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Momentum flux of Convective Gravity Waves: Spatiotemporal Variations at Source-level and Dissipation in the Stratosphere

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Introduction

- Parameterizations of convectively induced gravity waves (**CGWs**) have been developed based on analytical formulation of gravity wave momentum flux at the source-level (Beres et al. 2004; Song and Chun 2005).
- Song and Chun (2005) showed that momentum flux of CGWs at the source-level (cloud-top) (**CTMF**) is determined not only from convective source but also from wave-filtering and resonance factor (**WFRF**).
- Choi and Chun (2011) updated and validated Song and Chun (2005) by comparing CTMF spectra with those from 3-D mesoscale simulation**.**
- Implementation of this parameterization to global climate model (GCM) reproduced quasi-biennial oscillation (**QBO**) (Kim et al. 2013) and reduced excessively strong polar night jet in the southern hemisphere (Choi and Chun 2013).
- In this study, we focus on understanding CTMF spectrum and its variations through the long-term off-line calculation of **updated version of Choi and Chun (2011)**. Also we show the connection between CTMF spectrum and the gravity-wave drag (**GWDC**) in the stratosphere.

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Objectives

1. Parameterization of physically, mathematically consistent source-level gravity wave momentum flux (CTMF) spectrum
2. Off-line calculation of CTMF with realistic background

1. To understand **which factors determine** CTMF spectrum
2. To understand **variabilities of CTMF** itself
3. To know how the source spectrum (CTMF) and background condition contribute to the **GWDC** in the stratosphere

Data and methodology

Data	**CFSR** **(NCEP Climate Forecast System Reanalysis)**
Period	1979.01-2010.12 (**2002.01-2010.12**)
Horizontal resolution	$0.5^{\circ} \times 0.5^{\circ}$ (zonal wind, meridional wind, temperature, geopotential height, cloud top pressure, cloud bottom p ressure) $\mathbf{1^{\circ} \times 1^{\circ}}$ (deep convective heating rate)
Temporal resolution	**1 hour** (6-hourly analysis, 1-hourly forecast)
Vertical resolution	37 pressure levels (1000 hPa ~ 1 hPa)

Data and methodology

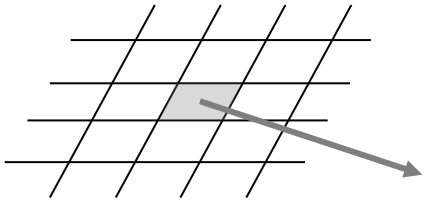
Parameterization: CTMF (cloud-top GWMF)

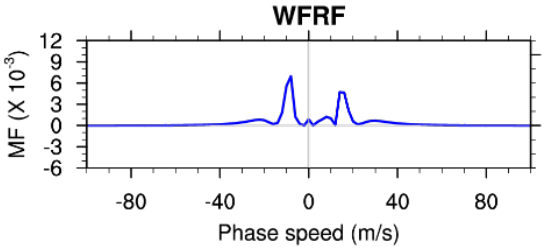
Choi and Chun (2011) + nonlinear forcing effect

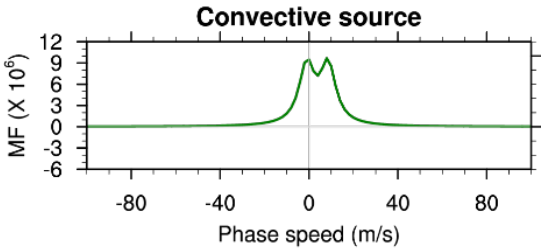
$$CTMF(c,\varphi) = \mathrm{sgn}[c - U_{ct}(\varphi)]\rho_{ct}\frac{2(2\pi)^3}{A_h L_t}\left(\frac{g}{c_p T_{ct} N_q^2}\right)^2 \times \frac{N_{ct}|X|^2}{|c - U_{ct}(\varphi)|}\Theta(c,\varphi) \times F(\mu)$$

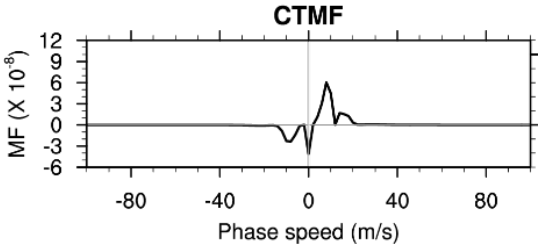
Wave-filtering and resonance factor (WFRF)

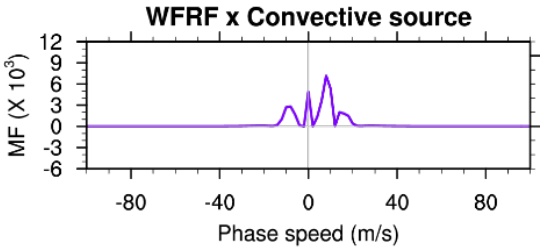
Convective source











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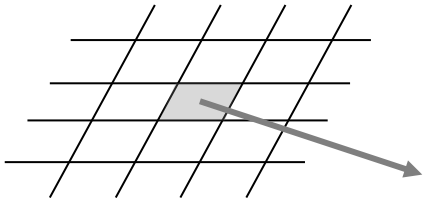
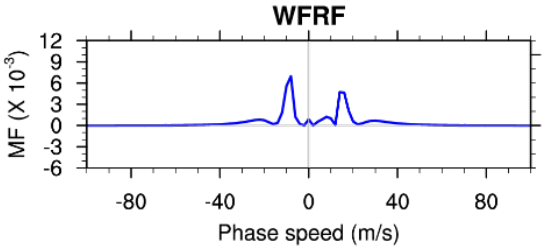
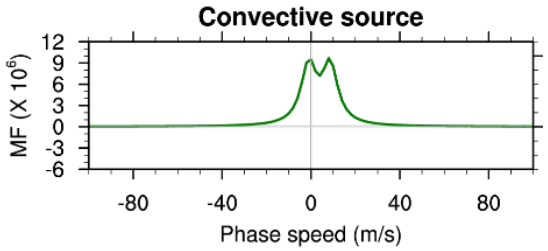
Wave-filtering and resonance factor (WFRF)

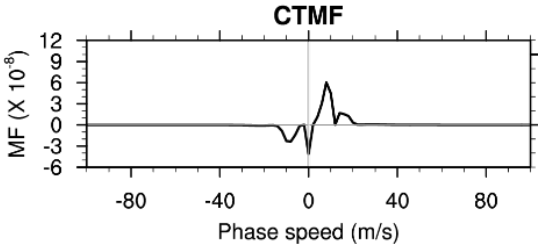
Convective source

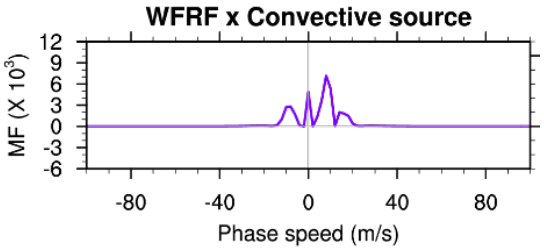
Determine spectral shape of CTMF











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Convective source

Nonlinear forcing effect

(Chun et al. 2008)

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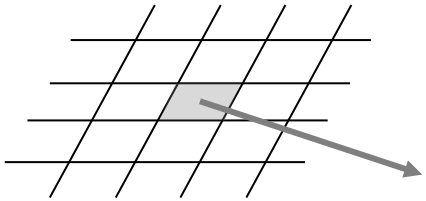

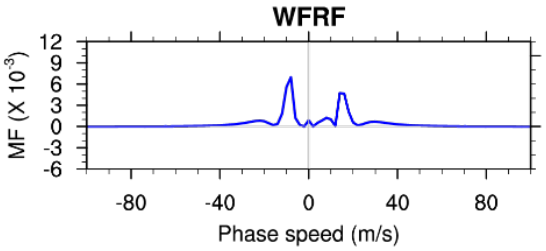

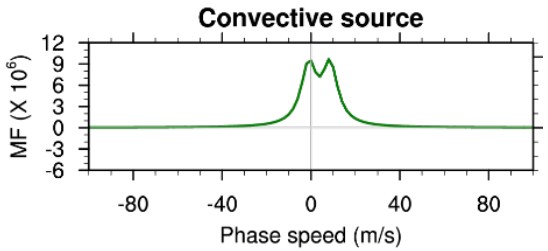

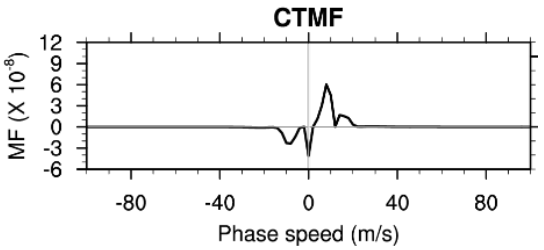

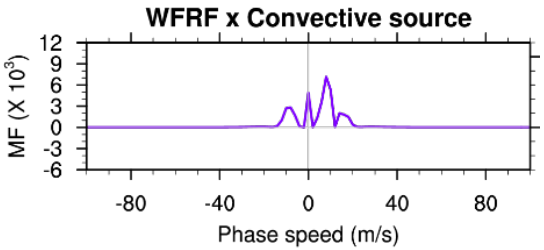

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Wave-filtering and resonance factor (WFRF) — **Convective source** — **Nonlinear forcing effect** (Chun et al. 2008)

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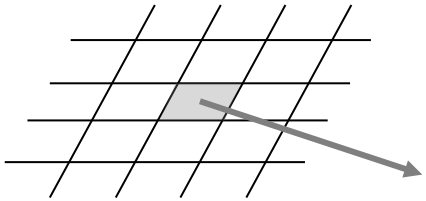

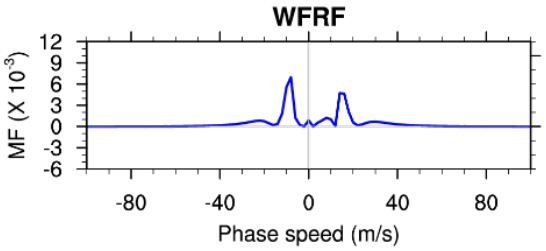

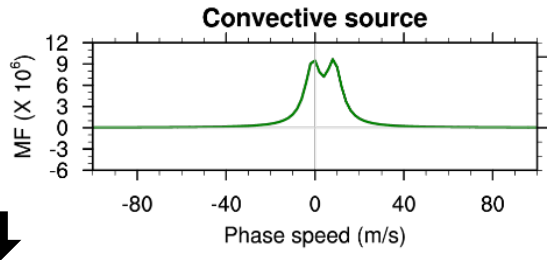

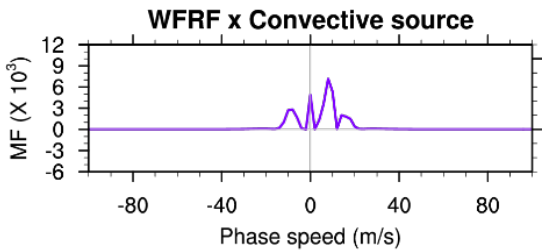

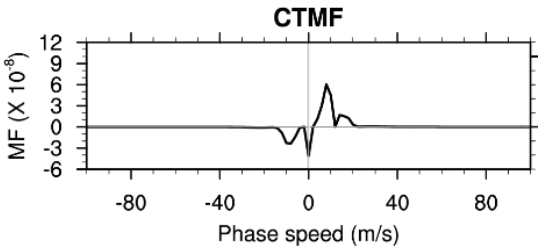

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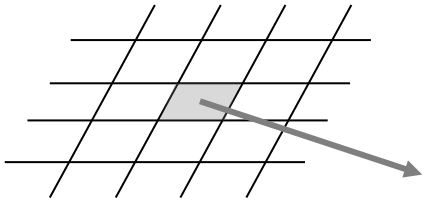

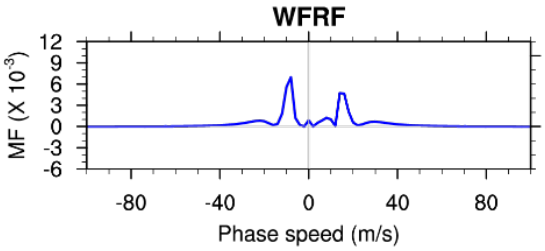

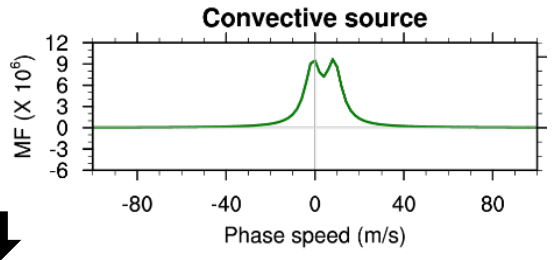

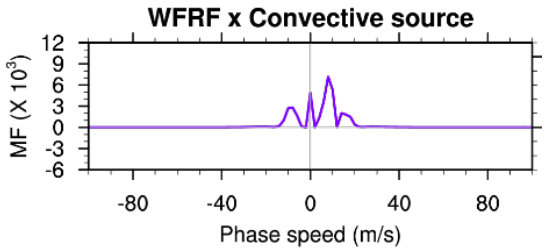

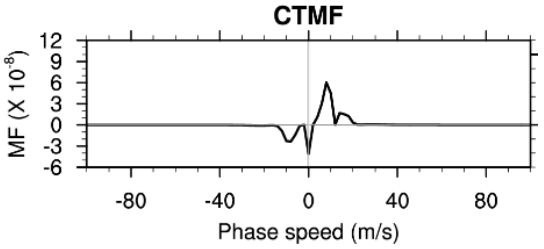

Sign & magnitude

sgn[c-U] × Nonlinear forcing effect × Several conditions within convection

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Wave-filtering and resonance factor (WFRF) — **Convective source** — **Nonlinear forcing effect** (Chun et al. 2008)

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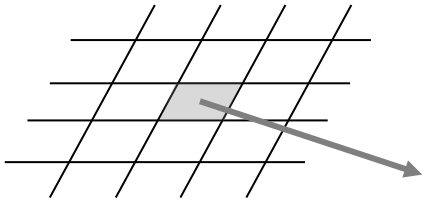

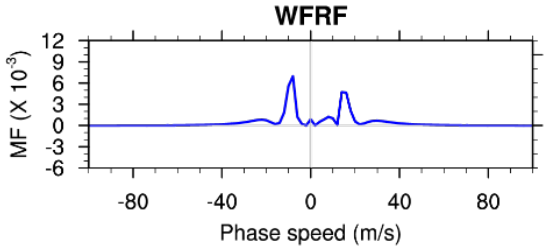

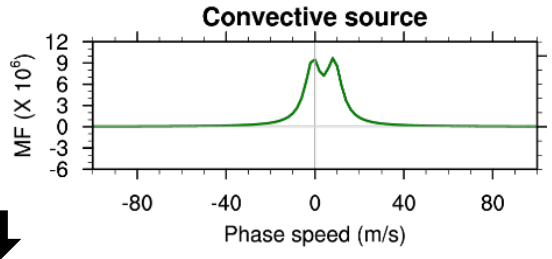

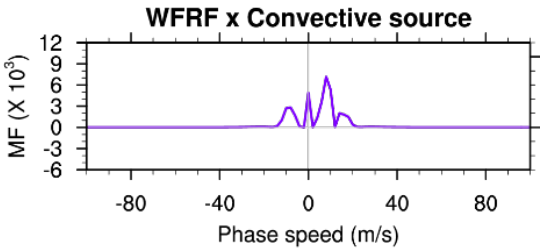

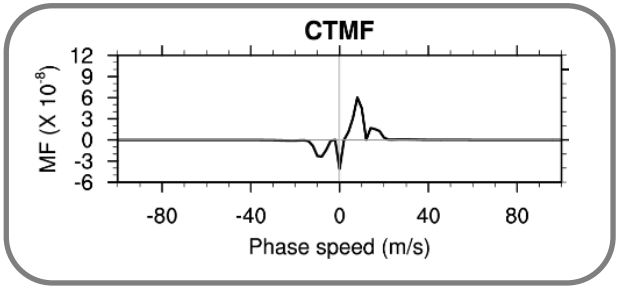

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Data and methodology

Parameterization: CTMF (cloud-top GWMF)

Choi and Chun (2011) + nonlinear forcing effect

$$M_{ct}(c,\varphi) = \mathrm{sgn}[c - U_{ct}(\varphi)]\rho_{ct}\frac{2(2\pi)^3}{A_h L_t}\left(\frac{g}{c_p T_q N_q^2}\right)^2 \times \frac{N_{ct}|X|^2}{|c - U_{ct}(\varphi)|}\Theta(c,\varphi) \times F(\mu)$$

Wave-filtering and resonance factor (WFRF)

Convective source

Nonlinear forcing effect

Parameterization: propagation

Lindzen-type method
(Kiehl et al. 1996; Song and Chun, 2006)
Columnar propagation

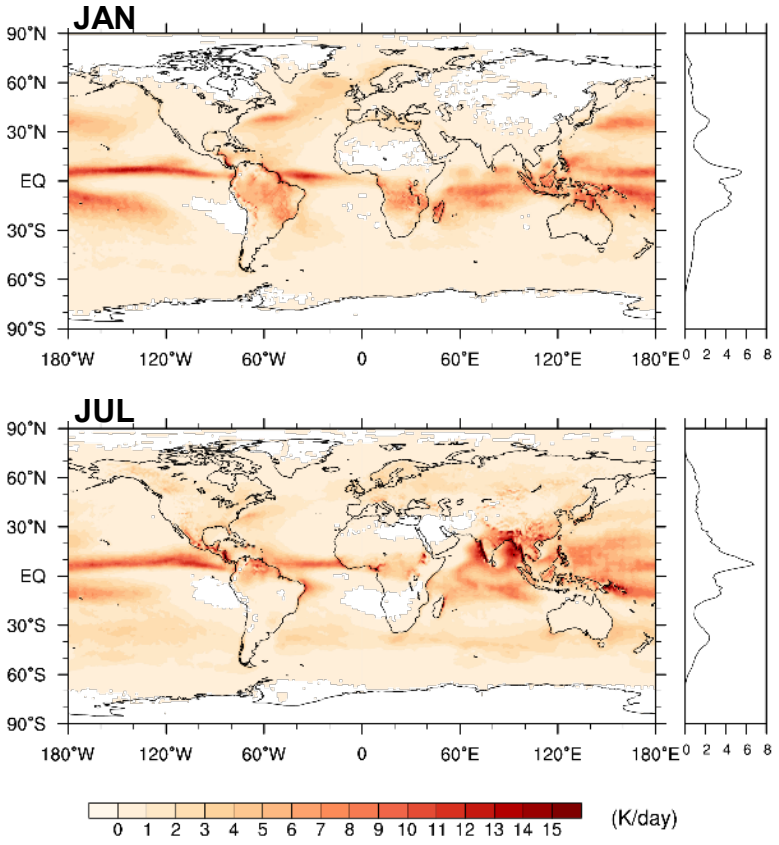
Spatiotemporal variations

$$CTMF(c,\varphi) = \mathrm{sgn}[c - U_{ct}(\varphi)]\rho_{ct}\frac{2(2\pi)^3}{A_h L_t}\left(\frac{g}{c_p T_{ct} N_q^2}\right)^2 \times \frac{N_{ct}|X|^2}{|c - U_{ct}(\varphi)|}\Theta(c,\varphi)\times F(\mu)$$

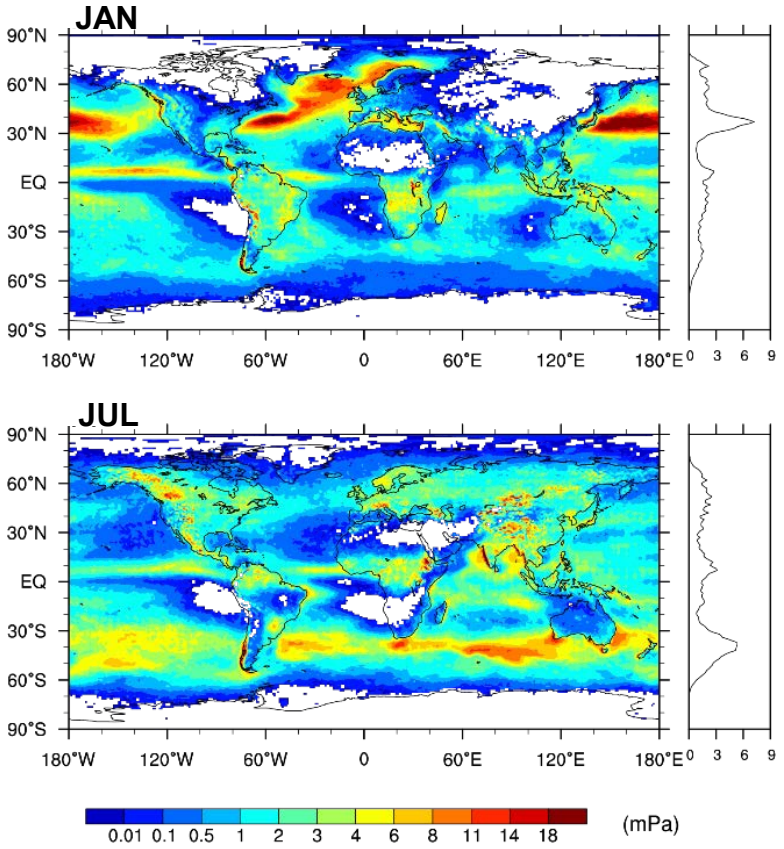
WFRF

Convective source ∝ DCH

Deep **C**onvective **H**eating rate



Absolute **CTMF**



2002-2010 avg.

- **CTMF** is not solely proportional to **DCH**.
- **WFRF** (wave-filtering and resonance factor), several conditions within convection (T_q, N_q), and nonlinearity also affect the magnitude of CTMF.

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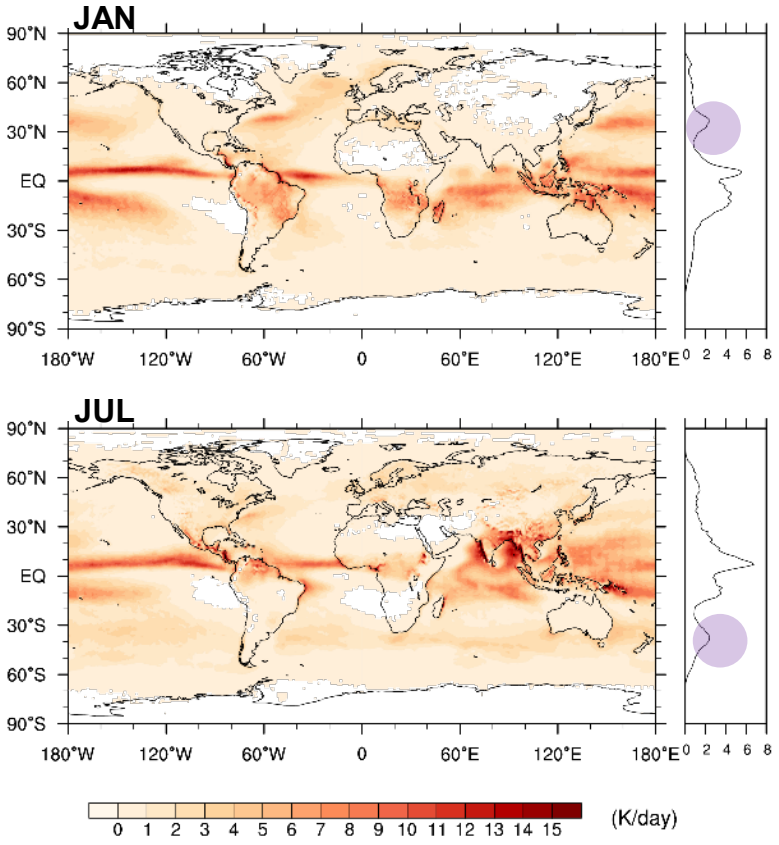

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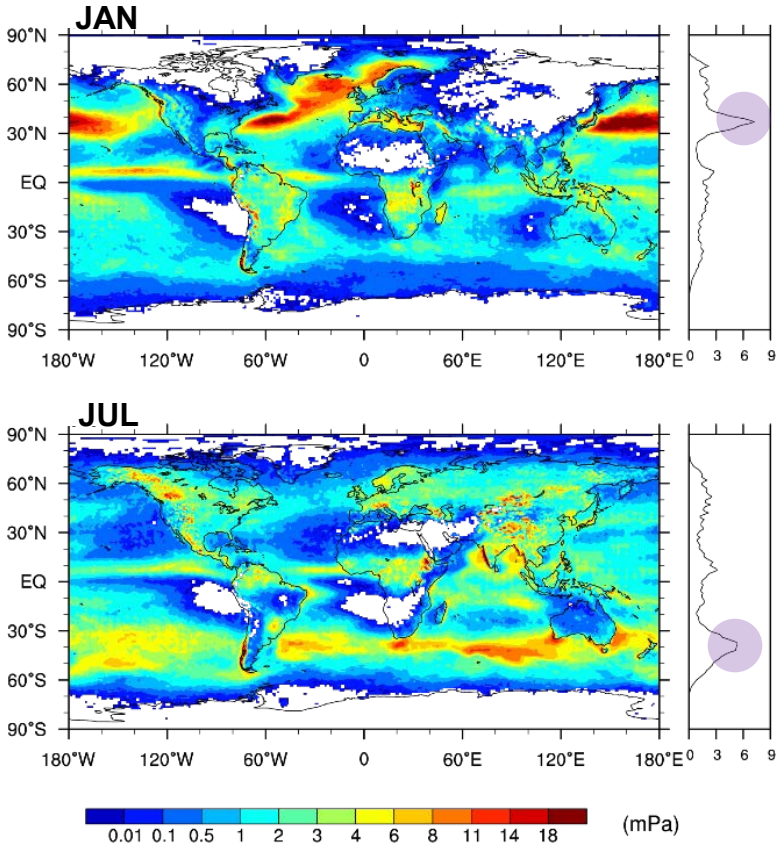

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WFRF

Convective source ∝ DCH

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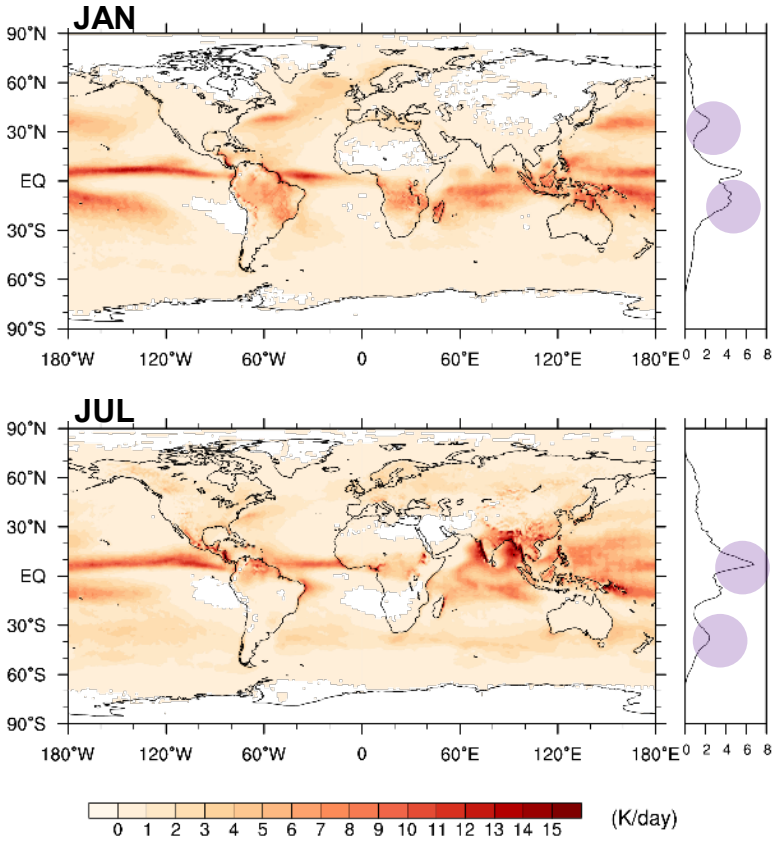

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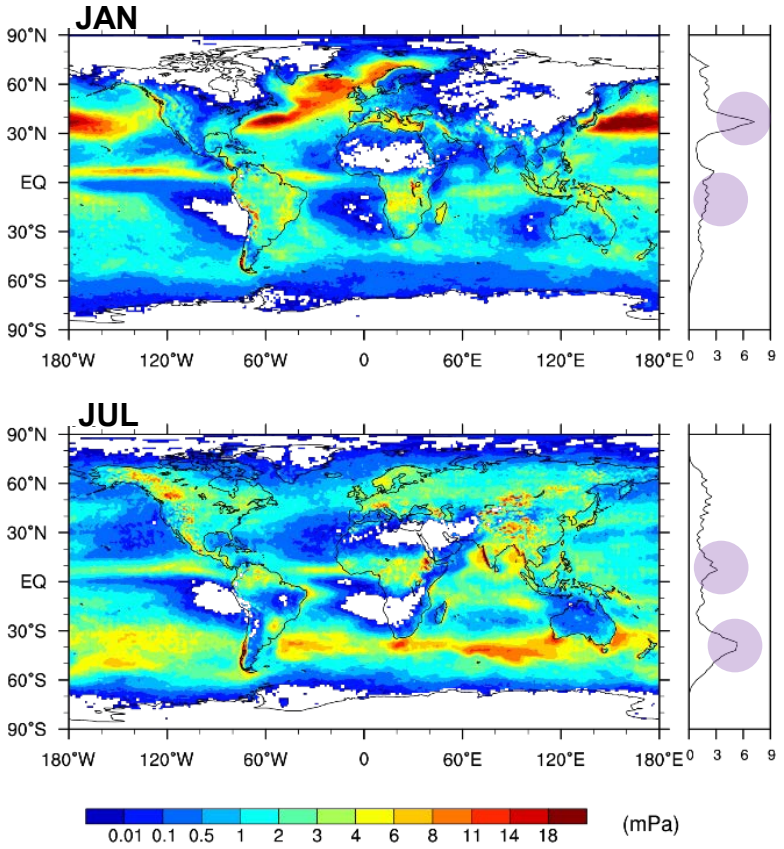

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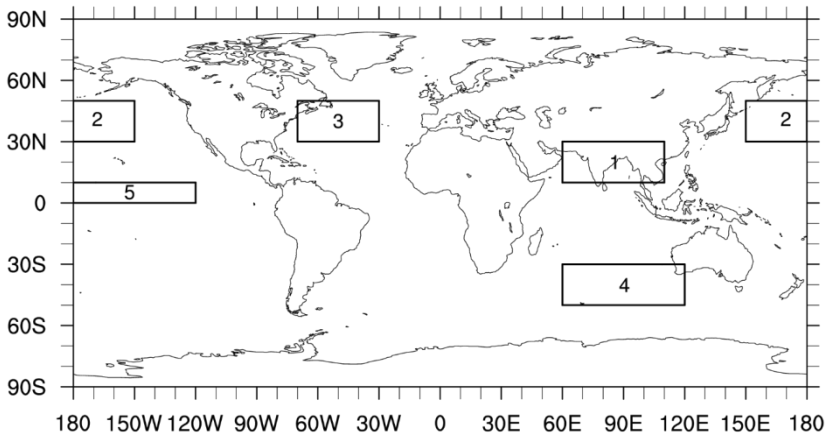
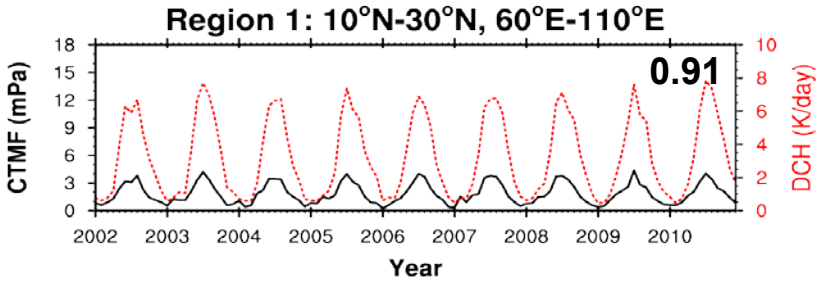
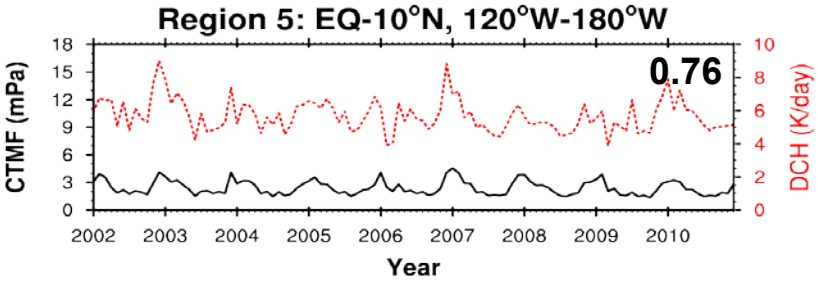
Spatiotemporal variations

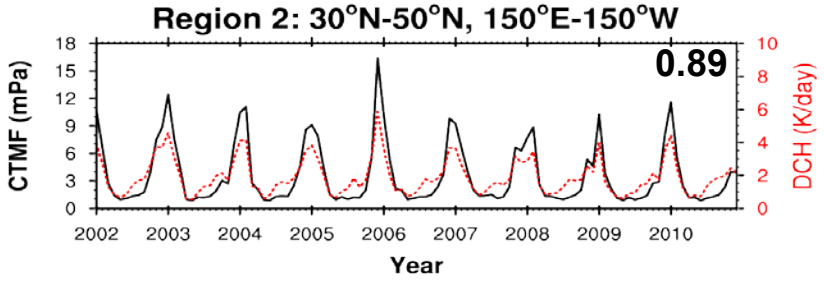
Time series

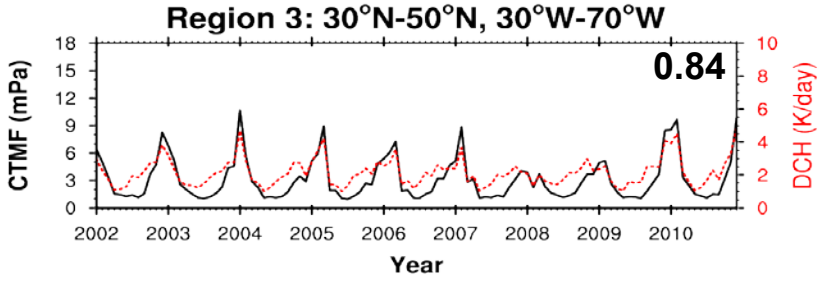


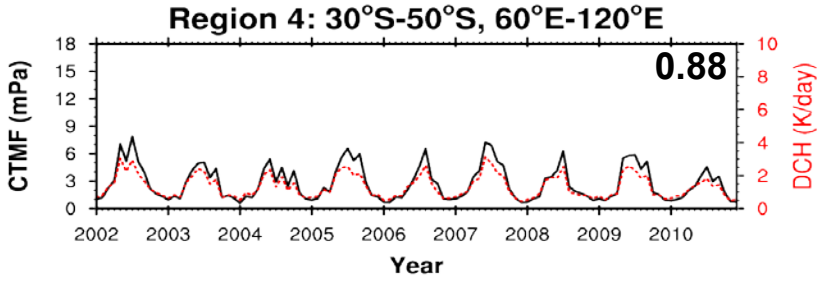
- **CTMF** is well correlated with **DCH** except in the tropical region (region 5).
- Compared to **DCH**, the magnitude of **CTMF** is relatively reduced in **low latitudes** than mid to high latitudes.









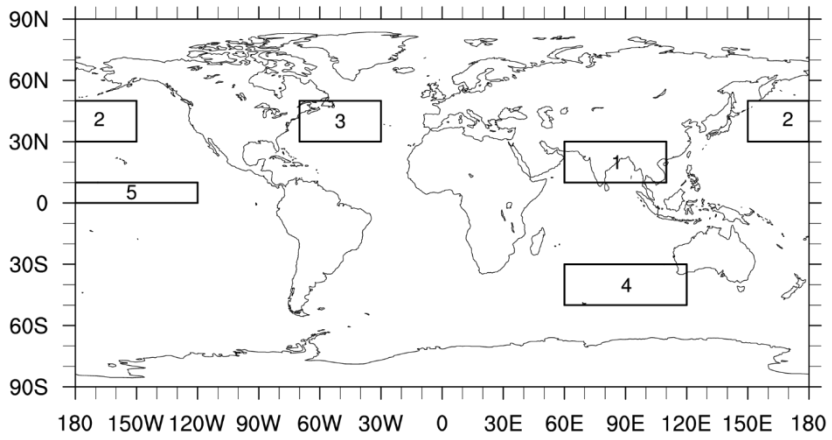


Low latitudes

Storm-track region (midlatitudes)

Spatiotemporal variations

Time series



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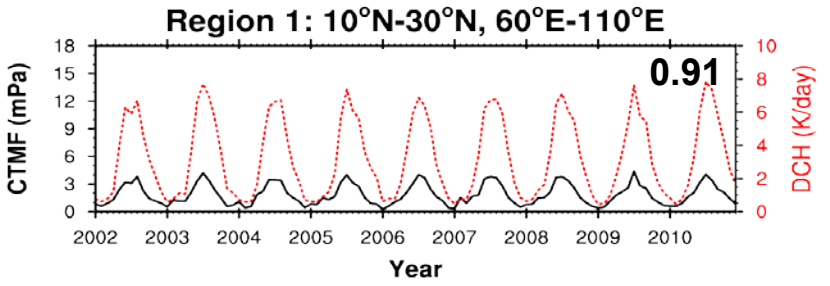
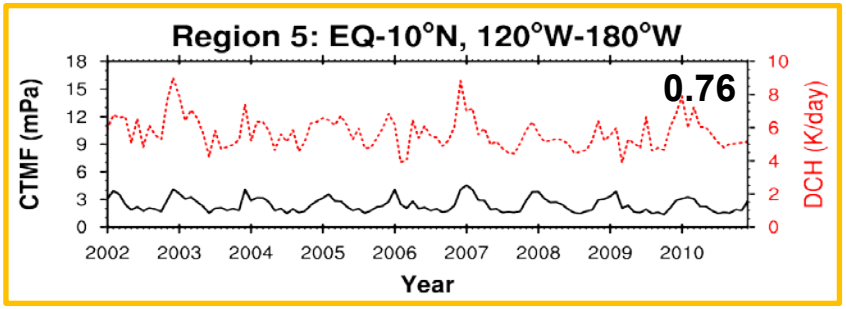
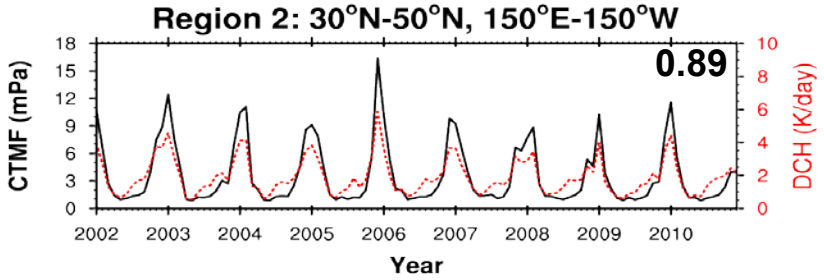
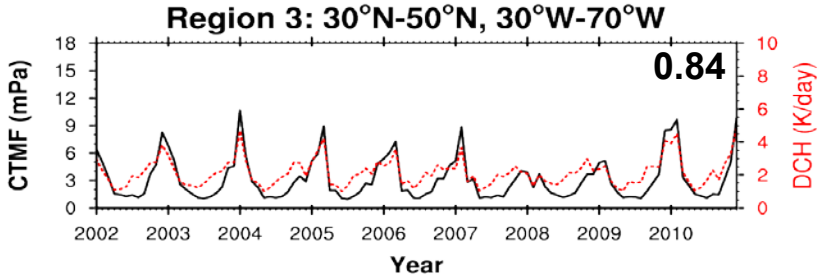
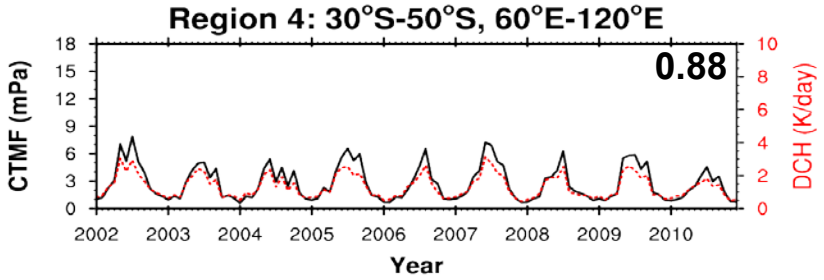








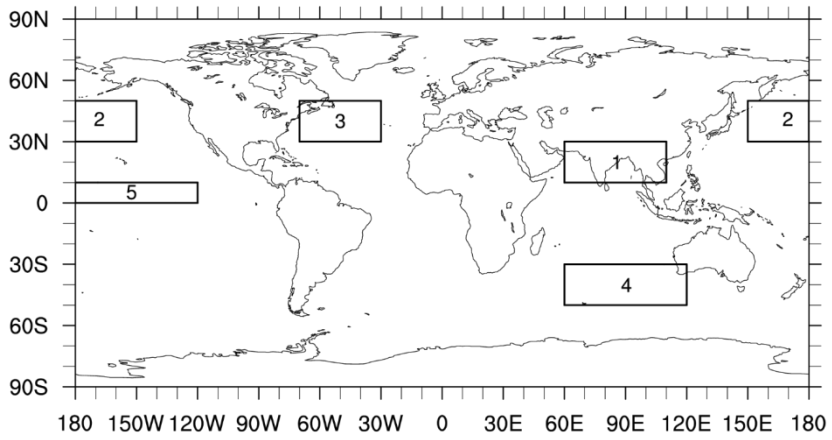


Low latitudes

Storm-track region (midlatitudes)

Spatiotemporal variations

Time series



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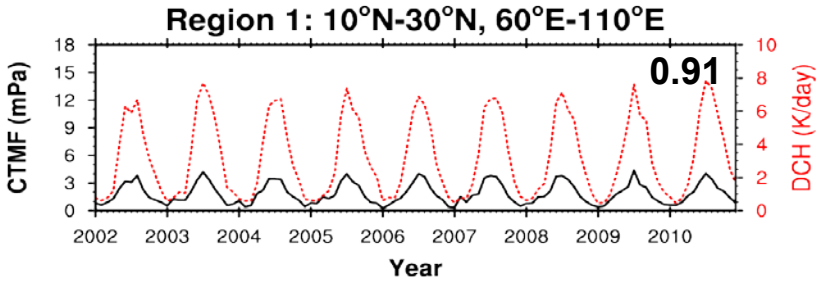
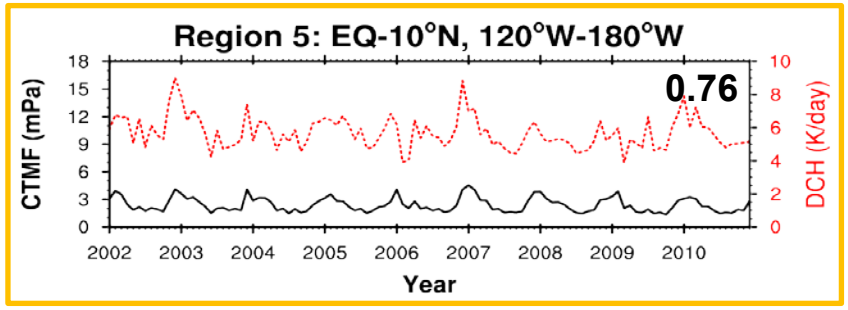
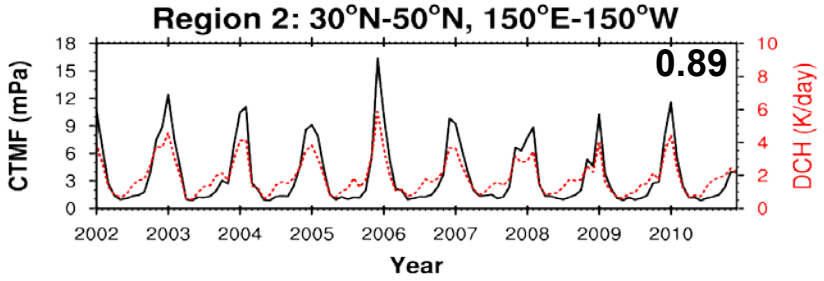
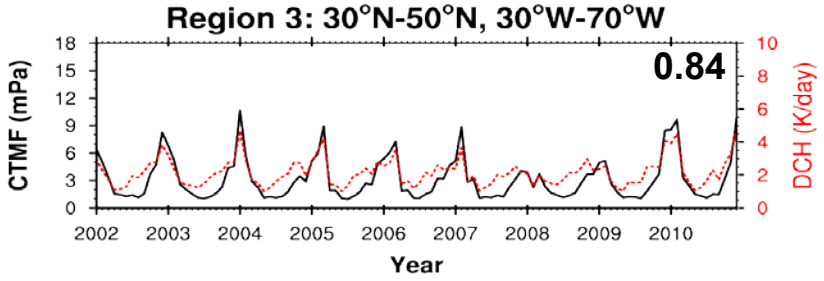
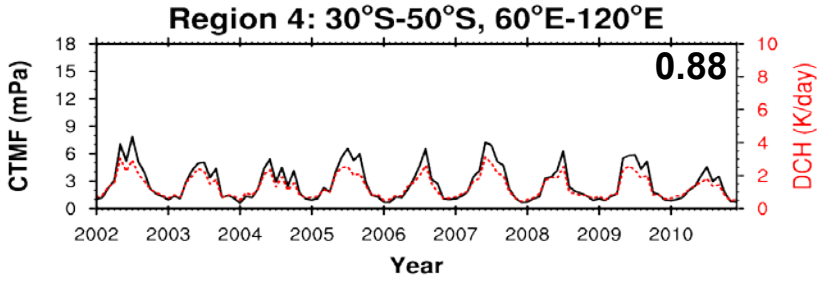








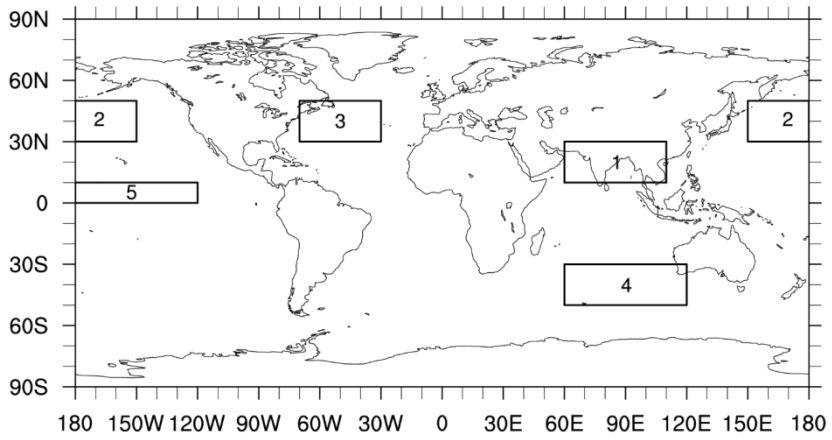


Low latitudes

Storm-track region (midlatitudes)

Spatiotemporal variations

Time series



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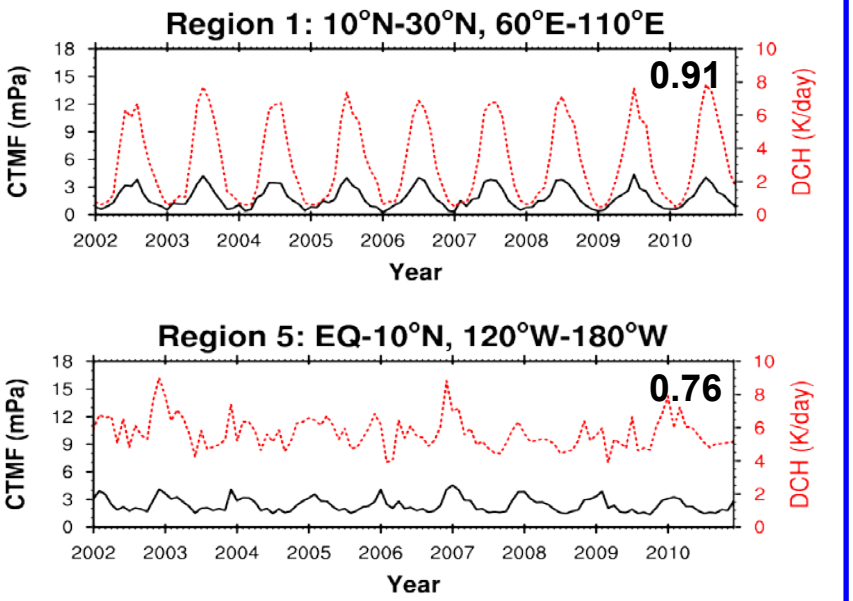
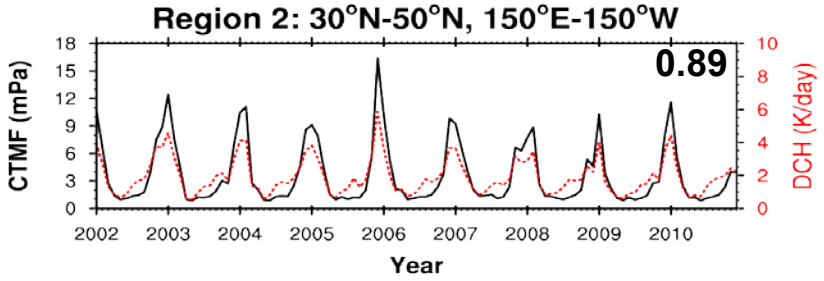
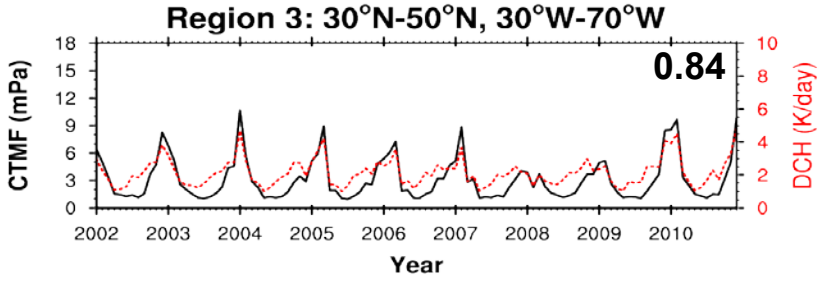
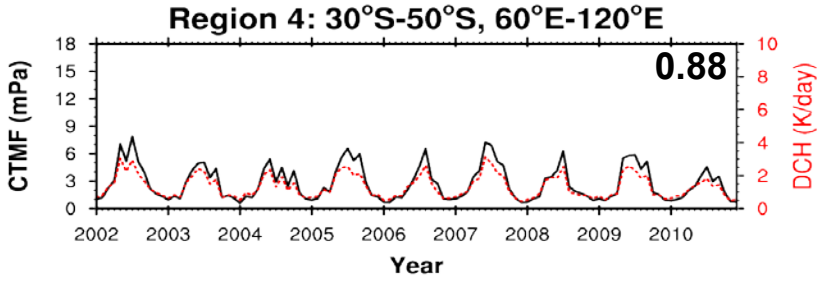






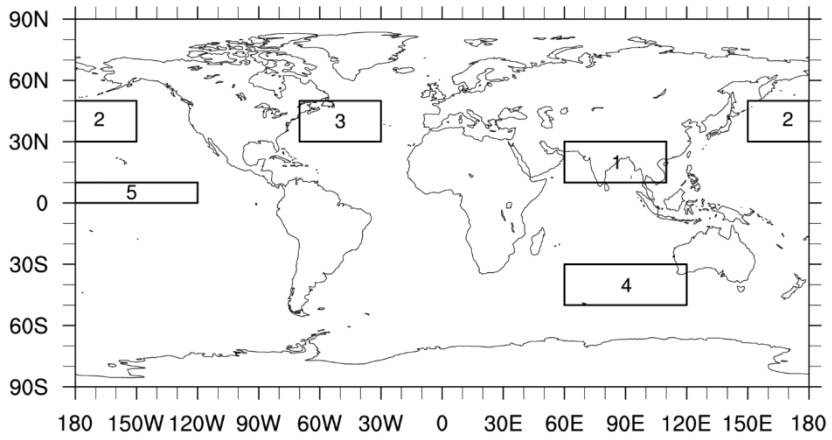


Low latitudes

Storm-track region (midlatitudes)

Spatiotemporal variations

Time series



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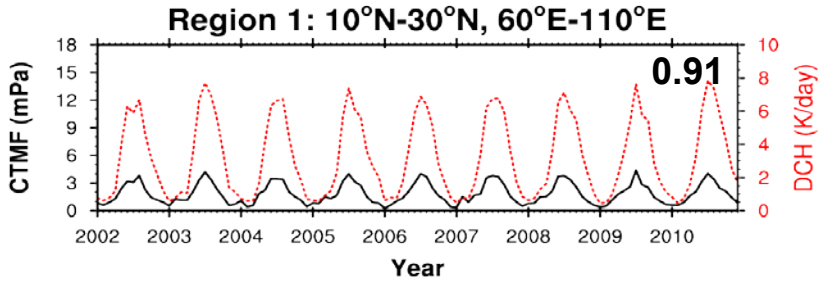
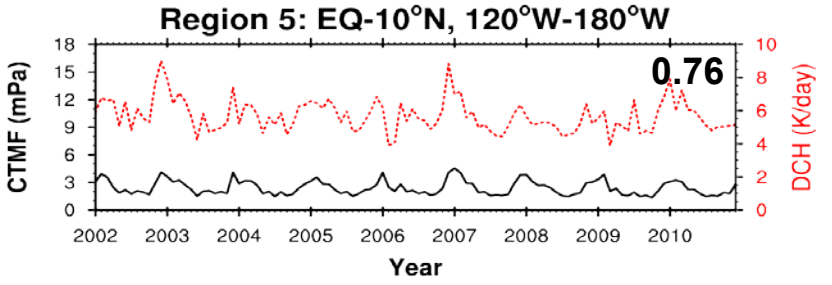
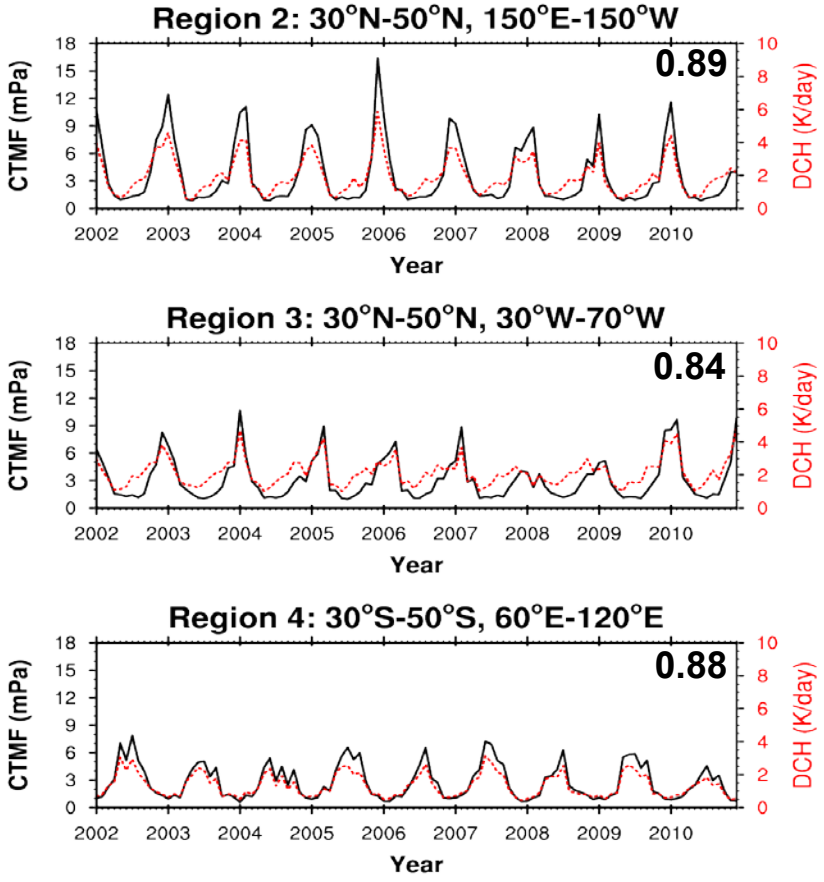




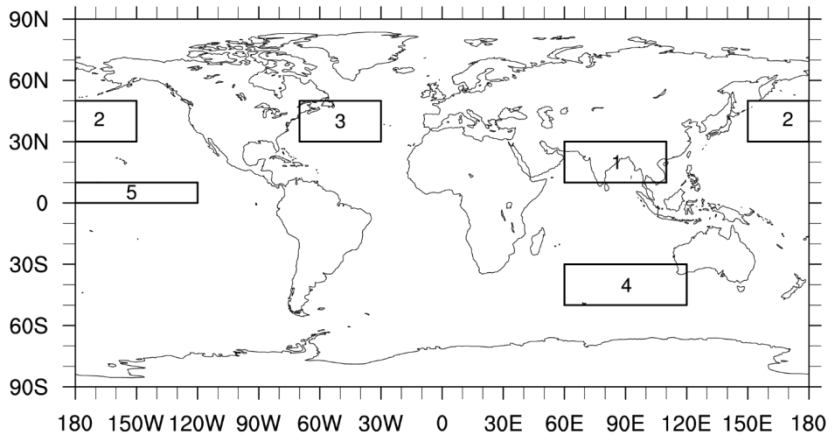
Low latitudes



Storm-track region (midlatitudes)

Spatiotemporal variations

Time series



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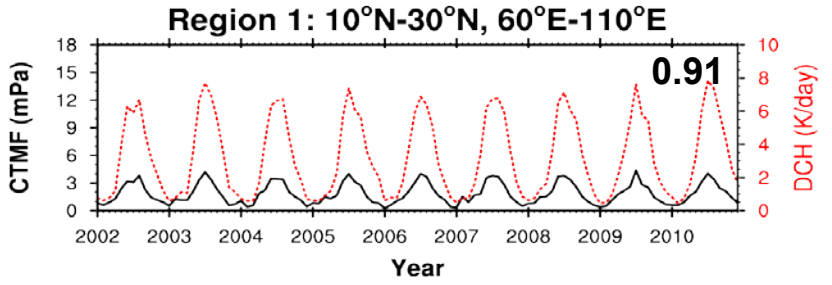
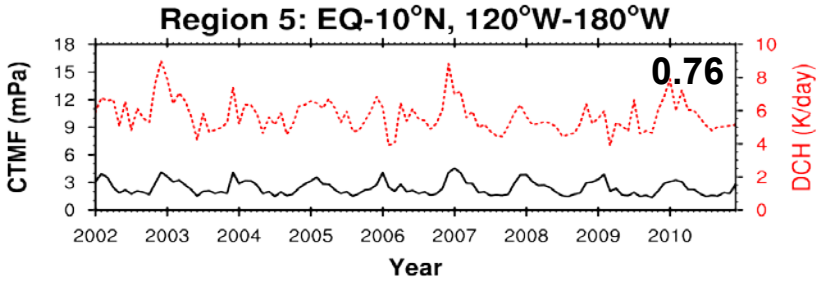
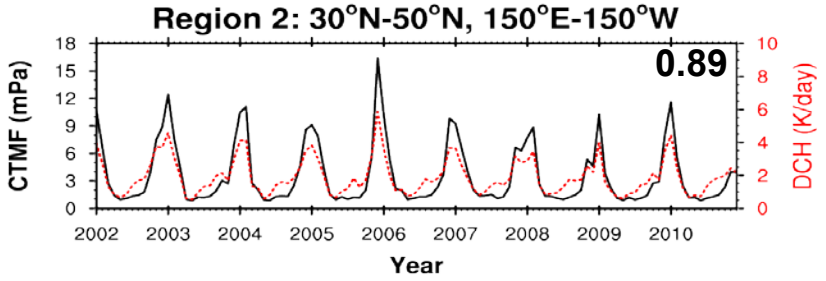
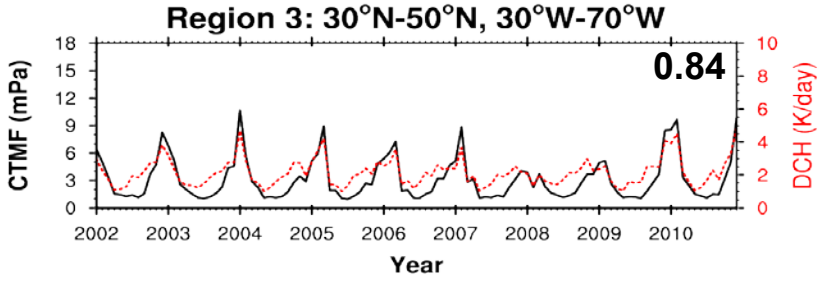
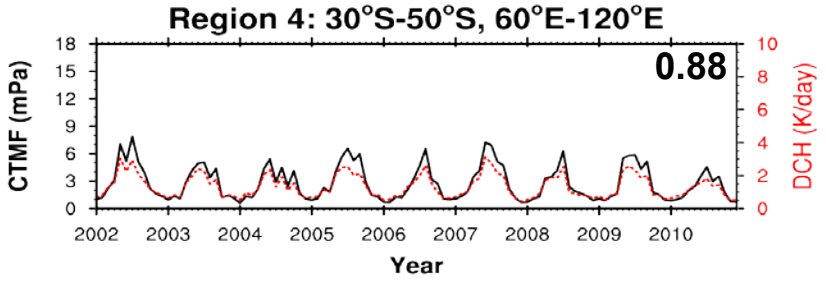








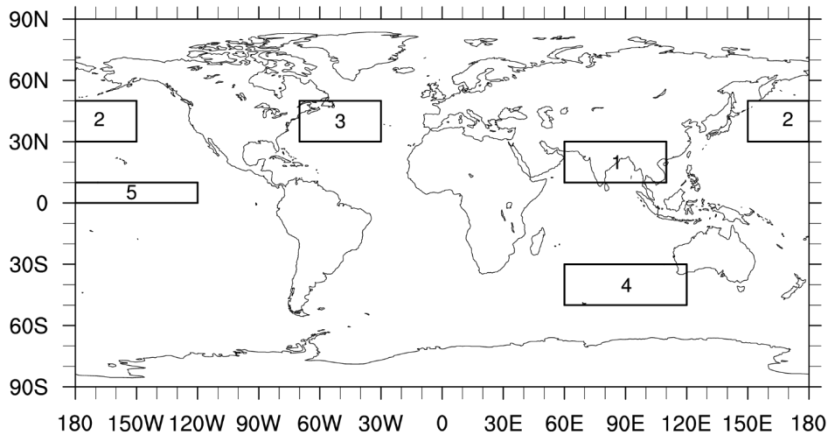


Low latitudes

Storm-track region (midlatitudes)

Spatiotemporal variations

Power Spectral Density



Black solid line: Power spectral density
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- **1 day**, **6 month**, **1 year** cycle is strongly related to the temporal variation of convection.
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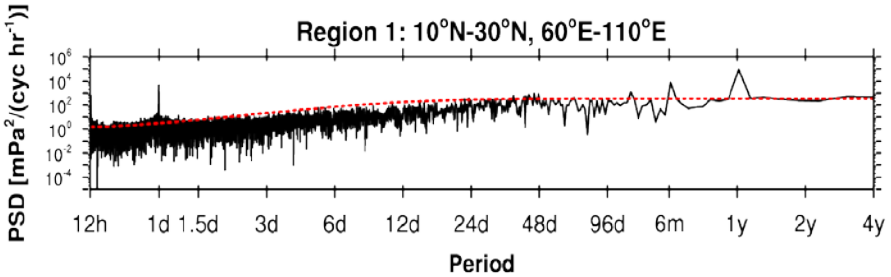
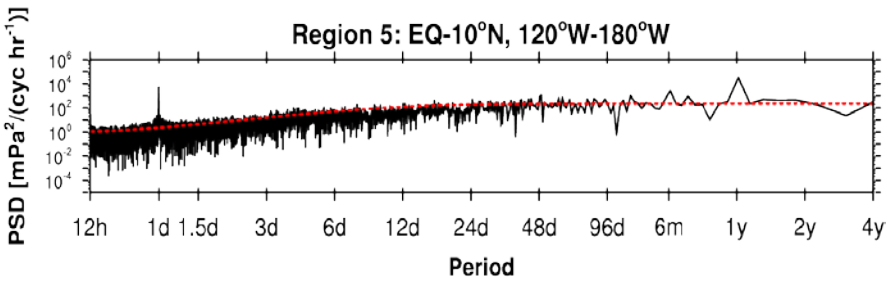
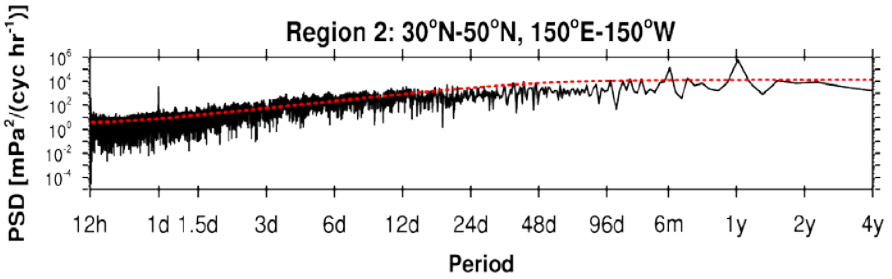
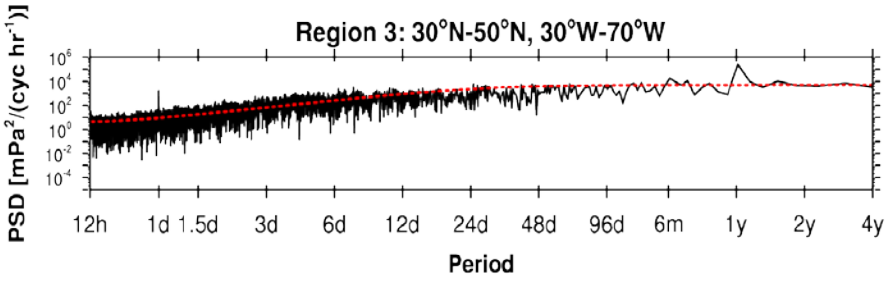
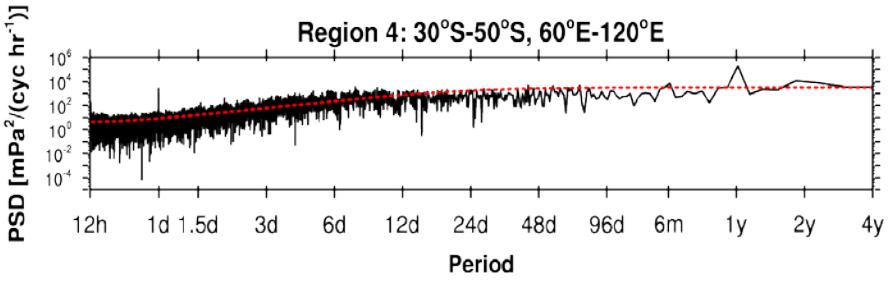








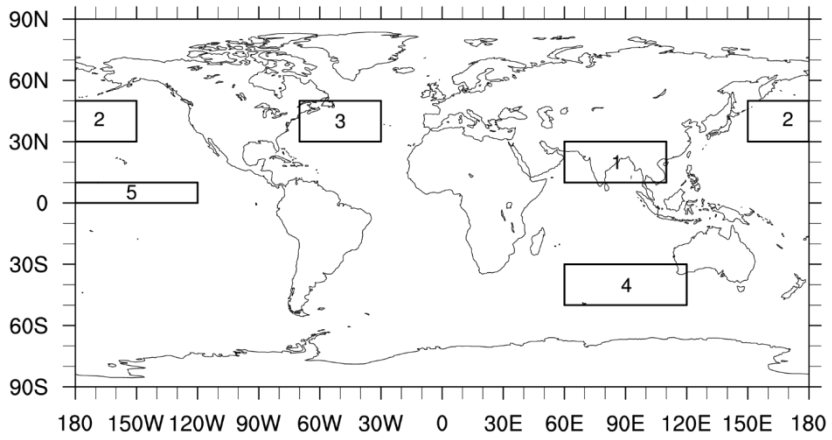


Low latitudes

Storm-track region (midlatitudes)

Spatiotemporal variations

Power Spectral Density



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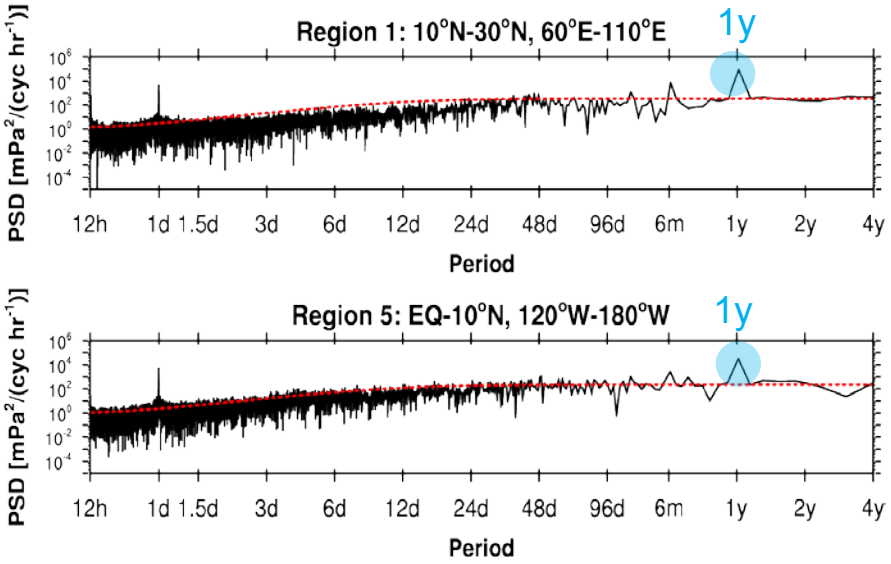
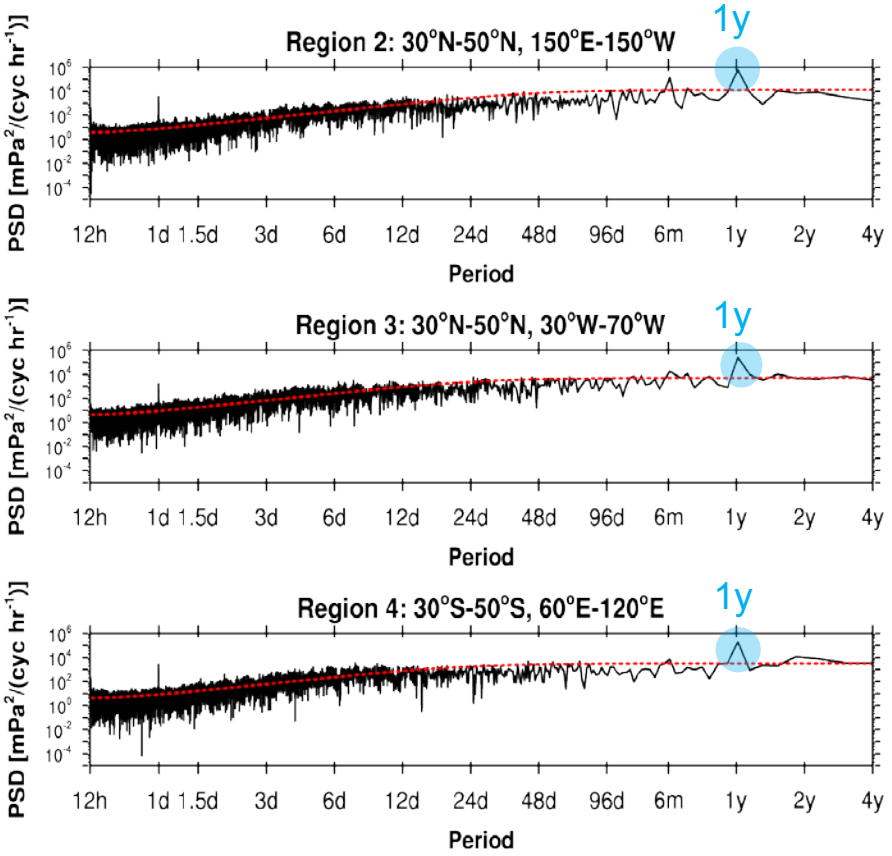


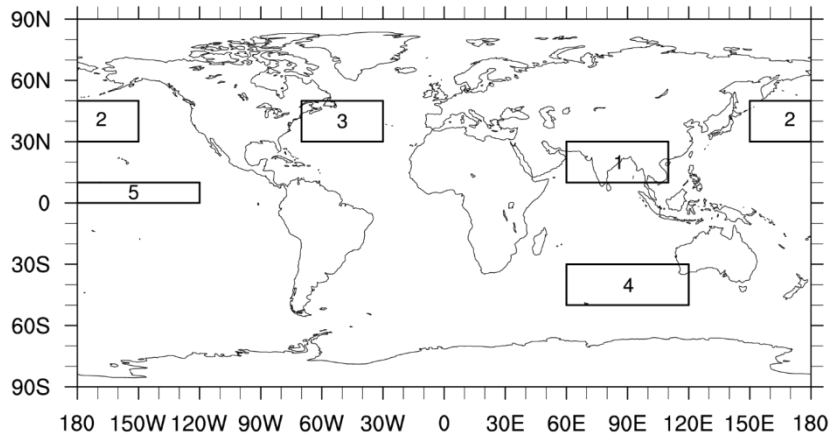


Low latitudes

Storm-track region (midlatitudes)

Spatiotemporal variations

Power Spectral Density



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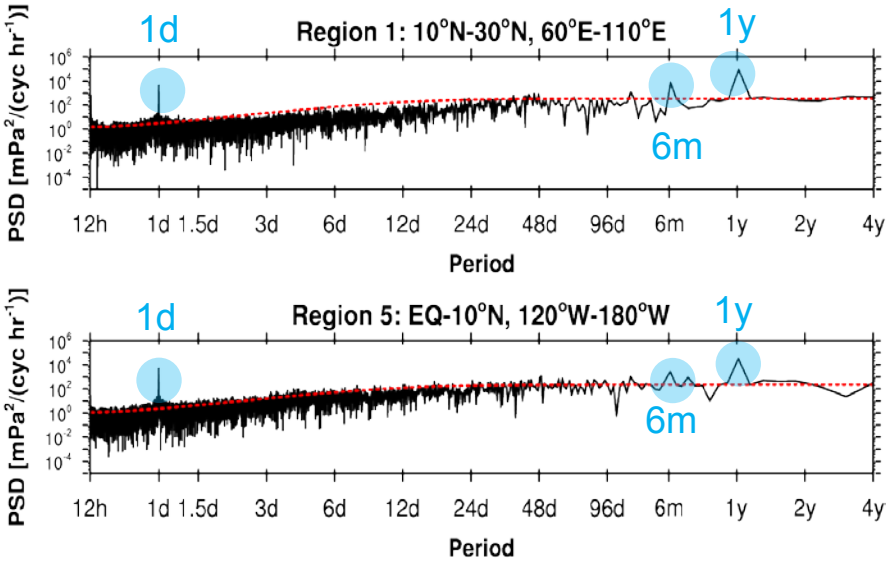
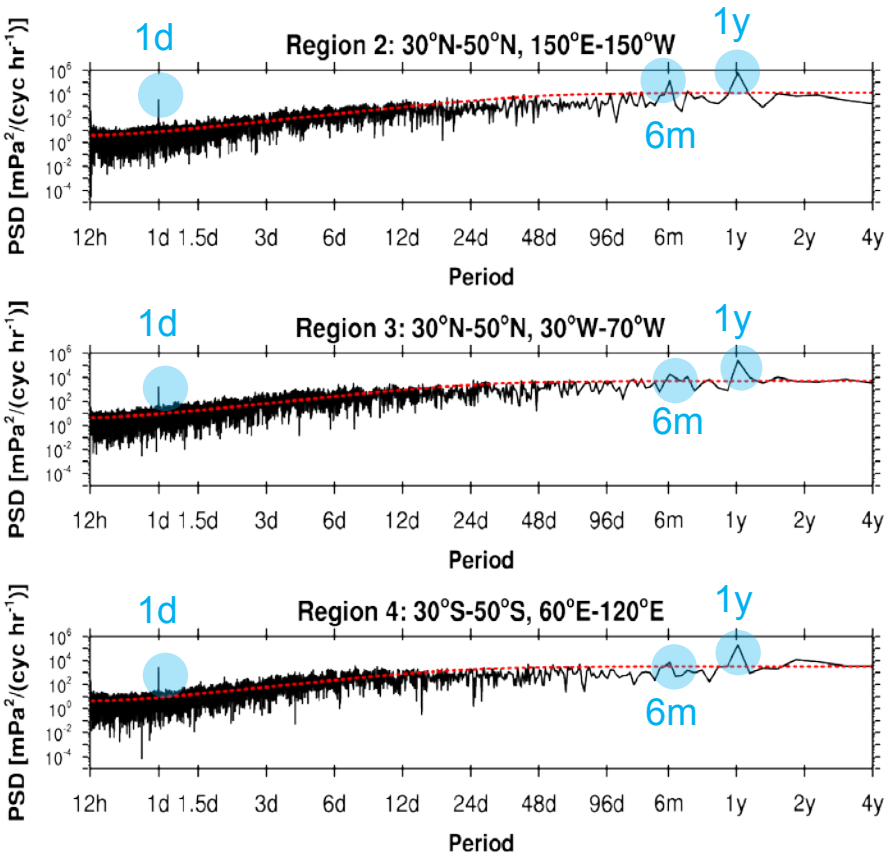


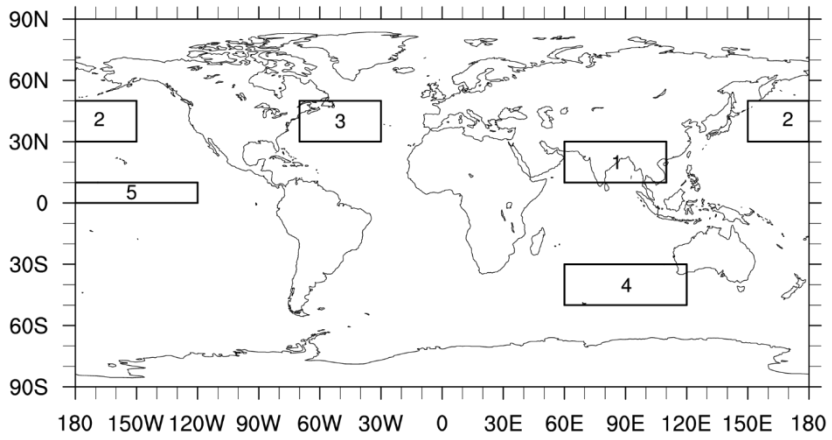


Low latitudes

Storm-track region (midlatitudes)

Spatiotemporal variations

Power Spectral Density



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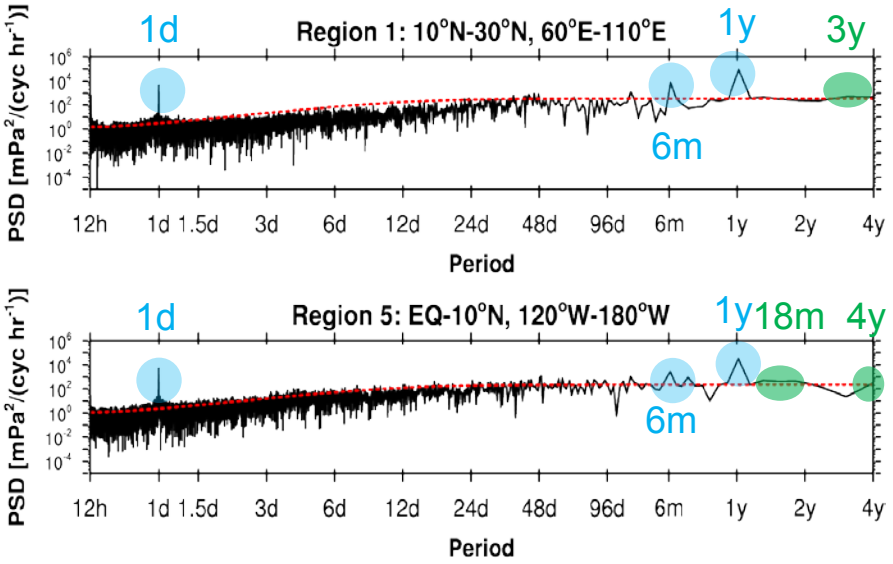
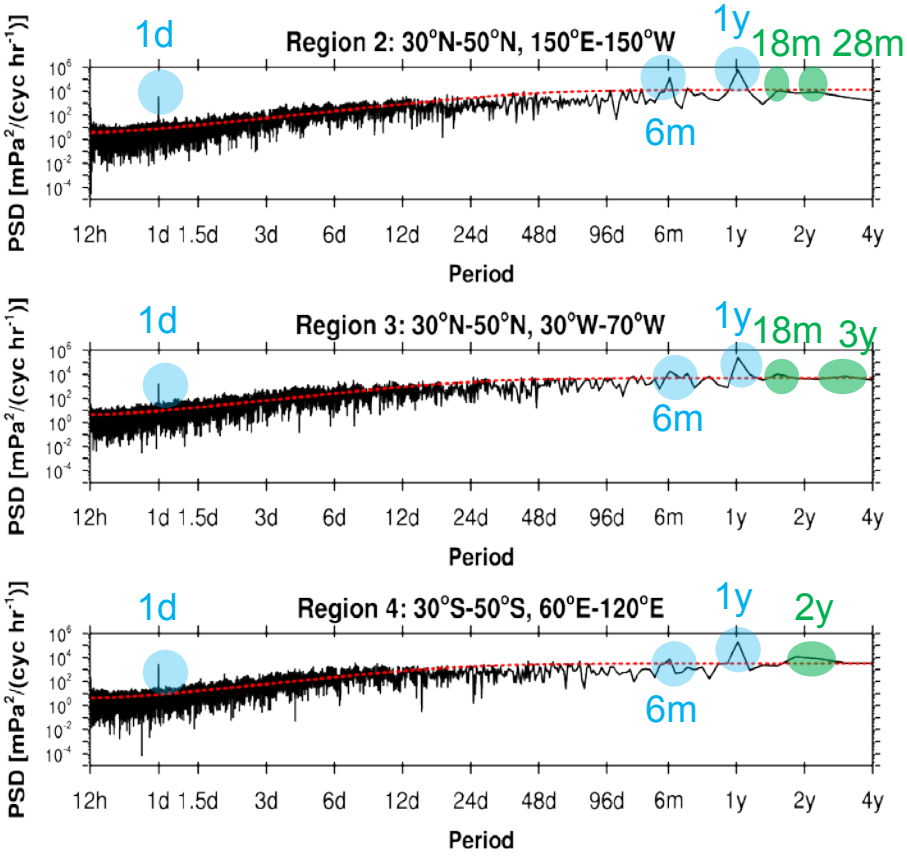


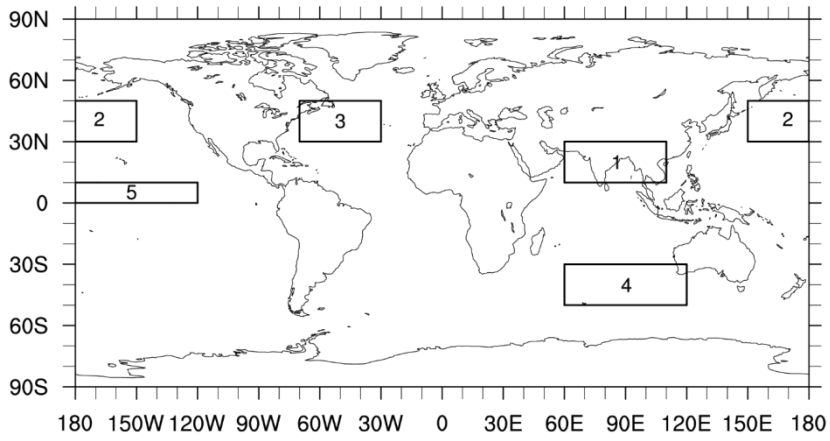
Low latitudes



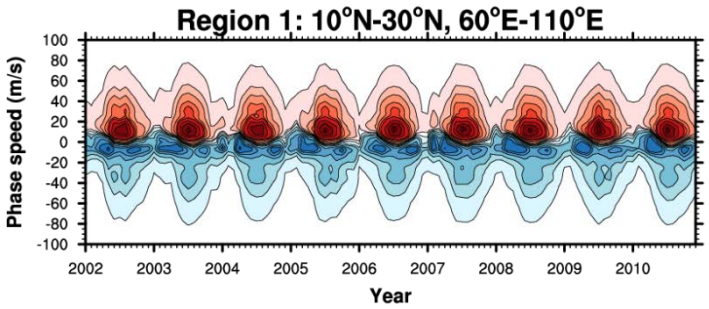
Storm-track region (midlatitudes)

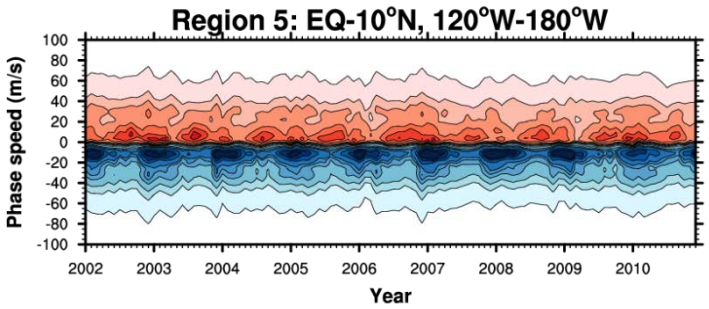
Spatiotemporal variations

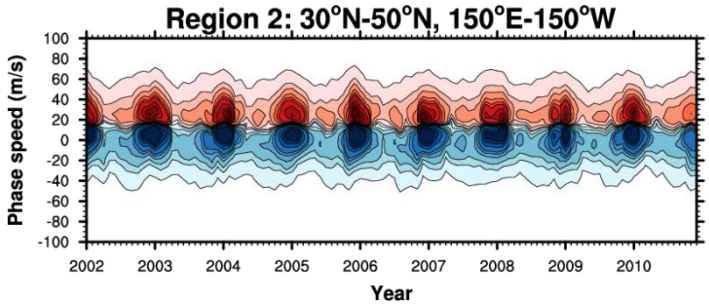
Zonal CTMF spectrum

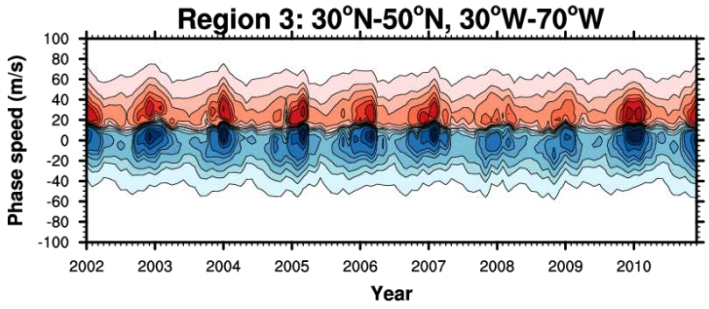


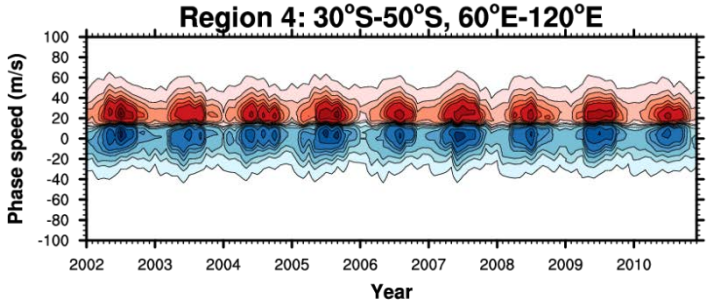
- **Annual variation** is large except in region 5.
- The **width** of the CTMF spectrum is large in the **low latitudes** (region 1 & region 5).







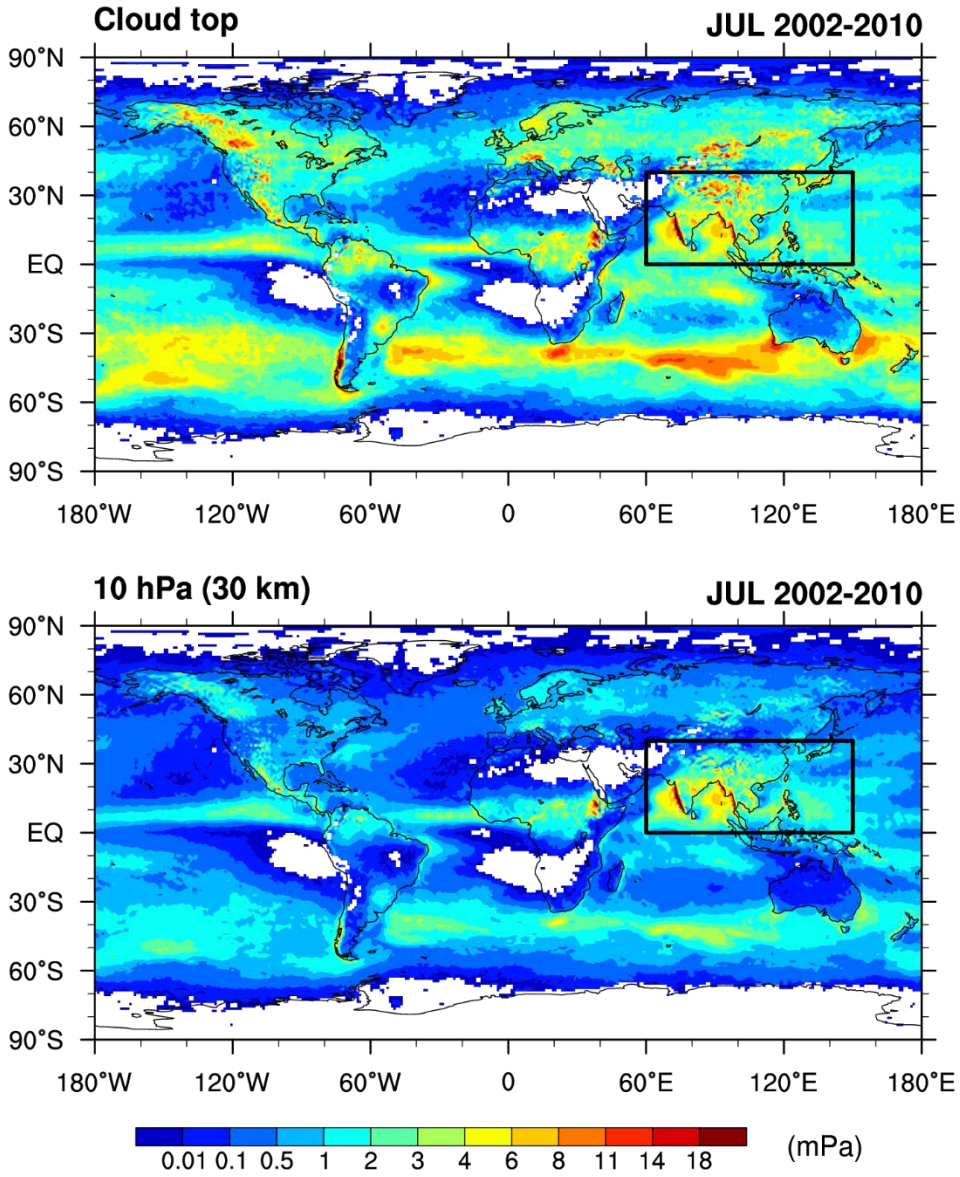




Low latitudes

Storm-track region (midlatitudes)

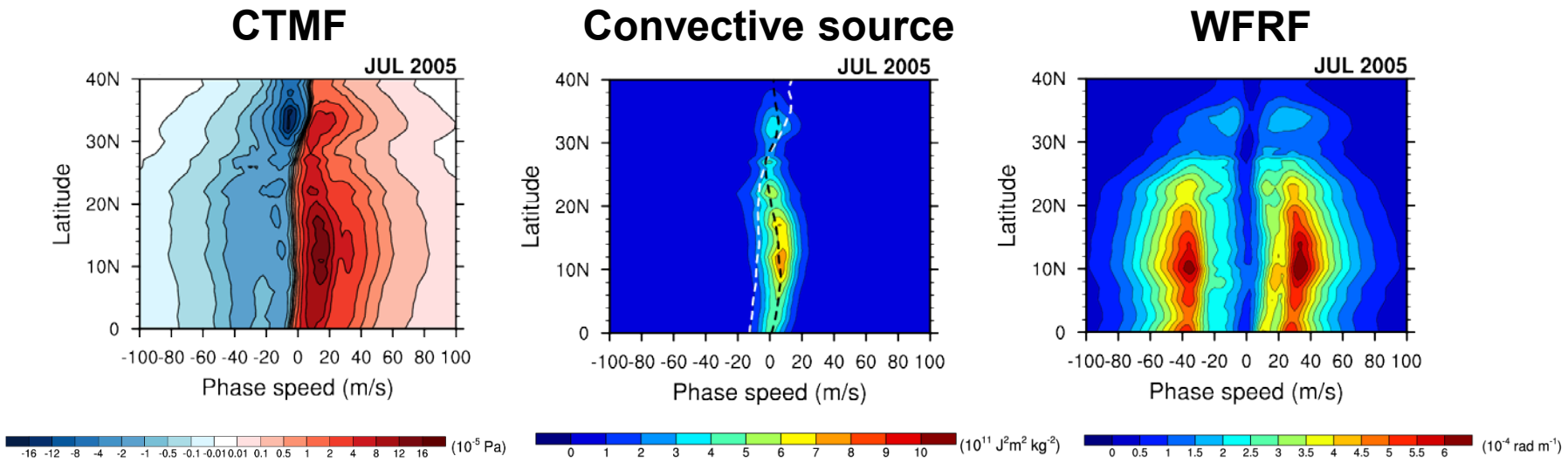
CGW momentum flux Asian summer monsoon region



Large convective gravity wave momentum flux at the **cloud top** and the **stratosphere (10 hPa)**

CTMF spectrum Asian summer monsoon region

$$CTMF(c,\varphi) = \mathrm{sgn}[c - U_{ct}(\varphi)]\rho_{ct}\frac{2(2\pi)^3}{A_h L_t}\left(\frac{g}{c_p T_q N_q^2}\right)^2 \times \frac{N_{ct}|X|^2}{|c - U_{ct}(\varphi)|}\Theta(c,\varphi)\times F(\mu)$$



- **CTMF** spectrum is amplified at the phase speed corresponding to the **moving speed of convection (c_{qh})**
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CTMF spectrum Asian summer monsoon region

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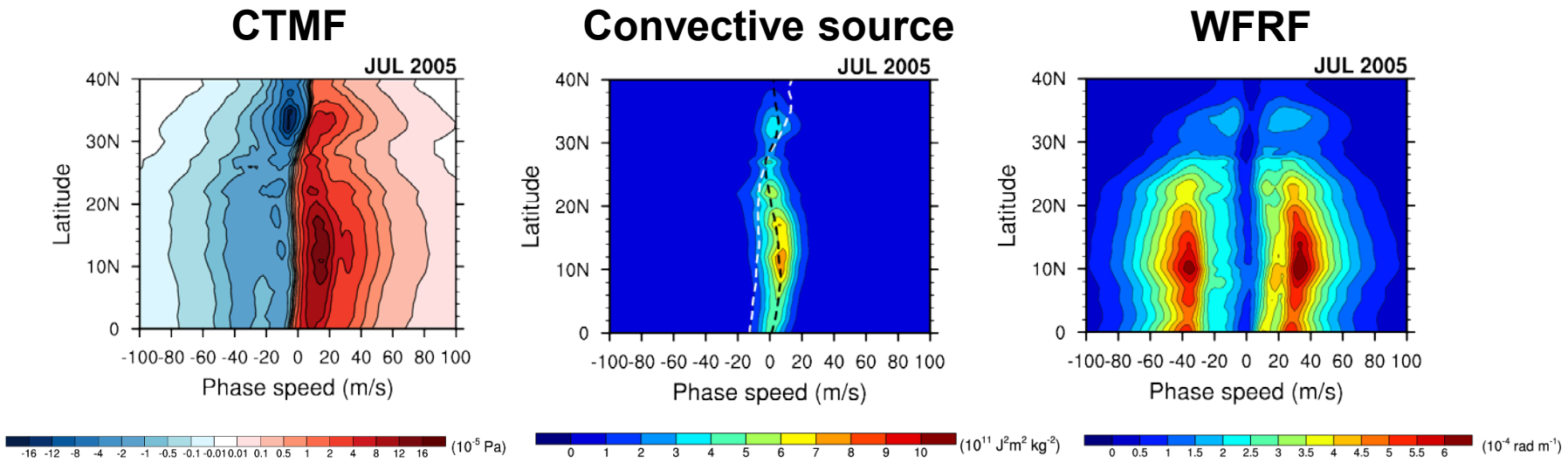
CTMF

WFRF

Convective source



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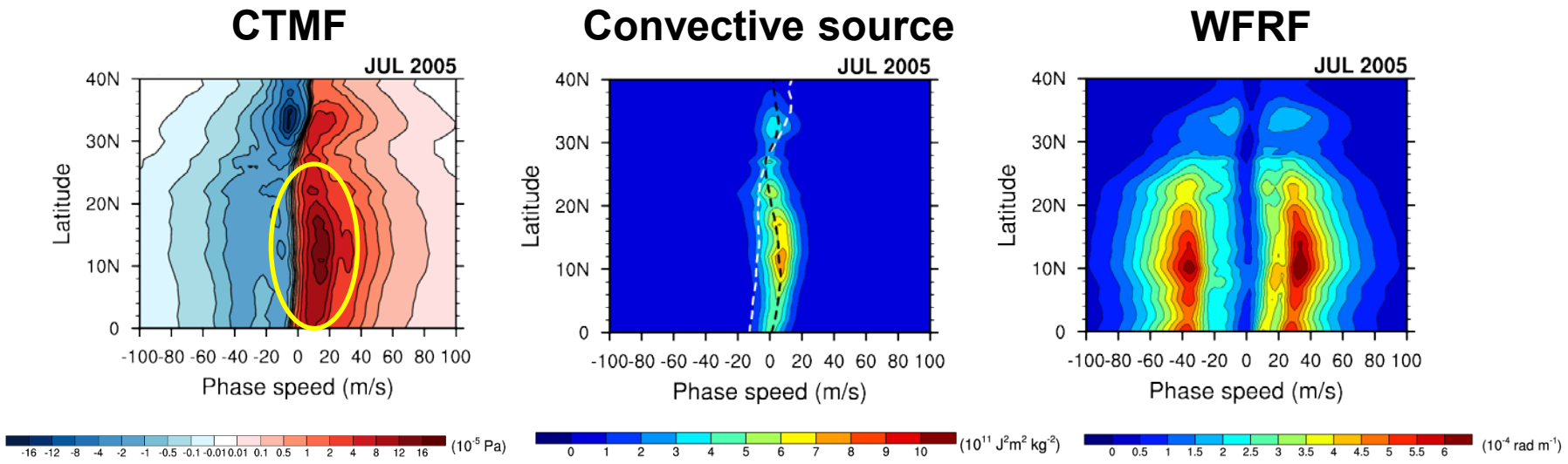

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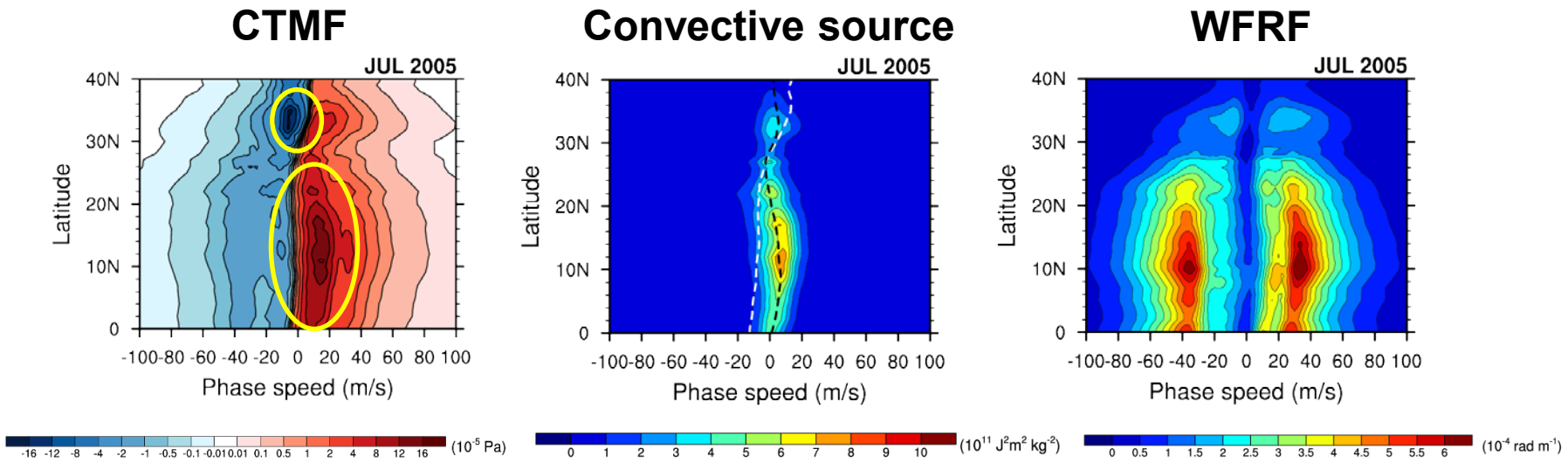

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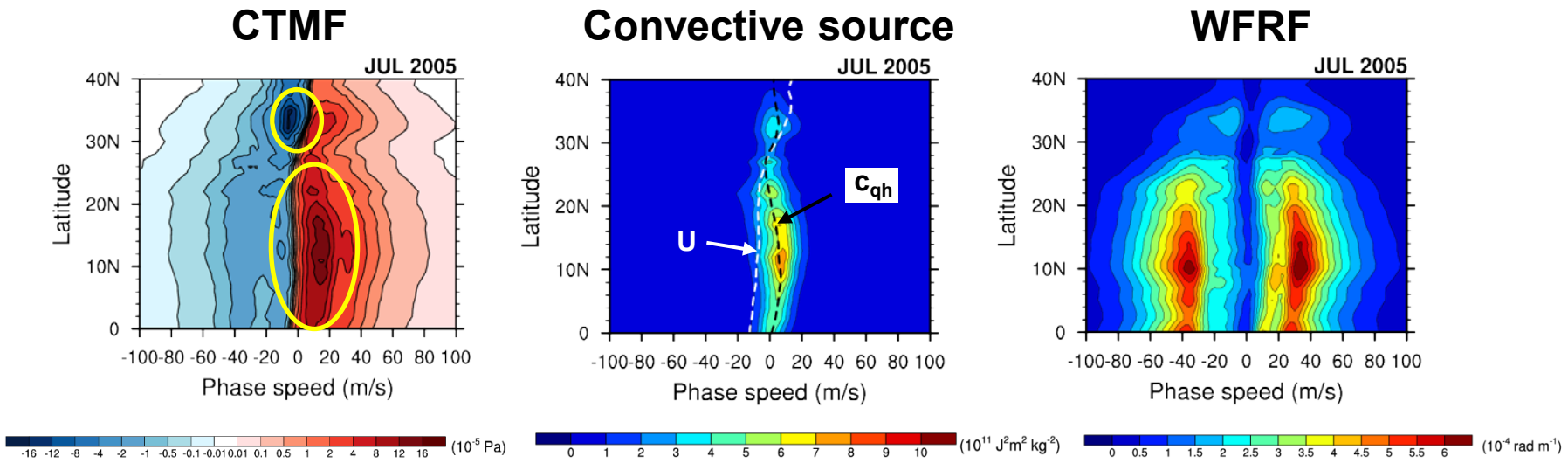

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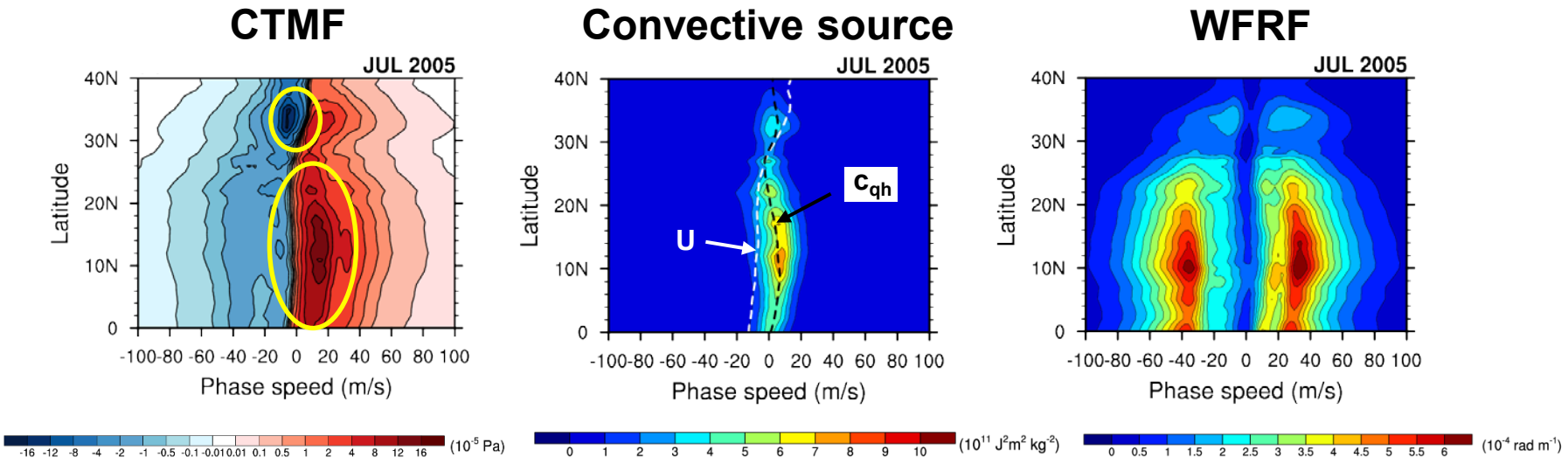
Convective source — Moving speed of convection



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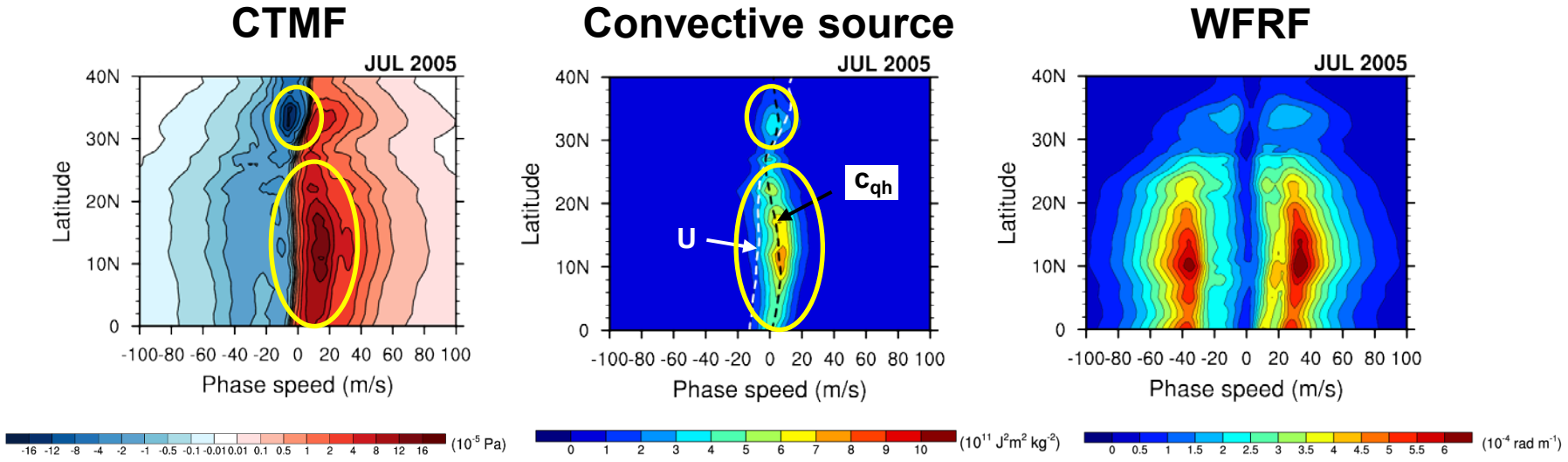

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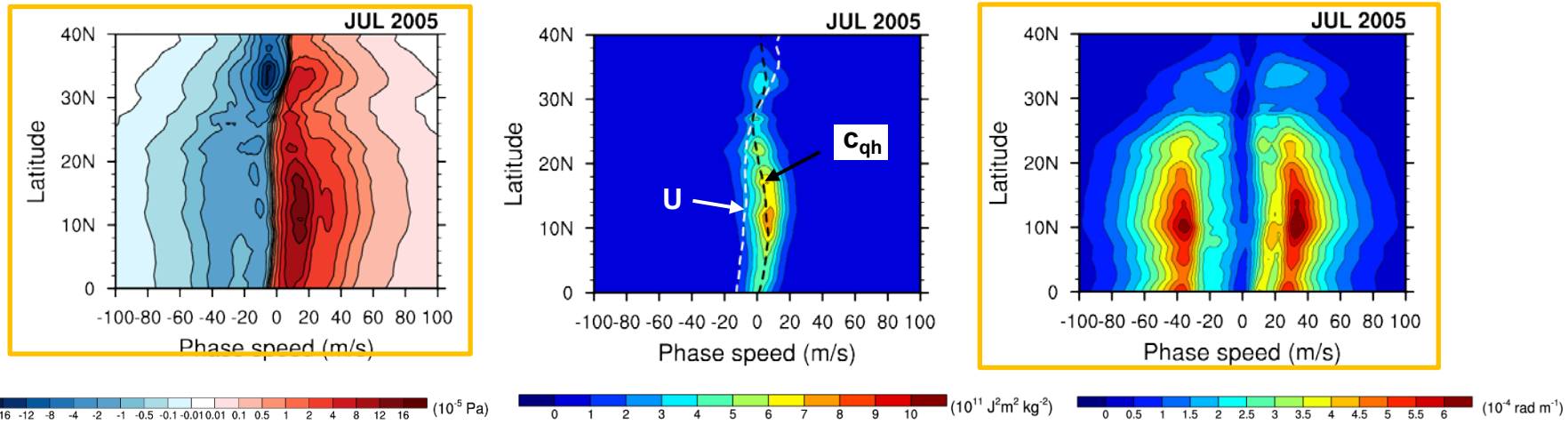

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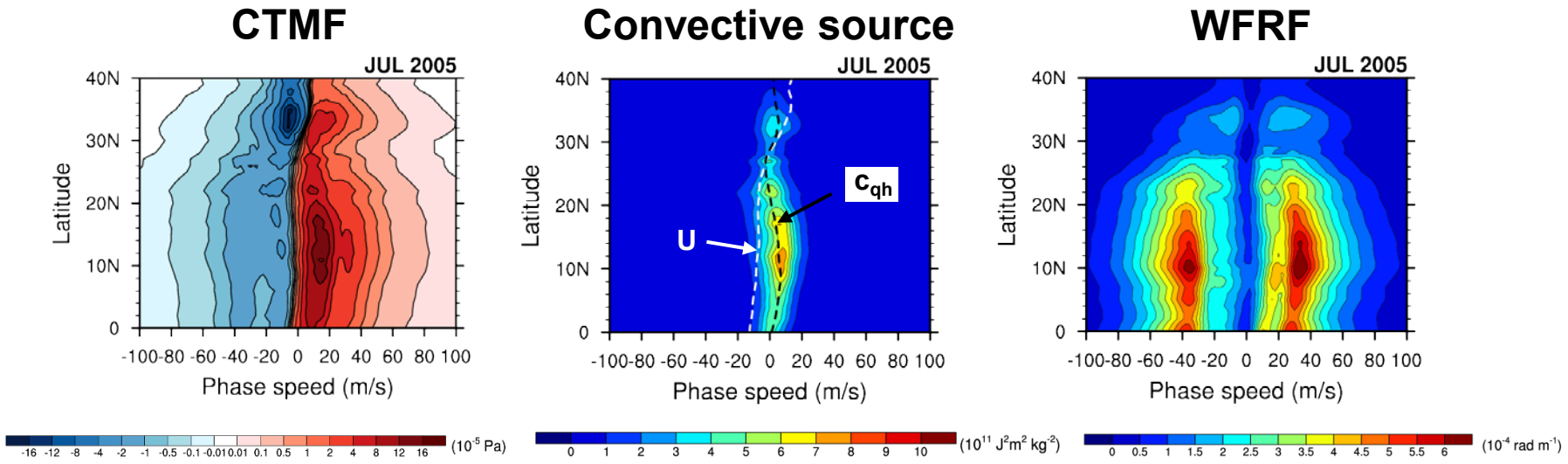

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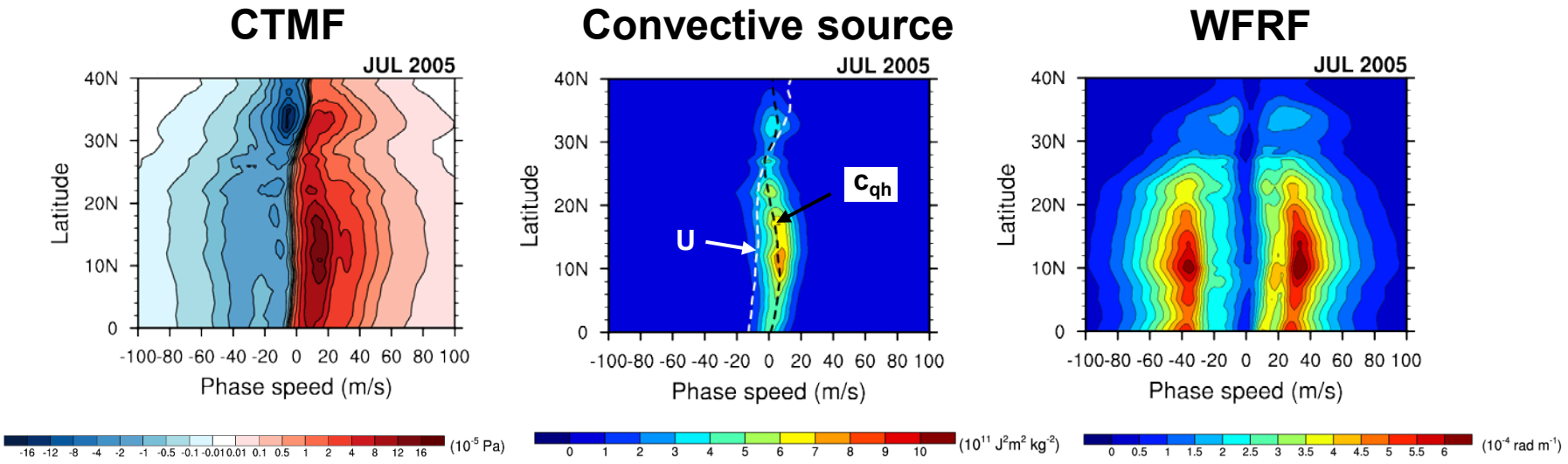

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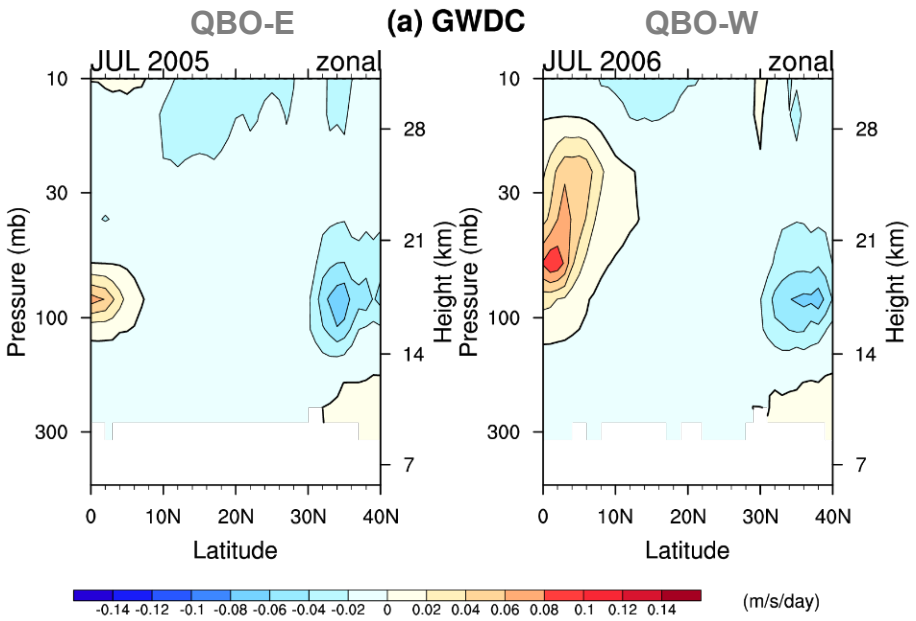
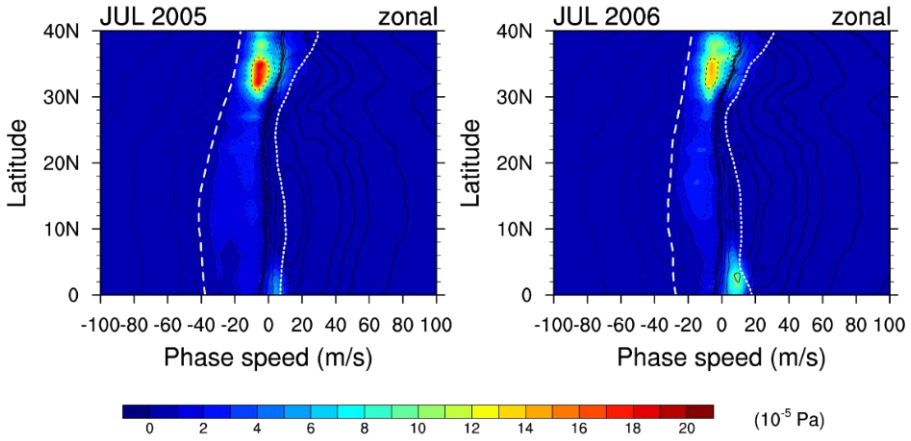
How this shape of the CTMF spectrum can affect GWDC?

CTMF spectrum → GWDC Asian summer monsoon region



Difference in GWMF spectrum between cloud top and 10 hPa ($=MF_{ct} - MF_{10\ hPa}$)



Dotted line: maximum zonal wind
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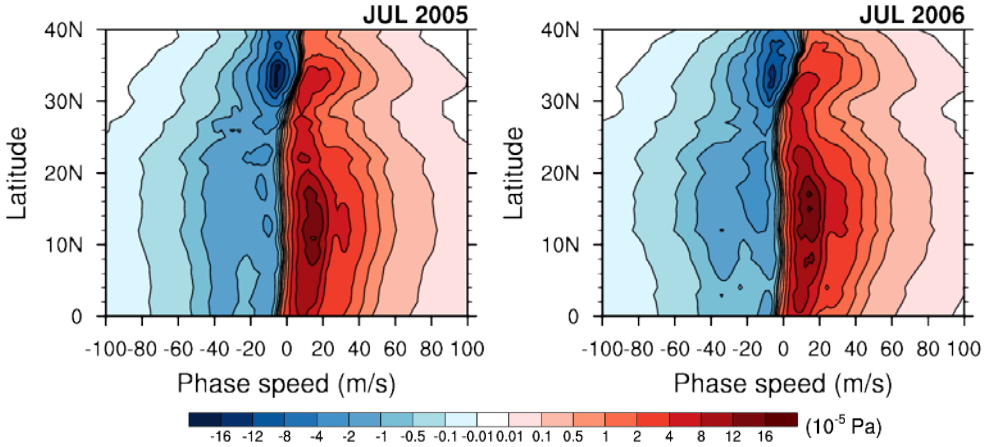
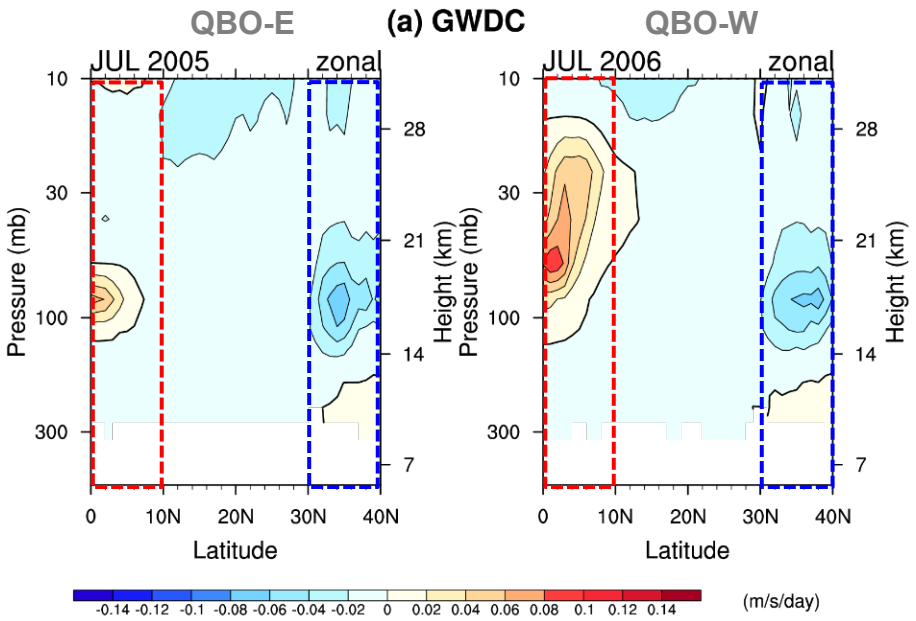
CTMF spectrum



CTMF spectrum → GWDC Asian summer monsoon region



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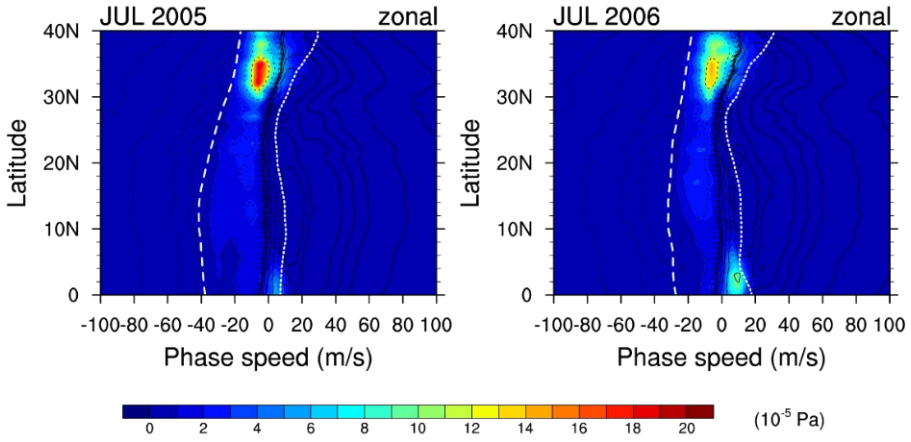

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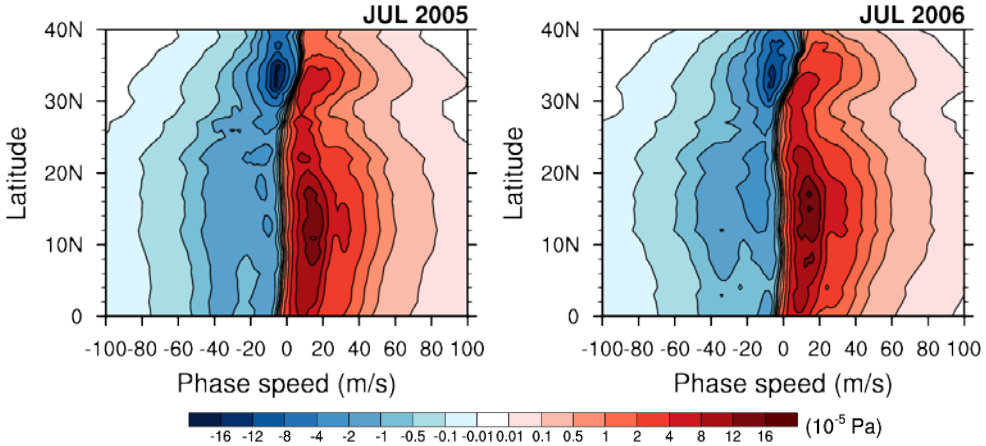

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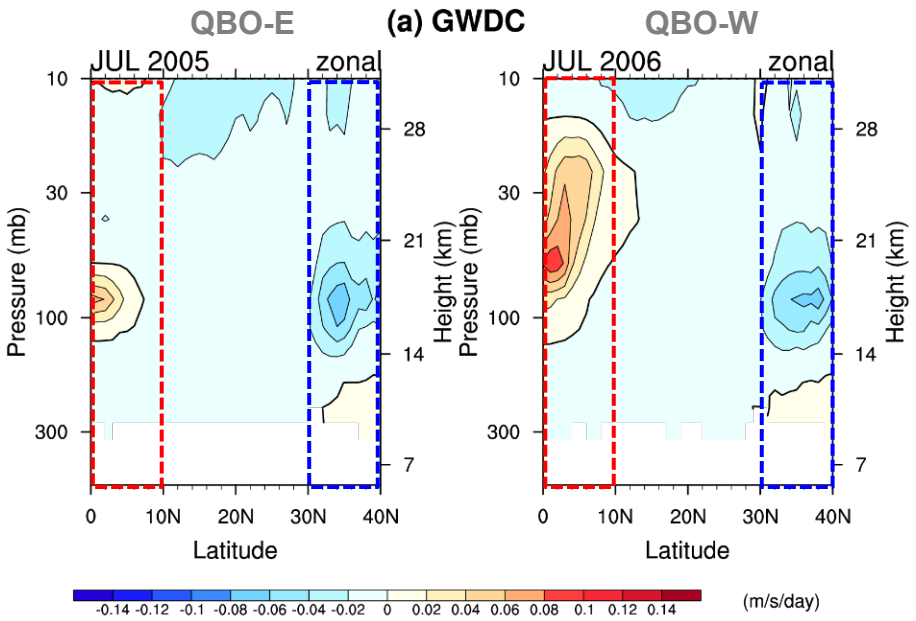

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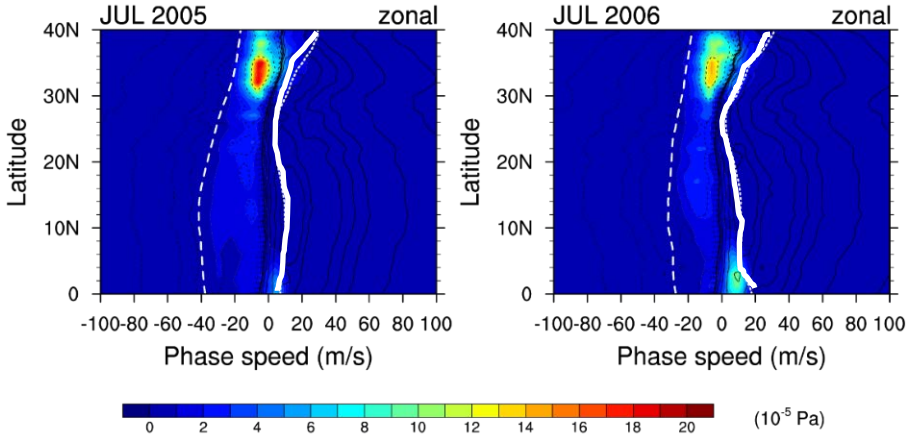

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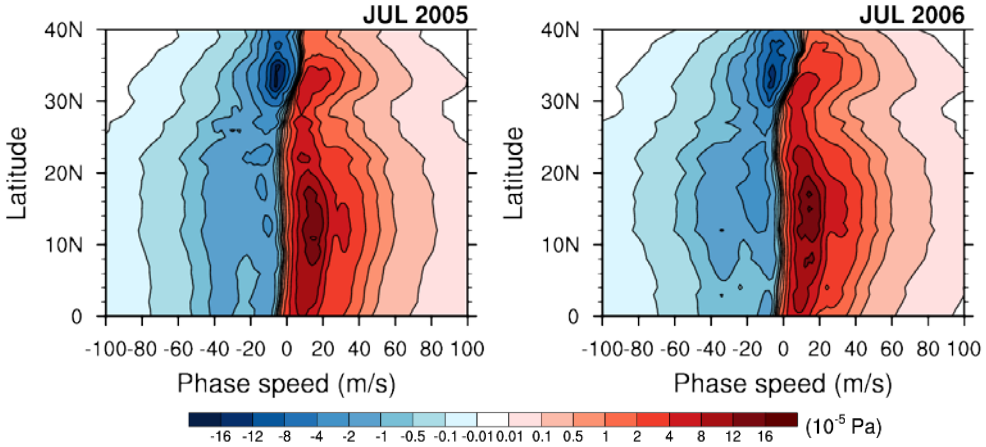

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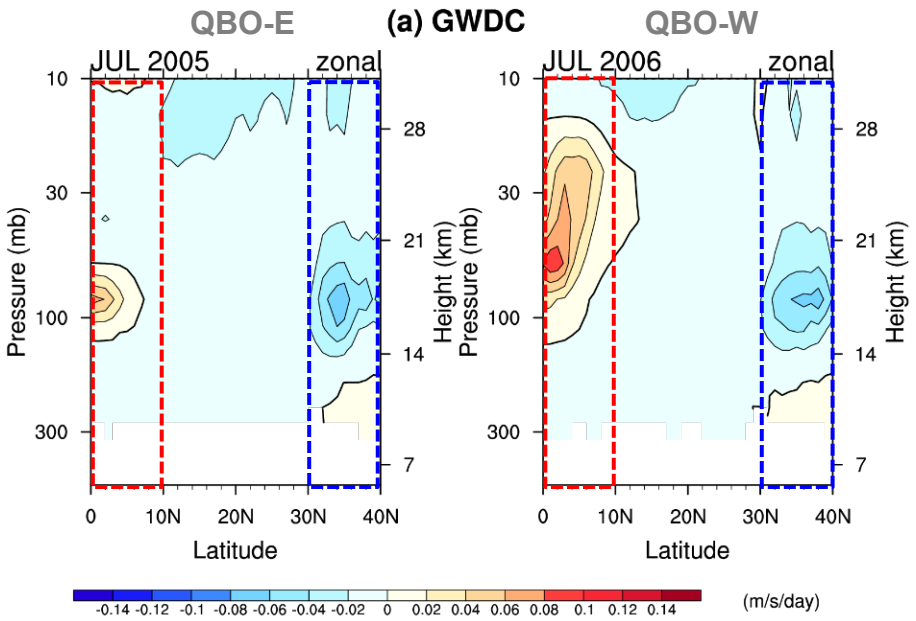

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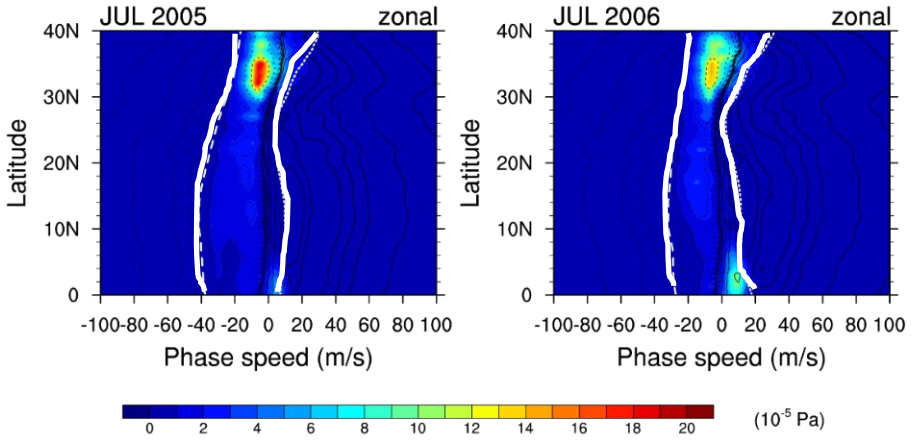

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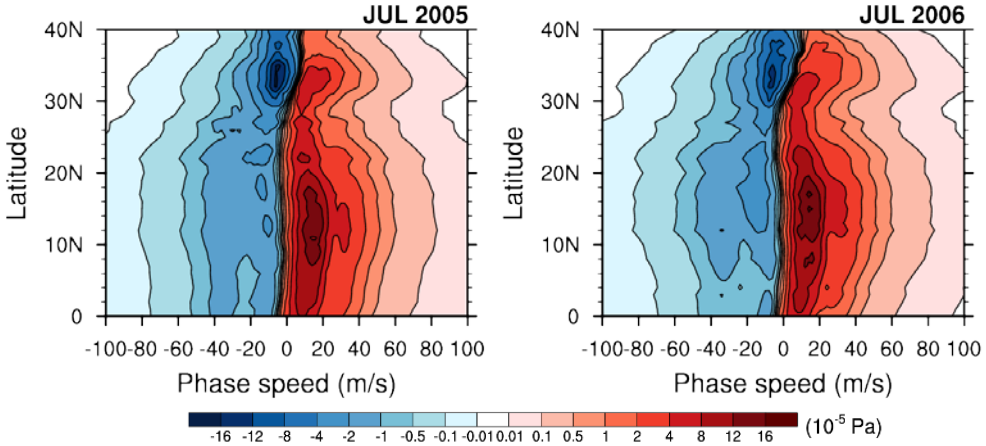

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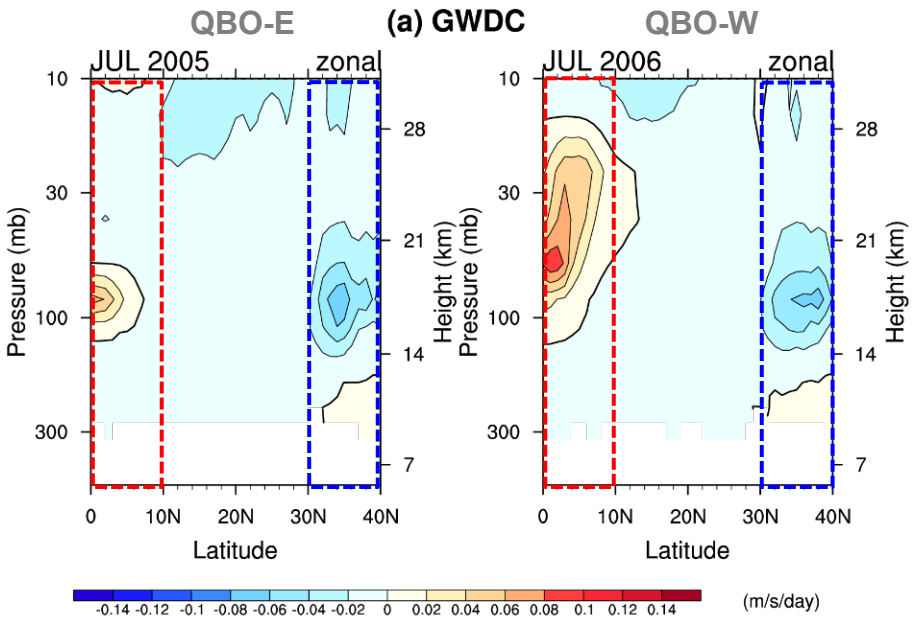

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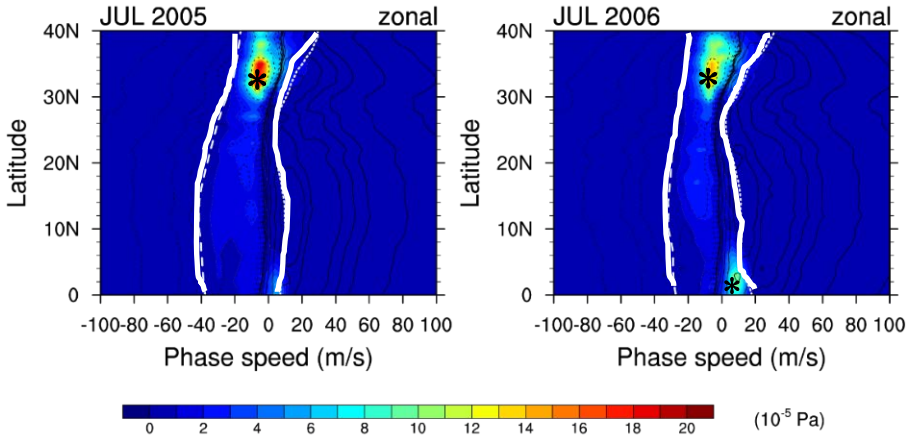

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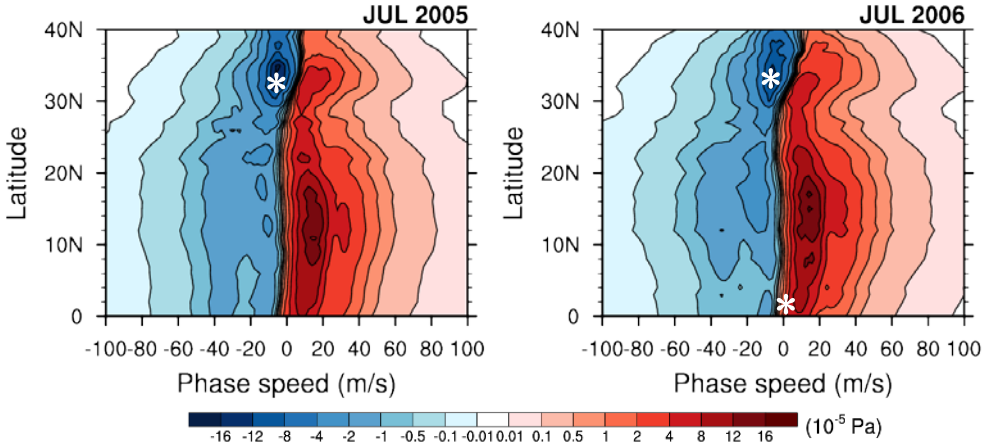

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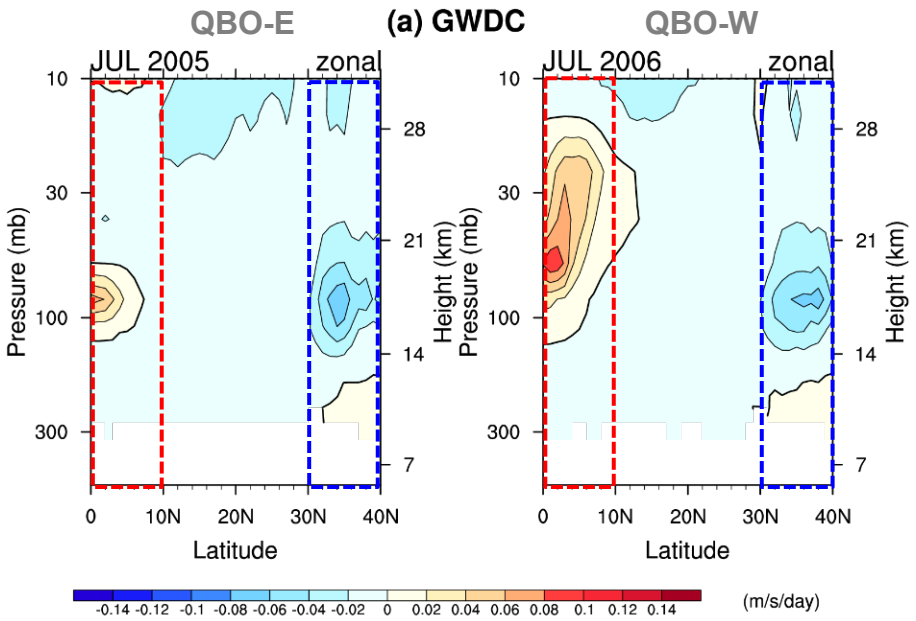

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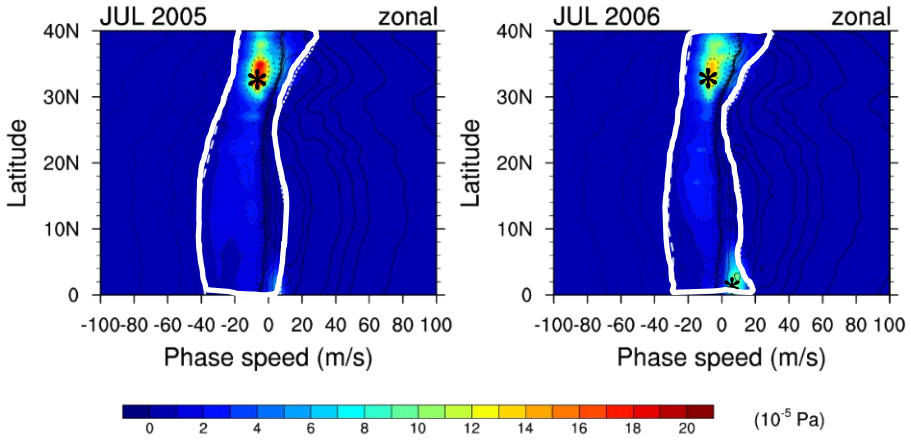

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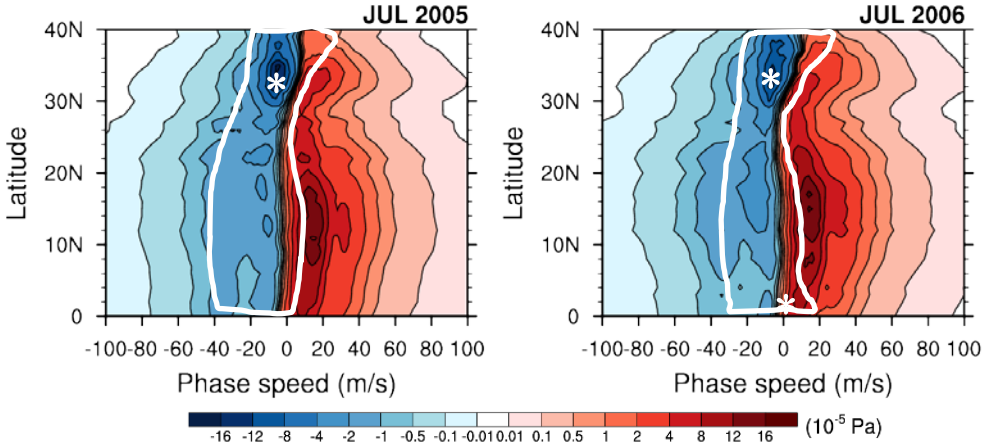

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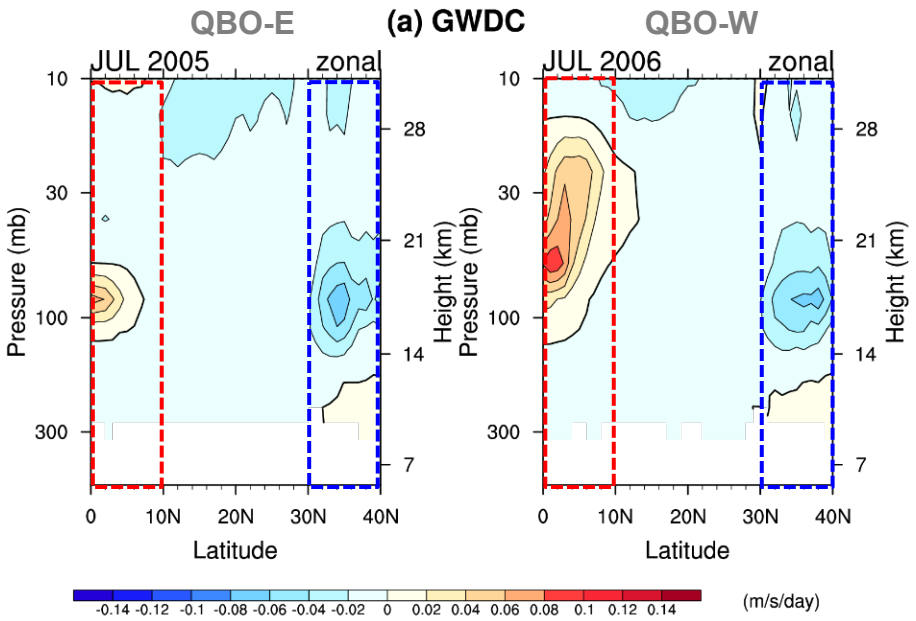

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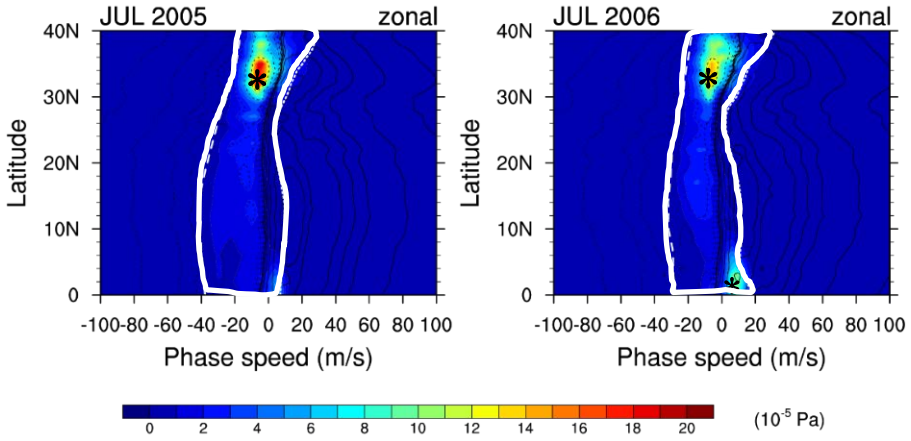

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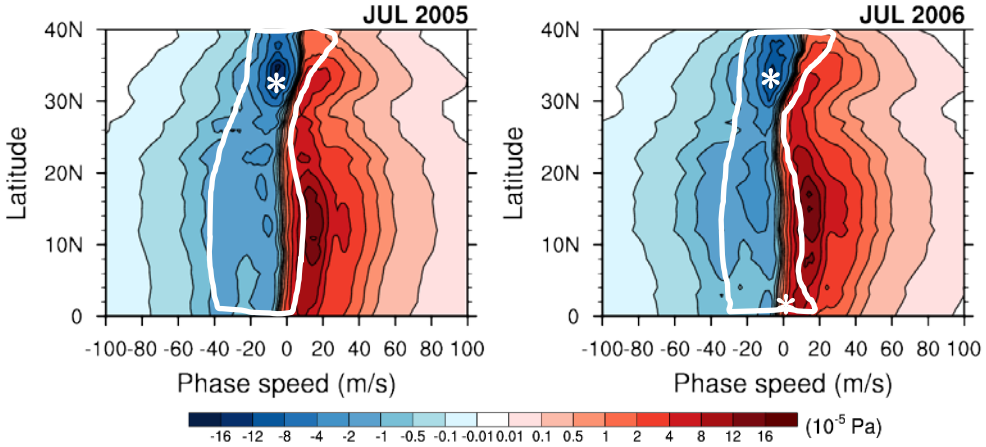
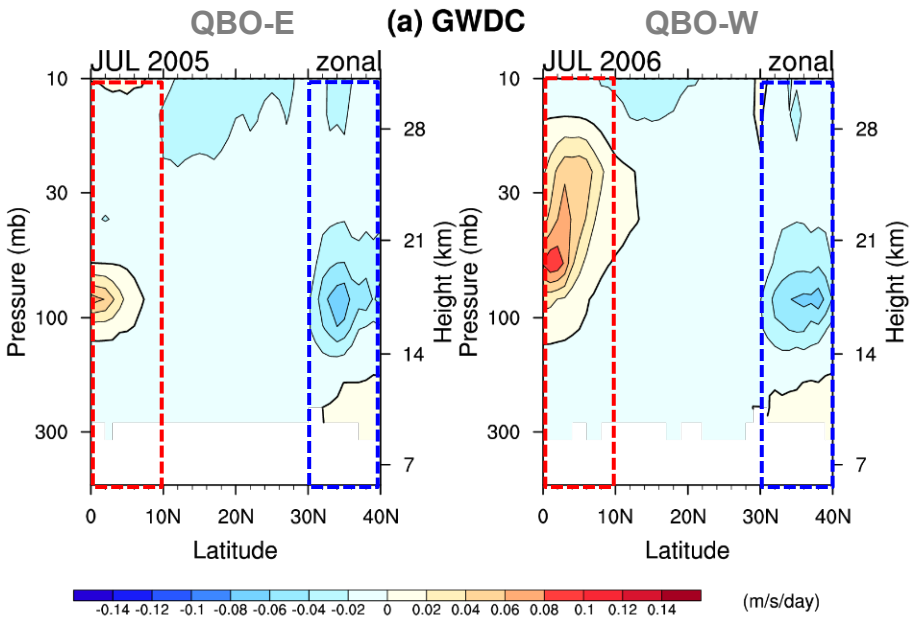


If **peak of the CTMF** is located within the wind filtering region

Large dissipation

Large GWDC

CTMF spectrum → GWDC Asian summer monsoon region



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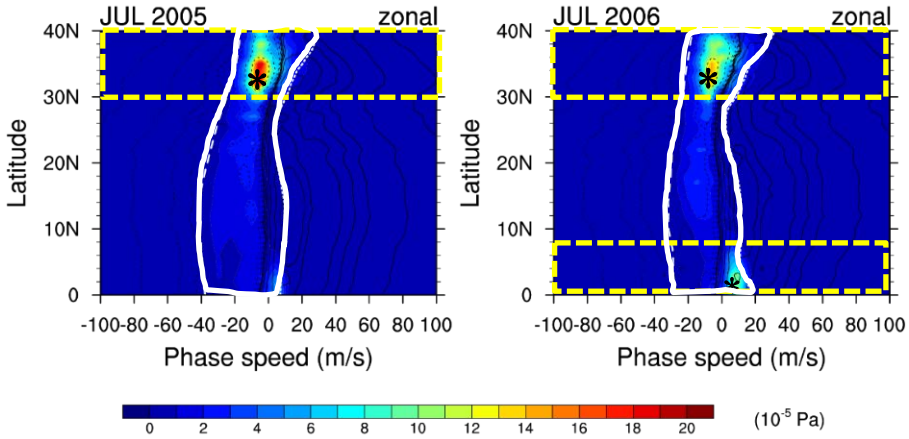

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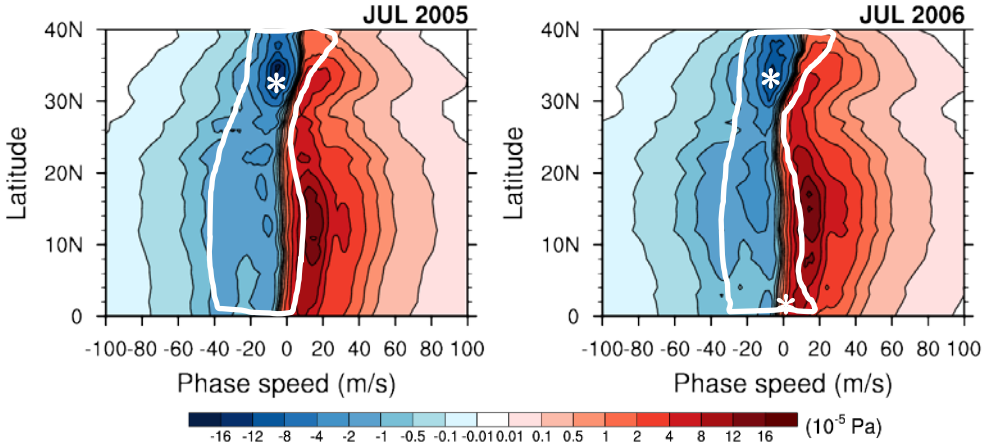

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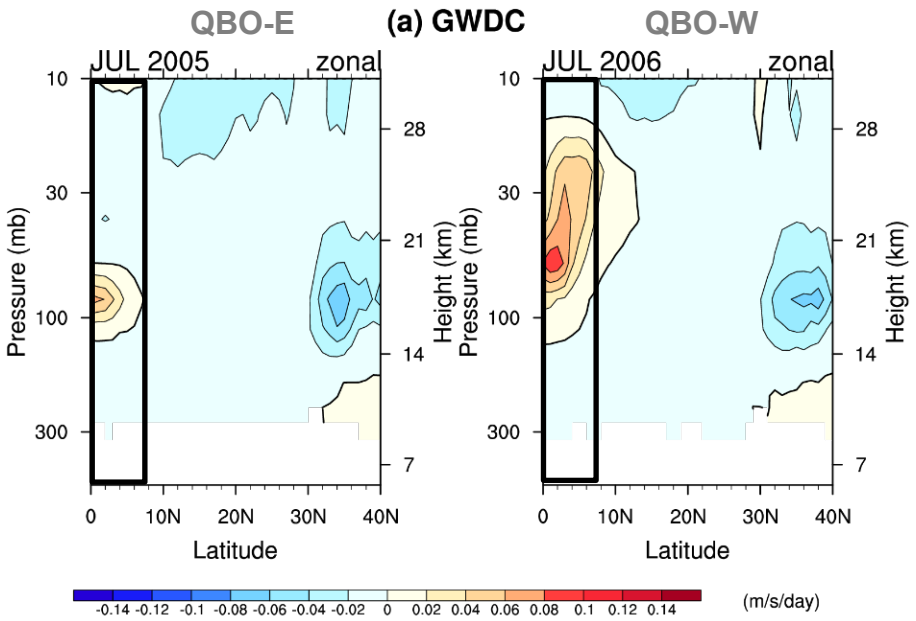

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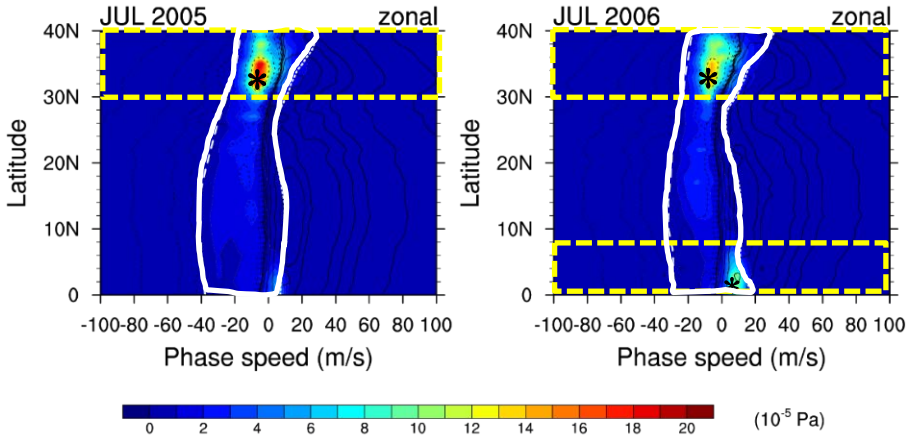

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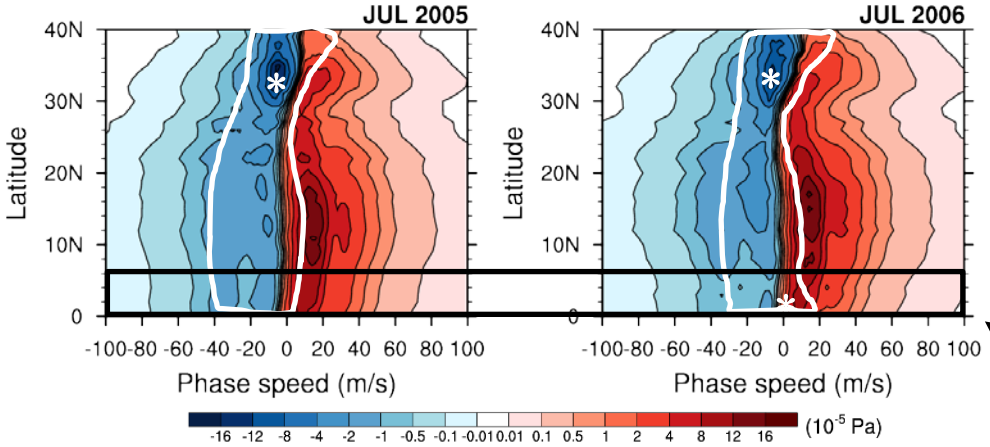

If **peak of the CTMF** is located within the wind filtering region

Large dissipation

Large GWDC

The **positive peak** can cause **large difference in GWDC between** two **QBO phases**

Summary and conclusion

Spatiotemporal variations in CTMF

- CTMF is determined not only by magnitude of convective heating but also by wave-filtering and resonance factor, several conditions within convection, and wave nonlinearity.
- CTMF spectrum is highly fluctuate with both time and space in terms of its shape and magnitude.

CTMF spectrum and GWDC in Asian summer monsoon region

- The magnitude of GWDC is largely influenced by the CTMF spectrum.
  - Maximum drag in the stratosphere occurs where spectral peak of CTMF is located within the critical-level filtering region.

➔ **Physically and mathematically consistent source spectrum (CTMF) of CGWs is required for realistic spatiotemporal variabilities in GWDC of the stratosphere.**

Thank you for your attention.

Spatial variability

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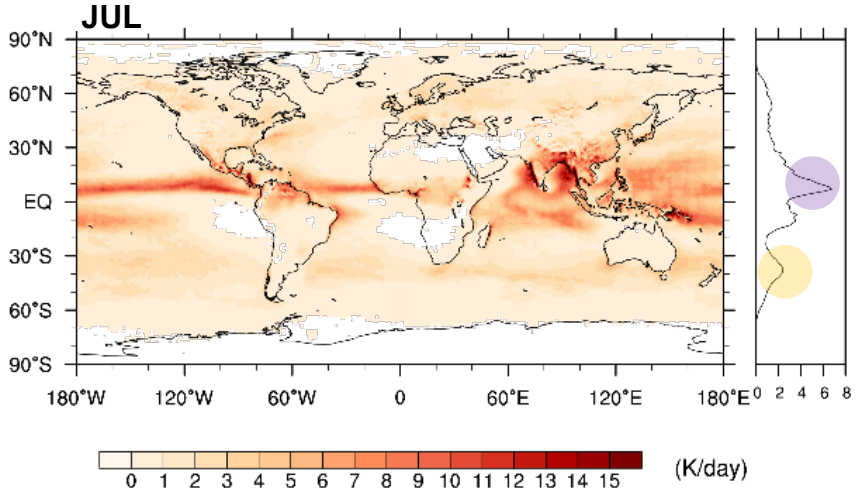
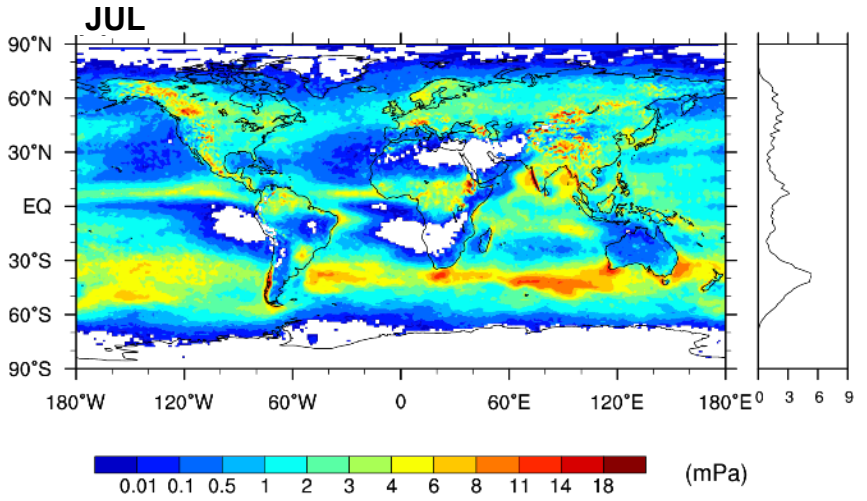
CTMF — WFRF — Convective source ∝ DCH

DCH (CFSR)

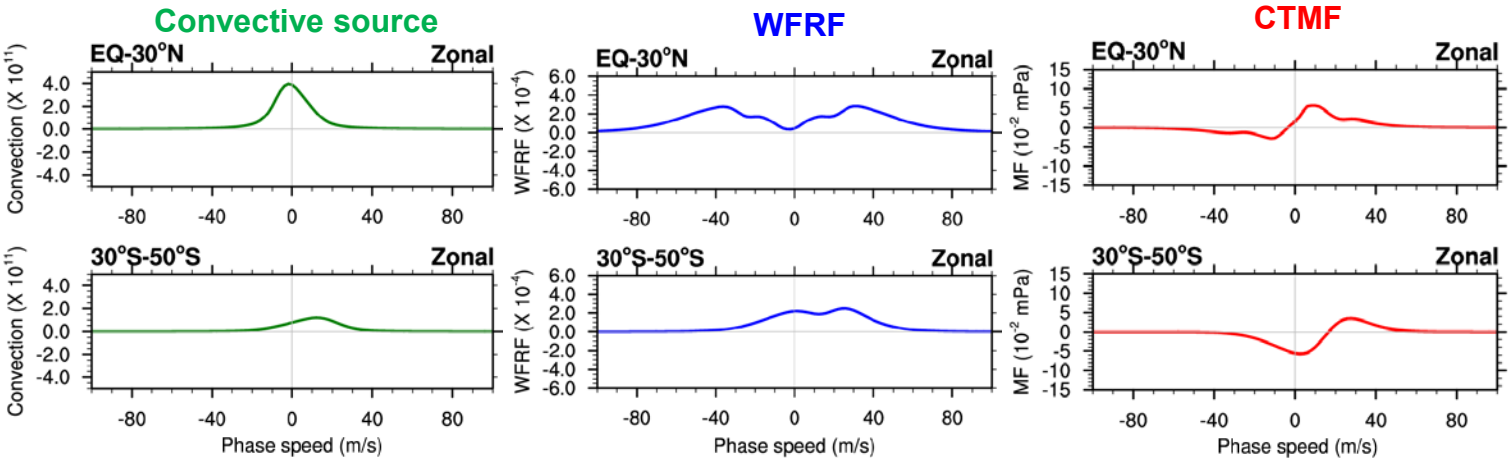


CTMF (CFSR)



Summer hemisphere subtropic

Winter hemisphere storm-track

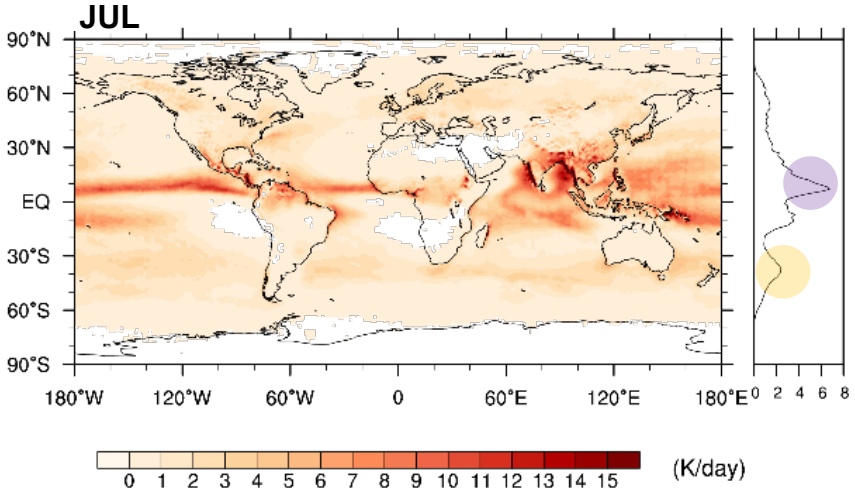


Spatial variability

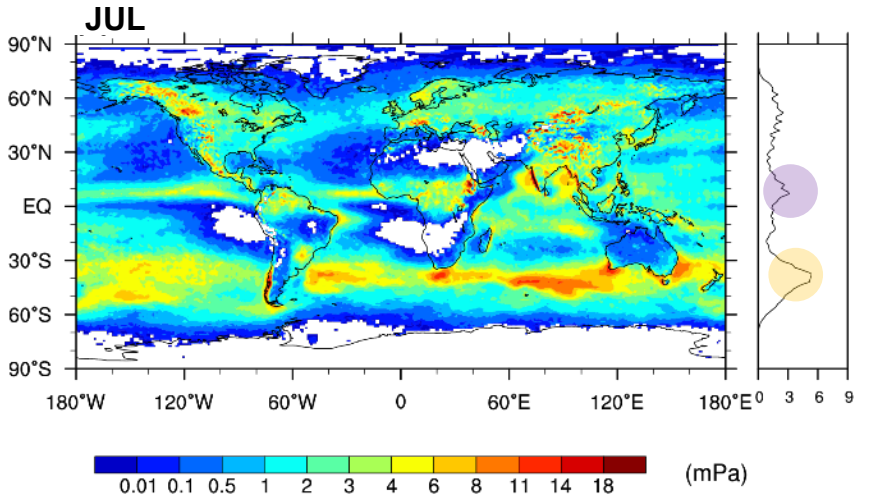
$$CTMF(c,\varphi) = \mathrm{sgn}[c - U_{ct}(\varphi)]\rho_{ct}\frac{2(2\pi)^3}{A_h L_t}\left(\frac{g}{c_p T_q N_q^2}\right)^2 \times \frac{N_{ct}|X|^2}{|c - U_{ct}(\varphi)|}\Theta(c,\varphi) \times F(\mu)$$

CTMF — WFRF — Convective source ∝ DCH

DCH (CFSR)



CTMF (CFSR)



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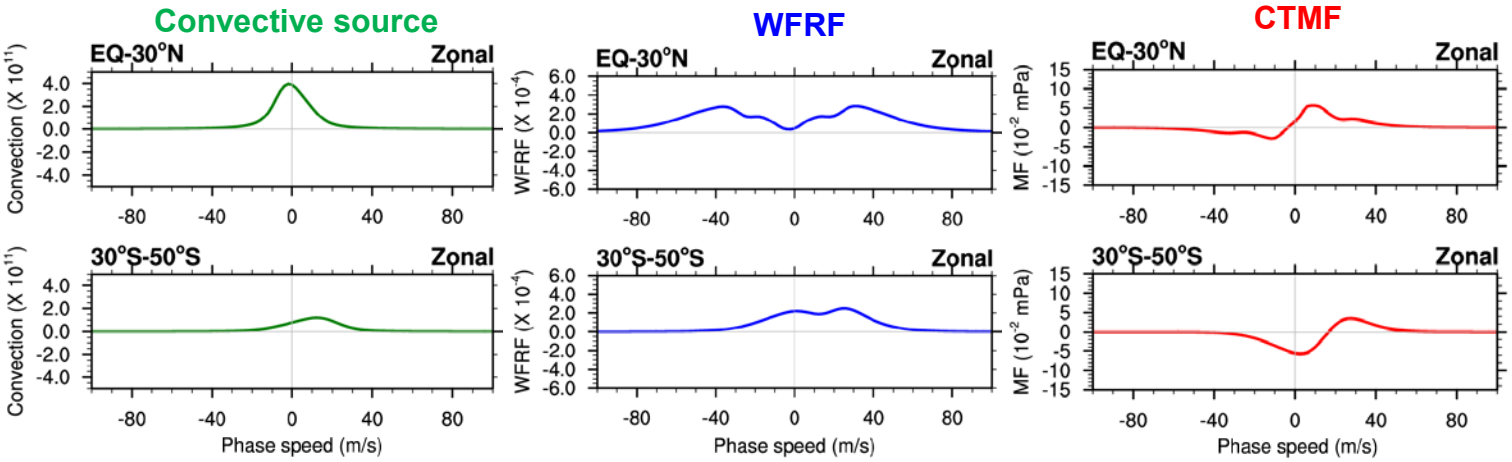


CTMF formulation

Cloud-Top Momentum Flux spectrum

$$CTMF(c,\varphi) = \mathrm{sgn}[c - U_{ct}(\varphi)]\rho_{ct} \frac{2(2\pi)^3}{A_h L_t} \left(\frac{g}{c_p T_q N_q^2} \right)^2 \times \frac{N_{ct} |X|^2}{|c - U'_{ct}(\varphi)|} \Theta(c,\varphi) \times F(\mu)$$

WFRF — Convective source — Nonlinear forcing effect

$$F(\mu) = 1/(1 + a\mu^b)$$

$$a = 0.48792 \quad b = 1.64896$$

$$\mu = \frac{gQ_0 L}{c_p T_0 N_c U_c^2}$$

Nonlinearity

WFRF (wave-filtering and resonance factor)

- basic-state wind
- stability
- vertical configuration of heating profile

$$X = \begin{cases} \dfrac{X_{u1}X_{u2}(2Y_{u1} - \overline{X}_{u2}\overline{Y}_{u1}) + \overline{X}_{u1}\overline{X}_{u2}(2\overline{Y}_{u1} - X_{u2}Y_{u1})}{2(X_{\_}X_{u1}X_{u2} + X_{+}\overline{X}_{u1}\overline{X}_{u2})} & \text{for } U_0 = U_t, \\ \dfrac{X_{s4}\overline{Y}_{s3}(X_{s2} - X_{s3}X_{s0}) + \overline{X}_{s4}Y_{s3}(\overline{X}_{s3} - \overline{X}_{s2}X_{s0}) + X_{s5}}{X_{\_}X_{s4}(X_{s2} - X_{s3}X_{s0}) + X_{+}\overline{X}_{s4}(\overline{X}_{s3} - \overline{X}_{s2}X_{s0})} & \text{for } U_0 \neq U_t, \end{cases}$$

Wave-filtering and resonance factor

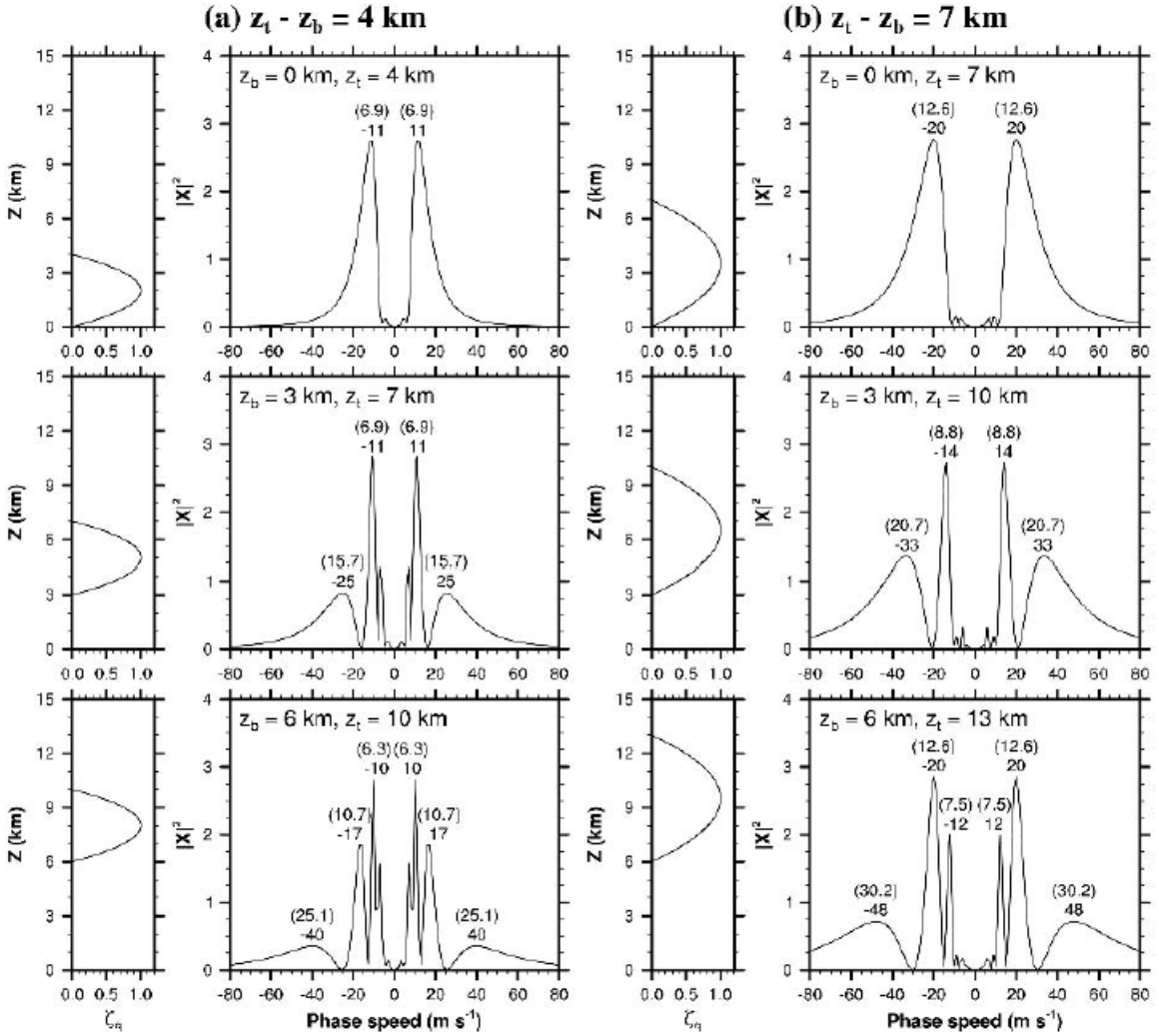


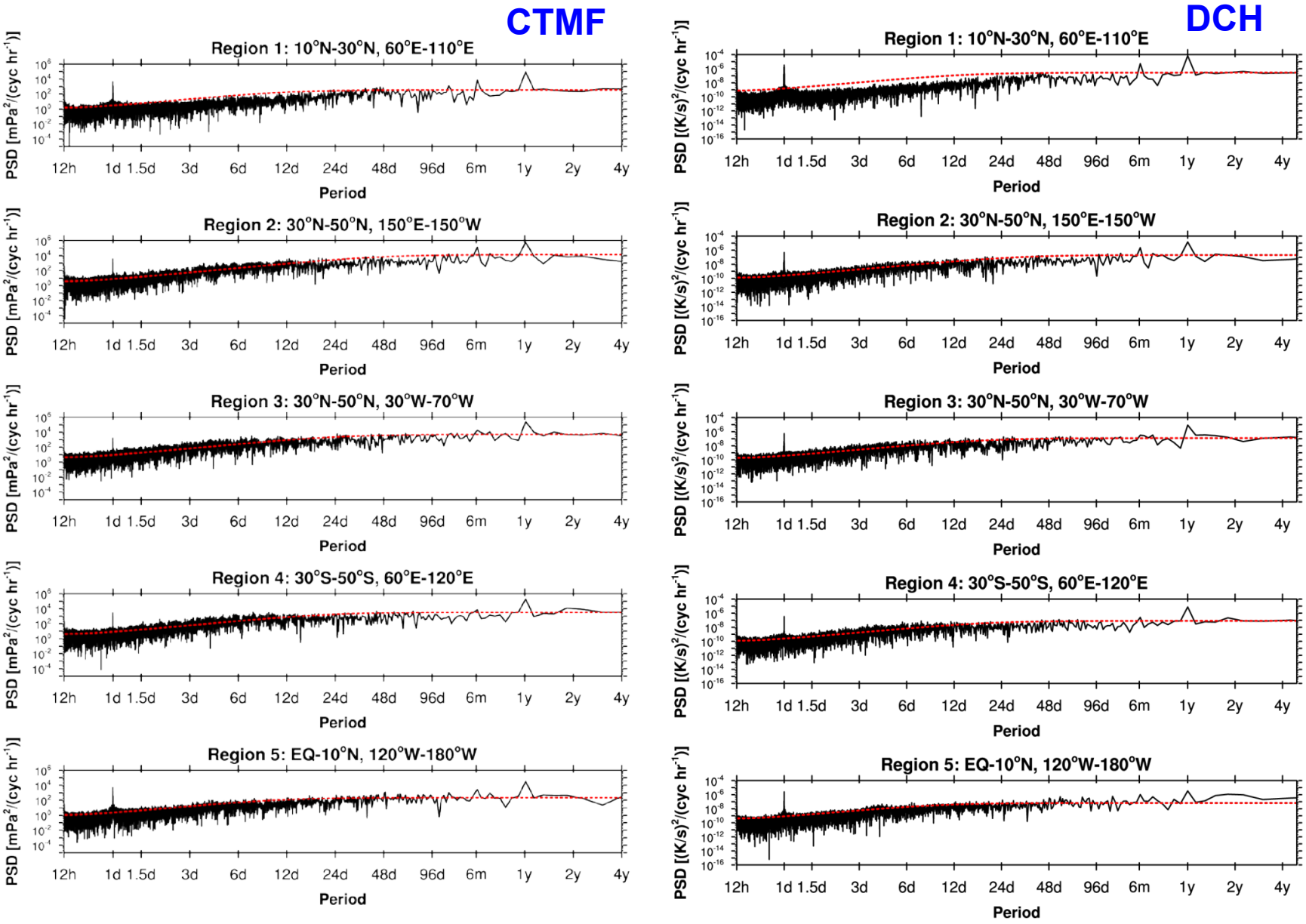
FIG. 4. The $|X|^2$ values for diabatic forcings with two different depths ($z_t - z_b$) of (a) 4 and (b) 7 km and their dependency on the center height $[(z_t + z_b)/2]$ of forcing under the vertically uniform basic-state wind ($U_0 = U_t = 0$ m s^{-1}) and stability ($N_1 = N_2 = 0.01$ rad s^{-1}) condition. Peak phase speeds are numbered over peaks, and numbers in parentheses are vertical wavelengths corresponding to the peak phase speeds.

$$\lambda_z = 2\pi \frac{|U_t - c|}{N_2}$$

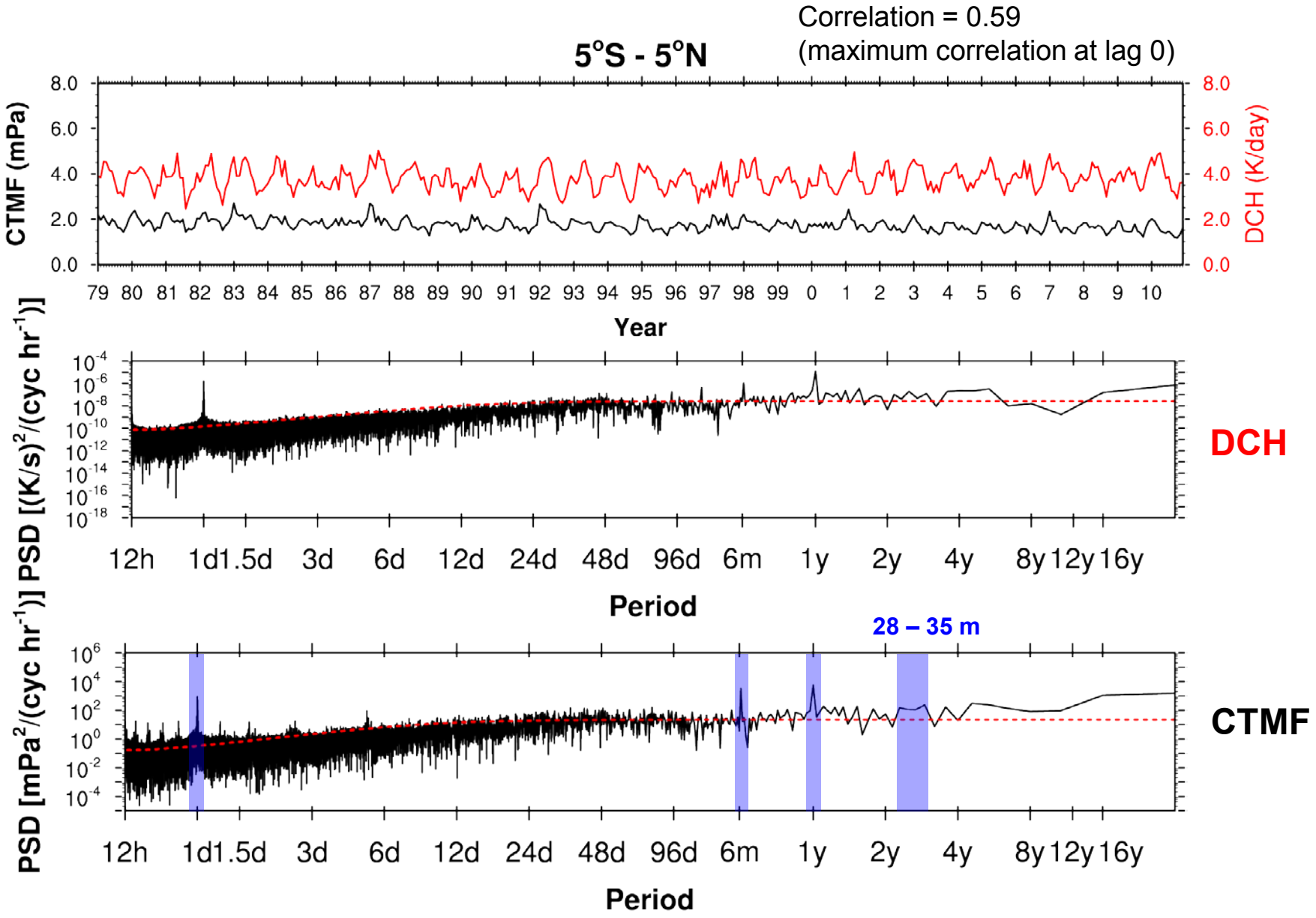
Song and Chun (2005)

Spatiotemporal variations

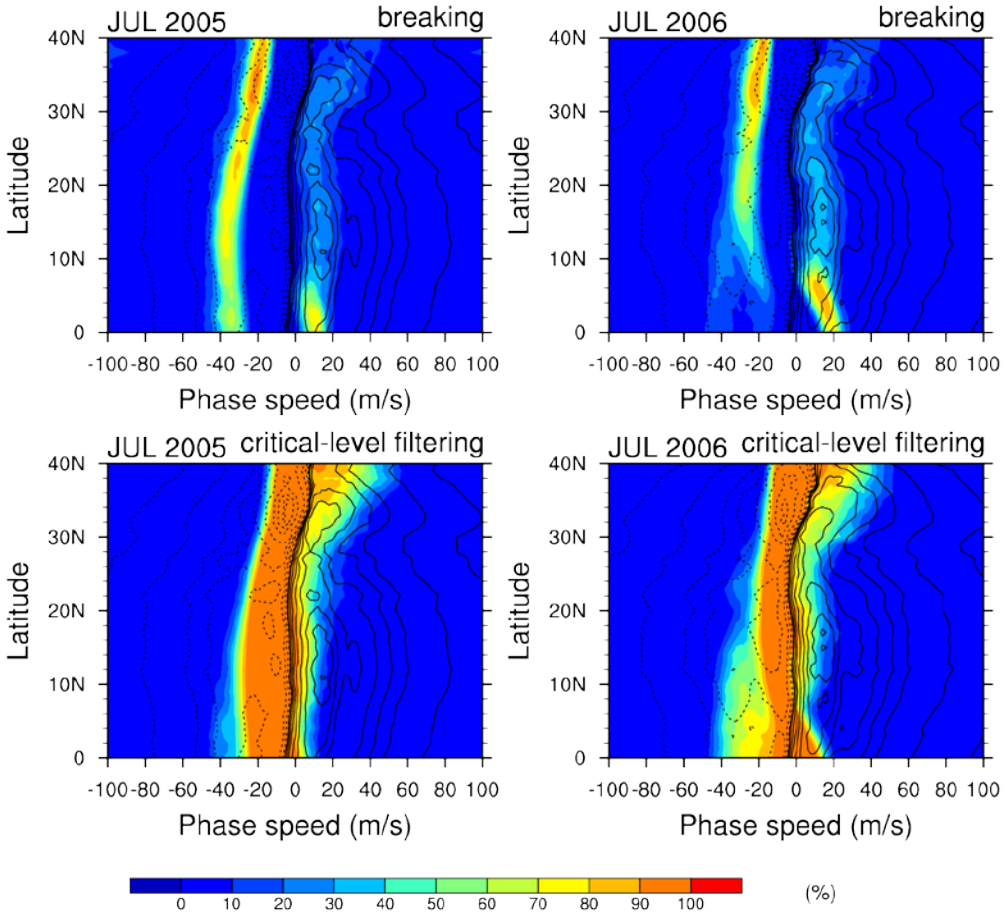
Power Spectral Density



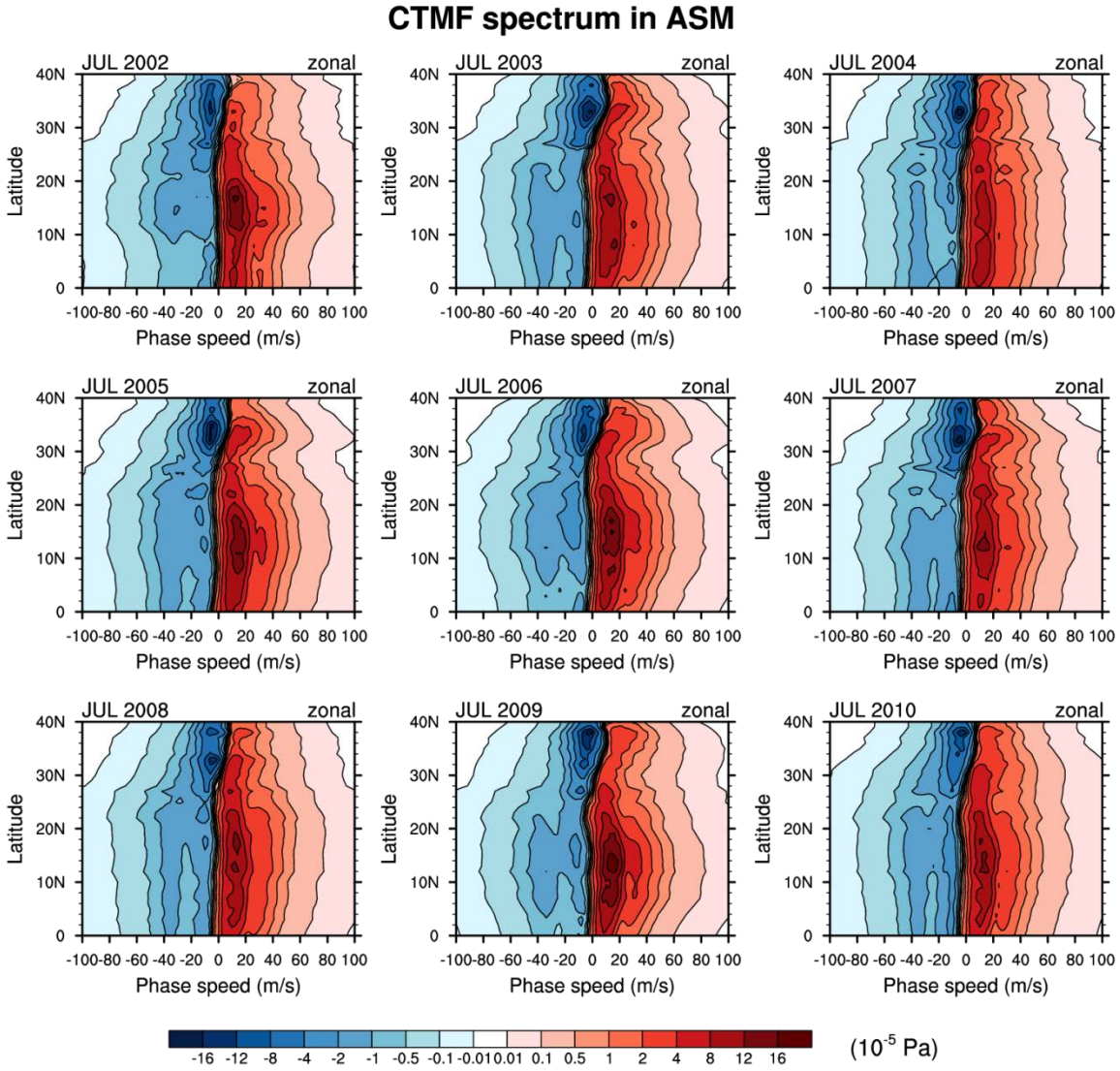
32 year time series & PSD of CTMF



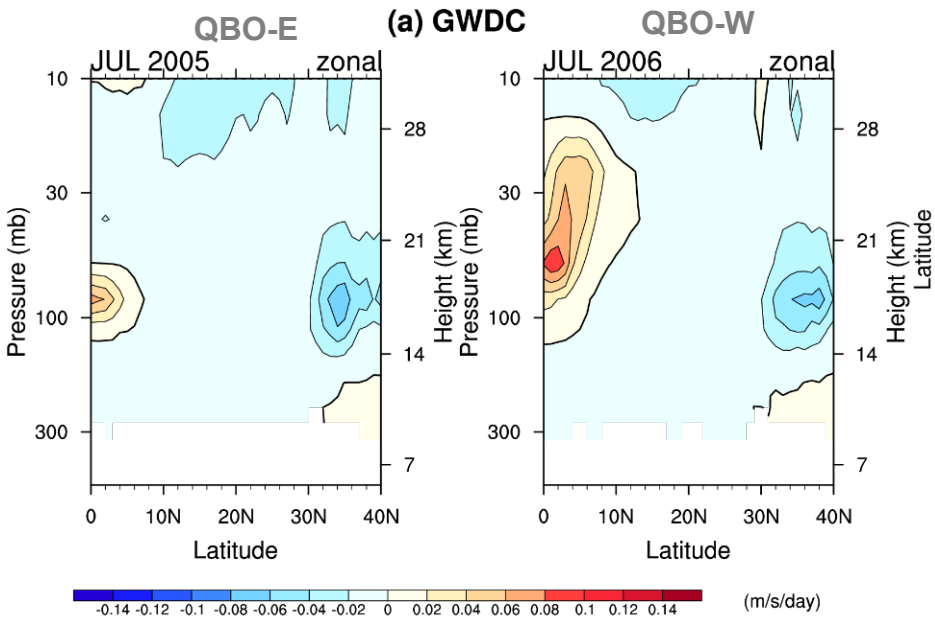
Percentage of each dissipation mechanism



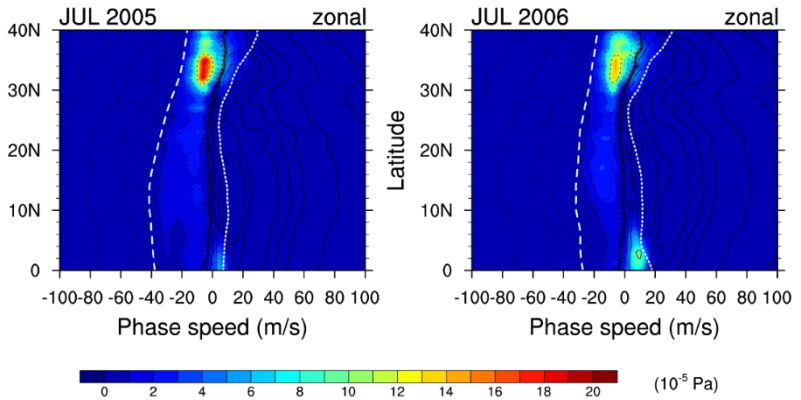
CTMF spectrum in ASM (2002-2010)



CTMF spectrum ↔ GWDC

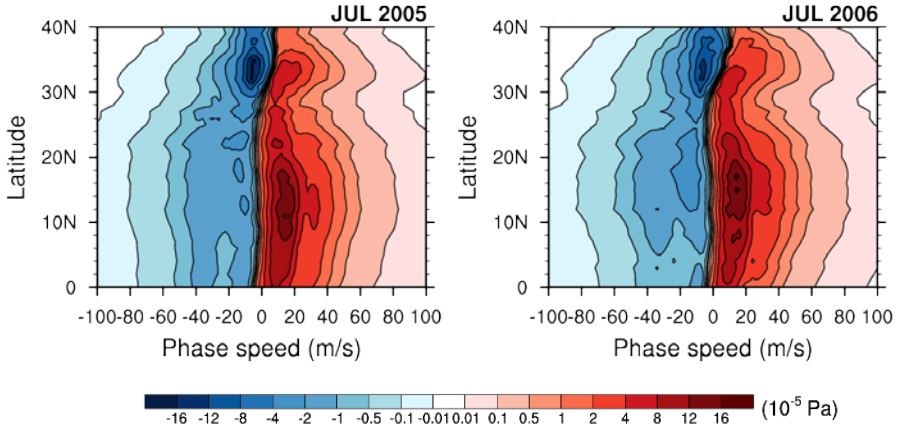


Difference in GWMF spectrum between cloud top and 10 hPa ($=MF_{ct} - MF_{10\ hPa}$)



Dotted line: maximum wind
Dashed line: minimum wind

CTMF spectrum



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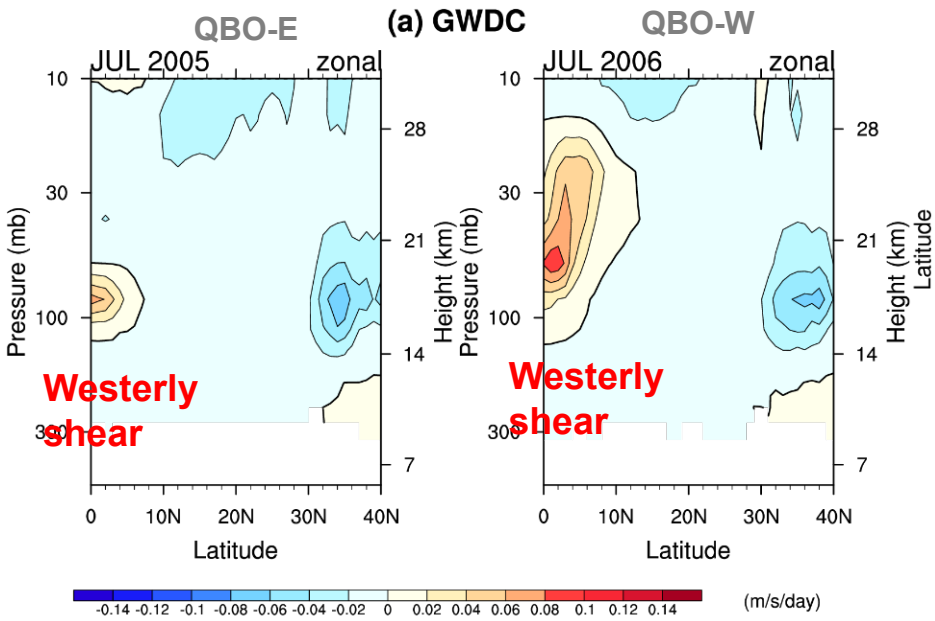
A. Within the filtering region, **spectral peaks** are located.

CTMF spectrum ↔ GWDC



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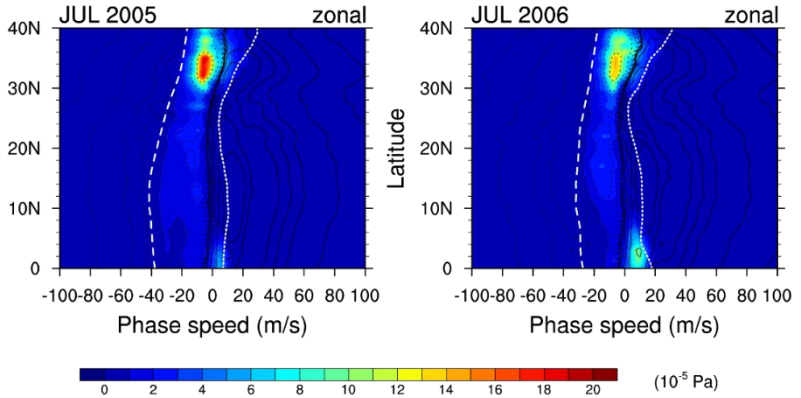

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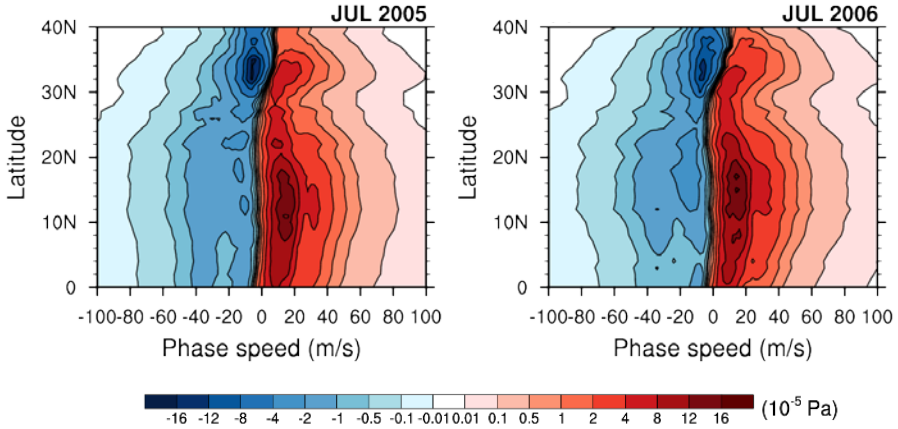

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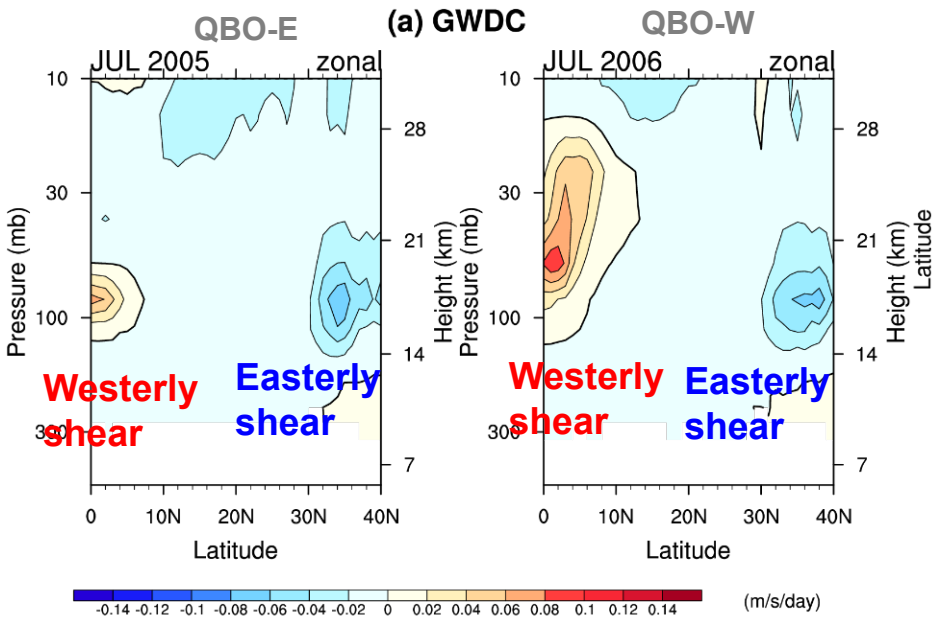

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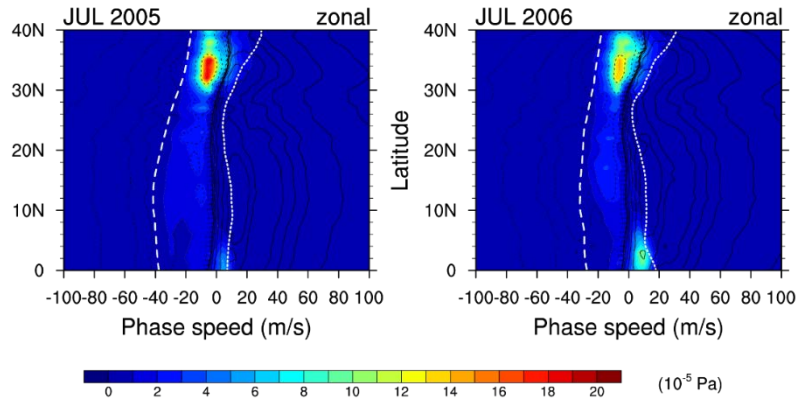

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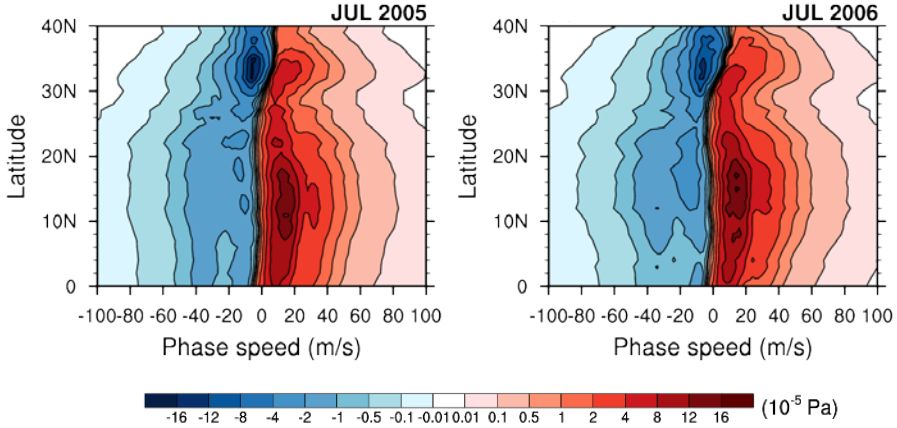
CTMF spectrum



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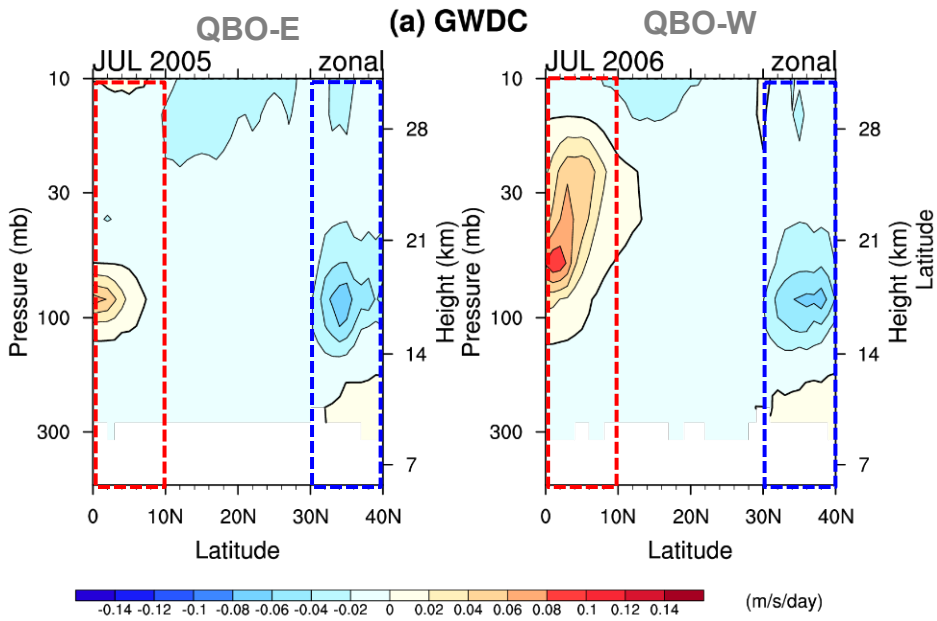

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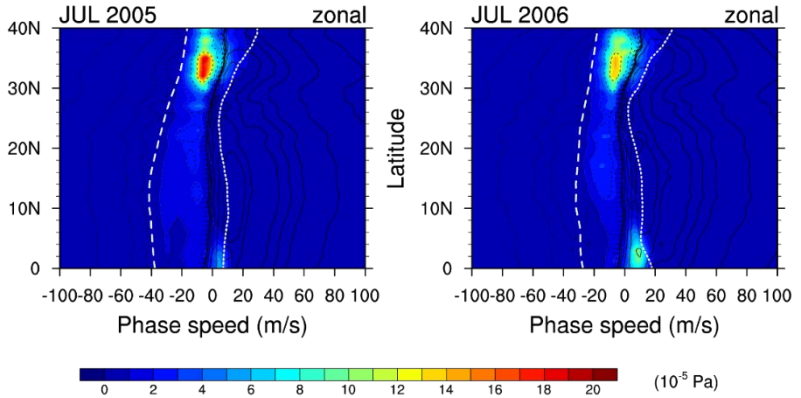

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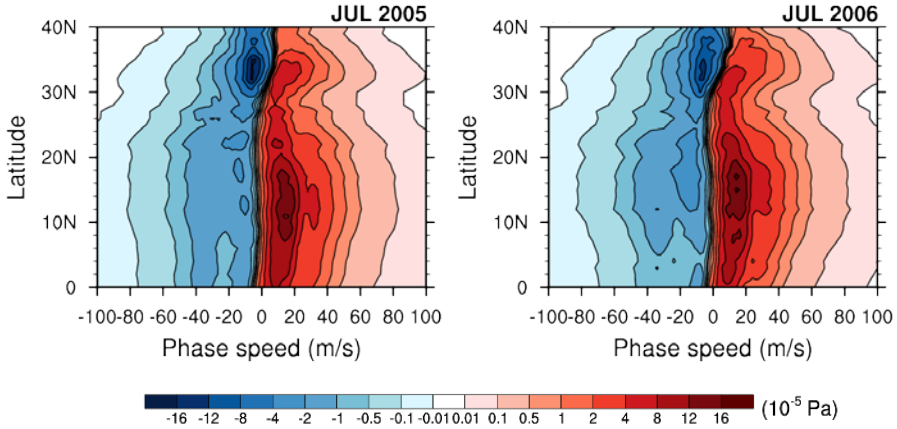
CTMF spectrum



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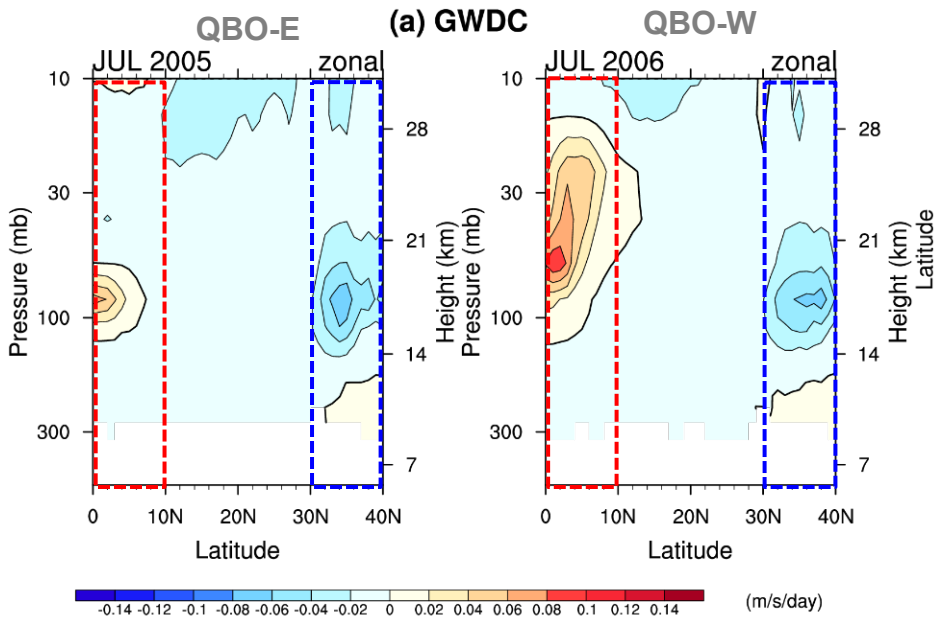

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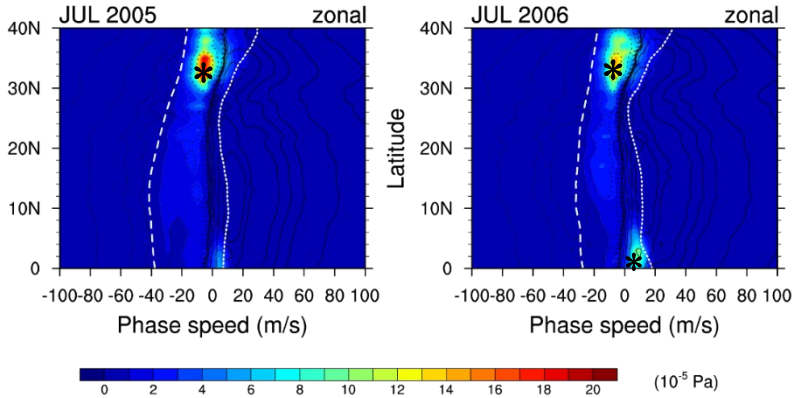

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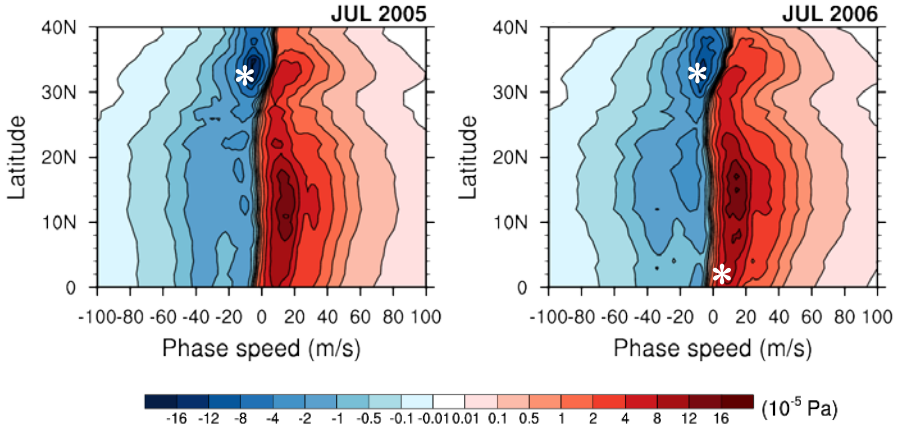

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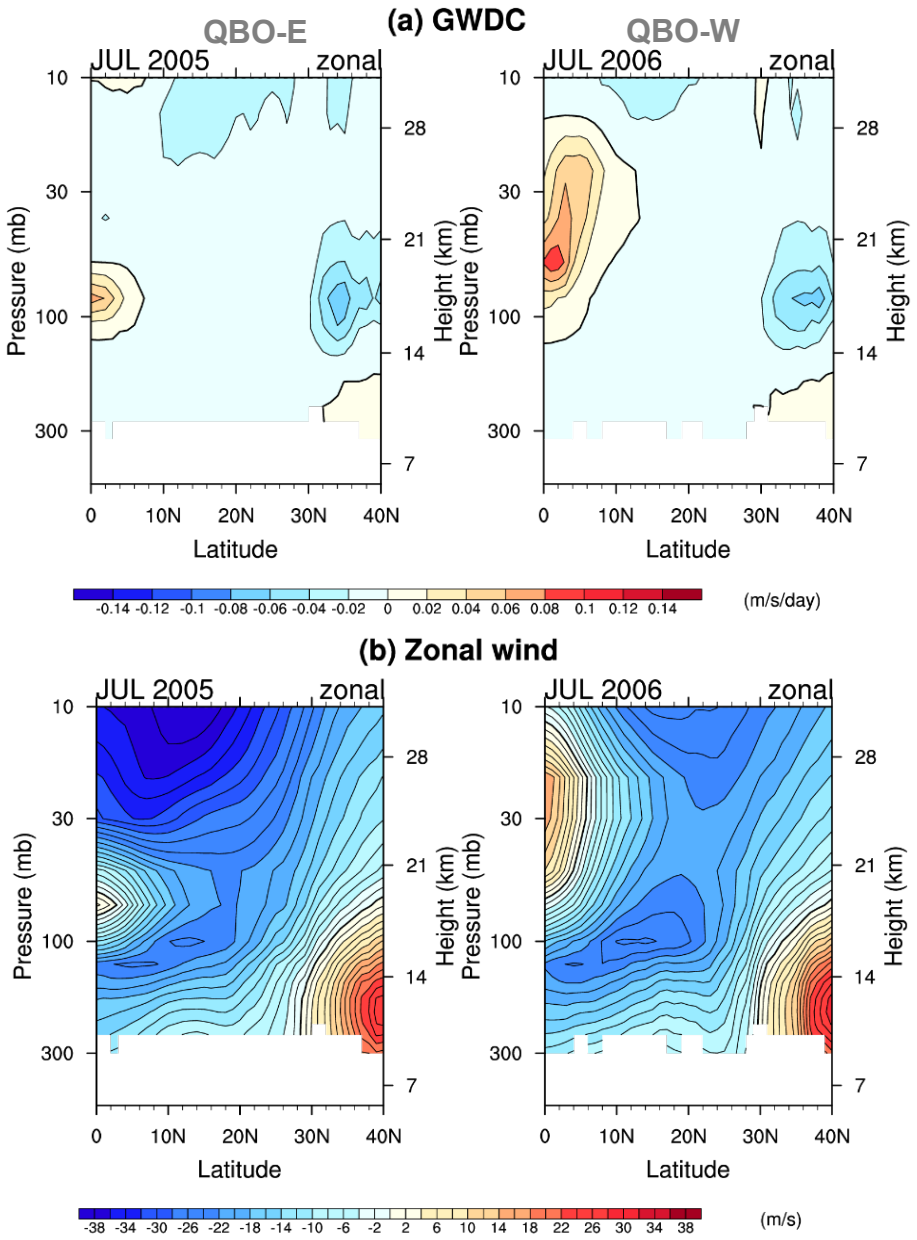

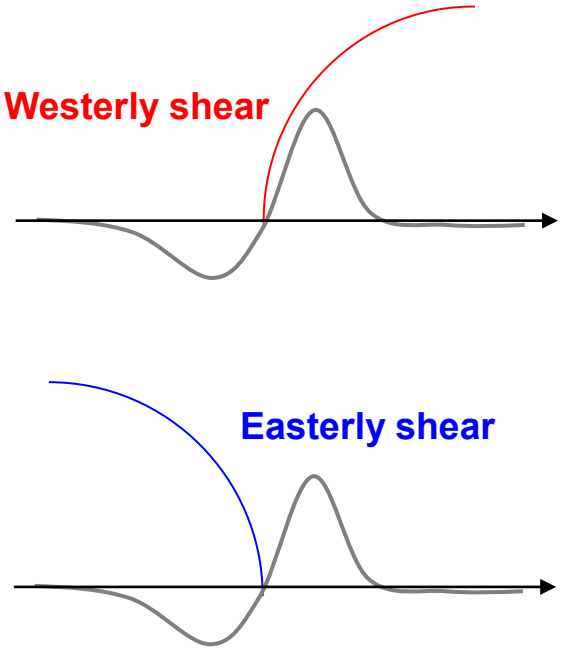

Q. What determines the **sign of drag** ?

A. Sign of the **vertical wind shear** (mainly due to the **critical-level filtering**)

CTMF spectrum Asian Summer monsoon region

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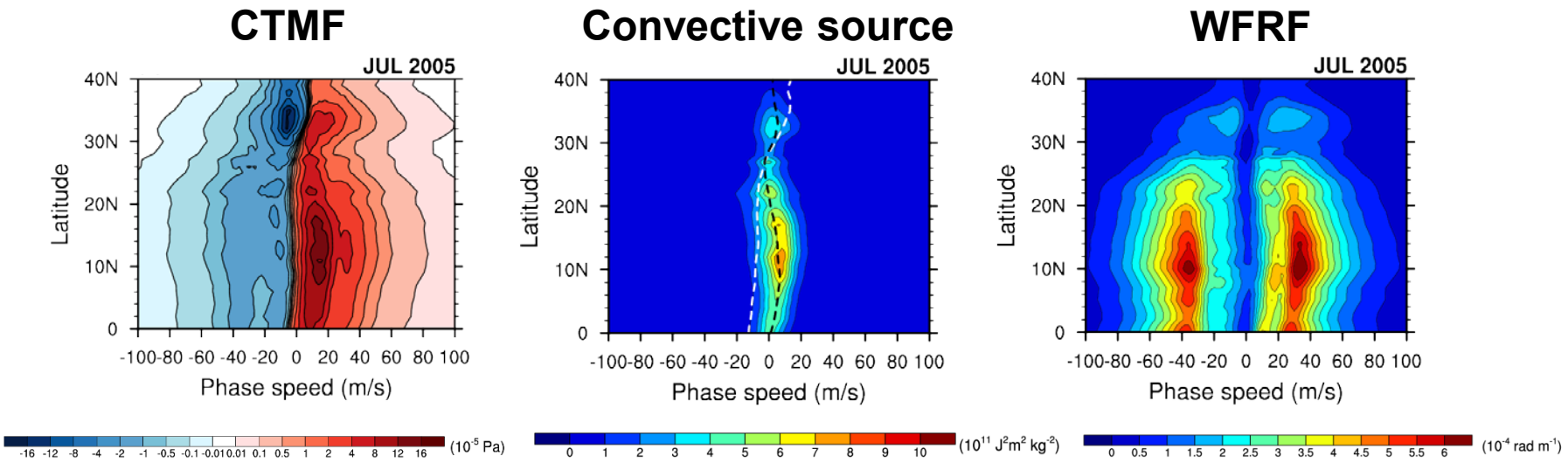

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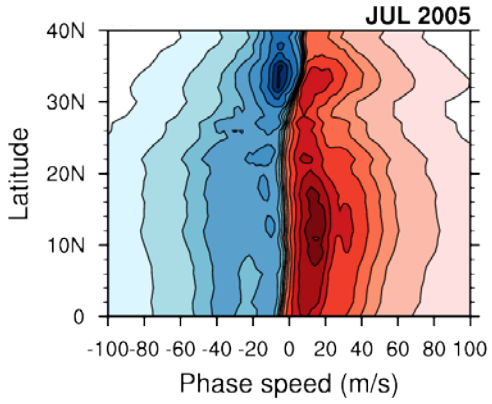
WFRF

Convective source

CTMF



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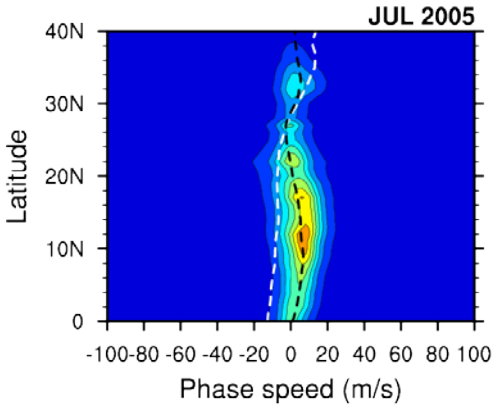
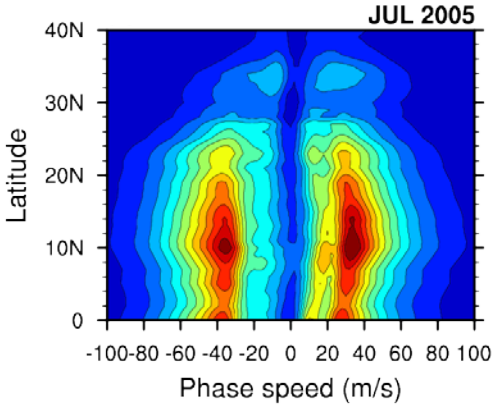
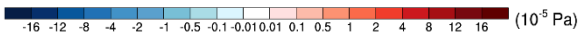
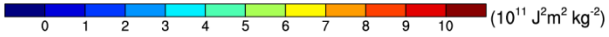
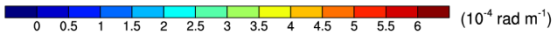


WFRF









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WFRF

Convective source

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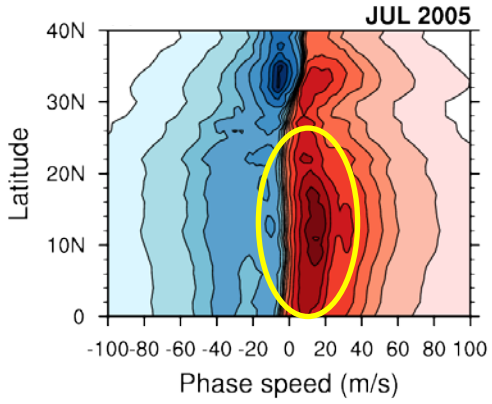

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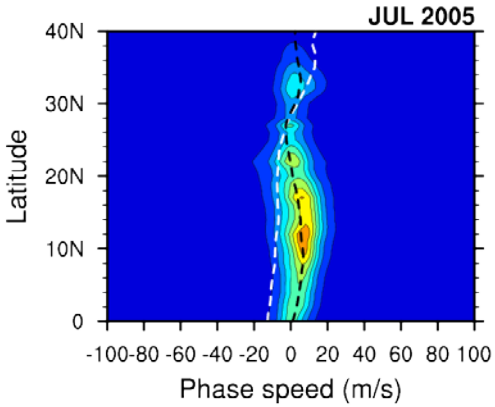

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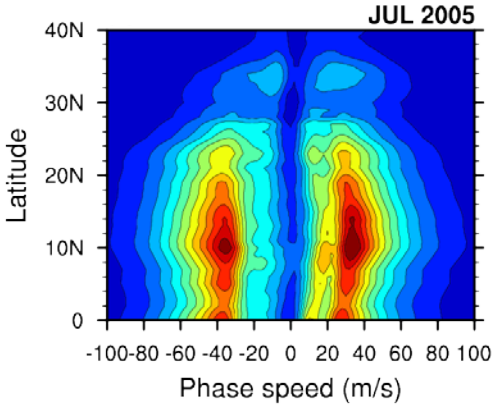

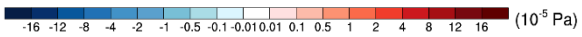

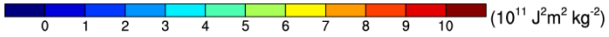

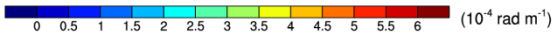

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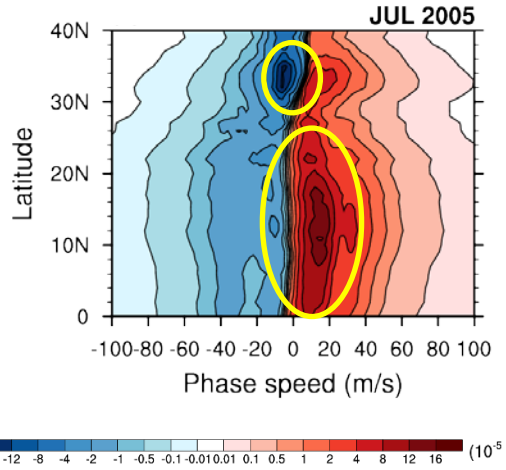
Convective source

CTMF



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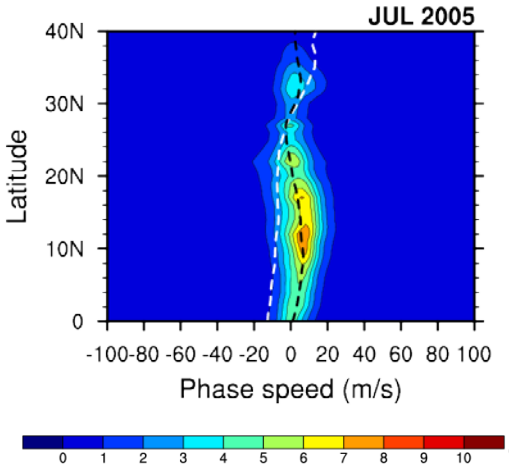
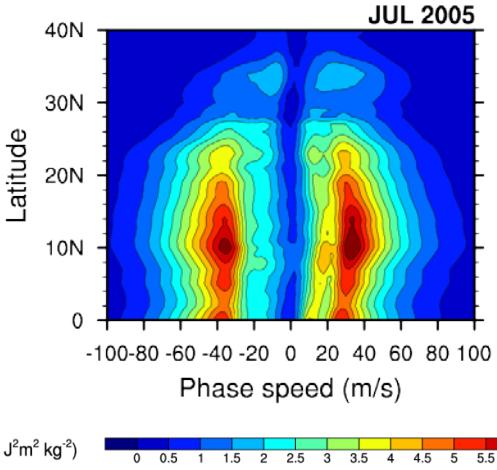


WFRF



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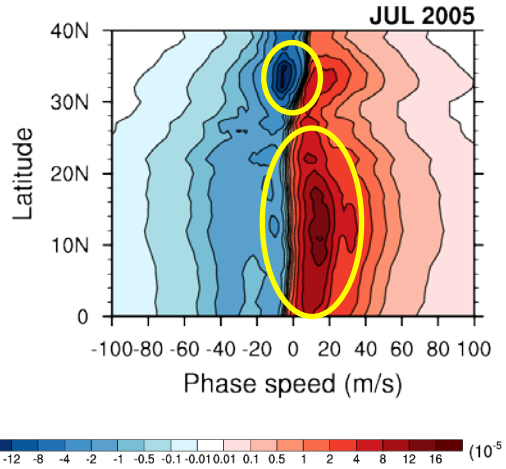
Convective source

CTMF



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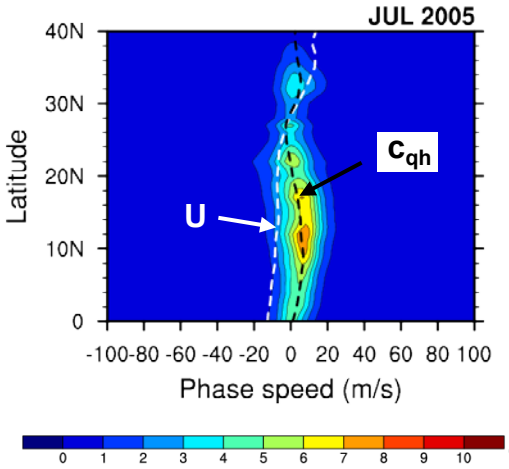
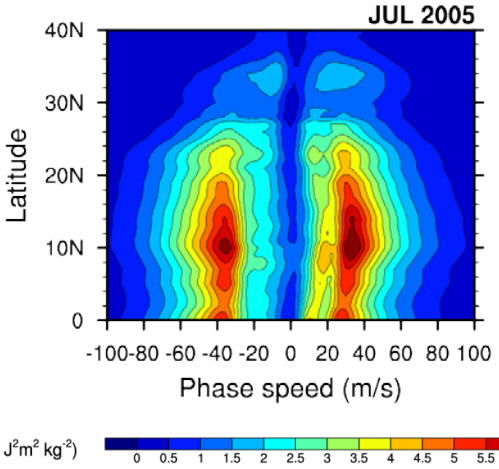


WFRF



- **CTMF** spectrum is amplified at the phase speed corresponding to the **moving speed of convection (c_{qh})**
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CTMF spectrum Asian Summer monsoon region

$$CTMF(c,\varphi) = \mathrm{sgn}[c - U_{ct}(\varphi)]\rho_{ct}\frac{2(2\pi)^3}{A_h L_t}\left(\frac{g}{c_p T_q N_q^2}\right)^2 \times \frac{N_{ct}|X|^2}{|c - U_{ct}(\varphi)|}\Theta(c,\varphi) \times F(\mu)$$

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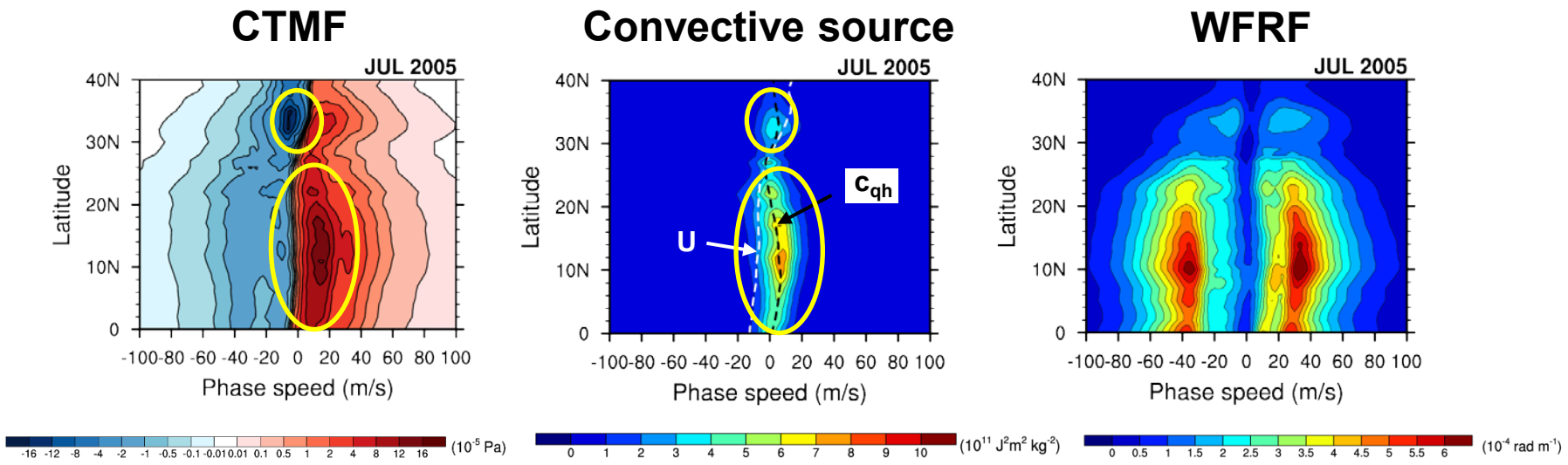

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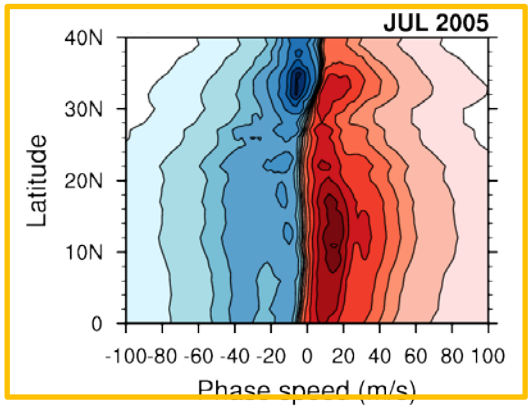

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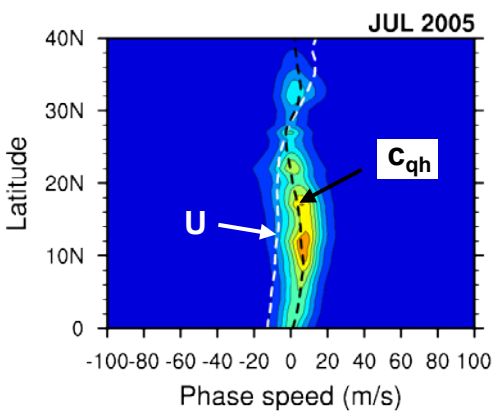

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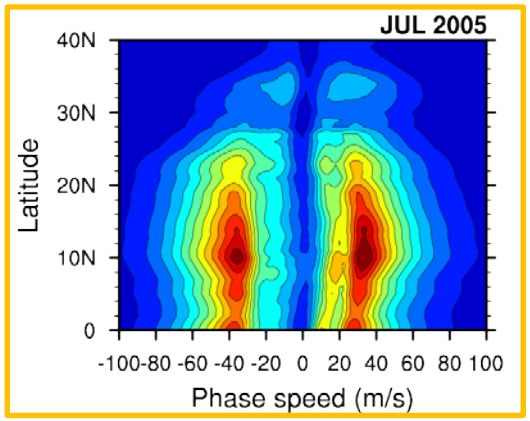

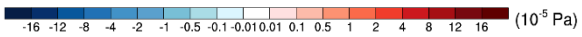

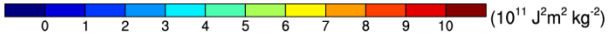

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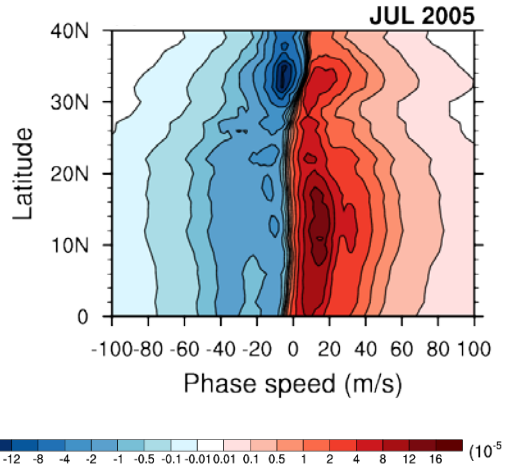

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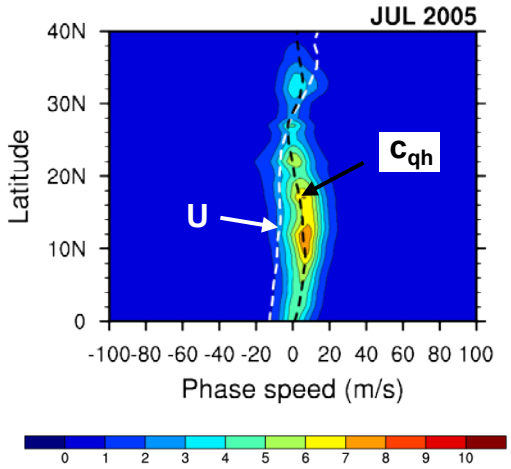

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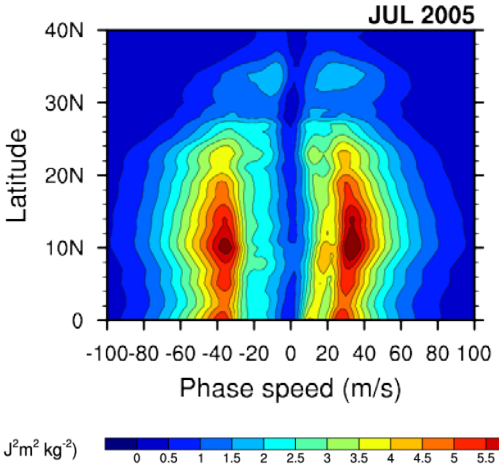

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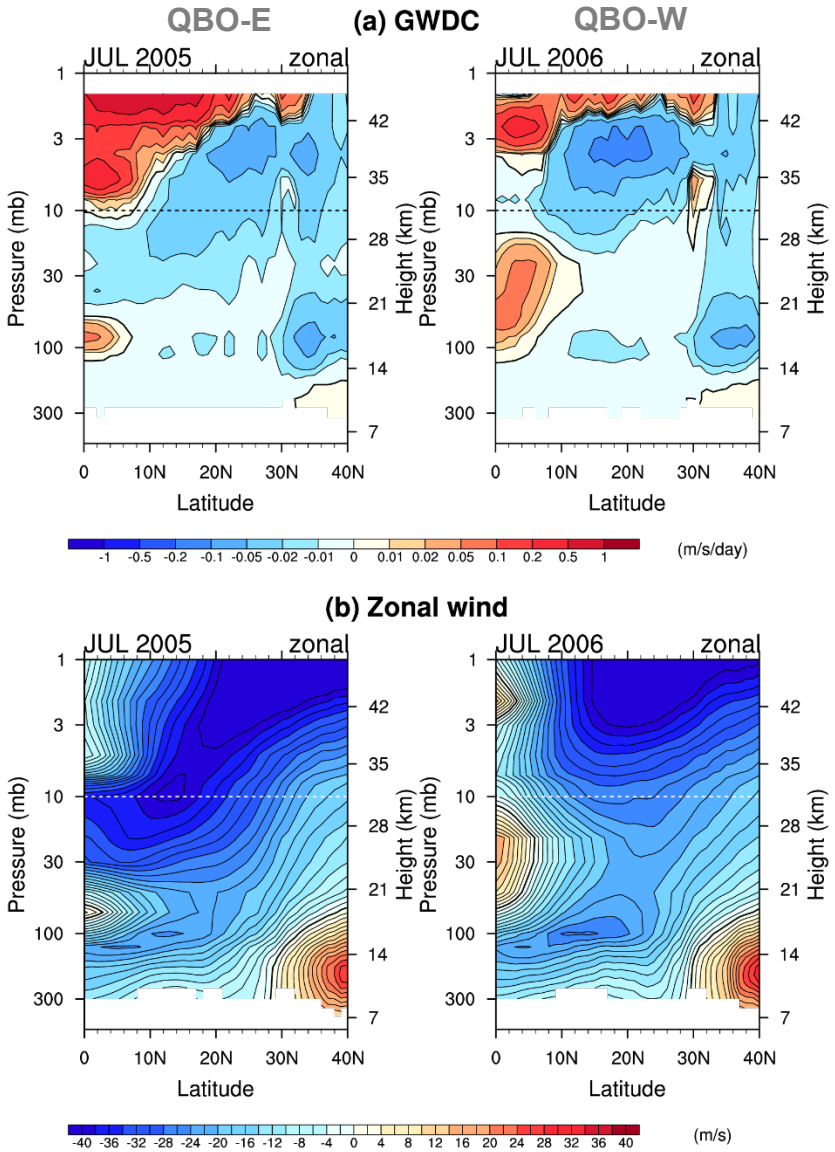
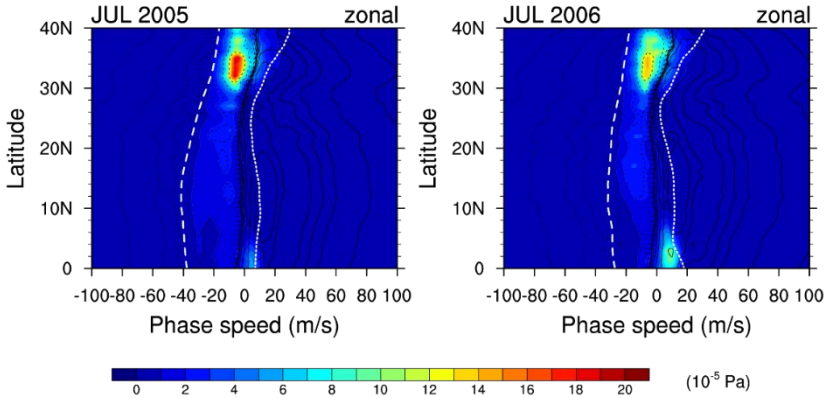
How this shape of the CTMF spectrum are linked to the GWDC?

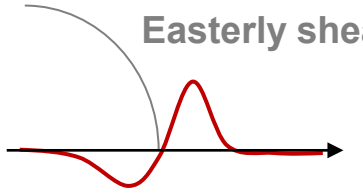
CTMF spectrum → GWDC



Difference in GWMF spectrum from cloud top to 10 hPa $(=MF_{ct} - MF_{10\ hPa})$



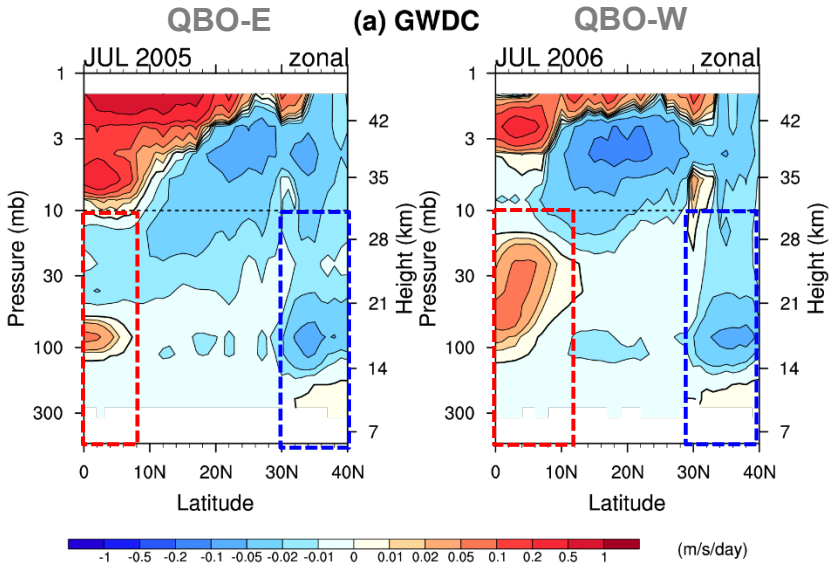
Solid line: maximum wind
Dashed line: minimum wind



Q. What determines the **sign of drag** ?

A. Sign of the **vertical wind shear** (mainly due to the **critical-level filtering**)

CTMF spectrum → GWDC



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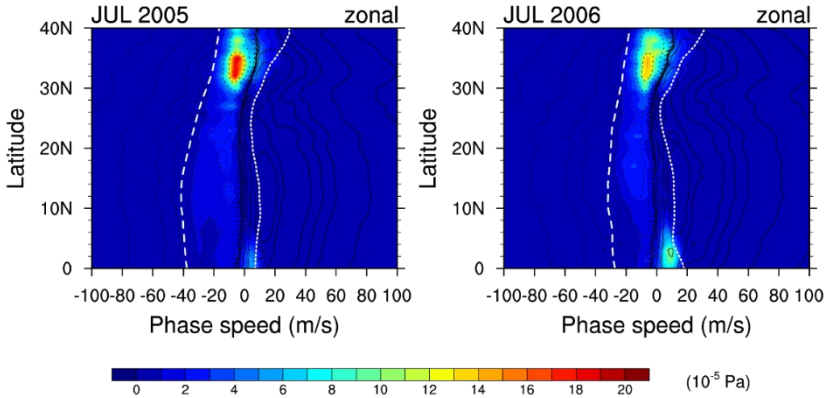

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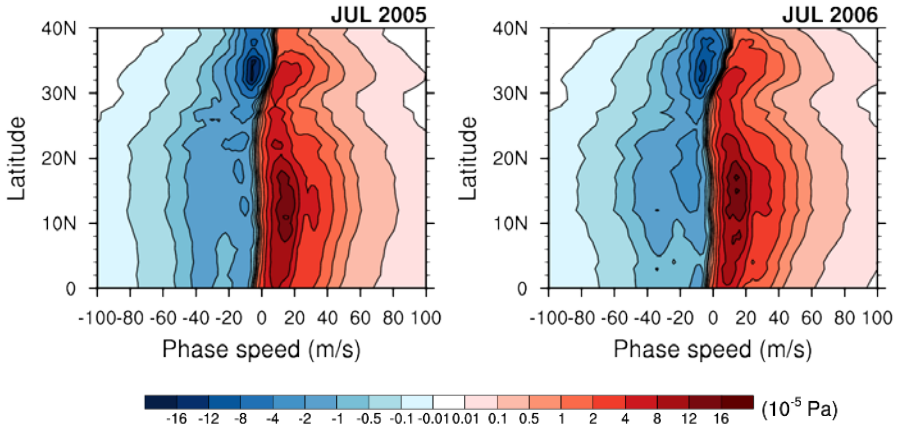
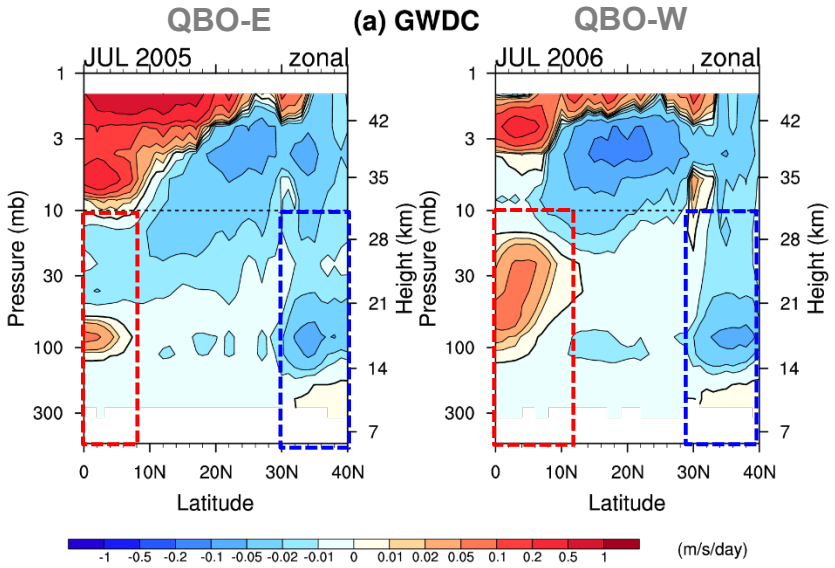


Q. Why is there strong drag in **EQ-10°N** & **30°N-40°N**?

A. Within the filtering region, **spectral peaks** are located.

CTMF spectrum → GWDC



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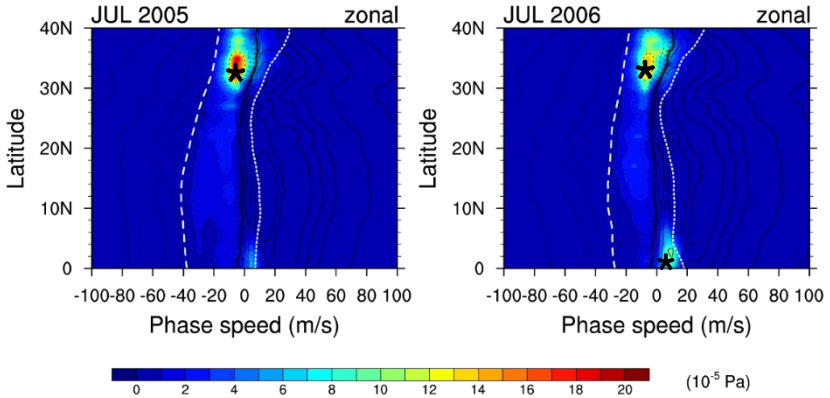

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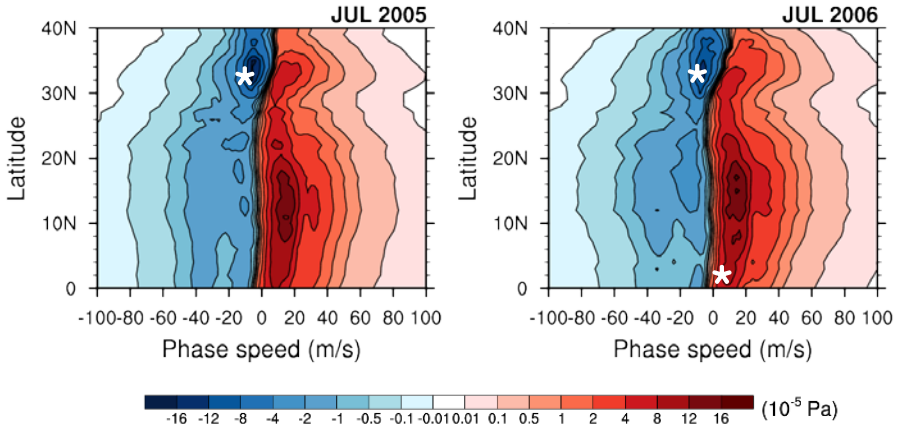

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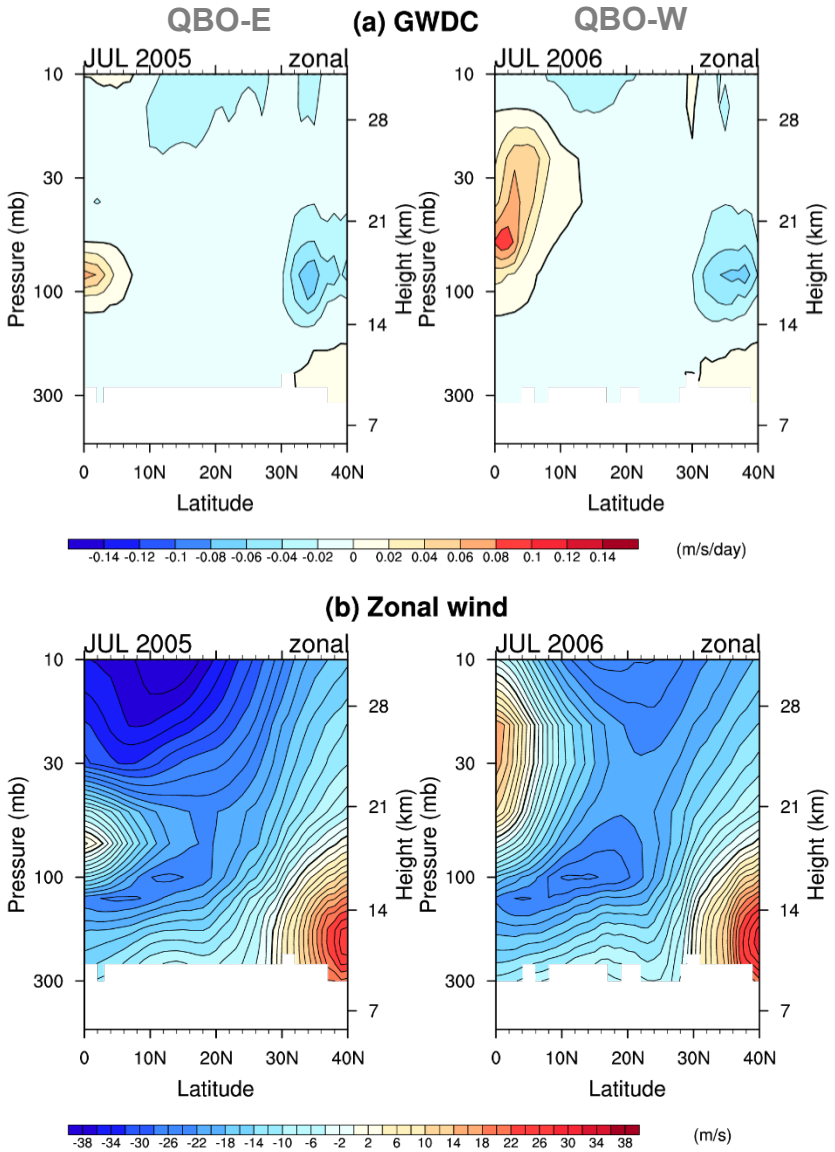

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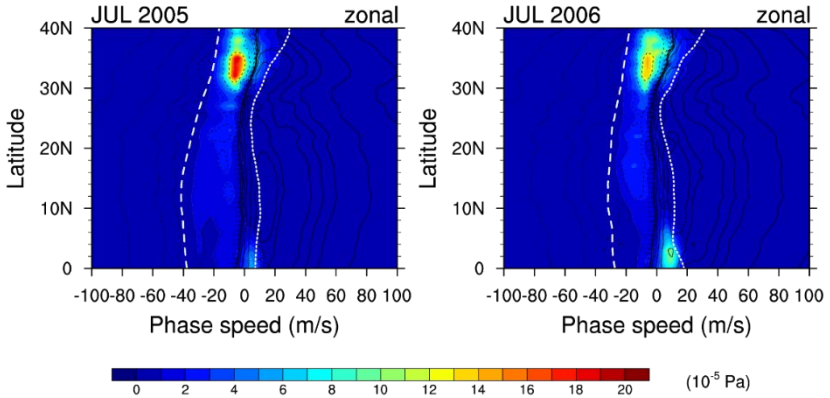

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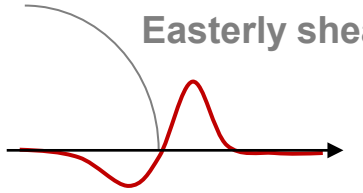

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- Parameterizations of convectively induced gravity waves (**CGWs**) have been developed based on **analytical formulation** of gravity wave momentum flux at the **source-level** (Beres et al. 2004; Song and Chun 2005).
- Song and Chun (2005) showed that momentum flux of CGWs at the source-level is determined not only from **convective source** but also from wave-filtering and resonance factor (**WFRF**).
- Choi and Chun (2011) **updated** and **validated** Song and Chun (2005) by comparing source-level (cloud-top) gravity wave momentum flux (**CTMF**) spectra with those from **3-D mesoscale simulation.**
- Implementation of this parameterization to global climate model (**GCM**) reproduced quasi-biennial oscillation (**QBO**) (Kim et al. 2013) and reduced excessively strong **polar night jet** in the southern hemisphere (Choi and Chun 2013).
- In this study, we focus on understanding CTMF spectrum and its **variation** through the **long-term off-line** calculation of Choi and Chun (2011). Also we find connection between CTMF spectrum and the gravity-wave drag (GWDC).

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Summary and conclusion

Spatiotemporal variations in CTMF

- CTMF is determined not only by magnitude of heating but also by vertical shape of the heating, wave propagation condition, wave nonlinearity.
- CTMF spectrum is highly fluctuate with both time and space in terms of its shape and magnitude.

CTMF spectrum and GWDC in Asian summer monsoon region

- The sign of GWDC is determined by the background wind.
  - There exists westerly (easterly) drag in the westerly (easterly) shear region.
- The magnitude of GWDC is largely influenced by the CTMF spectrum.
  - Maximum drag is located in the region where wave dissipation is occurred at the spectral peak of CTMF spectrum.

➔ **Physically and mathematically consistent source spectrum (CTMF) of CGWs is required for realistic spatiotemporal variabilities in GWDC of the stratosphere.**