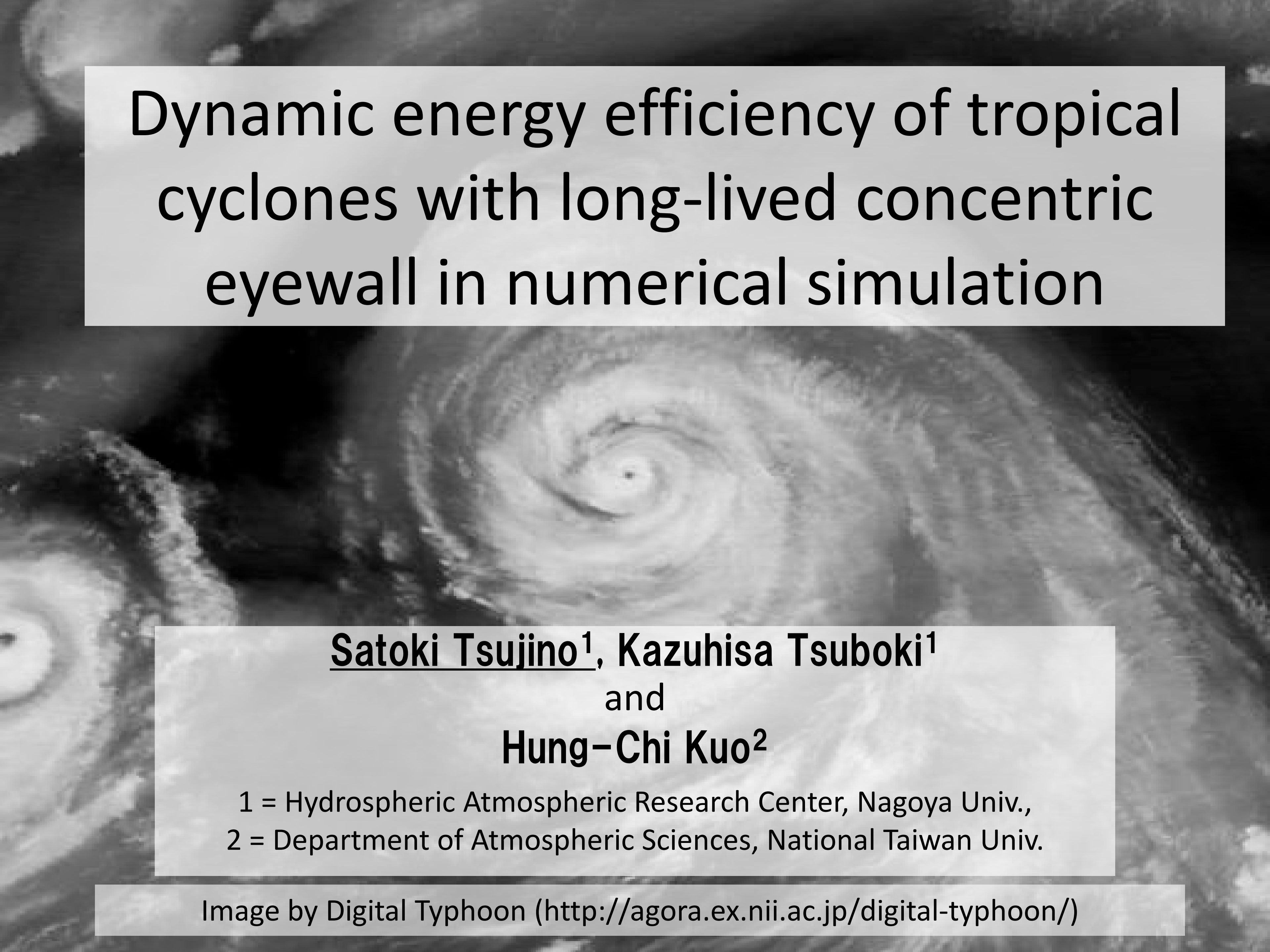


Dynamic energy efficiency of tropical cyclones with long-lived concentric eyewall in numerical simulation

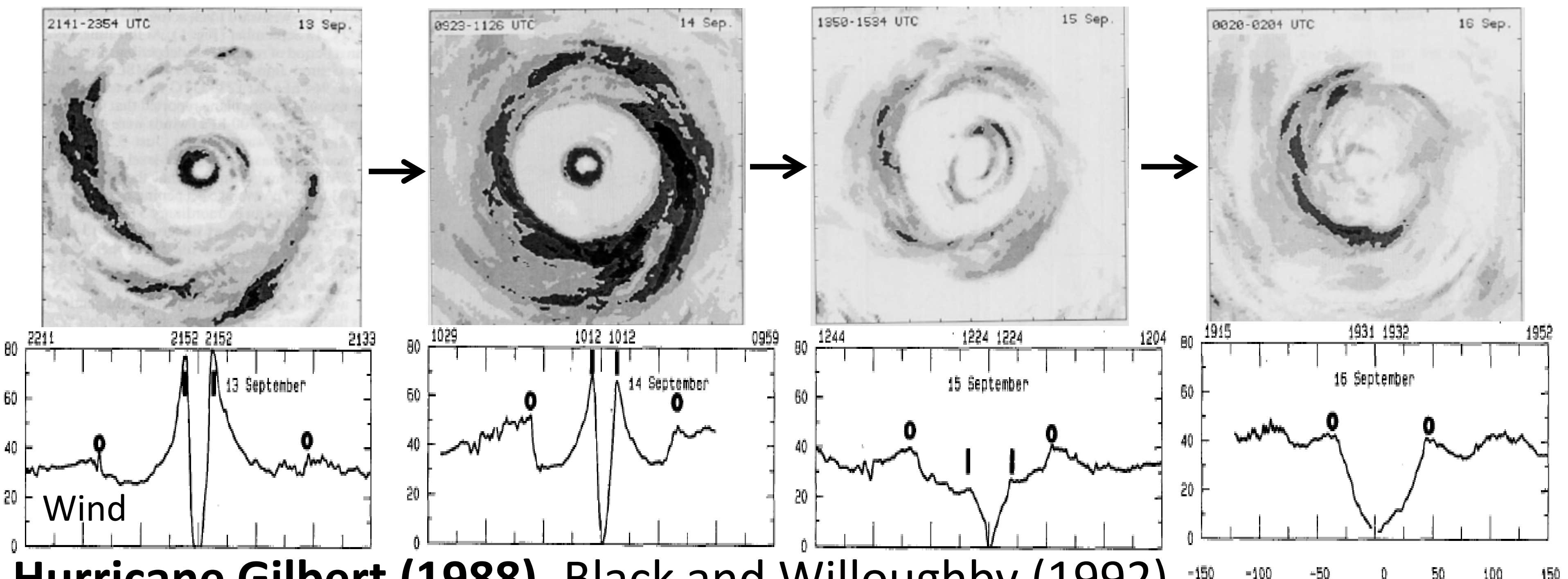
Satoki Tsujino[1], Kazuhisa Tsuboki[1]
and
Hung-Chi Kuo[2]

1 = Hydrospheric Atmospheric Research Center, Nagoya Univ.,
2 = Department of Atmospheric Sciences, National Taiwan Univ.

Image by Digital Typhoon (http://agora.ex.nii.ac.jp/digital-typhoon/)

Concentric eyewall and Eyewall replacement cycle

- The inner eyewall of tropical cyclone (TC) gradually disappears while the outer eyewall moves inward.
- The TC intensity changes drastically.
- 24 percentages of typhoons with concentric eyewall maintained over 20 hours (i.e., without eyewall replacement).
  - Yang et al. (2013, 2014, MWR).

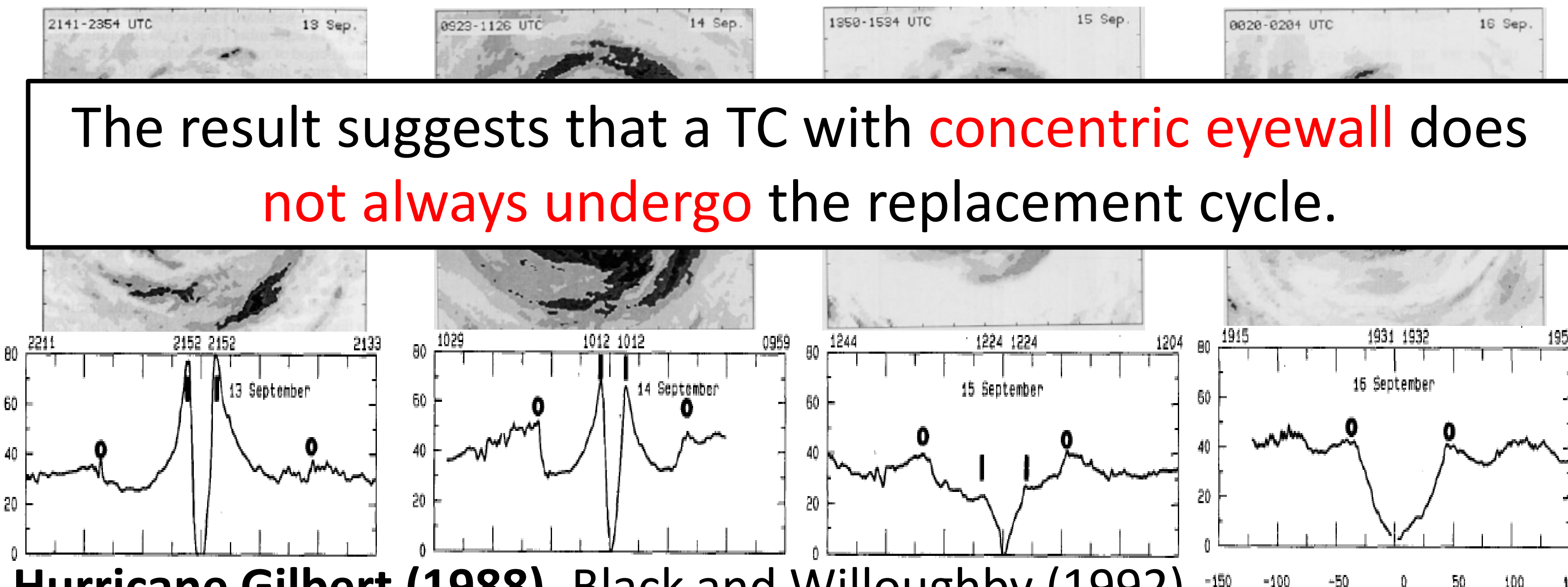


Hurricane Gilbert (1988), Black and Willoughby (1992).

Courtesy of Prof. H.C. Kuo.

Concentric eyewall and Eyewall replacement cycle

- The inner eyewall gradually disappears while the outer eyewall moves inward.
- The TC intensity changes drastically.
- 24 percentages of typhoons with concentric eyewall maintained over 20 hours (i.e., without eyewall replacement).
  - Yang et al. (2013, 2014, MWR).



The result suggests that a TC with concentric eyewall does not always undergo the replacement cycle.

Hurricane Gilbert (1988), Black and Willoughby (1992).

Courtesy of Prof. H.C. Kuo.

Motivation

- The maintenance mechanism of long-lived concentric eyewall is also not clear.
- It's believed that the internal dynamics of TC is important for the mechanism in some studies.
  - Kossin et al. (2000), Yang et al. (2013).
- We have conducted some numerical experiments of ideal TC with replaced and long-lived concentric eyewall, using a three-dimensional, non-hydrostatic model (Cloud Resolving Storm Simulator; CReSS).
- In order to understand the mechanism, we investigate the general feature of long-lived concentric eyewall.
- We focus on the intensity change in the outer eyewall region due to diabatic heating.

Motivation

(1) Calculating "dynamic energy efficiency" for idealized TCs with ERC and CEM, using fine resolution data of CReSS model.
(2) Comparing dynamic energy efficiency of ERC type with CEM type.

- We have conducted some numerical experiments of ideal TC with replaced and long-lived concentric eyewall, using a three-dimensional, non-hydrostatic model (Cloud Resolving Storm Simulator; CReSS).
- In order to understand the mechanism, we investigate the general feature of long-lived concentric eyewall.
- We focus on the intensity change in the outer eyewall region due to diabatic heating.

Dynamic energy efficiency

- Governing equations (f-plane, axisymmetry)

Radial wind eq. $$\left(f+\frac{v}{r}\right)v=\frac{\partial\phi}{\partial r},$$

Tangential wind eq. $$\frac{\partial v}{\partial t}+u\left(f+\frac{\partial(rv)}{r\partial r}\right)+w\frac{\partial v}{\partial z}=D,$$

Vertical wind eq. $$\frac{\partial\phi}{\partial z}=g\frac{T}{T_0},$$

Continuity eq. $$\frac{\partial(ru)}{r\partial r}+\frac{\partial(\rho w)}{\rho\partial z}=0,$$

Thermodynamic eq. $$\frac{\partial T}{\partial t}+u\frac{\partial T}{\partial r}+w\left(\frac{\partial T}{\partial z}+\frac{RT}{C_pH_s}\right)=\frac{Q}{C_p}$$

- Eliassen transverse circulation

$$(L\psi=)\ \frac{\partial}{\partial r}\left(A\frac{\partial r\psi}{r\partial r}+B\frac{\partial\psi}{\partial z}\right)+\frac{\partial}{\partial z}\left(B\frac{\partial r\psi}{r\partial r}+C\frac{\partial\psi}{\partial z}\right)=\frac{g}{C_pT_0}\frac{\partial Q}{\partial r}-\frac{2}{r}\frac{\partial vD}{\partial z}$$

$$\rho A=\frac{g}{T_0}\left(\frac{\partial T}{\partial z}+\frac{R_dT}{C_pH_s}\right),\quad \rho B=-\frac{g}{T_0}\frac{\partial T}{\partial r}=-\left(f+\frac{2v}{r}\right)\frac{\partial v}{\partial z},\quad \rho C=\left(f+\frac{2v}{r}\right)\left(f+\frac{\partial(rv)}{r\partial r}\right)$$

Dynamic energy efficiency

- Energy budget (whole domain of TC)

$$\frac{dK}{dt} = C + F,$$ Kinetic energy

$$\frac{dA}{dt} = -C + H$$ Potential energy

Conversion to kinetic energy

$$K = \iint \rho \frac{v^2}{2} r dr dz, \quad A = \iint \rho C_p T r dr dz, \quad \boxed{C = \iint \rho \frac{T}{T_0} g w r dr dz,}$$

$$\boxed{H = \iint \rho Q r dr dz,} \quad F = \iint \rho v D r dr dz$$

Diabatic heating

Carrying out some mathematical operations…

Dynamic energy efficiency

- Energy budget (whole domain of TC)

$$\frac{dK}{dt} = \boxed{\bar{\eta}_h H - \bar{\eta}_f F} + F, \quad \text{Kinetic energy}$$

Conversion to K

$$\frac{dA}{dt} = \boxed{-\bar{\eta}_h H + \bar{\eta}_f F} + H \quad \text{Potential energy}$$

$$L\chi = \frac{g}{T_0}\frac{\partial T}{\partial r}, \qquad \eta_h \equiv \frac{g}{C_p T_0 \rho}\frac{\partial (r\chi)}{r\partial r},$$

$$\boxed{\bar{\eta}_h \equiv \frac{\iint \eta_h \rho Q r dr dz}{\iint \rho Q r dr dz}}$$

Dynamic energy efficiency (of heating source)

Hack and Schubert (1986), Kuo et al. (2014)

Dynamic energy efficiency

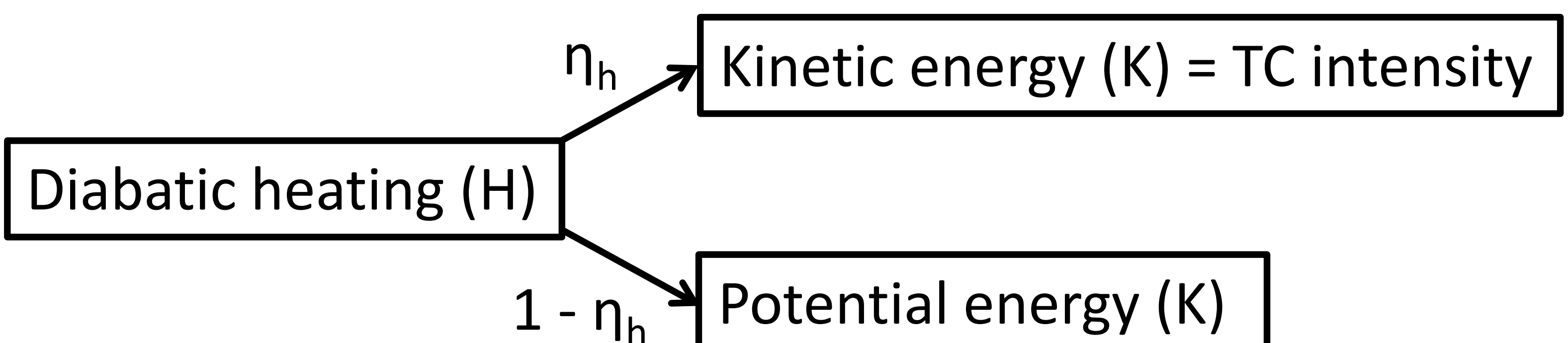
- Energy budget (whole domain of TC)

$$\frac{dK}{dt} = \boxed{\bar{\eta}_h H} - \bar{\eta}_f F + F,$$ Kinetic energy

Conversion to K for heating

$$\frac{dA}{dt} = \boxed{-\bar{\eta}_h H} + \bar{\eta}_f F + H$$ Potential energy

This parameter represents the conversion efficiency (%) to kinetic energy.
In this study, we focus on the efficiency of heating source (η_h).



Data (Idealized simulation)

- Weak axisymmetric vortex.
  - Terwey and Montgomery (2008).
- Tropical sounding data.
  - Jordan (1958).
- SST = 302 K (Constant).
- Horizontal grid interval = 2 km.
- Integration time = 500 hour.
- f – plane (15 degree N).

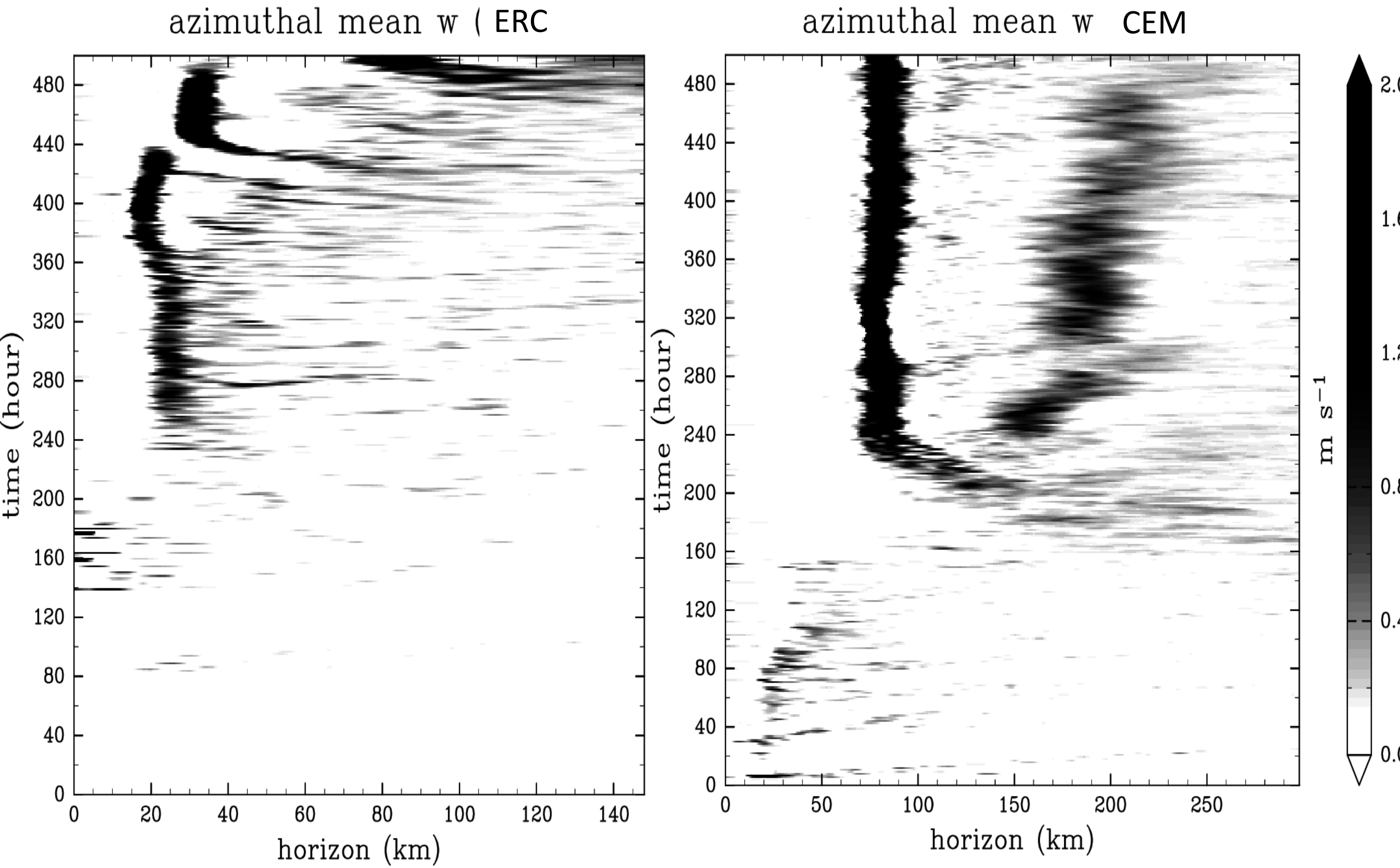
Sweeping parameter is sounding temperature.

- “ST302” experiment = sounding temperature + 3 K.
  - ST302 is more stable than CTL.

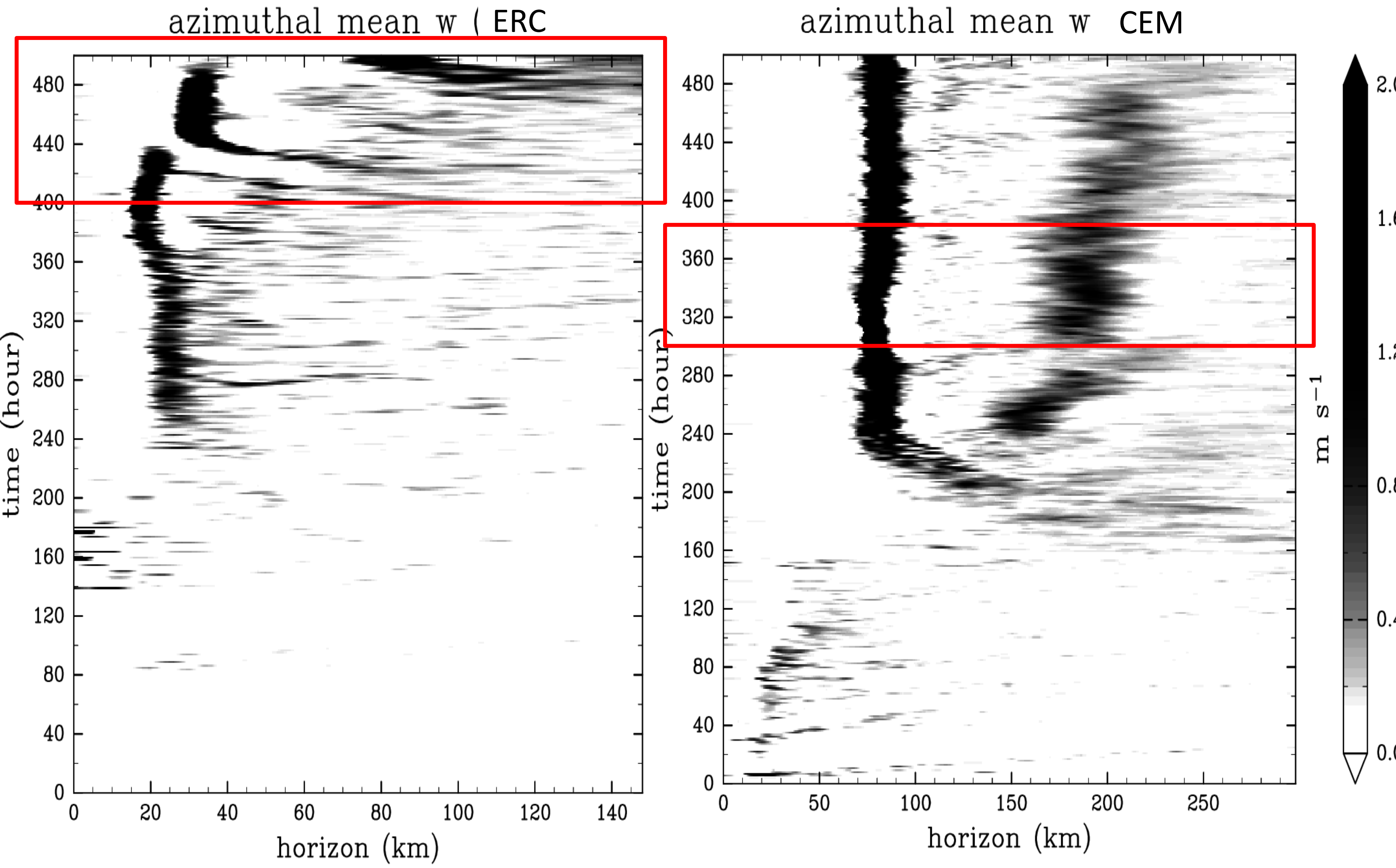
    The definition of our vertical stability : T_{top} －SST

    T_{top} is the temperature of the tropopause.

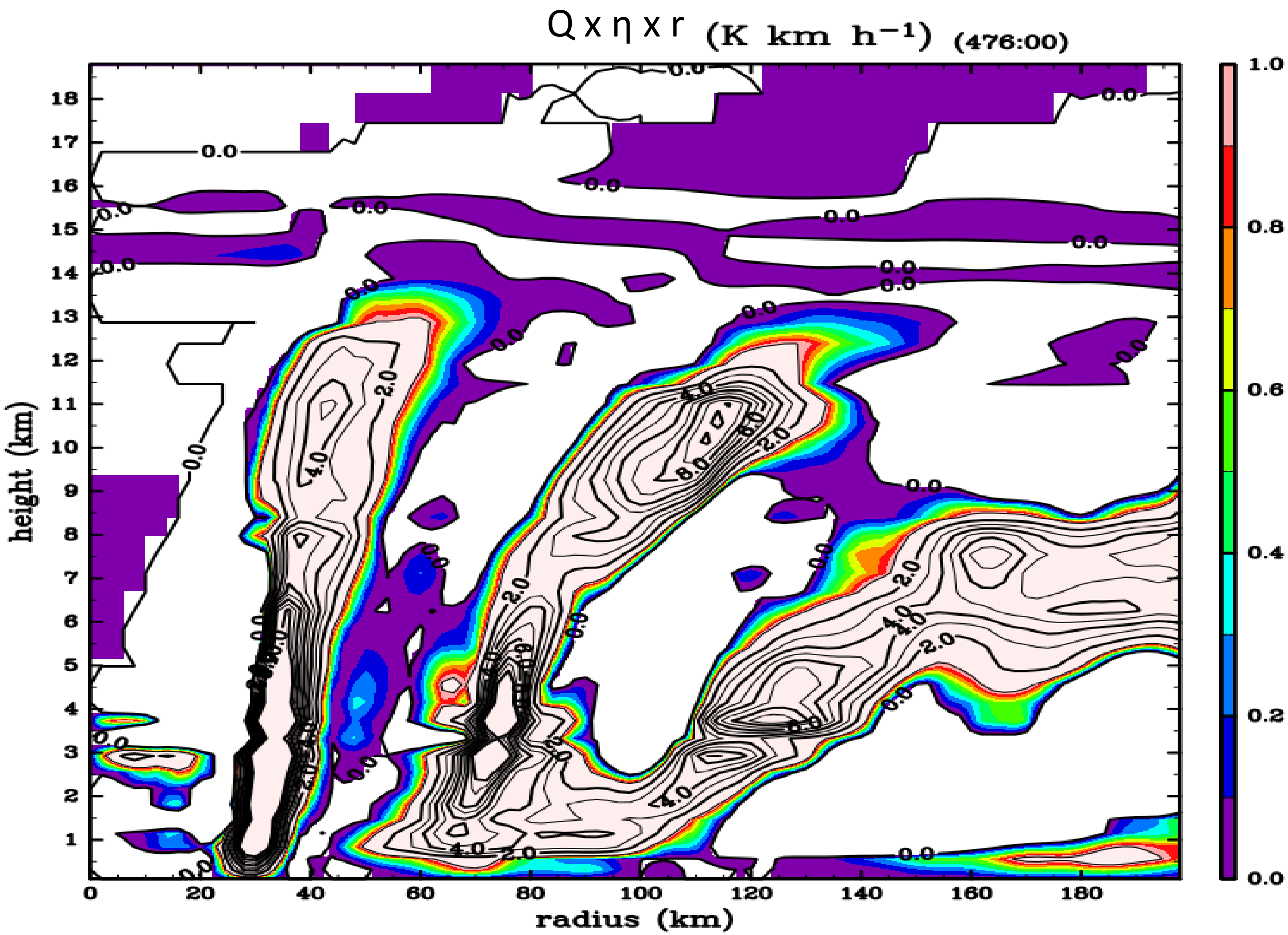
Data (Idealized simulation)



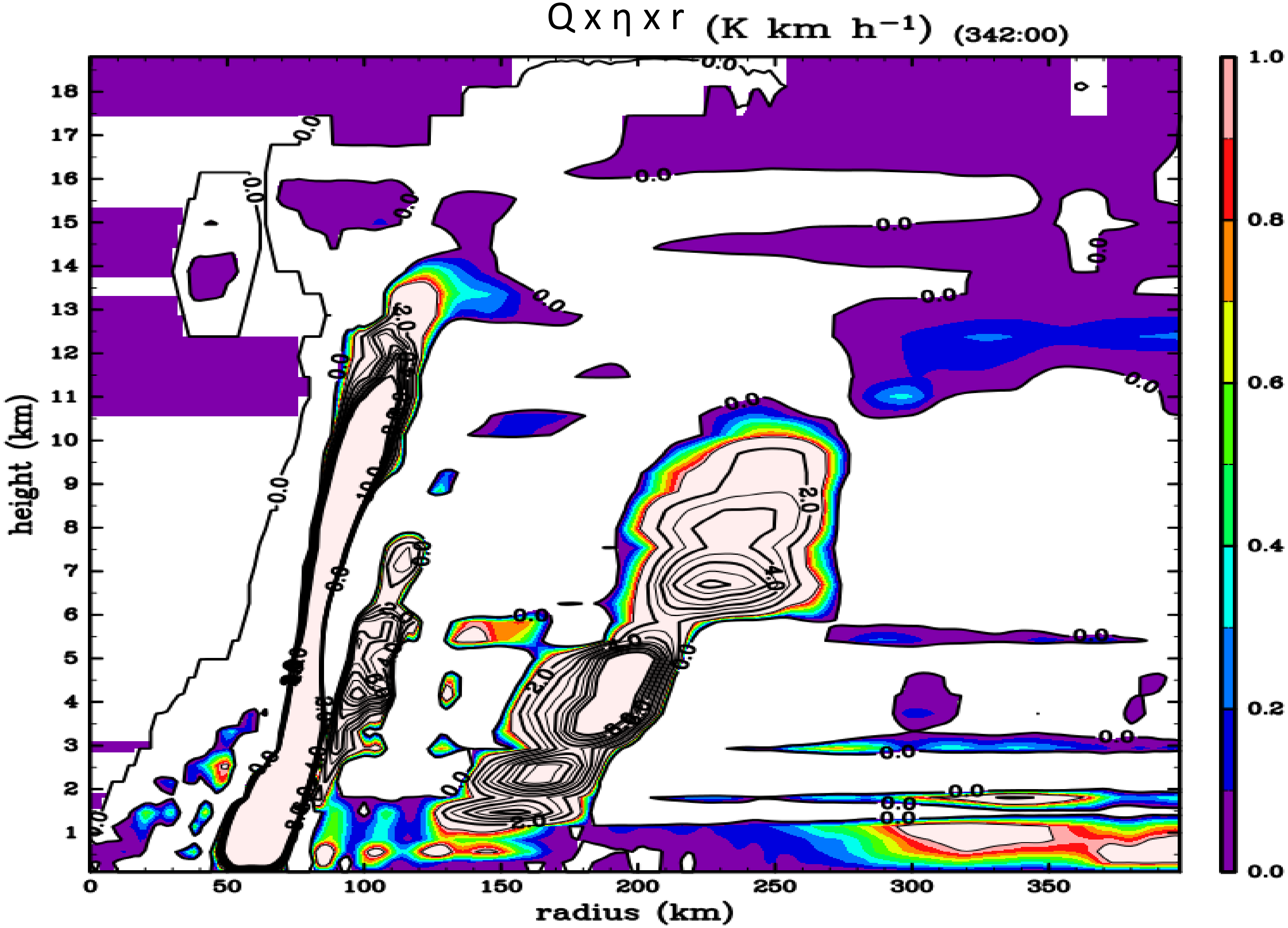
Data (Idealized simulation)



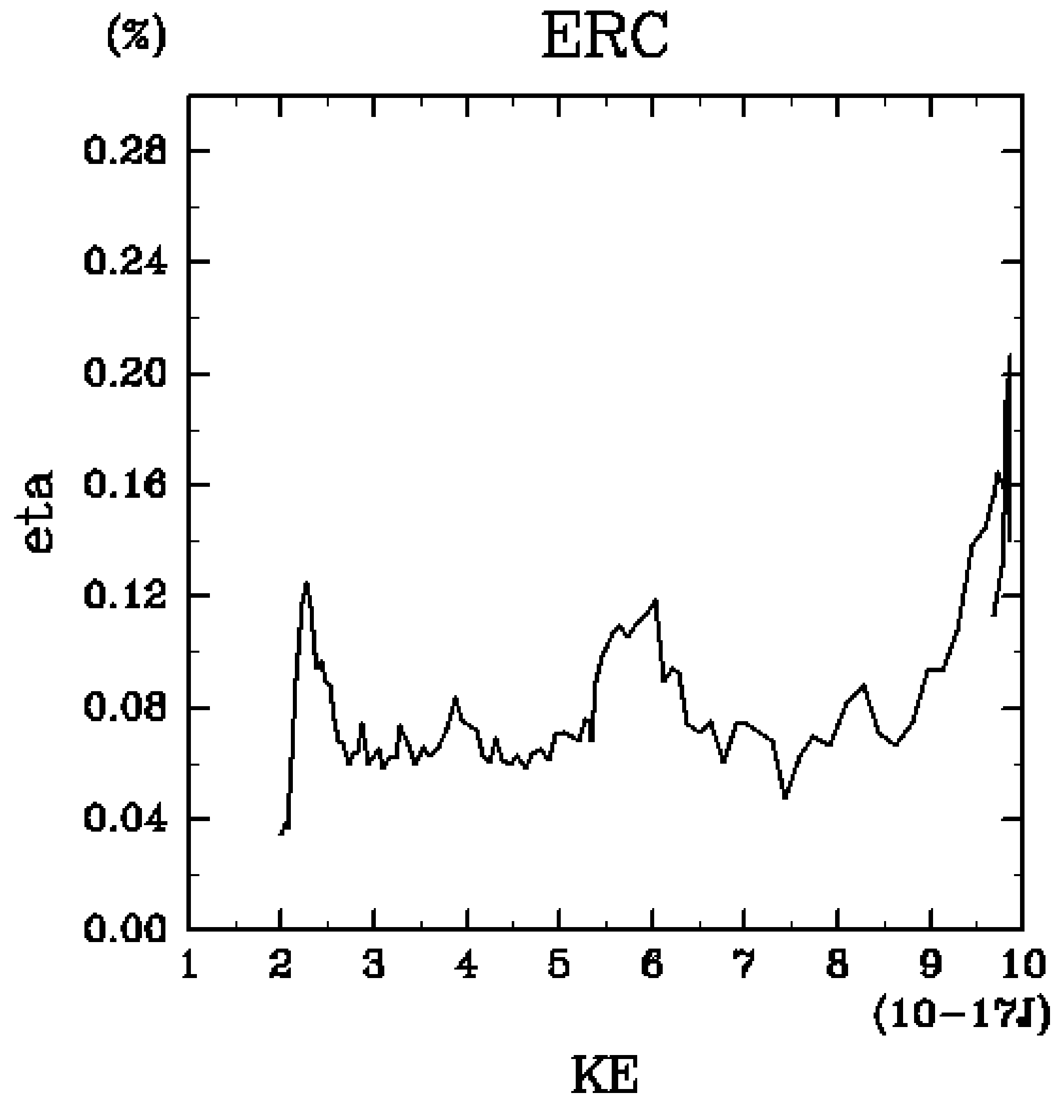
Conversion term (ERC)



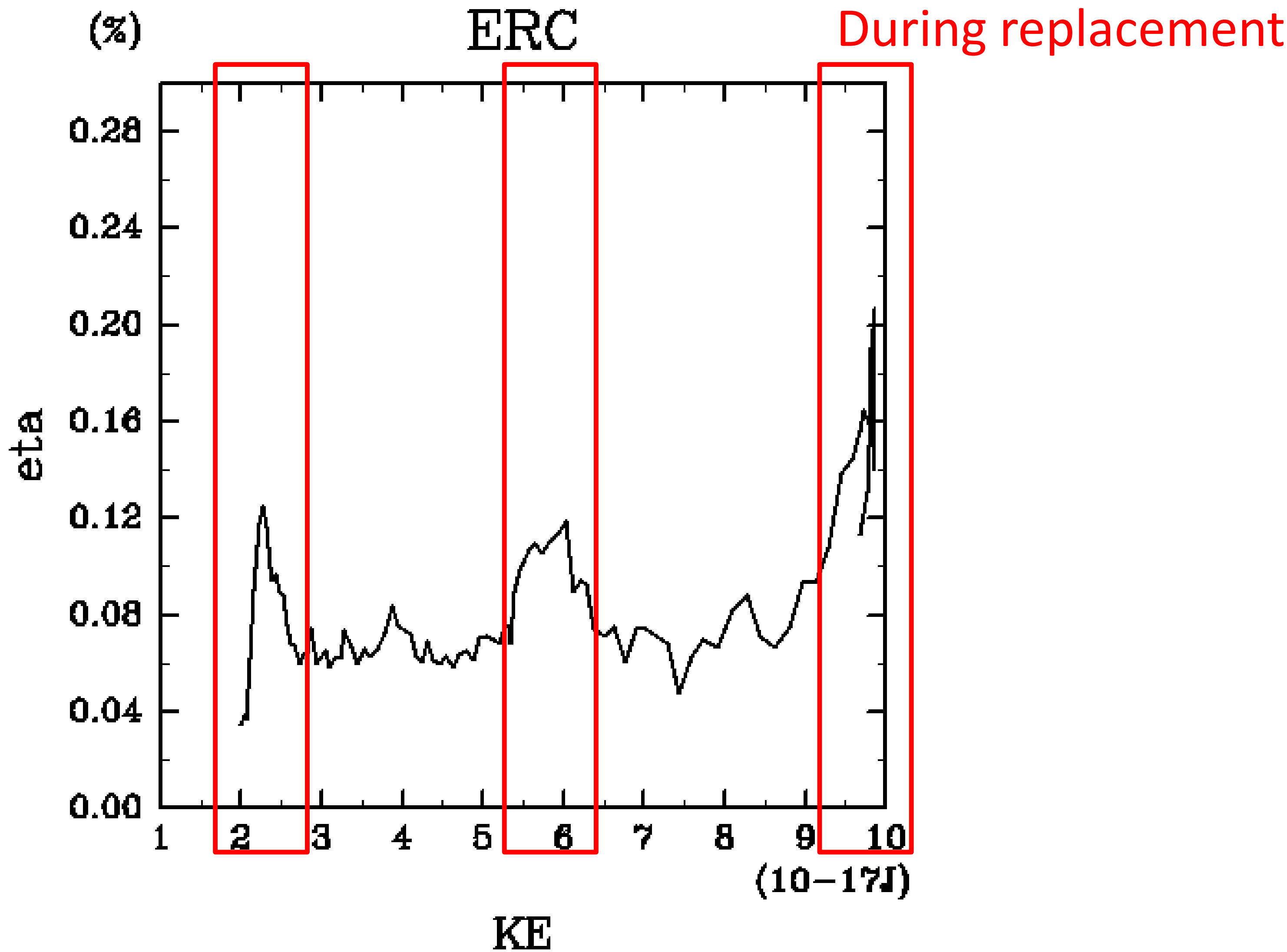
Conversion term (CEM)



η v.s. KE

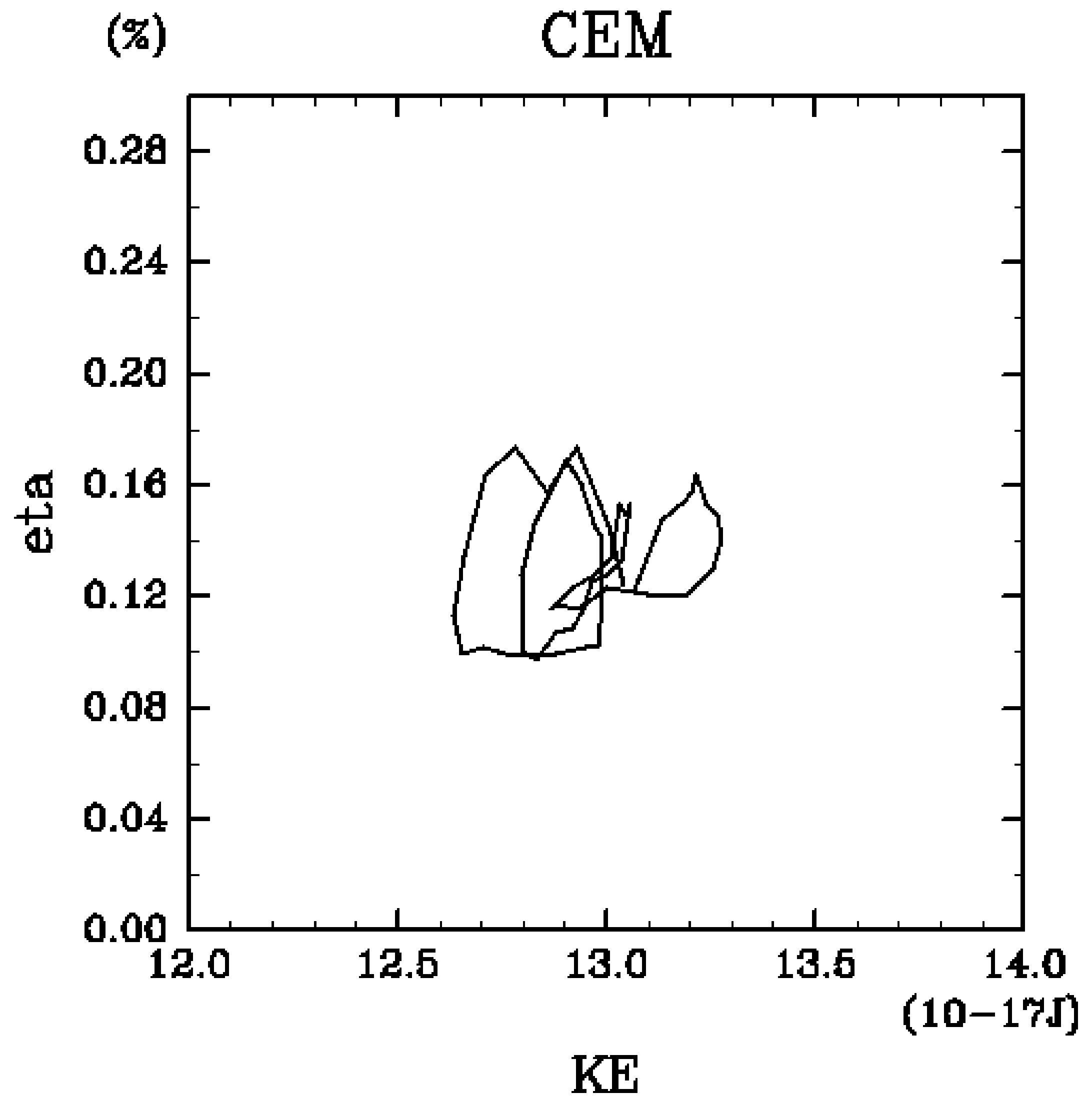


η v.s. KE

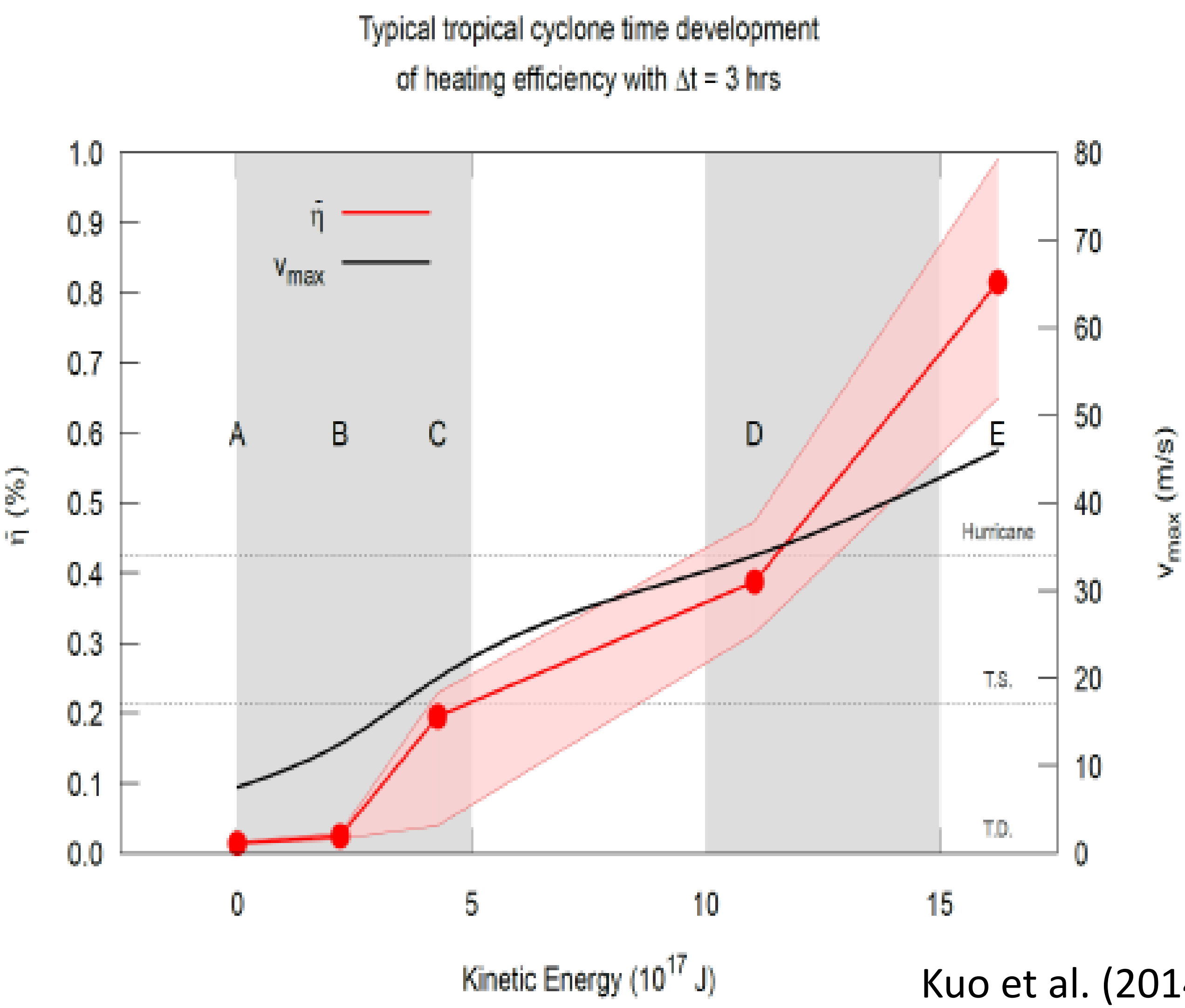


(%)
ERC
During replacement
0.28
0.24
0.20
0.16
0.12
0.08
0.04
0.00
eta
1
2
3
4
5
6
7
8
9
10
(10−17J)
KE

η v.s. KE


(%)
CEM
0.28
0.24
0.20
0.16
0.12
0.08
0.04
0.00
eta
12.0
12.5
13.0
13.5
14.0
(10−17J)
KE

Development of typical TC



Kuo et al. (2014)

Summary

- We calculated “dynamic energy efficiency” for idealized TCs with ERC and CEM, using fine resolution data of CReSS model.
- We compared dynamic energy efficiency of ERC type with CEM type.
    - ERC
        – The dynamic energy efficiency drastically changed during the eyewall replacement cycle.
        – The dynamic energy efficiency reached the maximum when the inner eyewall dissipated during the eyewall replacement cycle.
    - CEM
        – The dynamic energy efficiency did not change, significantly.

– The result suggests that, in ERC (CEM) case, diabatic heating is actively converted to kinetic energy in the outer (inner) eyewall region after forming the outer eyewall, relatively.

Sawyer-Eliassen Equation (傾度風)

$$\boxed{\frac{\partial}{\partial r}\left(A\frac{\partial r\psi}{r\partial r}+B\frac{\partial\psi}{\partial z}\right)+\frac{\partial}{\partial z}\left(B\frac{\partial r\psi}{r\partial r}+C\frac{\partial\psi}{\partial z}\right)=-\frac{2}{r}\frac{\partial v\dot{v}}{\partial z}+\frac{g}{C_pT_0}\frac{\partial Q}{\partial r},}$$

$$\rho A=\frac{g}{T_0}\left(\frac{\partial T}{\partial z}+\frac{R_dT}{C_pH}\right),$$

$$\rho B=-\frac{g}{T_0}\frac{\partial T}{\partial r},\quad \rho C=\left(f+\frac{2v}{r}\right)\left(f+\frac{\partial rv}{r\partial r}\right)$$

$$\boxed{R\equiv\frac{A}{C}H=\frac{N^2}{I^2}H}$$

局所ロスビー変形半径

$$N^2\equiv\rho A,\quad I^2\equiv\rho C$$

理想化実験

3 次元非静力学大気モデル :

CReSS (Cloud Resolving Storm Simulator)

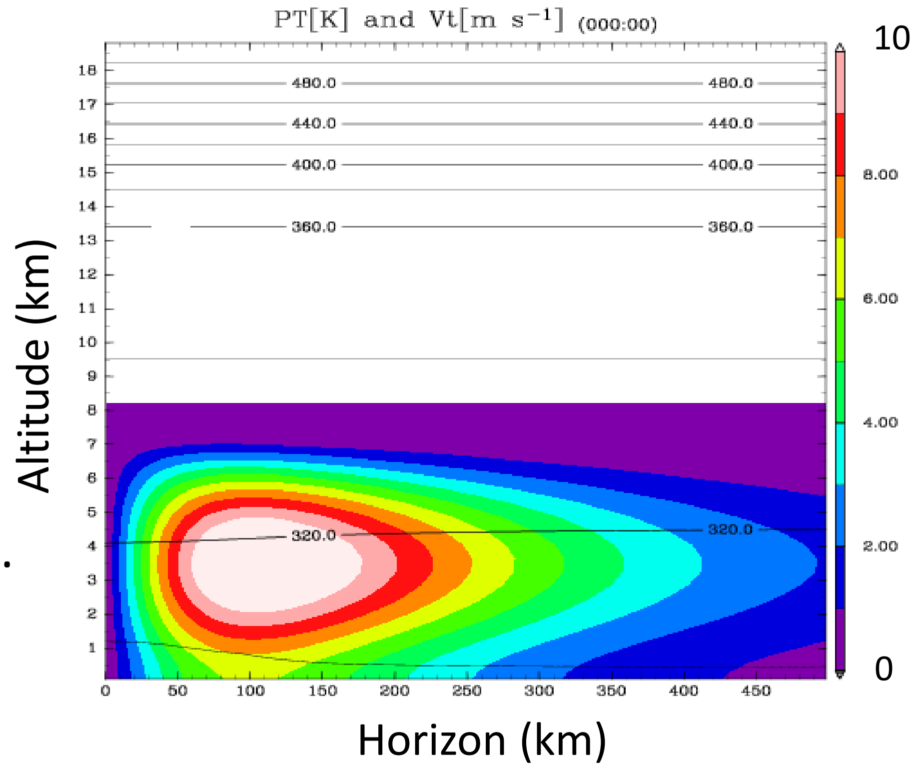
(Tsuboki and Sakakibara, 2007)

- 物理過程
  - 海面過程
    - バルク法パラメタリゼーション (Kondo, 1975)
  - 乱流過程
    - 乱流運動エネルギーを予報する 1.5 次のクロージャースキーム.
  - 雲物理過程
    - 雲水, 雨, 氷晶, 雪, 霰の混合比と氷晶, 雪, 霰の数濃度を予報するバルク法パラメタリゼーション.

理想化実験

コントロール実験 (CTL)

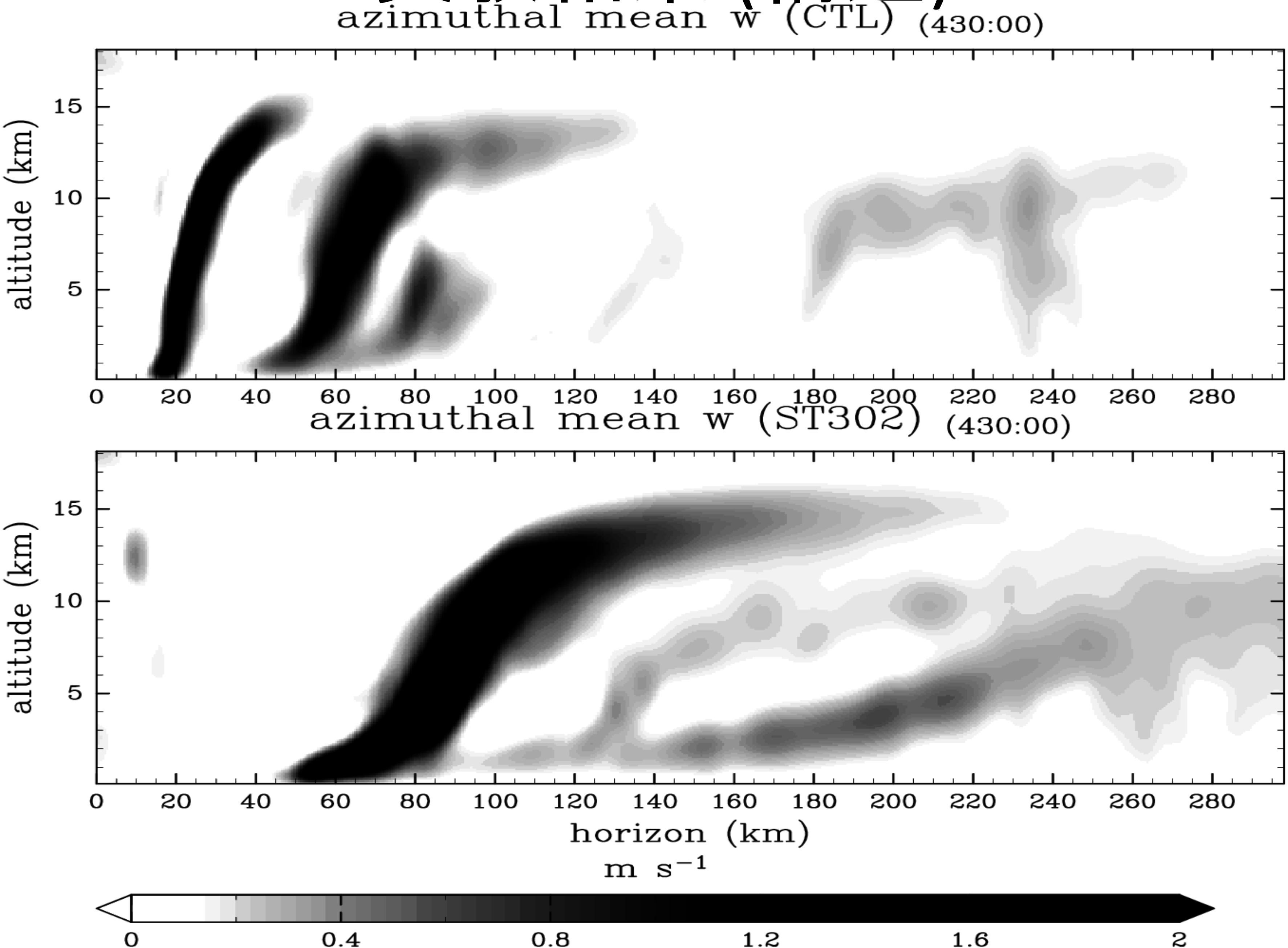
- 力学場 : 弱い低気圧性の軸対称渦.
  - Terwey and Montgomery (2008).
- 熱力学場 : 熱帯の高層気象観測値.
  - Jordan (1958).
- SST = 302 K (時間変化しない).
- 水平格子間隔 = 2 km.
- 鉛直格子 : 可変長格子 (45 層).
- 計算領域 : 2000 km x 2000 km x 23 km.
- f 面 (北緯 15゜).
- 積分時間 : 500 時間.



安定化実験 (ST302)

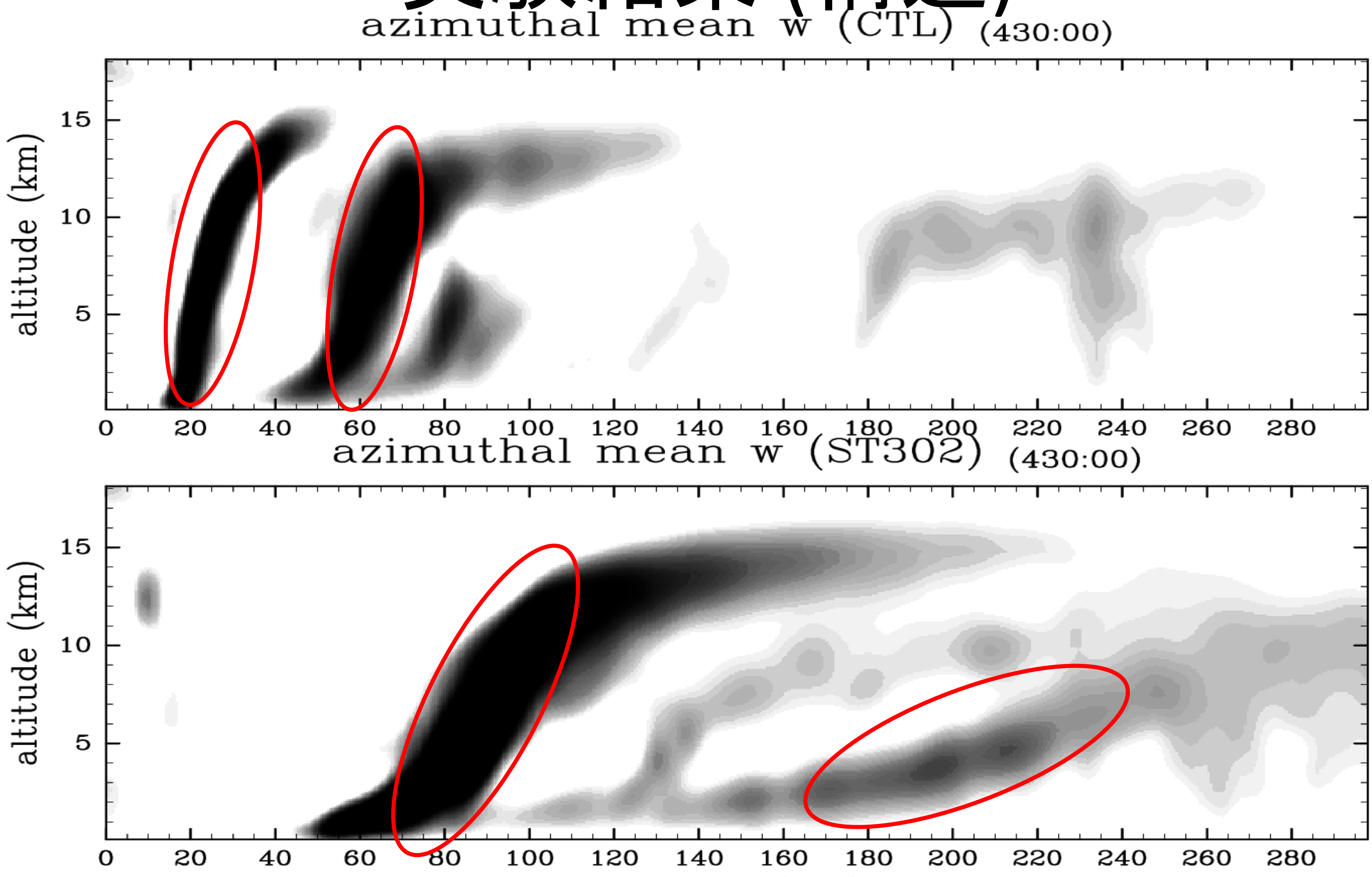
- 初期の熱力学場 : CTL + 3 K.
  - CTL より鉛直安定度が強い (～ 1.2 N).

実験結果 (構造)



azimuthal mean w (CTL) (430:00)
altitude (km)
15
10
5
0
20
40
60
80
100
120
140
160
180
200
220
240
260
280
azimuthal mean w (ST302) (430:00)
altitude (km)
15
10
5
0
20
40
60
80
100
120
140
160
180
200
220
240
260
280
horizon (km)
m s^{-1}
0
0.4
0.8
1.2
1.6
2

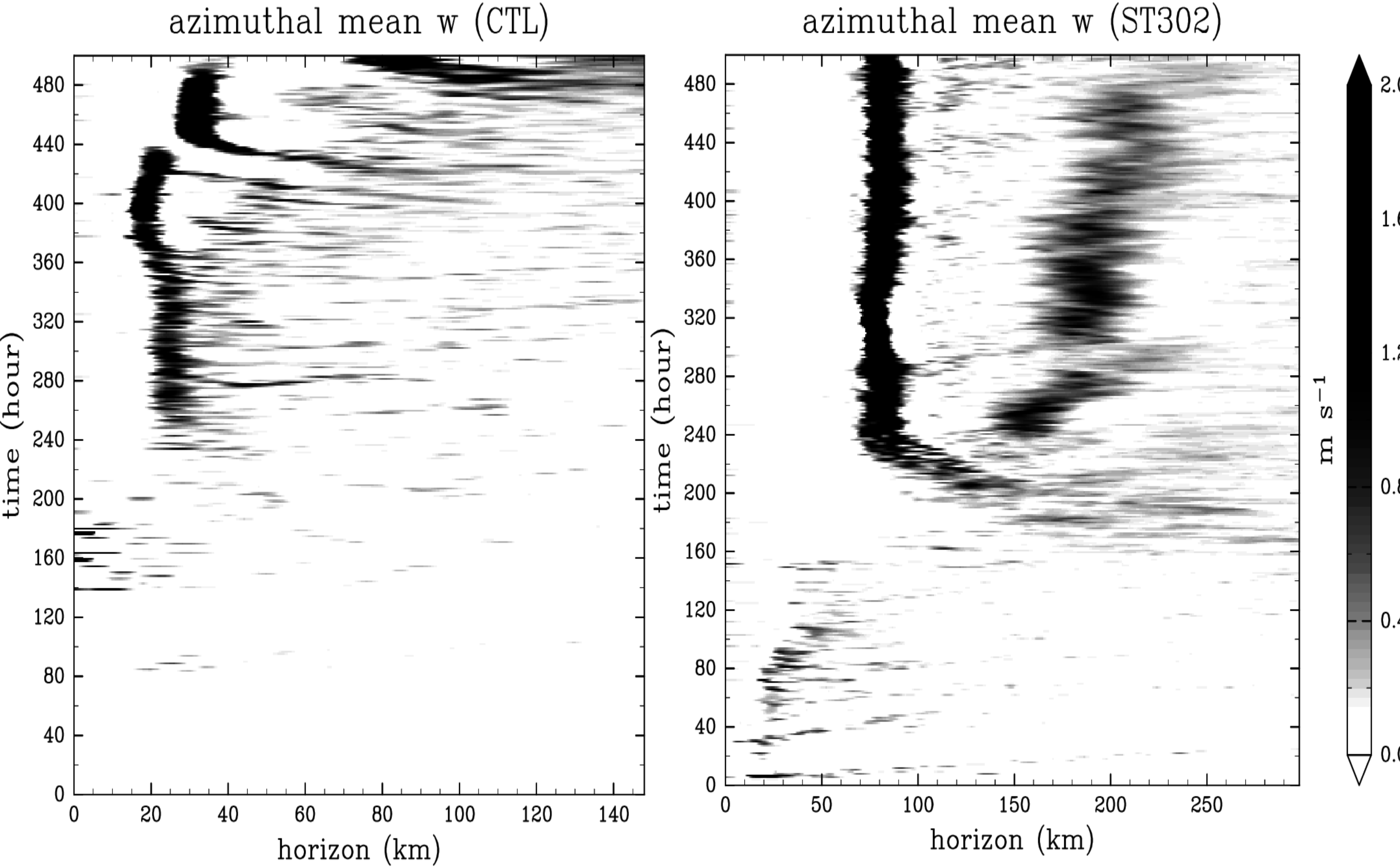
実験結果 (構造)



外側壁雲の特徴は Bolaven の構造と類似.

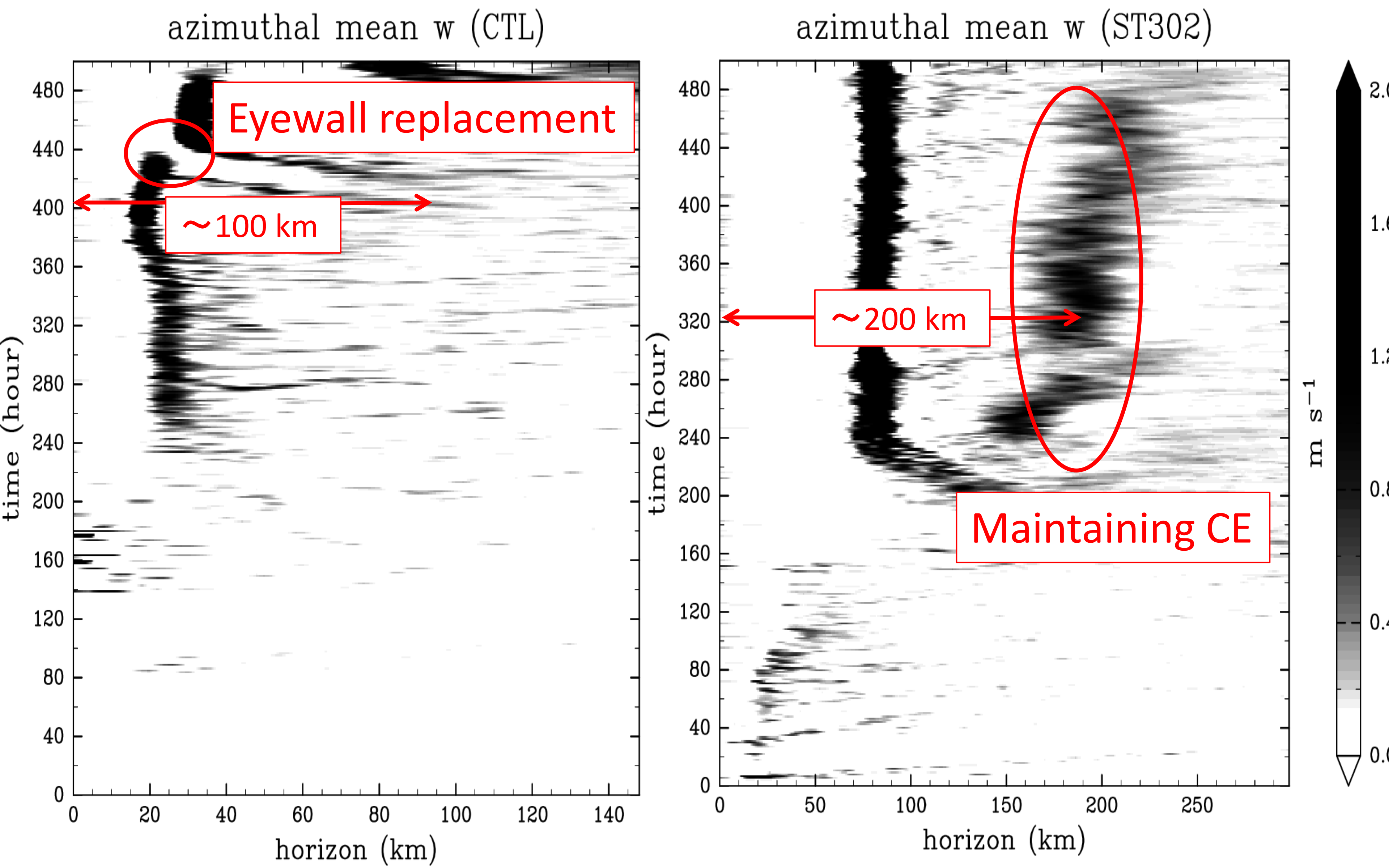
・外側に傾く. ・鉛直流が弱い.

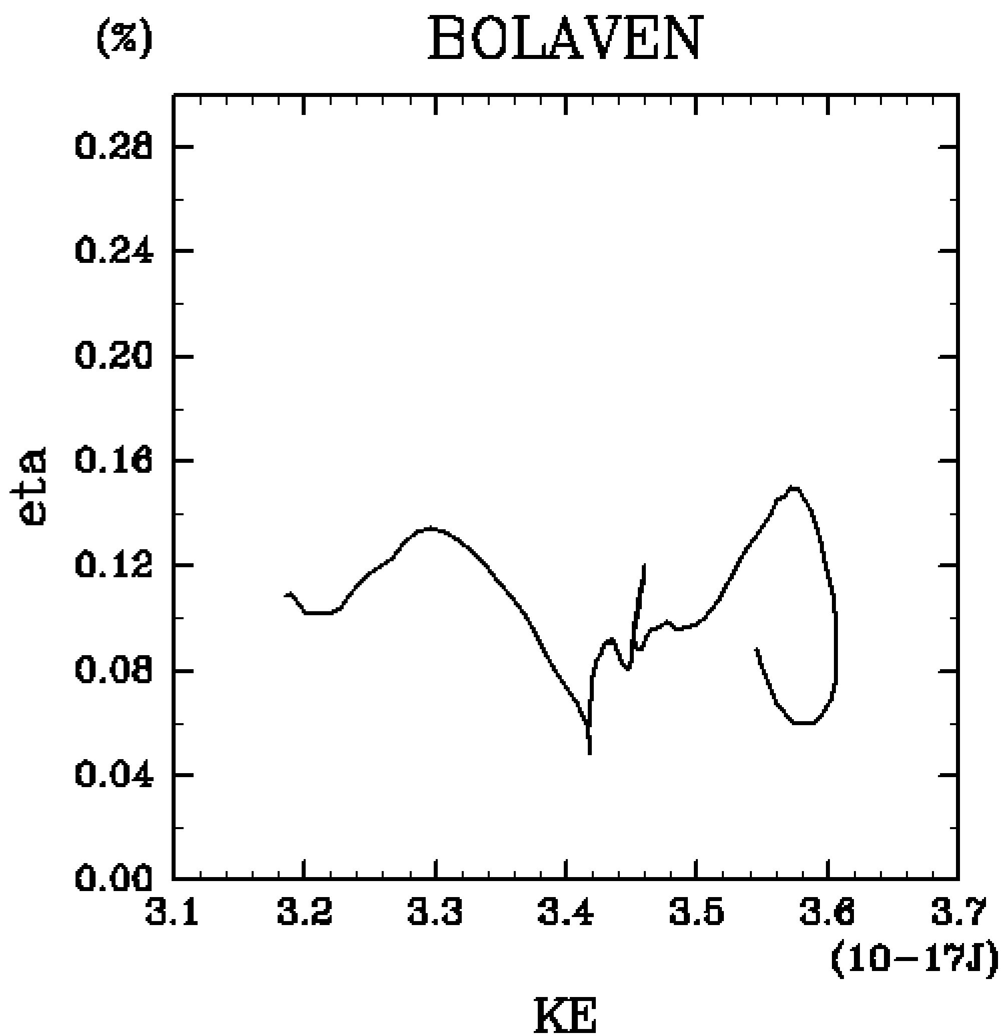
実験結果 (時間変化)



azimuthal mean w (CTL)
time (hour)
horizon (km)
azimuthal mean w (ST302)
time (hour)
horizon (km)
m s⁻¹

実験結果 (時間変化)


azimuthal mean w (CTL)
Eyewall replacement
～100 km
time (hour)
horizon (km)
azimuthal mean w (ST302)
～200 km
Maintaining CE
time (hour)
horizon (km)
m s⁻¹



BOLAVEN
(%)
eta
0.28
0.24
0.20
0.16
0.12
0.08
0.04
0.00
3.1
3.2
3.3
3.4
3.5
3.6
3.7
(10−17J)
KE