8th International SRNWP-Workshop
on Non-Hydrostatic Modelling

Impacts of evaporative cooling on tropical cyclone rainband

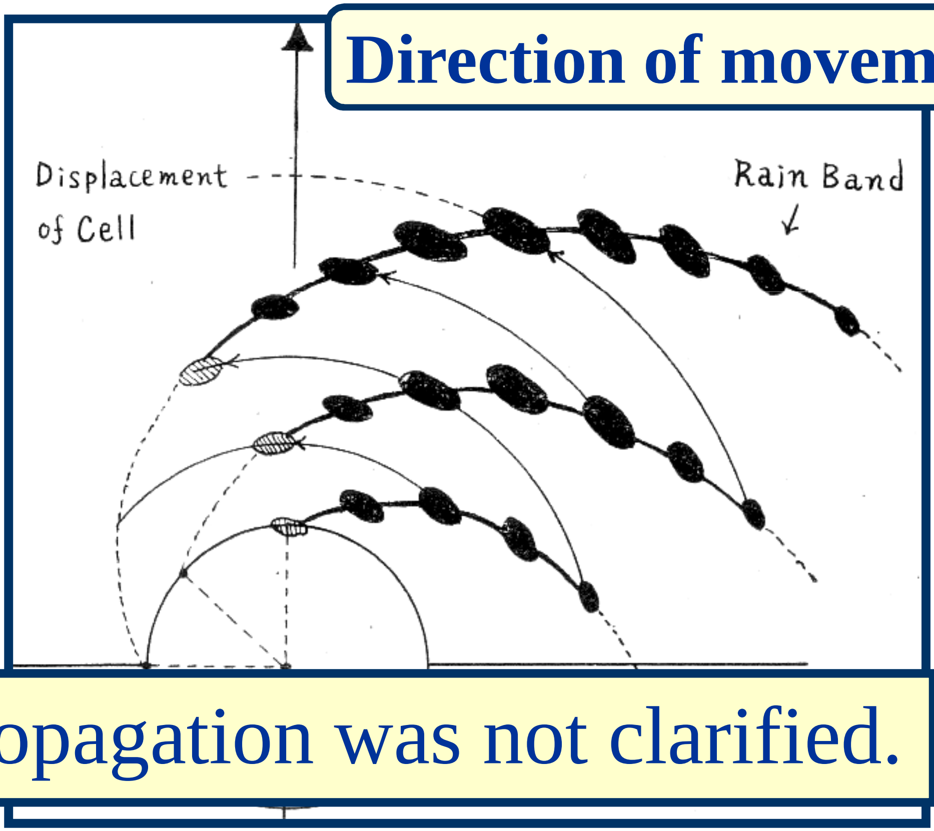
Masahiro SAWADA
Toshiki IWASAKI

Bad Orb, 26 - 28 October 2009

Background

Schematics of rainband propagation. This figure is based on radar echo in Typhoon Helen at 1958.

(Tatehira 1961, in japanese)



Direction of movement

Mechanism for rainband propagation was not clarified.

Evaporative cooling affects rainband formation and structure through cold pool dynamics (Yamasaki 1983).

=> This study used 2-D axisymmetric model, which cannot capture 3-D structures (spiral rainband).

Purpose of this study

Using 3-D models, impacts of evaporative cooling have been investigated (Wang 2002; Zhu and Zhang 2006; Pattnaik and Krishnamurti 2007).

=> These studies mainly focus on TC intensity, not rainband formation and propagation.

To clarify rainband behavior with focus on impacts of evaporative cooling using 3-D cloud-resolving simulations.

Model outline

JMA-NHM (Japan Meteorological Agency NonHydrostatic Model) (Saito et al., 2006)

Dynamical framework

3-dimensional, nonhydrostatic

dx=dy=2km, dz=40-1400m（36levels）, 2000 x 2000 x 24km

Lateral boundary: radiation condition

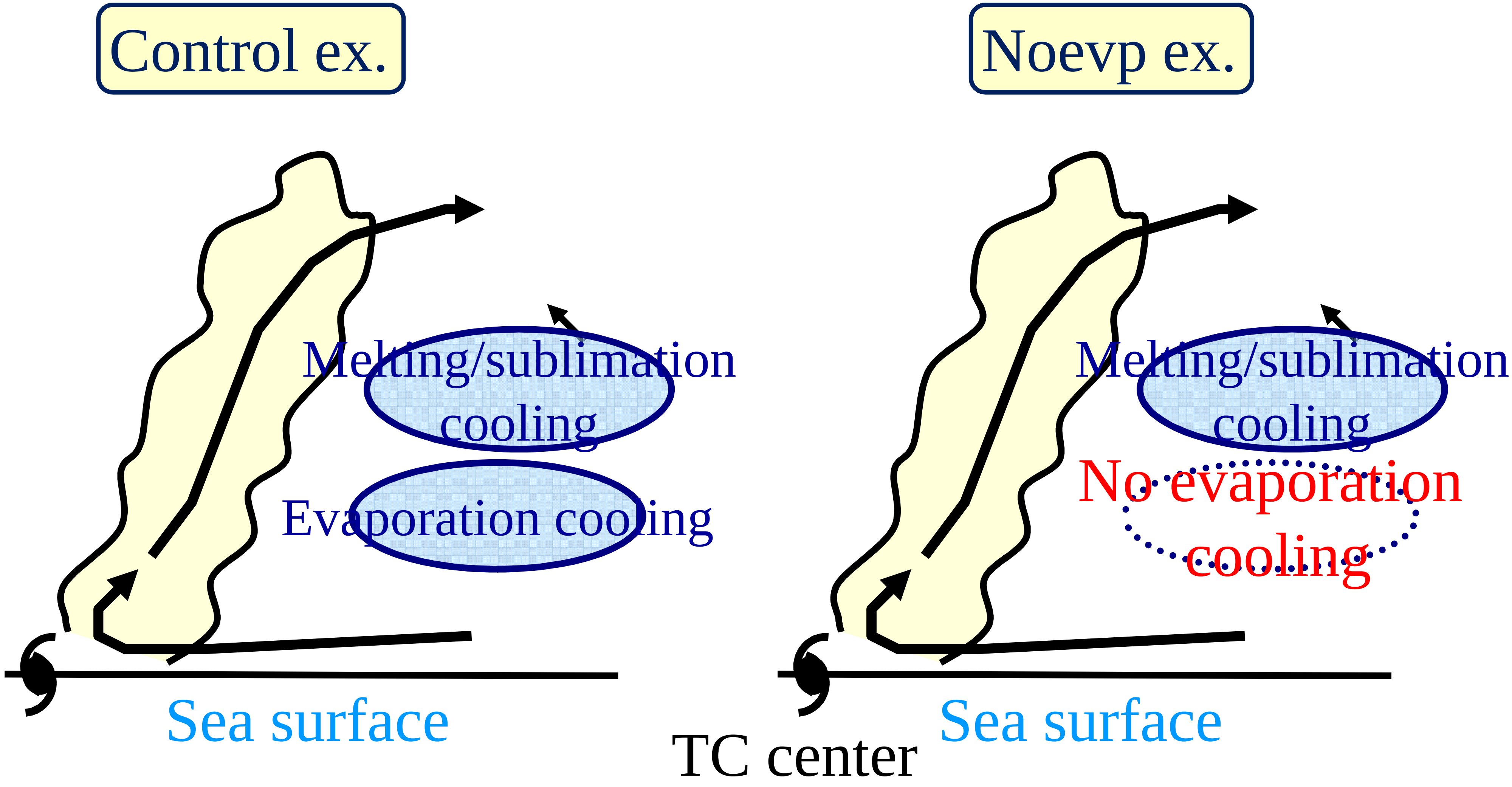
f-plane (constant Coriolis parameter at 15° N)

Physical processes

microphysics: cold rain, 3-ice Bulk method (Murakami, 1994) (solid: 2moment, liquid: 1moment)

turbulent closure: 2.5 turbulent closure (Deardroff 1980) with non-local mixing (Sun and Chang 1986)

Experimental design



Control ex.

Melting/sublimation cooling

Evaporation cooling

Sea surface

TC center

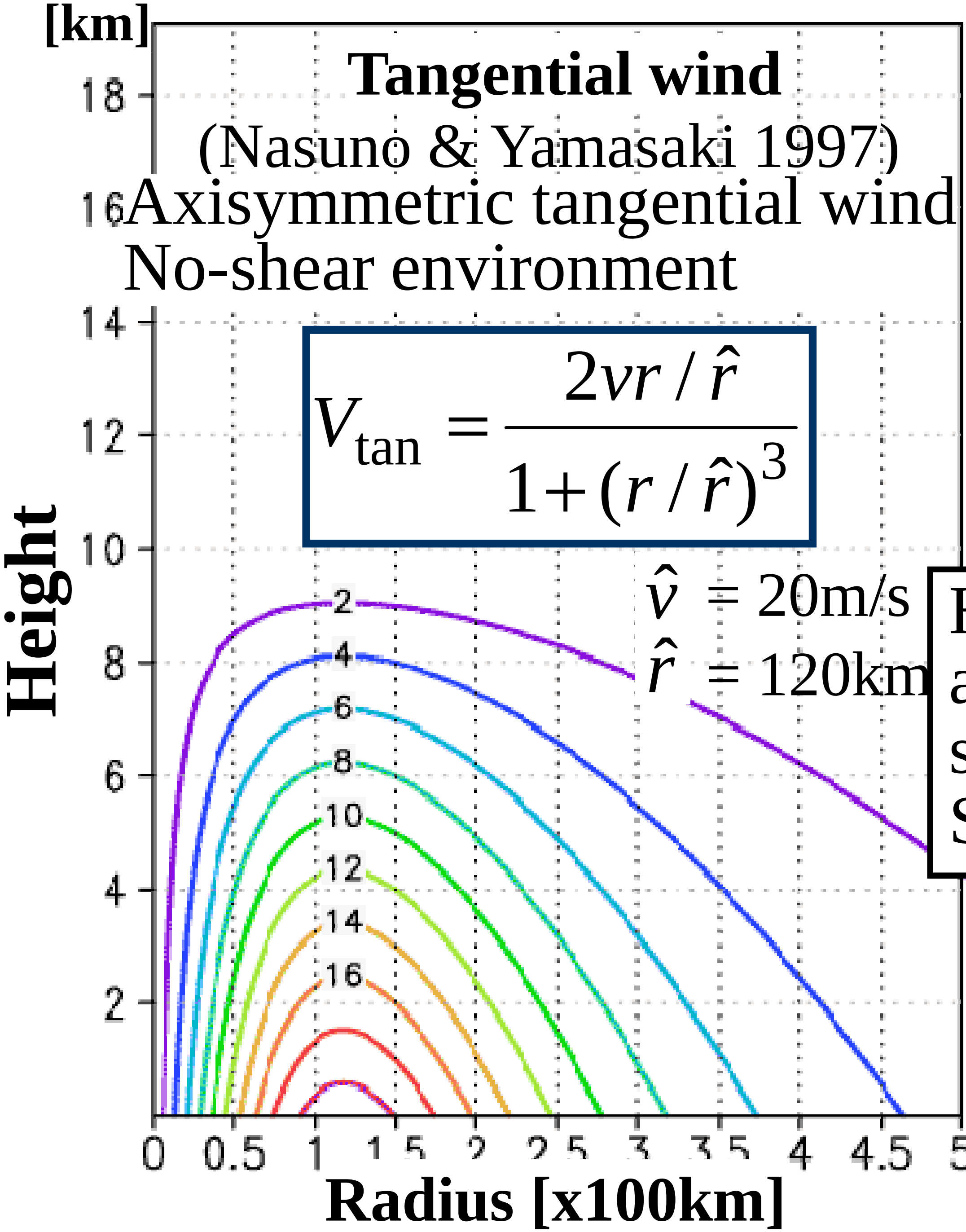
Noevp ex.

Melting/sublimation cooling

No evaporation cooling

Sea surface

Initial condition



Tangential wind

(Nasuno & Yamasaki 1997)

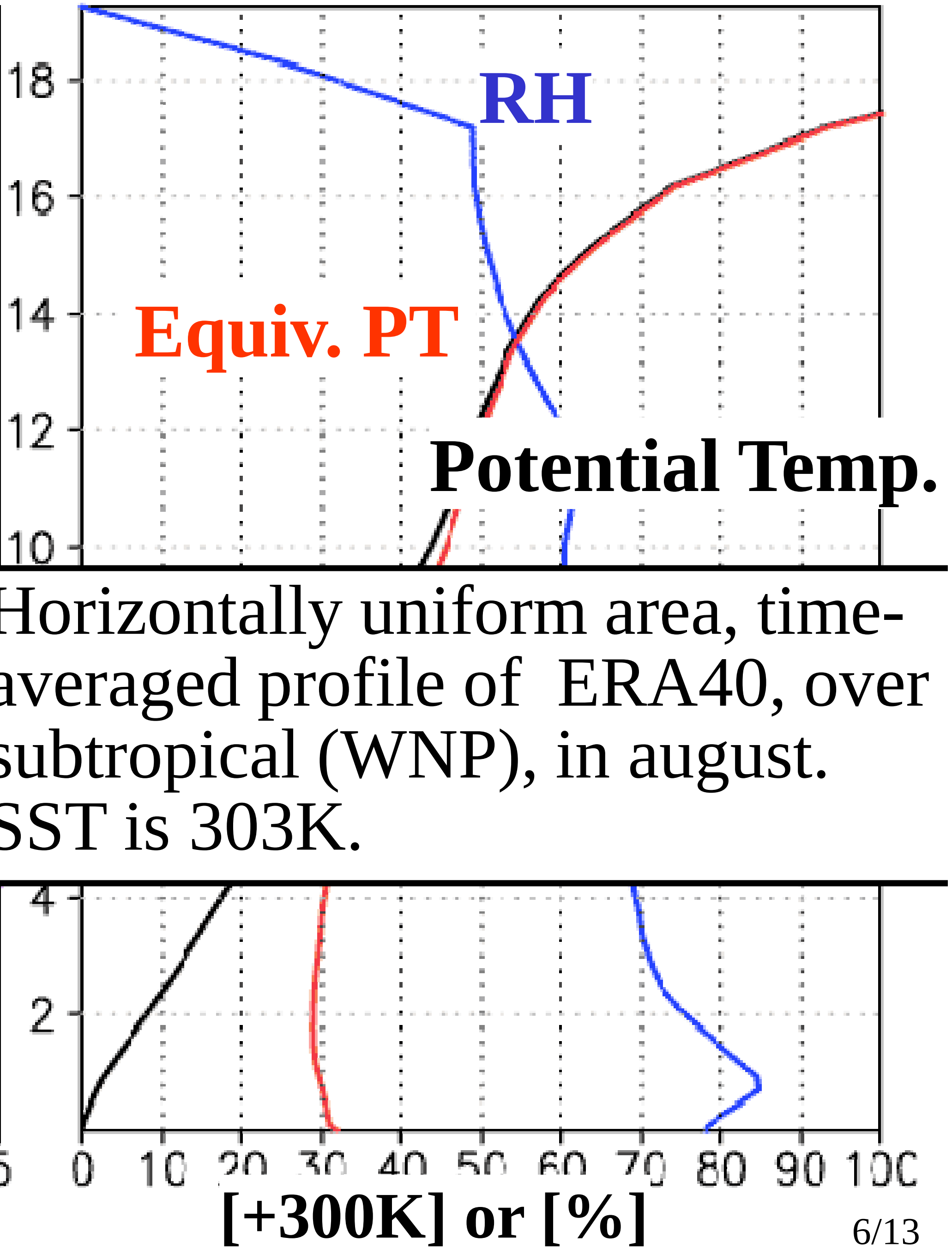
Axisymmetric tangential wind

No-shear environment

$$V_{\tan} = \frac{2vr/\hat{r}}{1+(r/\hat{r})^3}$$

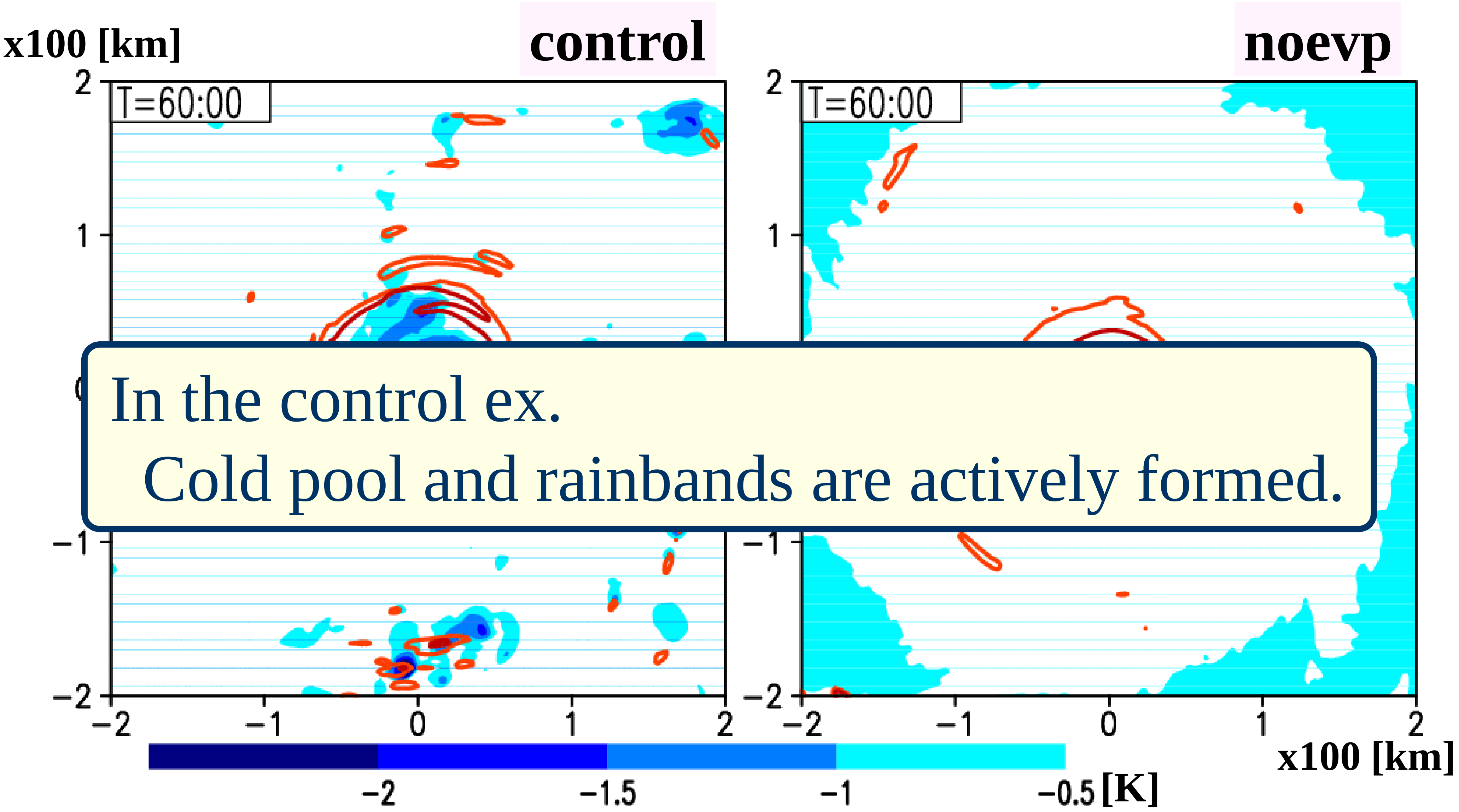
$\hat{v}$ = 20m/s

$\hat{r}$ = 120km



Horizontally uniform area, time-averaged profile of ERA40, over subtropical (WNP), in august. SST is 303K.

Results – impact of evaporation –



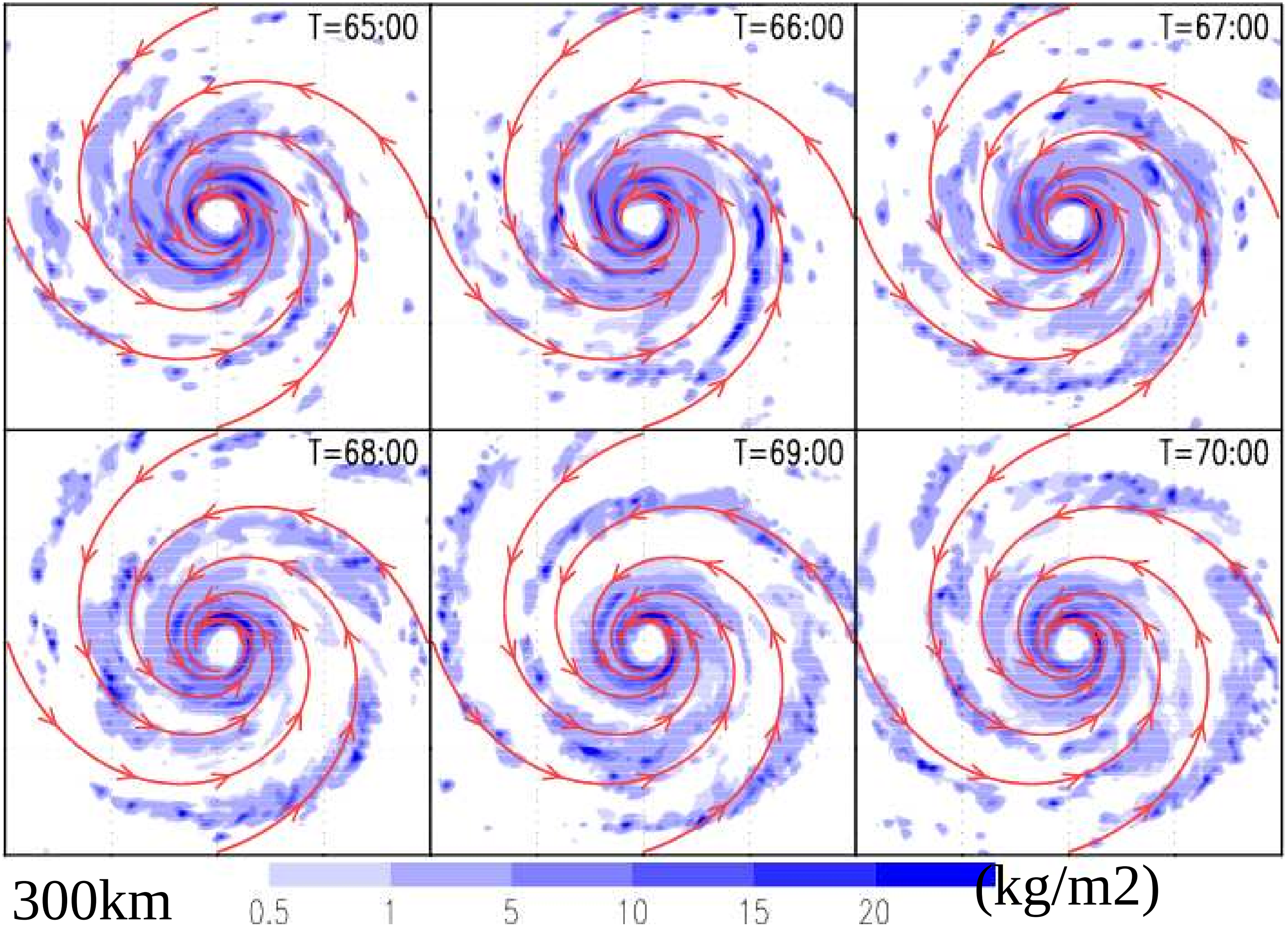
In the control ex.

Cold pool and rainbands are actively formed.

Color: PT anomaly from its areal average (K) at Z=20m
Contour: precipitation (mm/hour)

Results – spiral shape formation –

Accumulated rainwater & streamline @ z=260m



300km × 300km

Streamline is axially averaged and temporally averaged.

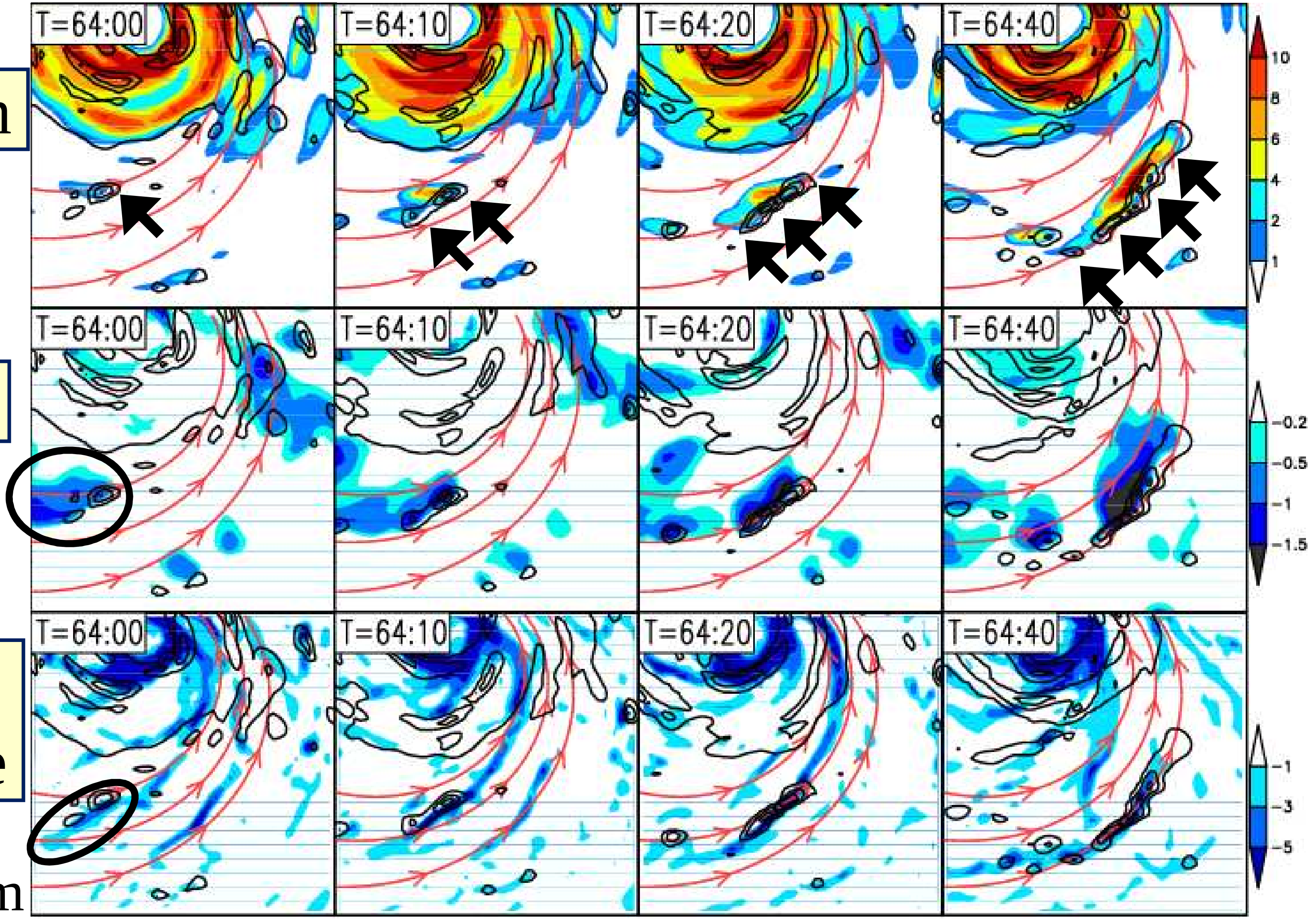
Results – spiral shape formation –

Horizontal structure of convective cells

precipitation

θ' (cold pool)

horizontal convergence

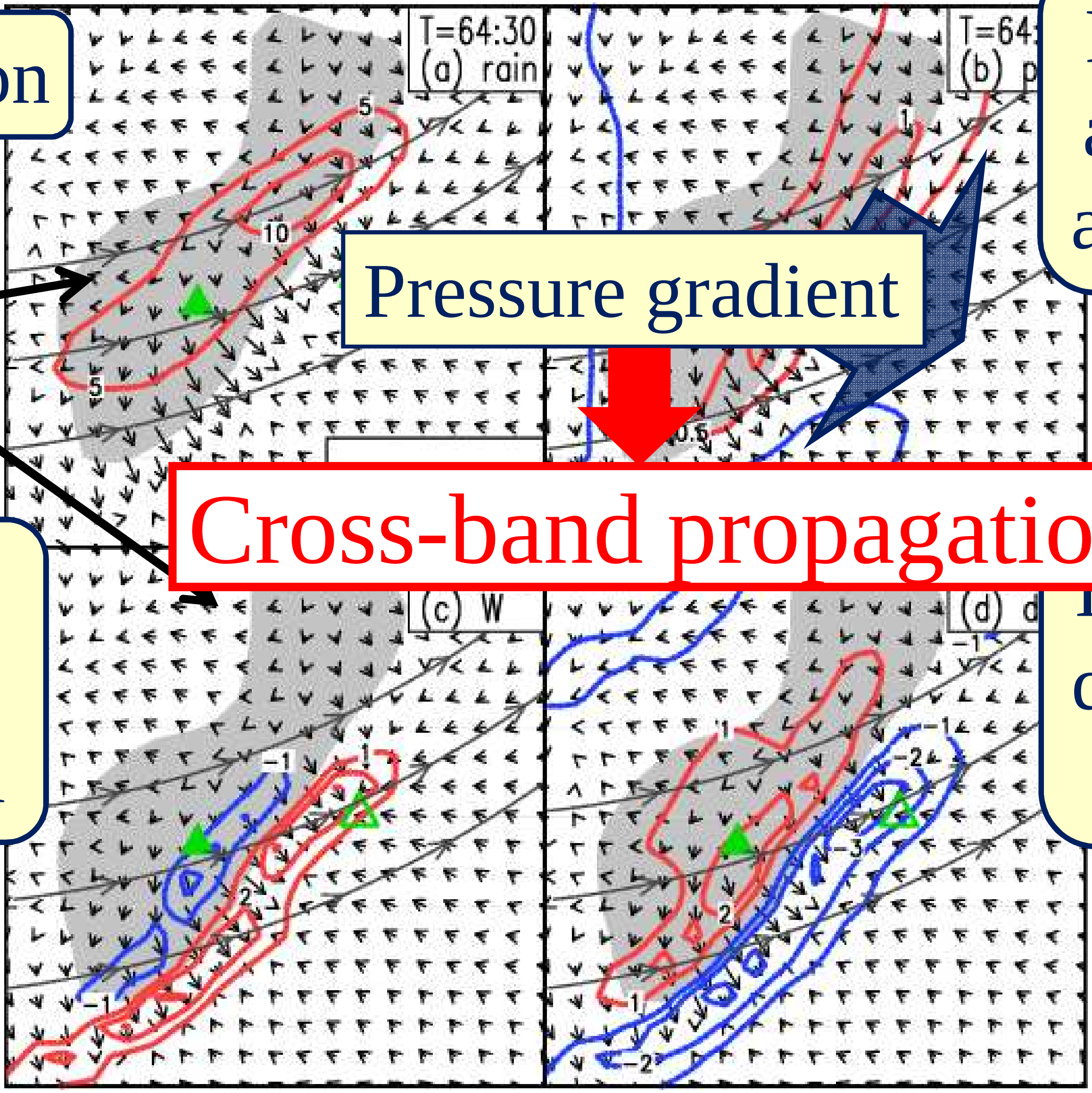


120km × 120km

Upstream development

Results – propagation mechanism –

Horizontal structure of cold pool



Precipitation

Pressure anomaly at z=20m

Cold pool

Pressure gradient

Cross-band propagation

Vertical Motion at = 620m

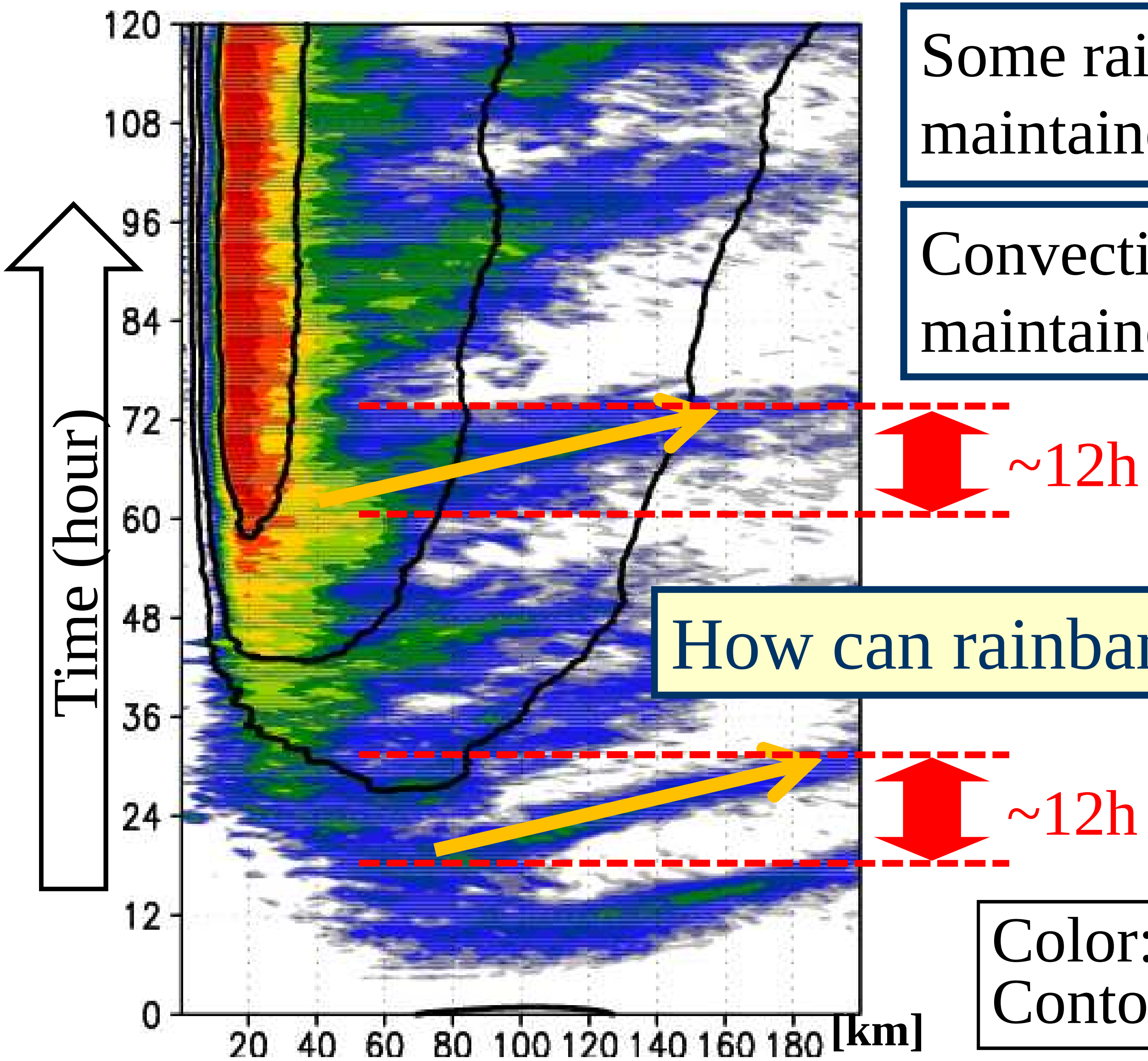
Horizontal divergence at = 20m

Red: positive

Blue: negative

36km × 36km

Lifetime of rainband



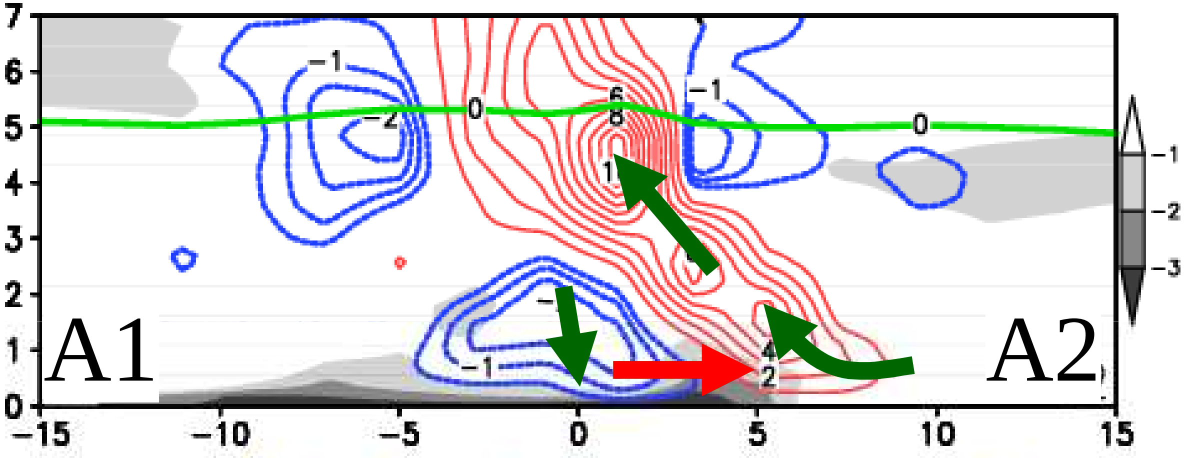
Some rainband are maintained for ~10 hours.

Convective cells are maintained for ~ 1 hour

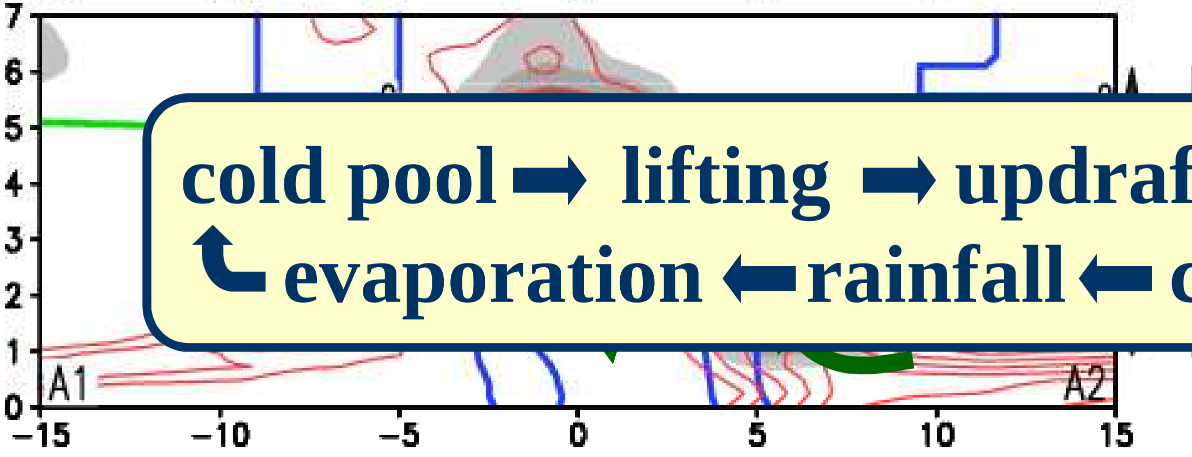
How can rainbands last longer?

Color: precipitation
Contour: wind speed

Results – maintenance mechanism –

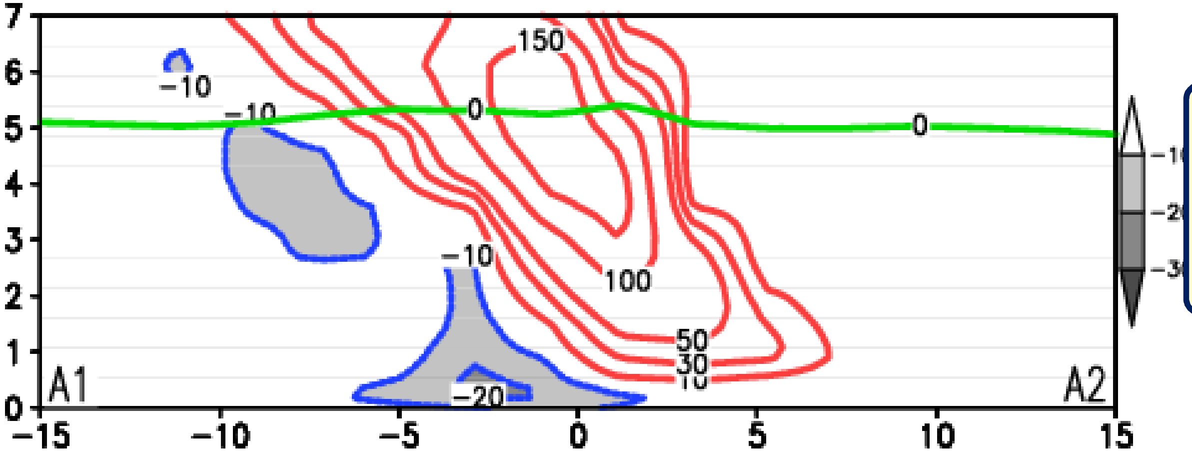


Contour: vertical motion
Shade: θ’ (cold pool)



cold pool ➡ lifting ➡ updraft ⤵
⮑ evaporation ⬅ rainfall ⬅ condensation

water
water



Contour: diabatic heating
Shade: negative value

Conclusion

- Cloud-resolving simulations of tropical cyclone are performed to investigate impacts of evaporation on rainband propagation and formation.

- Rainband propagation consists of 2 component; one is upstream dvelopment, other is cross-band propagation.

- Upstream development is caused by horizontal convergence between low-level inflows and cold pool at its upstream end.

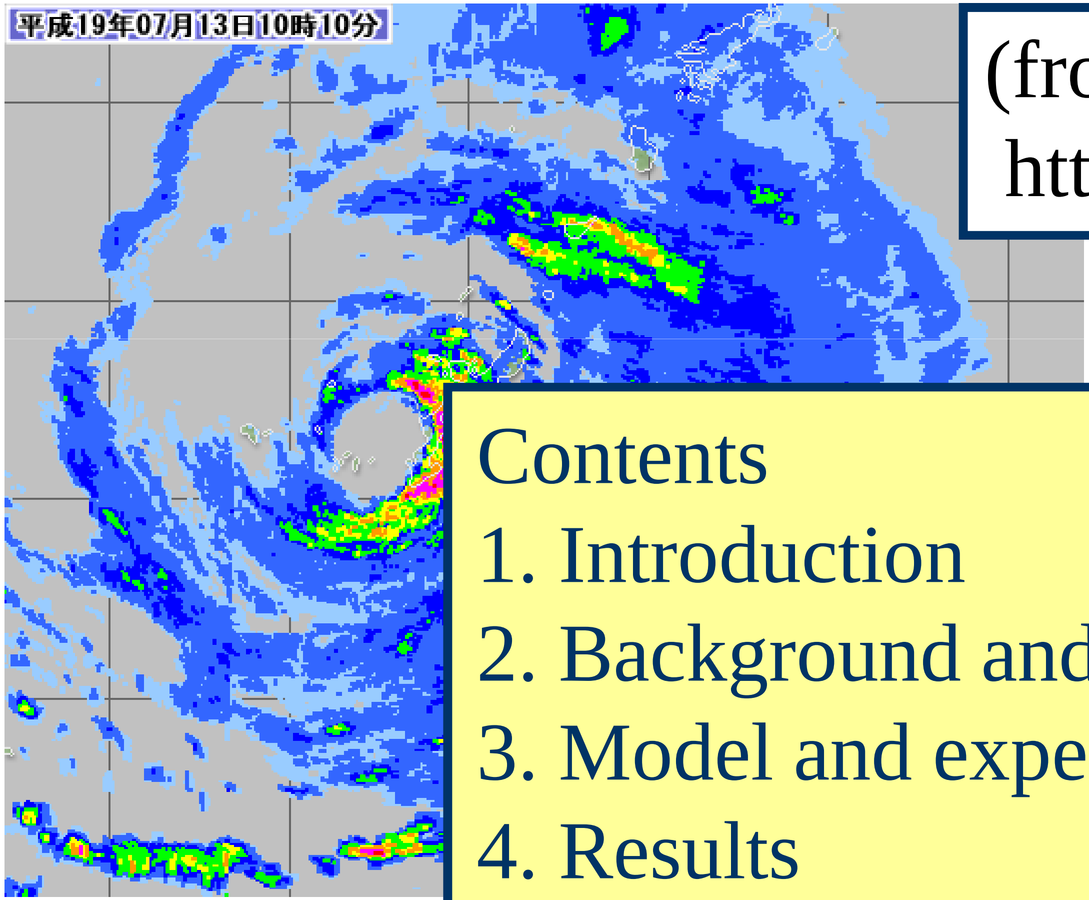
- Cross-band propagation is driven by divergence associated with cold downdraft/cold pool. It also plays an essential role in the rainband maintenance.

(Sawada & Iwasaki JAS, in press)

Potential works

- Impacts of wind shear, baroclinicity, TC movement under idealized condition (stationary band ⇔ moving band).
- Real cases.
- Full 2-moment scheme (cloud water & rainwater), bin scheme, aerosol interaction…
- High resolution ~ less than 1-km?
- Vortex Rossby waves ⇔ rainband? (secondary eyewall, eyewall contraction…)
- Other physical processes (turbulent, air-sea interaction)

Introduction



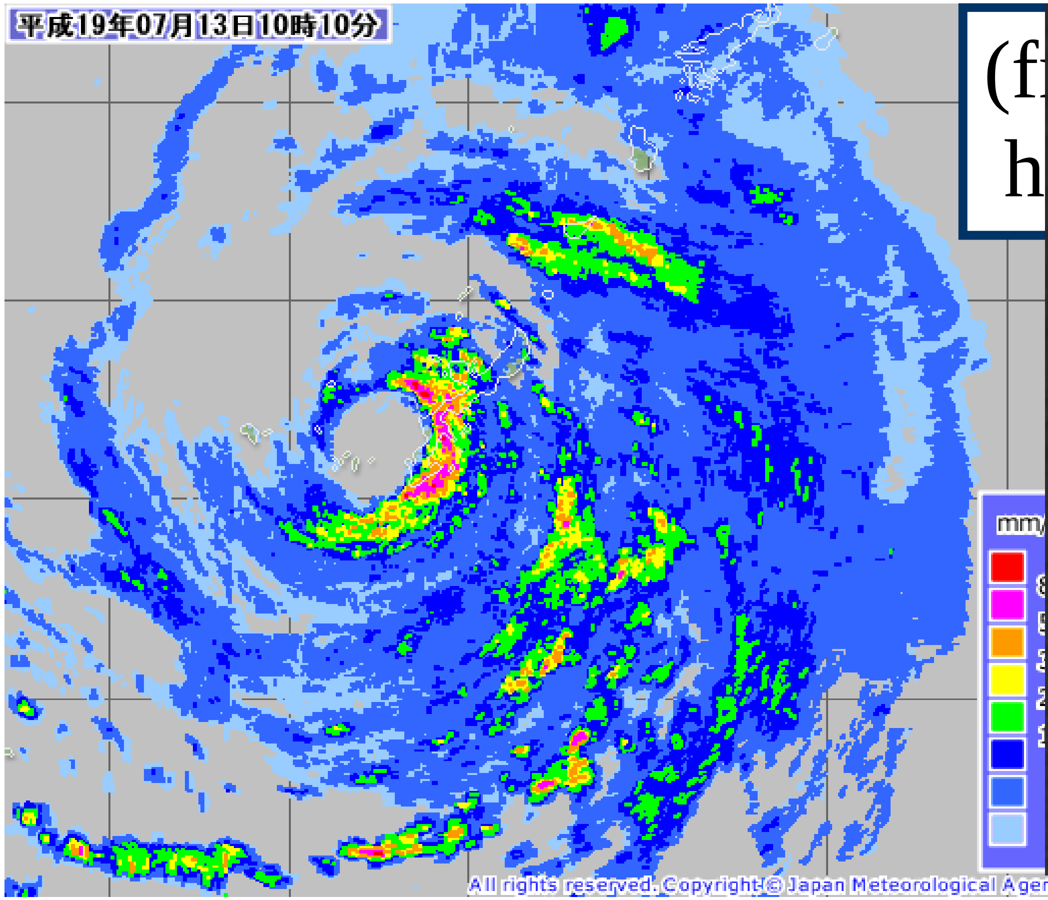
(from JMA-website
http://www.jma.go.jp/radnowc/)

Composite weather radar echoes
Typhoon MAN-YI (200704)
3 10:10-17:50
s intervals)

Contents
1. Introduction
2. Background and objective
3. Model and experimental design
4. Results
  i) rainband formation
  ii) rainband propagation
  iii) rainband maintenance
5. Conclusion

Introduction

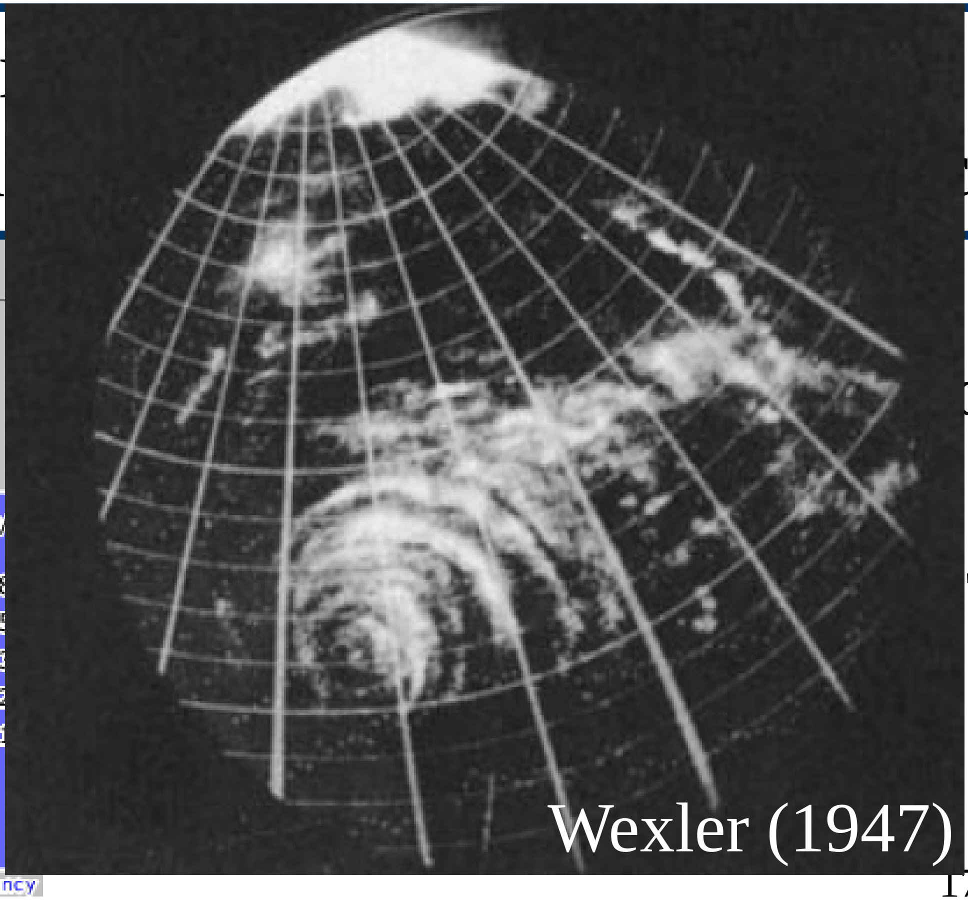
Tropical cyclone (hurricane, typhoon) ~
synoptic scale low-pressure system over tropical or sub-tropical waters with organized convection and definite cyclonic surface wind circulation (Holland 1993)



(f
h
:/)

bes

50

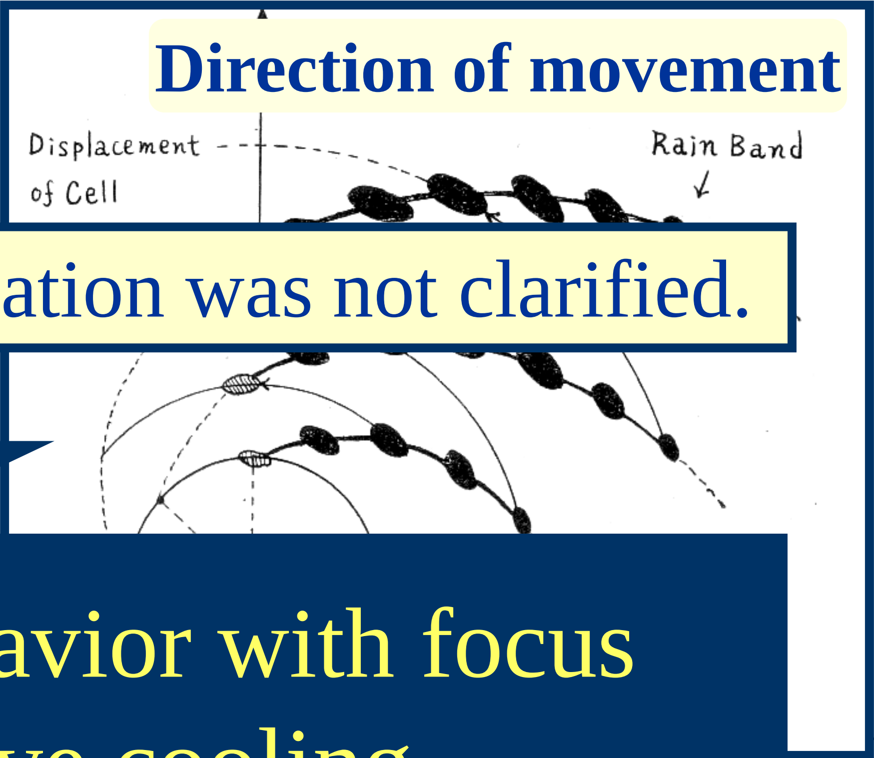

Wexler (1947)

Background and objective

Schematic of rainband

based on radar echo in

Typhoon Helen at 1958.



Direction of movement

Mechanism for formation/propagation was not clarified.

To clarify rainband behavior with focus on impacts of evaporative cooling through 3-D cloud-resolving simulations.

Mech

Inte

Vortex Rossby waves (Guiin & Schubert 1993; Montgomery & Kallenbach 1997)

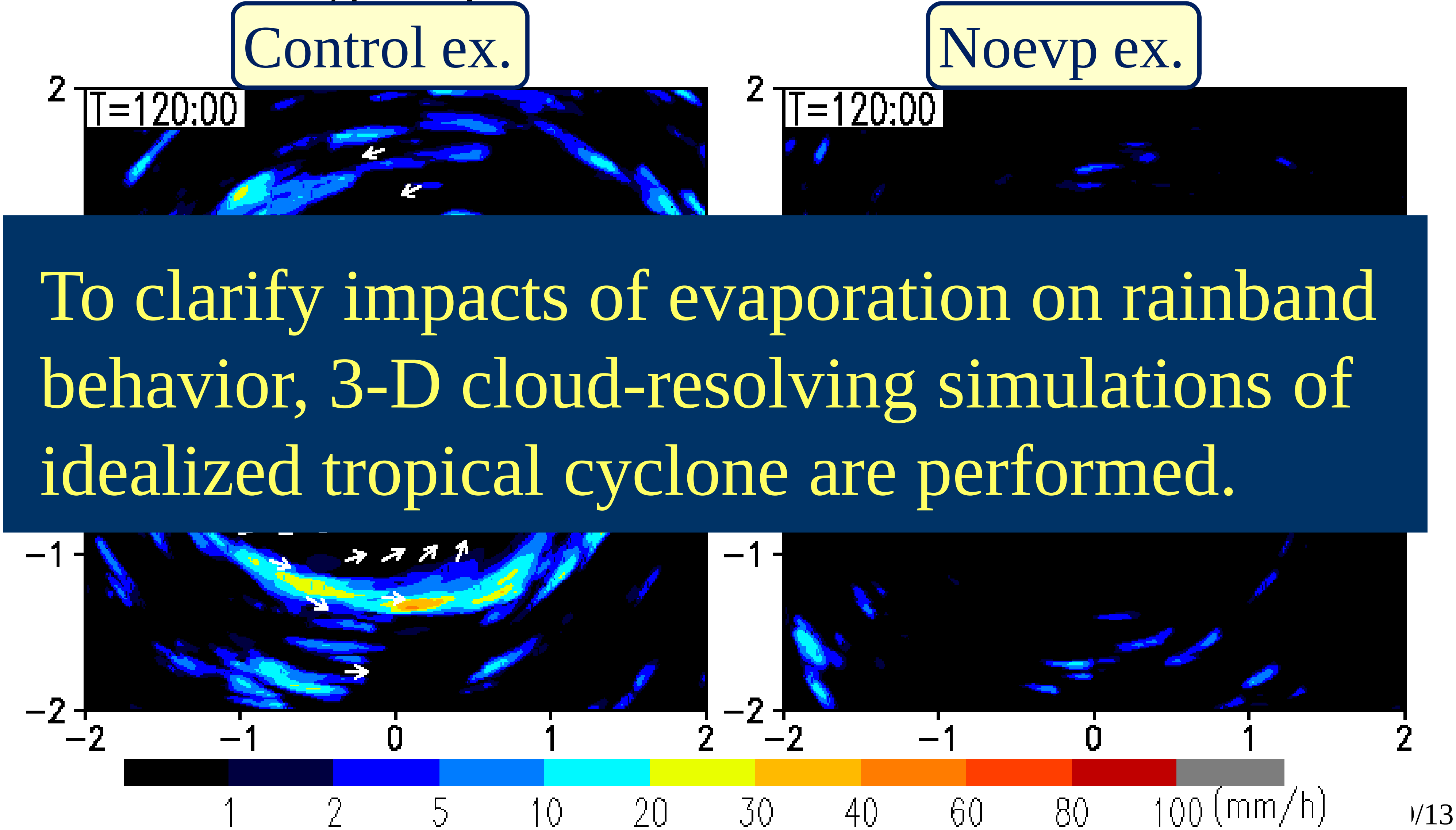
=> These are not always consistent with features of observed rainbands.

Propagation of cold outflow (Yamasaki 1983; Nasuno & Yamasaki 1997)

=> They used 2-D axisymmetric model, not 3-D.

Objective of this study

From my previous study, evaporation has an large impact on rainband behavior.

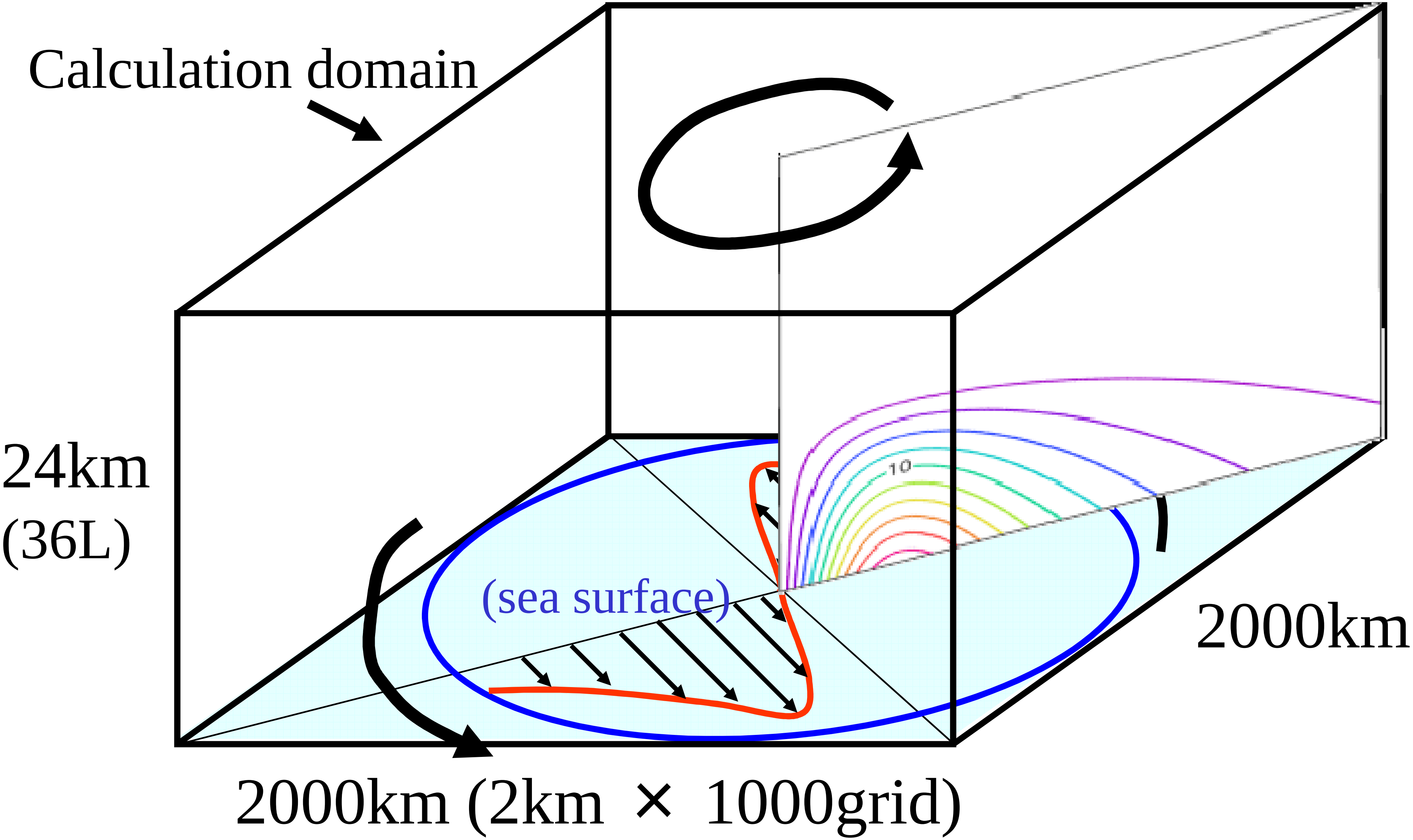


Control ex.

Noevp ex.

To clarify impacts of evaporation on rainband behavior, 3-D cloud-resolving simulations of idealized tropical cyclone are performed.

Schematics of numerical experiment



Calculation domain

24km
(36L)

(sea surface)

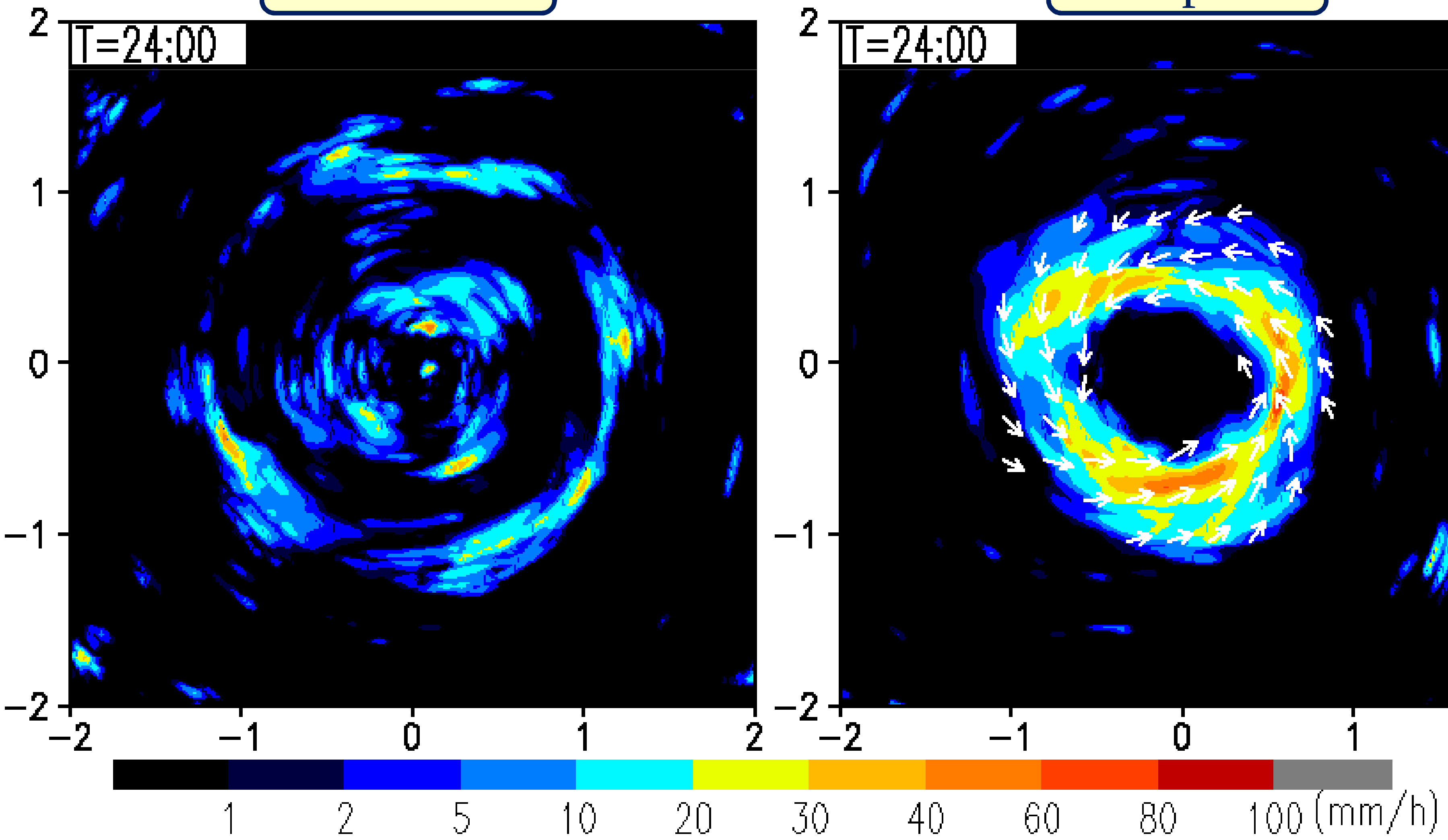
2000km

2000km (2km × 1000grid)

Results – impact of evaporation –

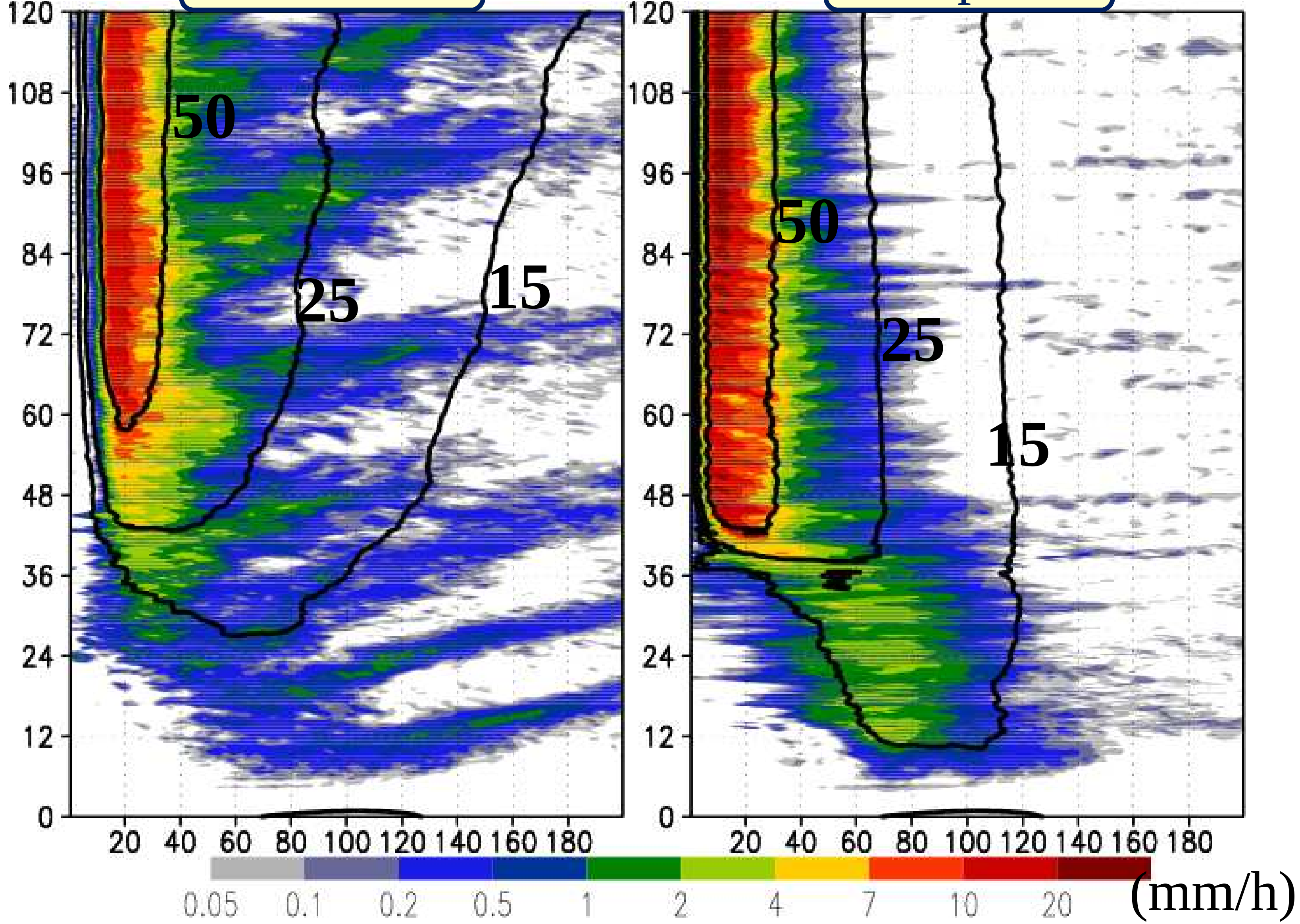
Horizontal structure of precipitation & wind

Control ex. Noevp ex.



Results – impact of evaporation –

Time-radius cross-section of precipitation & tangential wind



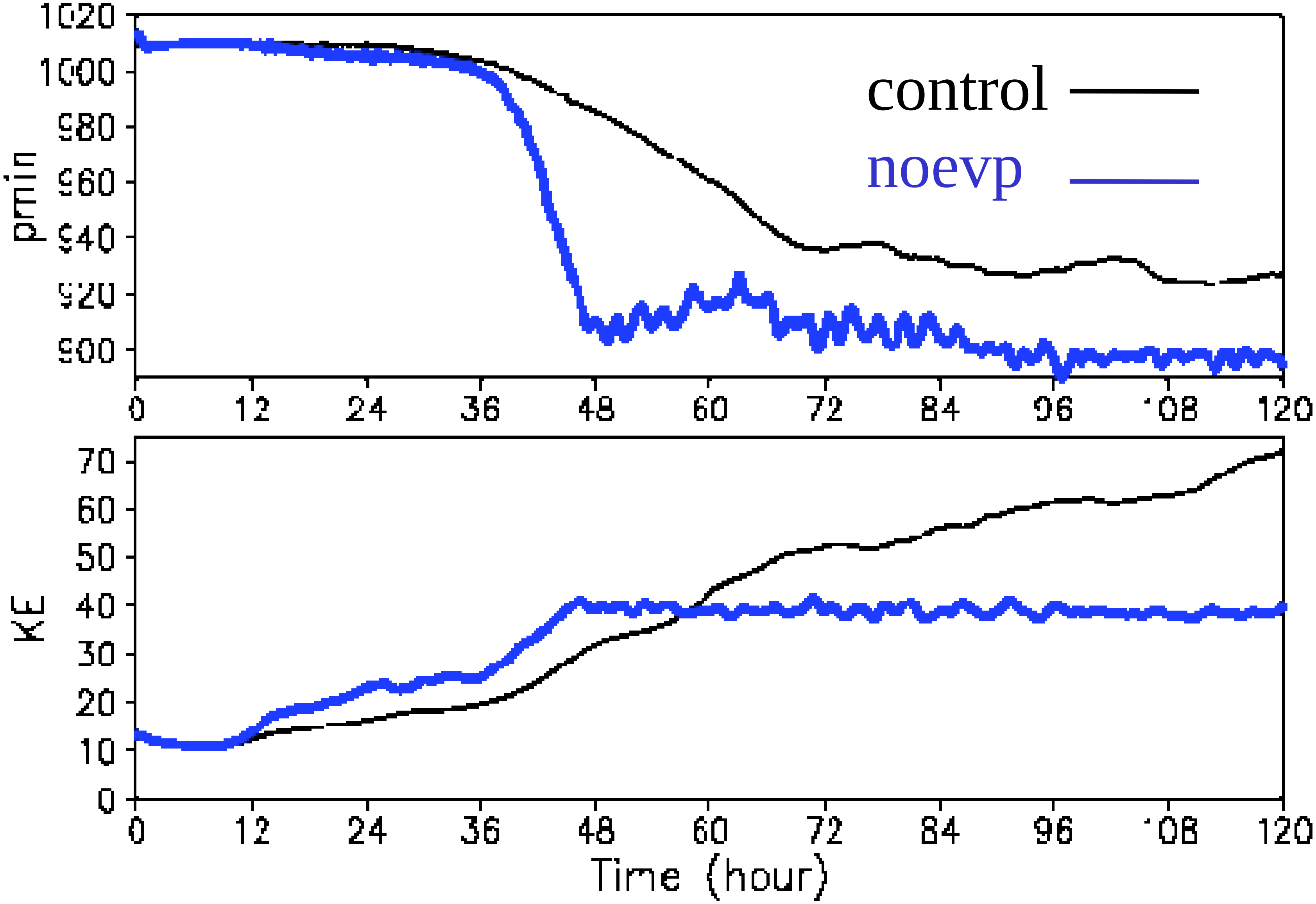
Control ex.

Noevp ex.

(mm/h)

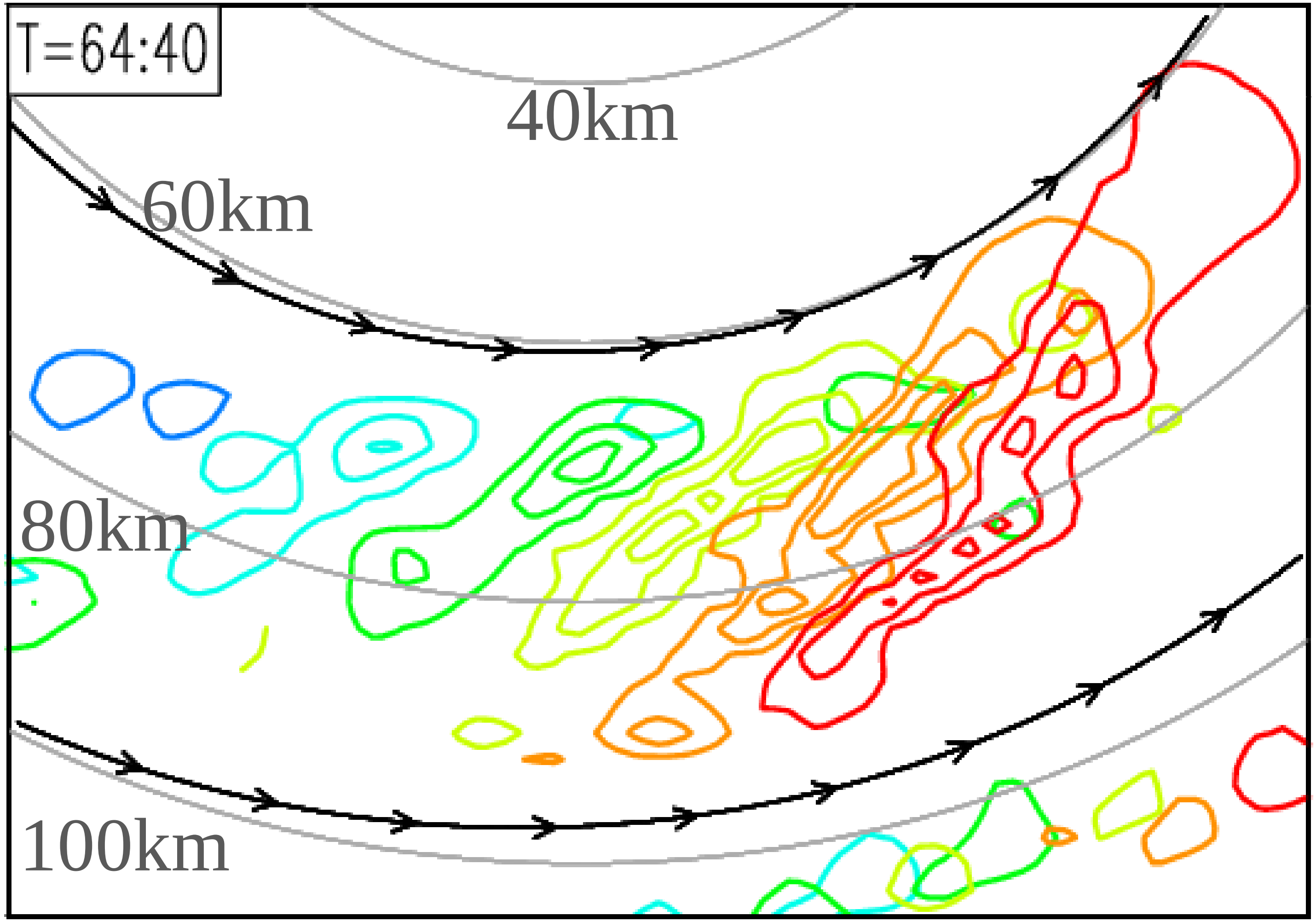
Results – impact of evaporation –

Time evolution of MSLP & kinetic energy



Results – propagation –

Movement of individual convective cells for T=63:50-64:40



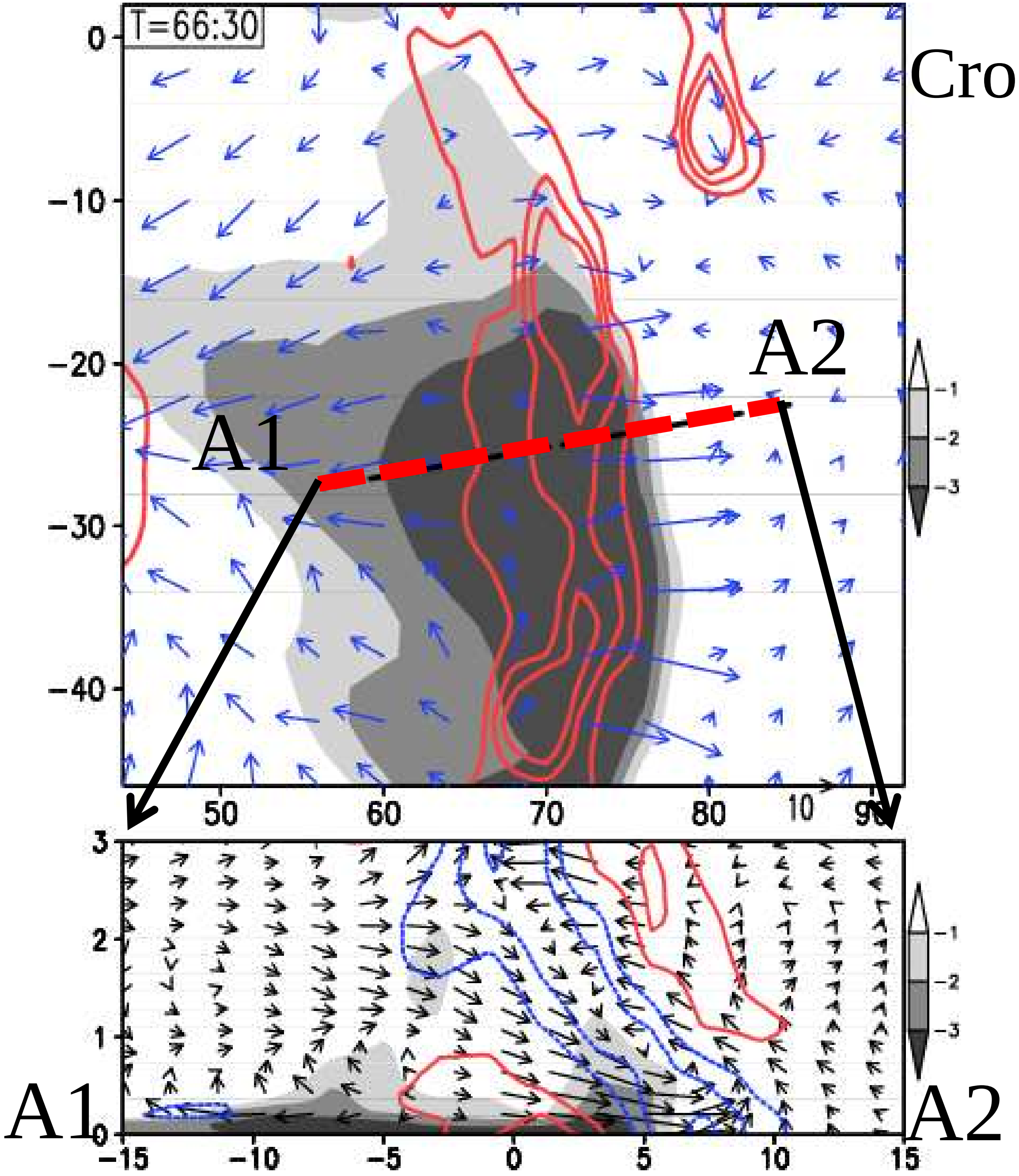
T=63:50
T=64:00
T=64:10
T=64:20
T=64:30
T=64:40

70km × 100km

Cross-band propagation

Results – maintenance mechanism –

Cross-band structure of rainband

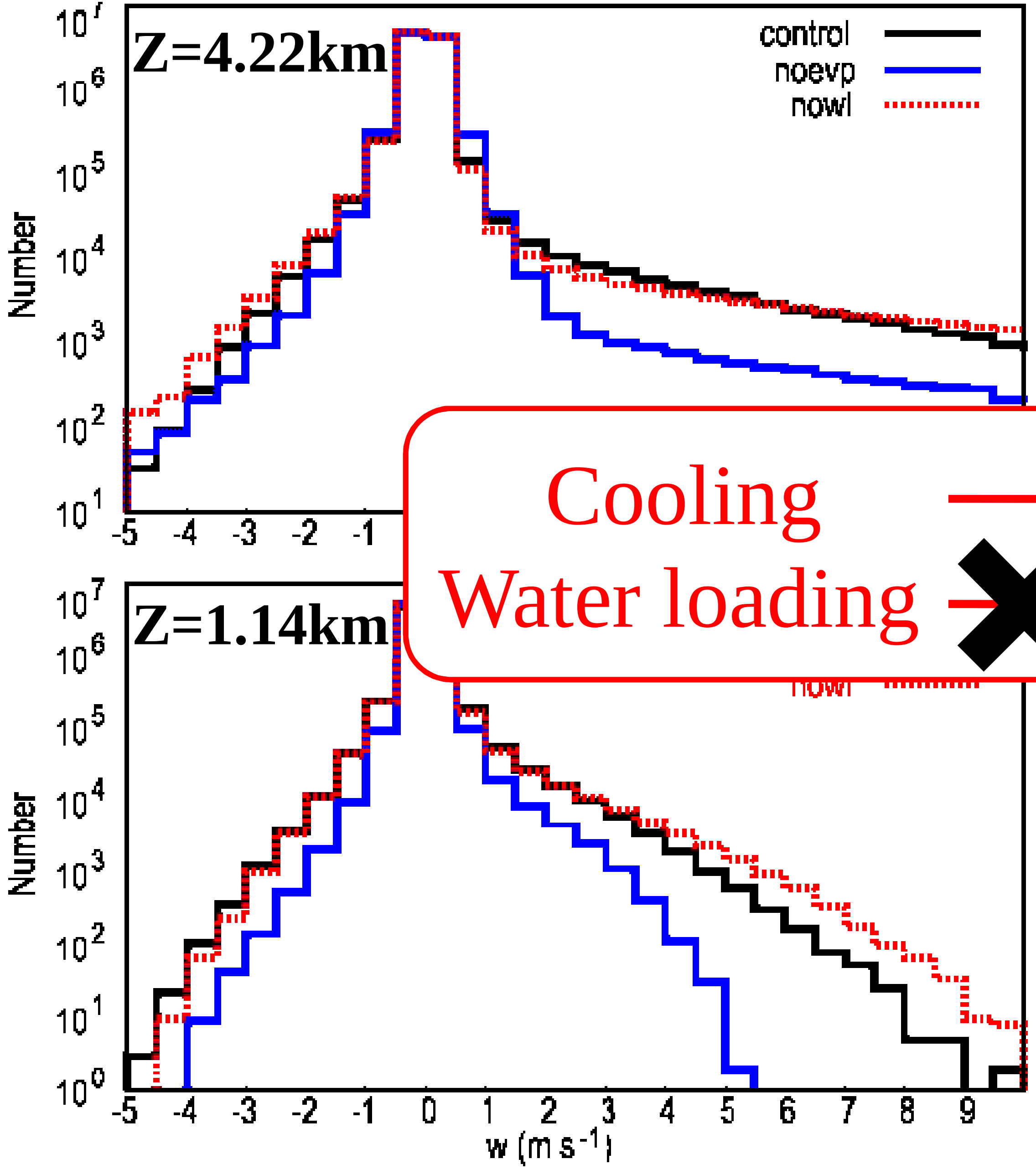


Contour: accumulated rainwater
Shade: θ’ (cold pool)

Contour: horizontal divergence/convergence
Shade: θ’ (cold pool)

Results – impacts of water loading –

Histogram of vertical wind velocity



Downdrats
[for z=4.22km]
control ~ nowl > noevp
[for z=1.14km]
l > noevp

control ~ nowl > noevp
[for z=1.14km]
nowl > control > noevp

Cooling →
Water loading ✖ →
downdraft

Discussion

Another mechanisms proposed by previous studies?

Internal gravity waves

(Kurihara 1976, Willoughby 1978)

Vortex Rossby waves

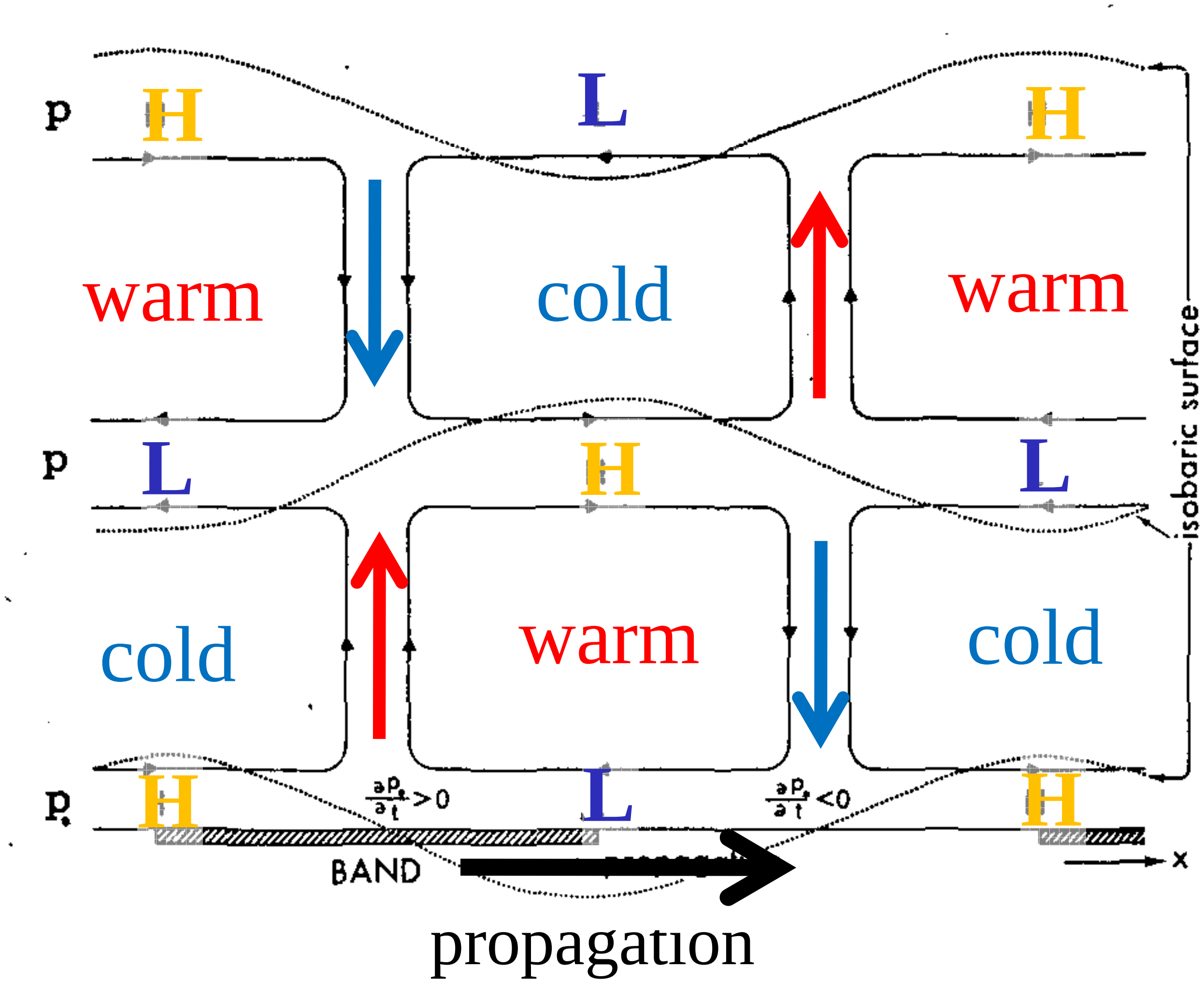
(Guiin & Schubert 1993; Montgomery & Kallenbach 1997)

Propagation of cold outflow

(Yamasaki 1983; Nasuno & Yamasaki 1997)

Discussion – internal gravity wave? –

Schematics of internal gravity waves



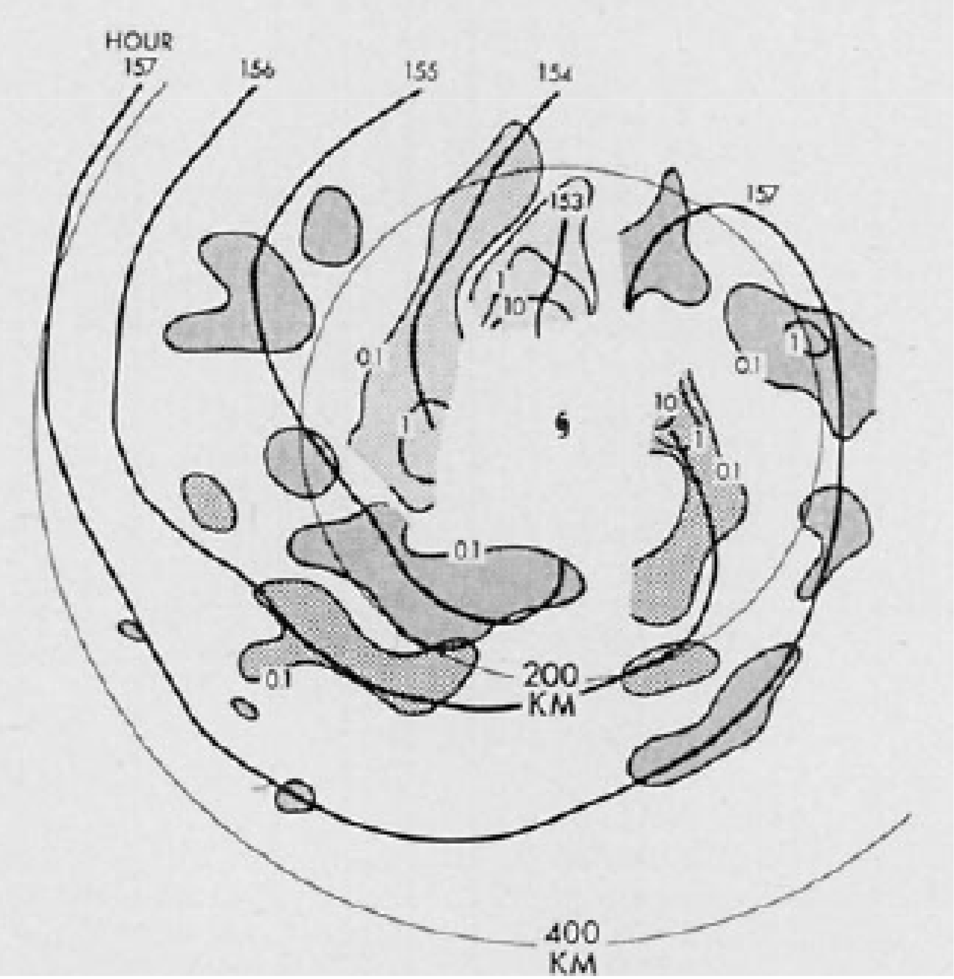
(Kurihara and Tuleya 1974)

Linearized equations

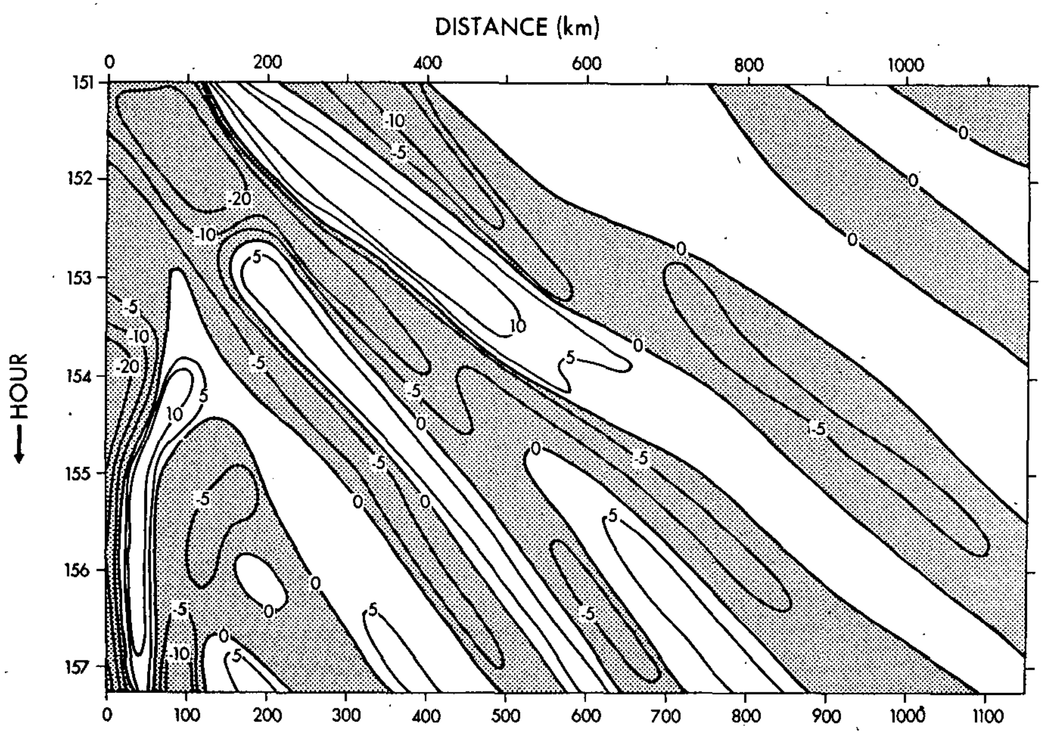
$$\begin{cases} \dfrac{\partial u}{\partial t} = -\dfrac{\partial \phi}{\partial x} \\ \dfrac{\partial}{\partial t}\left(\dfrac{\partial \phi}{\partial p}\right) = -S\omega \\ \dfrac{\partial u}{\partial x} + \dfrac{\partial \omega}{\partial p} = 0 \end{cases}$$

Discussion – internal gravity wave? –

Previous study by Kurihara and Tuleya (1974)



Composite map of a band

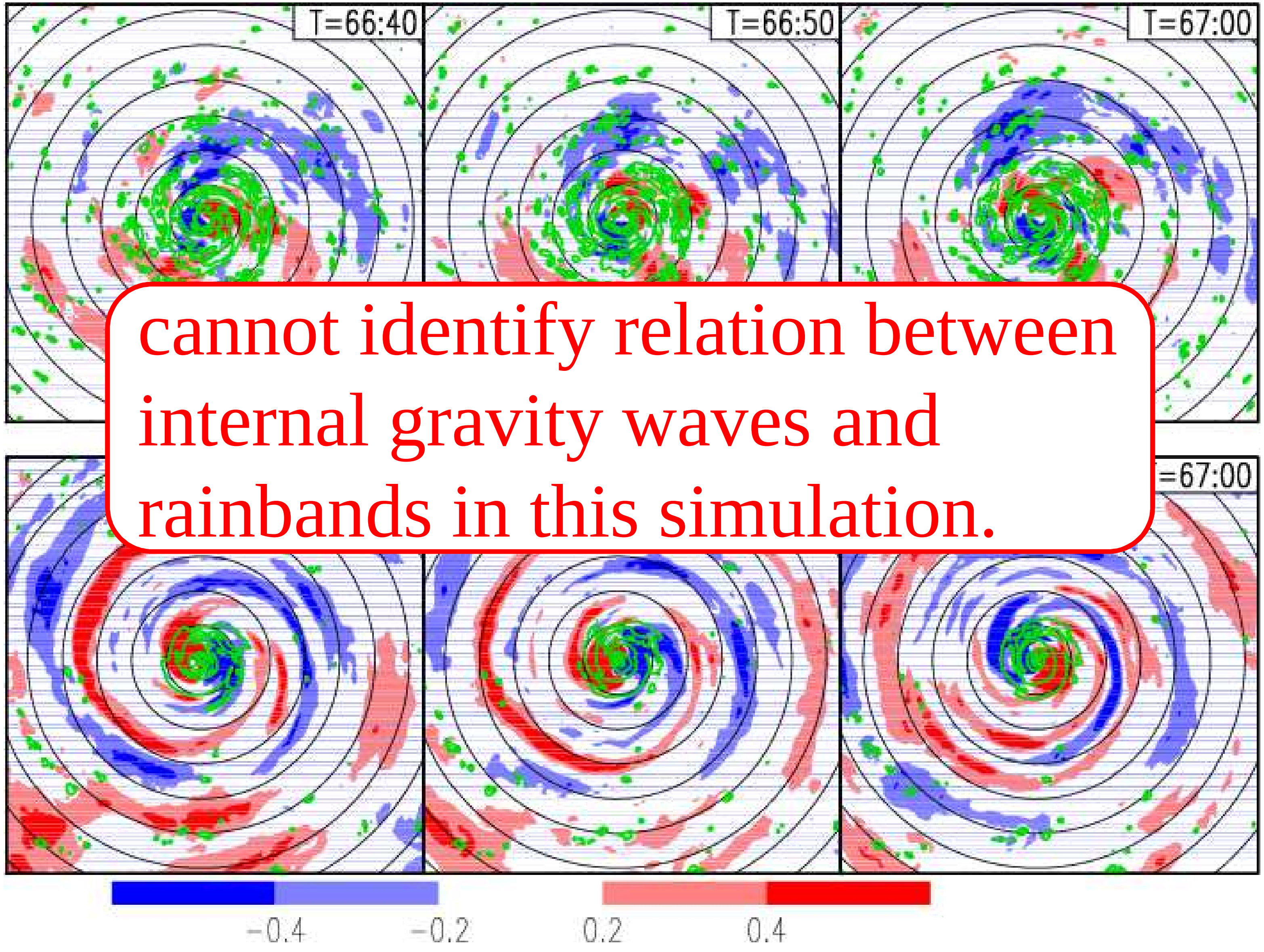


Time-radius section of ω

Numerical results

Discussion – internal gravity wave? –

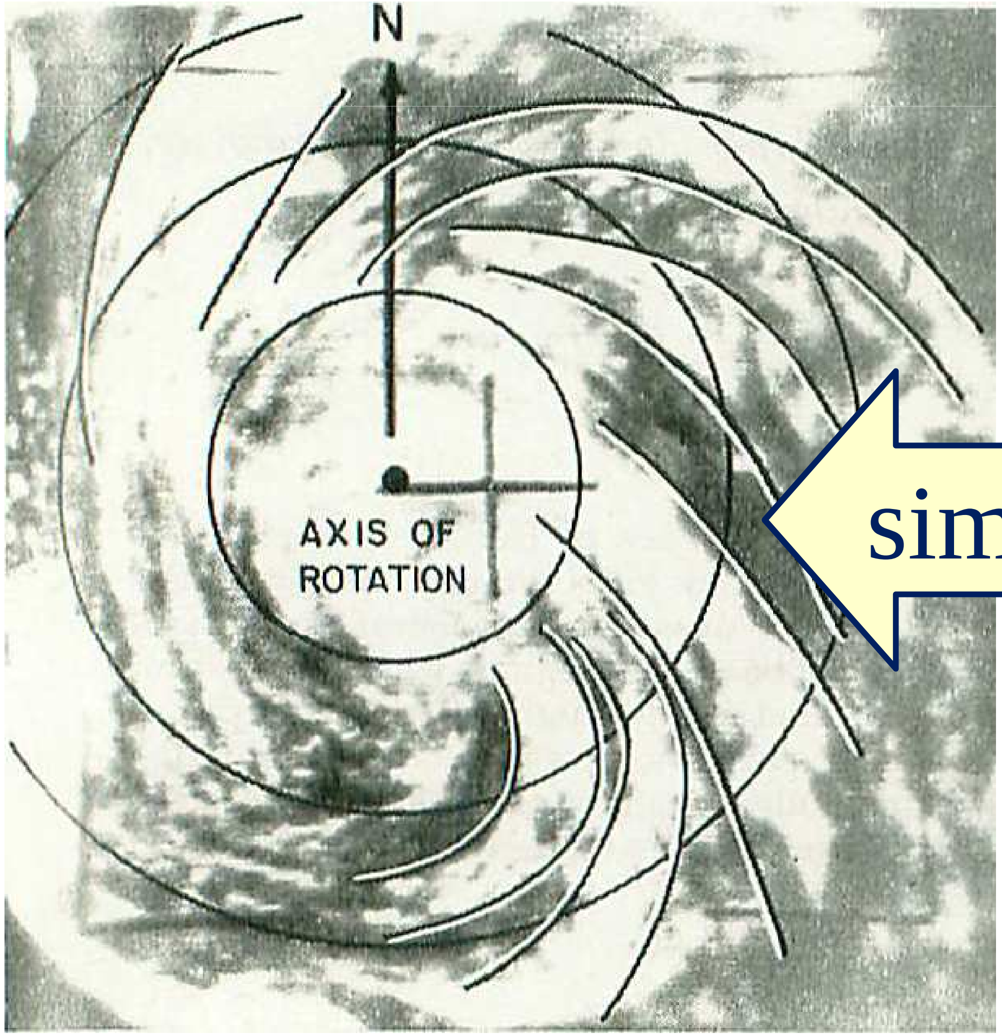
Pressure anomaly from its axisymmetric mean (z=1.82km)



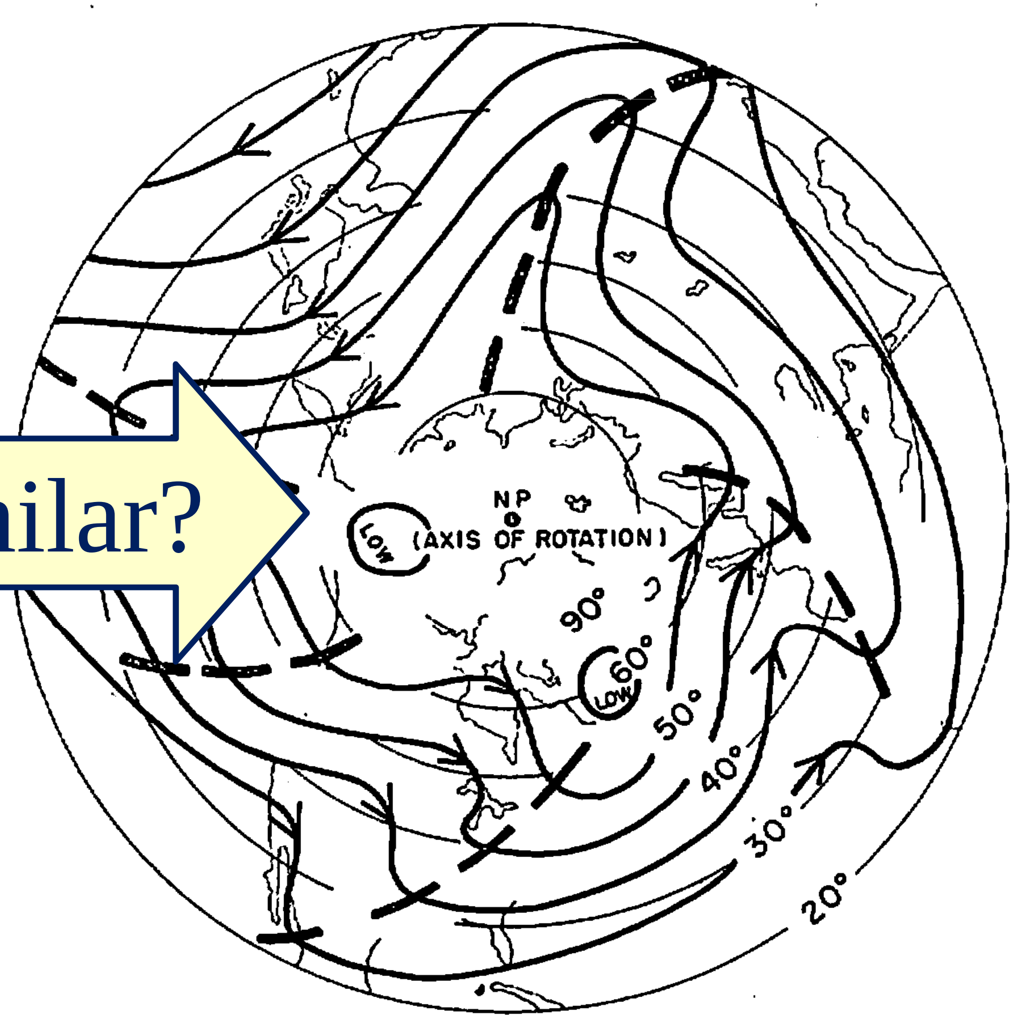
cannot identify relation between internal gravity waves and rainbands in this simulation.

Discussion – vortex Rossby wave? –

Satellite image of hurricane



Schematics of trough in N.H.

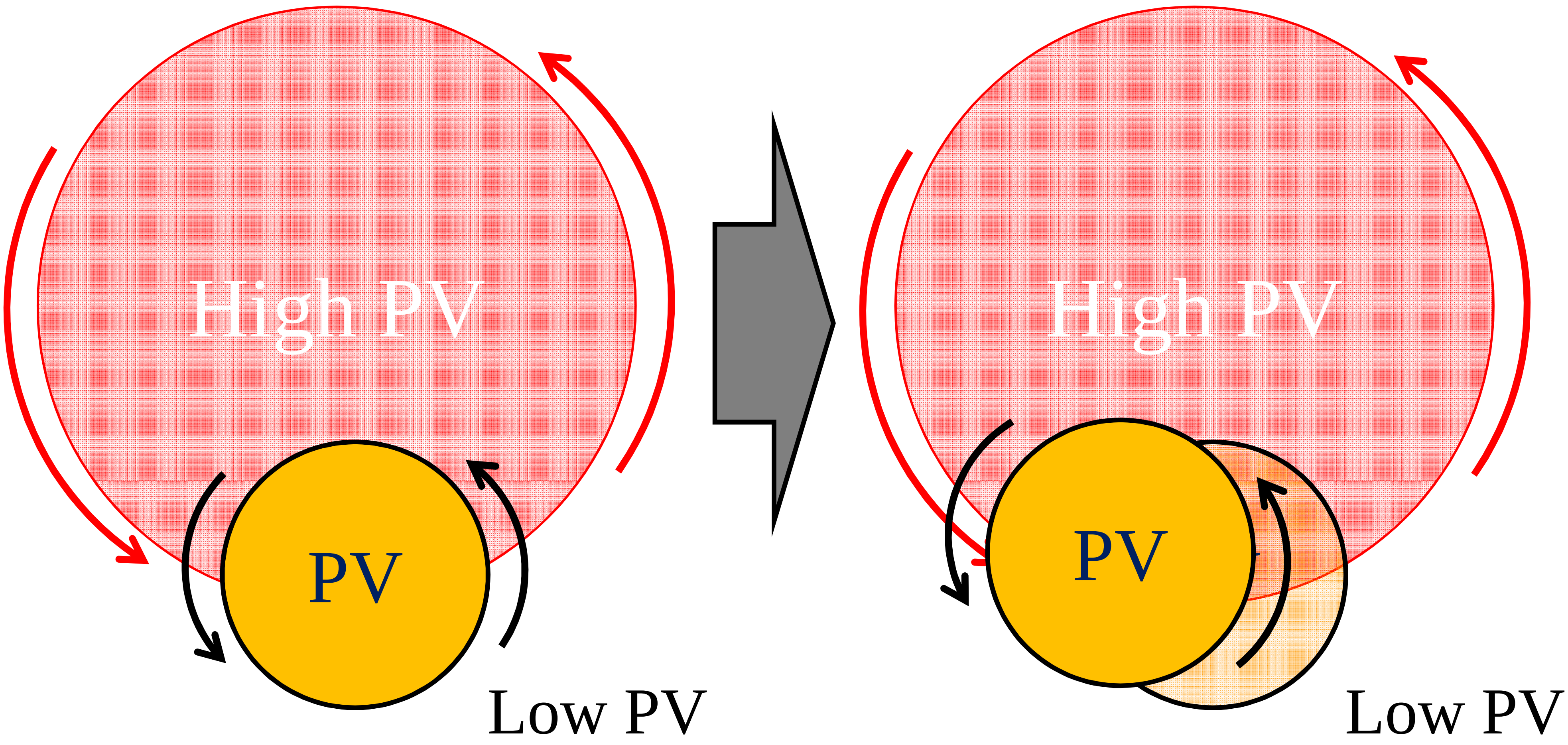


similar?

(MacDonald 1968)

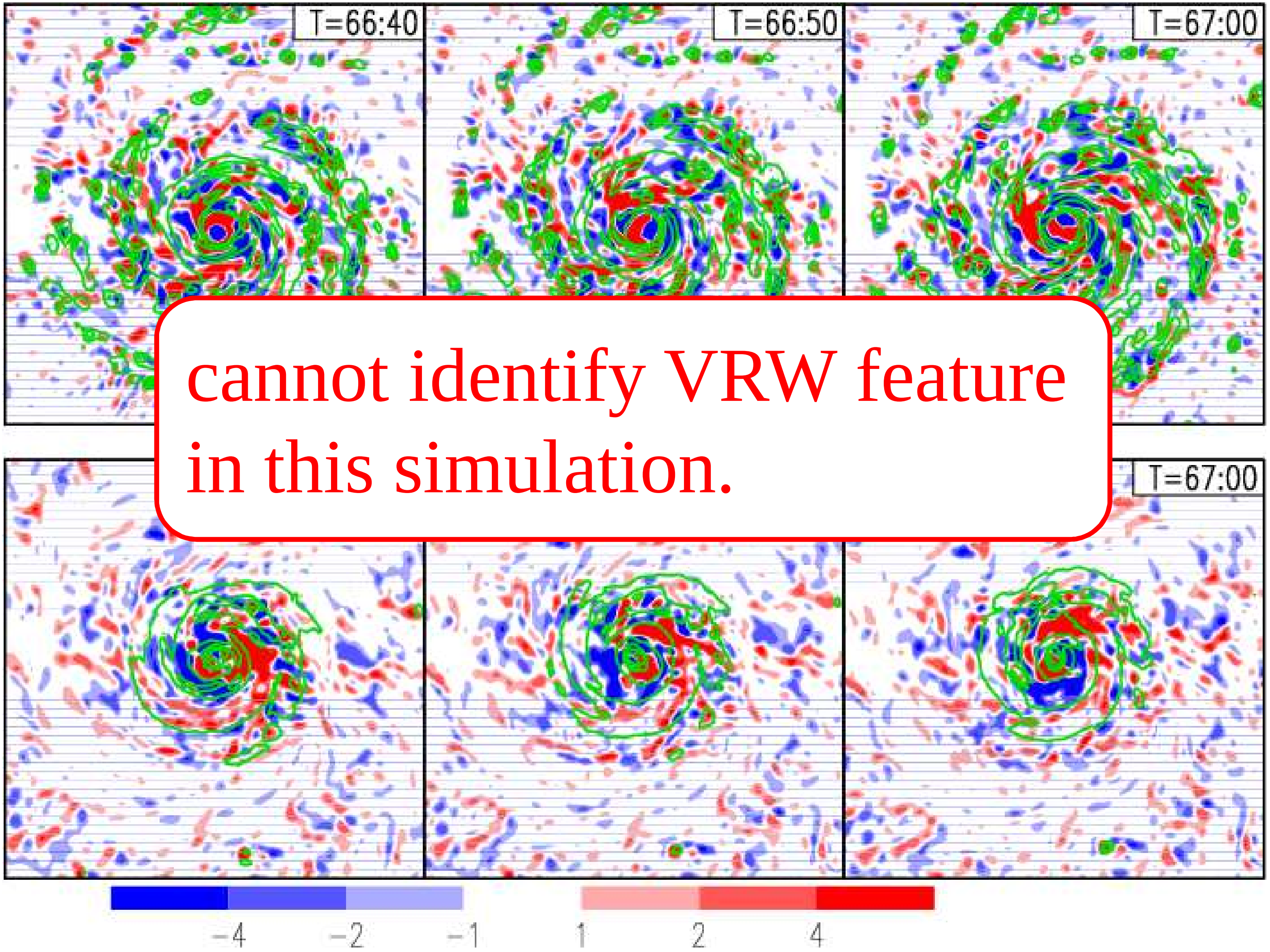
Discussion – vortex Rossby wave? –

Schematics of vortex Rossby waves



Discussion – vortex Rossby wave? –

PV anomaly from its axisymmetric mean (z=0.86km)



cannot identify VRW feature in this simulation.

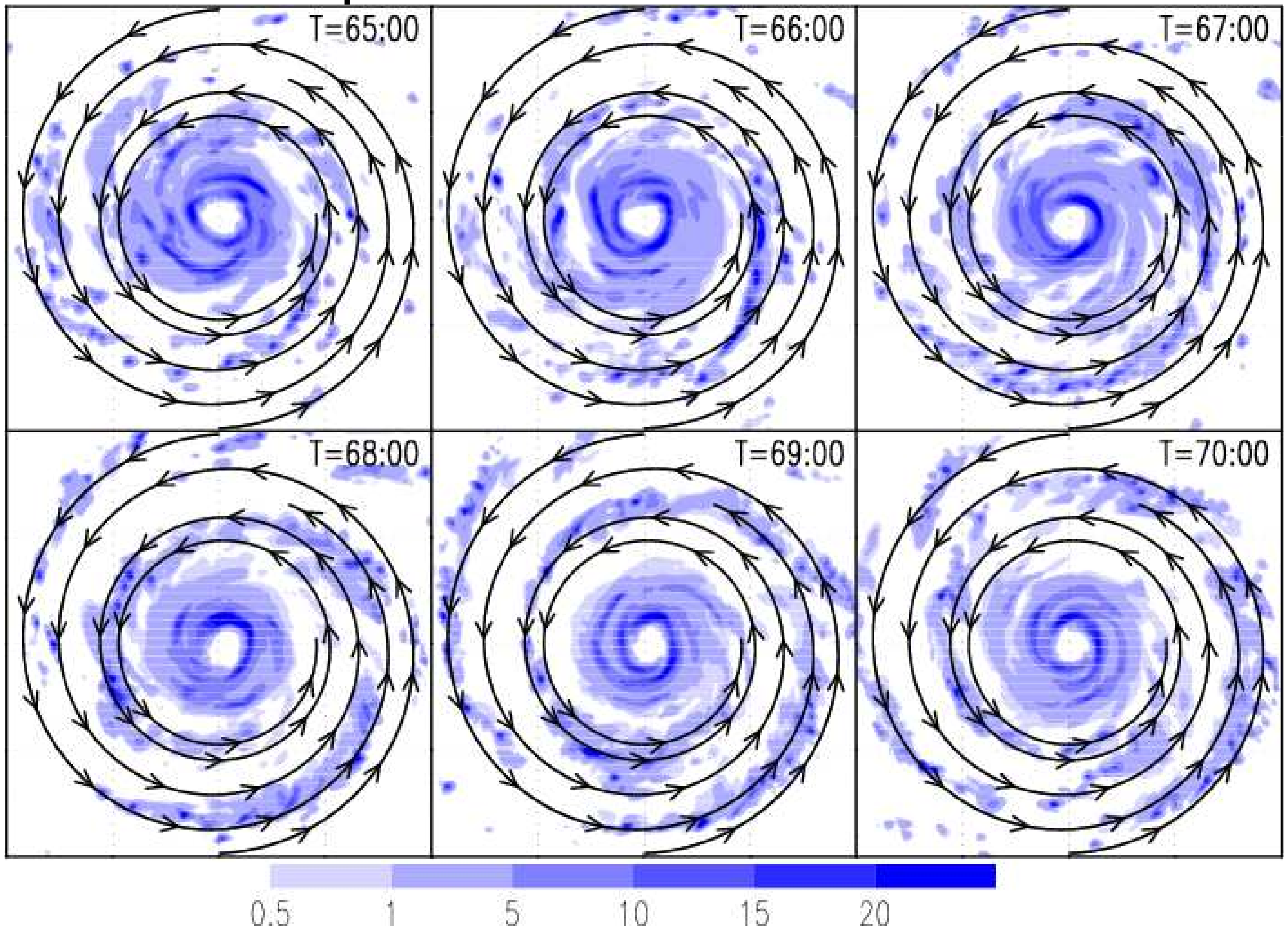
References

http://www.aoml.noaa.gov/hrd/tcfaq/A1.html
http://amsglossary.allenpress.com/glossary/search?id=tropical-cyclone1
http://www.bom.gov.au/bmrc/pubs/tcguide/globa_guide_intro.htm

a

Results – spiral shape formation –

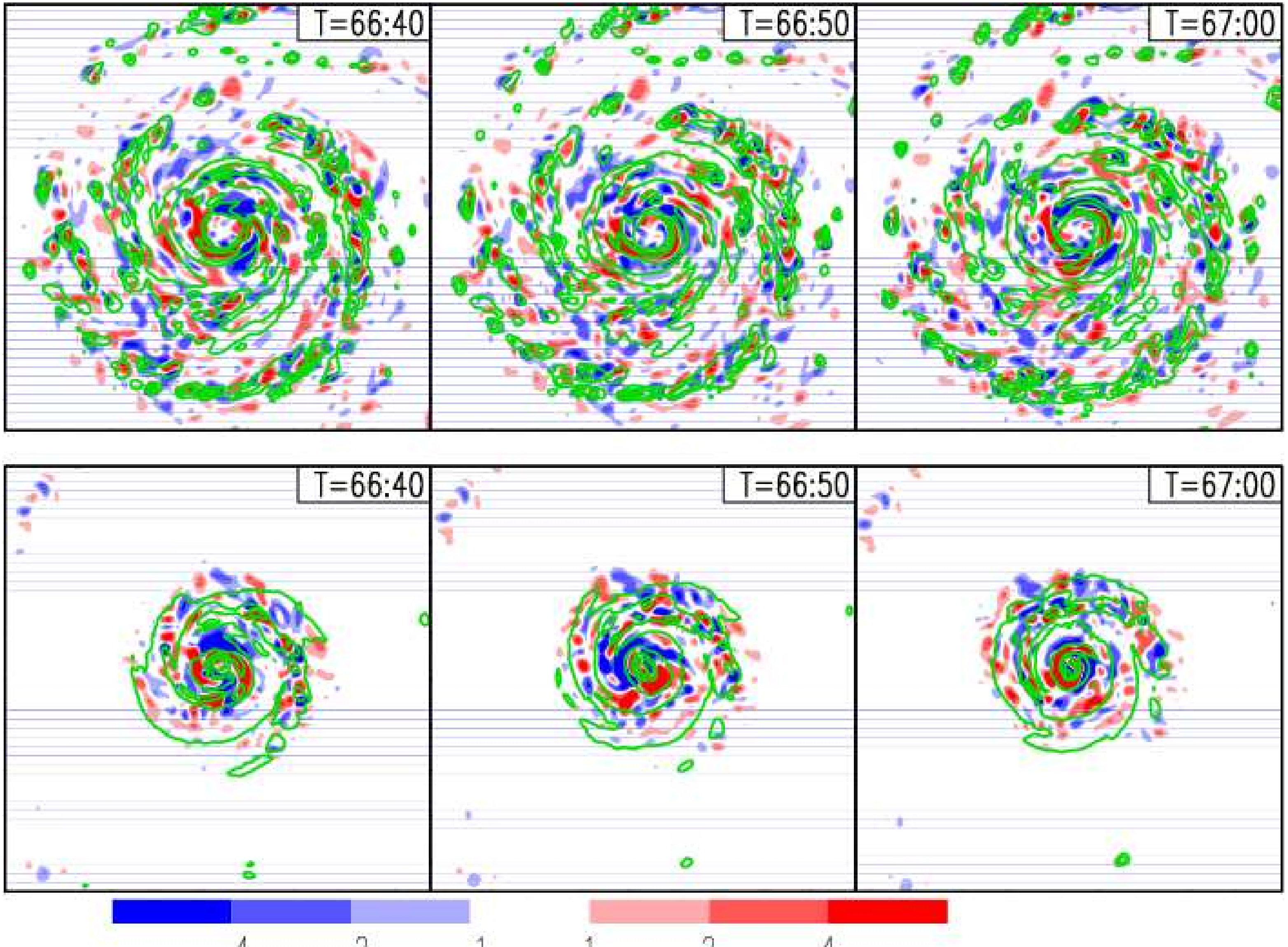
Rainband pattern & streamline at Z=1460m



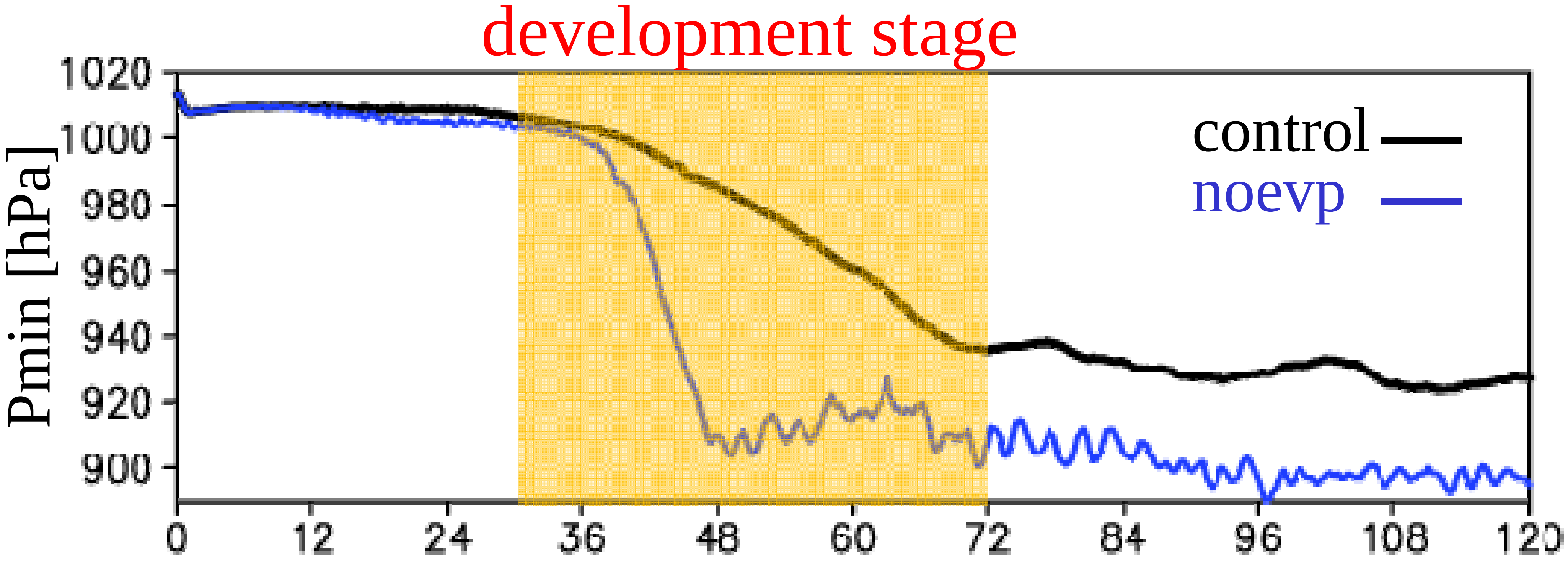
Discussion

Votex Rossby waves?

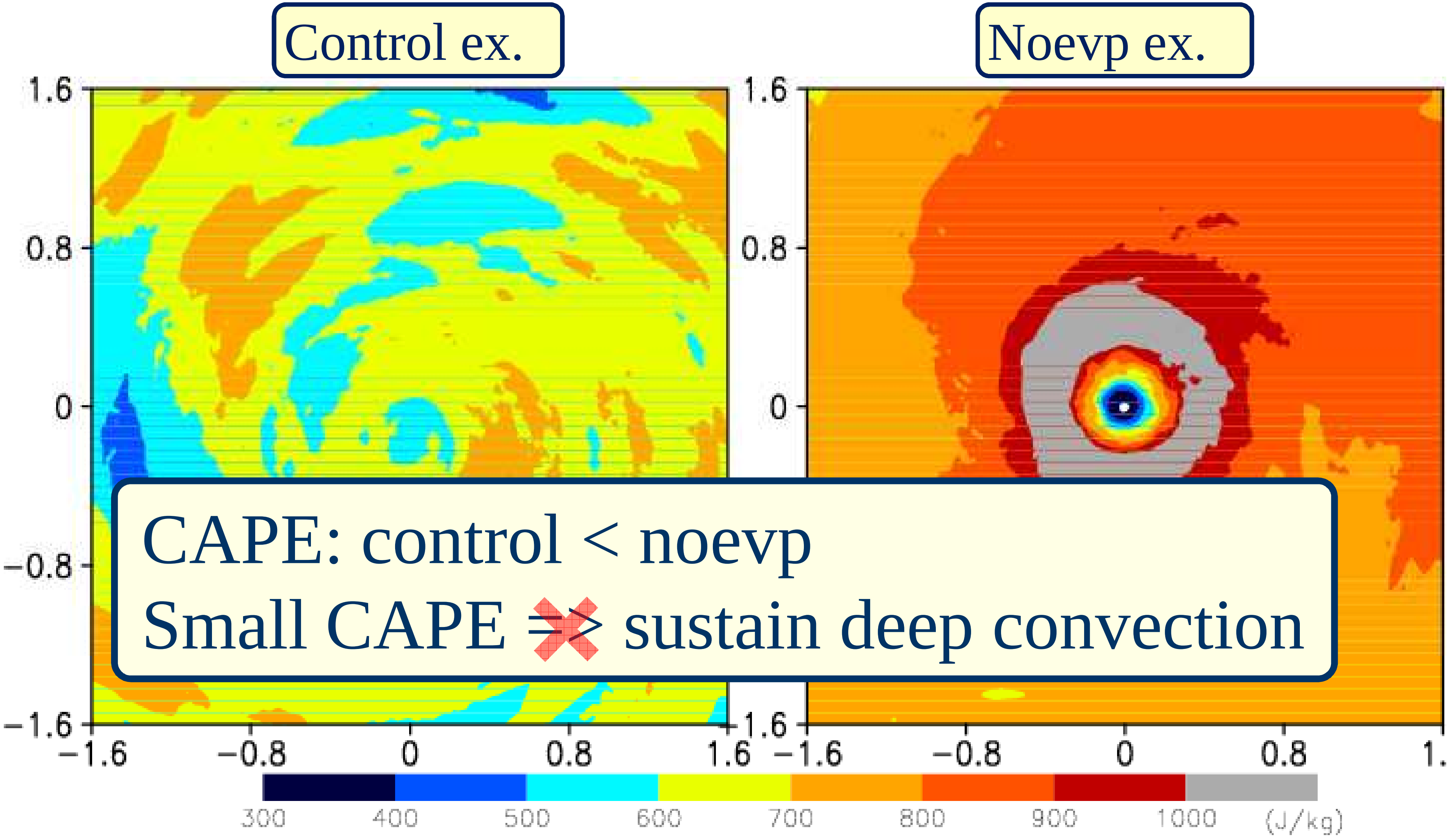
PV anomaly (z=4.22km)



Difference in rapid intensification < development stage >



Horizontal distribution of CAPE



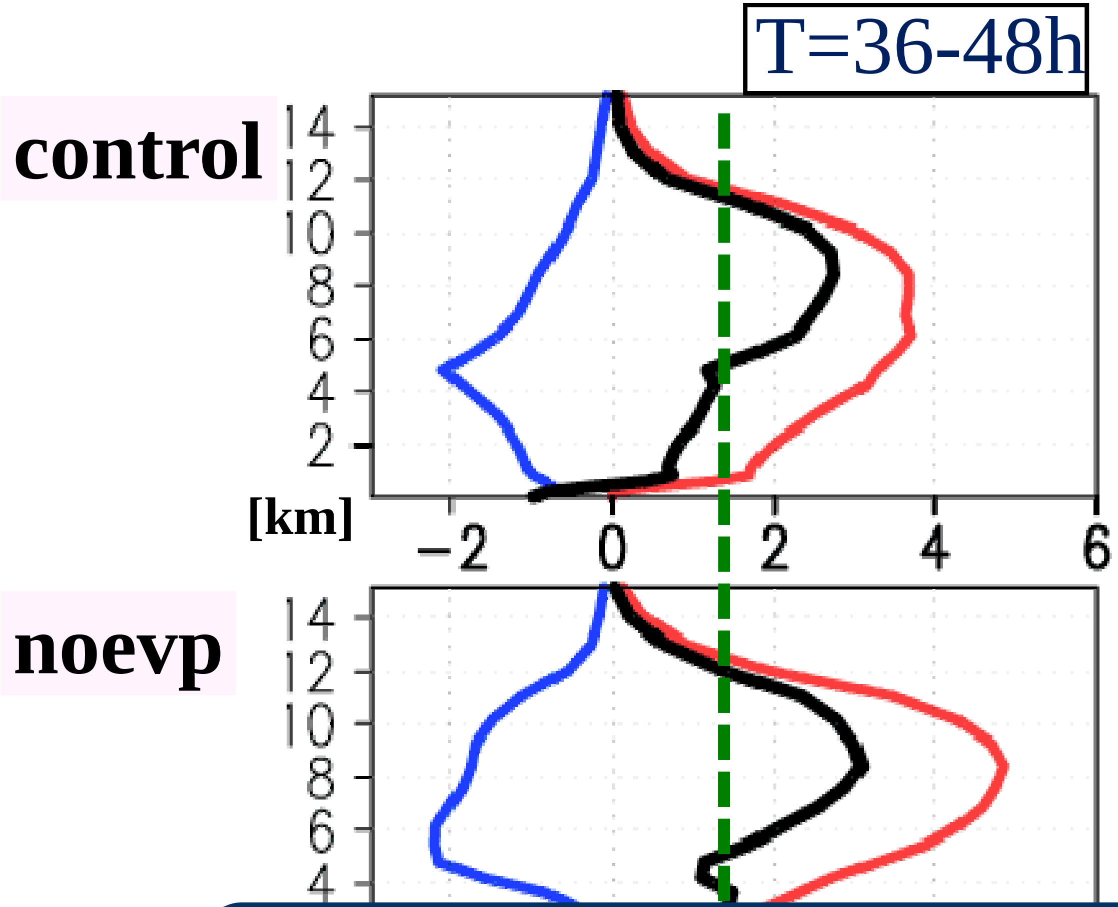
CAPE: control < noevp

Small CAPE ~~=>~~ sustain deep convection

CAPE temporally averaged for T=36-48h (J/kg)

Consistent with Wang (2002)

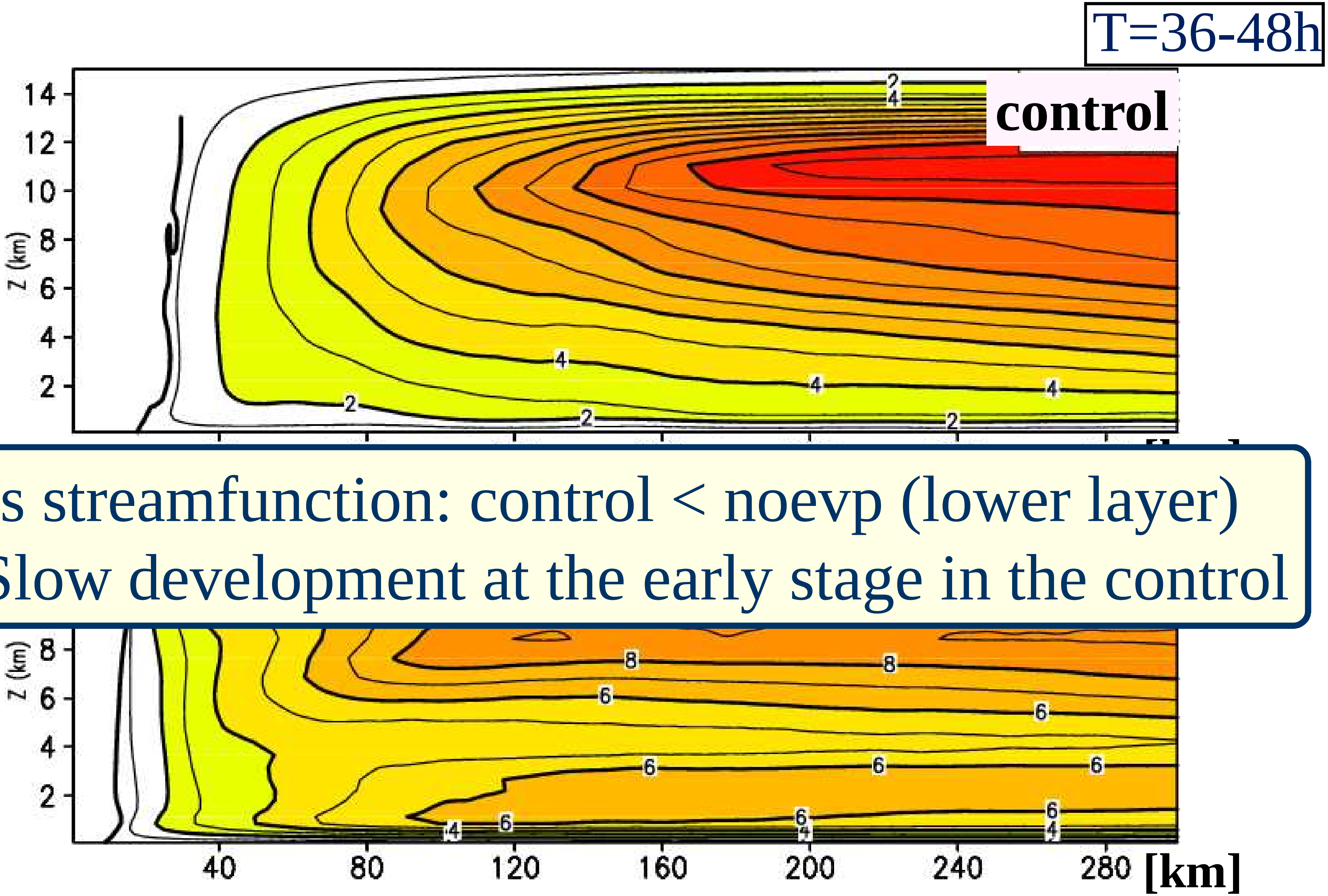
Diabatic heating/cooling



Temporal and area averaged
Black: net diabatic heating (K/h)
Red: diabatic heating (K/h)
Blue: diabatic cooling (K/h)
within 150-km radius for 36-48h

In the control ex.
Weak diabatic heating around the eyewall
=> rapid intensification is delayed

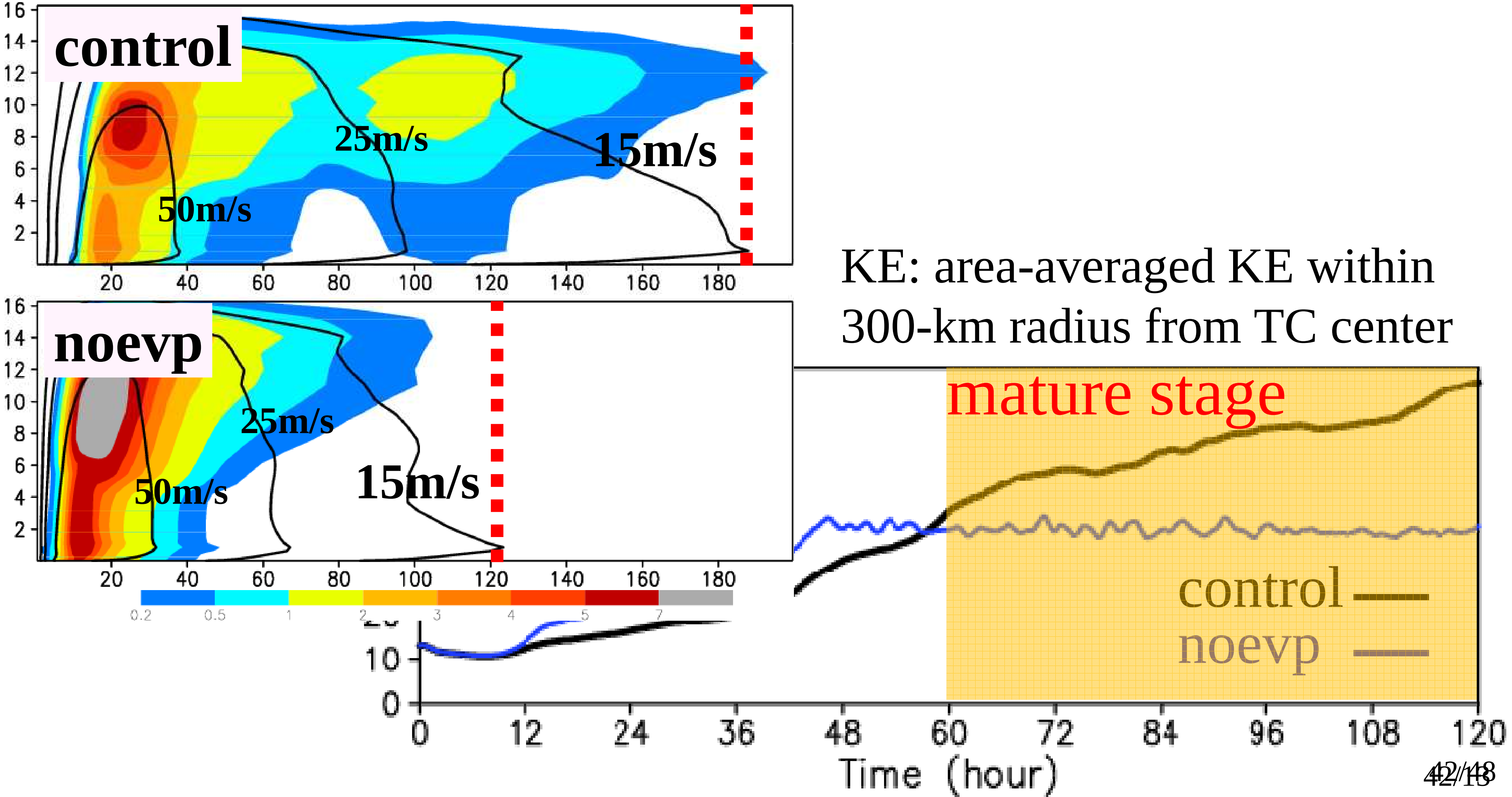
Mass streamfunction



Mass streamfunction: control < noevp (lower layer)
=> Slow development at the early stage in the control

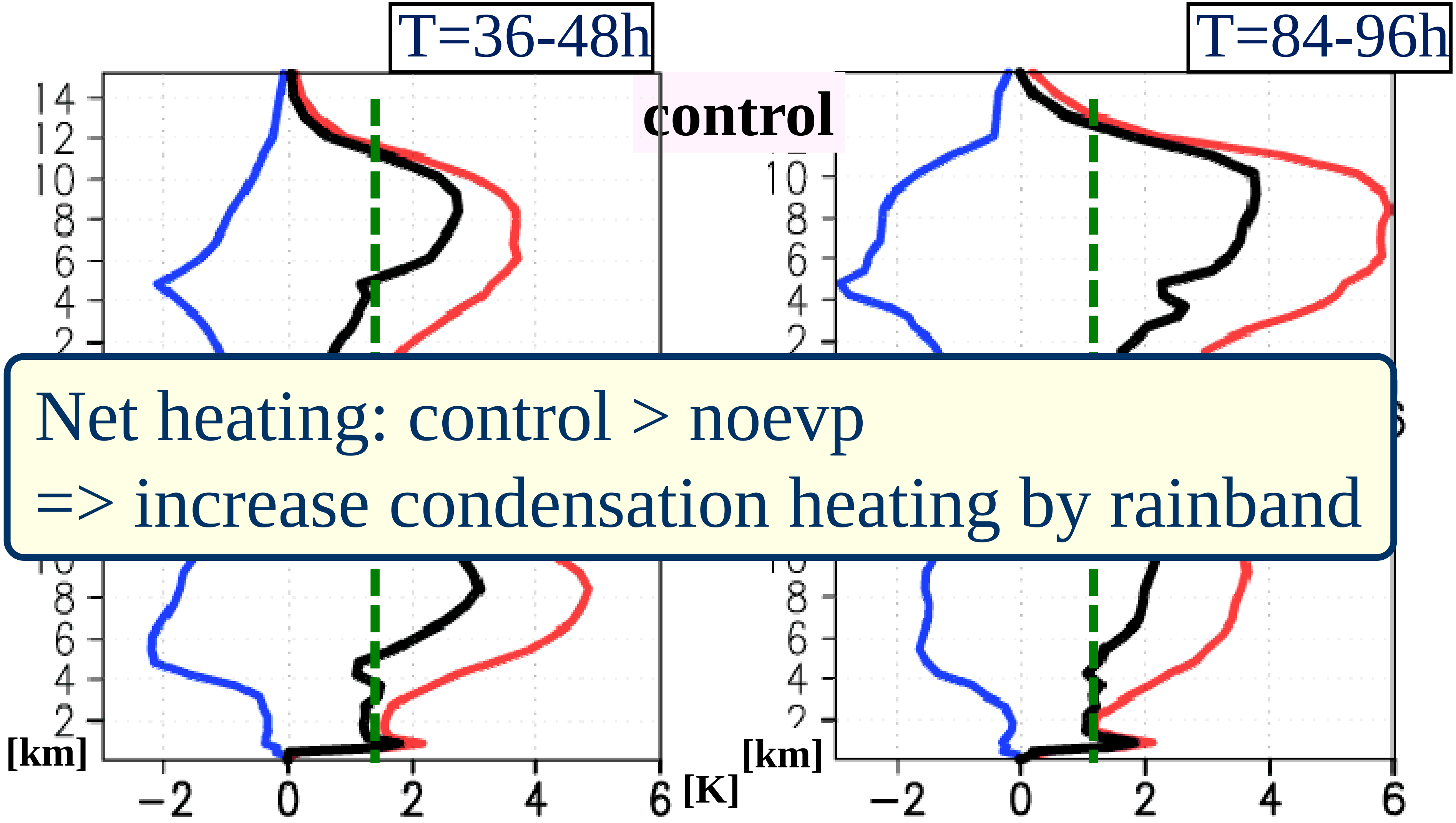
Azimuthally averaged mass streamfunction (10^8kg/s)

Difference in TC size/KE
< mature stage >



KE: area-averaged KE within 300-km radius from TC center

Diabatic heating/cooling

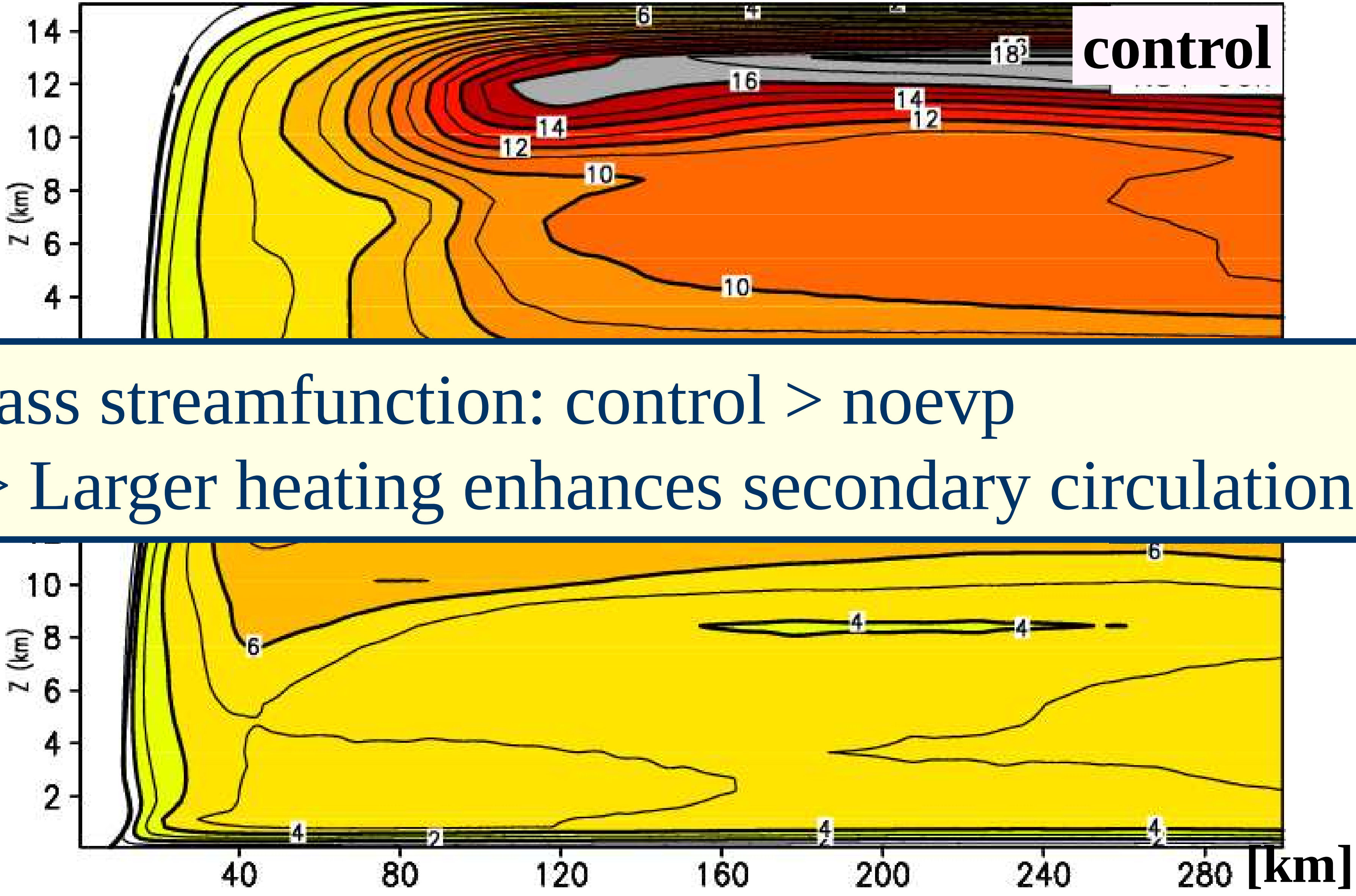


Net heating: control > noevp
=> increase condensation heating by rainband

Temporal and area averaged
Black: net diabatic heating (K/h)
Red: diabatic heating (K/h)
Blue: diabatic cooling (K/h)
within 150-km radius

Mass streamfunction

T=84-96h

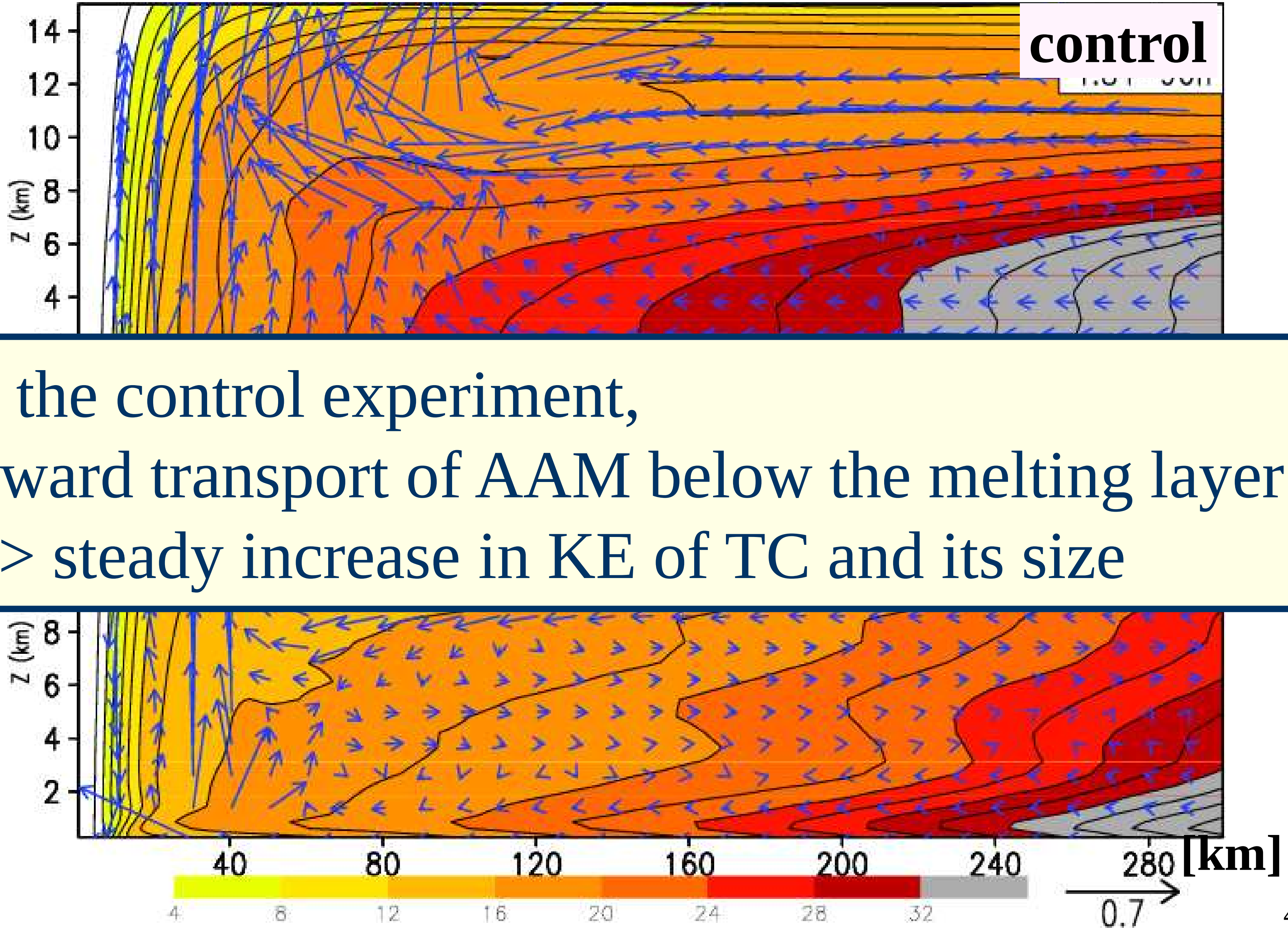


Mass streamfunction: control > noevp
=> Larger heating enhances secondary circulation

Azimuthally averaged mass streamfunction (10^8kg/s)

Absolute angular momentum (AAM)

< Vertical structure of AAM and its flux > T=84-96h



In the control experiment,
Inward transport of AAM below the melting layer
=> steady increase in KE of TC and its size

Summary on impact of evaporation ～Evolution and Size～

- Impacts of evaporative cooling on TC development and size are significantly different from those of melting/sublimation cooling (suppress TC size & reduce kinetic energy).

- When evaporative cooling is included, TC intensification becomes slow at the development stage, but its kinetic energy and size steadily increase at the mature stage.

- Evaporative cooling generates cold pools near the surface and decrease CAPE at the development stage.
  => suppress rapid intensification

- Cold pools form rainbands and induce precipitation outside the eyewall. Larger diabatic heating drives secondary circulation, which enhances the inward transport of angular momentum.
  => steadily increase in kinetic energy and TC size

(Sawada and Iwasaki, Part I, in press)

Relationship between diabatic heating and mass streamfunction

Thermodynamic equation in cylindrical coordinate

$$\cancel{\frac{\partial\theta}{\partial t}} = -u\cancel{\frac{\partial\theta}{\partial r}} - \cancel{\frac{v}{r}\frac{\partial\theta}{\partial\lambda}}\boxed{- w\frac{\partial\theta}{\partial z} + Q}$$

(Q : diabatic heating)

$$\overline{w_q} \approx \overline{Q}\left\{\frac{\partial\theta}{\partial z}\right\}^{-1}$$

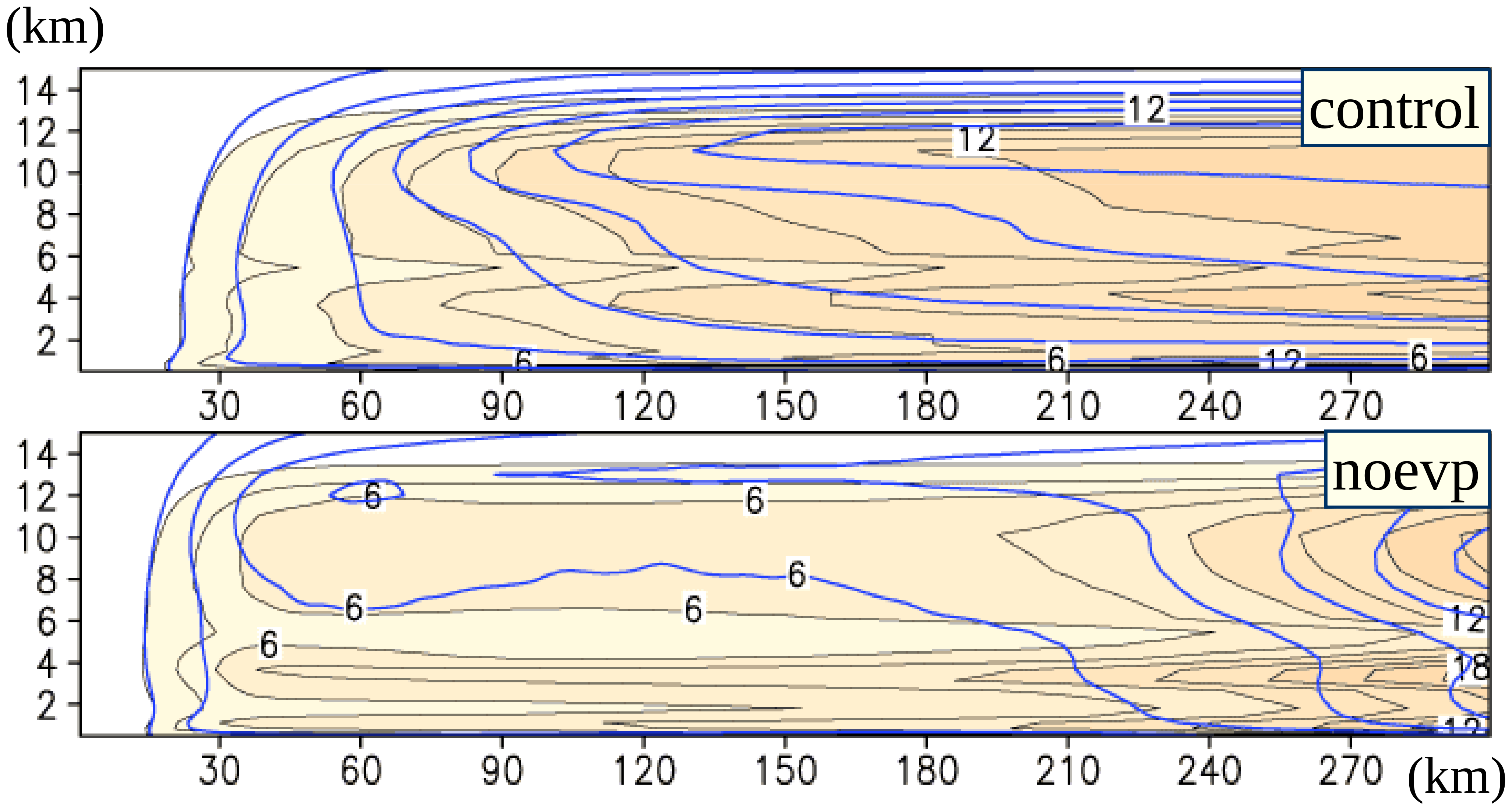
Vertical motion driven by diabatic heating

Relationship between mass streamfunction (ψ) and diabatic heating,

$$\boxed{\psi_q}\boxed{= \int_0^r r\rho w_q dr}\boxed{\approx \int_0^r r\rho\frac{Q}{\frac{\partial\theta}{\partial z}}dr}$$

Secondary circulation driven by diabatic heating

ψ calculated W & diabatic heating



Mass streamfunction calculated W [CI: 2×10^8 kg/s]

Mass streamfunction calculated diabatic heating [CI: 2×10^8 kg/s]

Time mean: 66-72h

Reconsider Relationship between mass streamfunction and other term

$$\cancel{\frac{\partial \theta}{\partial t}} = -u\cancel{\frac{\partial \theta}{\partial r}} - \frac{v}{r}\cancel{\frac{\partial \theta}{\partial \lambda}} - w\frac{\partial \theta}{\partial z} + Q$$

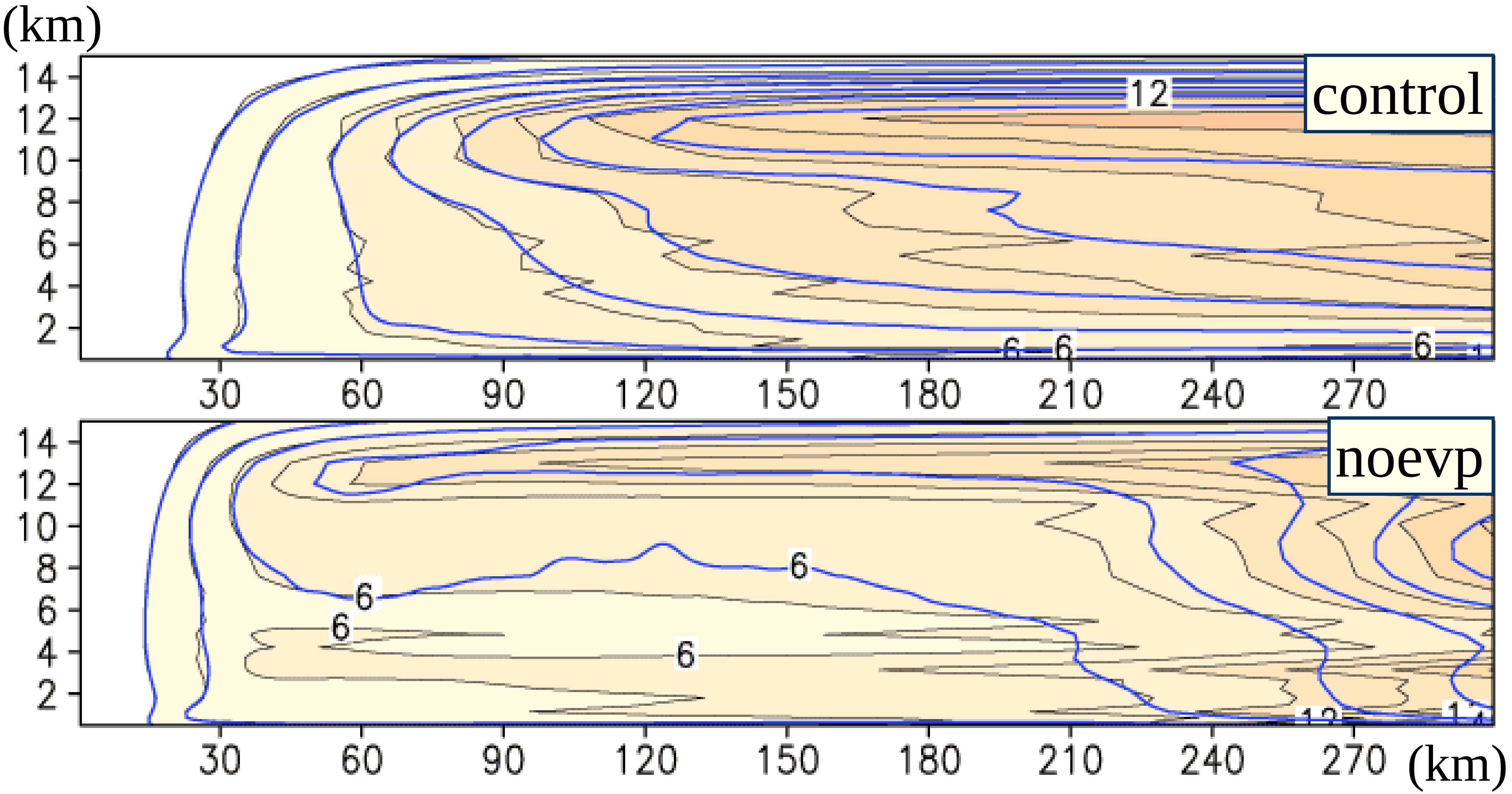
$$\overline{w_a} \approx \left\{ \underbrace{\overline{Q}}_{\text{dia}} \underbrace{- \overline{w'\frac{\partial \theta'}{\partial z}}}_{\text{eddy}} \underbrace{- \overline{u\frac{\partial \theta}{\partial r}} - \overline{\frac{v}{r}\frac{\partial \theta}{\partial \lambda}}}_{\text{advh}} \right\} \left\{ \frac{\partial \theta}{\partial z} \right\}^{-1}$$

$$\psi_a = \int_0^r r\overline{\rho}\,\overline{w_a}\,dr$$

$$= \psi_{dia} + \psi_{eddy} + \psi_{advh}$$

49/15

ψ calculated W & all terms



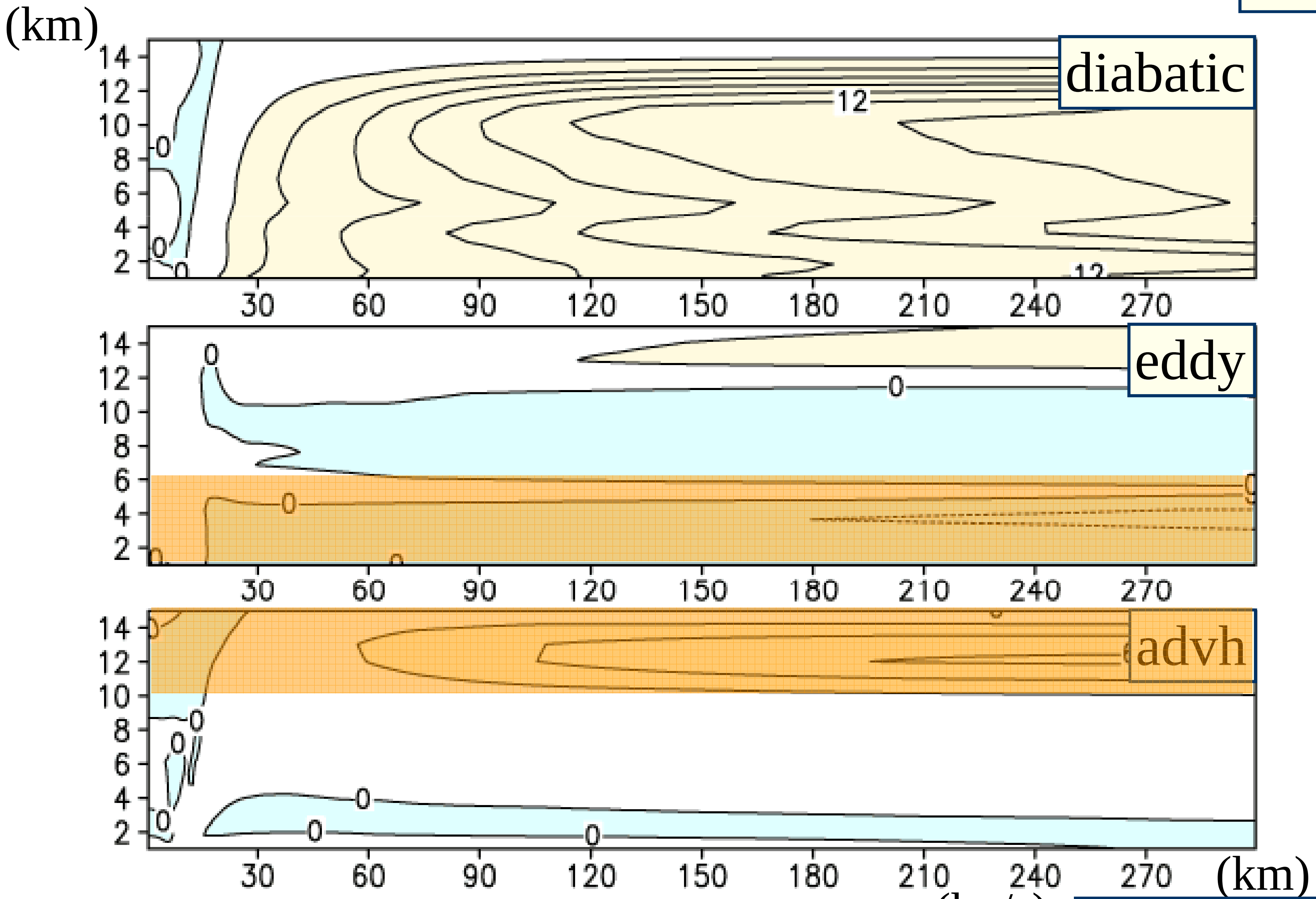
Mass streamfunction calculated W [CI: $2x10^8$ kg/s]

Mass streamfunction calculated diabatic heating [CI: $2x10^8$ kg/s]

Time mean: 66-72h

SC induced each term

control



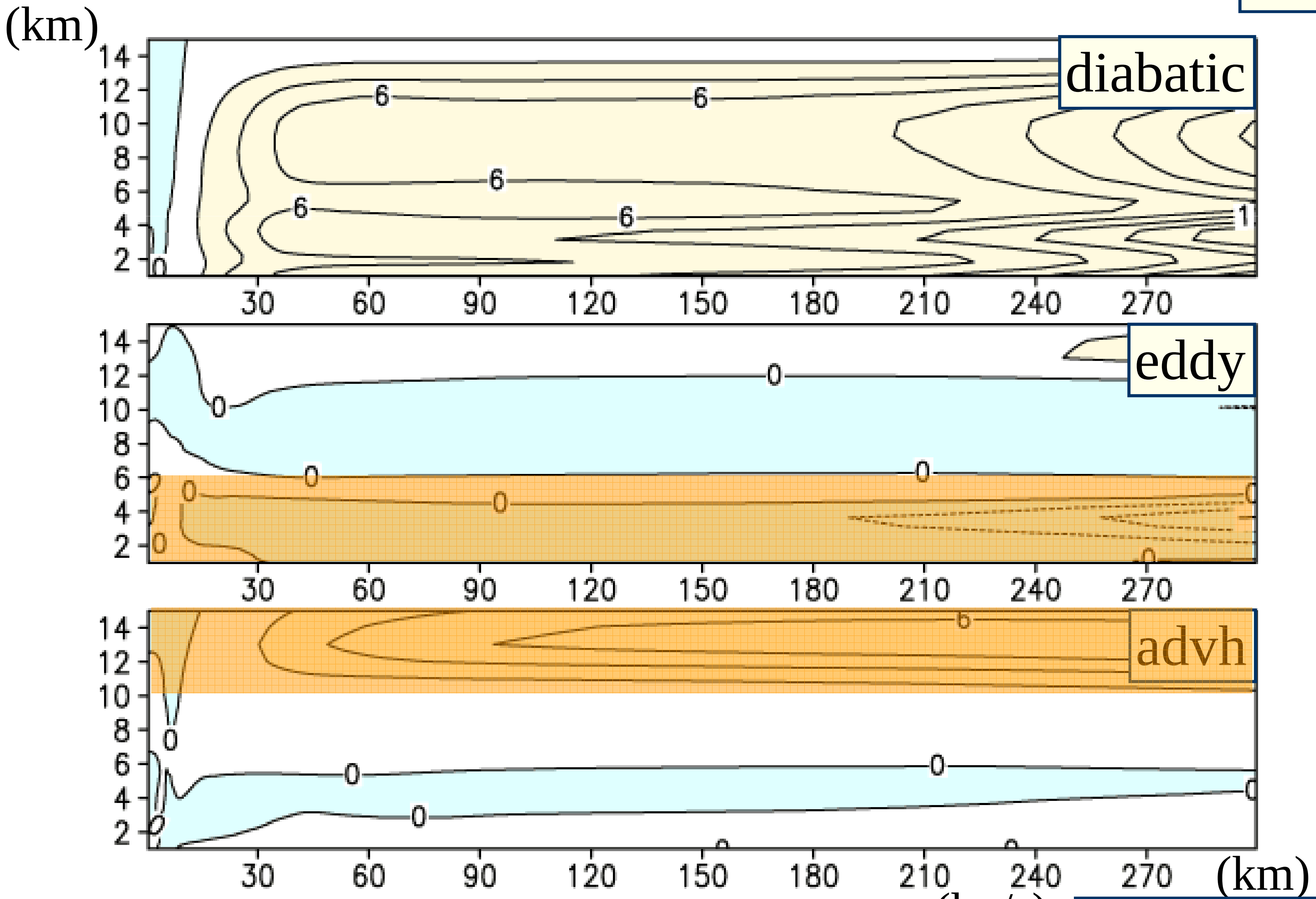
(kg/s)

CI: $2\text{x}10^8$ (kg/s)

Time mean: 66-72h

SC induced each term

noevp

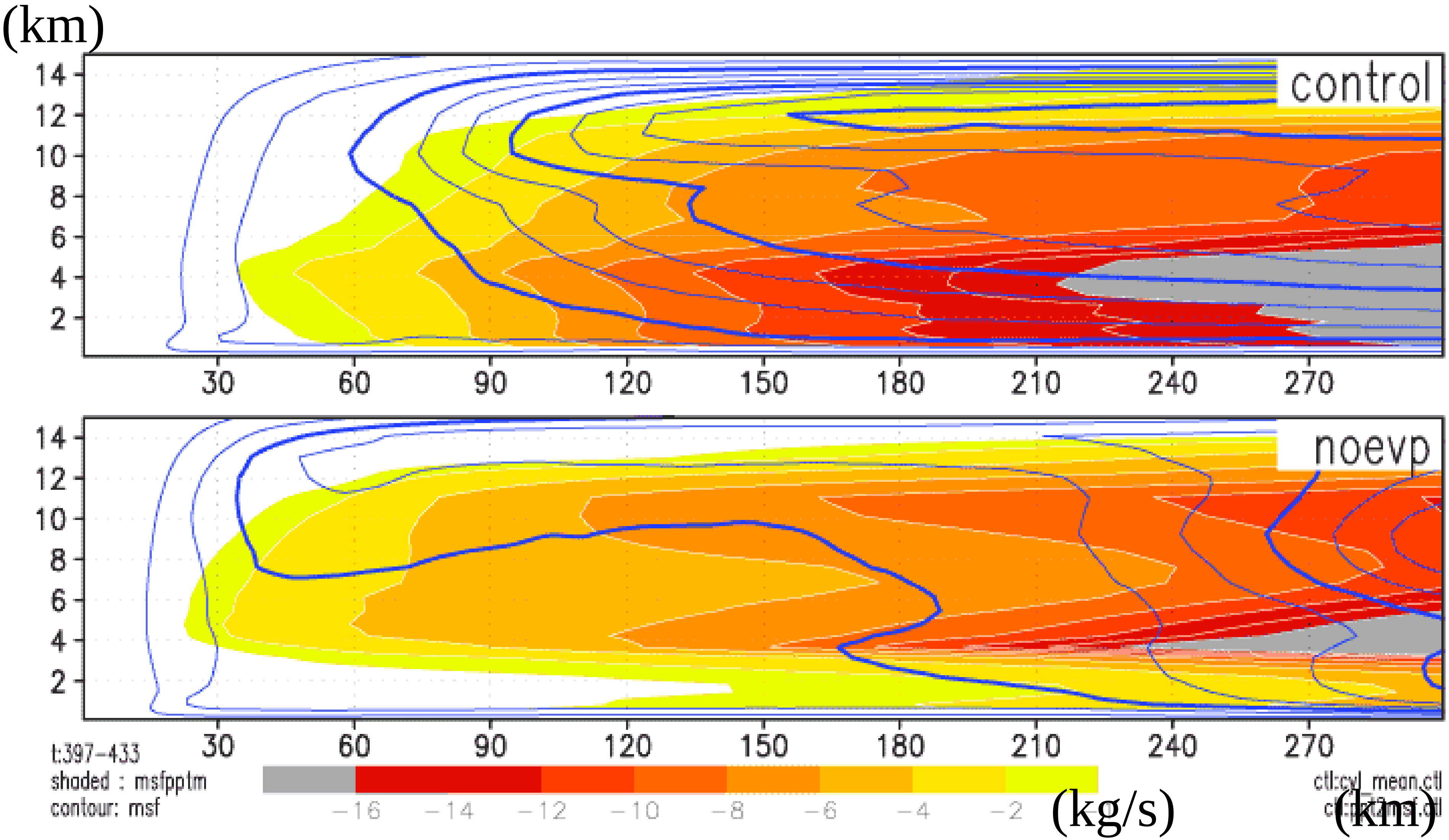


CI: $2x10^8$ (kg/s)

(kg/s)

Time mean: 66-72h

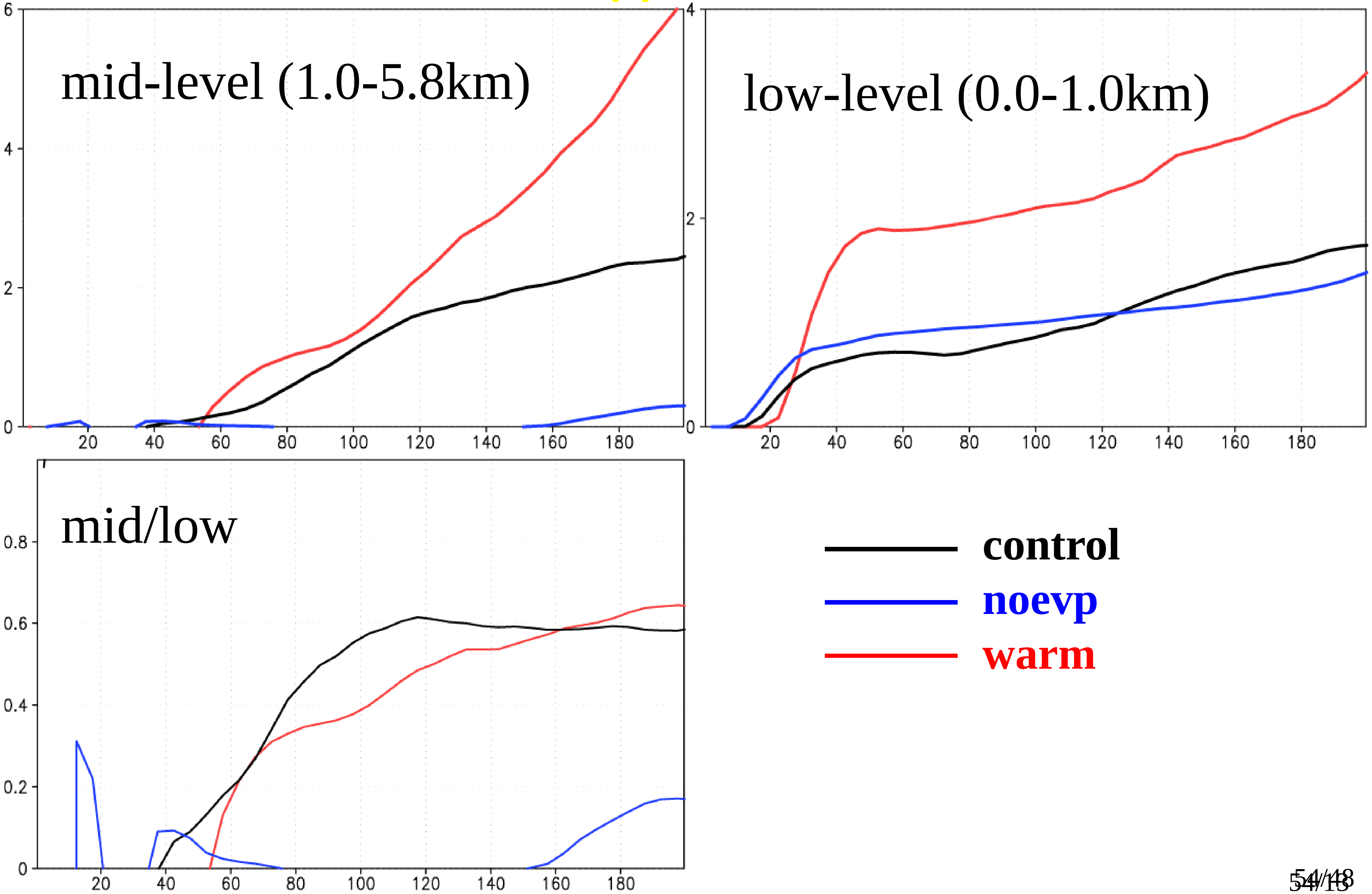
SC induced diabatic cooling



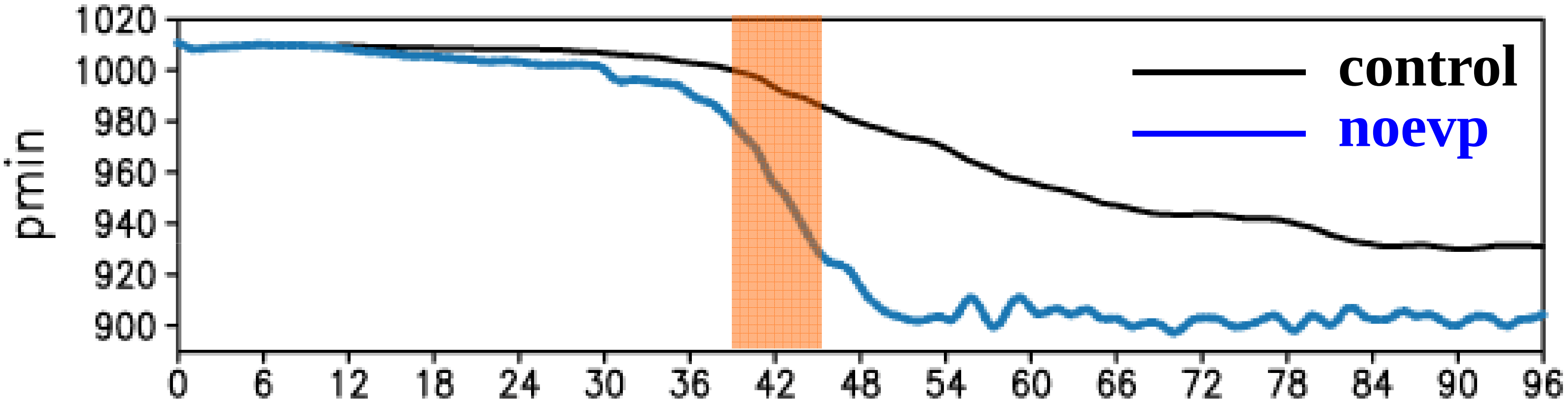
Mass streamfunction calculated W [CI: $2x10^8$ kg/s]

Time mean: 66-72h

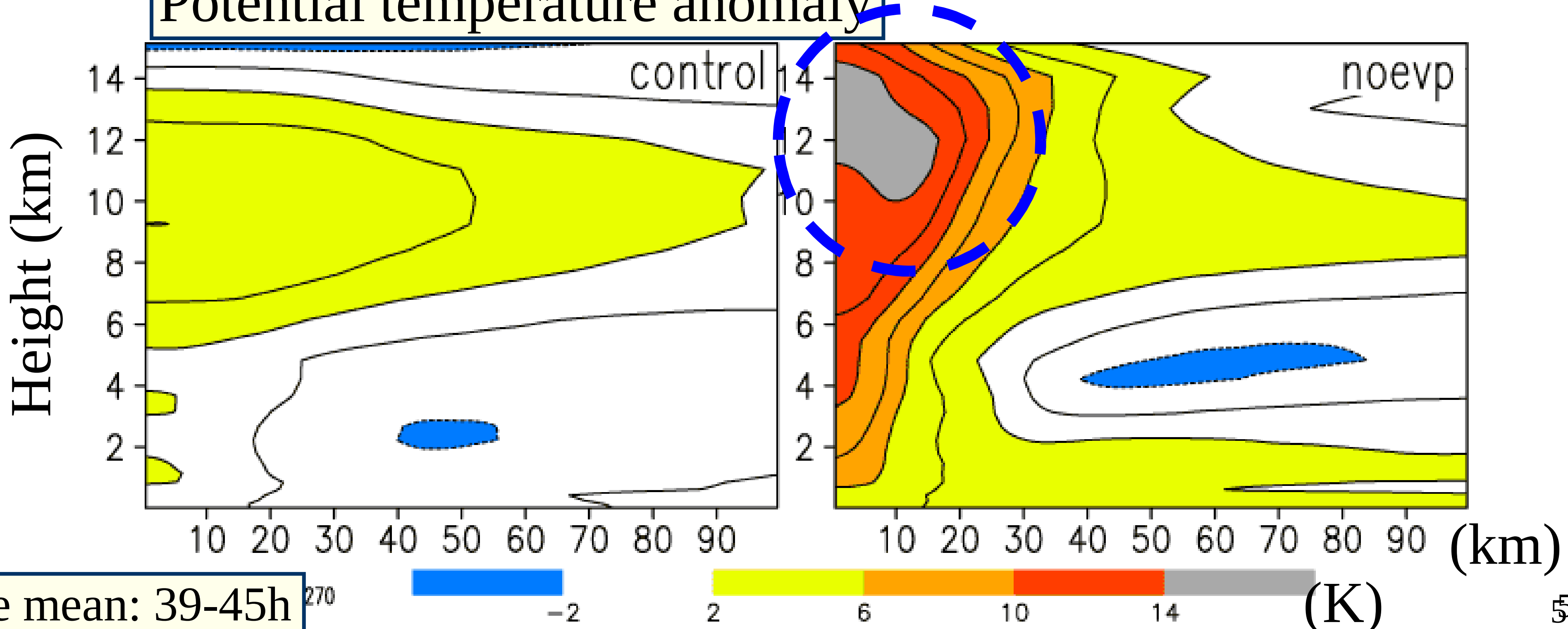
Vertical integrated AAM flux



Vertical structure of warm core



Potential temperature anomaly

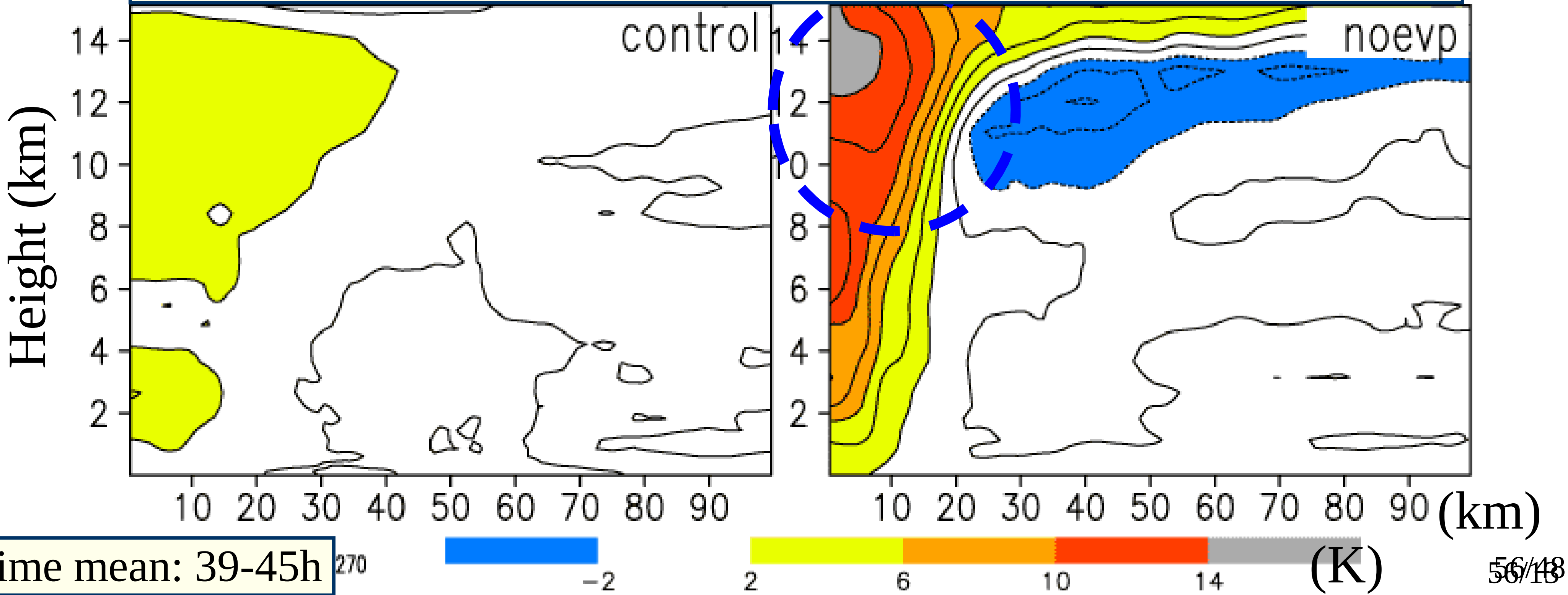


Time mean: 39-45h

Heat budget analysis

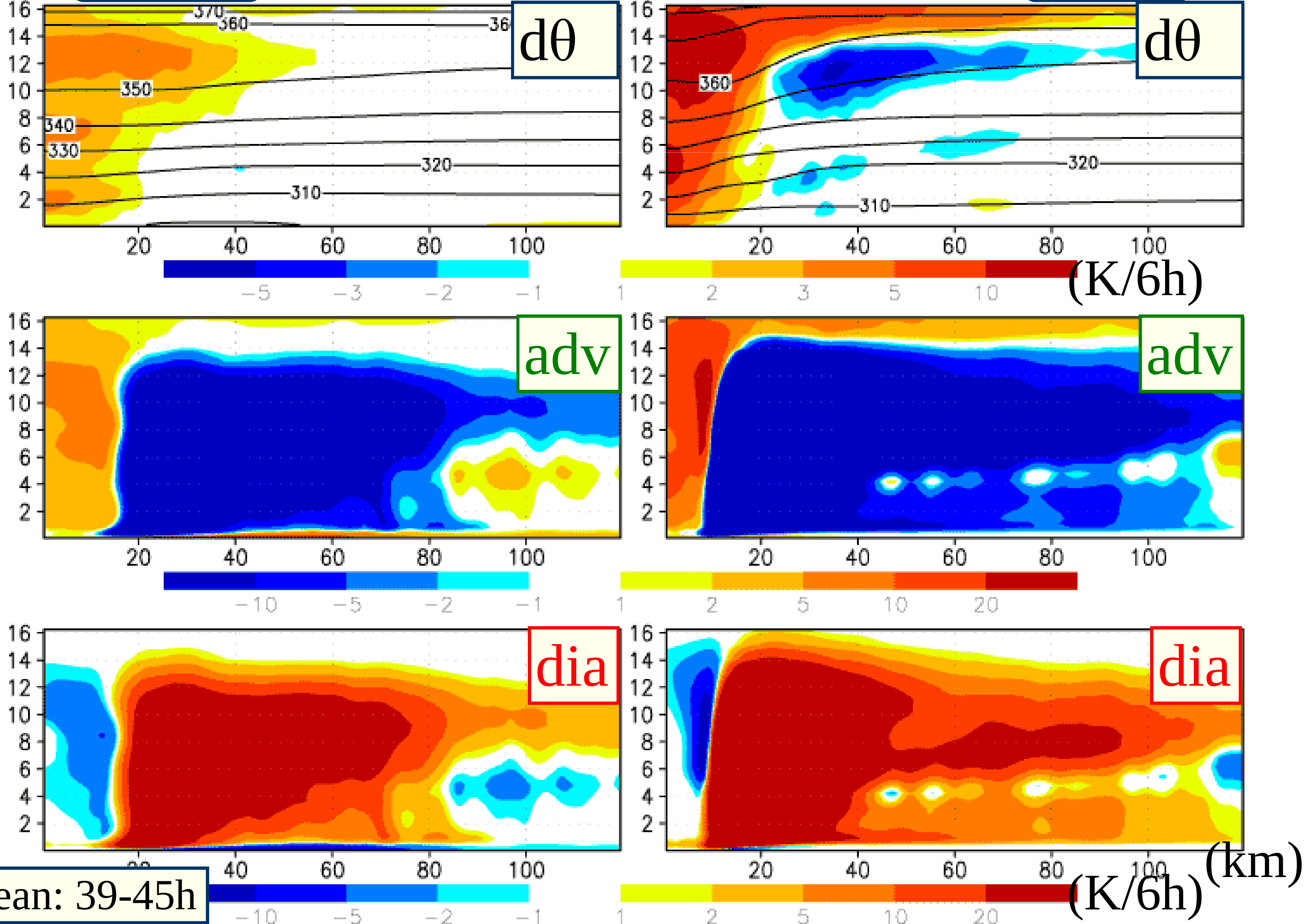
$$\frac{\partial\overline{\theta}}{\partial t} = \underbrace{-\overline{u\frac{\partial\theta}{\partial r}} - \overline{w\frac{\partial\theta}{\partial z}}}_{\text{adv}} + \underbrace{\overline{Q}}_{\text{diabatic}} + \underbrace{dif.\theta}_{\text{diff}}$$

Potential temperature tendency: dθ=θ(FT=45) -θ(FT=39)



Time mean: 39-45h

Heat budget analysis

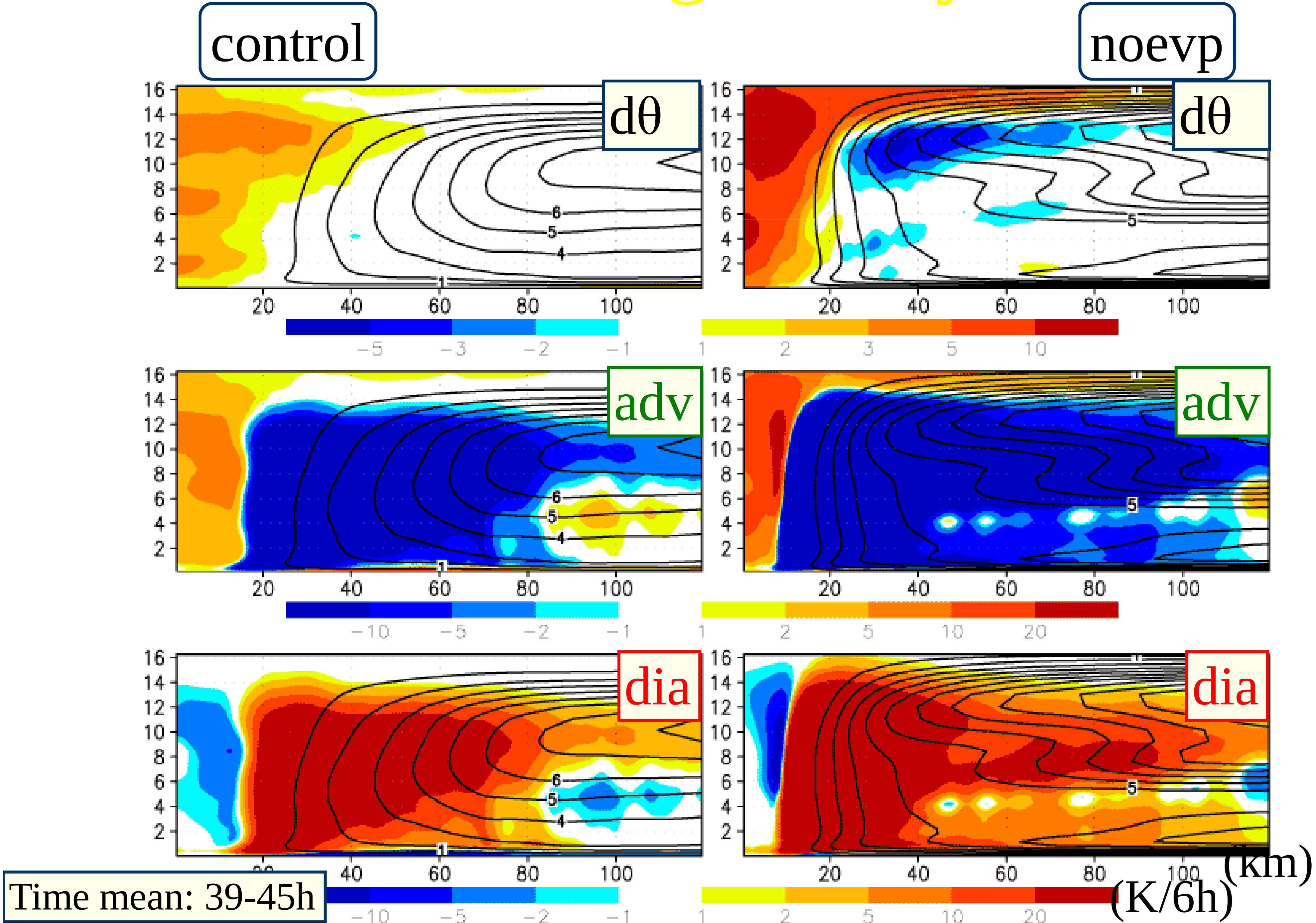


control

noevp

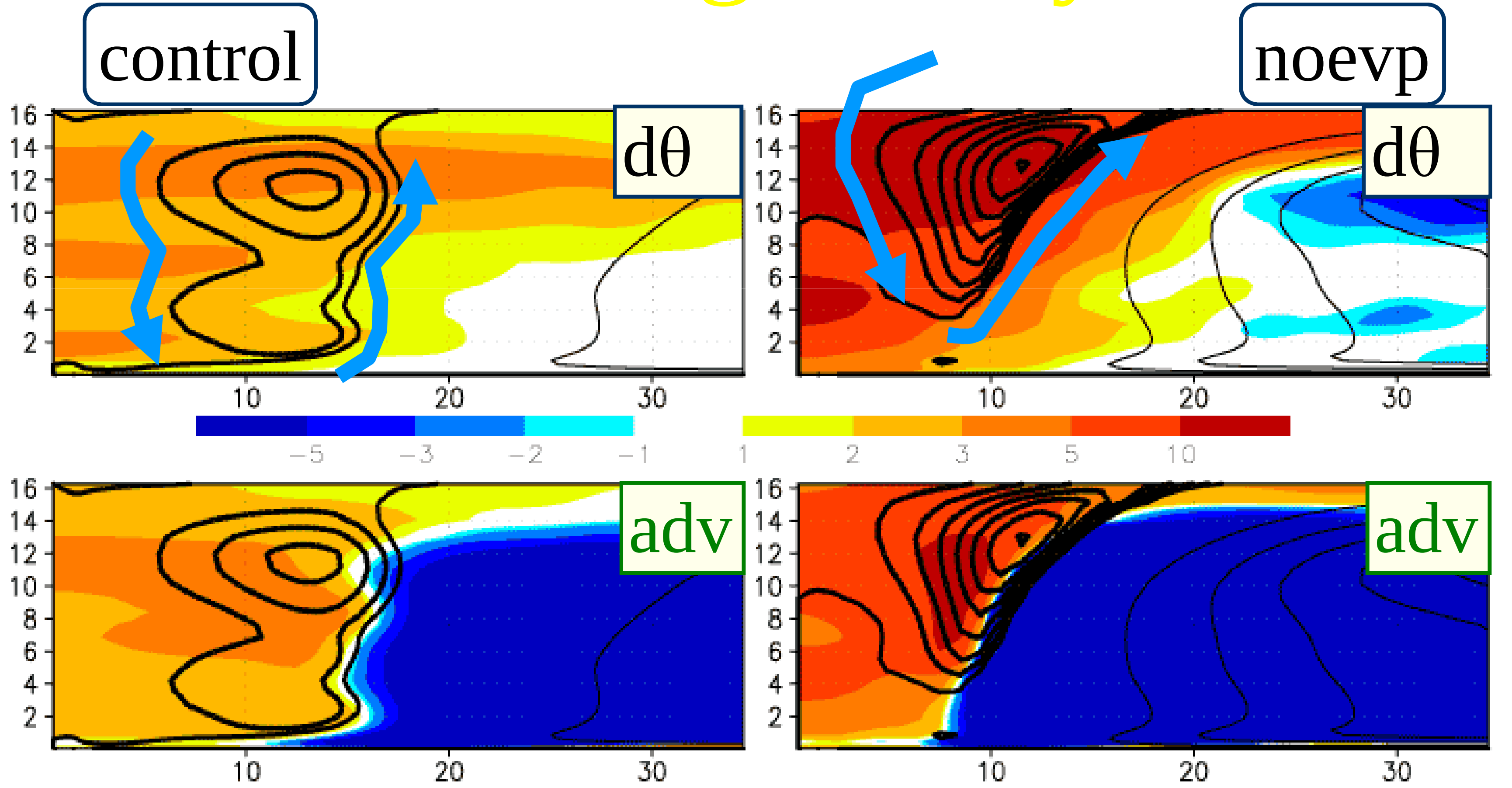
Time mean: 39-45h

Heat budget analysis



Time mean: 39-45h

Heat budget analysis



Air heated by condensation and deposition
is transported to eyewall from upper troposphere.
=> warm core formation

Time mean: 39-45h