Eastward propagation mechanism and asymmetric horizontal structure of super cloud clusters in the equatorial region

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Contents:

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(2) Observations and numerical results of super cloud clusters (SCCs),

(3) Simple linear or nonlinear models (32 constant vertical layers; N, C_s=constant),

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(grid location same as NICAM, and environmental fields, such as zonal wind, N, C_s etc, are given by NICAM outputs),
＊Role of the equatorial wave on EP mechanism of SCCs,

(5) Expansion of our results.

(1) Our strategy

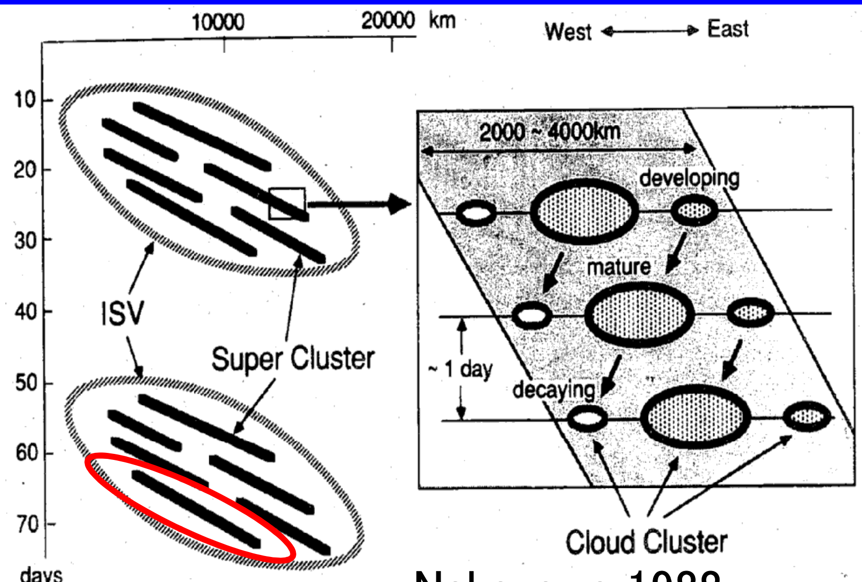
- To get coherent organized structures, "instability" is essential, while "neutral waves" are only needed to make response patterns around forcing. However, tropical (large-scale) researchers tend to consider that "waves" are primary and "instability (=convection)" is secondary. However, "CONVECTION" is PRIMARY and "equatorial waves" are secondary.

- Main doubts: "Is the coupling of instability and neutral waves, such as convectively coupled Kelvin waves, available ?"
  At least, NO in the linear theory. Then, what about nonlinear case?
  >> (I want to conclude) NO !

<u>Assumptions</u> (to get deep physical understanding as simply as possible)

- Positive-only wave CISK is included to describe the isolated features of diabatic heating due to precipitation.
- Large horizontal viscosity/diffusivity is included to attain preferred disturbances of a horizontal scale O(1,000 km). These large-scale disturbances are needed for the equatorial beta effect to work.

(2) Observations



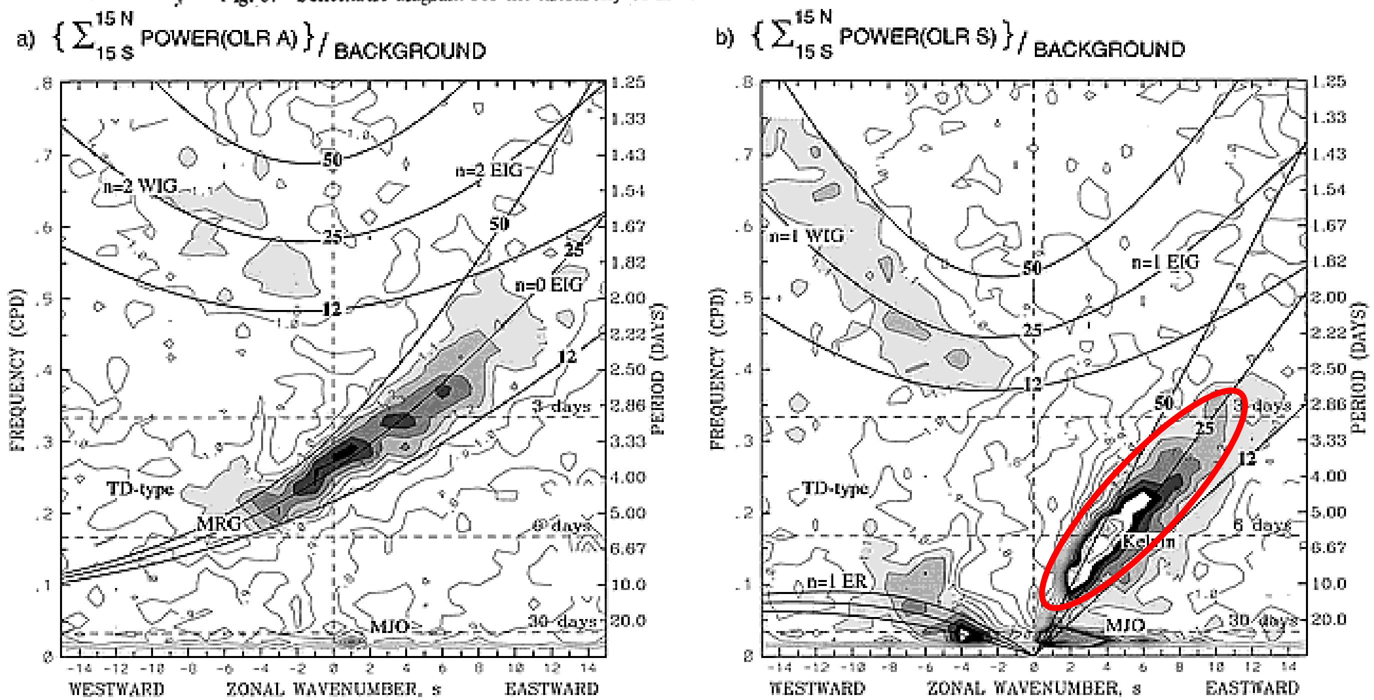
Nakazawa 1988

Fig. 5. Schematic diagram for the hierarchy of ISV.

Super cloud clusters (SCCs)

* horizontal scale: O (1,000 km)
* time scale: O (10 days)

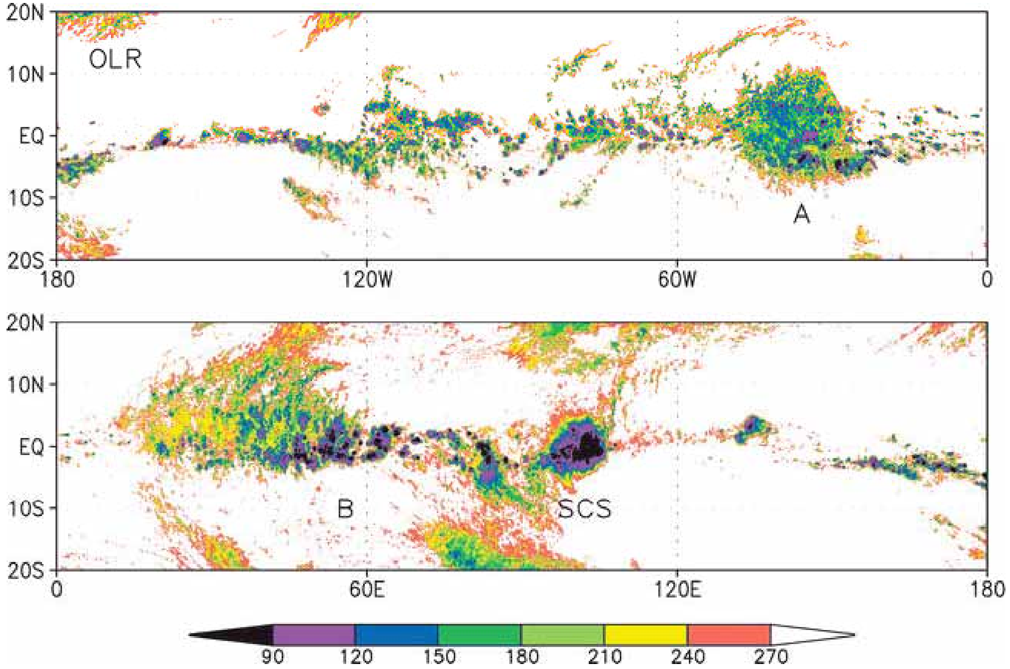
SCCs; fundamental components of MJO with horizontal scale of O (10,000 km), and MJO may be an envelope of SCC-ensembles



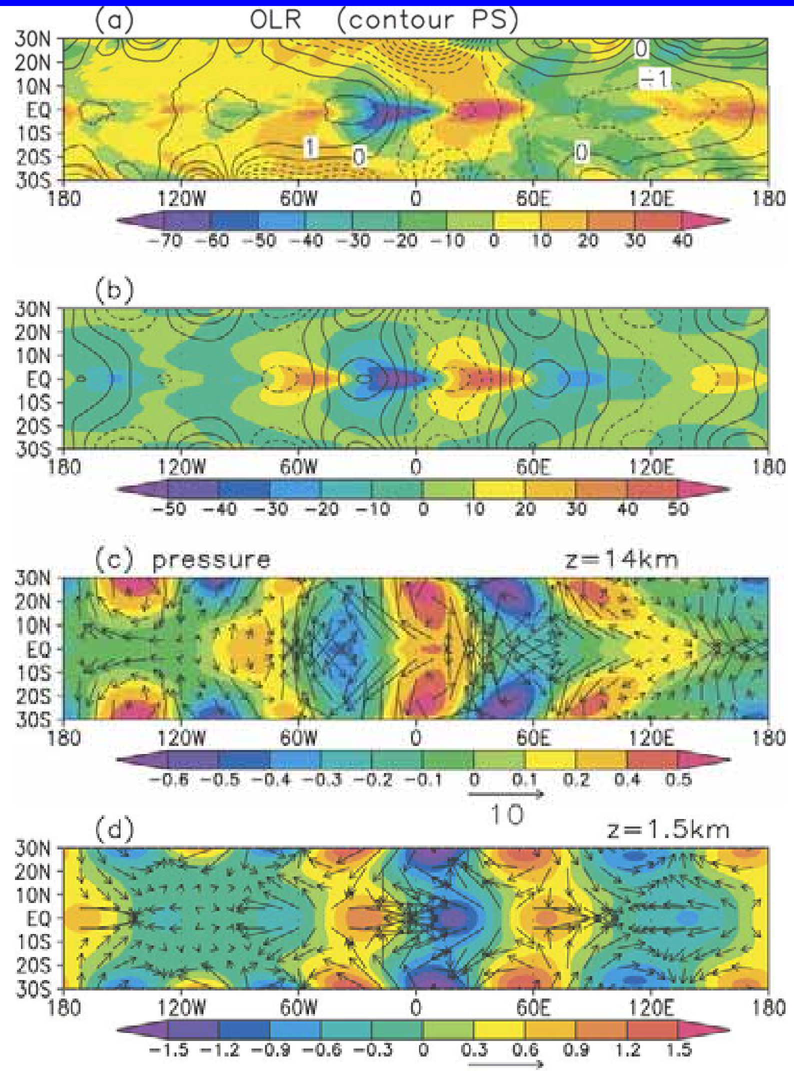
Wheeler・Kiladis 1999

(2)' Numerical results

NICAM aquaplanet simulation



Nasuno et al. 2007



Nasuno et al. 2008

In O(1000km) scale of SCCs,

- O(100km) mesoscale convective system (MCS),
- O(10km) scale cumulonimbus cloud

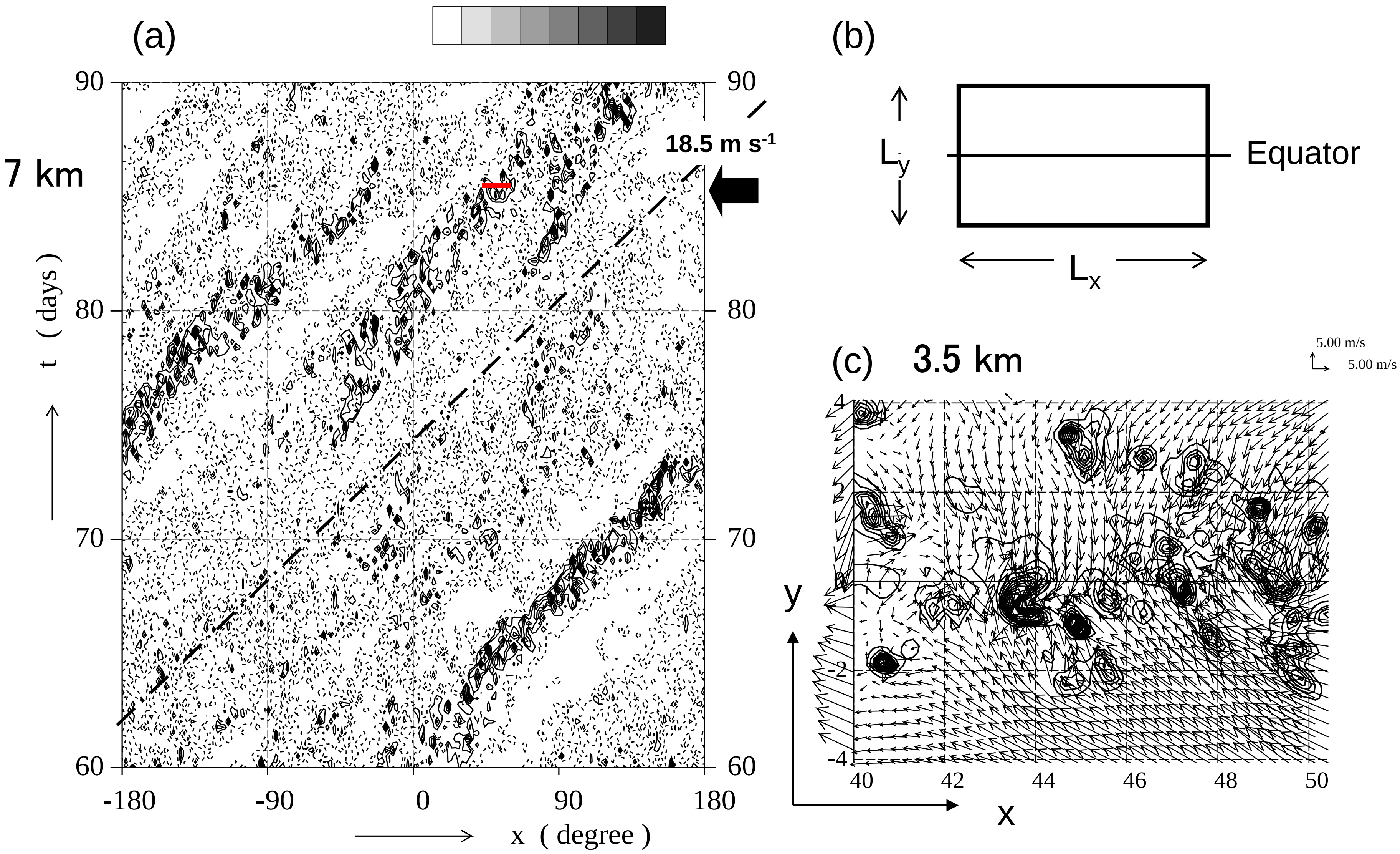
→ Multi-scale (hierarchical) structures of cloud systems

Structure of SCC mode

- a pair of off-equatorial gyre

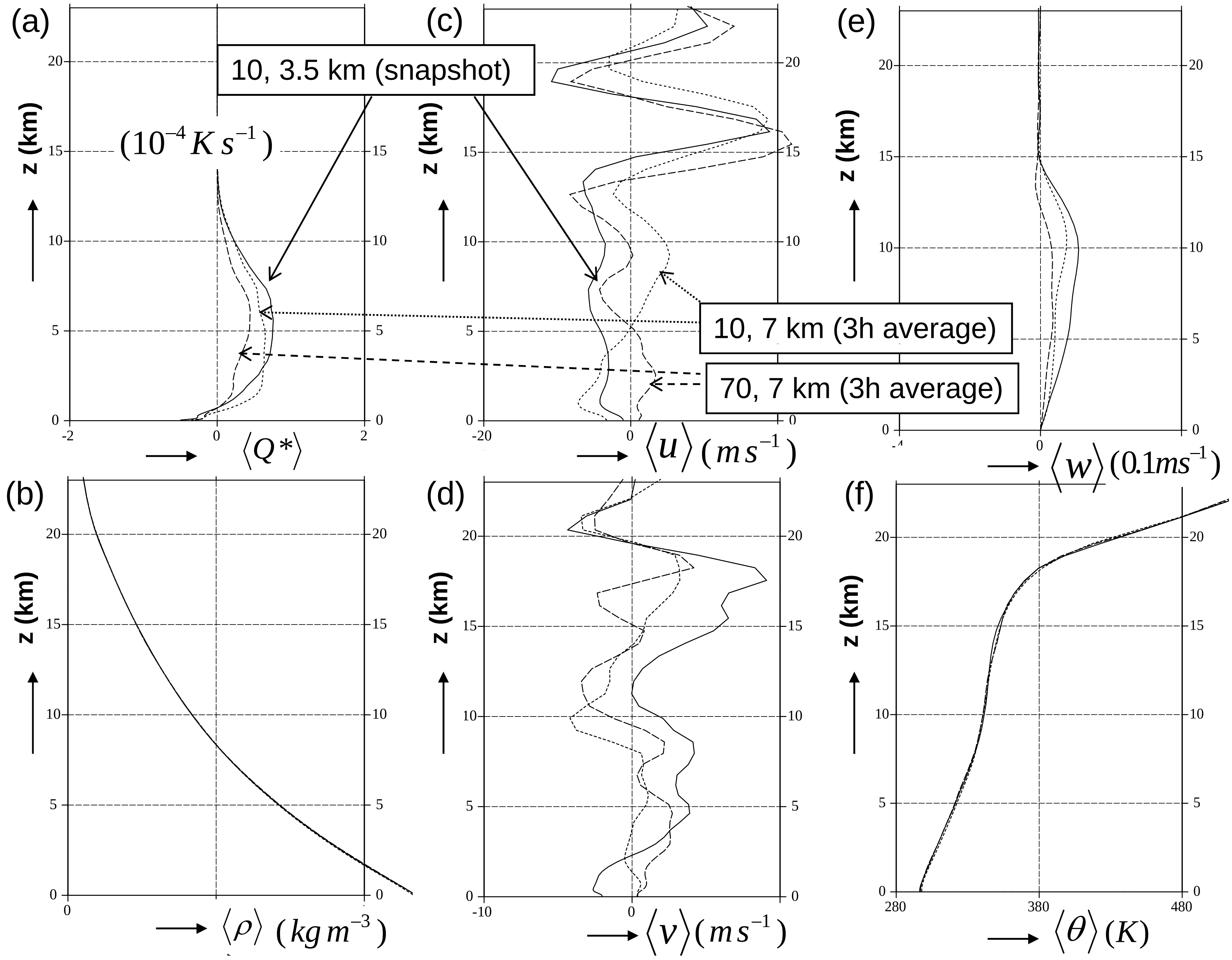
⇒ Gill pattern

NICAM aquaplanet simulation



< >: (L_x, L_y) averaging

( )‘: deviations



(a)
(b)
(c)
(d)
(e)
(f)
z (km)
$(10^{-4} K s^{-1})$
$\langle Q^* \rangle$
$\langle \rho \rangle \; (kg\, m^{-3})$
$\langle u \rangle \; (m s^{-1})$
$\langle v \rangle \; (m s^{-1})$
$\langle w \rangle \; (0.1 m s^{-1})$
$\langle \theta \rangle \; (K)$
10, 3.5 km (snapshot)
10, 7 km (3h average)
70, 7 km (3h average)

Numerical simulation with a dry model

$$U' = \langle\rho\rangle u', V' = \langle\rho\rangle v', W' = \langle\rho\rangle w', B' = \langle\rho\rangle g \frac{\theta'}{\langle\theta\rangle},$$

$$N^2 = \frac{g}{\langle\theta\rangle}\frac{\partial\langle\theta\rangle}{\partial z}, \quad C_s = \text{speed of sound wave}:$$

- Horizontal grid size: 1 degree (360×60)
- Vertical grid size : uniform or variable

$$\frac{\partial U'}{\partial t} = \varepsilon_1 NL(U') - \varepsilon_2 \langle u\rangle \frac{\partial U'}{\partial x} - \varepsilon_2 W' \frac{\partial\langle u\rangle}{\partial z} - \frac{\partial p'}{\partial x} + \beta y V' + \nu_H \Delta_H U' - \varepsilon_3 r U',$$

$$\frac{\partial V'}{\partial t} = \varepsilon_1 NL(V') - \varepsilon_2 \langle u\rangle \frac{\partial V'}{\partial x} - \frac{\partial p'}{\partial y} - \beta y U' + \nu_H \Delta_H V' - \varepsilon_3 r V',$$

$$0 = -\frac{\partial p'}{\partial z} - \frac{g}{C_s^2} p' + B',$$

$$\frac{\partial B'}{\partial t} = \varepsilon_1 NL(B') - \varepsilon_2 \langle u\rangle \frac{\partial B'}{\partial x} - W' N^2 + Q + \nu_H \Delta_H B' - \varepsilon_3 r B',$$

$$\frac{\partial U'}{\partial x} + \frac{\partial V'}{\partial y} + \frac{\partial W'}{\partial z} = 0.$$

Large viscosity

Large diffusivity

Diabatic heating Q :

* Positive-only wave-CISK

$$Q = \begin{cases} w_B \cdot F(z) & \text{for } w_B > 0 \\ 0 & \text{for } w_B \leqq 0 \end{cases}$$

Cloud base Height ≃1km

* Parameters ε : 0 / 1
  - ε_1 : Nonlinear (NL) / Linear
  - ε_2 : Zonal wind / No zonal wind
  - ε_3 : Rayleigh damping / No damping
  - N^2 : Variable / Uniform
  - ν_H : Large values to attain O(1,000km)-scale disturbances

(3) Simple linear model (32 layers; N, C_s=constant)

$$N^2 = \frac{g}{\langle\theta\rangle}\frac{\partial\langle\theta\rangle}{\partial z},\ C_s = \textit{speed of sound wave}:$$

$$\frac{\partial U'}{\partial t} = -\frac{\partial p'}{\partial x} + \beta y V' + \nu_H \Delta_H U',\ \frac{\partial V'}{\partial t} = -\frac{\partial p'}{\partial y} - \beta y U' + \nu_H \Delta_H V',$$

$$0 = -\frac{\partial p'}{\partial z} - \frac{g}{C_s^2} p' + B',\quad \frac{\partial B'}{\partial t} = -W' N^2 + Q + \nu_H \Delta_H B',$$

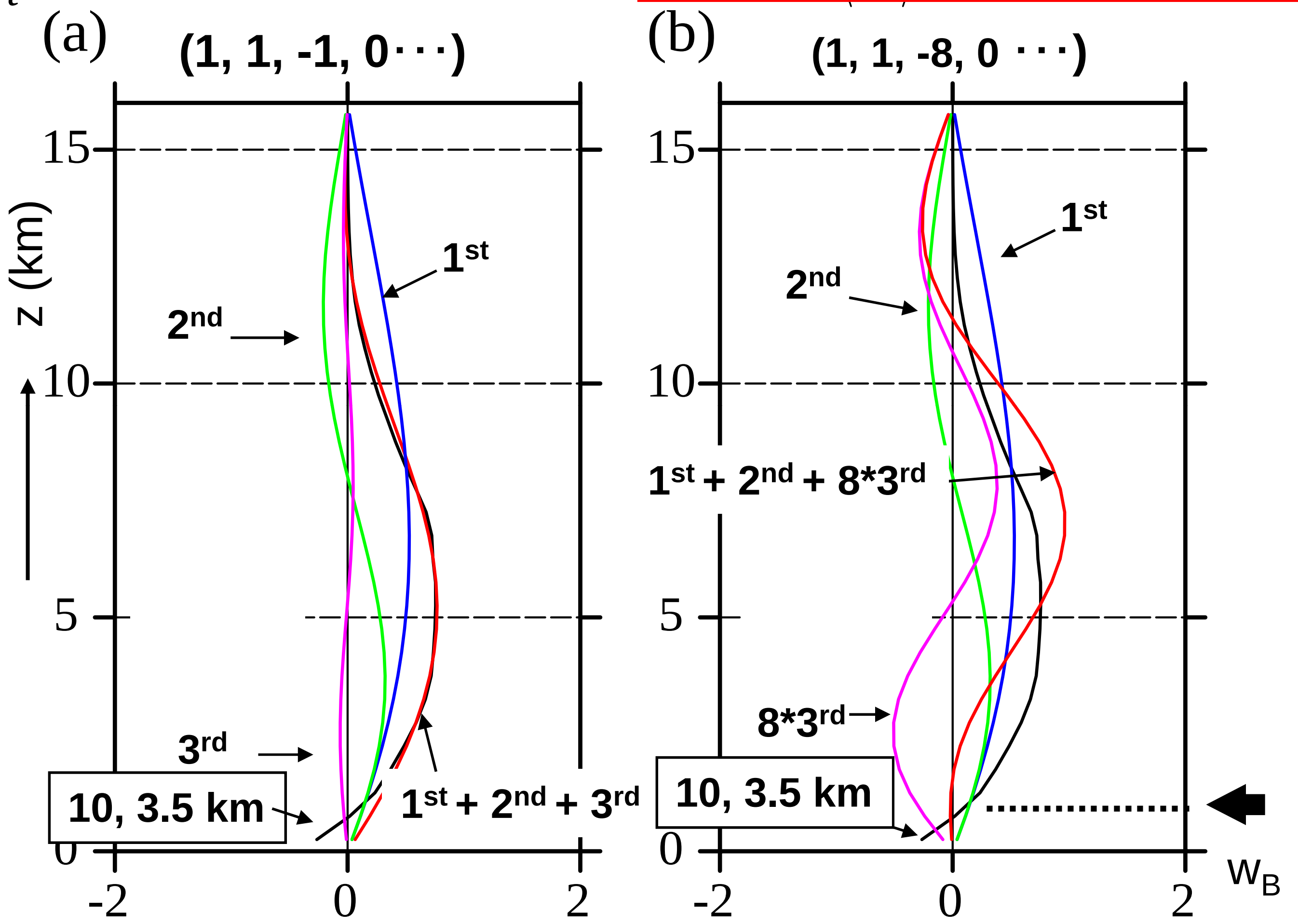
$$\frac{\partial U'}{\partial x} + \frac{\partial V'}{\partial y} + \frac{\partial W'}{\partial z} = 0.$$

- Δz = 500m, 32 layers, N = $10^{-2}\ s^{-1}$, C_s = 300 m s^{-1}
- vertical-mode expansion

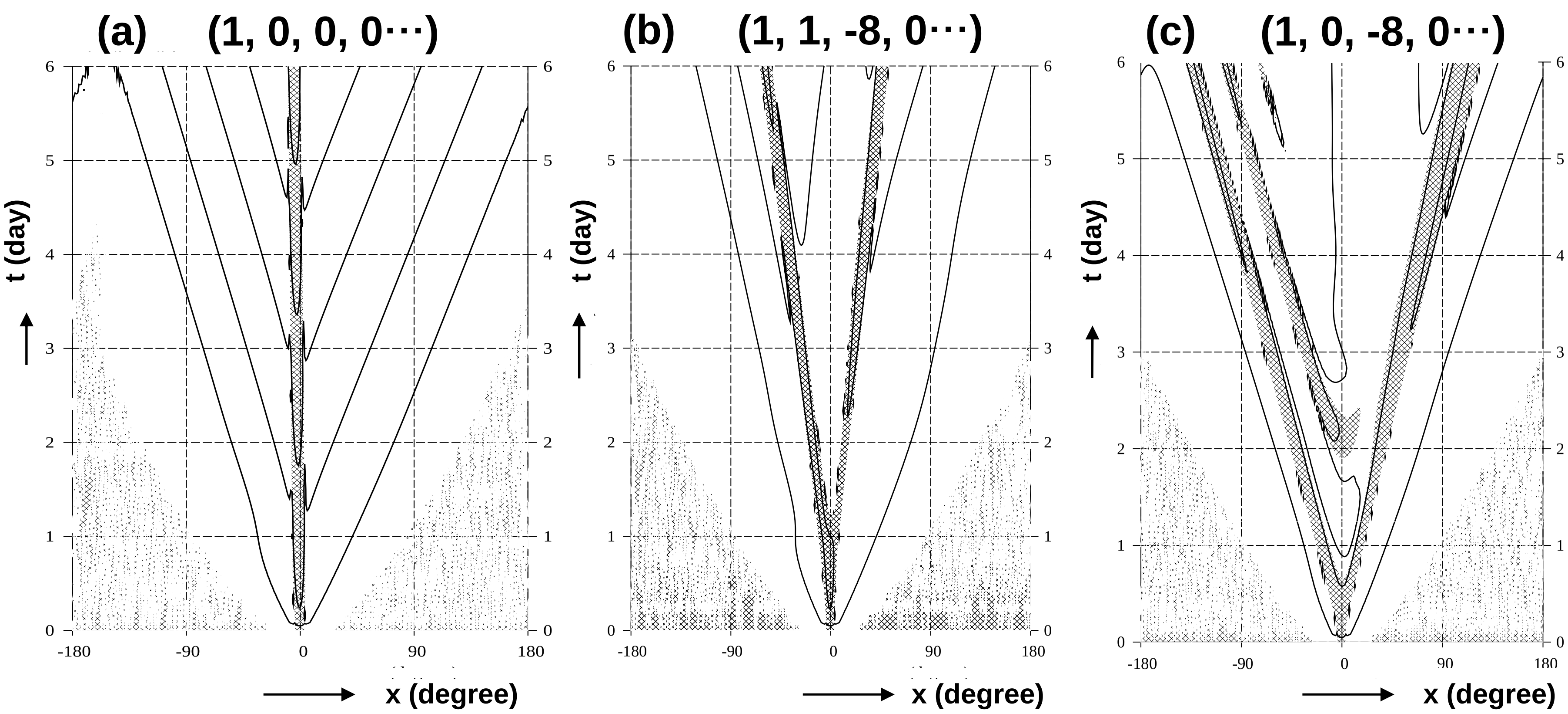
$$\frac{d^2 h_n(z)}{dz^2} + \frac{g}{\langle C_s^2 \rangle}\frac{d\,h_n(z)}{dz} + n\pi h_n(z) = 0$$

- (Q, W', B') vs. (U', V', p')
- Vertical-mode expansion of Q = 0.559 $h_1(z)$ + 0.282 $h_2(z)$ − 0.053 $h_3(z)$ − 0.040 $h_4(z)$ ⋯ as (1, 1, −1, −1⋯)
- Q can be nearly expressed by three vertical modes.

→ (1,1, −8, 0⋯) for comparison



Linear case （ $\log_{10}|w_{3.5km}|$ ）



A slowly WP unstable D.

A pair of WP and EP unstable Ds.

A pair of WP and EP unstable Ds.

Propagation property:

(0,1,−8) is essential

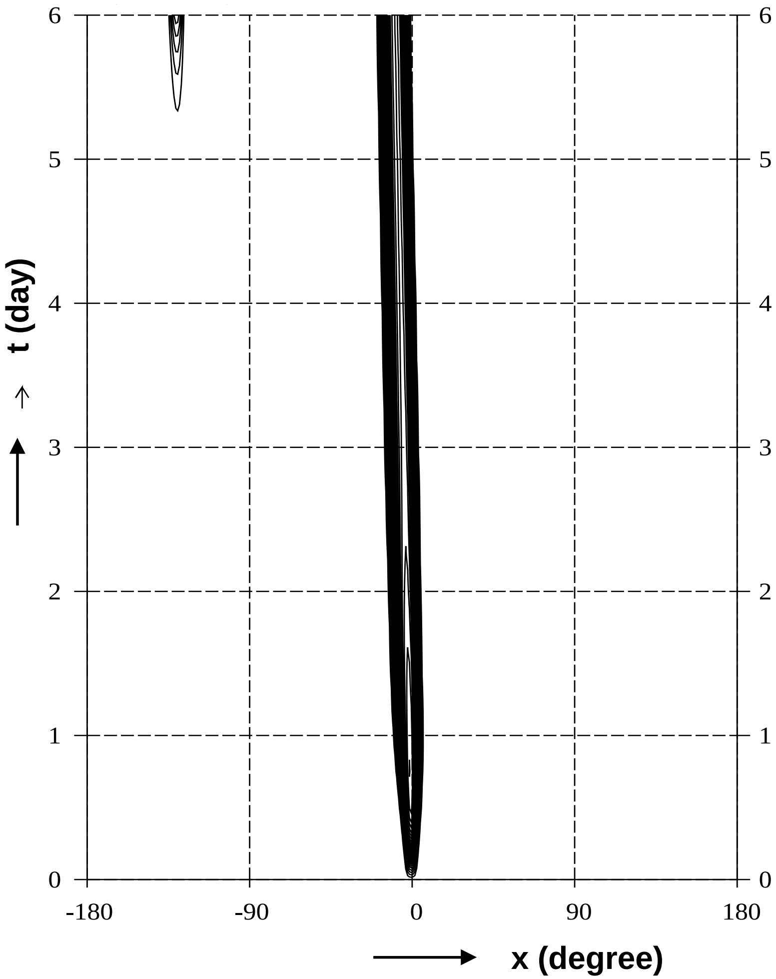
(0,1,0) is NOT essential

Two propagation properties of growing disturbances

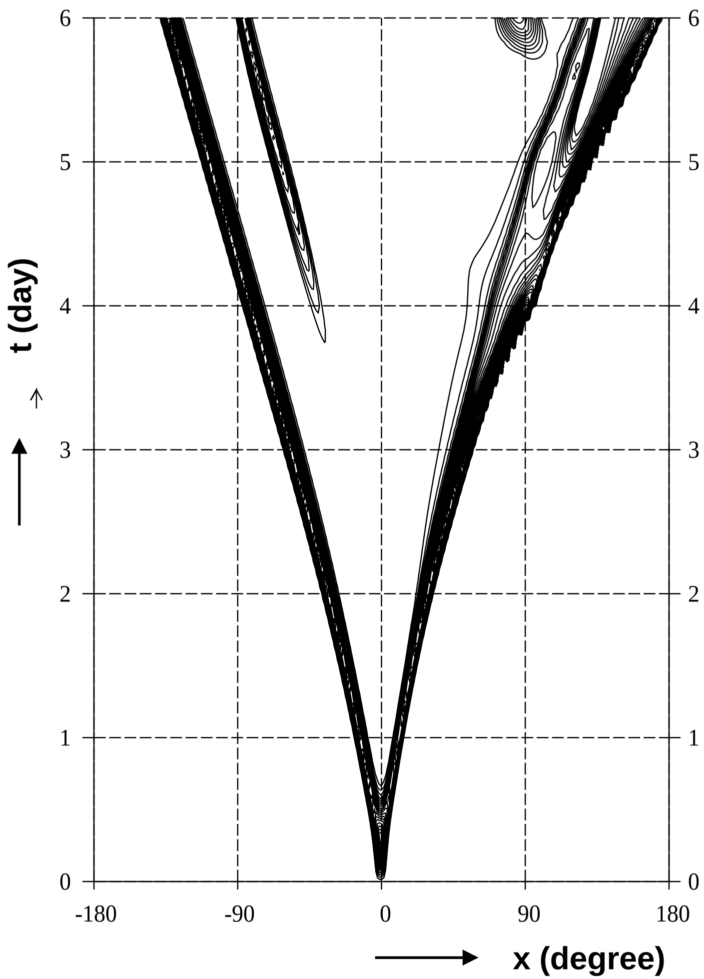
< A slowly WP D. and oppositely−propagating (WP and EP) Ds.>

(3)' Simple nonlinear model (32 layers; N, C_s=constant) ($w_{3.5km}$)

(a) (1, 0, 0, 0···)



(b) (1, 1, -8, 0···)

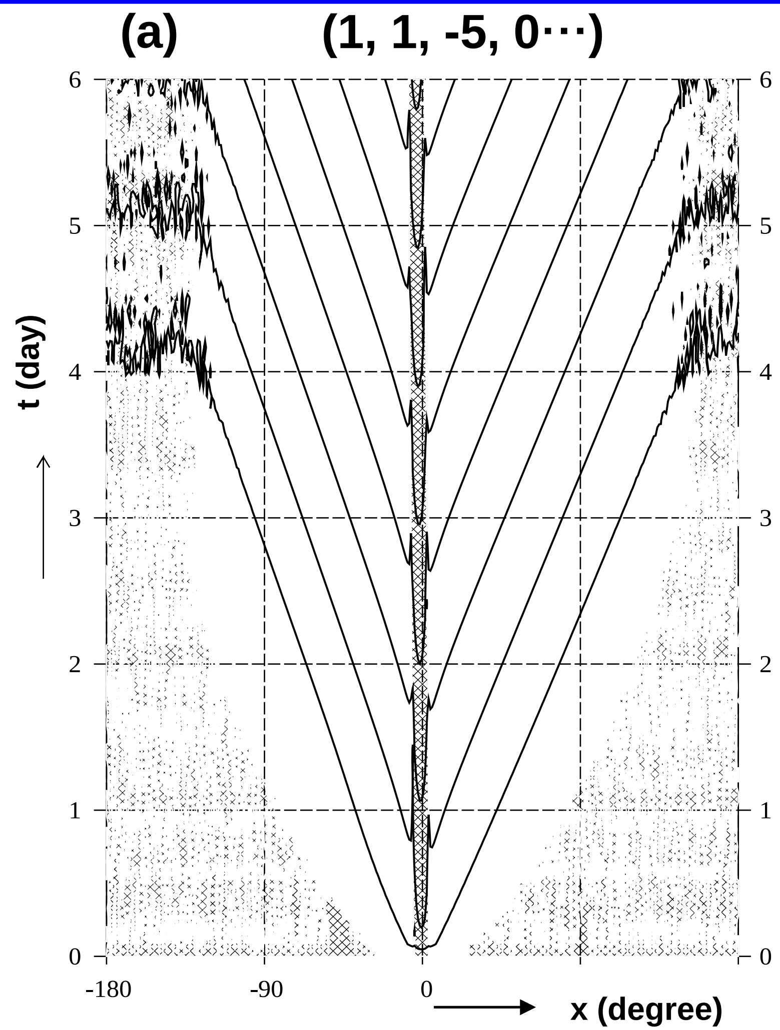


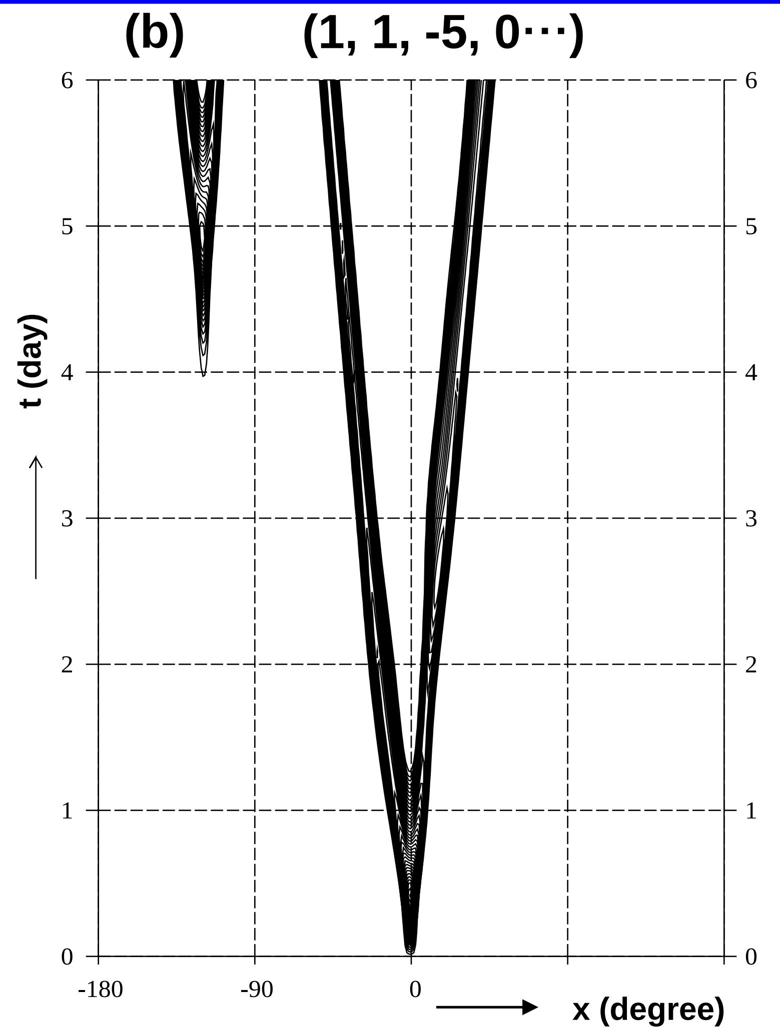
∗ Comparison of linear ($\varepsilon_1 = 0$) and nonlinear ($\varepsilon_1 = 1$) cases:

- These two cases agree with those in the linear cases about the propagation.
- Amplitude saturation and additional developing disturbances are found

← Not found in the linear cases

Linear and nonlinear cases of (1, 1, −5, 0・・・)





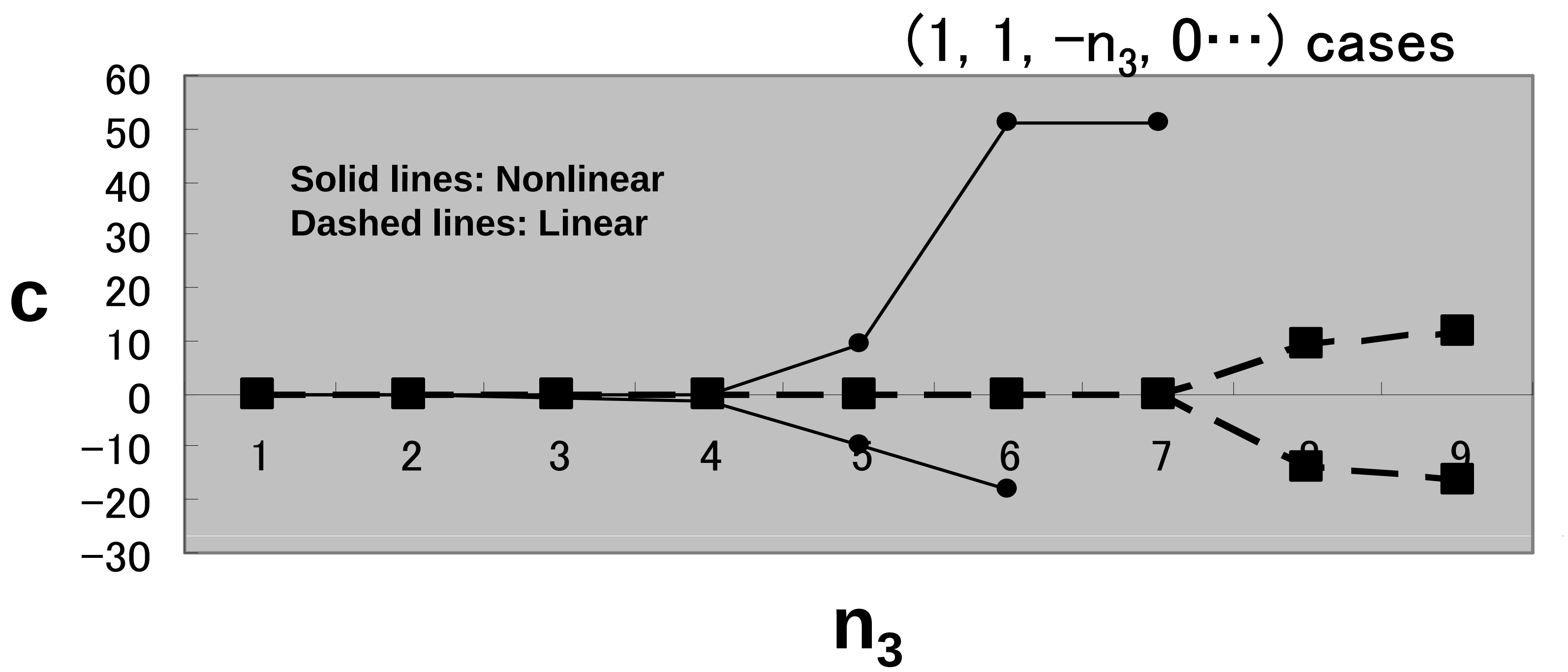
- Linear : a slowly WP D.
- $\log_{10}|w|$

- Nonlinear : a pair of WP and EP Ds.
- w

Propagation property may change between linear and nonlinear cases.

Dependence of propagation property on n_3

Among $(n_1, n_2, -n_3, 0\cdots)$, the values of "$-n_3$" are essential to determine the propagation property of disturbances.



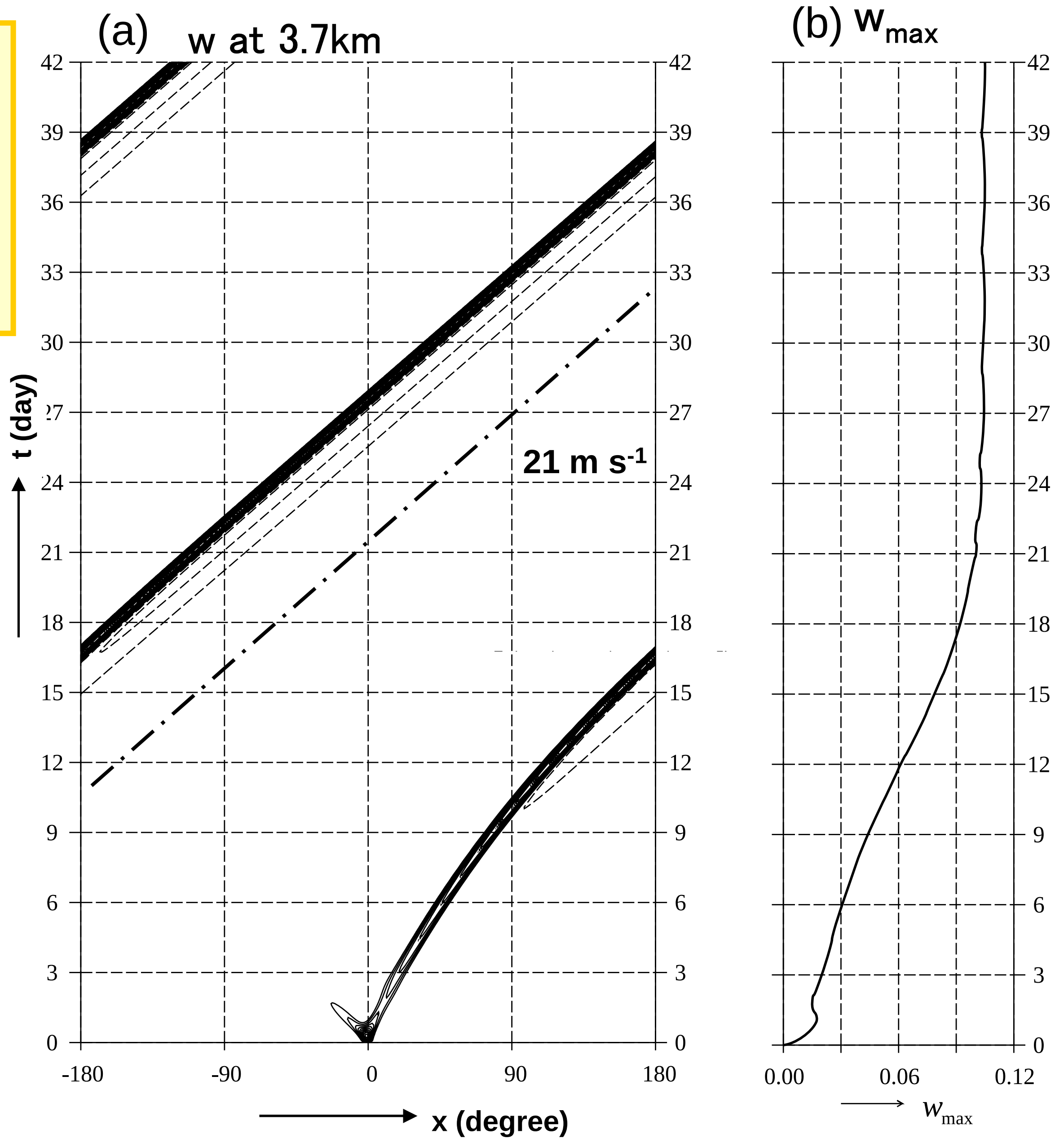
Threshold values between non-propagation and propagation are different between linear and nonlinear cases. The value in the linear case is larger.
→ Propagating disturbances are likely to occur in the nonlinear cases.

(4) Full nonlinear model

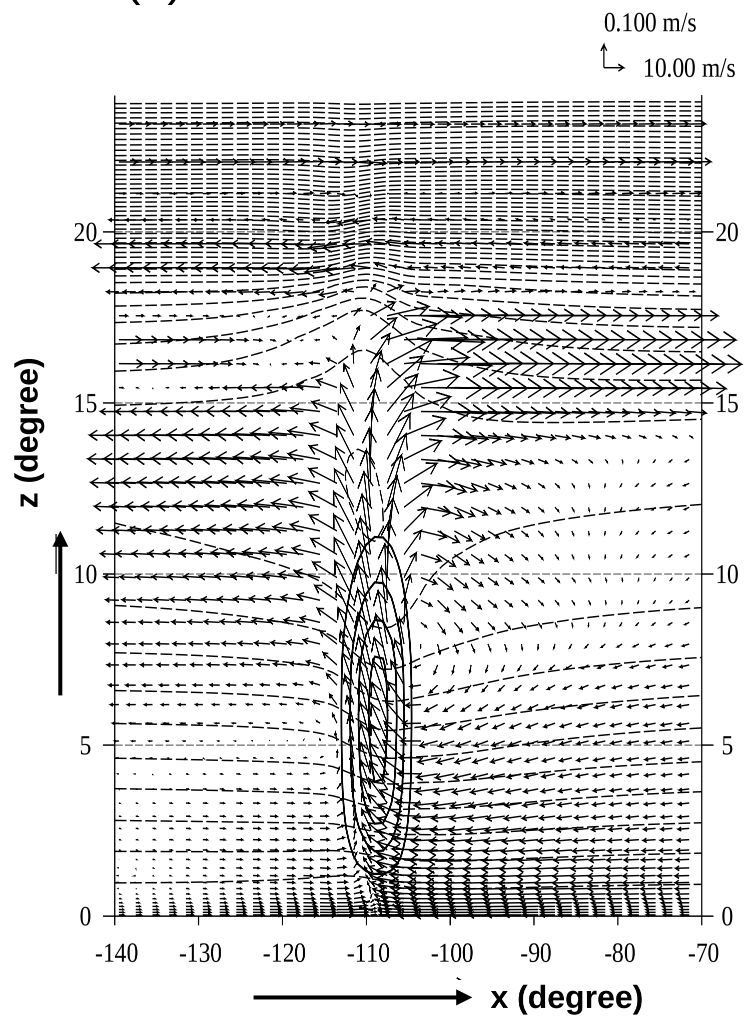
(grid location = NICAM, and NICAM outputs are given as environmental fields, i.e., N, Cs etc.)

- Vertical grid:
  54 layers, variable
- Environmental fields obtained by NICAM
- $\varepsilon_1 = \varepsilon_2 = \varepsilon_3 = 1$

- Propagation speed and amplitudes are synchronized, and attain constant values
- Propagation speed ～21ms^{-1}
  NICAM ～18.5ms^{-1}

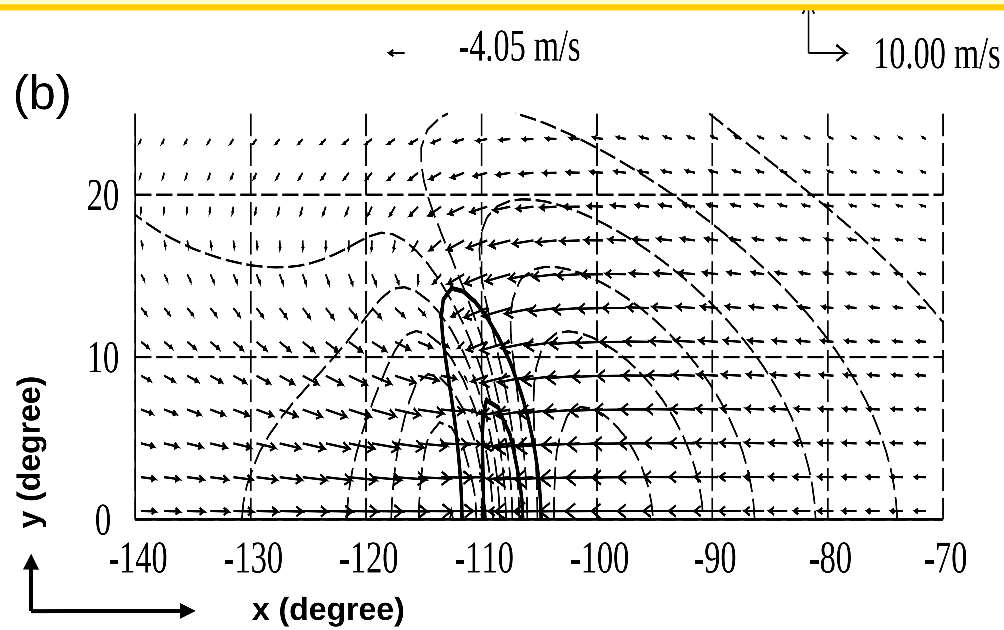


Structures of disturbances



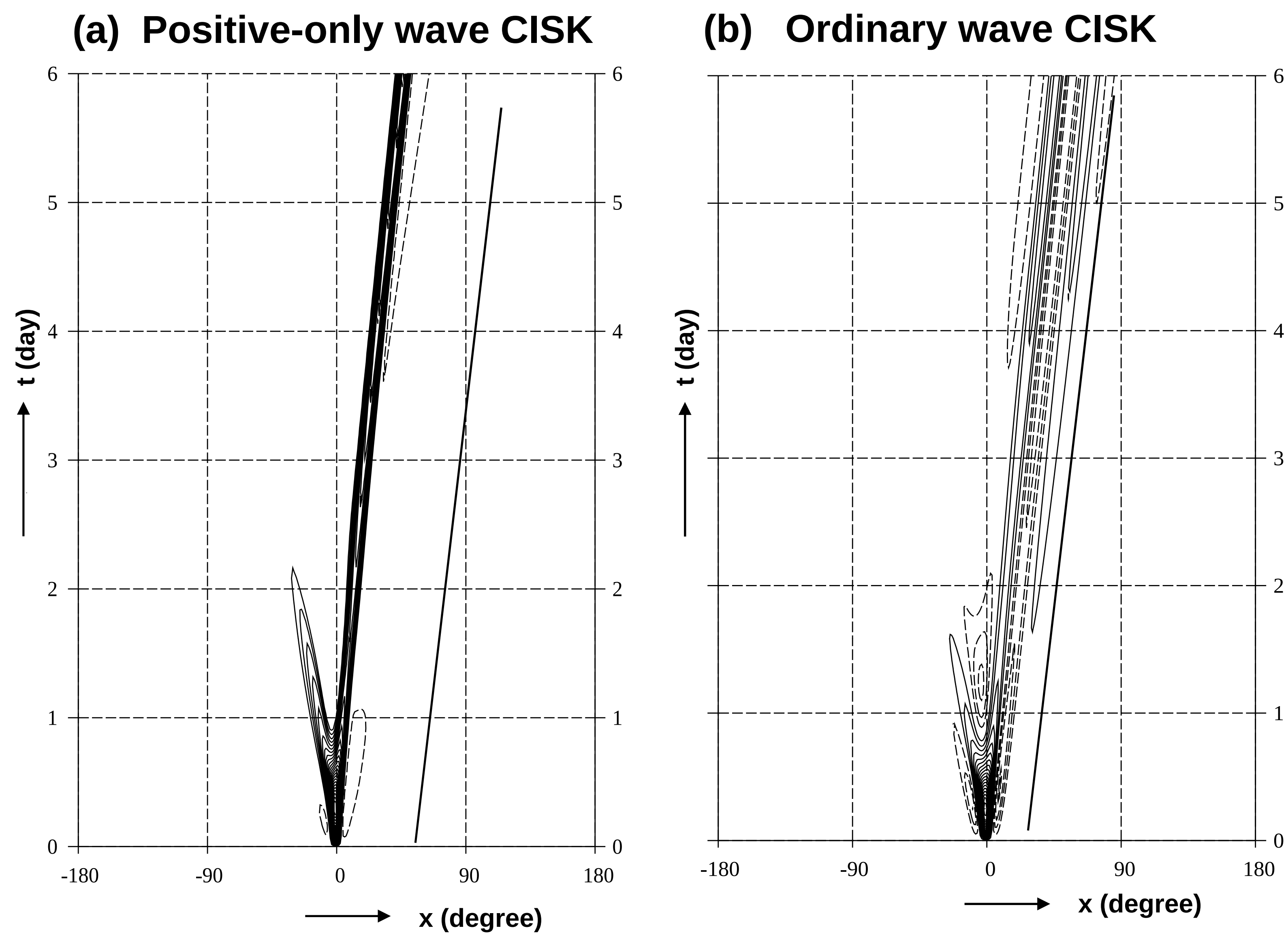
- Vertical structure
  - Vertically erected structure
  - The tops of upward motions are different on the eastern and western sides of heating

- Horizontal structure
  - East of heating ; Kelvin wave–like features
    West of heating ; Rossby wave–like features
    off–equatorial vortical core
  - Gill response pattern



- Slanted structures are observed frequently. → preconditioning.
- Some techniques, such as time–lag between w and Q are needed.

Do equatorial waves play some roles on EP SCCs？

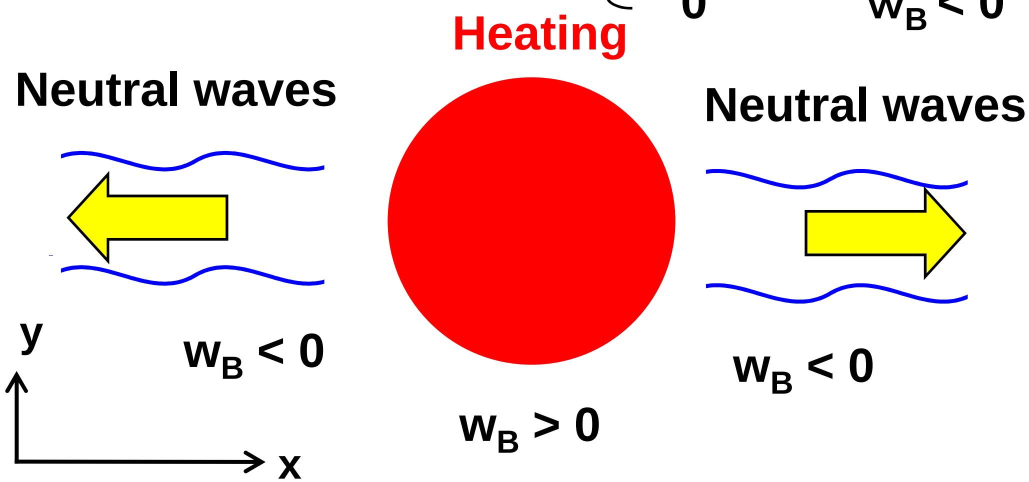


Solid lines： upward motion, dashed lines： downward motion

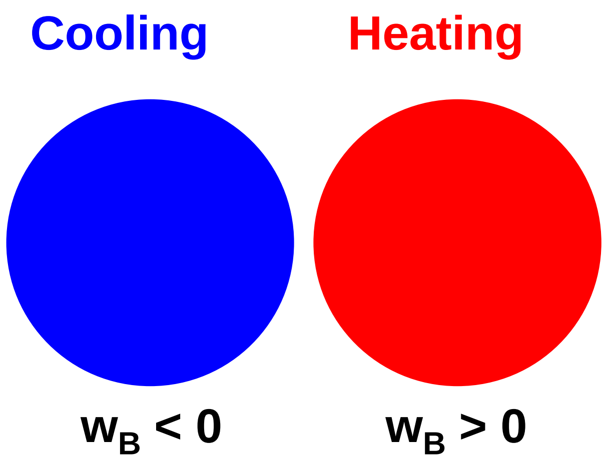
Propagation property between positive−only and ordinary wave CISK is same.

No role of equatorial waves for EP mechanism

- Localized heating $Q = \begin{cases} w_B F(z) & w_B > 0 \\ 0 & w_B < 0 \end{cases}$



- Heating/cooling $Q = w_B F(z)$



Localized heating produces neutral waves and induces the response patterns outside of heating

In ordinary wave CISK, neutral waves are NOT excited.

>> Equatorial waves (= neutral waves) play NO ROLE on EP mechanism of SCCs.

>> Convection is PRIMARY, and neutral waves are secondary.

>> Convection always excites neutral waves outside it, while neutral waves sometimes induce convection.

Present summary

〈Assumptions used in this study〉

- Heating : positive-only wave CISK
- Large values of horizontal viscosity/diffusion

(1) In the linear cases, the propagation property of growing disturbances is determined by the sign of baroclinic modes of heating at the cloud base. Due to positive-only wave CISK and equatorial beta effect, preferred EP disturbances were attained.

(2) Using the positive-only wave CISK, preferred EP disturbances have asymmetric horizontal structure: Kelvin wave-like features on the eastern side of heating and Rossby wave-like ones on the western side, i.e., Gill response pattern.

* Using positive-only wave CISK, neutral equatorial waves are excited by the localized heating and the response pattern is formed around the heating.

(3) For the EP mechanism of disturbance induced by positive-only wave CISK, neutral equatorial waves play no role.

* EP mechanism produced by positive-only wave CISK is completely different from the propagation property in the neutral waves related to the dispersion relation.