# Current Status and Issues On the Parameterizations of Convective Gravity Waves

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# Outline

- Development history of convective GWD (CGWD) parameterizations
- Ray-based CGWD parameterization
- Some issues on CGWD parameterizations
  - Reality of source-level (cloud-top) momentum flux spectrum
  - Using satellite data to constraint source-level momentum flux
  - Coupling GW momentum flux with cloud momentum flux
  - Including effects of the secondary GWs generated by breaking of convective GWs

# Parameterizations of Convective GWs

**First generation:**

- Rind et al. 1988: wave momentum flux is proportional to convective mass flux
- Kershaw 1995: wave energy above convection is proportional to convective kinetic energy in the cloud region

**Second generation:**

- Chun and Baik 1998, 2002: analytical formulation of wave momentum flux induced by specified diabatic forcing in a uniform/sheared background wind
- Chun et al. (2001, YONU GCM), Kim and Hogan (2002, NOGAPS), Chun et al. (2004, CCM3), Kim et al. (2007, GDAPS)
- Waves stationary relative to convective sources are considered

**Third generation (Spectral CGWD parameterizations):**

- Beres et al. (2004), Beres (2004) – uniform basic-state
- Song and Chun (2005) – shear flow with stability difference
- Kim and Chun (2005) – multiple waves in Chun and Baik (2002)'s
- Chun et al. (2008) – include nonlinear forcing effect in Song and Chun (2005)'s
- Beres et al. (2006, WACCM), Song et al. (2007, WACCM)

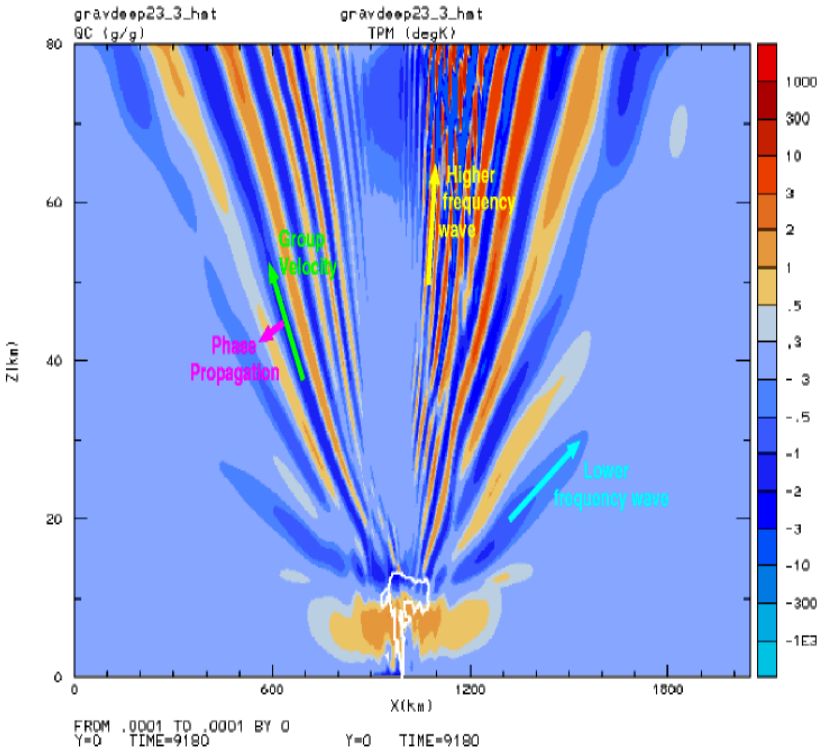
*Spatiotemporal variations of source spectrum can be included in the spectral GWD parameterization*

# A New Concept of GWD Parameterization

- **Assumptions in the current convective GWD parameterizations**
  - Column-based parameterization
  - GWs propagate only in the vertical direction
  - GWs propagate from a source level to model top within one GCM time step

- However, convective GWs can propagate horizontally as far as 1000 km when they reach the middle atmosphere

- ***It is necessary to develop a new convective GWD parameterization that includes horizontal as well as vertical wave propagations based on the ray theory***




**Holton and Alexander (1999)**

# LSGWDC: Lagrangian (Ray-based) Spectral Convective GWD Parameterization

## Reference-level (cloud-top) gravity-wave properties

wavenumbers, frequency, pseudomomentum flux are obtained at cloud top ($k$, $l$, $m$, $\omega$, $kc_{gz}A$, and $lc_{gz}A$) using Song and Chun (2005)'s formulation

## Wave propagation

Calculation of a trajectory of each ray and amplitude of the momentum flux following the ray (3-D ray-tracing model)

## Wave breaking and dissipation

Lindzen-type method based on Kiehl et al. (1996)

- Saturation threshold
- Wave diffusion
- Deposition of GW momentum flux

*Song and Chun (2008, JAS)*

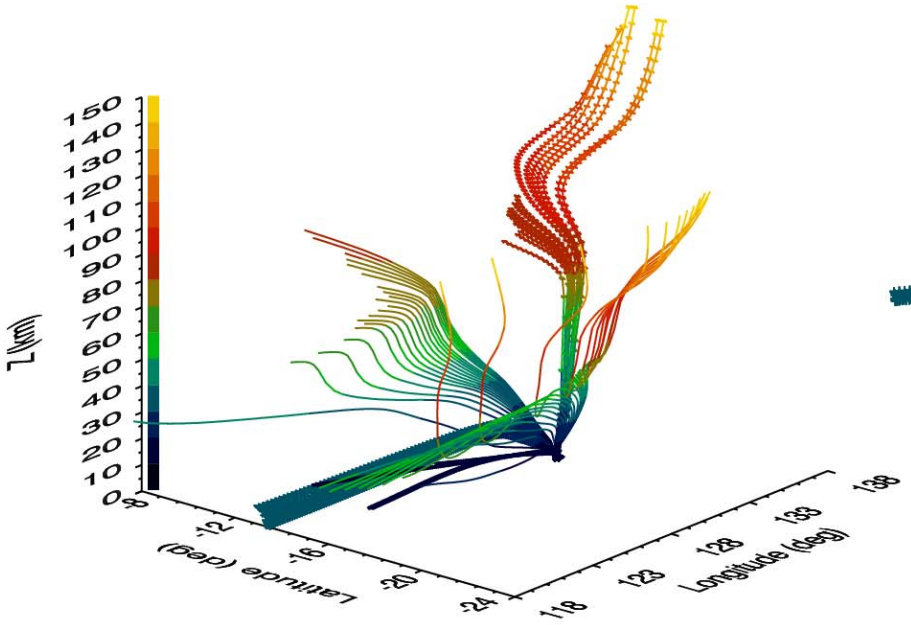
# NCAR Whole Atmosphere Community Climate Model (WACCM1b)

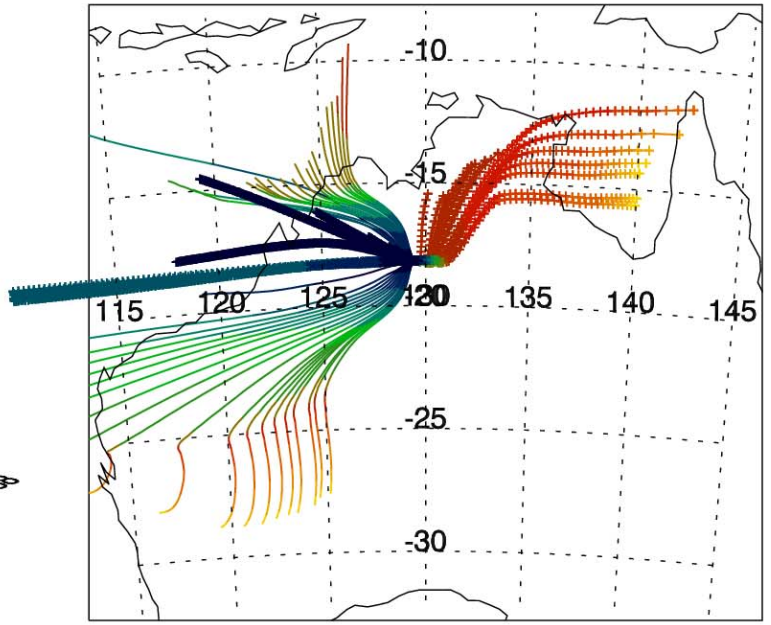
- Dynamics
  - Global spectral model [**T63** (128x64), semi-Lagrangian technique]
  - **66** vertical levels from the ground to about **z = 140 km**
  - **Vertical resolution:** less than 1.5 km below the lower strstosphere, 3.5 km in the mesosphere and above

- Physics
  - mostly the same as in **CCM3**
  - Additional processes for better simulation of middle atmosphere
    - Nonorographic gravity waves (GWD)
    - Nonlocal thermodynamic equilibrium longwave cooling
    - Shortwave heating for upper atmosphere
    - Molecular viscosity
    - Ion drag
    - Loss rates of green house gases and photolysis rates of water vapor

# Propagation of Rays (1 day, not interactive in WACCM1b)

Trajectories of internal gravity wave packets generated by deep convection at 18.1S, 129E at 00 UTC on 1 January 1979




Horizontal extent of propagation can be 10-20$^{o}$

Meridional propagation is relatively symmetric and waves propagate a great distance westward

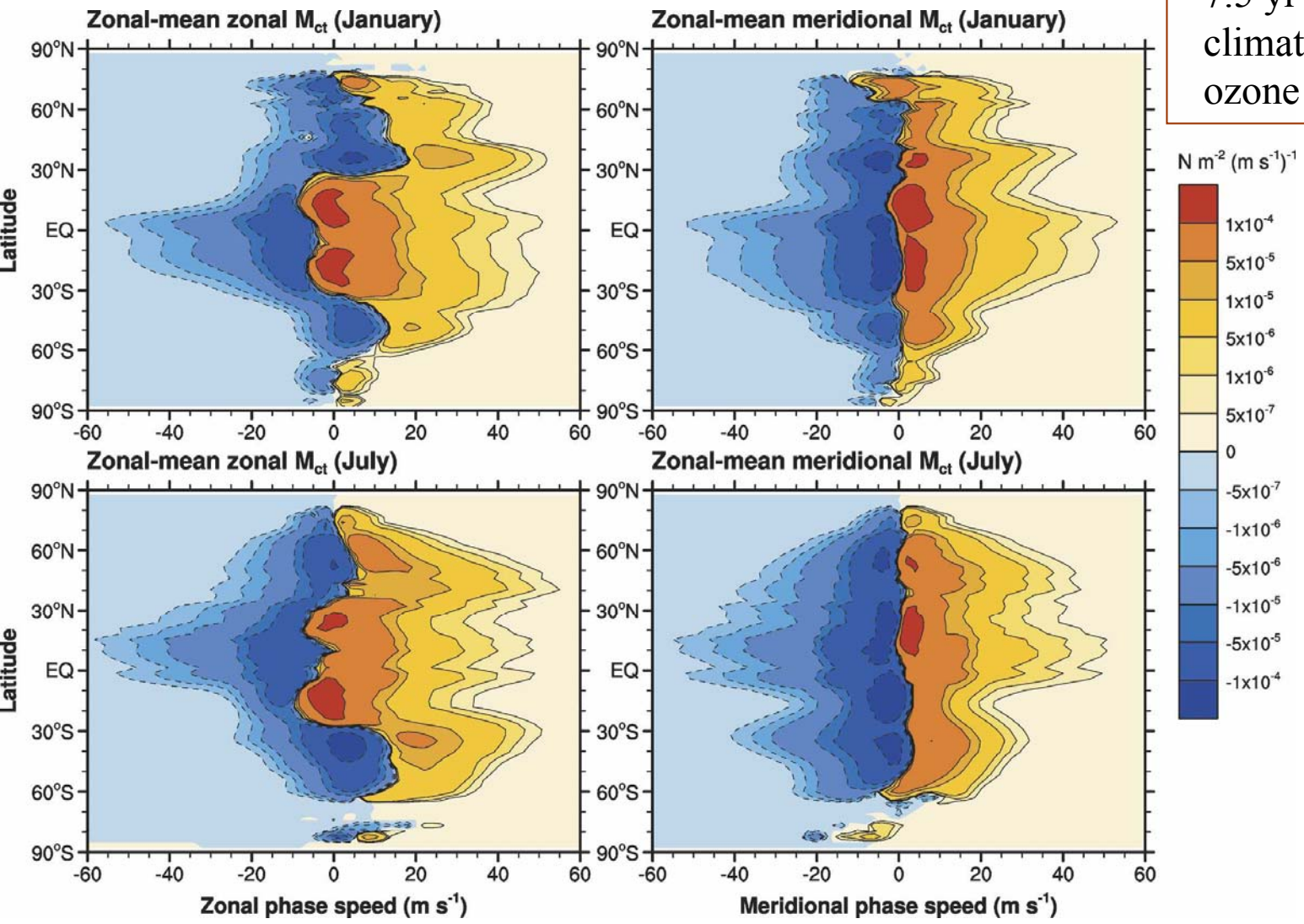
Zonal propagation is asymmetric due to Doppler shifting by the easterly flow

$$c_{gx} = \bar{u} + kN^2 \Big/ \left(\hat{\omega} m^2\right)$$

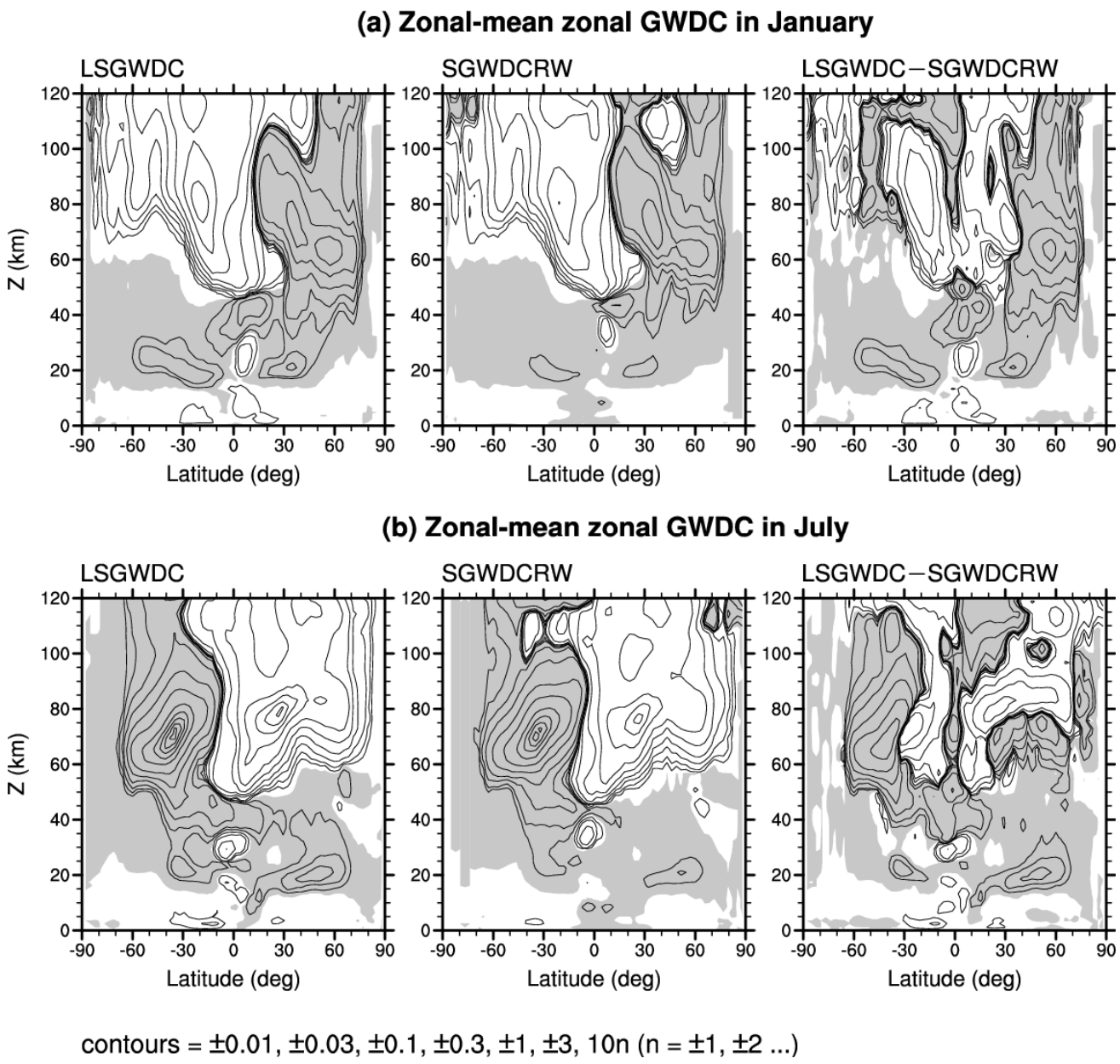
$$c_{gy} = \bar{v} + lN^2 \Big/ \left(\hat{\omega} m^2\right)$$

# Climate Simulations (6 yrs, interactive): Cloud-Top Momentum Flux Spectrum

7.5 yr simulation with climatological SST and ozone in WACCM1b



# Zonal-mean zonal drag (6 yr, interactive)




SGWDCRW: Song and Chun (2005) with reflection and WKB condition

- Generally similar with each other: negative drag in the winter mesosphere and most stratosphere and positive drag in the summer mesosphere
- Magnitude of drag forcing increases in the LSGWDC simulation

-Waves can be converged horizontally

- The low-frequency waves can stay longer in the tropical region

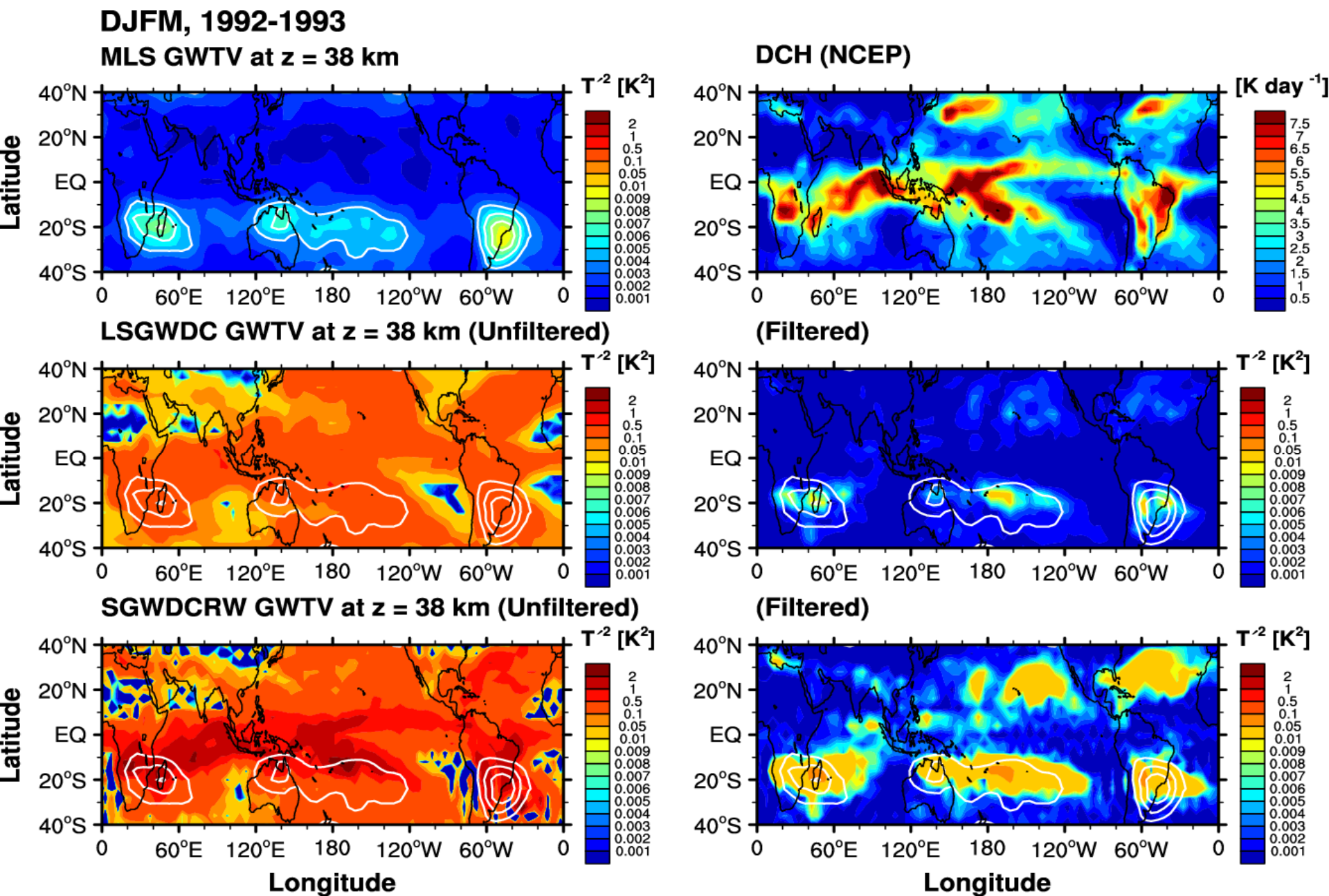
# Validation of LSGWDC Compared with Satellite Observations

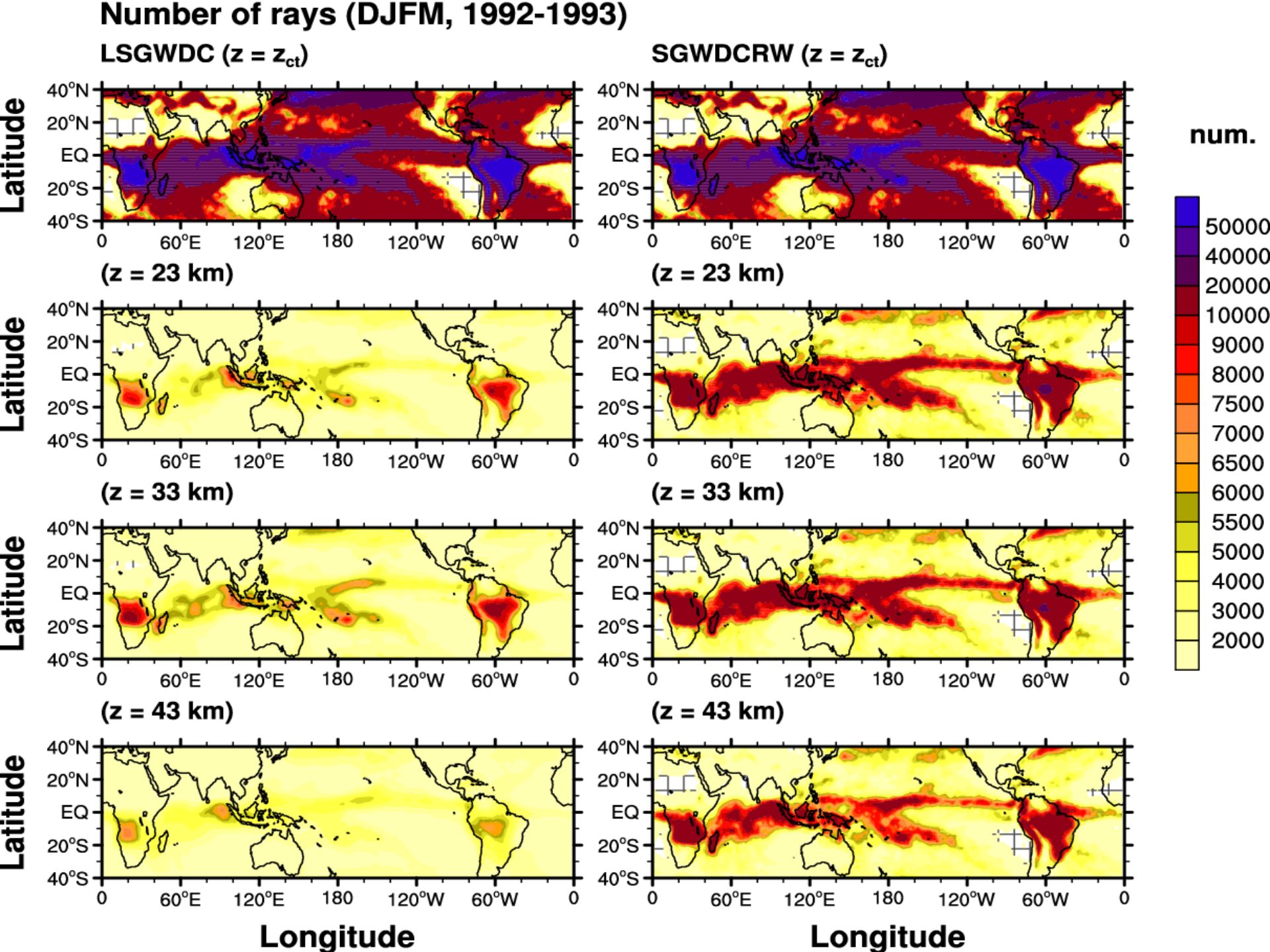
| | |
|---|---|
| **Observations** | Upper Atmosphere Research Satellite (UARS) Microwave Limb Sounder (**MLS**) **GW temperature variances at z = 38 km** reported by Jiang et al. (2004, JGR) |
| **Period** | 1) December-March (DJFM) 1992-1993<br>2) June-September (JJAS) 1993 |
| **Input data for LSGWDC parameterization** | ▪ **DCH (Deep Convective Heating rate)**<br>**- NCEP/NCAR reanalysis data**<br>(192×94 Gaussian grids, 6 hourly)<br>▪ **Background fields (U,V,T)**<br>**- ECMWF reanalysis data**<br>[23 pressure levels (1000-1 hPa), 2.5°×2.5° grids, 6 hourly]<br>▪ **Wave launch frequency:** 6 hr |

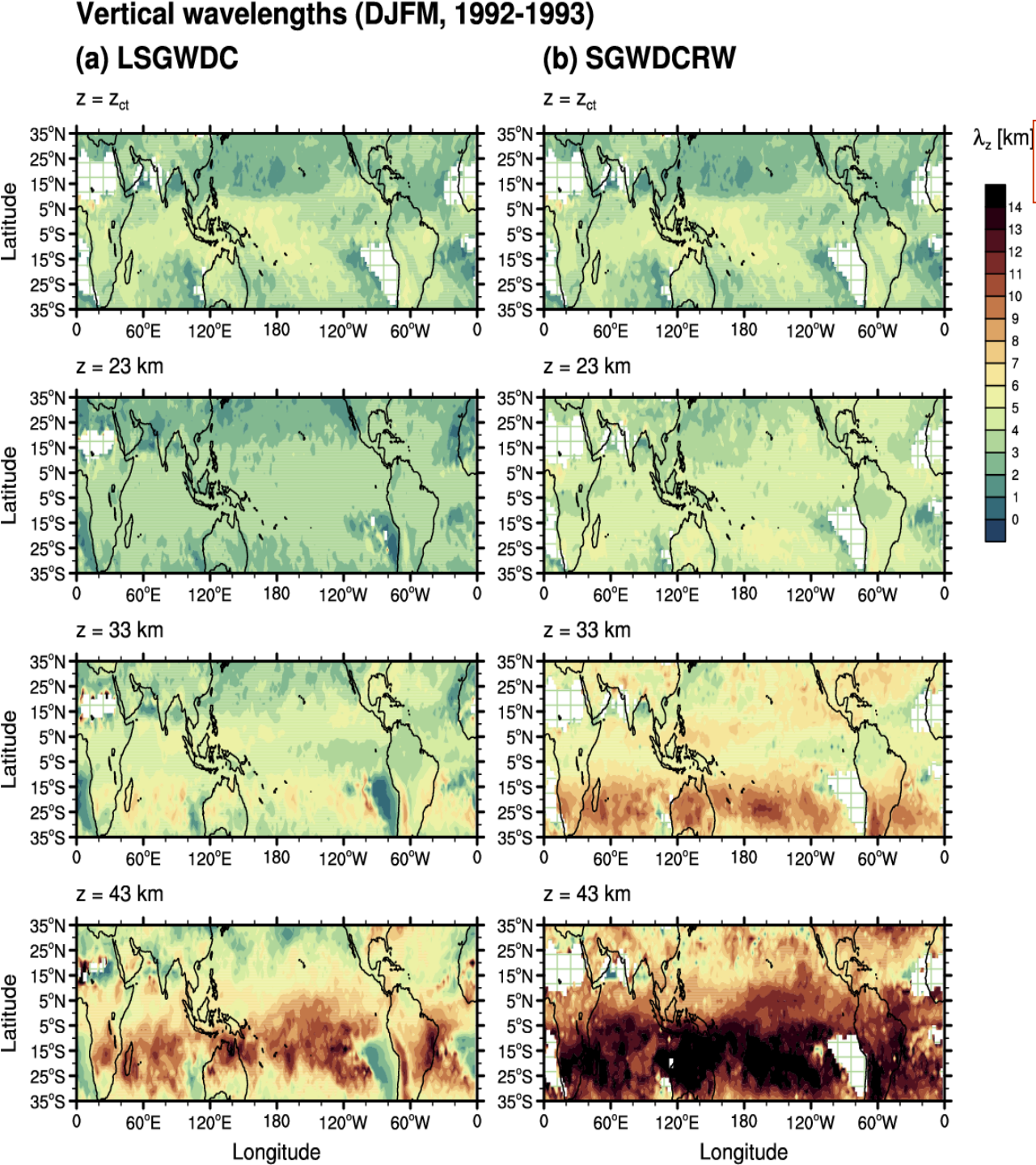
For comparison with MLS data ($\lambda_x < 100$ km, $\lambda_z > 10$ km), a 3-D MLS analytical filter function at z = 38 km by Jiang et al. (2004b, JGR) is used

*Choi et al. (2009, JGR)*

# Comparison with MLS GW Temperature Variance




Number of rays (DJFM, 1992-1993)
LSGWDC (z = z_ct)
SGWDCRW (z = z_ct)
(z = 23 km)
(z = 33 km)
(z = 43 km)
Latitude
Longitude
40°N
20°N
EQ
20°S
40°S
0
60°E
120°E
180
120°W
60°W
num.
50000
40000
20000
10000
9000
8000
7500
7000
6500
6000
5500
5000
4000
3000
2000




# Vertical wavelength

$$\lambda_z = \frac{\sum_n \lambda_{z\,n} GWTV_n}{\sum_n GWTV_n}$$

- $z\uparrow \rightarrow \lambda_z\uparrow$ due to reduction of the GWs with small vertical wavelength by the critical-level filtering, and this is significant in the southern subtropical region where stratospheric easterly wind shear is strong.
- Smaller $\lambda_z$ over the stratosphere in the LSGWDC parameterization due to long lasting GWs with small group velocities ($c_{gz} \propto \lambda_z^{\,2}$)

# Some Issues on the CGWD Parameterizations

- **Reality of the source-level (cloud-top) momentum flux spectrum**

- **How global observation data sets can be used for the validation and development of CGWD parameterization**

- **Coupling GW momentum flux with cloud momentum flux**

- **Including effects of secondary GWs generated by breaking of convective GWs**

# Cloud-top Momentum Flux Spectrum

*Song and Chun (2005, JAS)*

## Governing equations

In the three-dimensional, hydrostatic, nonrotating, inviscid, and Boussinesq airflow system, governing equations for small perturbations forced by a diabatic forcing ($Q$) are written as

$$\frac{\partial u}{\partial t}+U\frac{\partial u}{\partial x}+V\frac{\partial u}{\partial y}+w\frac{dU}{dz}+\frac{\partial \phi}{\partial x}=0$$

$$\frac{\partial \phi}{\partial z}=b$$

$$\frac{\partial b}{\partial t}+U\frac{\partial b}{\partial x}+V\frac{\partial b}{\partial y}+N^2 w=\frac{gQ}{c_p T_0}$$

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial x}+\frac{\partial w}{\partial z}=0$$

$$\frac{D^2}{Dt^2}\left(\frac{\partial^2 w}{\partial z^2}\right)-\frac{d^2U}{dz^2}\frac{D}{Dt}\left(\frac{\partial w}{\partial x}\right)-\frac{d^2V}{dz^2}\frac{D}{Dt}\left(\frac{\partial w}{\partial y}\right)+N^2\left(\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2 w}{\partial y^2}\right)=\frac{g}{c_p T_0}\left(\frac{\partial^2 Q}{\partial x^2}+\frac{\partial^2 Q}{\partial y^2}\right)$$

$$\frac{D}{Dt}=\frac{\partial}{\partial t}+U\frac{\partial}{\partial x}+V\frac{\partial}{\partial y}$$

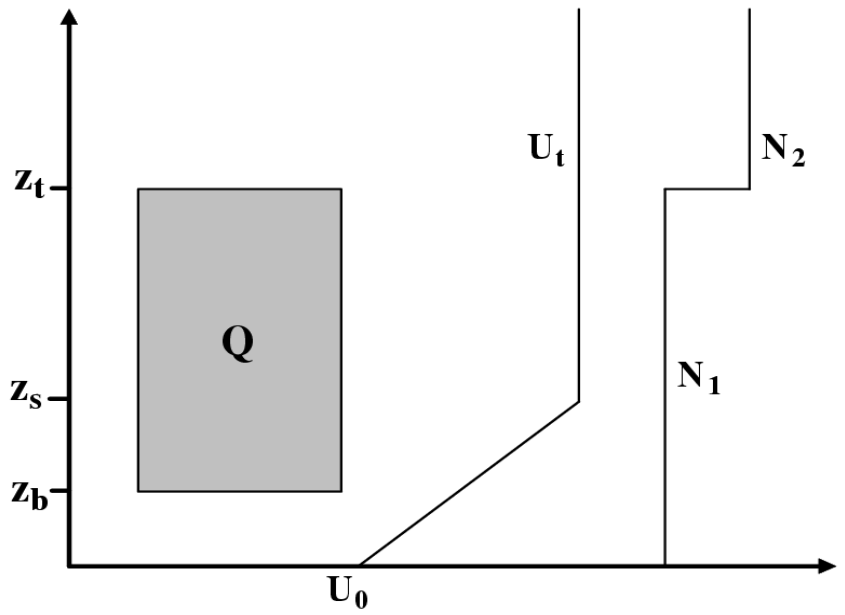
Fourier transform in x, y, and t

$$\frac{\partial^2 \hat{w}}{\partial z^2}+\left[\frac{N^2}{\left(\overline{U}-c\right)^2}-\frac{d^2\overline{U}/dz^2}{\left(\overline{U}-c\right)}\right]\hat{w}=\frac{g\hat{Q}}{c_p T_0\left(\overline{U}-c\right)^2}$$

$$\overline{U}(\varphi,z)=U(z)\cos\varphi+V(z)\sin\varphi$$

$$c=\omega/k_h,\quad k_h=\sqrt{k^2+l^2}$$

# Three-layer atmosphere and analytical solution




$$\hat{w}_2 = A_4 e^{i\lambda_1(z-z_t)} + B_4 e^{i\lambda_1(z-z_t)}$$

$$\hat{w}_1 = A_3 e^{i\lambda_1(z-z_s)} + B_3 e^{i\lambda_1(z-z_s)} + \tilde{Q}\zeta_b$$

$$\hat{w}_1 = A_2(z-z_\alpha)^{\frac{1}{2}+i\mu} + B_2(z-z_\alpha)^{\frac{1}{2}-i\mu} + \tilde{Q}\zeta_a$$

$$\hat{w}_1 = A_1(z-z_\alpha)^{\frac{1}{2}+i\mu} + B_1(z-z_\alpha)^{\frac{1}{2}-i\mu}$$

$\tilde{Q}\zeta_a \left[= \tilde{Q}(\zeta_q + \zeta_s)\right]$: particular solution when $dU/dz \neq 0$

$\tilde{Q}\zeta_a \left[= \tilde{Q}(\zeta_q + \zeta_u)\right]$: particular solution when $dU/dz = 0$

$$\mu = \sqrt{\text{Ri} - 1/4},\ \lambda_1 = \frac{N_1}{|U_t - c|},\ \lambda_2 = \frac{N_2}{|U_t - c|},\ \text{and}\ z_\alpha = \frac{c - U_0}{dU/dz}$$

$\tilde{Q} = \dfrac{g\hat{Q}}{c_p T_0 N_1^2}$, $\zeta_q$ = vertical structure function of forcing

$$Q(x,y,t) = Q_0 \exp\left[-\left(\frac{x - x_0 - c_{qx}(t-t_0)}{\delta_h/2}\right)^2\right] \exp\left[-\left(\frac{y - y_0 - c_{qy}(t-t_0)}{\delta_h/2}\right)^2\right] \exp\left[-\left(\frac{t-t_0}{\delta_t/2}\right)^2\right]$$

**Boundary condition at $z = 0$,**

**interface conditions at $z = z_b$ , $z_s$, and $z_t$, and upper radiation condition as $z$ goes infinity .**

→

**$A_1$, $B_1$, $A_2$, $B_2$, $A_3$, $B_3$, $A_4$, and $B_4$ are determined**

# Cloud-top momentum flux spectrum

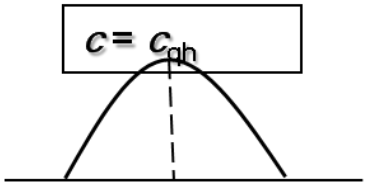
$$M_{ct}(c,\varphi,z_{ct}) = \mathrm{sgn}\left[c - U_{ct}(\varphi)\right]\rho_{ct}\frac{2(2\pi)^3}{A_h L_t}\left(\frac{g}{c_p T_{ct} N_q^2}\right)^2 \frac{N_{ct}|X|^2}{|c - U_{ct}(\varphi)|}\Theta(c,\varphi)$$

| WFRF | Source |
|---|---|

$|X|^2$ : dependent on basic-state wind and stability from the surface to cloud top and the vertical configuration (structure, height, and depth) of diabatic forcing:

- **Wave-filtering-and-resonance-factor (WFRF)**
  - ✓ wave filtering by the vertical propagation condition
  - ✓ resonance between the vertical harmonics consisting of convective source and natural wave modes with the vertical wavenumbers given by the dispersion relation of internal GWs
- Convective source spectrum

$$\Theta(c,\varphi) = q_0^2\left(\frac{\delta_h \delta_t}{32\pi^{3/2}}\right)^2 \frac{1}{\sqrt{1+(c-c_{qh})^2/c_0^2}},$$




✓ $\delta_h$, $\delta_t$ : spatial and time scales of the convective source), $c_o = \delta_h / \delta_t$

✓ $c_{qh}$ : moving speed of the convective source: $c_{qh}(\varphi) = c_{qx}\cos\varphi + c_{qy}\sin\varphi$

# Some Issues on the CGWD Parameterizations

- **Reality of the source-level (cloud-top) momentum flux spectrum**
  - **Validated Song and Chun (2005) based on the explicitly calculated 3-D convective gravity waves using the WRF model for various ideal and real storm cases**
  - **Determined two free parameters in the parameterization**
  - **Parameterization is well matched with the simulations (Choi and Chun, 2011, JAS, in press: Hyun-Joo Choi will present result in this session)**

- **How global observation data sets can be used for the validation and development of CGWD parameterization**

- **Coupling GW momentum flux with cloud momentum flux**

- **Including effects of secondary GWs generated by breaking of convective GWs**

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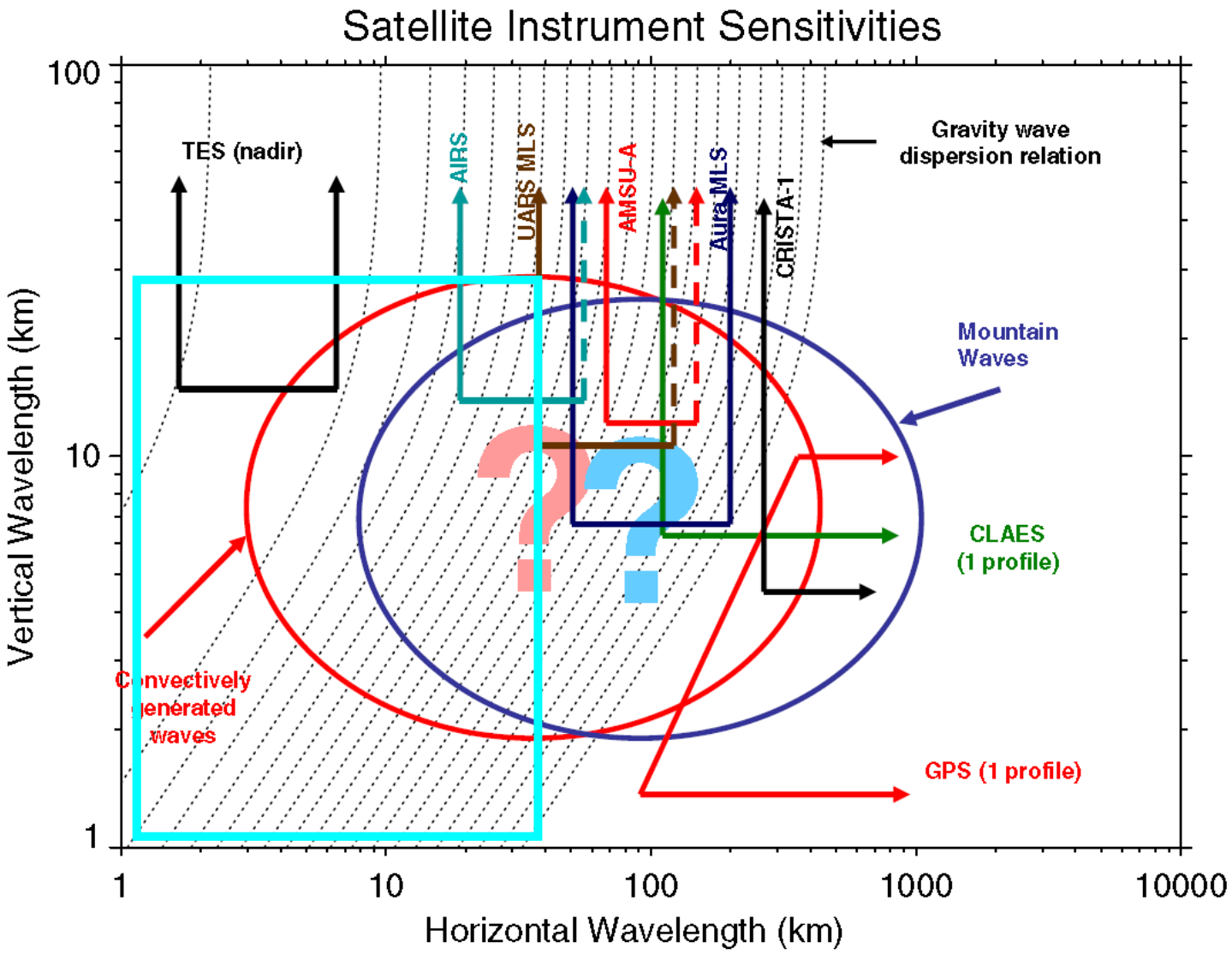
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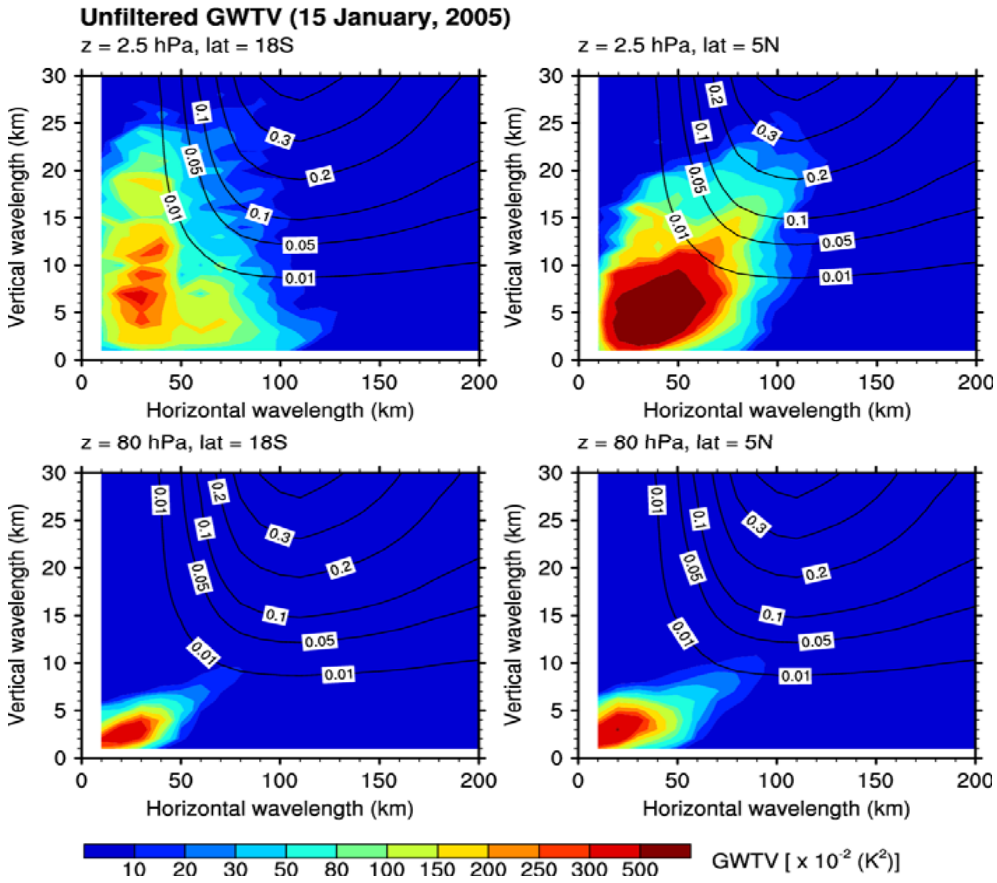
- **Coupling GW momentum flux with cloud momentum flux**
  - **cloud momentum flux profile in the cloud region should be combined with GW momentum flux profile above to make a momentum conservation**

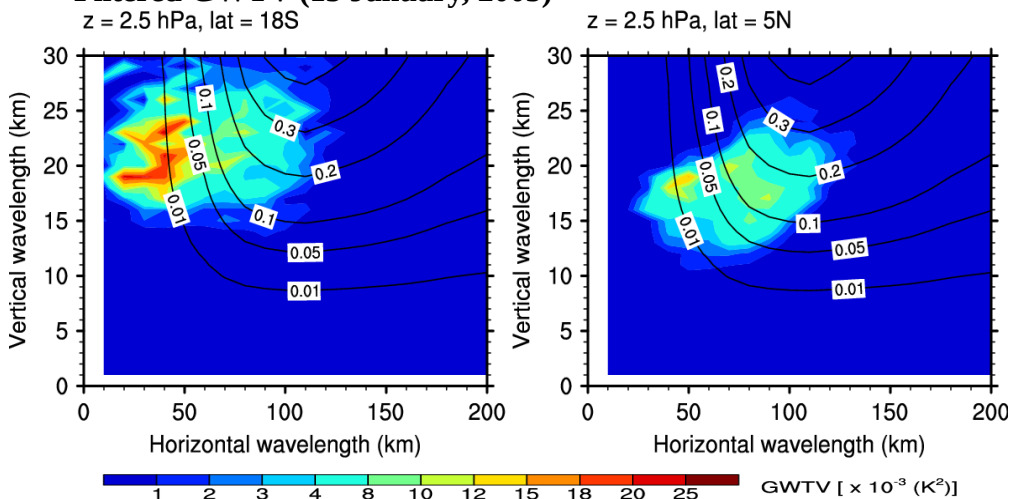
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# Limitation in using satellite data for validation/development of CGWD parameterization

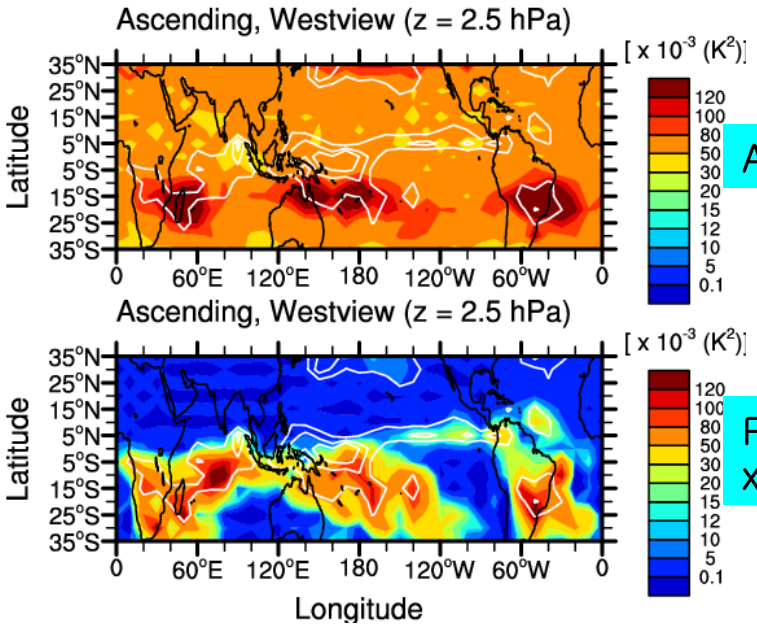


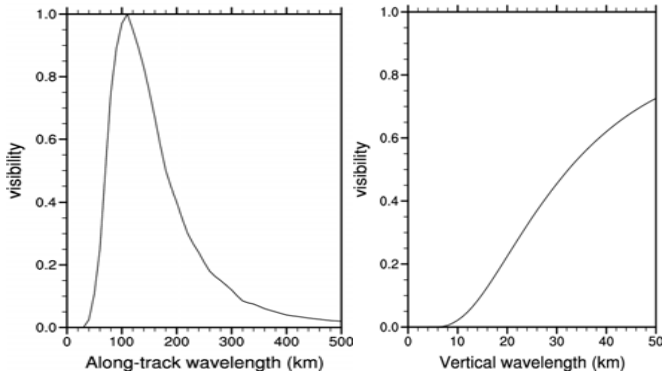

*Wu et al. (2006, Adv. Space Res.)*



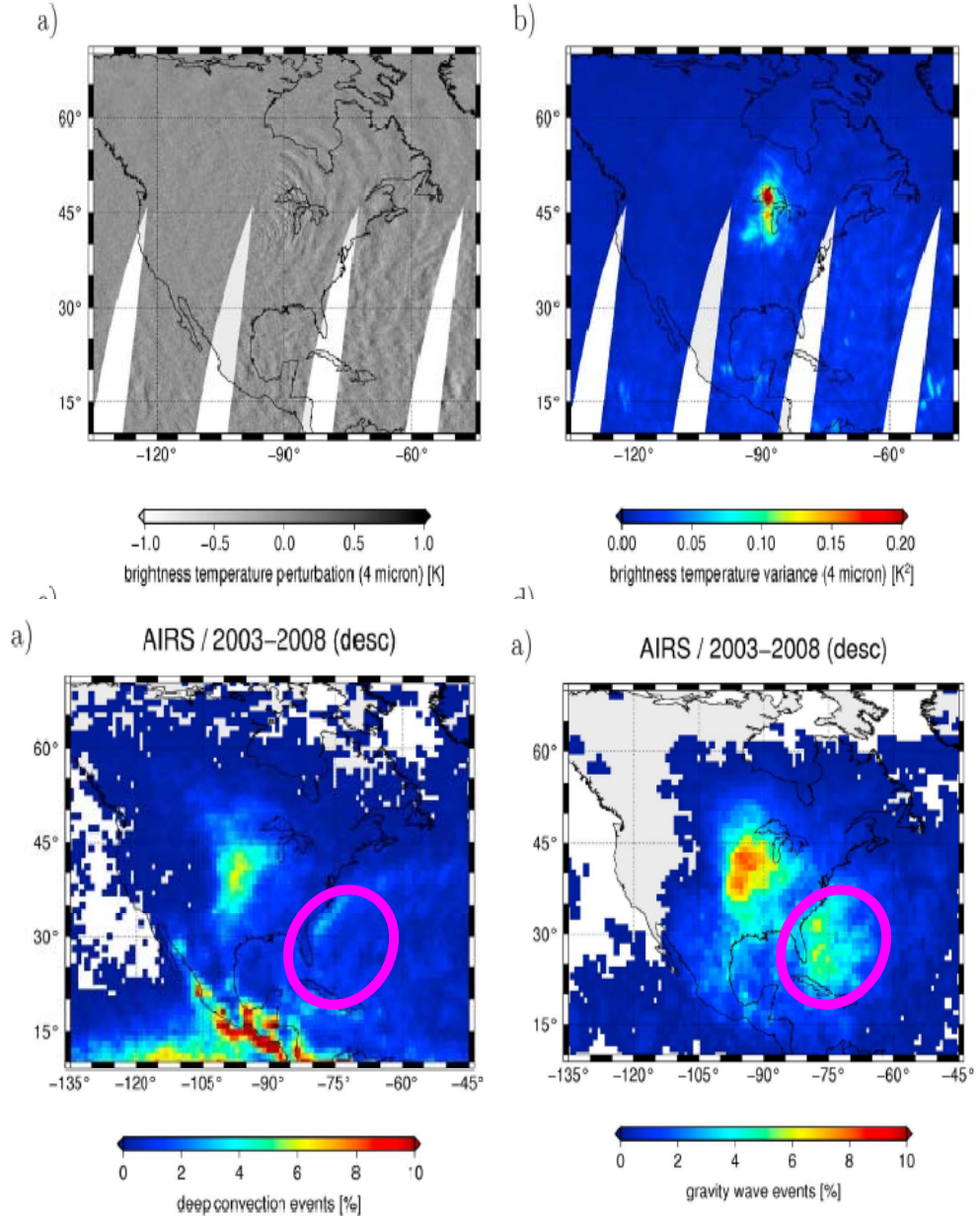




**Gravity Wave Temperature Variance calculated using reanalysis data (NCEP diabatic heating, ERA-Interim wind and temperature) and ray-based CGWD parameterization by Song and Chun (2008)**



# Convective GWs Observed in AIRS




- **Correlation between convective activity and gravity wave activity is strong in a core convection region, but not in other regions**
- **Direct correlation between convective sources and gravity waves can be valid for only high-frequency waves, and horizontal propagation from the source regions should be considered for relatively low-frequency waves generated by convective sources**
- **Ray-based CGWD parameterization is required**

  **: should ray-based CGWD parameterization more be efficient for use in GCMs**

***Hoffman and Alexander (2010, JGR)***

# Some Issues on the CGWD Parameterizations

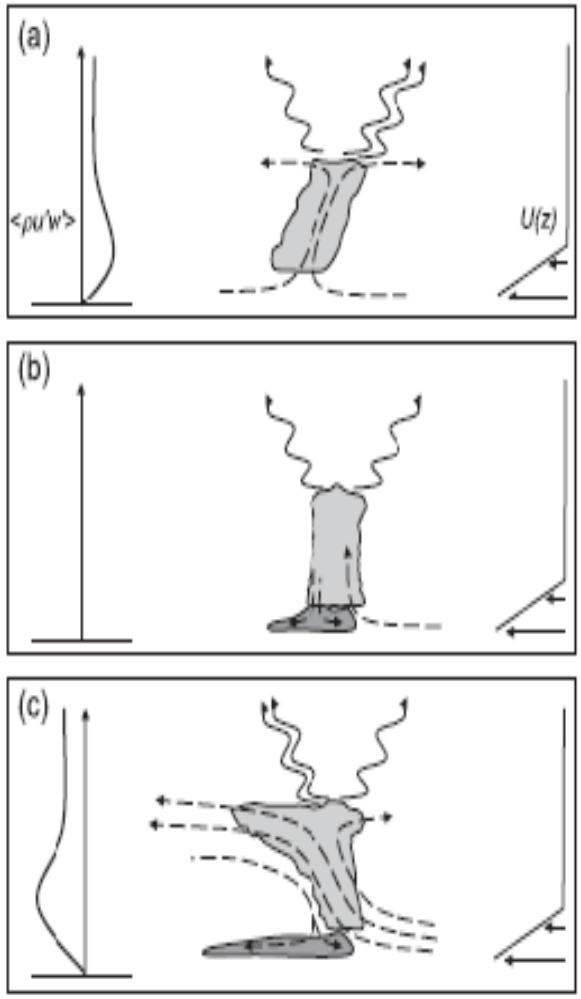
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# Coupling GW and Cloud Momentum Fluxes




Lane and Moncrieff (2010, JAS)

- Cloud momentum flux associated with organized convective system should be included in GCMs (*Wu and Yanai, 1994, Wu and Moncrieff 1996*), for better representation of cumulus convection, especially the location

- Momentum conservation including cloud-momentum flux profile is required: currently add compensating GW momentum at the upper few levels of cumulus clouds (*Chun and Baik, 1998, 2002; Song and Chun, 2005*)

$$\int_0^{Z_{mT}} \rho \frac{\partial U}{\partial t} = \int_0^{z_{cT}} \rho \frac{\partial U}{\partial t} + \int_{z_{cT}}^{Z_{mT}} \rho \frac{\partial U}{\partial t} = 0$$

$$\int_0^{z_{cT}} \rho \frac{\partial U}{\partial t} = -\int_{z_{cT}}^{Z_{mT}} \rho \frac{\partial U}{\partial t}$$

# Some Issues on the CGWD Parameterizations

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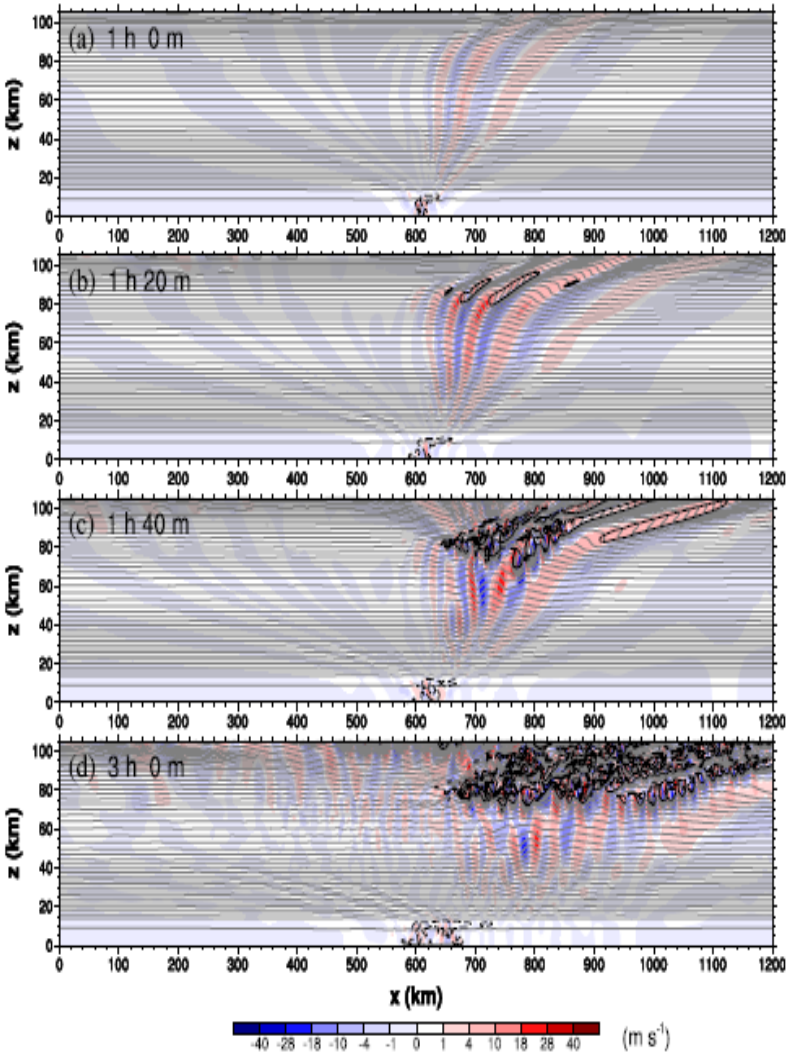
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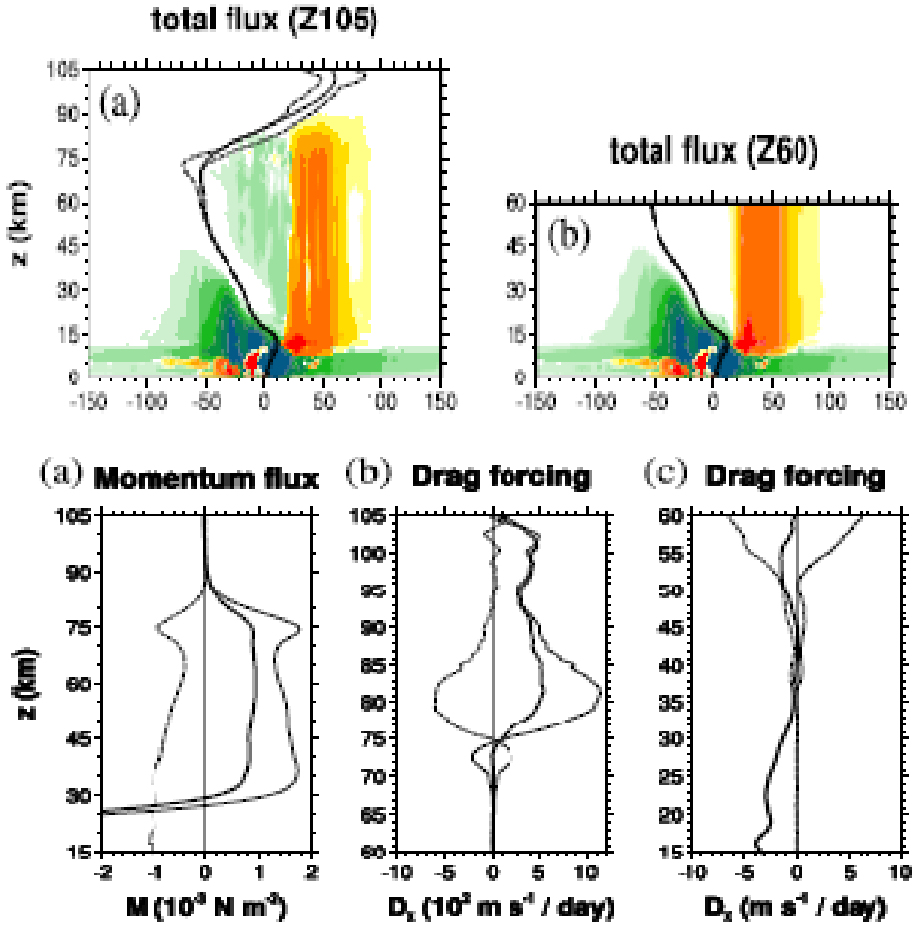
- **Including effects of secondary GWs generated by breaking of convective GWs**

# Effects of Secondary Waves

2-D APRS model simulation of convective GWs




Chun and Kim (2008, JGR)




Secondary waves generated by nonlinear momentum forcing by breaking of primary waves can influence on momentum profile significantly above and below the wave breaking region

**Thank you for your attention**