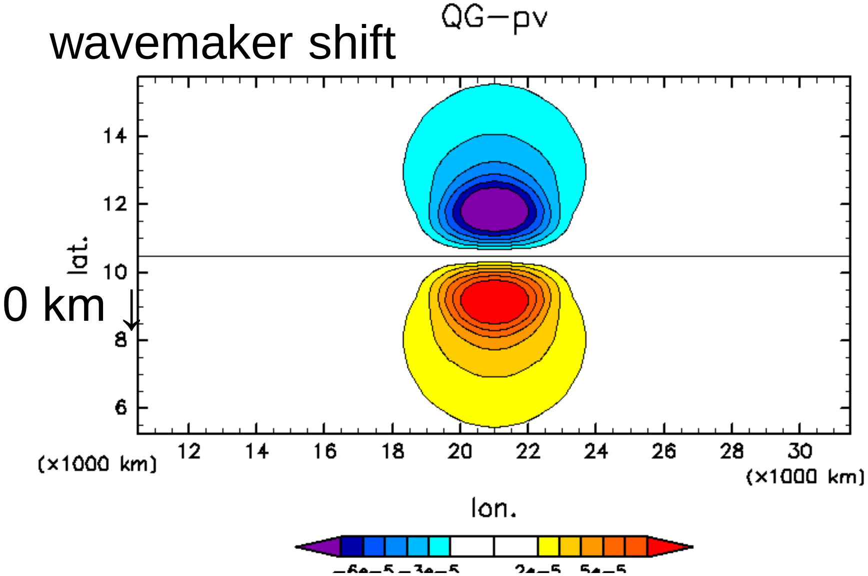
Almost all situations

PV fields & PV maintenance rates

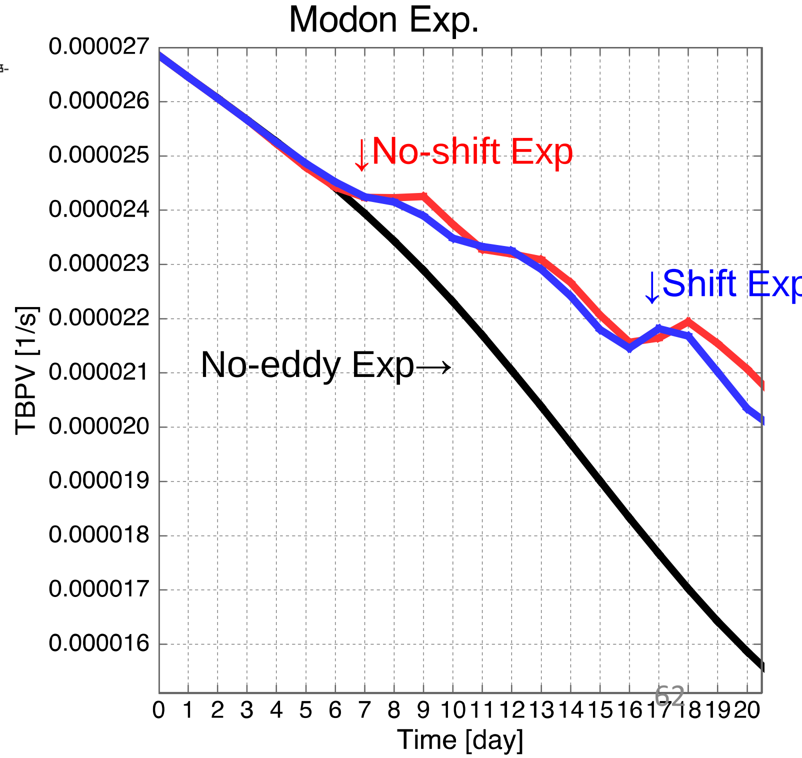
no wavemaker shift

wavemaker shift





PV anomaly (shade, [1/s]) from uniform westerly.

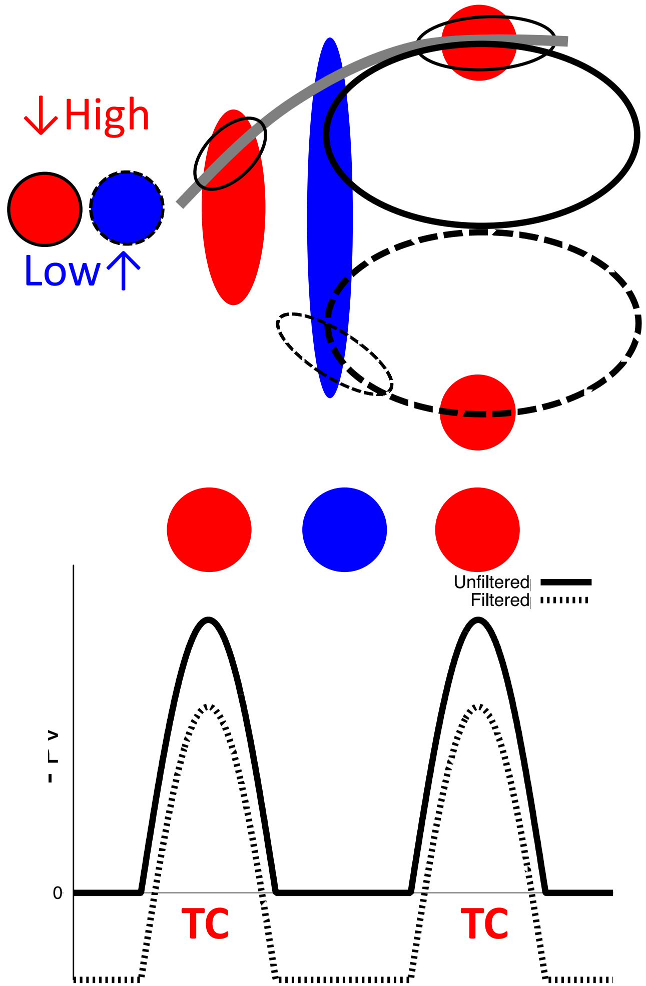


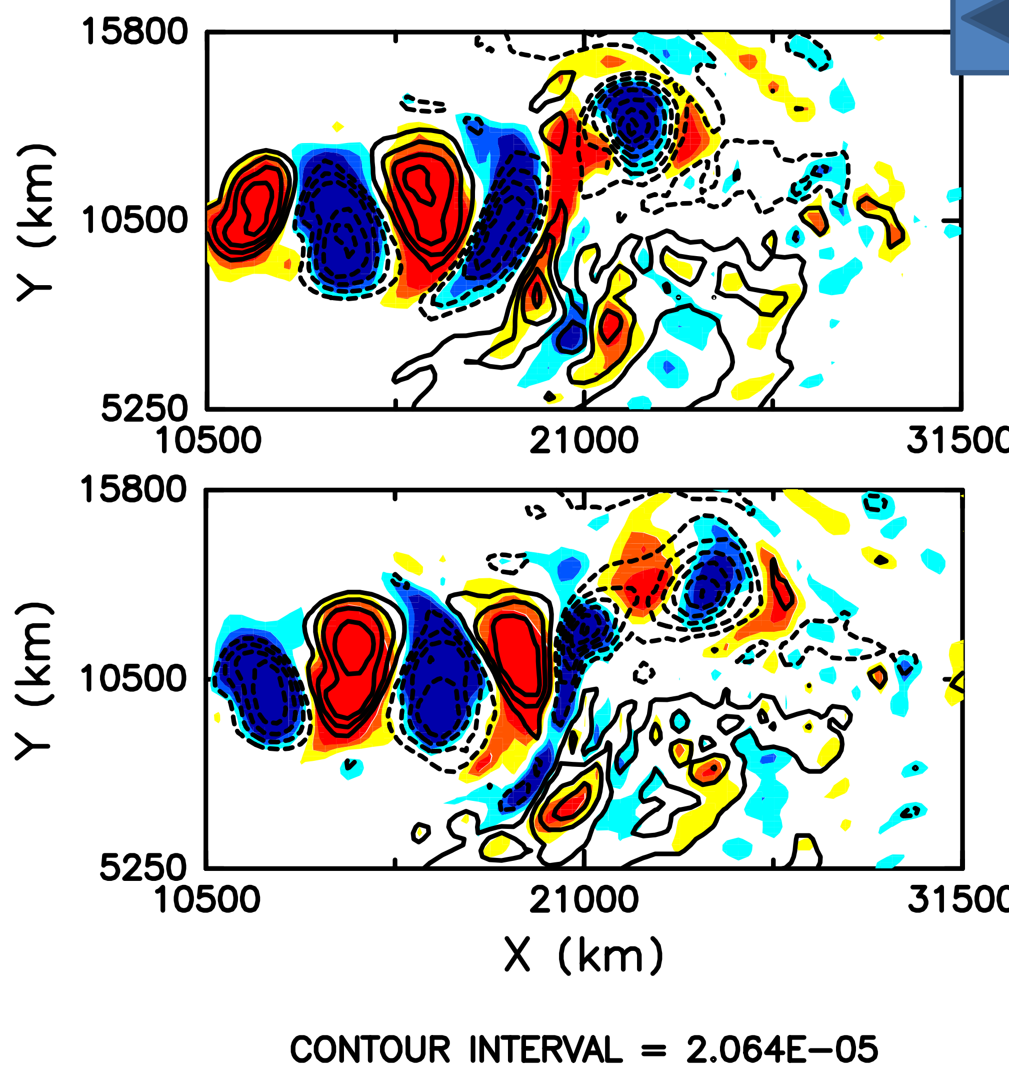
Robust

Straining seen in data analyses

Still real?

Time filtering and straining structure





6-day highpassed PV (color) and original

- Shapes of eddies obtained by a time filter is fictitious near blocking.

Summary

- A new maintenance mechanism of blocking (Selective Absorption Mechanism, SAM), which is based on vortex-vortex interaction, is proposed.
- Blocking high persists for long periods, by selectively absorbing low PV (conserved quantity) supplied by anticyclonic eddies.
- Selective absorption is not sensitive to various parameter settings.
- Eddy straining analyzed previously is fictitious due to time filtering. (Be cautious in the use of time filters.)

The idea of vortex-vortex interaction originating from TC research could thus be applied to another target.

3-3

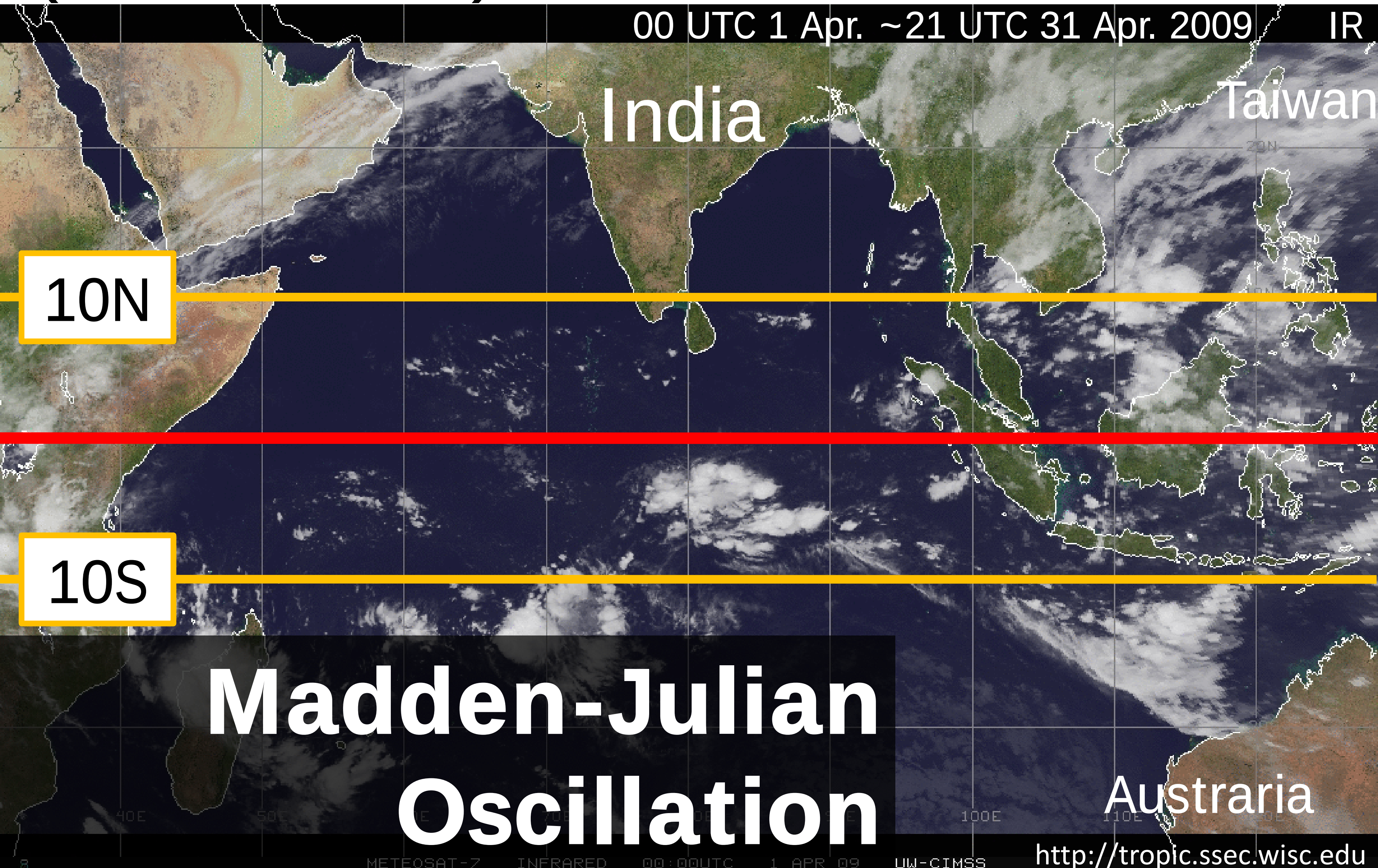
Slow moving speed of the MJO

The Mechanism of the Eastward Propagation of Unstable Disturbances with Convection in the Tropics

(cumulus)

MJO : Madden-Julian Oscillation

Eastward-moving Cumulus cluster (about 5 m/s)



内容削除

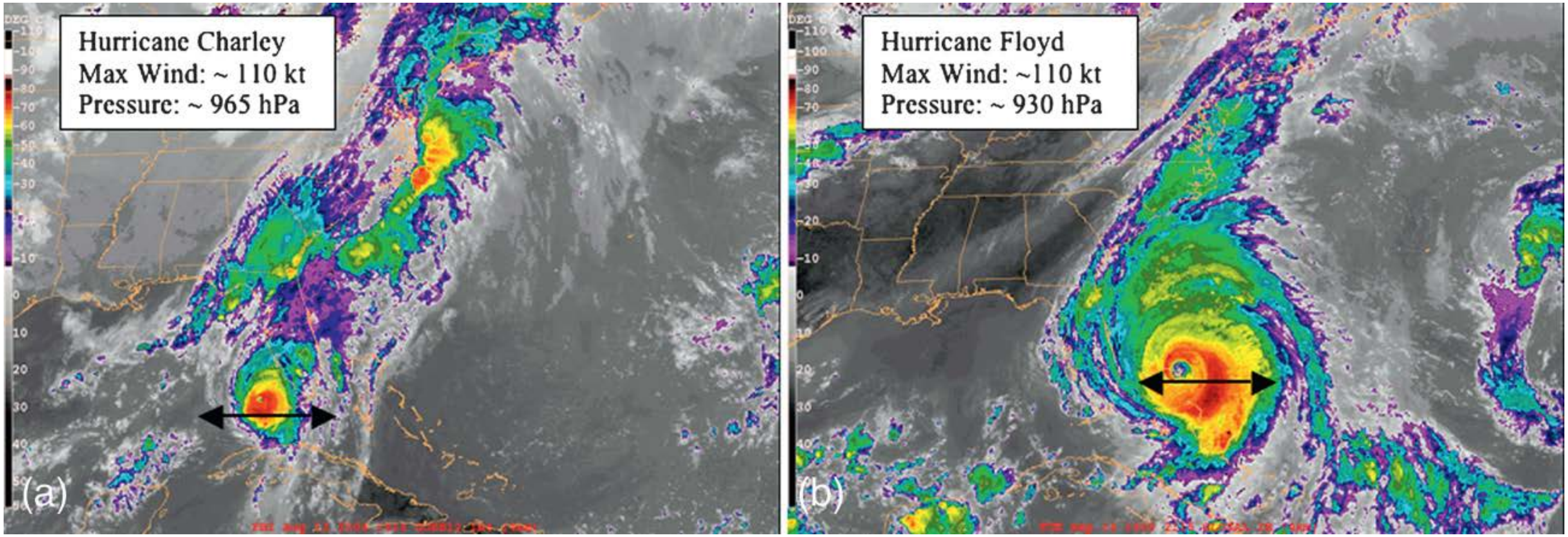
3-4. Size of TCs

1. Introduction
2. Review of TC size research
3. Issues and stuffs to consider

Key words: Rossby RD,
secondary circulation,
absolute angular momentum

MW: Maximum Wind
RMW: Radius of Maximum Wind
MSP: Minimum Surface Pressure
WNP: Western North Pacific

Hill and Lackmann (2009)



Geostationary Operational Environmental Satellite (GOES) IR imagery for a size comparison of Hurricanes Charley (2004) and Floyd (1999):
(a) Hurricane Charley at 1415UTC13 Aug 2004 and (b) Hurricane Floyd for 2115UTC14 Sep 1999. Wind and pressure data are taken from the Tropical Prediction Center best-track analyses. The double-headed arrow corresponds to the diameter of the region with cloud-top temperatures colder than -60℃ for Hurricane Floyd, a distance of ～650 km.

Merrill (1984)

Why so many varieties?

Tip (1979) MW 65 m/s more than 17 m/s ～1100 km
Tracy (1974) 50 km

2. Review of TC size research

Definition of TC size

Japan Meteorological Agency

R15 : Radius of wind speeds above 15 m/s (R25)

500-800 km large	Large
800 km -	Very Large

JTWC (Joint Typhoon Warning Center)

ROCI (Radius of the Outermost Closed Isobar)

Size descriptions of tropical cyclones

ROCI	Type
Less than 2 degrees latitude	Very small/midget
2 to 3 degrees of latitude	Small
3 to 6 degrees of latitude	Medium/Average
6 to 8 degrees of latitude	Large
Over 8 degrees of latitude	Very large

Radius of vorticity above 1×10^{-5} /s

Observational study

Brand (1972)

Merrill (1984)

ROCI by using weather maps + observed wind

TCs in the Pacific (Pac.) are about 1.5º larger than TCs in the Atlantic (Atl.)

(4.4 º and 3.0º)

Correlation between intensity (MSP) and size is weak.

0.28

Similar results in later studies

Weatherford and Gray (1988)

airplane

Latitudinal dependence (Size is larger in mid-latitudes than in low-latitudes under the same MSP.)

Liu and Chan (1999)

scatterometer

Seasonal dependence (Pac. Oct. and Nov., Atl. Sep. and Oct.)

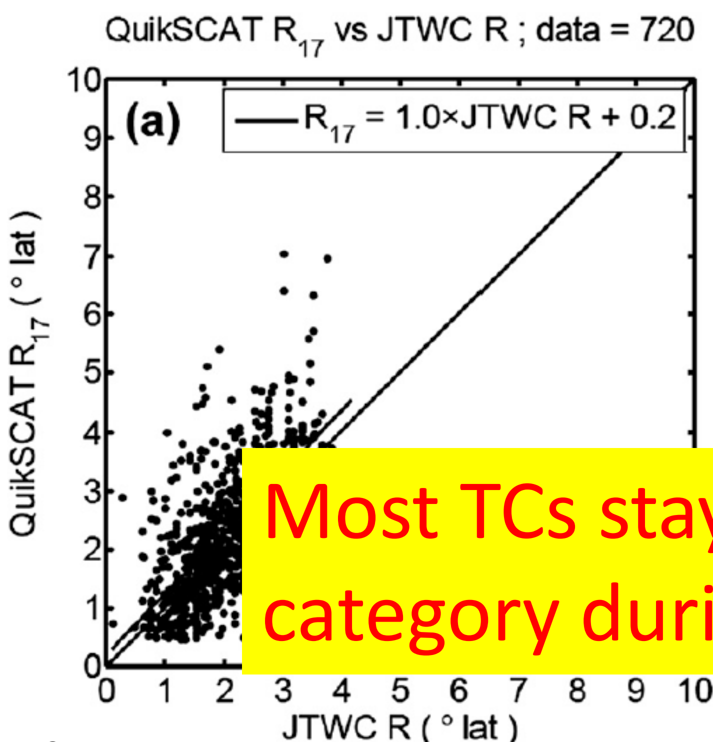
……………………

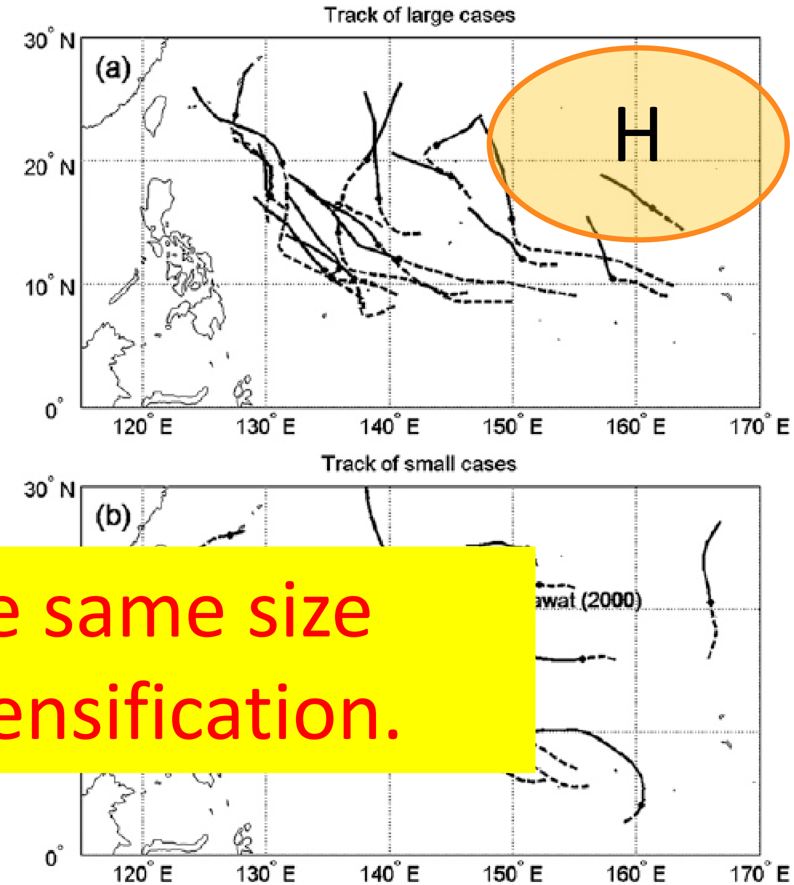
Lee et al. (2010) WNP comprehensive

TS 17-33 m/s
TY more than 33 m/s

R15 QuikSCAT small, medium, large (relatively)

2000-2005 145 TCs JTWC Best Track





Most TCs stay in the same size category during intensification.

intensification → TY

TS

TS/TY	Small [<1.8° (24)]	Medium [1.8°–2.6° (24)]	Large [>2.6° (25)]
Small [<1.1° (24)]	**16/24 (67)**	5/24 (21)	3/24 (12)
Medium [1.1°–1.8° (24)]	8/24 (33)	**12/24 (50)**	4/24 (17)
Large [>1.8° (25)]	0/25 (0)	7/25 (28)	**18/25 (72)**

Theory and numerical experiments

Inner-core size

Wang (2009) influence of outer spiral rainband

Xu and Wang (2010) influence of initial vortex size

inner-core: region of over hurricane-force wind (33 m/s)
(including inner rainbands)

TC size itself

Hill and Lackmann (2009) importance of relative humidity (RH)

Smith et al. (2011) optimum *f* to obtain the largest size

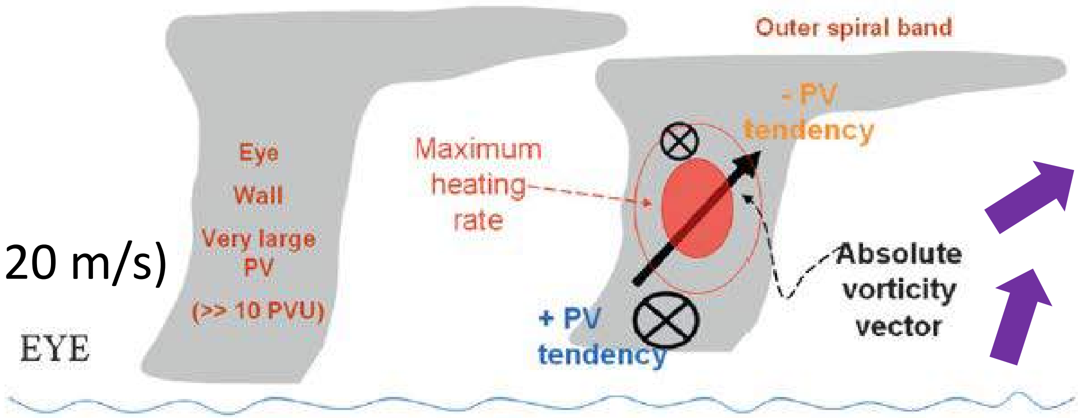
Fudeyasu and Wang (2011) importance of diabatic heating

outer-core heating → transport of AAM from the outside

full physics model

Hill and Lackmann (2009)

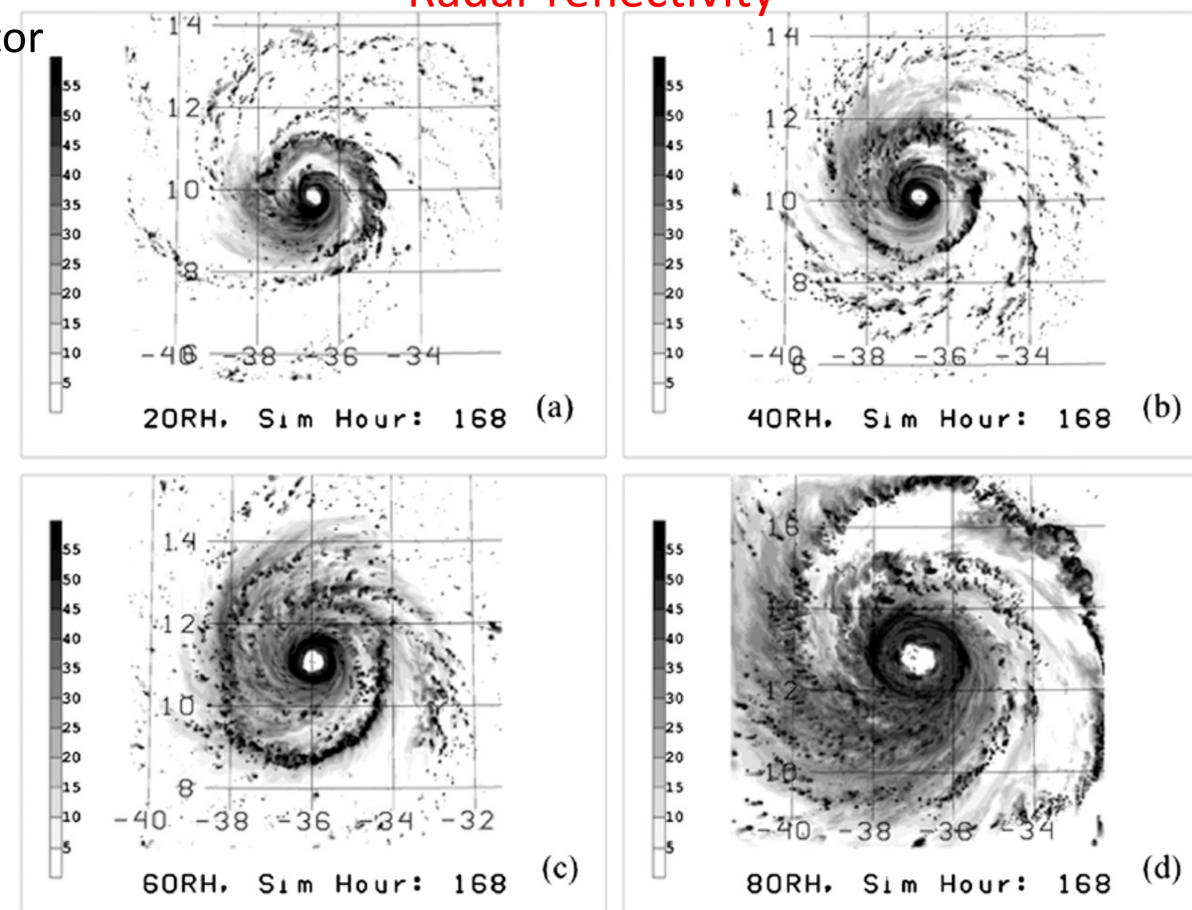
To see the change of TC size, by changing RH in environments.
(intial vortex: RMW 50km, MW 20 m/s)



$$\frac{DP}{Dt} = \frac{1}{\rho}\left(\boldsymbol{\eta_a} \cdot \nabla\dot{\theta} + \nabla \times \boldsymbol{F} \cdot \nabla\theta\right)$$

$\boldsymbol{\eta_a}$: absolute vorticity vector

Radar reflectivity



Result : Size enlarges with RH.

Diabatic heating is large in outer spiral rainband region. → PV is generated → Wind is induced.

Another interpretation is more relevant.

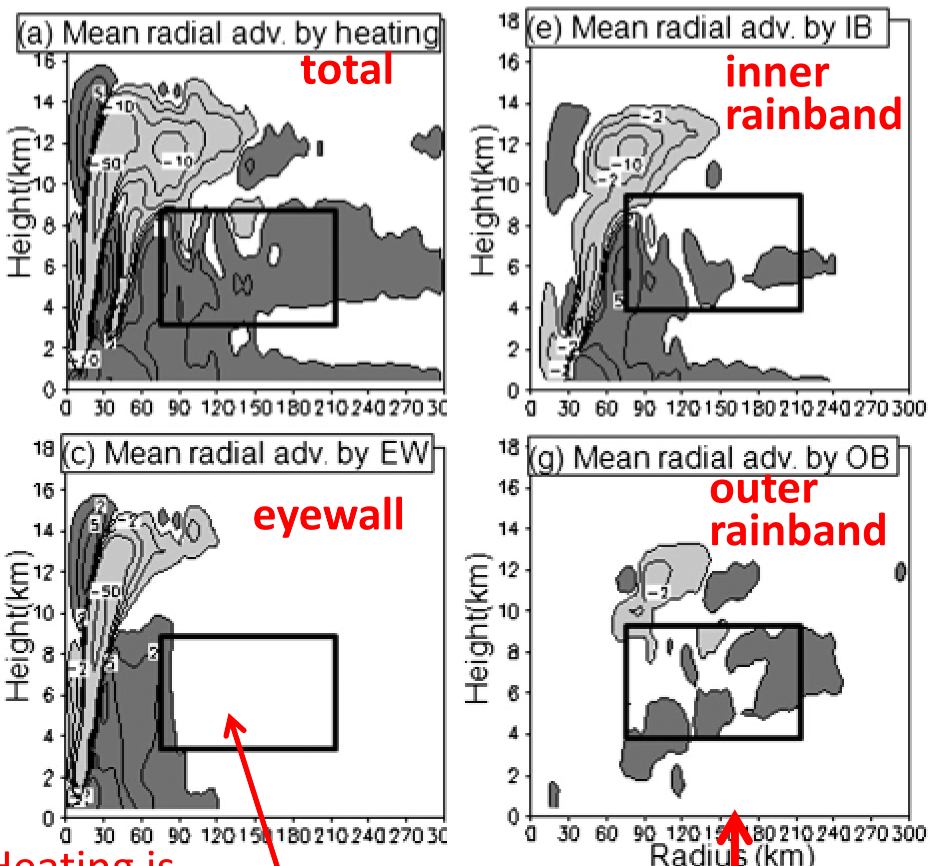
Fudeyasu and Wang (2011)

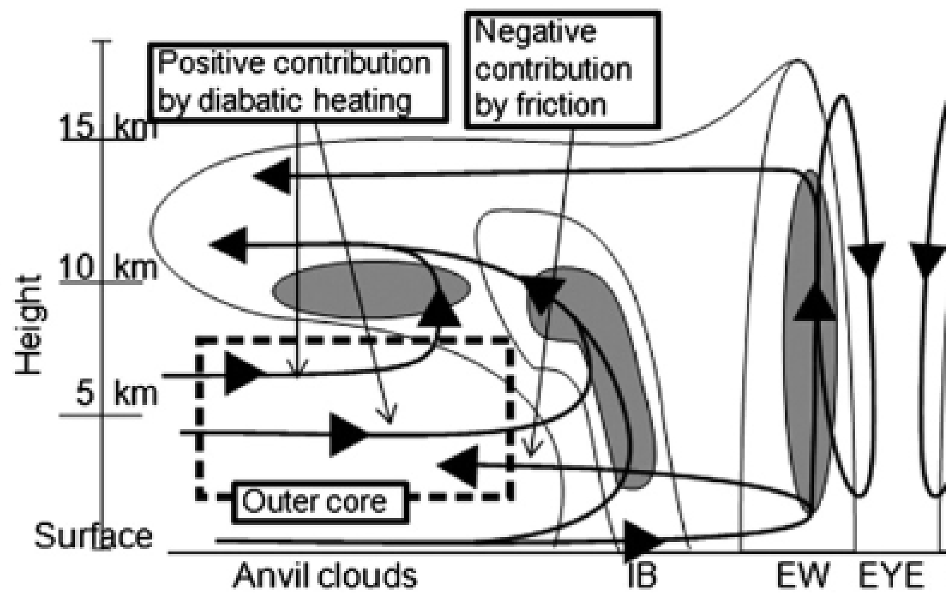
Outer-core spinnup process ← Sawyer-Eliassen eq.

Secondary circulation induced by IB and OB diabatic heating

Supply of outer absolute angular momentum (AAM)

Hill and Lackmann





Heating is the largest

outer-core

mid-troposphere

R15

Not directly to TC size (over surface)

内容削除

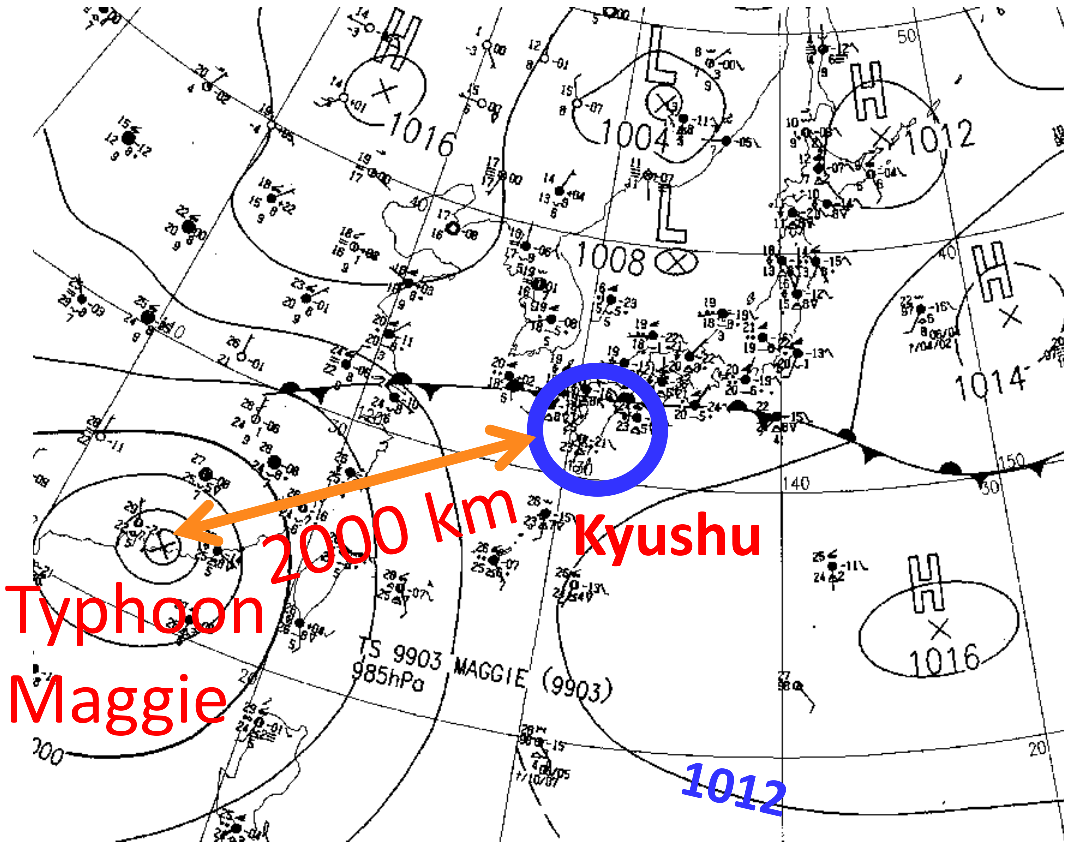
4. Indirect Effects of Tropical Cyclones on Heavy Rainfall Events

Yoshida, K., and Itoh, H., 2012, Indirect effects of tropical cyclones on heavy rainfall events in Kyushu, Japan, during the Baiu season. *J. Meteor. Soc. Japan*, **90**, 377–401.

7 June (JST) Heavy rainfall in Kyushu, Japan

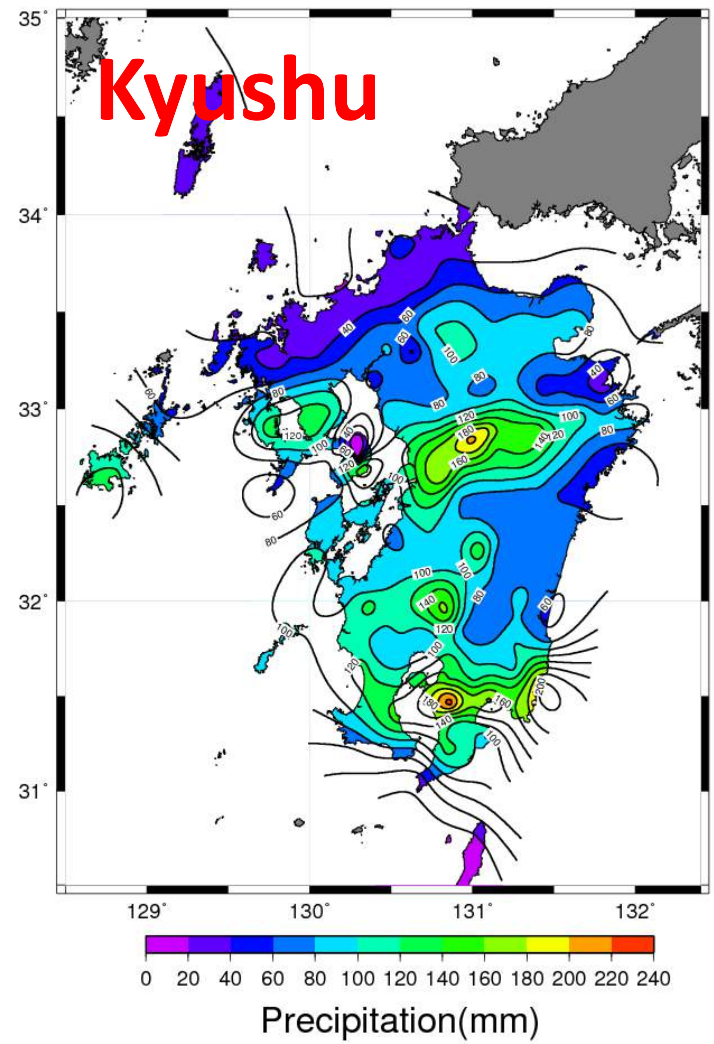
03 JST 7 June 1999

(JST = UTC +9)



West(northwest)ward extension of the Pacific high

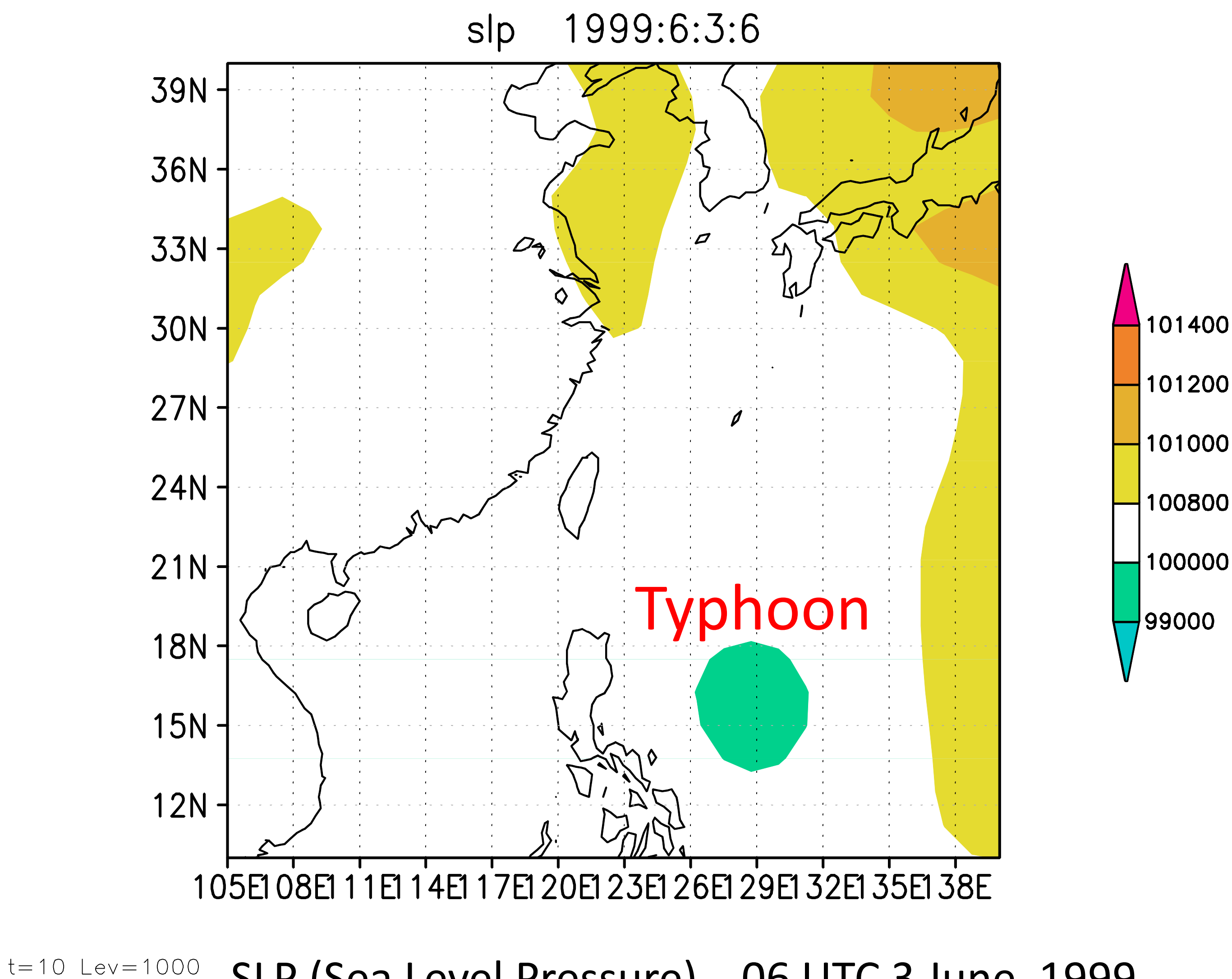
Daily Precipitation 7 June 1999



many rain-gage stations recorded above 100 mm/d

Westward extension of the Pacific high

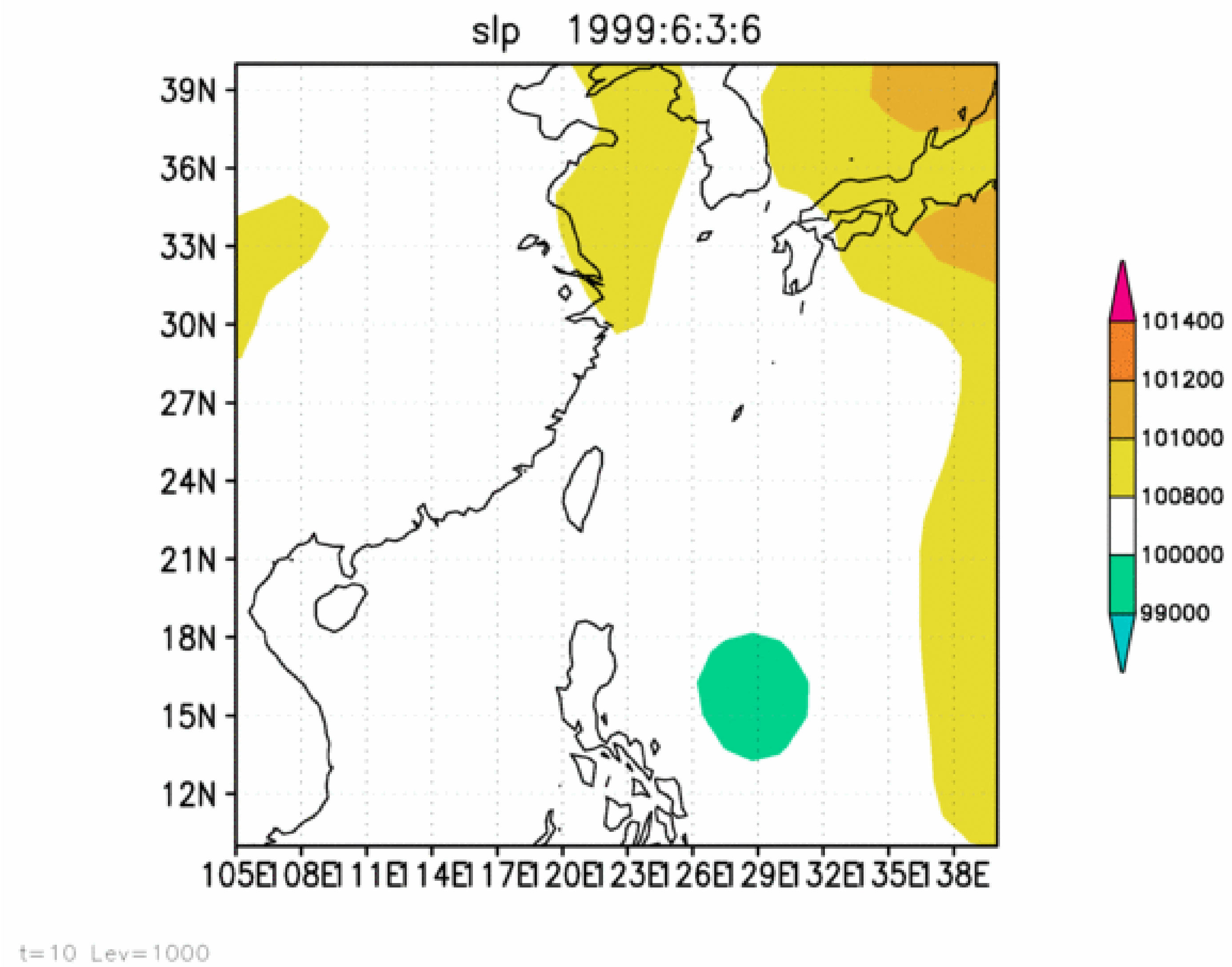
Every 6 hours UTC



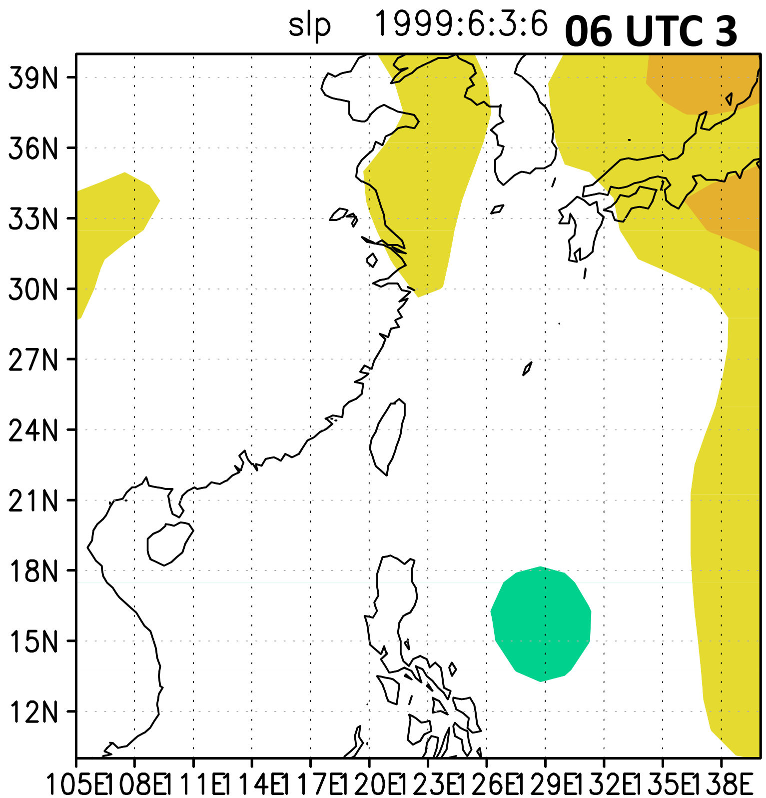
SLP (Sea Level Pressure) 06 UTC 3 June, 1999
(unit: Pa)

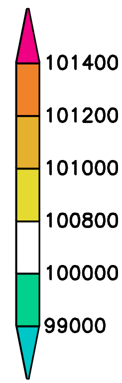
Westward extension of the Pacific high

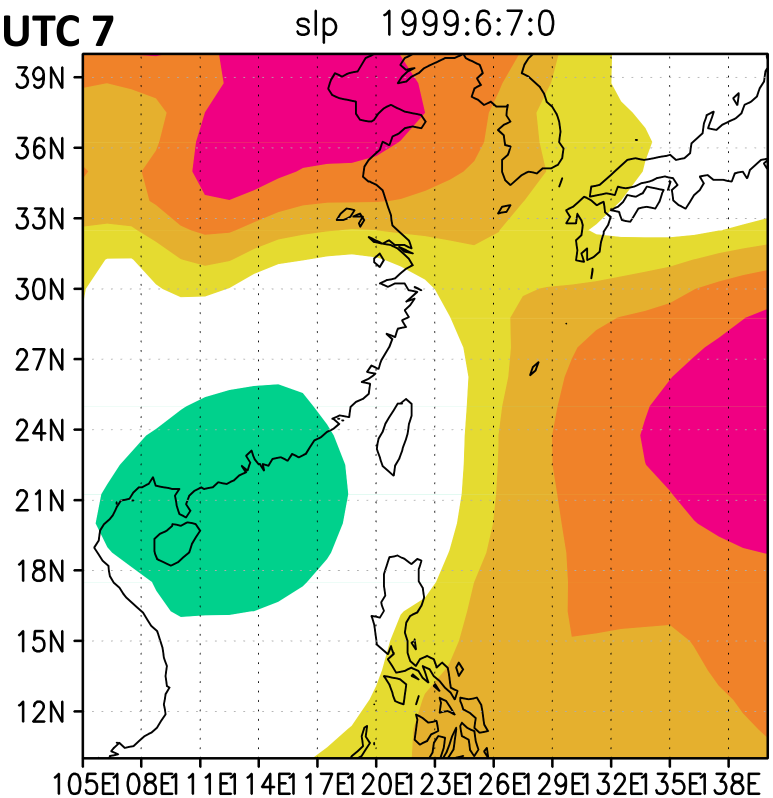
Every 6 hours UTC



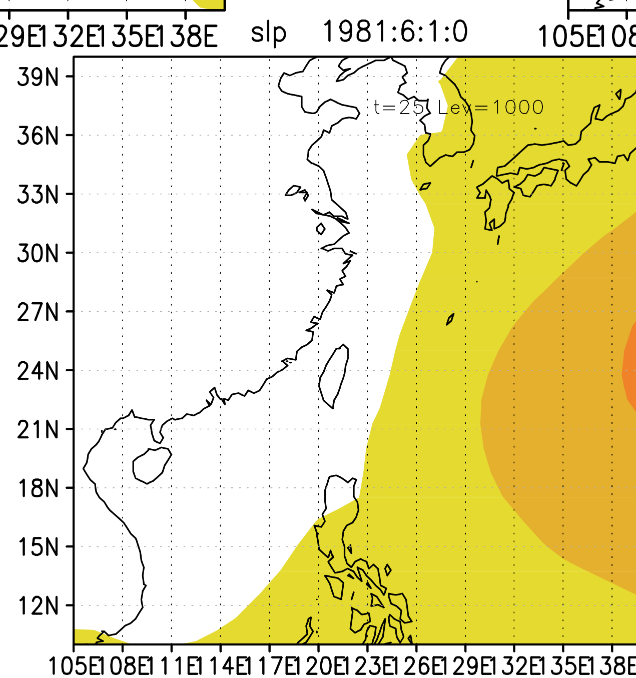
06 UTC 3 June **00 UTC 7**

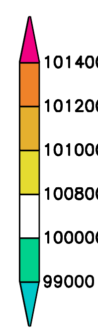






Lev=1000





June climate

1. Introduction
2. Data and the main target event
3. Data Analysis
4. Piecewise PV Inversion Diagnosis
5. Numerical Experiments
6. Discussion
7. Generality   Applicability to other cases and areas
8. Conclusions

1. Introduction

Damage by Tropical Cyclones (TCs)

Direct effect near TCs

heavy rain, strong wind, storm surge and so on

Indirect effect (Remote effect)

Heavy rainfall by the interaction with other systems in remote areas which are different from near-TC rain areas

Its importance

Lack of provision for heavy rainfall

When, where, why, and how

Scientific interest and social importance

Previous Studies

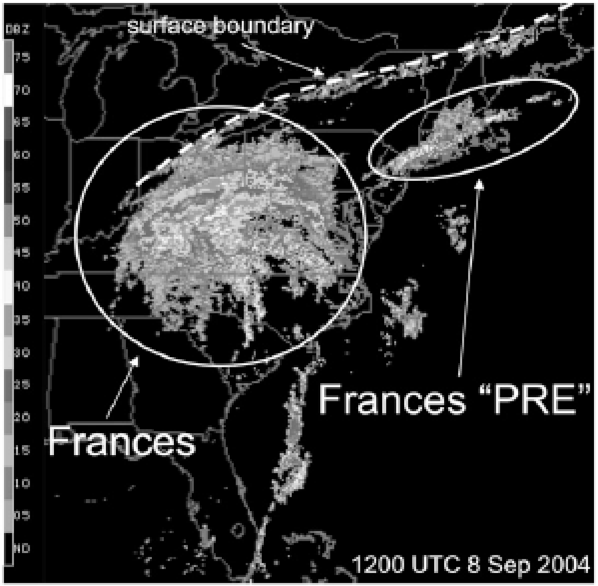
Almost all studies point out
moisture transport by the outer circulation of TCs

Bosart and Carr (1978)
Supply of water vapor in the area with upward vertical motion associated with synoptic waves

➡ Generalized as predecessor rain events (PRE)

Galarneau Jr. et al. (2010), Schumacher et al. (2011)

Frances (2004)



South side of the entrance of upper-level jet

Distance between the hurricane and heavy rain region
1000 km

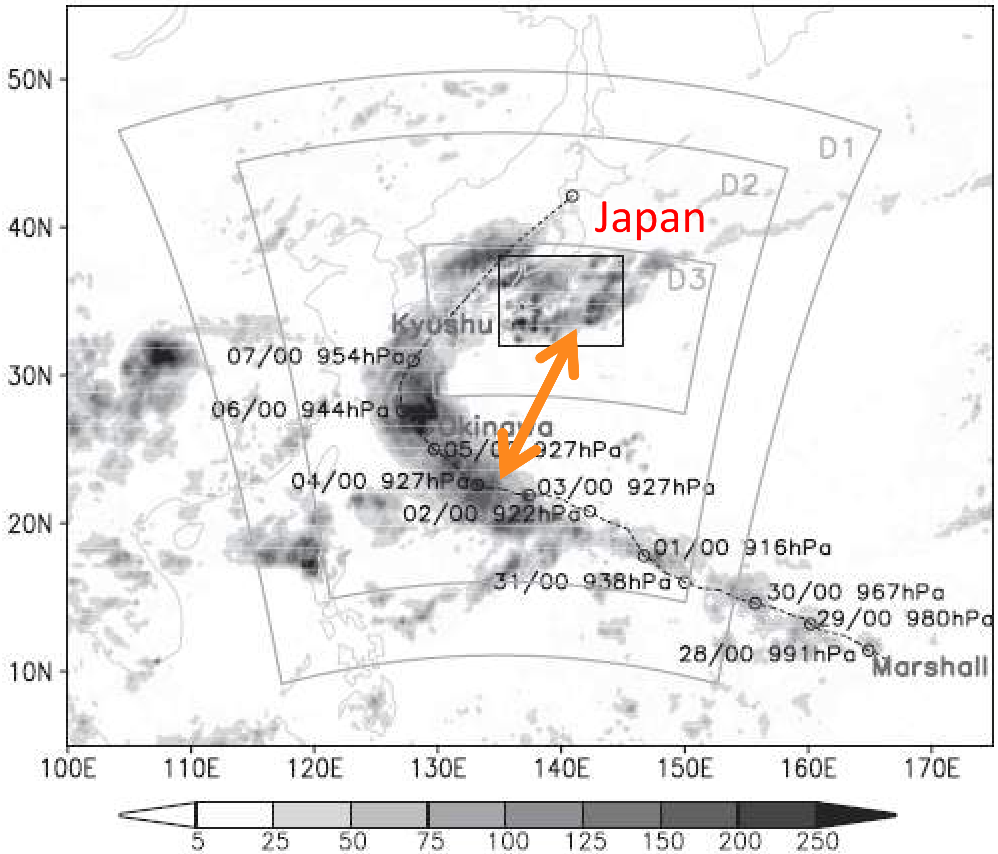
Called PRE, because hurricanes themselves come along the jet afterwards.

Pacific region

Wang et al. (2009)

1000 km

18 UTC 2 Sep and 00 UTC 5 Sep 2004



Typhoon Songda (2004)

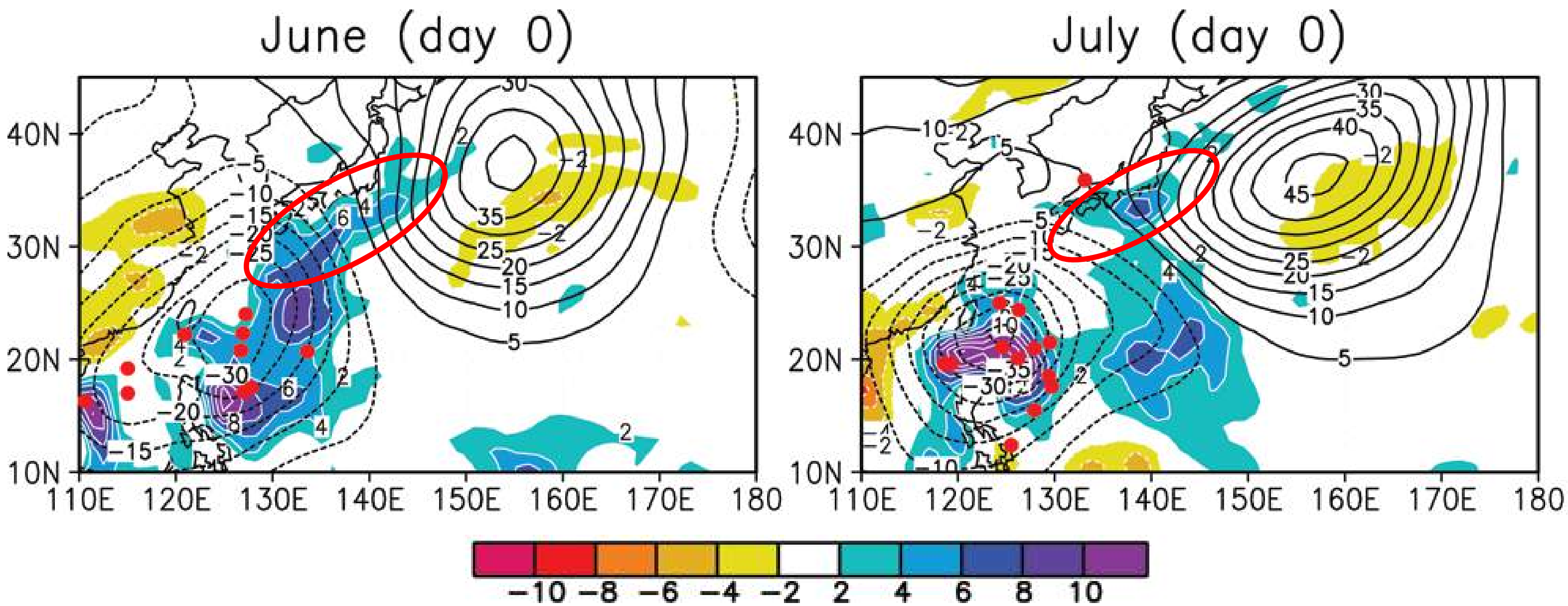
Maybe, one kind of PRE

Murata (2010)
near Japan

500 km

Second category TCs can increase precipitation in remote areas via teleconnection.

Kawamura and Ogasawara(2006) Yamada and Kawamura(2007)



Rainfall anomaly (color) and 850 hPa geopotential height anomaly (contour)
Composite on days when the PJ pattern shows its maximma

Kawamura and Ogasawara (2007)

Small Increase of precipitation

→ cannot be said that TCs can cause remote heavy rainfall.

TCs can cause remote heavy rainfall.

⬇

There have been a few studies and no systematic studies (in the Pacific area).

First step of a systematic study

Target phenomenon: Baiu (Meiyu, Changma) front
(June and July)

already contains the potential for heavy rain,
which indirect effects of TCs could further enhance.

ubiquitous and persistent nature. → many target events

Target area: Kyushu, Japan

Several heavy rainfall events associated with the Baiu front occur every year.

New types of indirect effects may be extracted.

2. Data and the main target event

JRA-25 (Japanese 25-Year ReAnalysis) :

Potential Vorticity (PV) on isentropic surfaces,

Vertically Integrated Moisture Flux, Others

1.25° ×1.25° enough resolution because targets are synoptic scale (or T106 Gaussian grid about 1.125°)

JMA Weather Station Data

JMA Weather Charts

RSMC Best Track Data

Many analyses are made at 310 K surface (near 700 hPa)

Potential Vorticity ; PV

PV : $q \equiv (\zeta_\theta + f)/\sigma \qquad \sigma \equiv -\frac{1}{g}\frac{\partial p}{\partial \theta}$

$$\frac{\tilde{D}q}{Dt} \equiv \frac{\partial q}{\partial t} + \mathbf{V}\cdot\nabla_\theta q = \boxed{\frac{q}{\sigma}\frac{\partial}{\partial\theta}(\sigma\dot{\theta})} + \sigma^{-1}\mathbf{k}\cdot\nabla_\theta\times\left(\mathbf{F} - \dot{\theta}\frac{\partial \mathbf{V}}{\partial\theta}\right)$$

Low PV → High Pressure

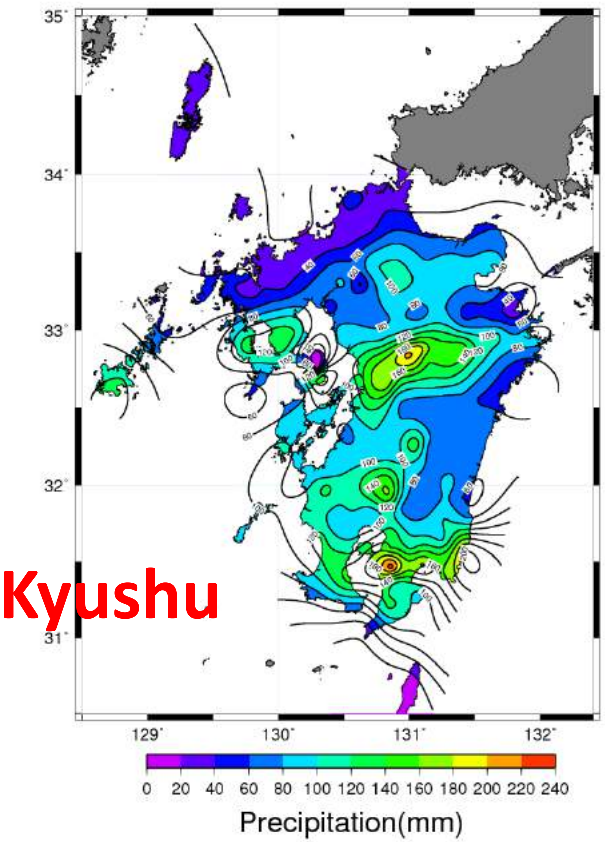
High PV → Low Pressure

- It is conserved under adiabatic and frict
- It is directly generated or destructed by diabatic heating.
- Height and wind fields can be obtained from PV fields（PV inversion）.

Main Target Event : Heavy rain on 7 June 1999 (JST) and Typhoon 9903 (Maggie)

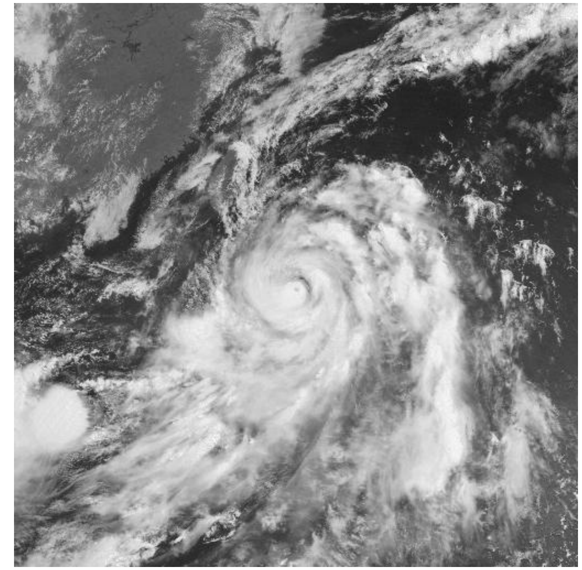
2000 km (Kyushu and near Hong-kong)

Daily Precipitation 7 June 1999

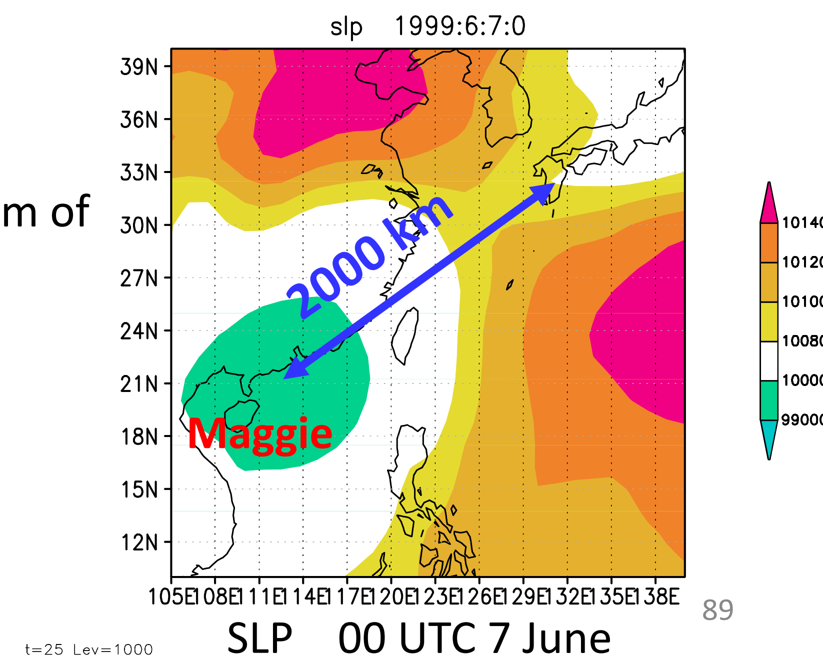


55 rain-gage stations (among 165 stations) recorded above 100 mm of daily precipitation

Typhoon 9903 (Maggie)



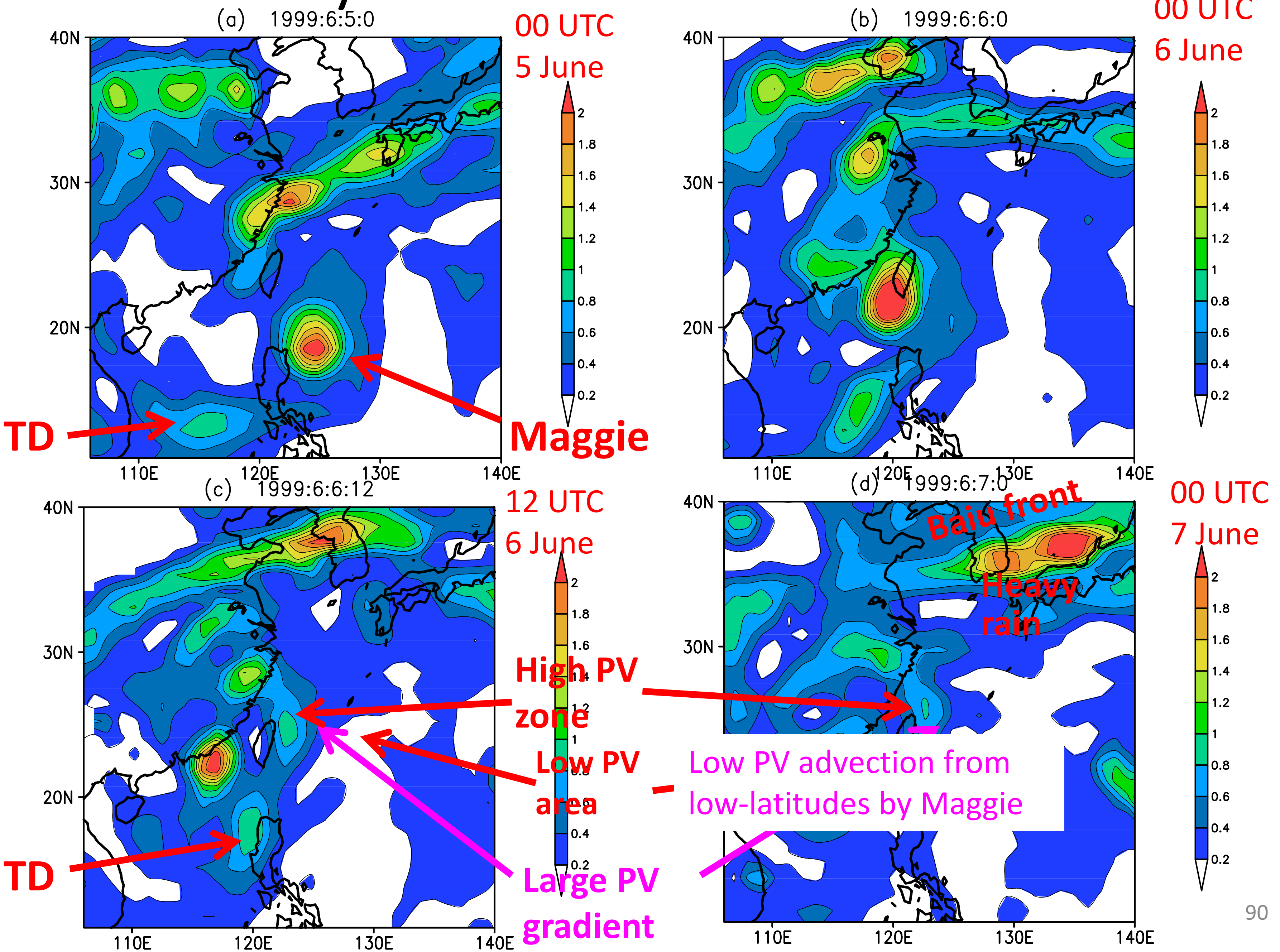
Visible 00 UTC 5 June



SLP 00 UTC 7 June

3. Data Analysis

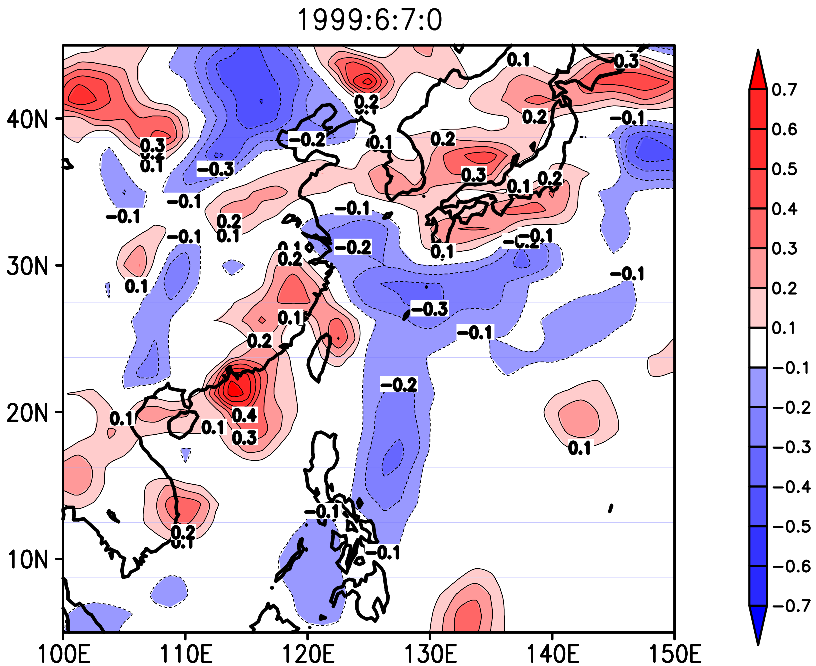
PV (unit: PVU) on 310 K surface



00 UTC 7 June

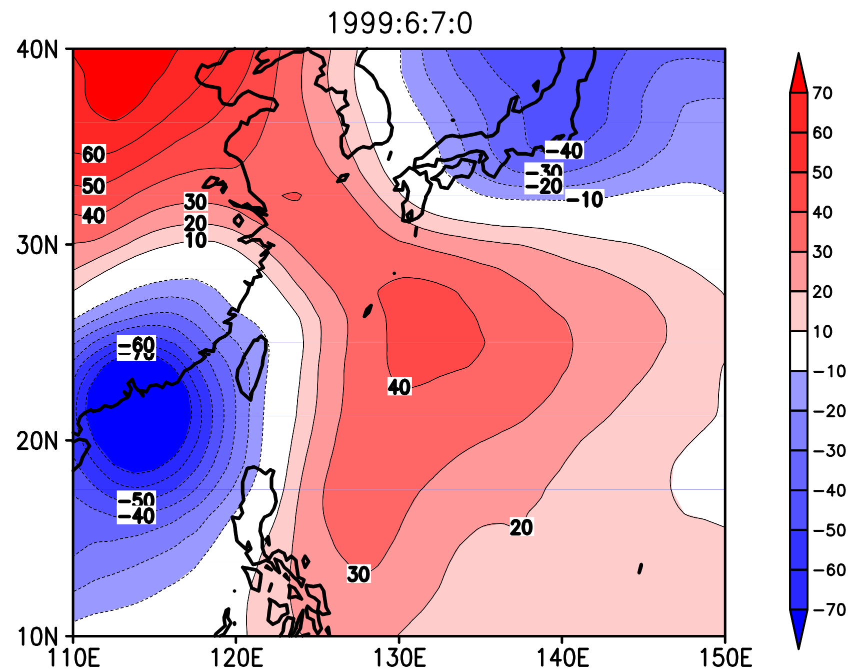
Basic field: 1999 June-July average

Anomaly field: Deviation from the average



PV anomaly at 305 K surface

Height Anomaly at 850 hPa surface



The westward extension of the Pacific high was caused by the TC via low PV advection from low-latitudes !

This will be once more demonstrated quantitatively.

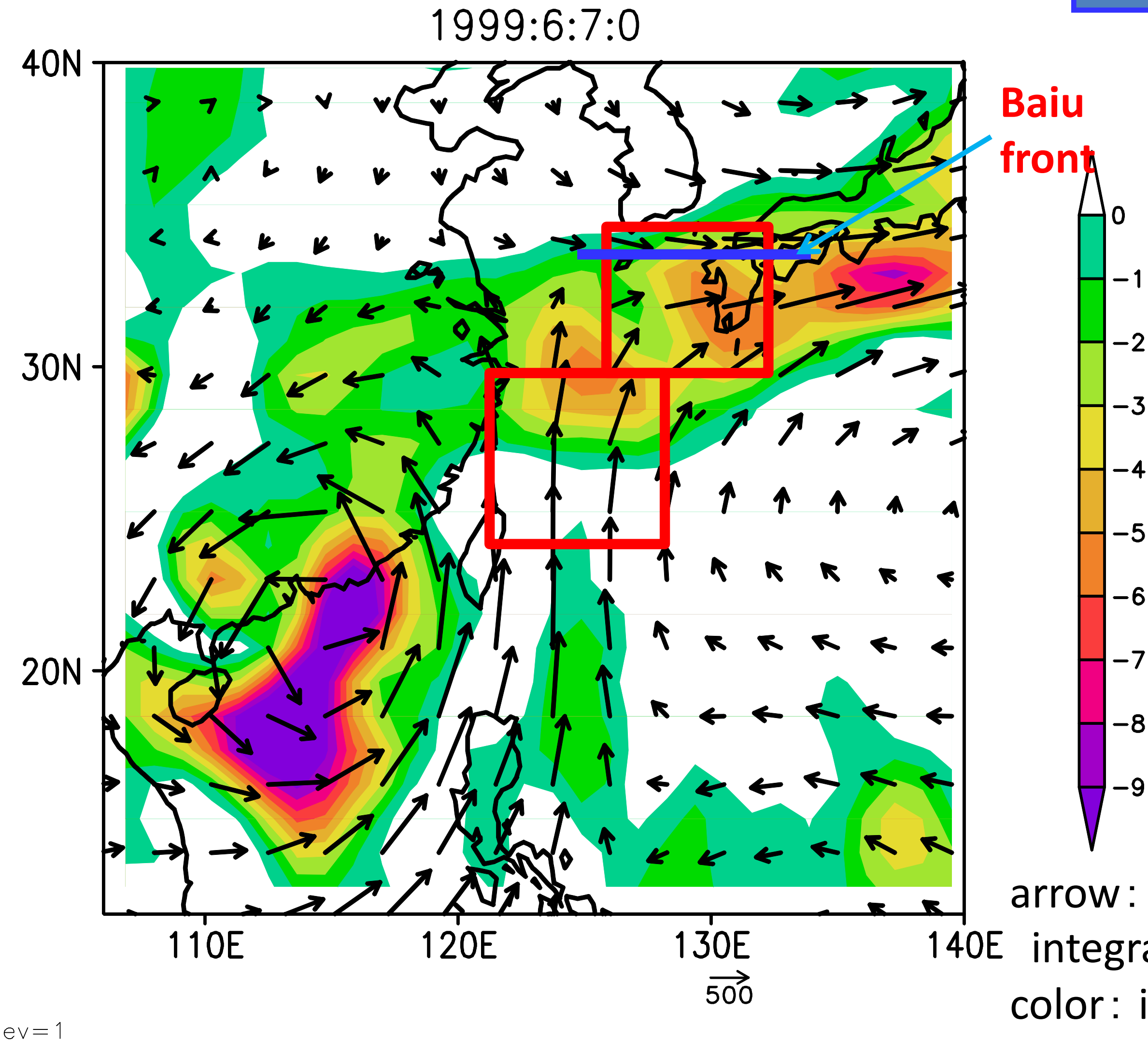
00UTC 7 June

Large PV gradient between the high and low PV areas → Large moisture flux

Moisture road → Large convergence near Kyushu

= Heavy rainfall

Calculation areas of moisture flux and its convergence



arrow : vertically integrated moisture flux

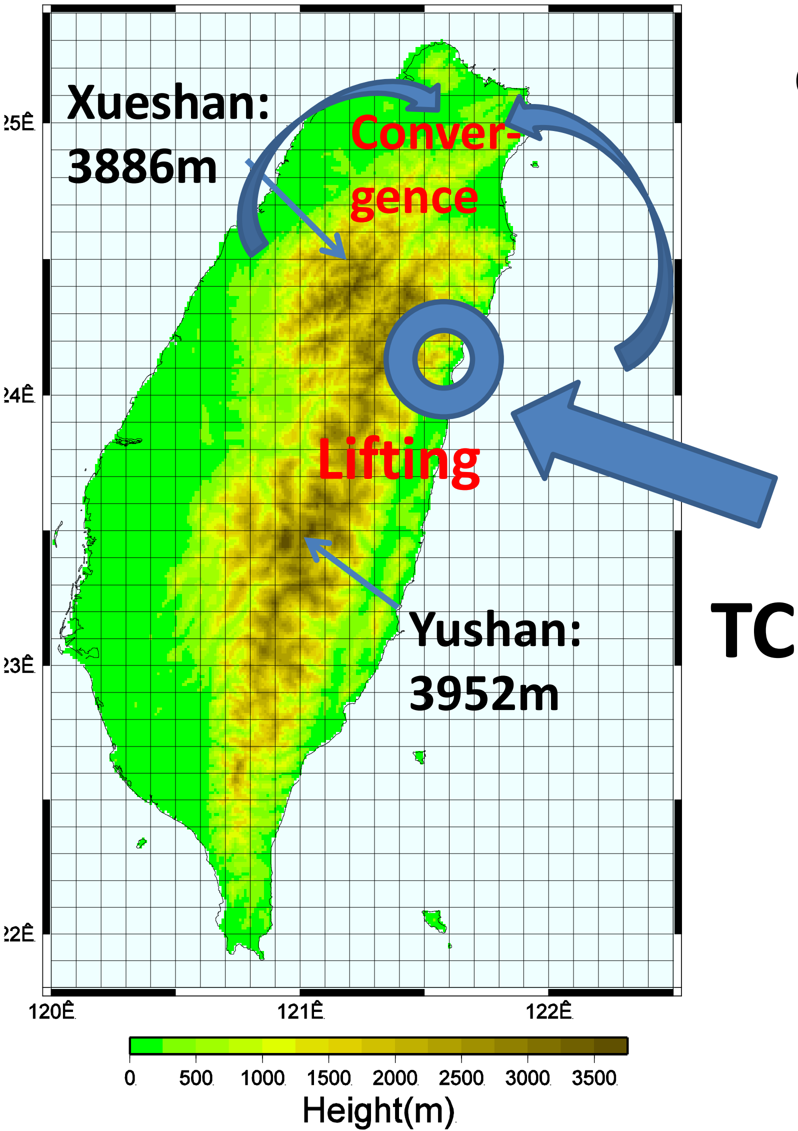
color : its convergence

Guess

Low PV in the east

(extension of the Pacific high

←low PV advection by the TC)



Why was the high PV in the west (north of Taiwan) formed ?

Topography of Taiwan + the TC

Central Mountain Range (CMR)
many high mountains (above 3000m ASL).

Strong winds by the TC blow to the CMR

→

Strong lifting and convergence by the turn-around

→

Condensation and diabatic heating

→

PV generation in the lower layer

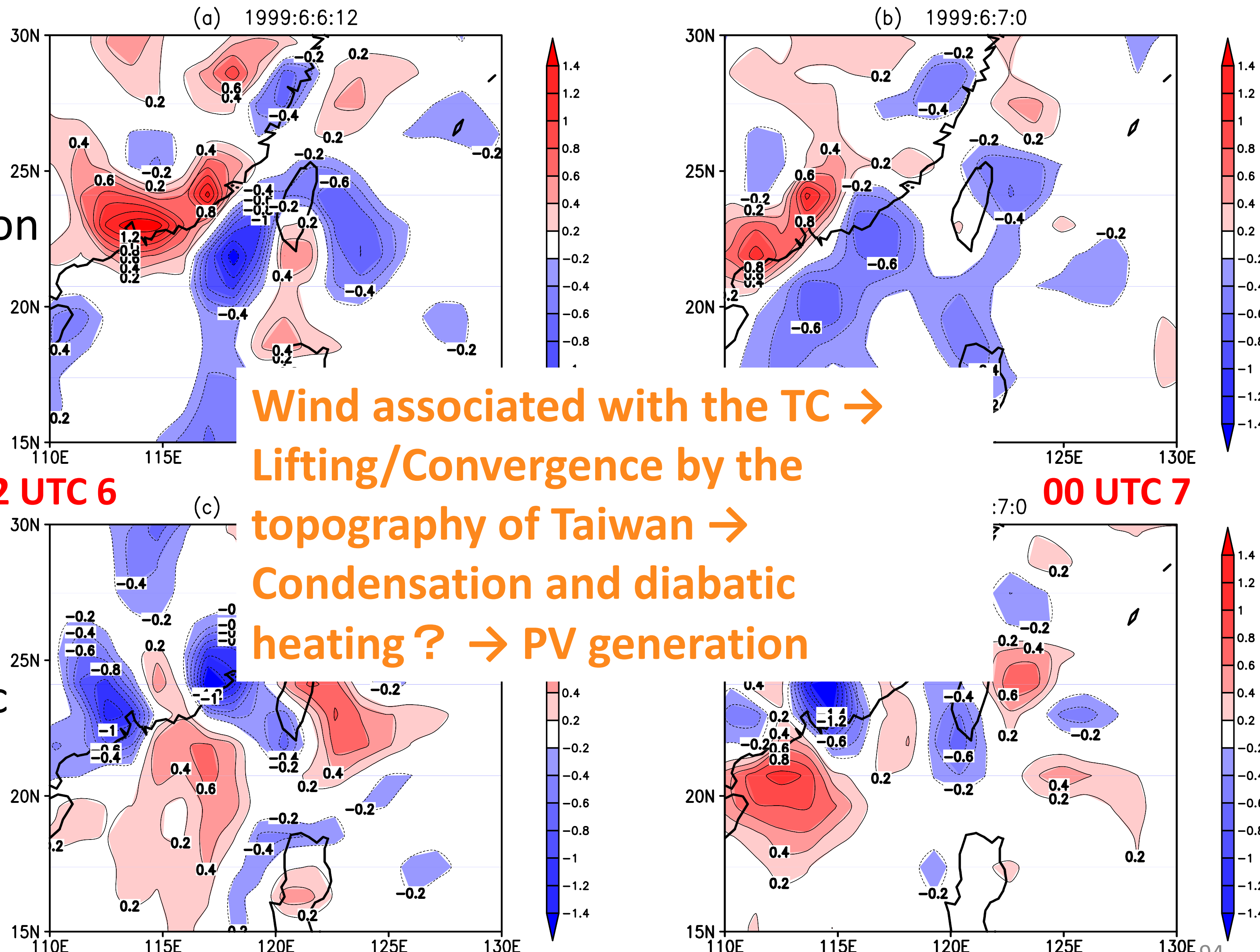
→

northward advection by southerly

PV changes by advection and diabatic heating (residual)

advection

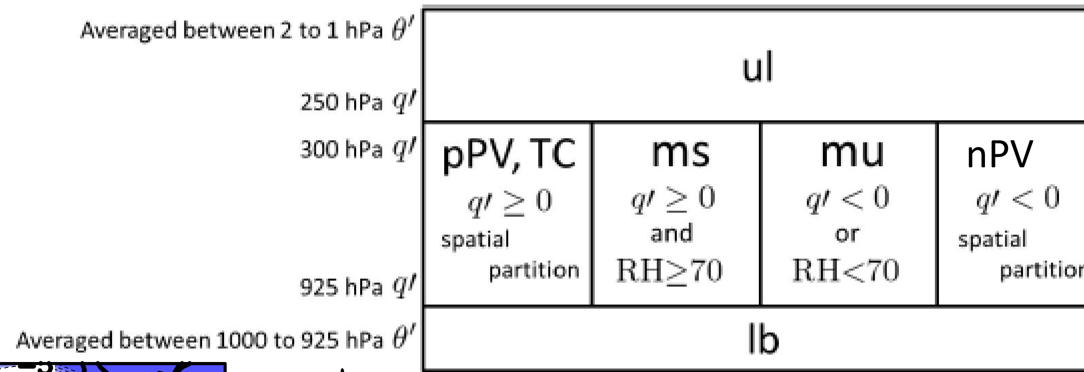
diabatic heating



Wind associated with the TC → Lifting/Convergence by the topography of Taiwan → Condensation and diabatic heating？ → PV generation

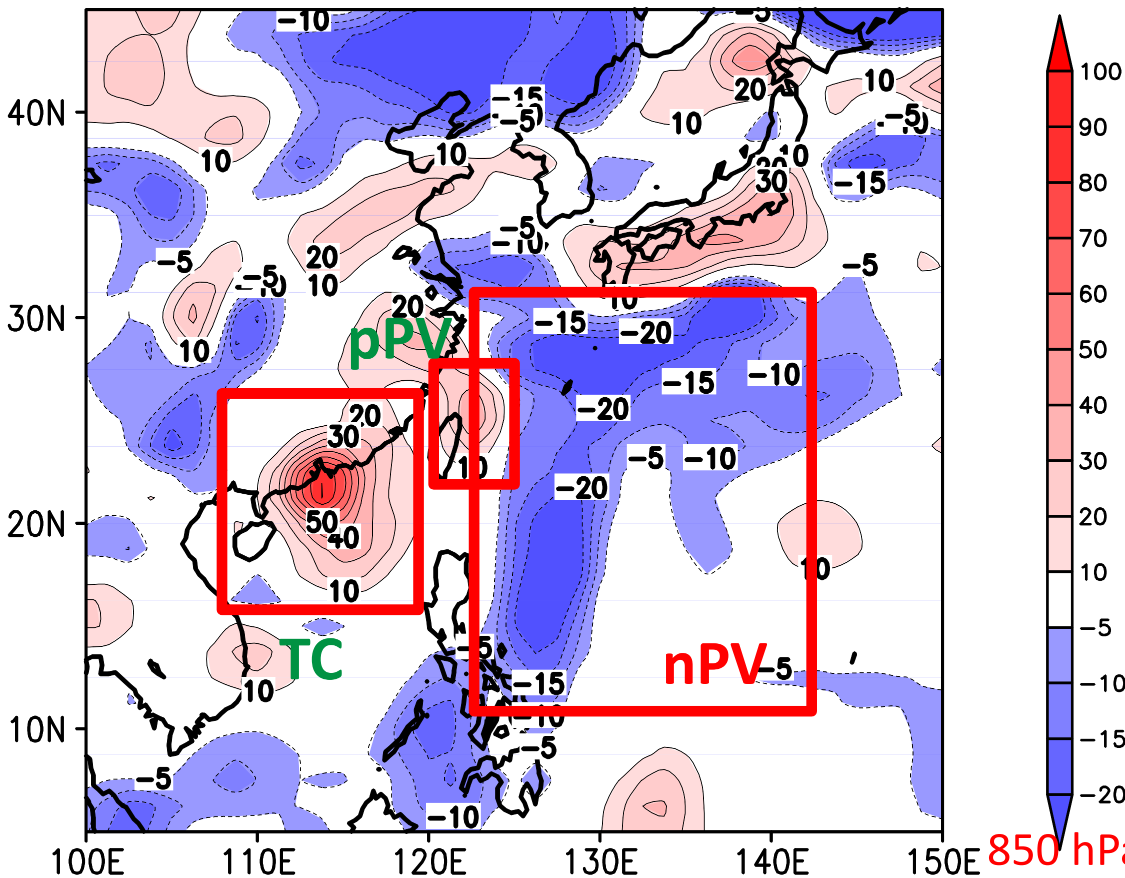
4. Piecewise PV inversion diagnostics

To see whether the high PV (pPV) north of Taiwan and low PV (nPV) at the east really cause the strong northward wind



00 UTC 7 June 1999

1999:6:7:0



850 hPa PV anomaly (PVU) ×100

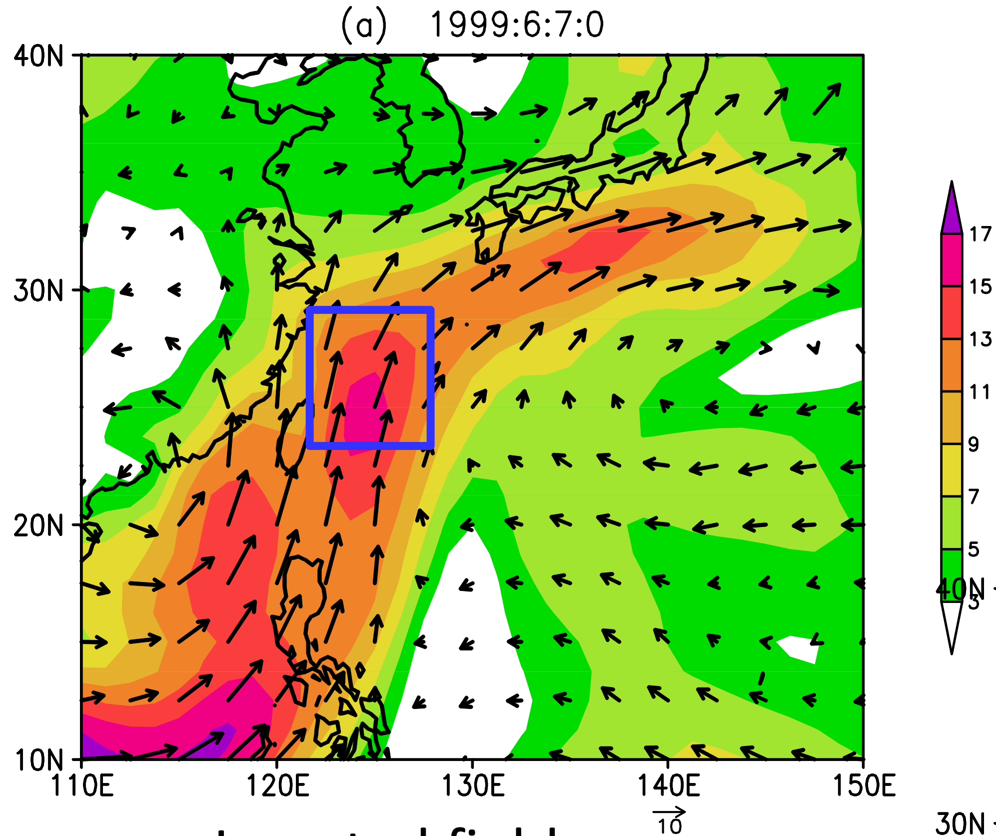
nPV : negative PV

pPV : positive PV

area

60E-180°

0° -80N



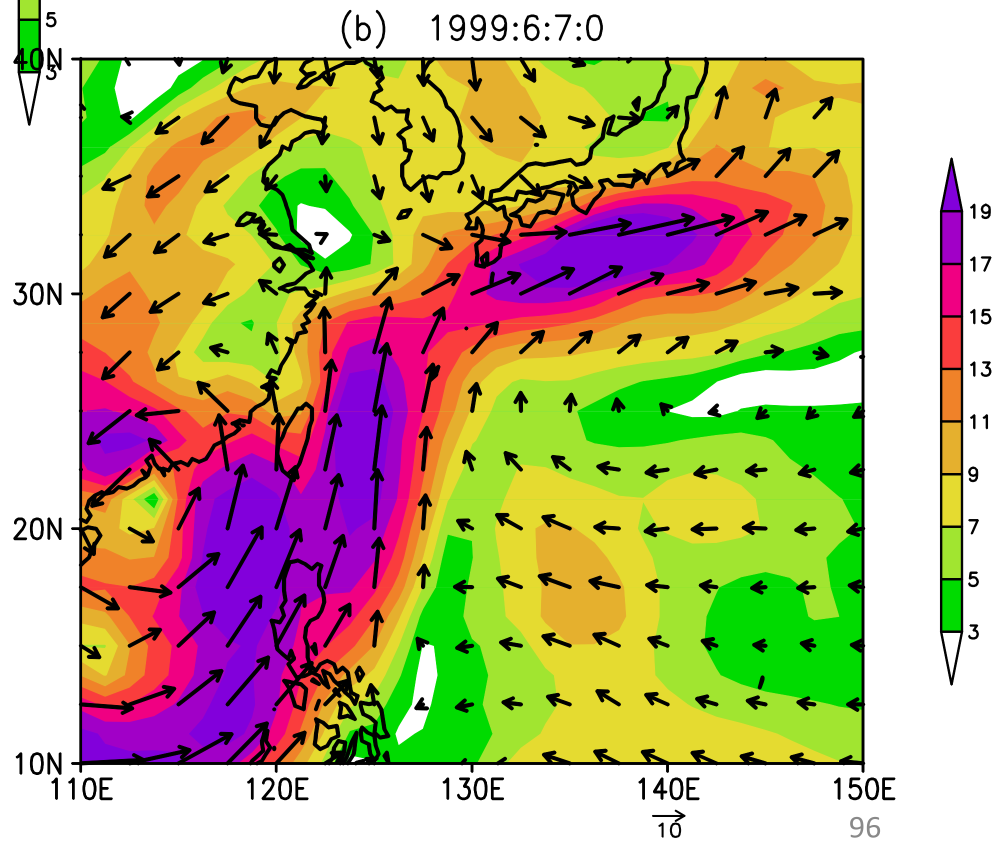
850 hPa wind speed (color) and wind vector

Inverted field

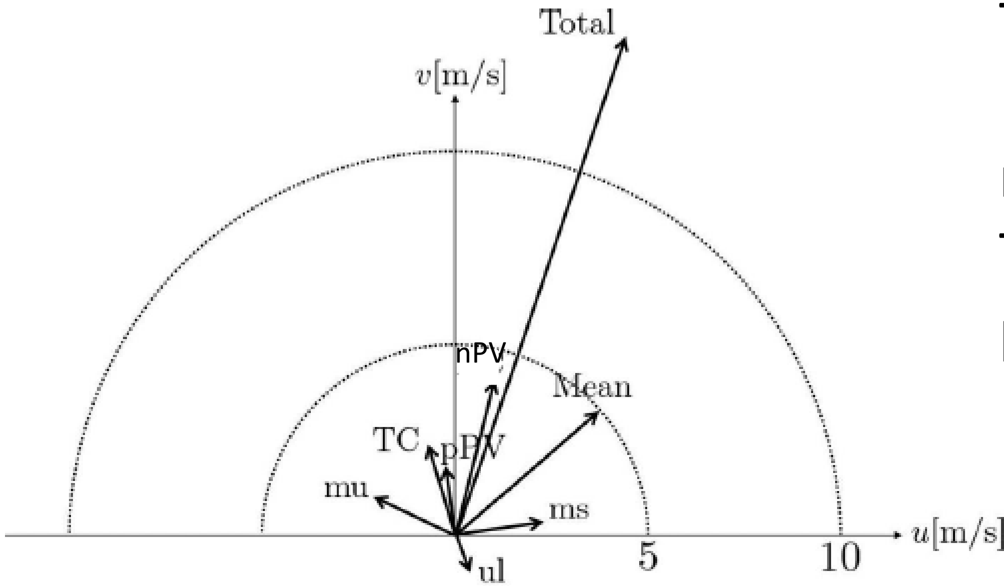
Area for estimations of partitioned winds

Pattern can be reproduced, though winds become weak (the influence of divergent winds).

Original field



Result of Inversion



Total: 13.7 m/s

Mean: 4.9 unrelated to heavy rain

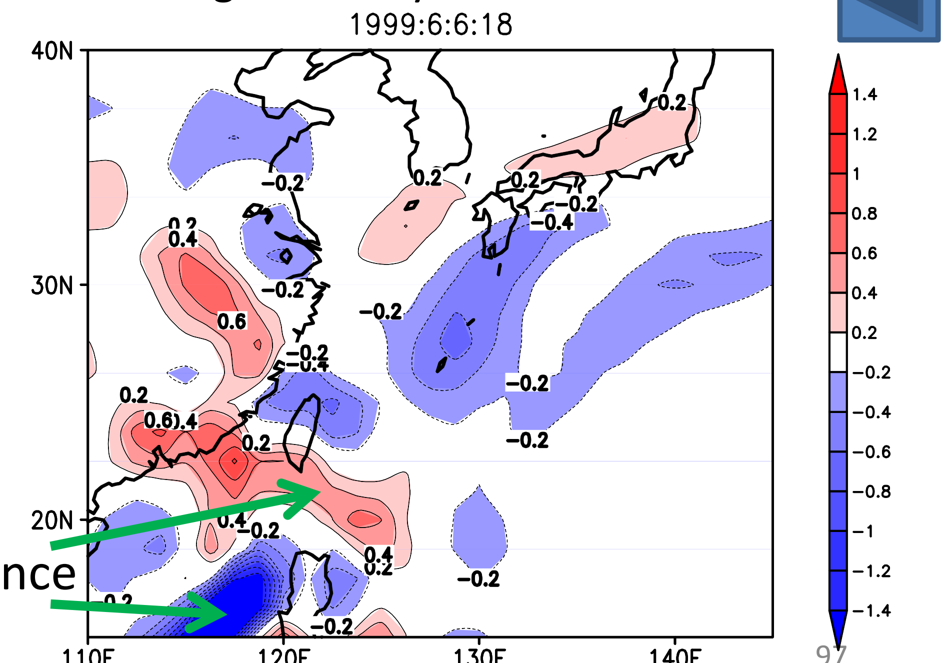
nPV: 4.2

TC: 2.5

pPV: 1.8

$$-\sum_t \left(u' \frac{\partial(\mathrm{PV})}{\partial x} + v' \frac{\partial(\mathrm{PV})}{\partial y} \right) \Delta t$$

Change of PV by the TC wind



310 K surface

Influence of TD

Quantitative estimation of low PV advection (i.e., extension of the Pacific high) by the TC

PV inversion of the TC component from 18 UTC 3 to 18 UTC 6 June

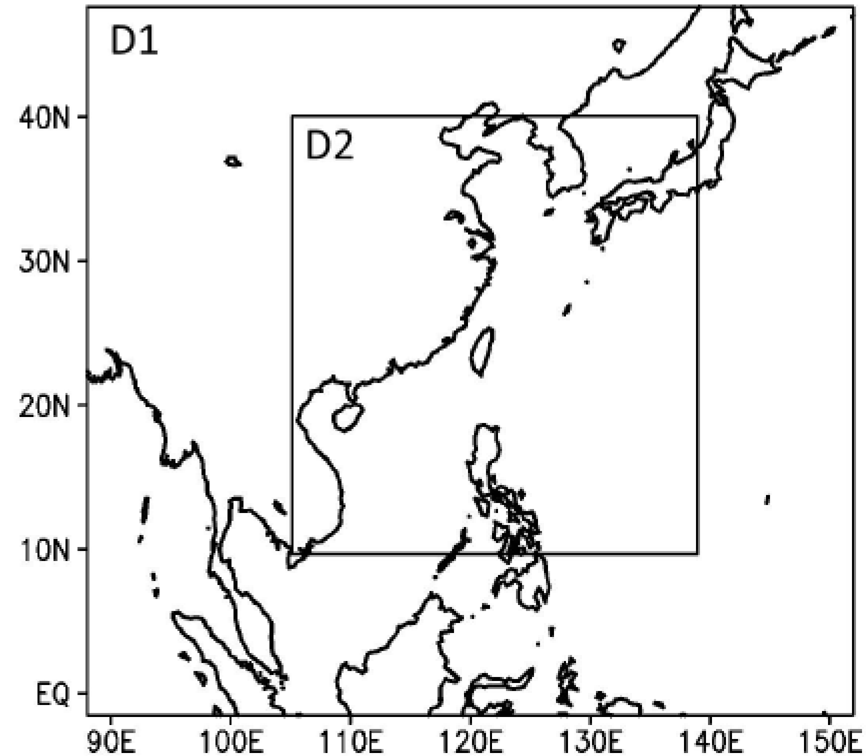
→

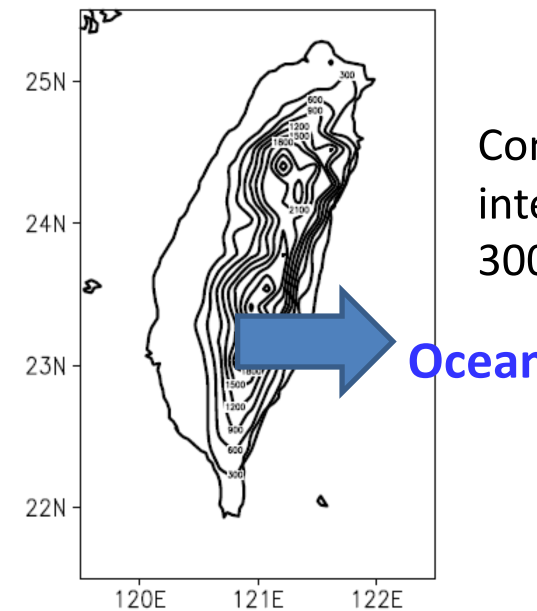
Calculation of PV advection by the wind of the TC

5. Numerical Experiments

MM5 v. 3.7

Domain 1: 140 × 160, 45 km
2: 250 × 250, 15 km
Initial and boundary values JRA25 Reanalysis
SST : Reynolds SST
Integration period 18 UTC 3 ー18 UTC 8 June
Physical Processes
- Goddard microphysics scheme
- Burk-Thompson PBL scheme
- Cloud longwave-/shortwave-radiation
- Cumulus parameterization
  - Betts-Miller scheme (domain 1)
  - Kain-Fritch 2 scheme (domain 2)





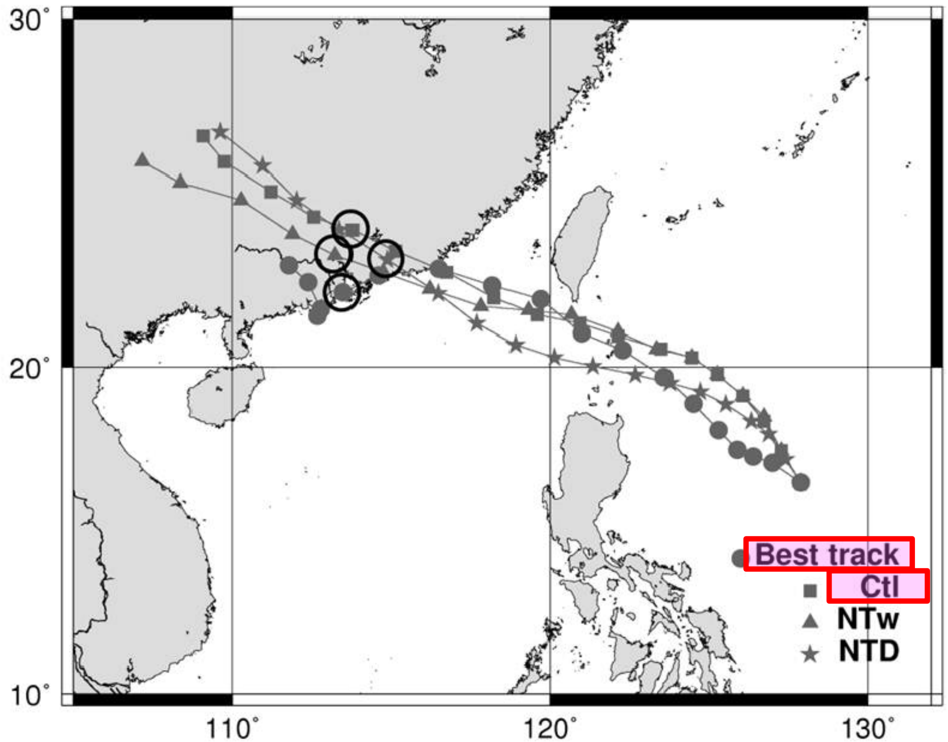
Contour interval : 300 m

Three Experiments

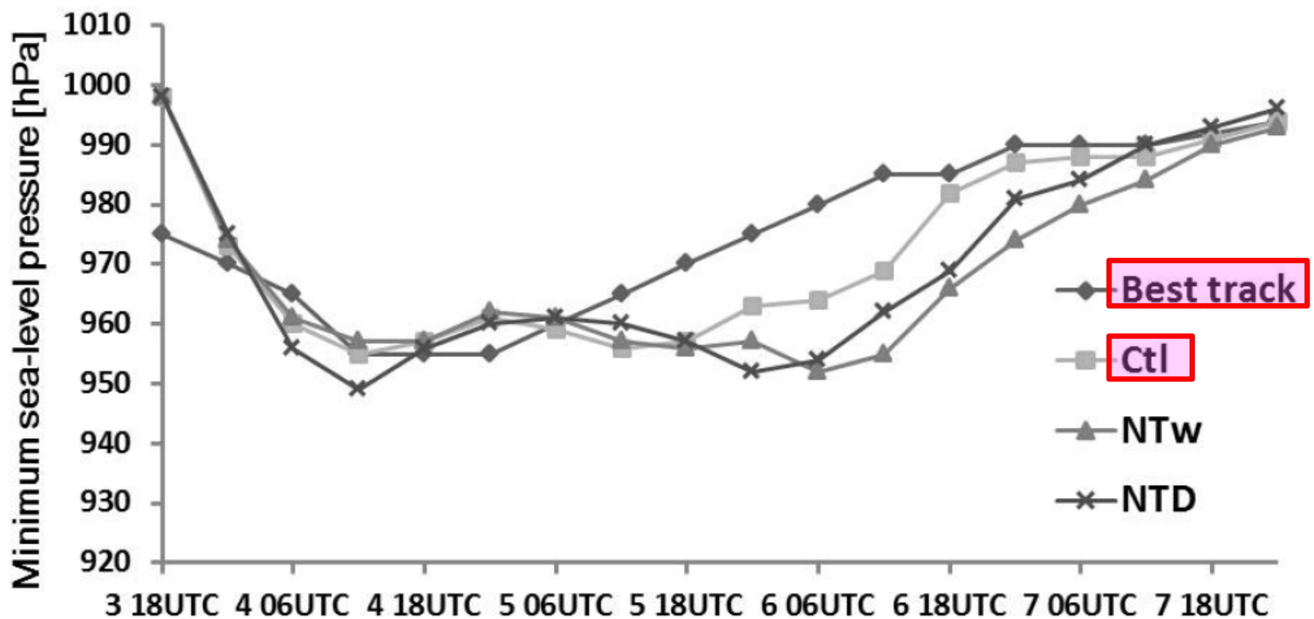
1. Control (Ctl) 2. No-Typhoon (Nty)
3. No-Taiwan (NTw)

Tracks and central pressures of the TCs

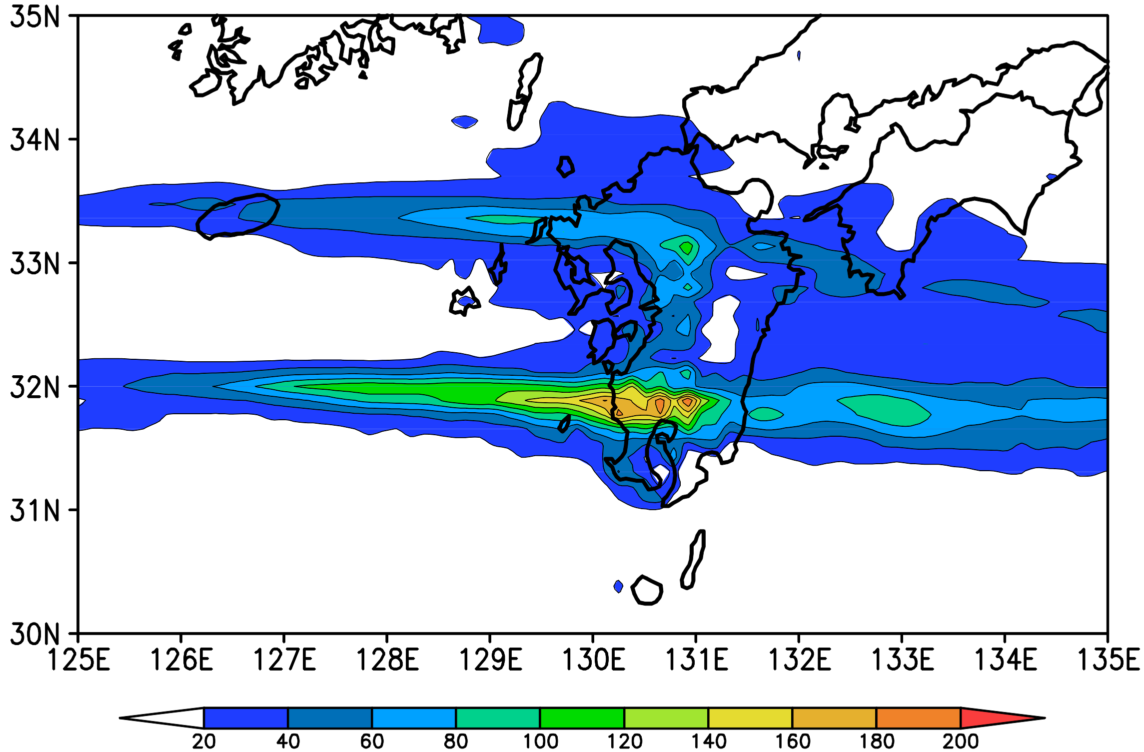
using typhoon bogus



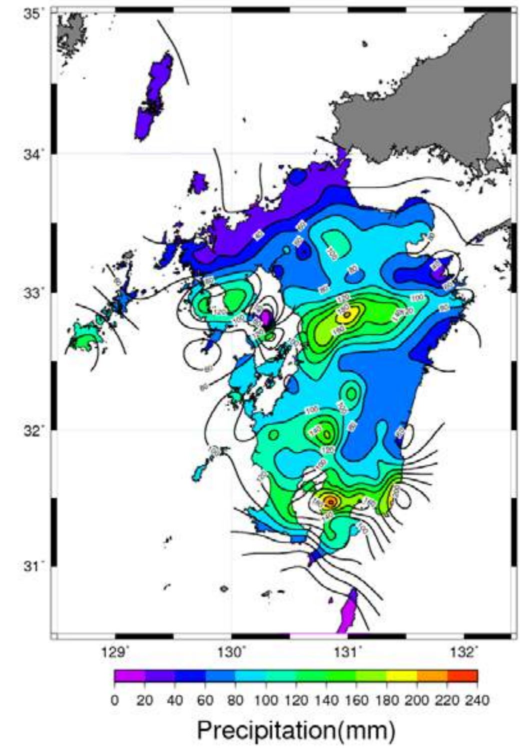
○ : Position at 00 UTC 7 June



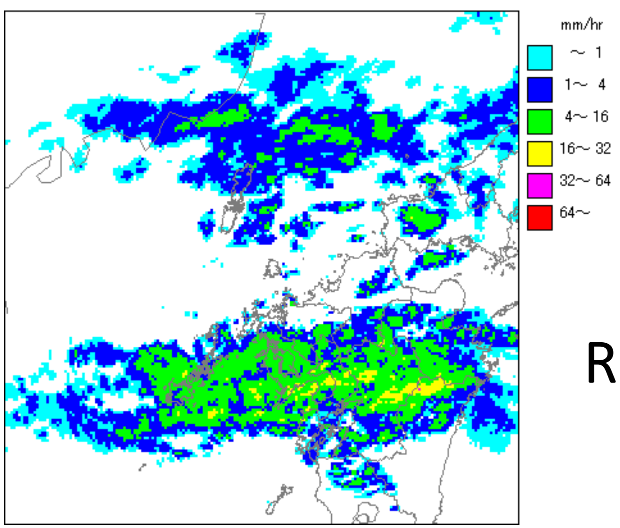
Ctl Accumulated precipitation on 7 June (JST)



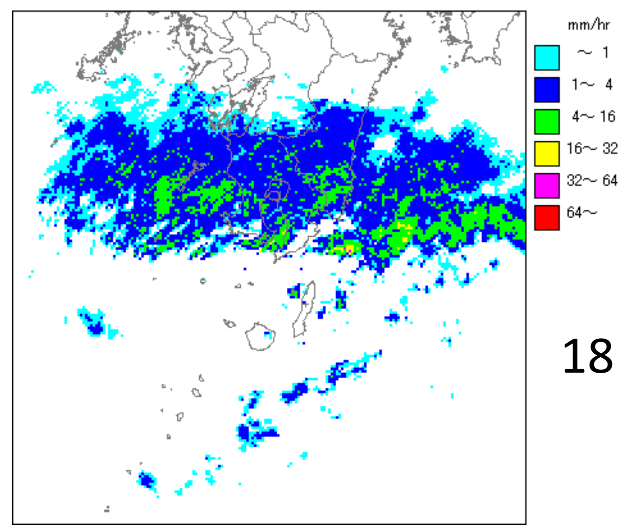
Daily Precipitation 7 June 1999



08 JST



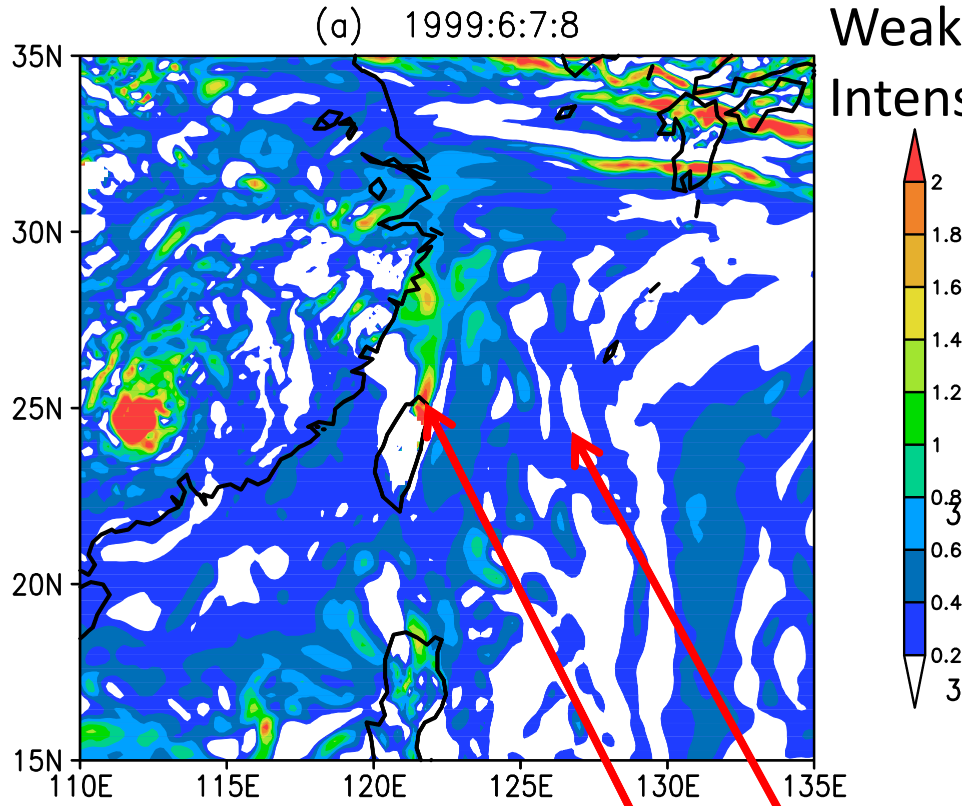
Radar



18 JST

Ctl

High PV formation from 12 UTC 6 → Weakening (about 00 UTC 7) → Intensification

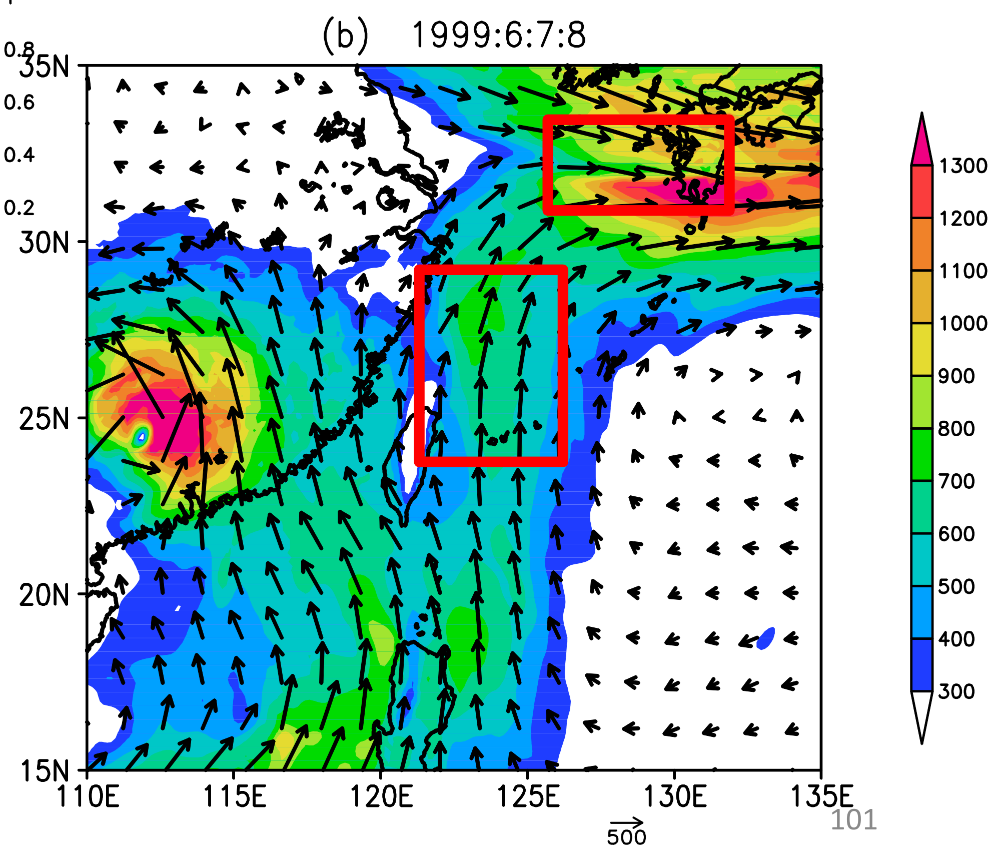


PV on 310 K surface at 08 UTC 7 June

High PV

Low PV

Vertically integrated moisture flux (arrow) and its convergence (color) at 08 UTC 7 June



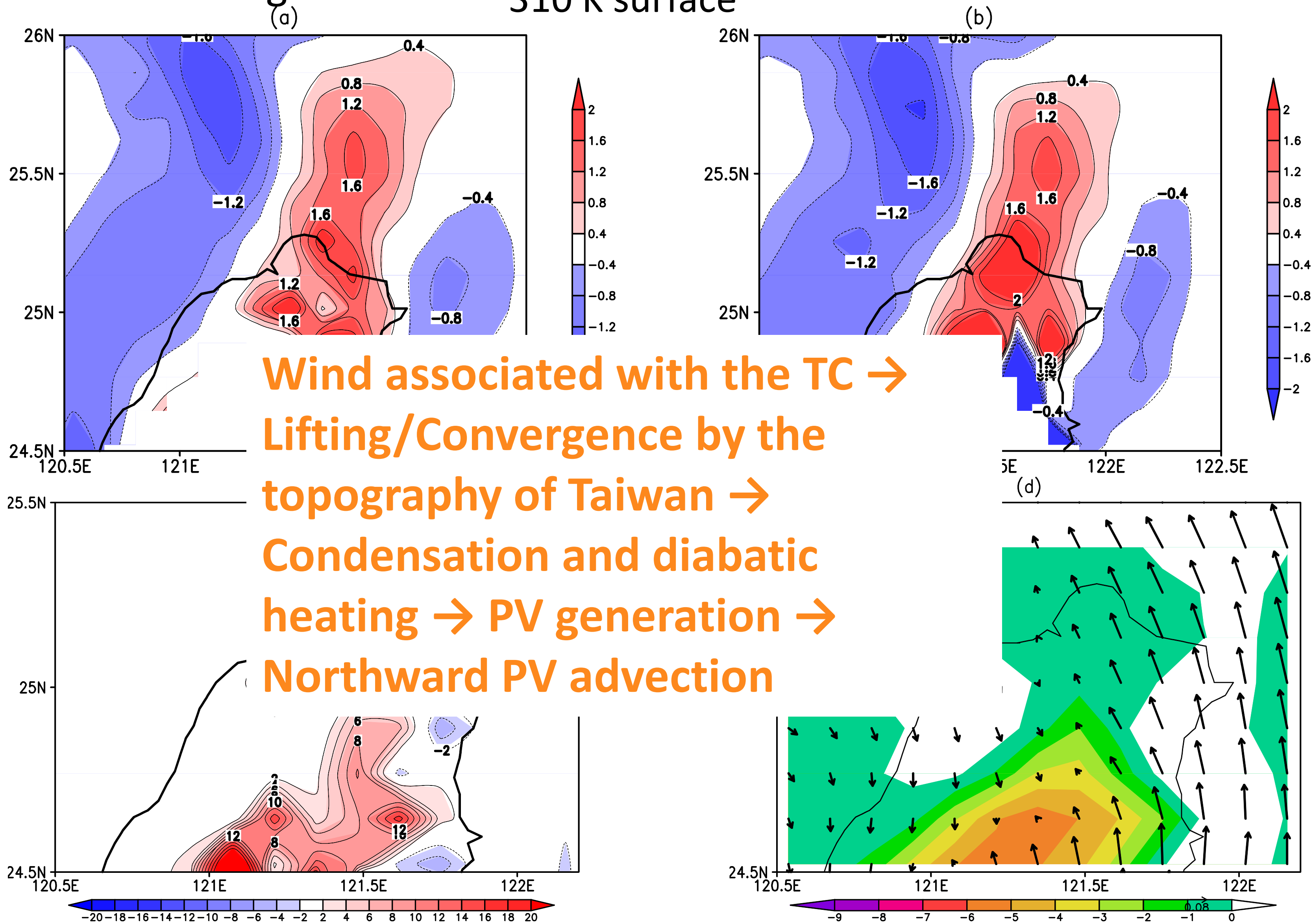
Calculation areas of moisture flux and its convergence

PV budget (09 UTC 6—09 UTC 7, June)

PV change

310 K surface

advection



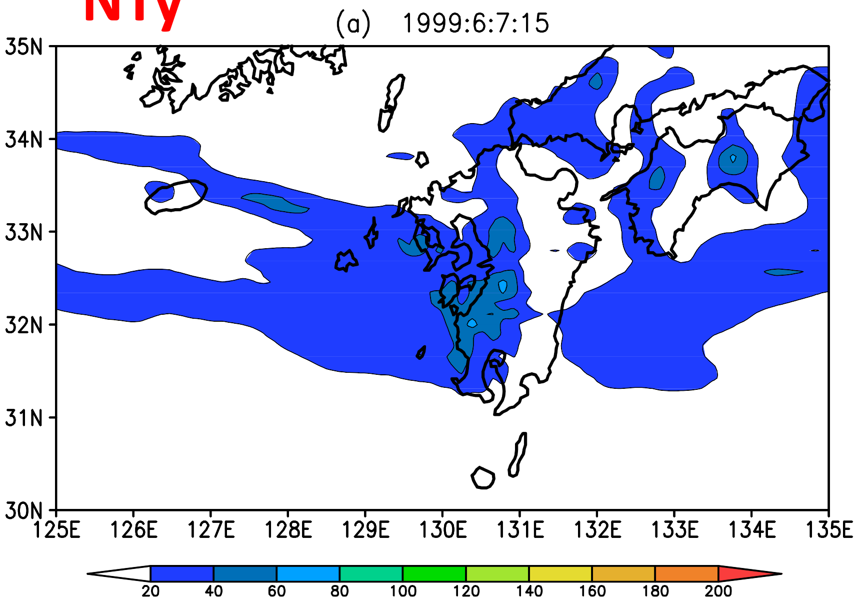
Wind associated with the TC → Lifting/Convergence by the topography of Taiwan → Condensation and diabatic heating → PV generation → Northward PV advection

Diabatic heating(0.91σ level)

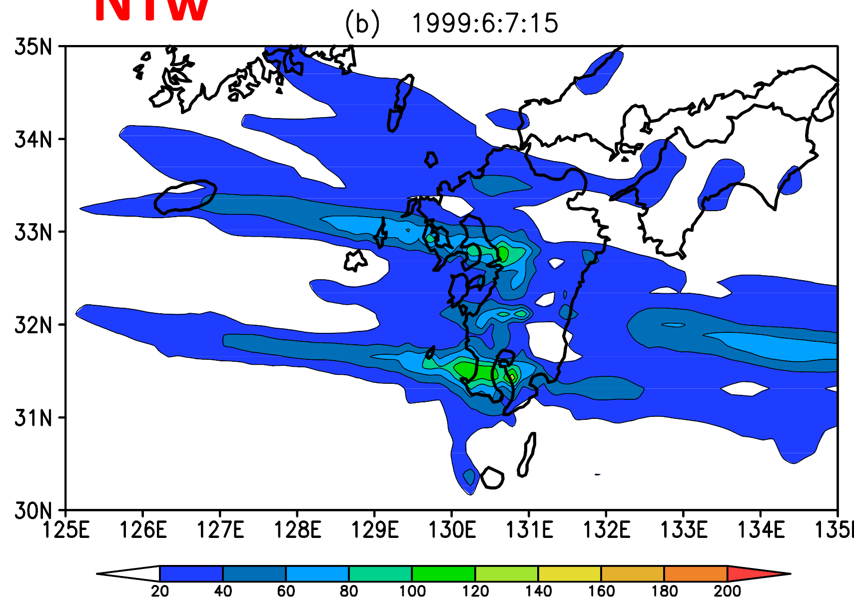
Moisture flux and its conv. (0.965σ level)

Precipitation in each experiment

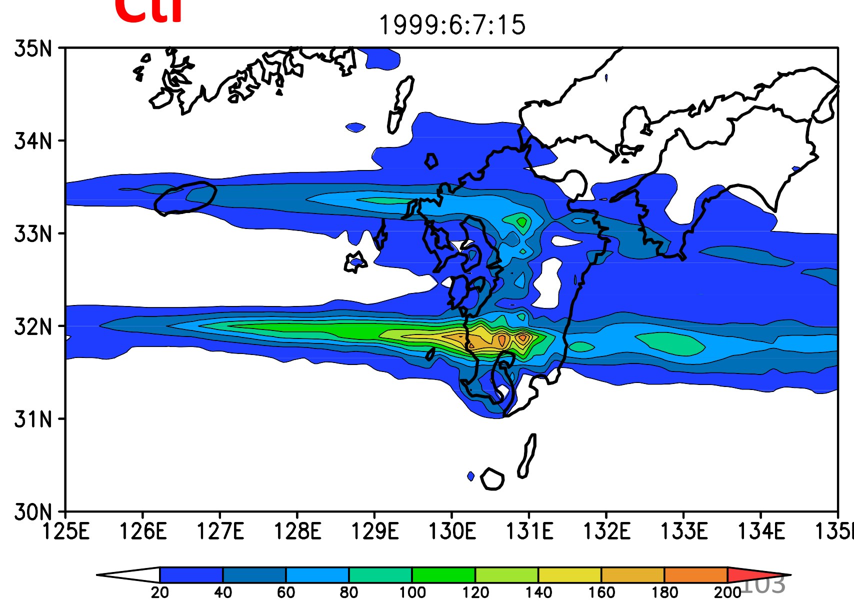
NTy



NTw

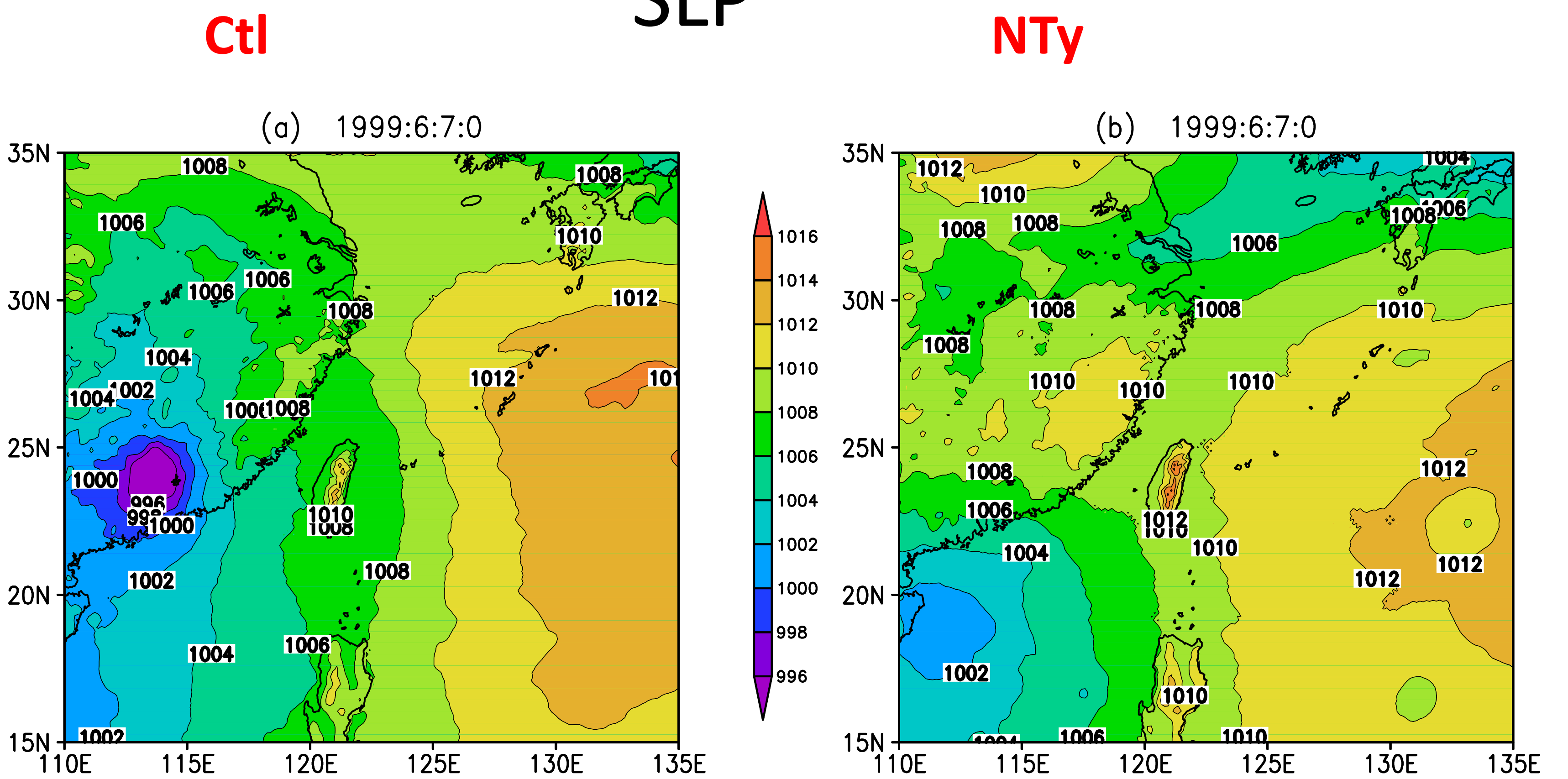


Ctl

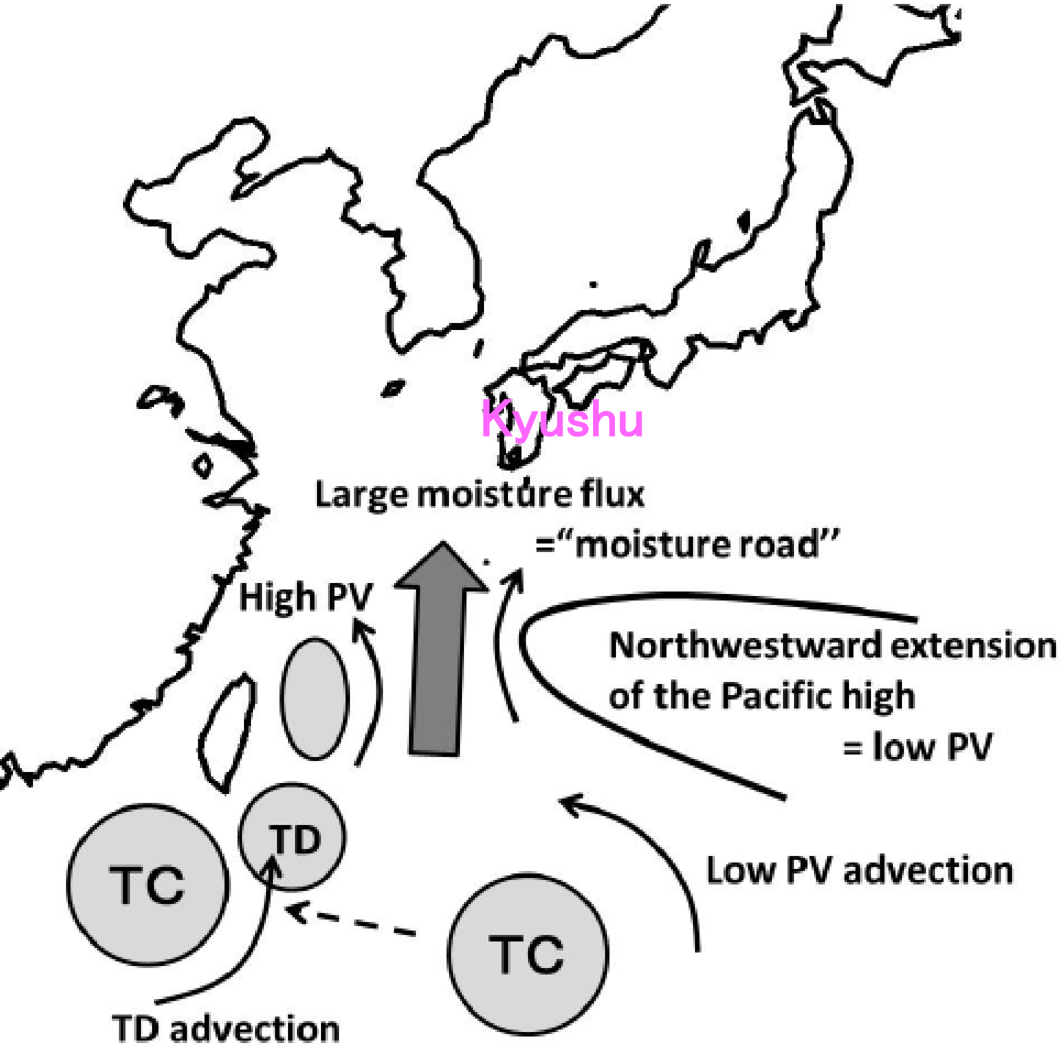


Extension of the Pacific High

SLP



6. Discussion -Mechanism



This situation may be generalized.

New mechanism in various aspects

- not by the direct outer circulation
- not PRE

- Extension of the Pacific high by the TC
  (→ application to other phenomena)
- Generation of the high PV region by the TC (topography of Taiwan is involved)

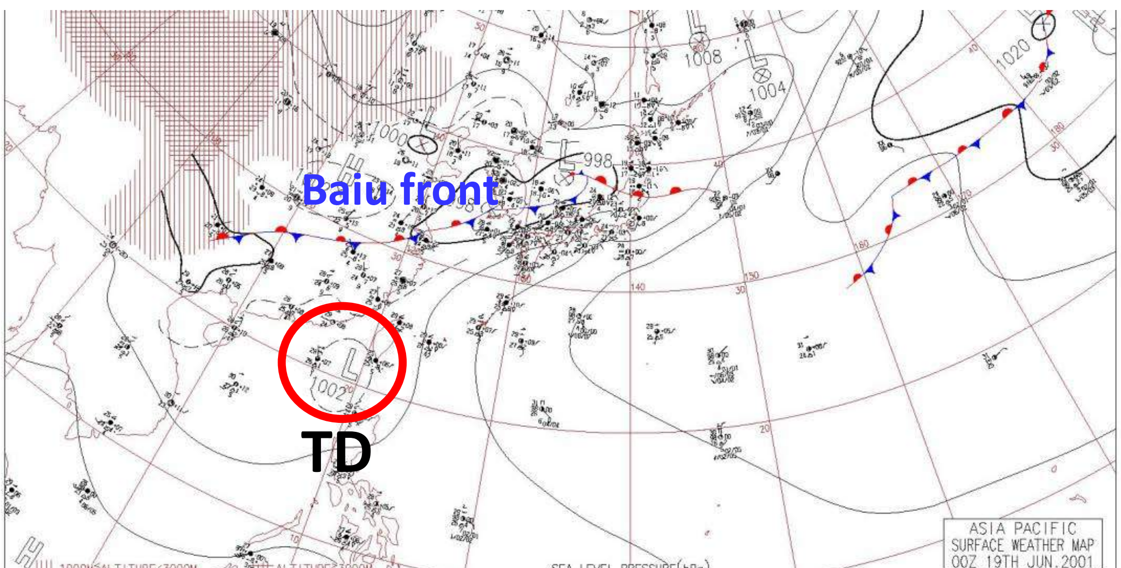
Heavy rain by the TC located 2000 km away from Kyushu

7. Generality

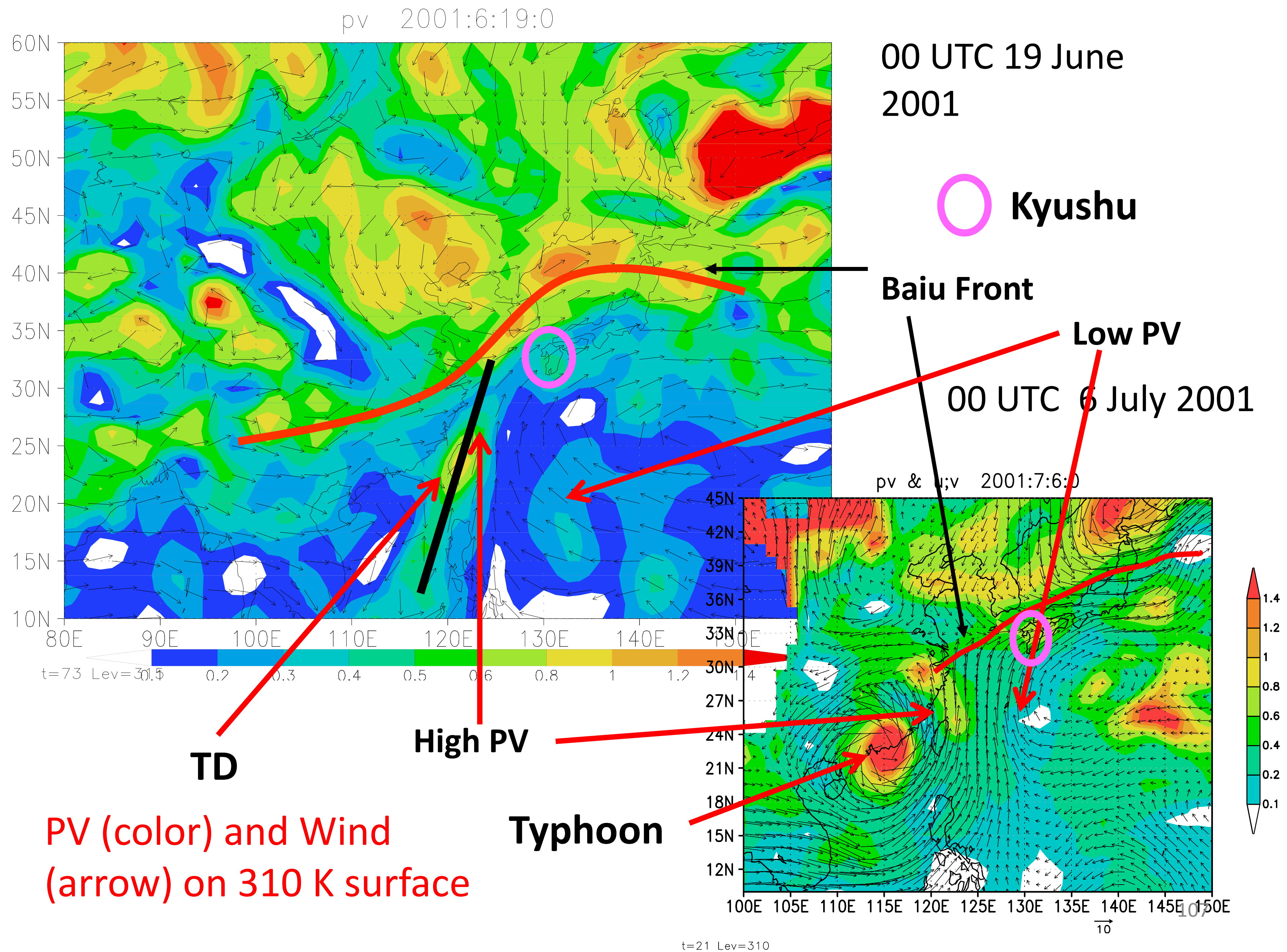
More than 20 weather stations with more than 100 mm/d rainfall
＋ TC (including TD) far from Kyushu (more than 1000 km)

Group	Characteristics	Dates	
A	high PV zone and low PV intrusion	21 June 1985, 7 June 1999 (Maggie's case) 19-20 June 2001, 6 July 2001	4
B	high PV zone	2 July 1985, 2 June 1988, 12 July 2001	3
C	low PV intrusion	9 July 1980, 25-28 June 1985, 20 July 1987, 23 June 1988 18 July 1988, 25 July 2000, 17 June 2003	7
D	no feature	1 July 1980, 15-16 July 1983, 15 June 1990, 30 June 1990 2 July 1990, 7 July 1997, 20 July 2003 6 July 2005, 5 July 2006, 23 July 2006	

24 cases



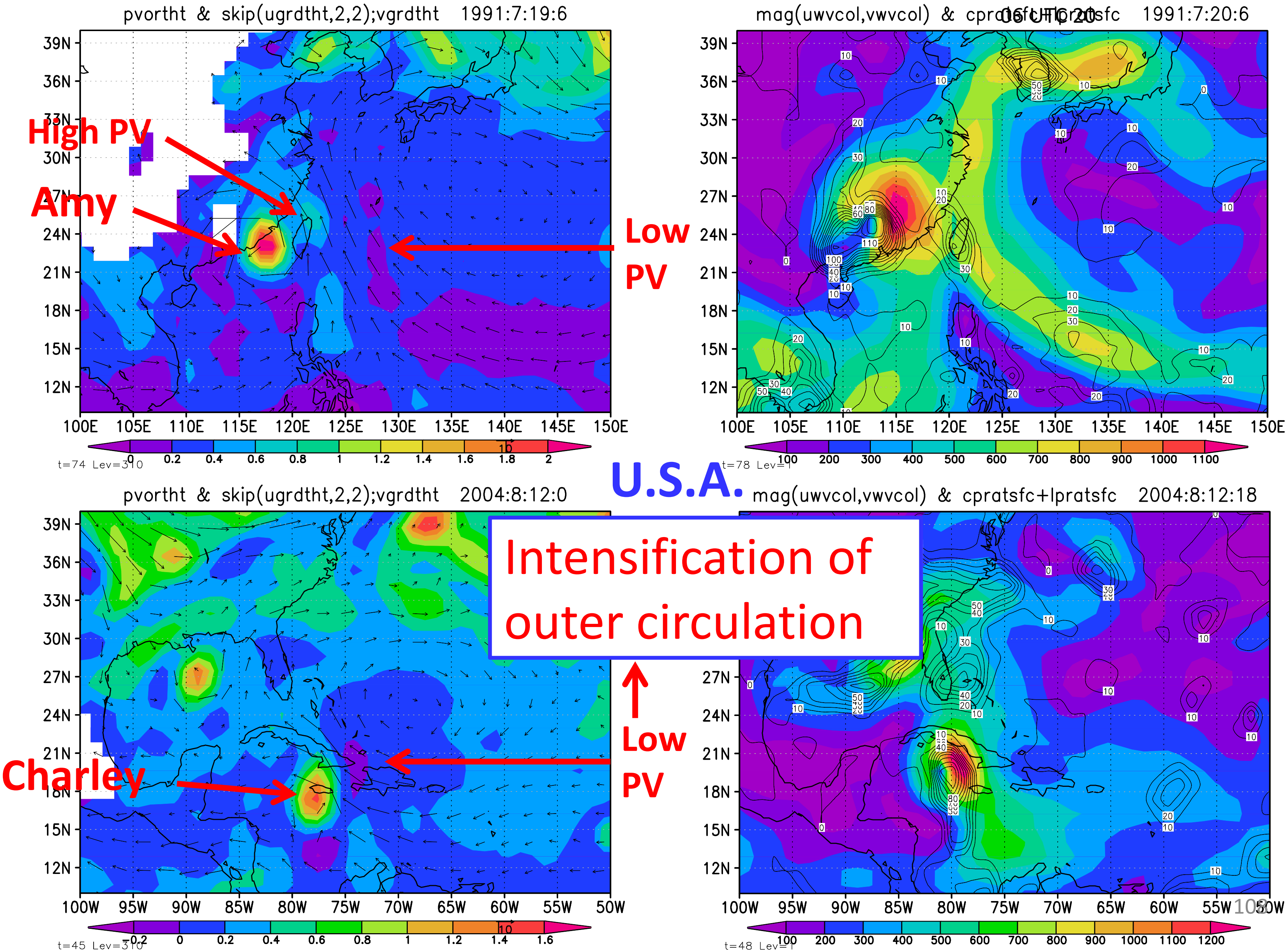
00 UTC 19 June 2001


pv 2001:6:19:0
00 UTC 19 June 2001
Kyushu
Baiu Front
Low PV
00 UTC 6 July 2001
pv & u;v 2001:7:6:0
t=73 Lev=315
TD
High PV
Typhoon
t=21 Lev=310
PV (color) and Wind (arrow) on 310 K surface

Other Areas

Korea during the Baiu season

310 K PV and Wind 06 UTC 19 July 1991 Moisture flux (color) and Prec. (contour, mm/d)



4-8. Conclusions

We found a new mechanism of remote rainfall events caused by TCs during the Baiu season.

After TCs pass near Taiwan, strong moisture flux northeast of Taiwan is formed (= moisture road), and then converges near Kyushu.
The following two are involved in this mechanism.

- Westward extension of the Pacific high
  - ← Low PV advection from low latitudes by TCs
- High PV region north of Taiwan
  - ← Diabatic heating by topography of Taiwan and TC winds

corollary : Close relationship between TCs and
the westward extension of the Pacific high

Importance of analyses using PV

5. Summary (of summary)

- Several examples which vortex-vortex interaction originating from TC research can be applied to.

→ Wide perspective of researches

TC → SED

"Convective storms cannot be advected by waves"

- Conserved quantities are useful in many situations if they are applicable.

Blocking maintenance : PV supply

TC size : AAM

Way of thinking is simple.

Interpretation is easy.

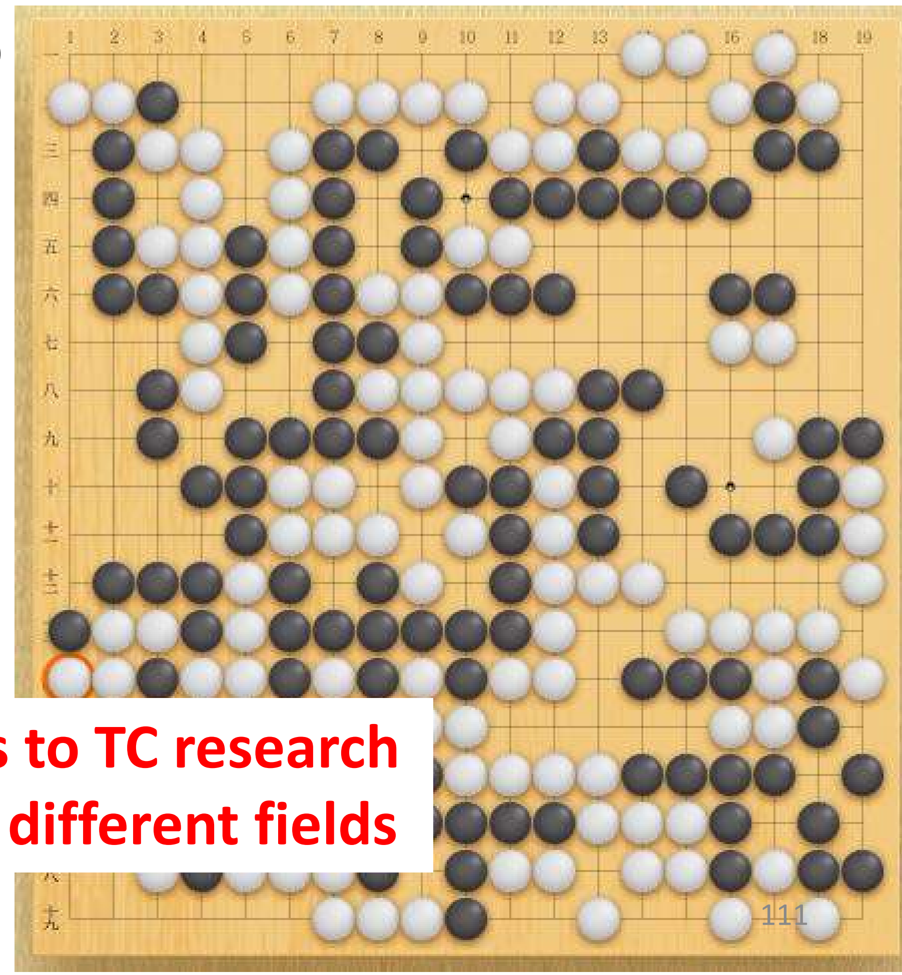
Yuta Iyama : the most popular professional *igo* player
sextuple crown including the most
authoritative triple crown.

Another player Cho says that he has two *gobans* in his head.
He can think about many, completely different aspects in one stage of a game. Many players admire him for being able to put a stone which no one cannot think of.
(Asahi Shinbun (newspaper), 18 Oct. 2013)

We want to always have two "*gobans*", one of which is an ordinary "*goban*",

TC research

and the other is a "*goban*" viewed from different sites.



Application from different fields to TC research
to TC research from different fields

goban