The roles of equatorial trapped waves and internal inertia-gravity waves in driving the QBO

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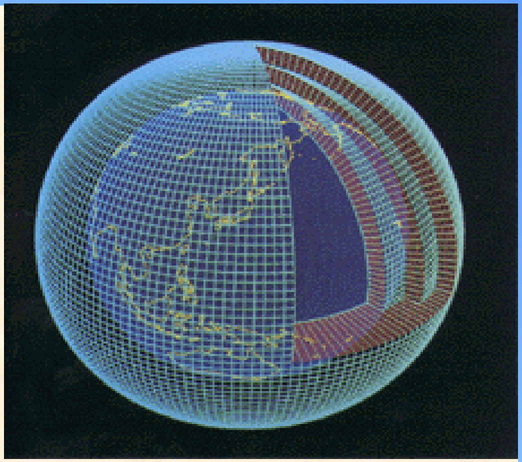
KANTO

Kawatani, Y., K. Sato, T. J. Dunkerton, S. Watanabe, S. Miyahara, and M. Takahashi, 2010
The roles of equatorial trapped waves and internal inertia-gravity waves in driving the quasi-biennial oscillation.

Part I: Zonal mean wave forcing, J. Atmos. Sci. 67, 963-980
Part II: Three-dimensional distribution of wave forcing, J. Atmos. Sci, 67, 981-997

Model Description



<CCSR/NIES/FRCGC AGCM version 5.7b>

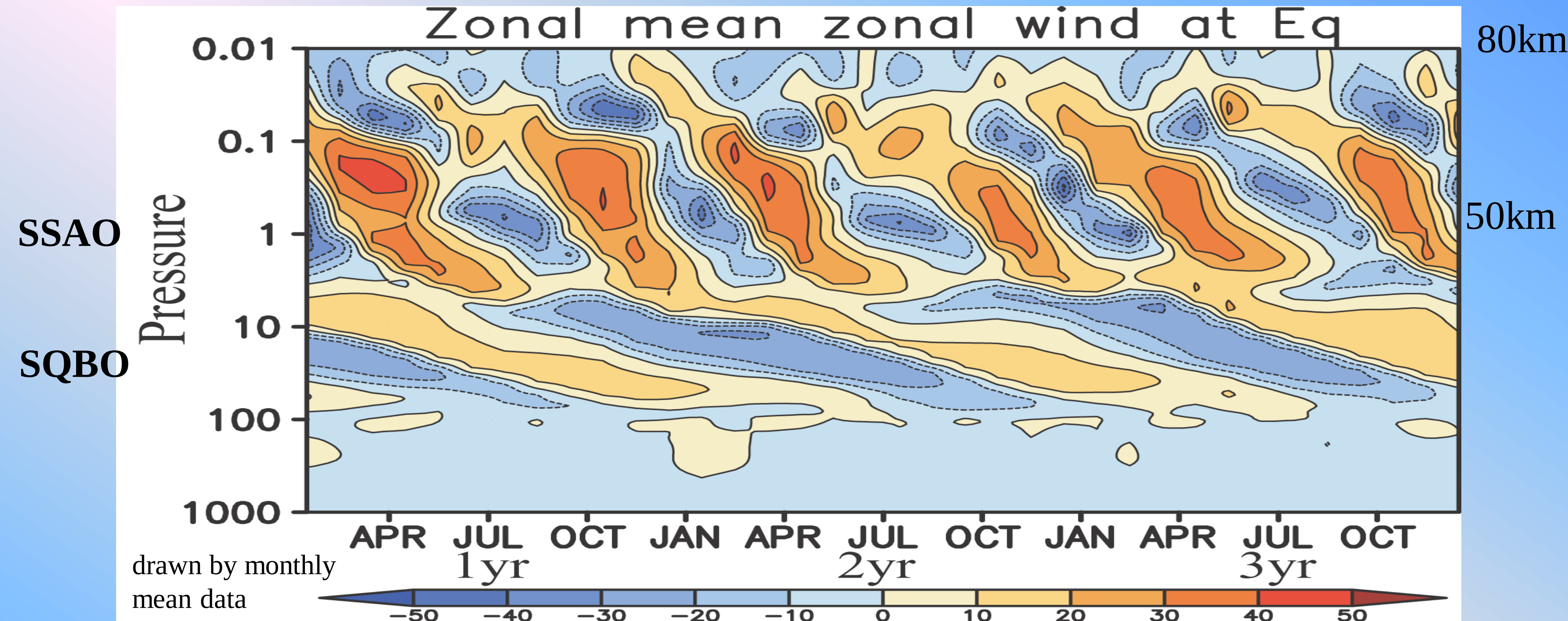
- **T213** ($\Delta\lambda$ and $\Delta\phi$ ~0.56° ΔH = ~**60 km** at EQ)
  minimum resolvable horizontal wavelengths: ~**188 km**
- **L256** (**0-85km**), Sponge layer above 80km (6-level)
  ⊿Z = **300 m** from the upper troposphere to the mesosphere
- **GWD parameterization : None, resolved waves only!**
- Cumulus parameterization : Arakawa-Schubert
- Realistic topography and SST/Sea ice
- Sampling time interval: 1-hour
- Simulated period: 3-years

GCM: primitive equation

$$\frac{|w'|}{(u'^2+v'^2)^{1/2}} \approx (k^2+l^2)^{1/2}/m << 1, \quad \frac{\omega}{\mathrm{N}} \approx \frac{\left(k^2+l^2\right)^{1/2}}{m} << 1$$

GWs with period much longer than Brunt-Väisälä period

Time-height cross section of zonal mean zonal wind at equator for 3-years

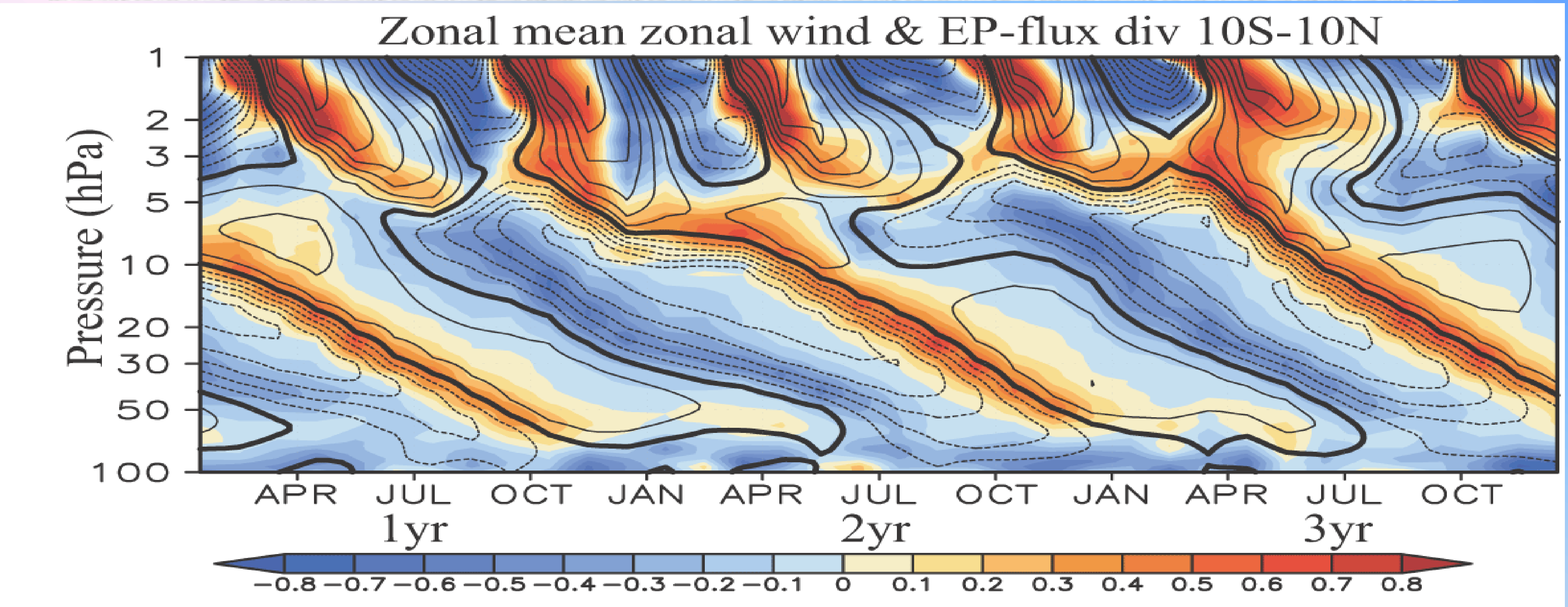


easterly (westward wind): blue   westerly (eastward wind): red

QBO-like oscillations with periods ~15 months
easterly (westward wind): ~ -25 (m/s)
westerly (eastward wind): ~ 15 (m/s) at 30hPa
Bottom level: ~80hPa, period: ~15 month

SSAO
first cycle > second cycle
westward wind : -70 (m/s)
eastward wind: 35 (m/s)
(when seen in daily data)

Time-height cross section of zonal mean U & EP-flux DIV 10S-10N



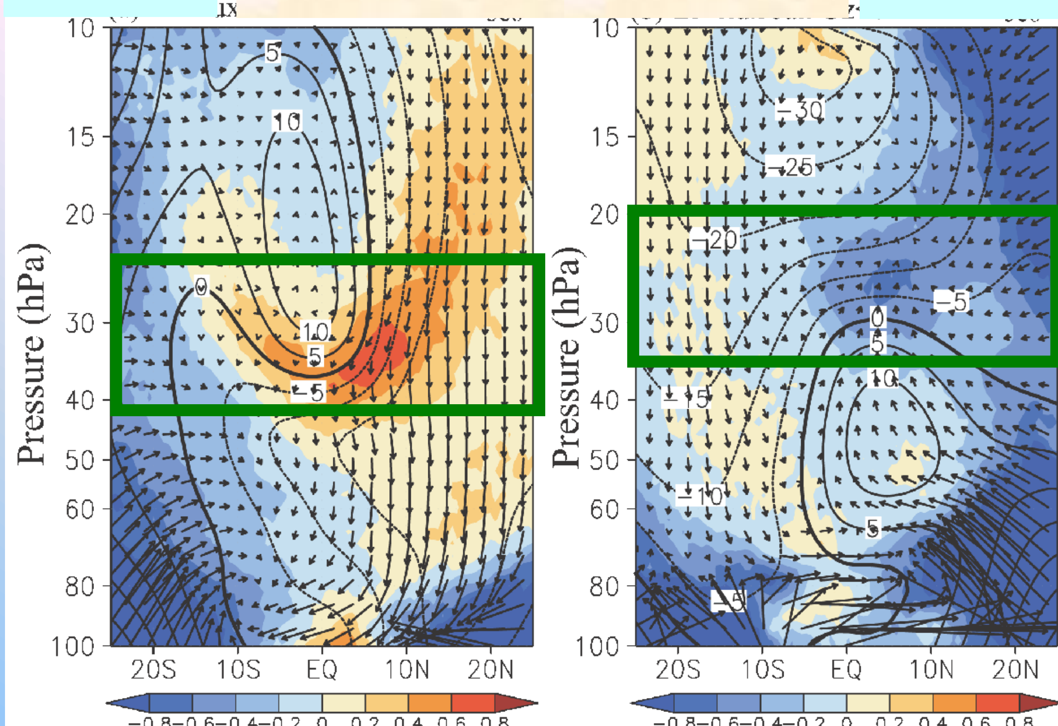
Blue: westward forcing

Red: eastward forcing

Maximum **eastward forcing ~ 0 ms^{-1}** around **eastward wind shear** Uz>0
Maximum **westward forcing ~ -10 ms^{-1}** around **westward wind shear** Uz<0
spontaneously generated waves resolved in the model drive the QBO

1. simulated wave forcing might not be much overestimated compared to past studies (validation of wave momentum flux has been conducted)
2. equatorial upwelling w* might be about half of that in the real atmosphere

Uz>0 Jul EP-flux & its div of all waves Uz<0 Jan



Maximum wave forcing in the shear zone not symmetrically distributed on the equator

waves other than EQWs also contribute

eastward wave forcing during Uz>0

$2\ ms^{-1} < Cx < 20\ ms^{-1}$, $s \leq 140$

westward wave forcing during Uz<0

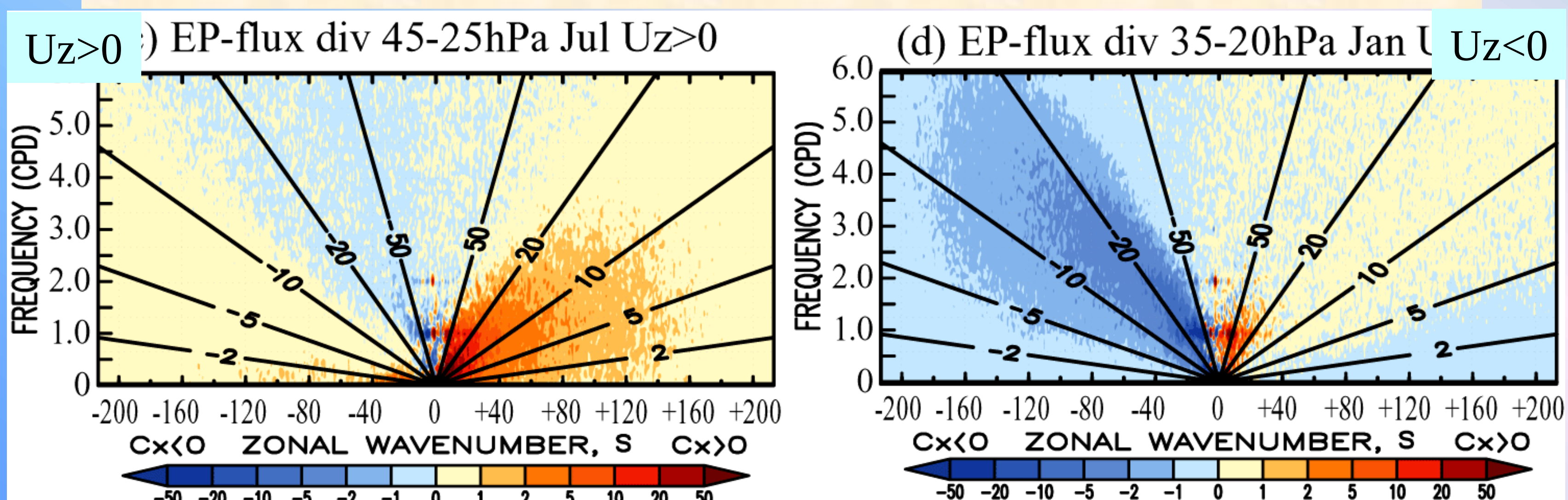
$-30\ m\ s^{-1} < Cx < -5\ ms^{-1}$, $s \leq 180$

wave forcing with smaller horizontal scale

faster Cx dominated in the Uz<0

waves with continuous Cx contribute

zonal wavenumber - frequency distribution of EP-flux divergence (10S-10N)



red:

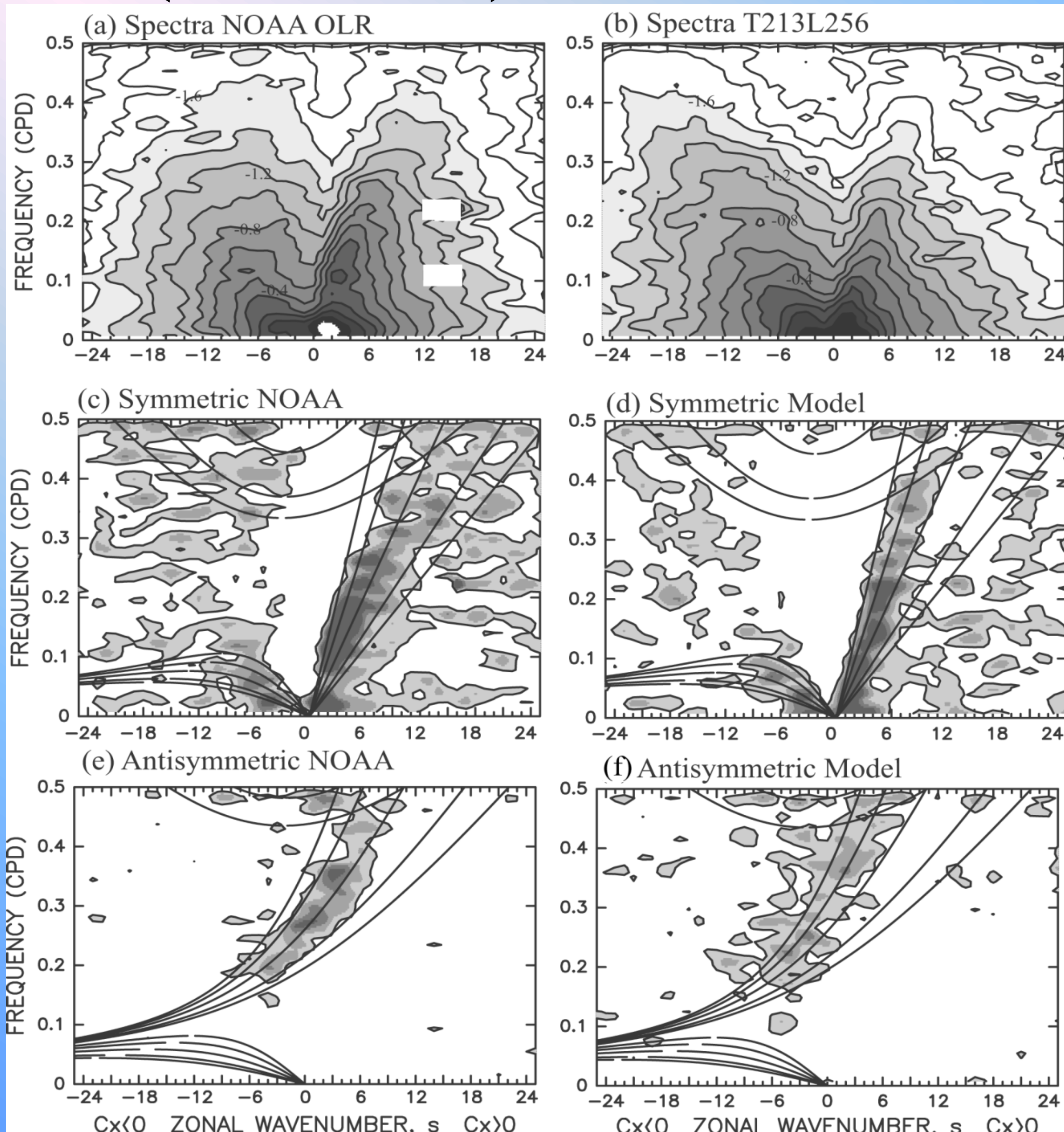
eastward forcing

blue

westward forcing

lines: Cx

Obs (NOAA OLR) T213L256

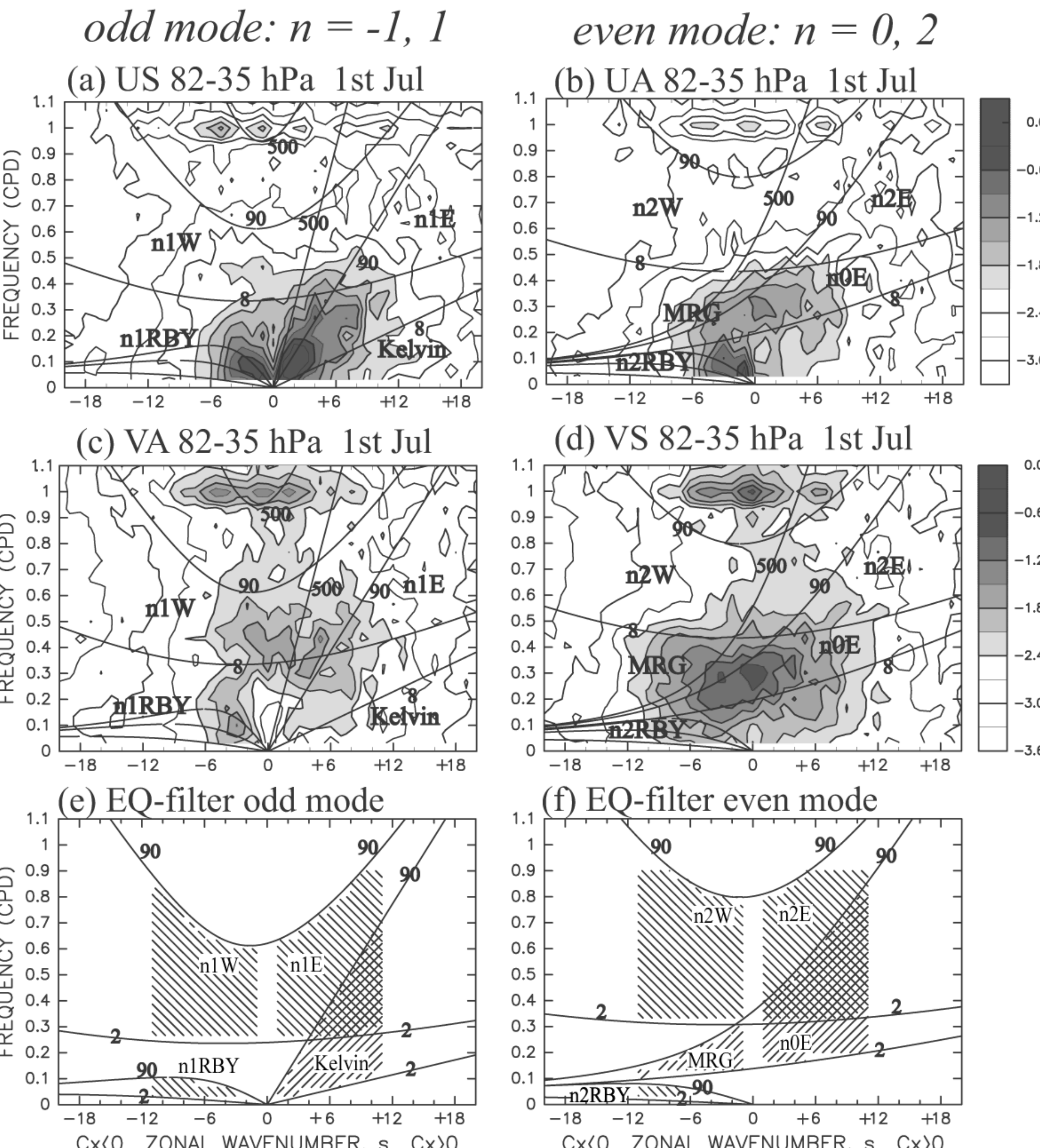


OLR spectra
zonal wavenumber – frequency
(10S-10N average)

top: (S+A)/2
mid: symmetric
bottom: Antisymmetric

he of 8, 12, 25, 50, and 90 m of EQW
Kelvin waves, n = 1 ER
MRG waves and n = 0 EIGWs

Lin *et al.* (2006)
the present model was also one of the best models for realistically simulating spectral power at periods of ≤6 days.



zonal wavenumber-frequency
U & V spectra
(left) n = -1, 1
(right) n = 0, 2

(top) zonal wind
(mid) meridional wind
(bottom) EQW filter

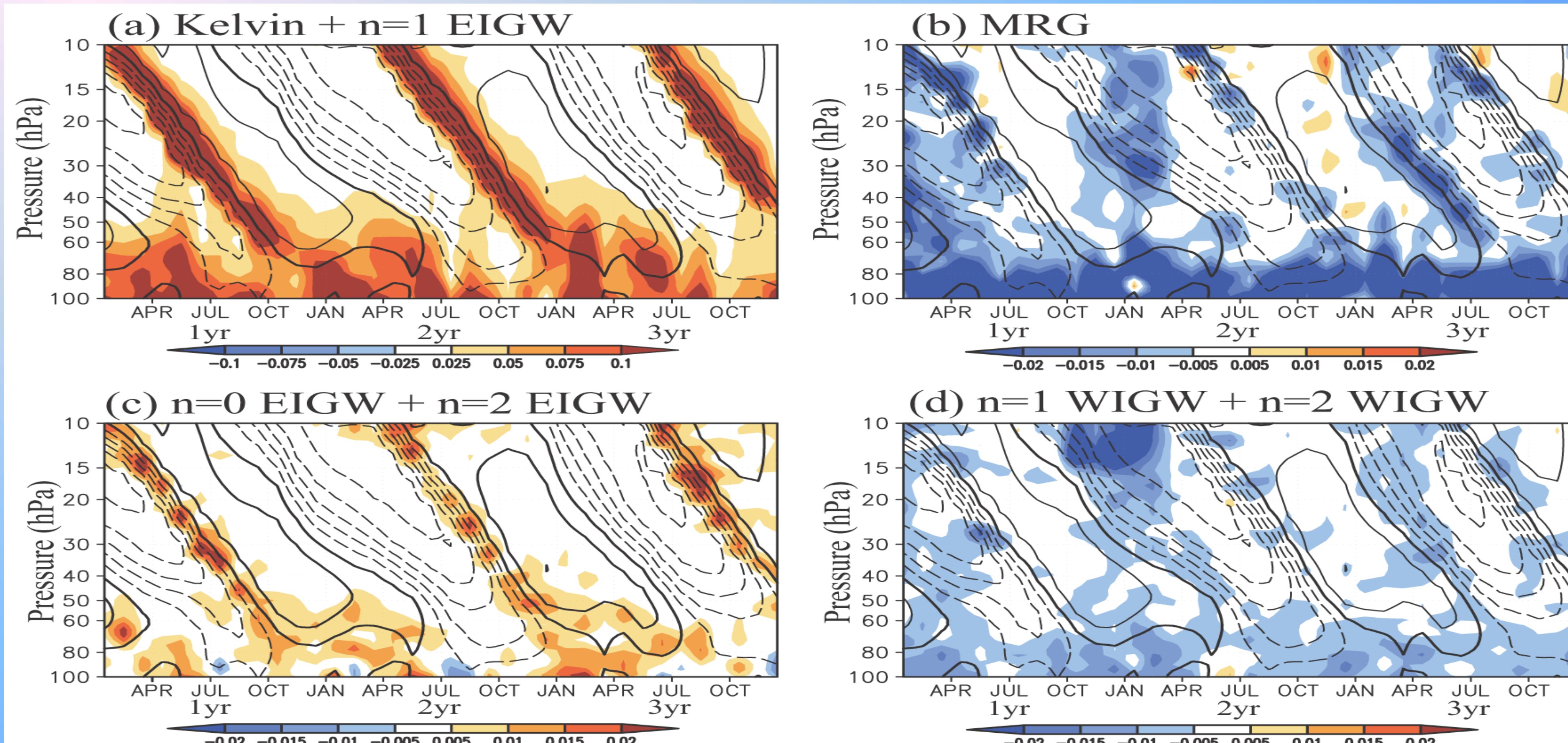
<criteria of EQWs>

- **s = 1 - 11 (λx ≥ ~3600km)**
- equivalent depth ***h*: 2-90 (m):**
  ~ 1 km ≤λz ≤ ~ 8 km
- minimum periods: 1.1day
- extracted EQW mode:
  n = - 1 to n = 2

<criteria of intrernal gravity waves>

s ≥ 12 (λx ≤ ~ 3300 km)

Time-height cross section of EP-flux DIV due to EQWs at 10S-10N

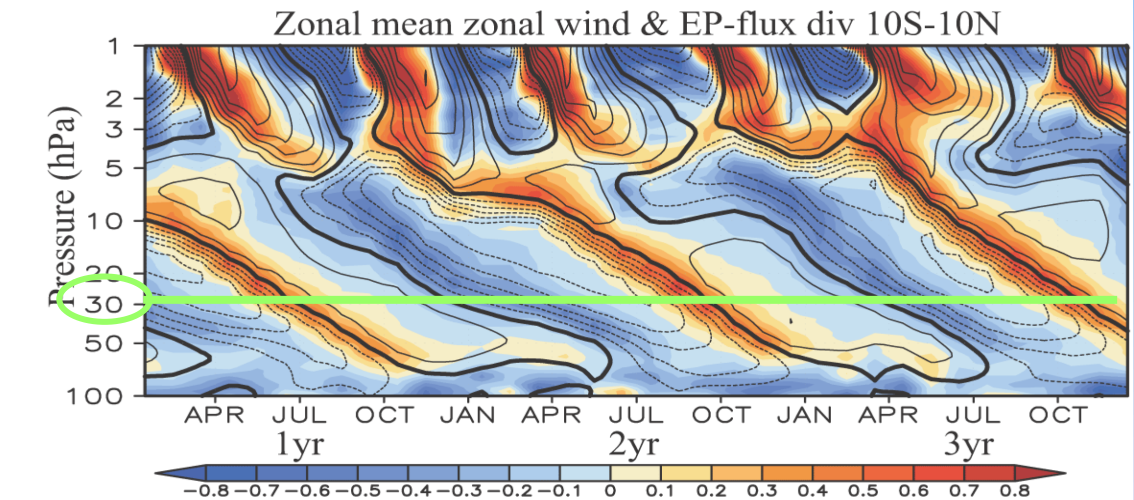


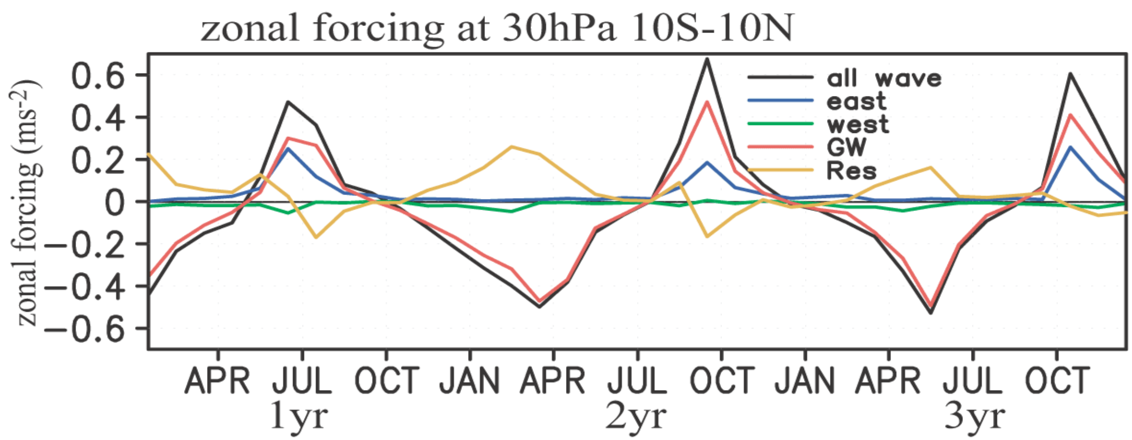
※Shading interval of Kelvin + n=1E is 5 times greater than that of other EQWs

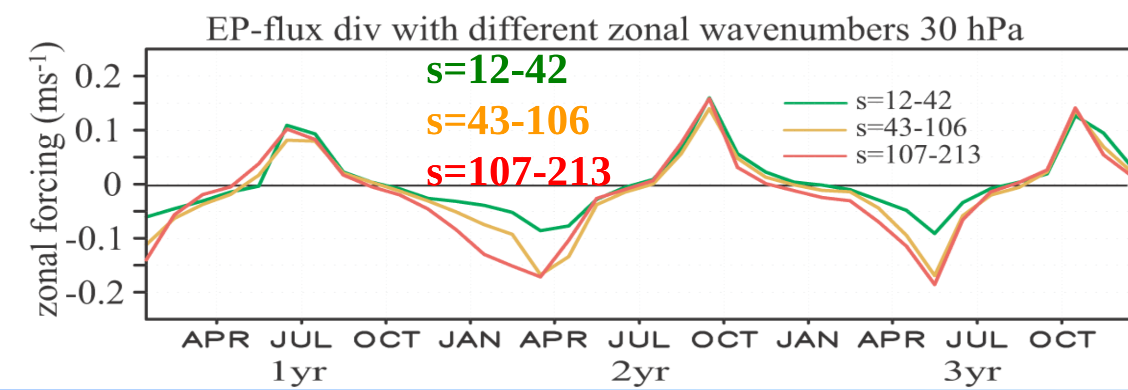
Eastward forcing due to odd mode (Kelvin and n=1E waves) >> even mode (n=0E & n=2E)
July of the 1st year: **odd mode 35%**, **even mode 8 %** contribution of total wave forcing

Westward forcing due to MRG waves is stronger than that due to n=1W/n=2W at 20-40hPa

Relative role of EQWs and internal inertia-GWs (10S-10N, 30hPa)







<eastward wind shear phase Uz>0>
eastward EQWs: ~0.25 $m\ s^{-1}\ day^{-1}$
internal gravity waves: ~0.5 $m\ s^{-1}\ day^{-1}$

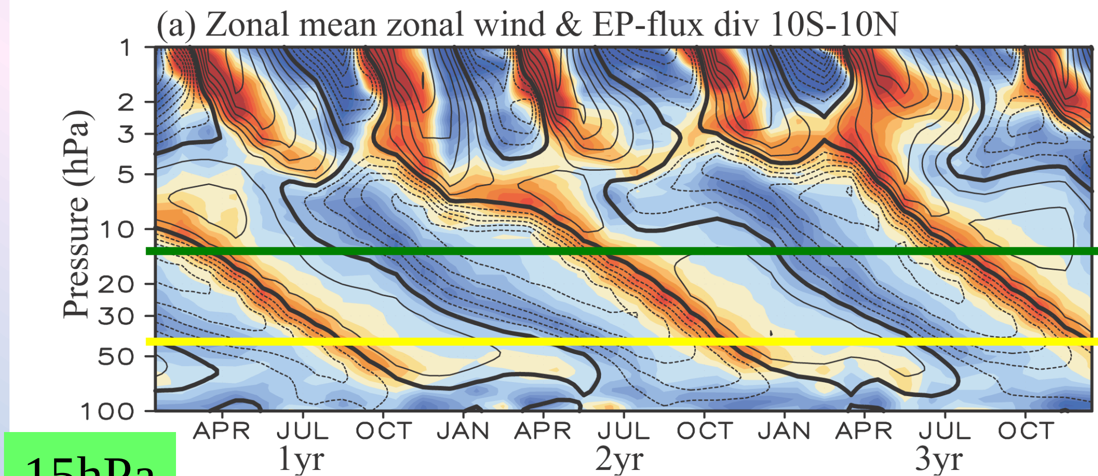
eastward EQWs: ~ **25-50 %**
internal GWs: ~ **50-75 %**

<westward wind shear phase Uz<0>
westward EQWs: ~ -0.05 $m\ s^{-1}\ day^{-1}$
internal gravity waves: ~ -0.5 $m\ s^{-1}\ day^{-1}$

westward EQWs:
~**10%** during **weak westward** wind
~**0 %** during **strong westward** wind

For **westward** wind shear (Uz<0)
waves with **s≥43** (**λx≤~1000km**)

T42 AGCM by Giorgetta et al. (2006)
resolved wave → eastward wind shear
parameterized wave → westward wind shear

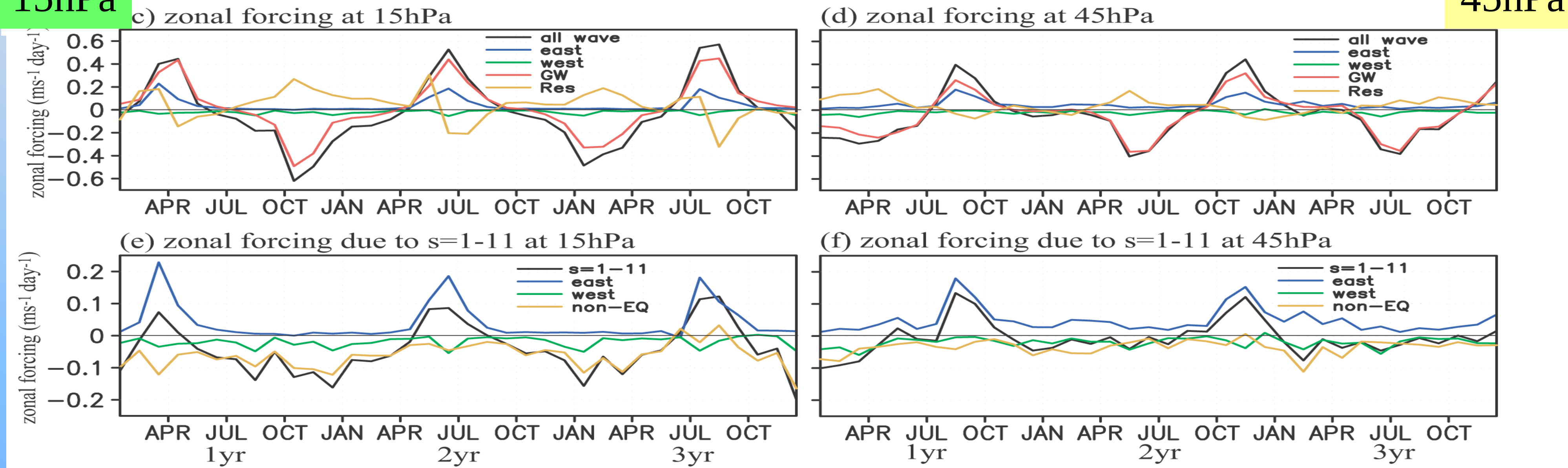


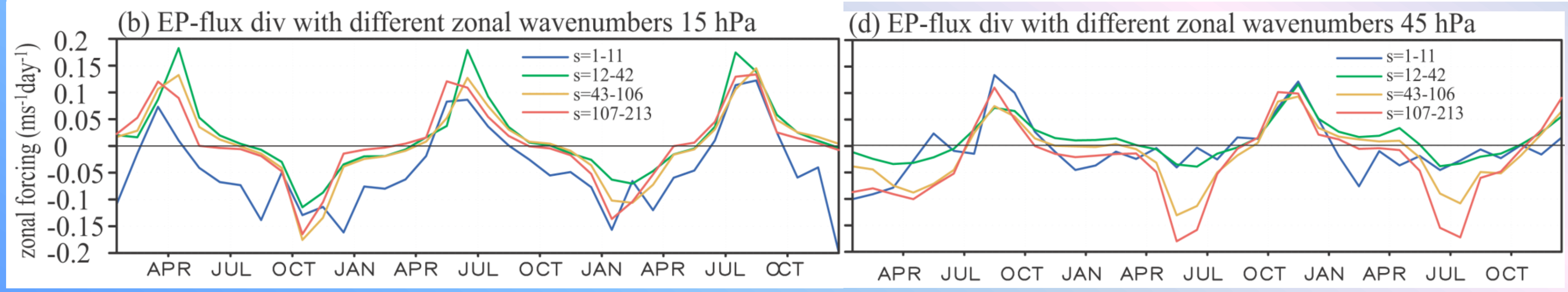
15hPa: extratropical
Rossby wave 10-25%

45hPa: GWs with s>106

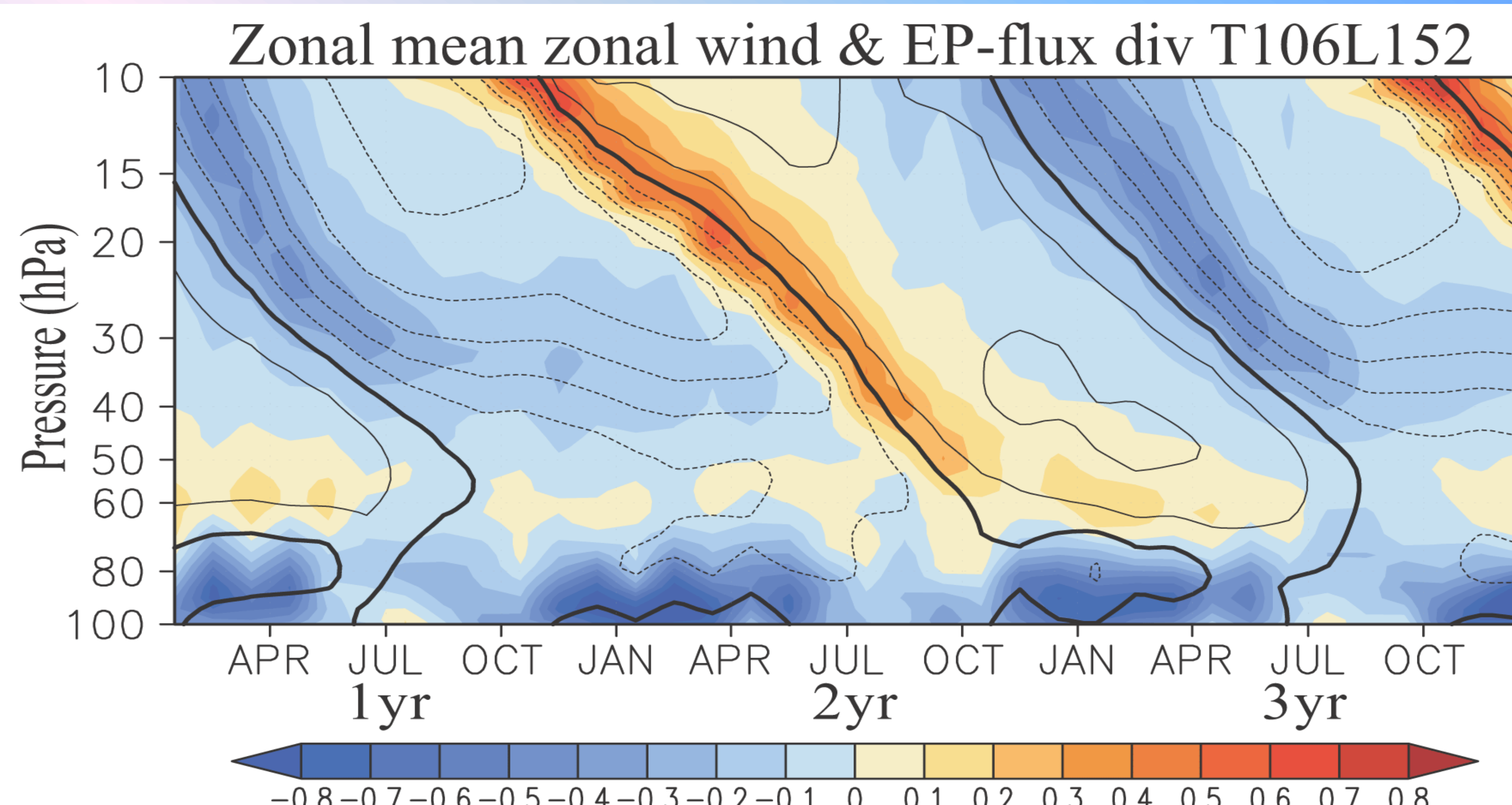
15hPa

45hPa





QBO simulated in T106L152



failed to simulate the realistic strictures of the QBO in the lower stratosphere
lowermost level of westward wind phase locates around 45 hPa

T213L256 AGCM: ⊿h=60km, ⊿z=300m, data for 3-year

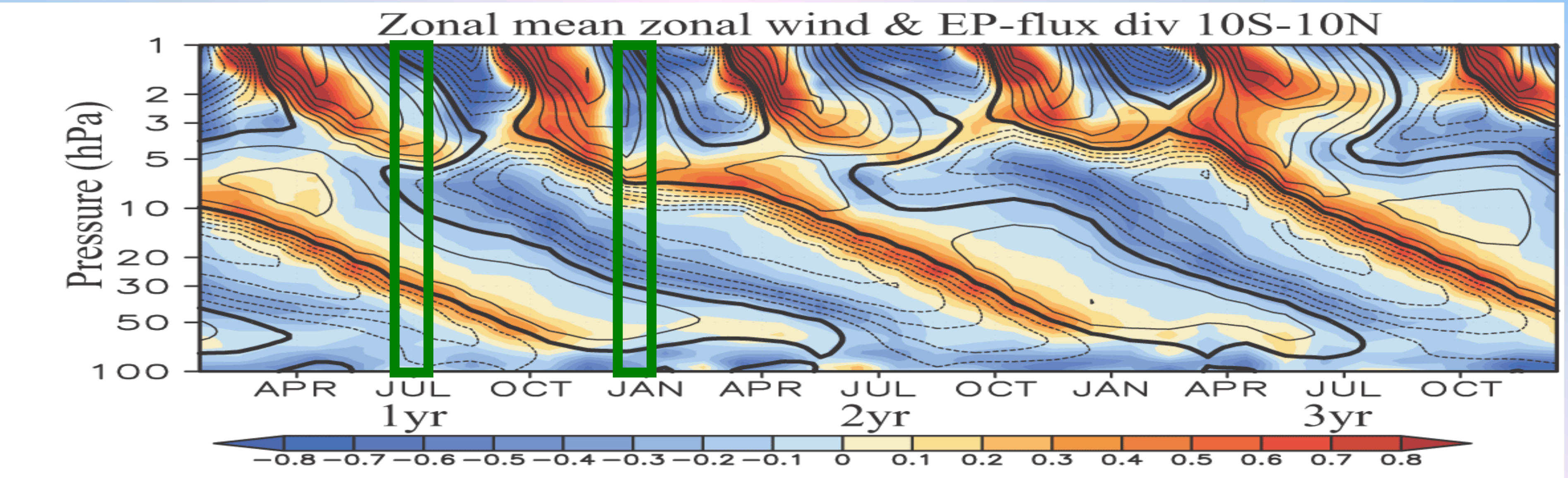
	EQWs	internal inertia-gravity waves	Extratropical Rossby waves
eastward wind shear	~**25-50%** maximum around 0m/s	~**50-75%** maximum around 0m/s	
westward wind shear	~**10%** during **weak** westward wind nearly **0%** during **stronger** westward wind	main forcing **λx≦~1000km** lowermost level of westward wind **λx≦~380km**	~**10-25%** large in the upper level

Analyze 3-year data
Relative role of EQWs, internal inertia-GWs, extratropical Rossby waves
Roles of waves differ with altitude

3-D distribution of wave forcing

Wave generation and propagation depend greatly on zonal/meridional direction (COSMIC by Alexander et al. 2008a,b; AGCM by Kawatani et al. 2009, JGR)

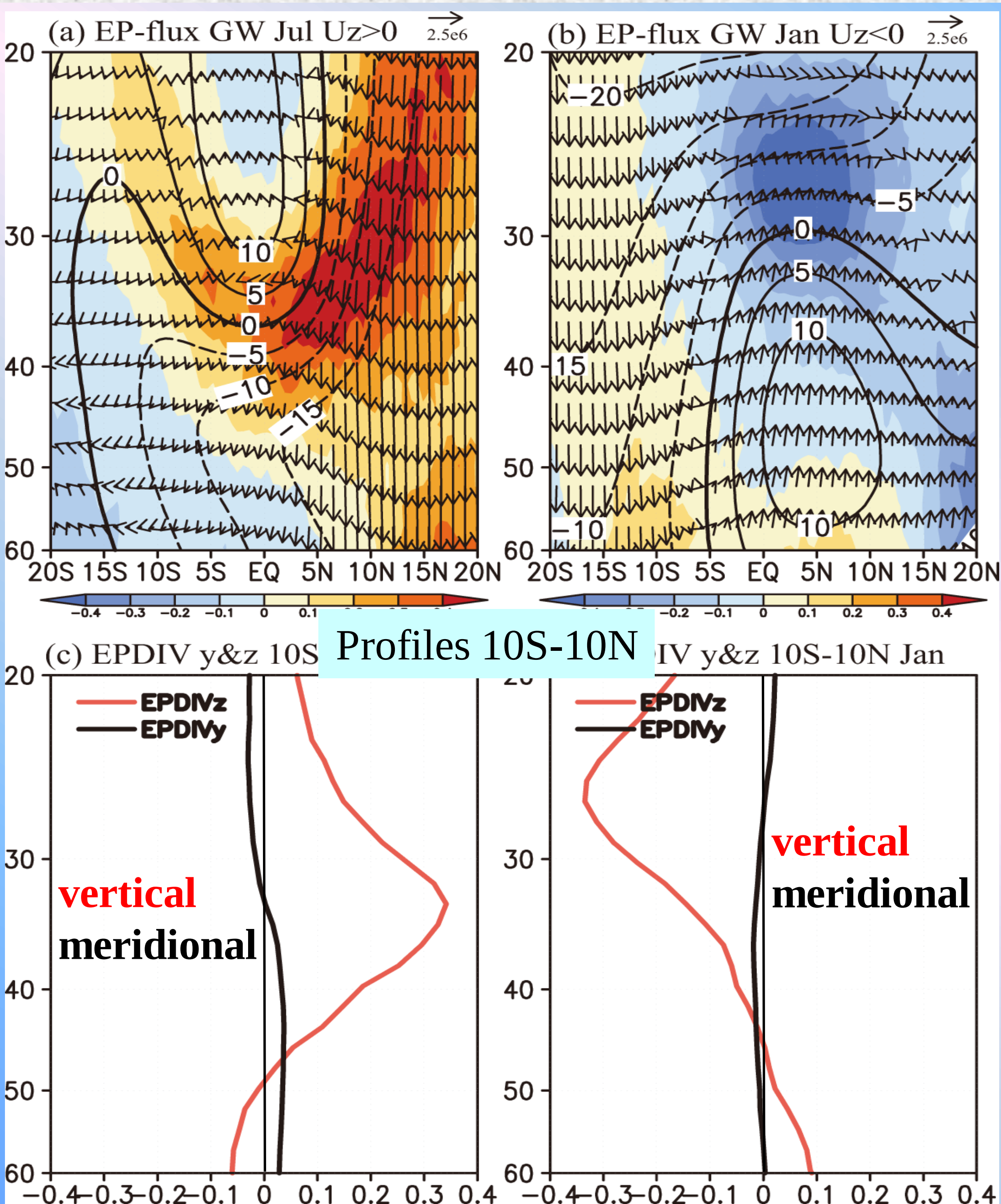
Model investigations of the 3-D distribution of wave momentum flux and wave forcing should provide useful informaiton for future in situ and satellite observations, as well as for the development of gravity wave parameterization



July of the 1st year during eastward wind shear phase (Uz>0)
January of the 2nd year during westward wind shear phase (Uz<0)

EP-flux due to internal inertia-gravity waves

Uz>0
Jul

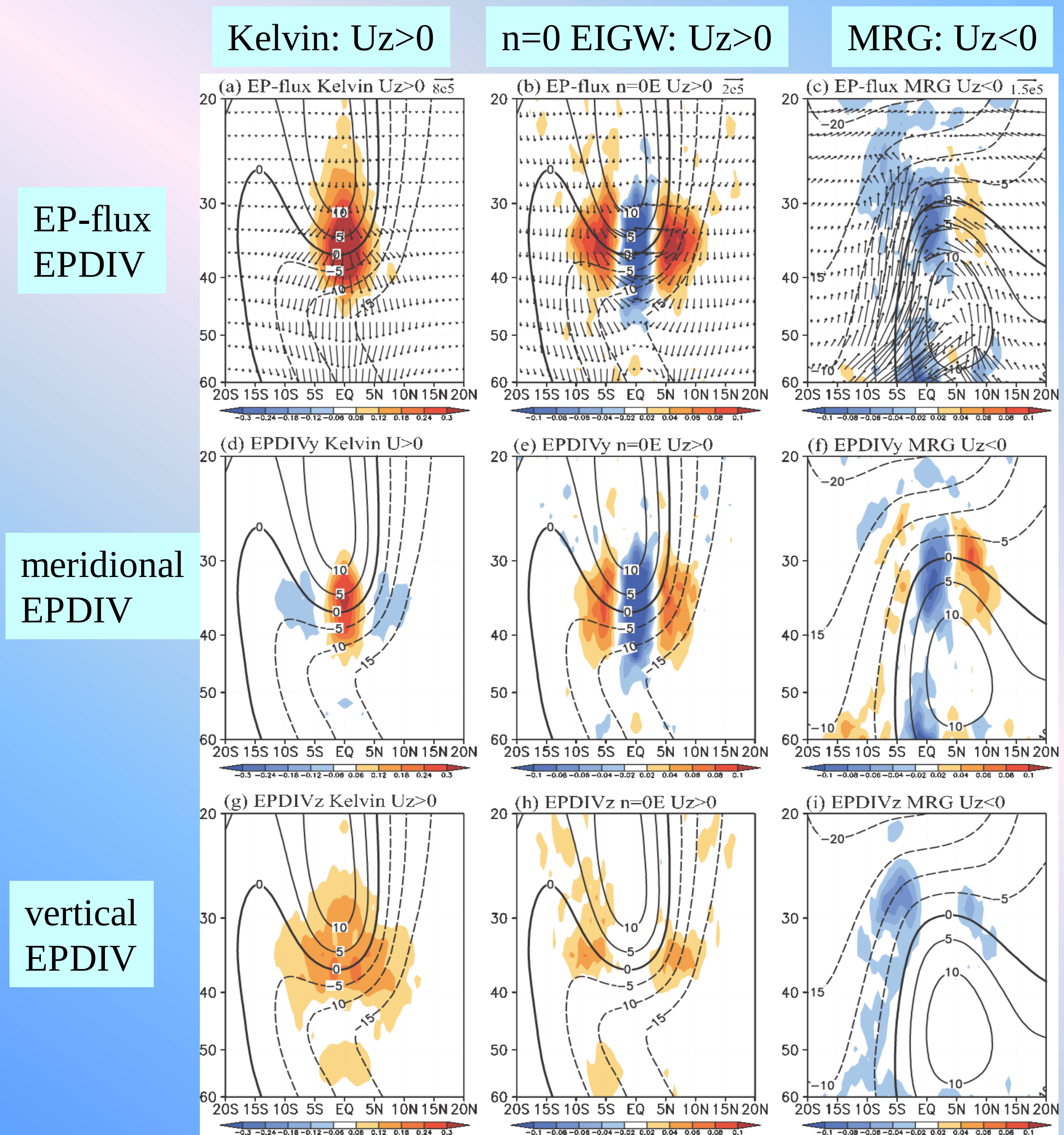


Uz<0
Jan

Profiles 10S-10N

In both Uz>0 and Uz<0 nearly all EP-flux consist of its **vertical component**

→GWD parameterization including **only vertical wave propagation** is suitable at least for the QBO.



<Kelvin>
converge both meridionally and vertically around Uz>0

eastward forcing is concentrated on the equator

<n=0 EIGW>
eastward forcing off the EQ
westward forcing over the EQ

<MRG>
converge both meridionally and vertically around Uz<0

westward forcing is maximized around the equator

meridional momentum transport by EQWs

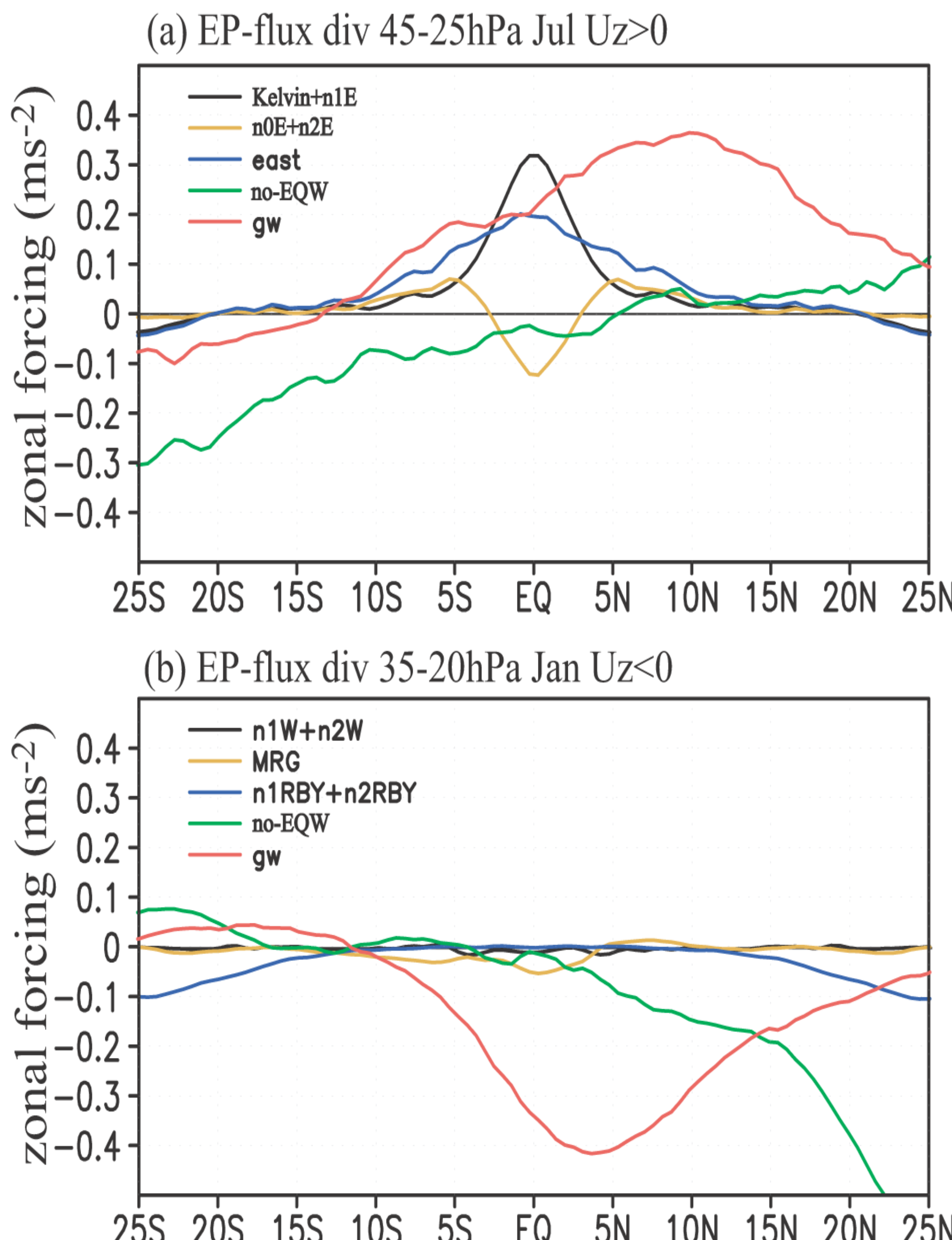
Latitudinal distribution of the EP-flux divergence

eastward shear

July
45-25 hPa

westward shear

Jan
35-20 hPa



<eastward wind shear Uz>0>
Kelvin + n1E confined around Eq
n=0E + n=2E eastward (westward) off (over) the equator

Wave forcing due to **internal GWs comparable to that due to eastward EQWs over the Eq**
it prevails off the equator.

Consequently, EQWs contribute to **~38%** of total forcing in **10S-10N**

<westward wind shear Uz<0>
westward EQWs contribute to **~17% over the equator**, but the contribution is reduced to **~8%** in **10S-10N** mean field

extra-tropical Rossby waves contribute ~10% in 10S-10N

3-D Wave Activity flux appreciable to inertio-Gravity waves: Miyahara (2006), SOLA, vol.2, 108-111

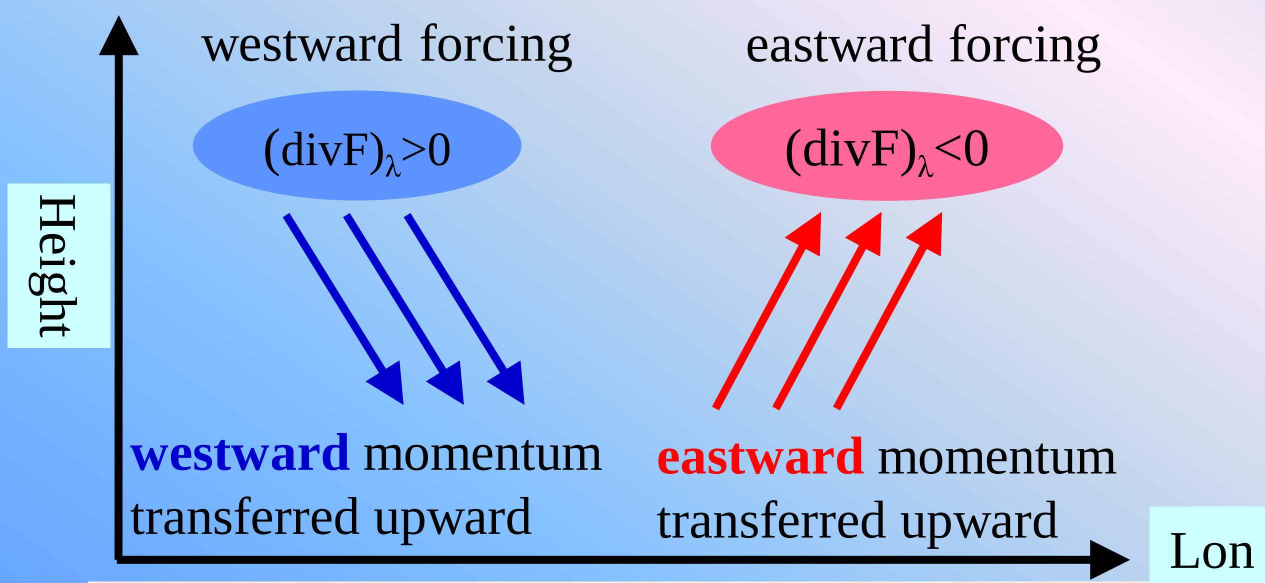
- wave-action density fluxes are relative to the **local time mean** flow

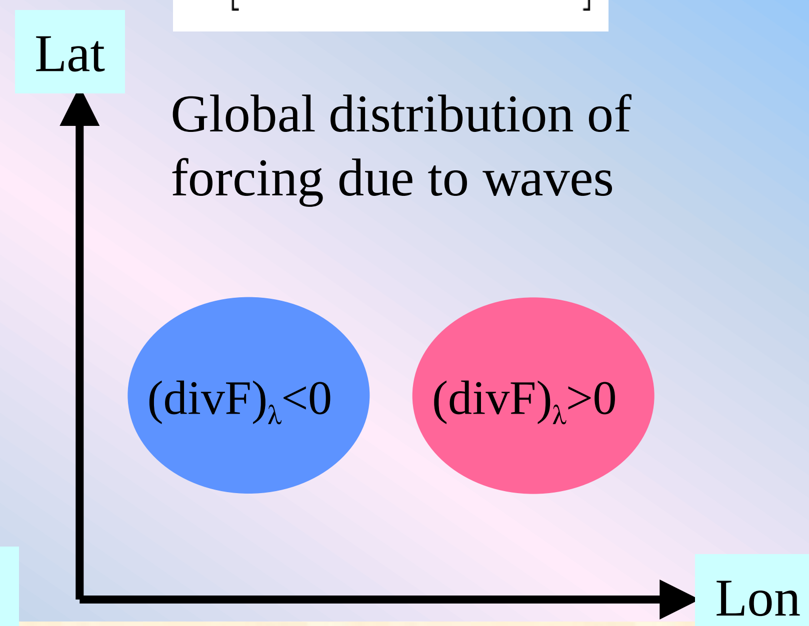
Zonal

$$\frac{D\bar{u}}{Dt} - \frac{\bar{u}\tan\phi}{a}\bar{v} - 2\Omega\sin\phi\,\bar{v}^{*} = -\frac{1}{a\cos\phi}\frac{\partial\bar{\Phi}}{\partial\lambda} - (pa\cos\phi)^{-1}(\nabla\cdot F)_{\lambda}$$

$$F \equiv \begin{bmatrix} \frac{1}{2}\left(\overline{u'^2} - \overline{v'^2} + \frac{\overline{\Phi_z'^2}}{N^2}\right) & \overline{u'v'} & \overline{u'w'} - \frac{2\Omega\sin\phi}{N^2}\overline{v'\Phi_z'} \\ \overline{v'u'} & \frac{1}{2}\left(\overline{v'^2} - \overline{u'^2} + \frac{\overline{\Phi_z'^2}}{N^2}\right) & \overline{v'w'} + \frac{2\Omega\sin\phi}{N^2}\overline{u'\Phi_z'} \\ 0 & 0 & 0 \end{bmatrix} pa\cos\phi$$

$$F \equiv \begin{bmatrix} \hat{C}_{gx}\frac{E}{\hat{C}_x} & \hat{C}_{gy}\frac{E}{\hat{C}_x} & \hat{C}_{gz}\frac{E}{\hat{C}_x} \\ \hat{C}_{gx}\frac{E}{\hat{C}_y} & \hat{C}_{gy}\frac{E}{\hat{C}_y} & \hat{C}_{gz}\frac{E}{\hat{C}_y} \\ 0 & 0 & 0 \end{bmatrix}$$

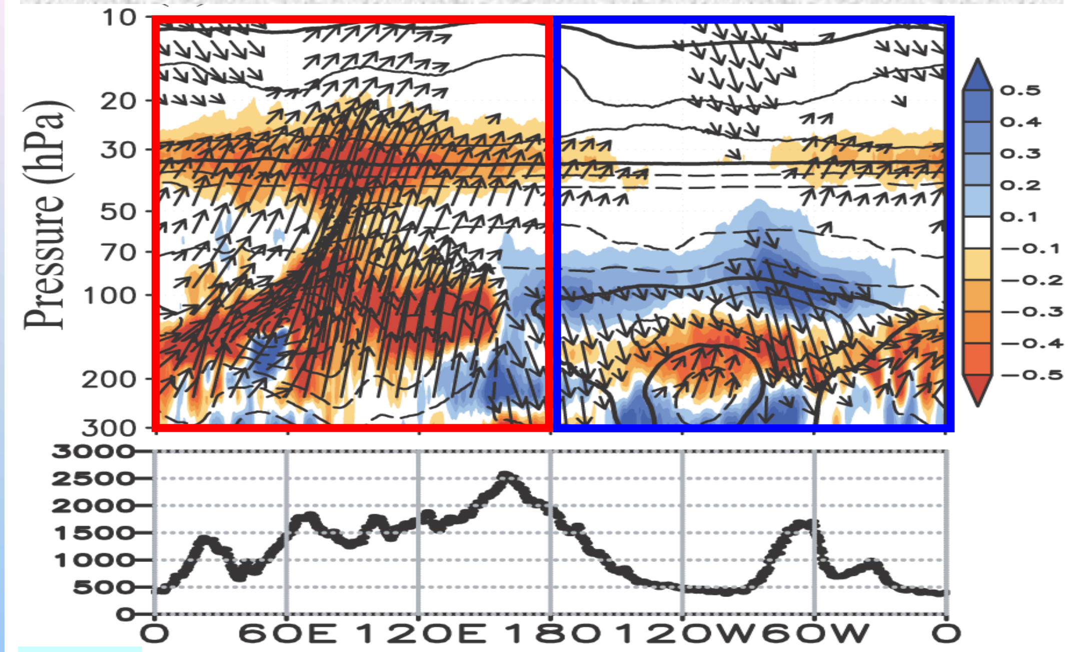




Contents of flux tensor F are expressed with intrinsic group velocity and phase velocity

eastward wind shear Uz>0

3-D wave flux during Uz>0 in July (10S-10N)

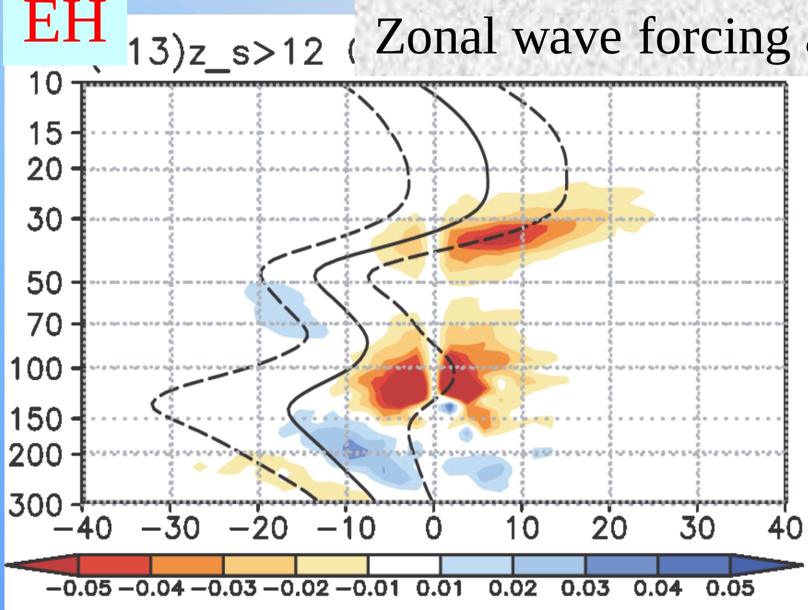


GWs in the EH,
$-5\ ms^{-1} < Cx < +20\ ms^{-1}$
induce large eastward forcing

GWs in the WH
much smaller contribution
eastward wind of the Walker circulation in the WH prevent eastward GWs from entering to the stratosphere

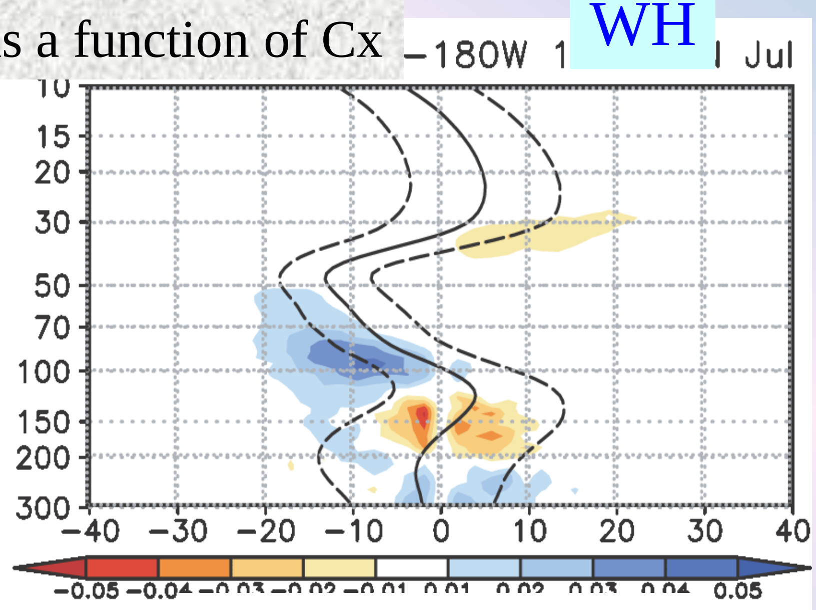
Zonal wave forcing as a function of Cx

EH



westward eastward

WH

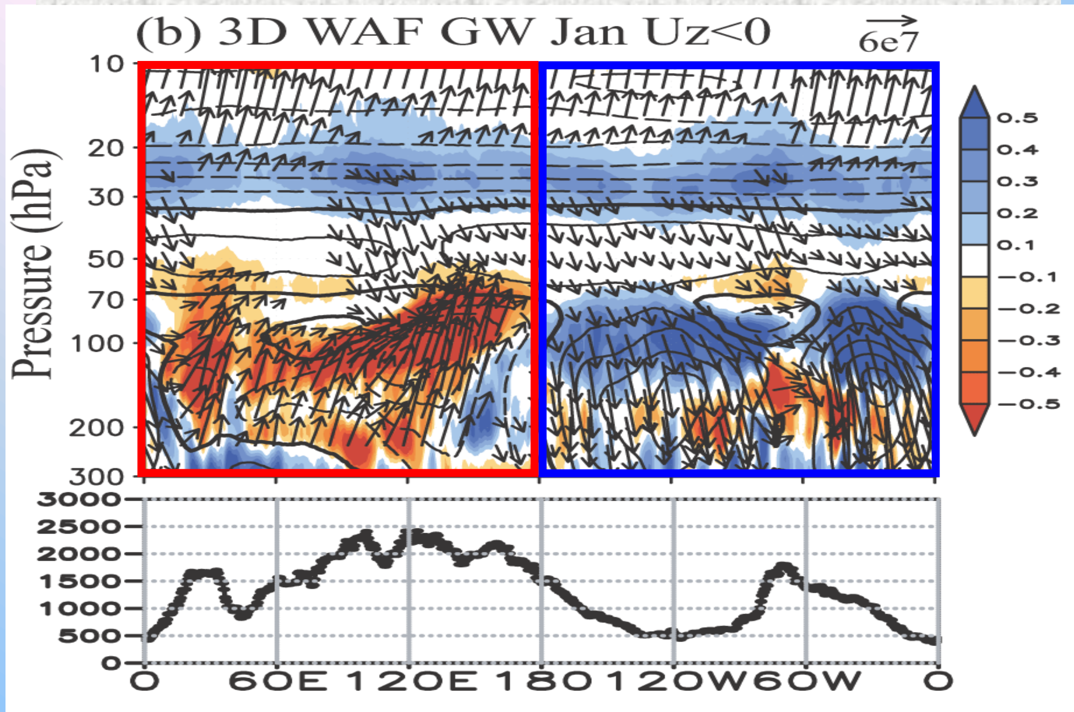


westward eastward

solid line
mean zonal wind
with s≤11

dashed line
STD of zonal wind

3-D wave flux during Uz<0 in Jan (10S-10N)



westward wind shear Uz<0

GWs **-30 ms-1 ≤ Cx ≤ ~-5 ms-1**

small difference between EH & WH

Larger range of Cx in QBO westward shear zone reduced hemispheric asymmetry

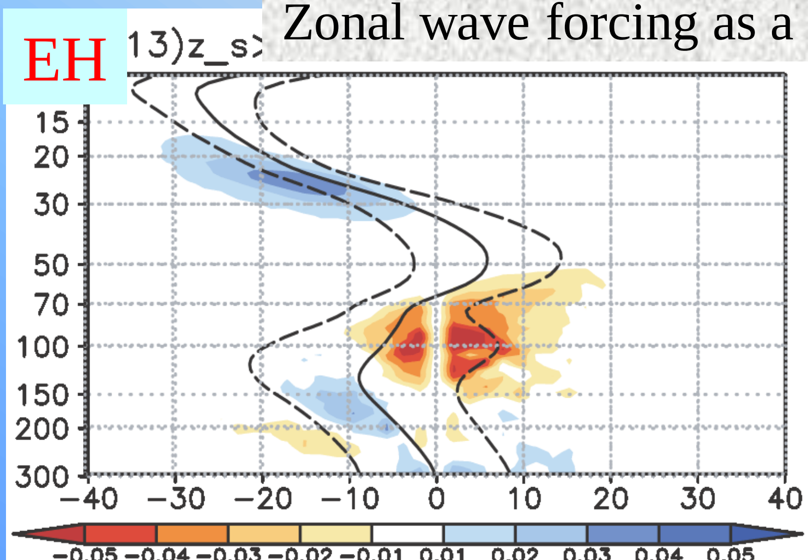
PRCP in the EH is larger than in the WH

<near top of the Walker circulation>

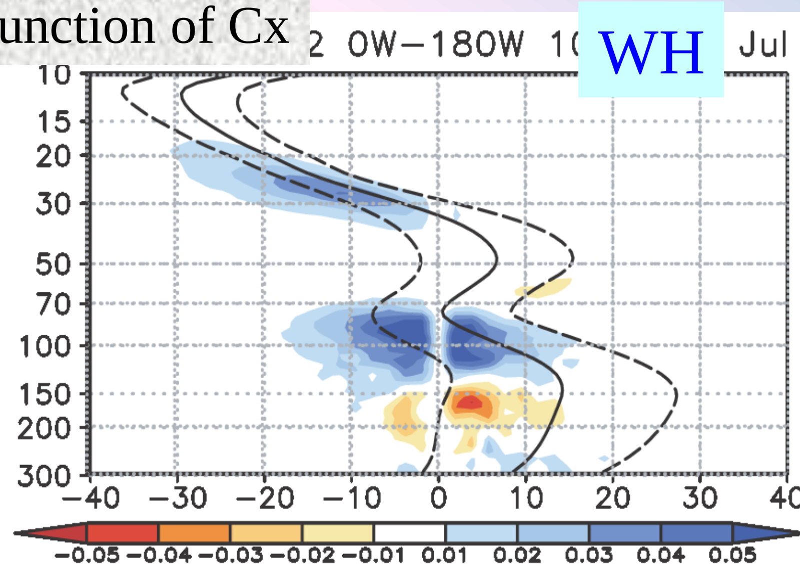
EH (WH): eastward (westward) forcing

3-D GWs with small Cx (small λz) dominate around the tropopause

Zonal wave forcing as a function of Cx



westward eastward



westward eastward

GWs with small Cx around the tropopause

GWs with small λz

different wave forcing between EH and WH

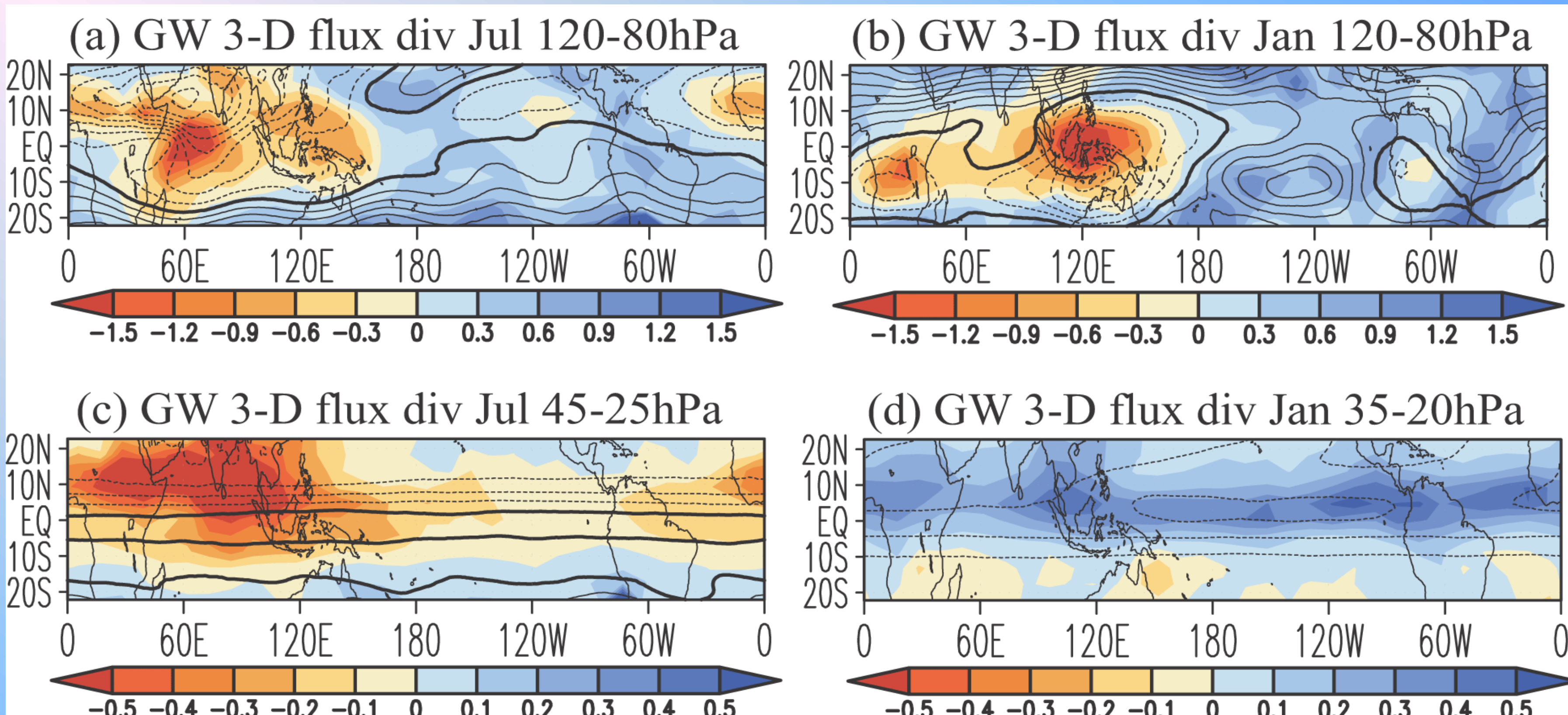
Global distribution of 3-D wave flux divergence associated with internal GWs

Jul, eastward wind shear Uz>0

Jan, westward wind shear Uz<0

Top of Walker 120-80 hPa

QBO sheared ~30hPa



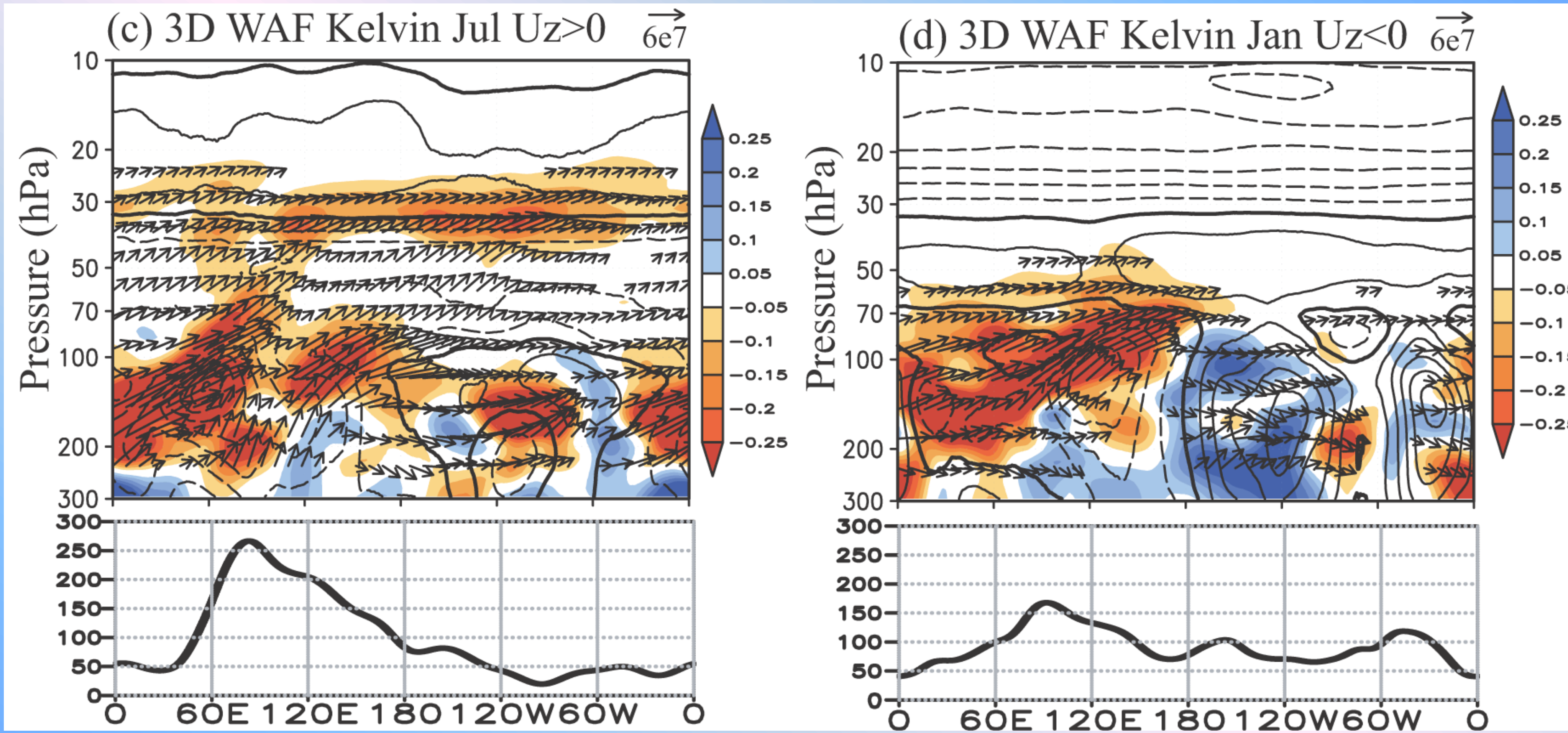
At 120-80 hPa large eastward wave forcing distributes widely in the EH
Zonally inhomogeneous distribution of internal gravity wave forcing is apparent

At 45-25 hPa in Jul, large (very weak) eastward forcing distribute in the EH (WH)
At 35-20 hPa in Jan, westward forcing elongates more zonally over the equatorial region.
(ex. Wave forcing at (100E, 0.2S: EAR) would be stronger than those in other longitudes)

3-D wave flux due to Kelvin waves

eastward wind shear Uz>0

westward wind shear Uz<0



Kelvin wave source is larger in the EH than in the WH

most Kelvin waves generate in the EH propagate into the stratosphere

zonally elongated wave forcing **apart from source region**

Conclusion

T213L256 AGCM: ⊿h=60km, ⊿z=300m, data for 3-year

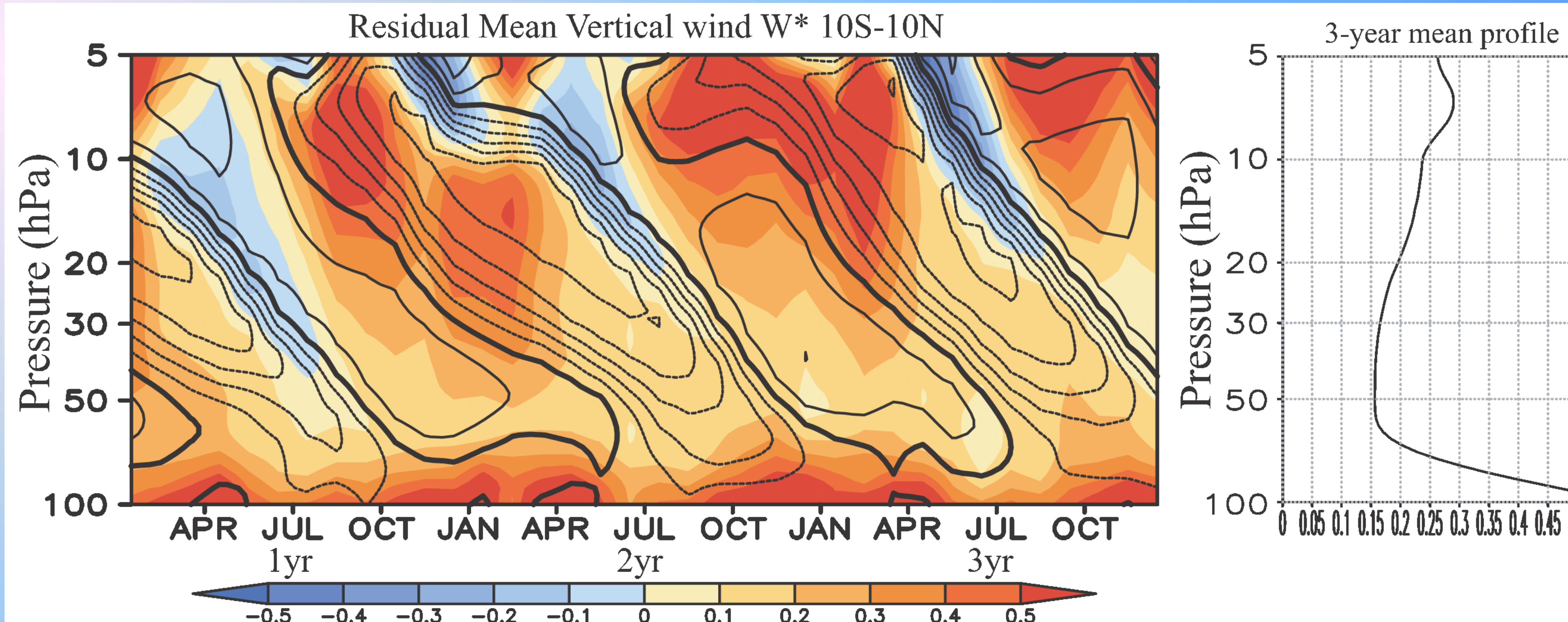
	EQWs	internal inertia-GWs	Extratropical Rossby waves
eastward wind shear	~**25-50%** maximum around 0m/s	~**50-75%** maximum around 0m/s	
westward wind shear	~**10%** during **weak** westward wind nearly **0%** during **stronger** westward wind	main forcing **λx≤~1000km** (**unresolved by T42**)	~**10-25%** large in the upper level

Nearly all EP-flux divergence due to 3-D GWs consists of its vertical components (not shown)
→GWD parameterization of only vertical wave propagation is suitable for QBO
Meridional momentum transports by EQWs occurs around vertically sheared zonal winds

The wave forcing to drive the QBO does not show zonally uniform distributions but has large **dependence in the zonal direction**, especially in the eastward wind phase of the QBO (wave momentum flux at (100E, 0S) would have larger than the zonal mean fluxes)

GWs with small |Cx| interact with the **top of the Walker circulation,** resulting in large **eastward (westward) wave forcing in the EH (WH) → short λz** dominate

Observation (radar, sonde, rocket, satellite) + model (global, regional)



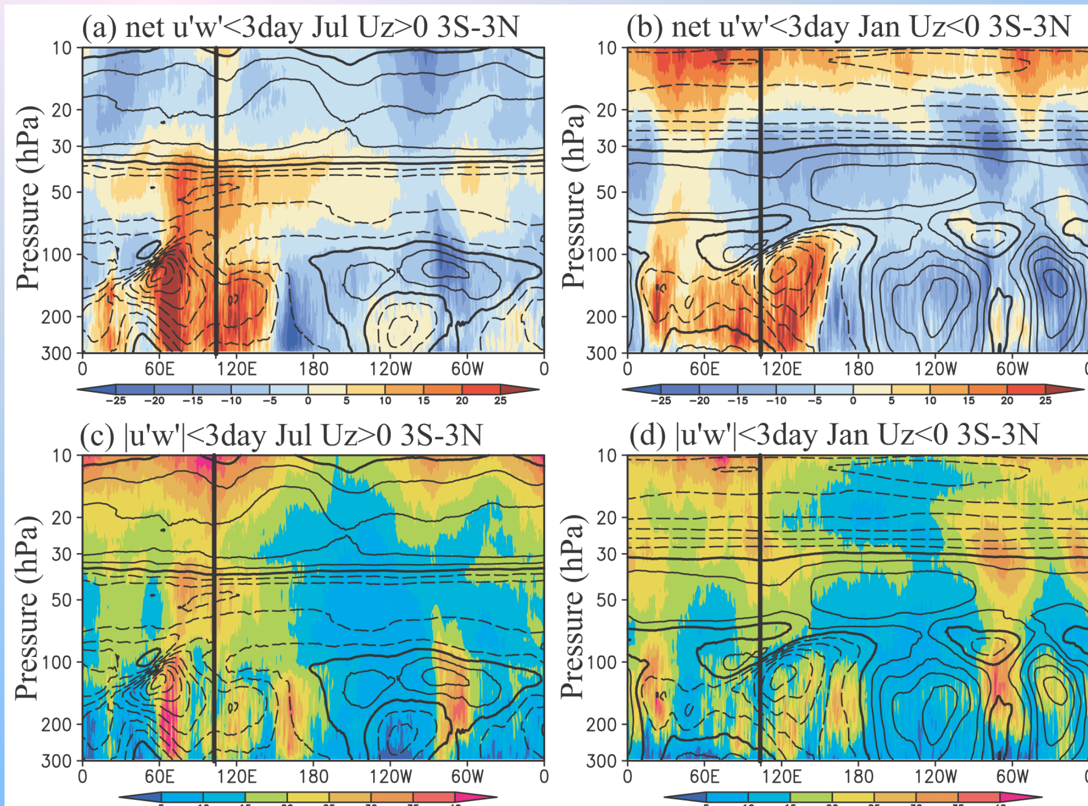
The simulated period of the oscillation is about half that of the QBO in the real atmosphere.
One is underestimation of mean ascent motion in the equatorial lower stratosphere
The other is overestimation of the wave forcing that brings the downward phase of the QBO.

w* might be half that in the real atmosphere, resulting in the shorter period of simulated QBO. Roughly speaking, we expect that if upwelling in the model were doubled, the rate of eastward shear-zone descent would be reduced by about 0.5 km per month, bringer the total descent rate into better agreement with observations.

The model overestimates the strength of stratospheric westerly in the extratropical winter hemisphere, implying underestimation of wave forcing due to gravity waves and/or Rossby waves in the mid- to high latitudes. Underestimated wave forcing in the mid- to high latitudes would result in weaker in the tropics.

Validation of wave momentum flux

|u|<5 m/s



Compared with Sato and Dunkerton (1997)

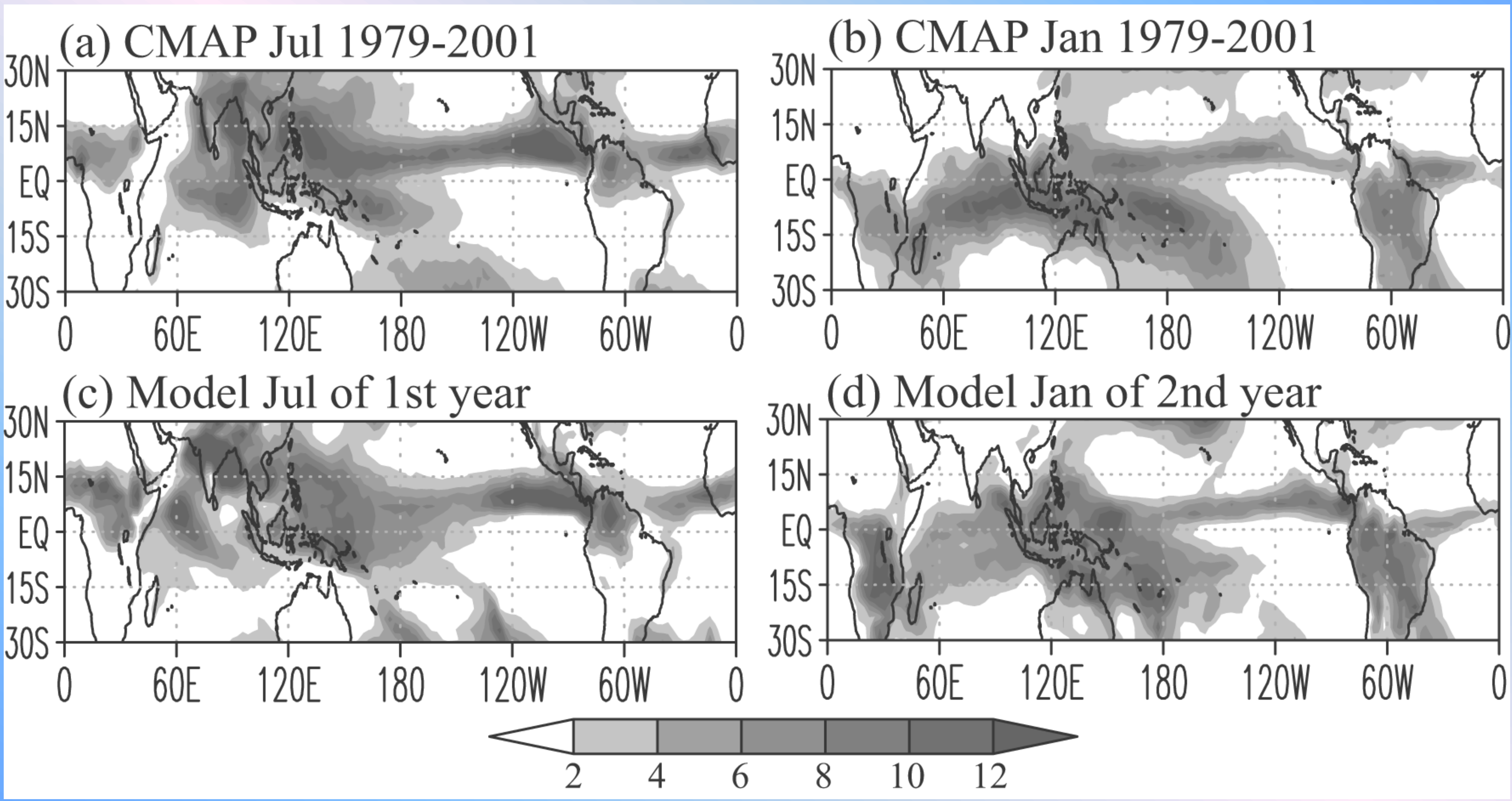
Uz>0	observation	AGCM
u'w'	0-+4 $\times 10^{-3}$	+10 $\times 10^{-3}$
|u'w'|	20-60 $\times 10^{-3}$	26 $\times 10^{-3}$

Uz<0	observation	AGCM
u'w'	nearly zero	-10 $\times 10^{-3}$
|u'w'|	10-30 $\times 10^{-3}$	23 $\times 10^{-3}$

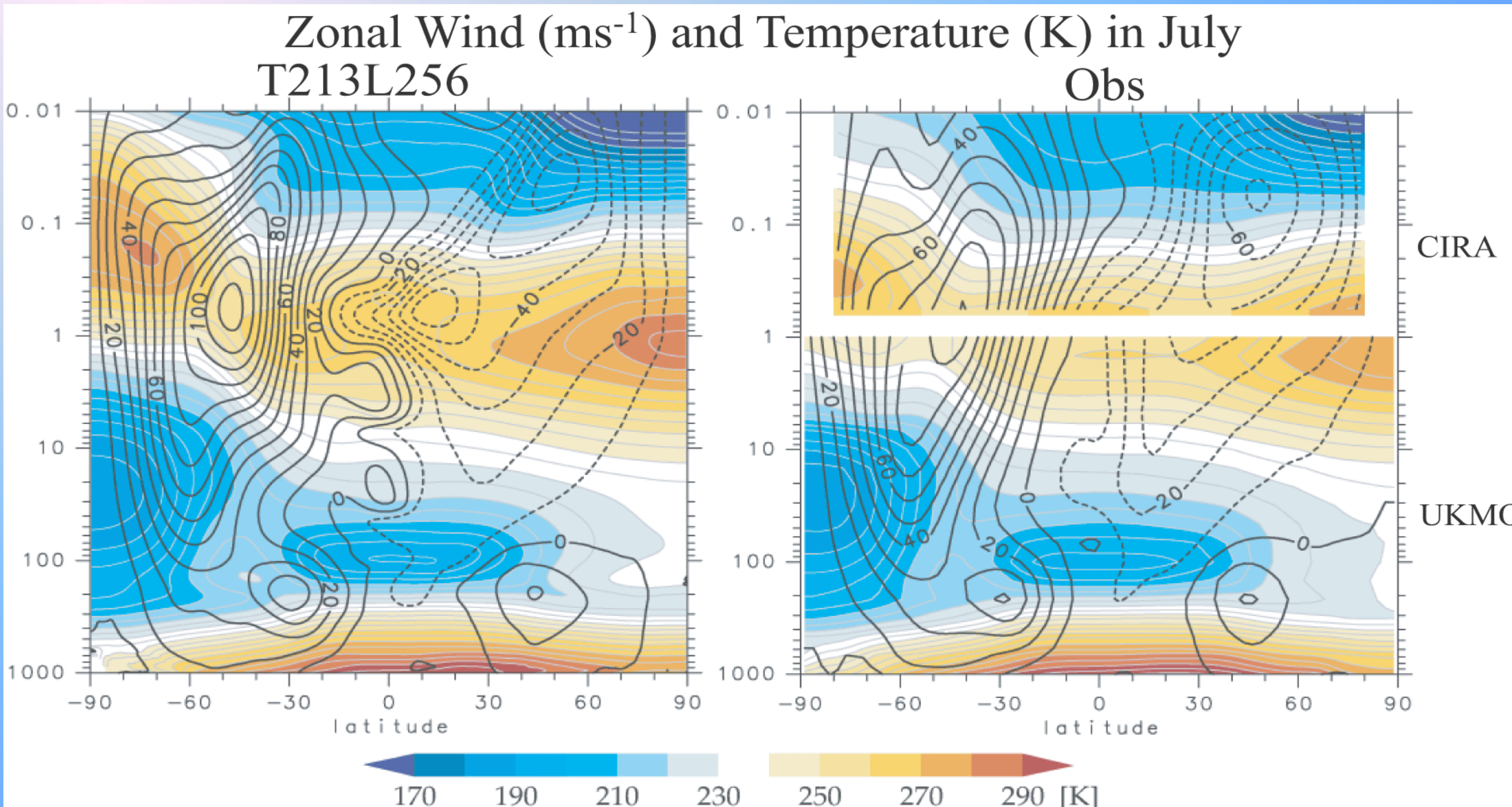
Momentum fluxes with eastward GWs would be simulated reasonably
Momentum fluxes with westward GWs might be a little overestimated

Momentum flux associated with Kelvin waves is simulated realistically (not shown)

Precipitation



Zonal mean U (contour) & T (color) in July



qualitatively simulates observed structure of U and T

Jet tilts equatorward with height, Stronger westerly, well simulated easterly in mesosphere