Barotropic and Baroclinic Processes Associated with Convective Development in the Tropical Deep Convective Regime

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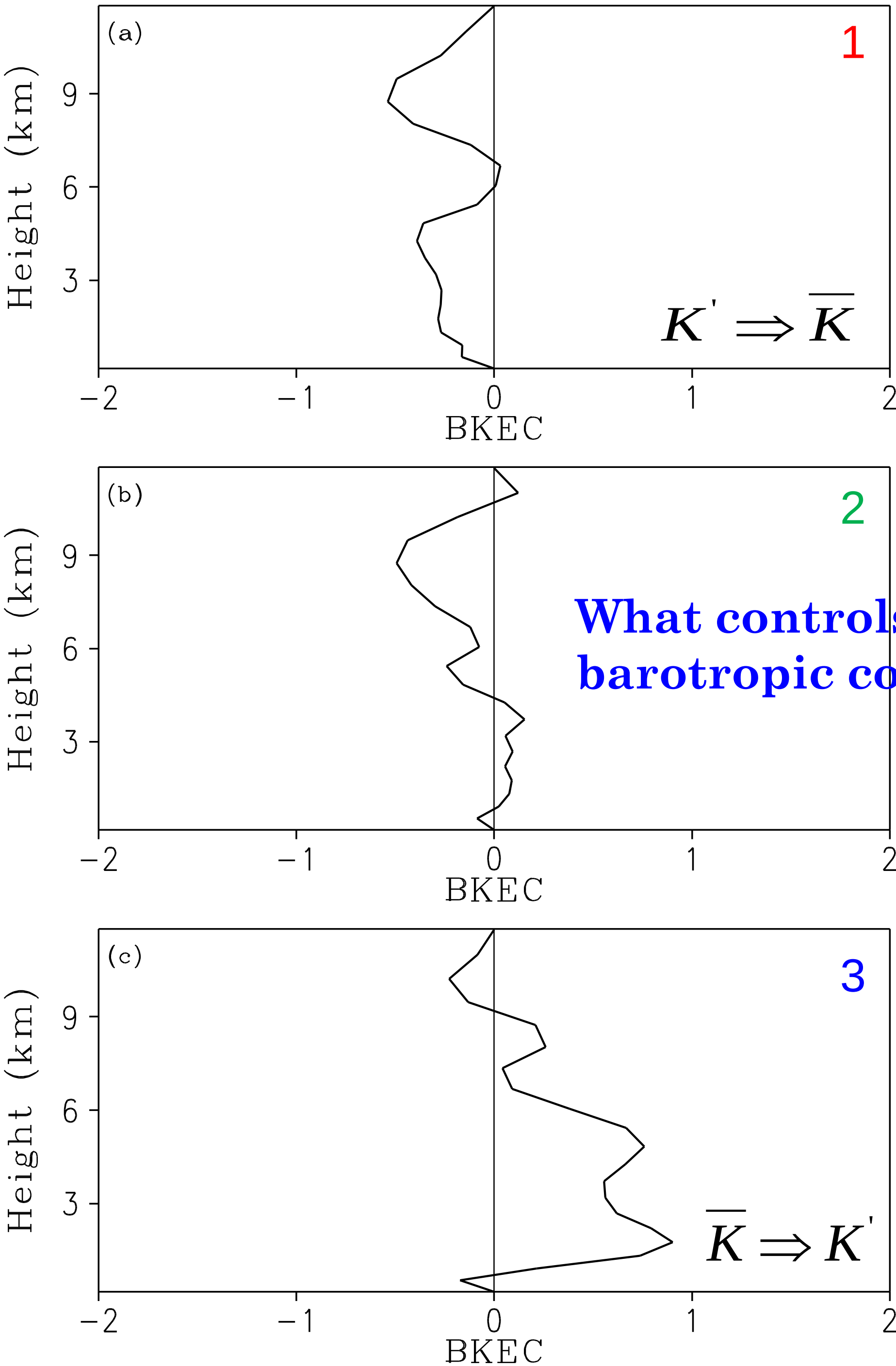
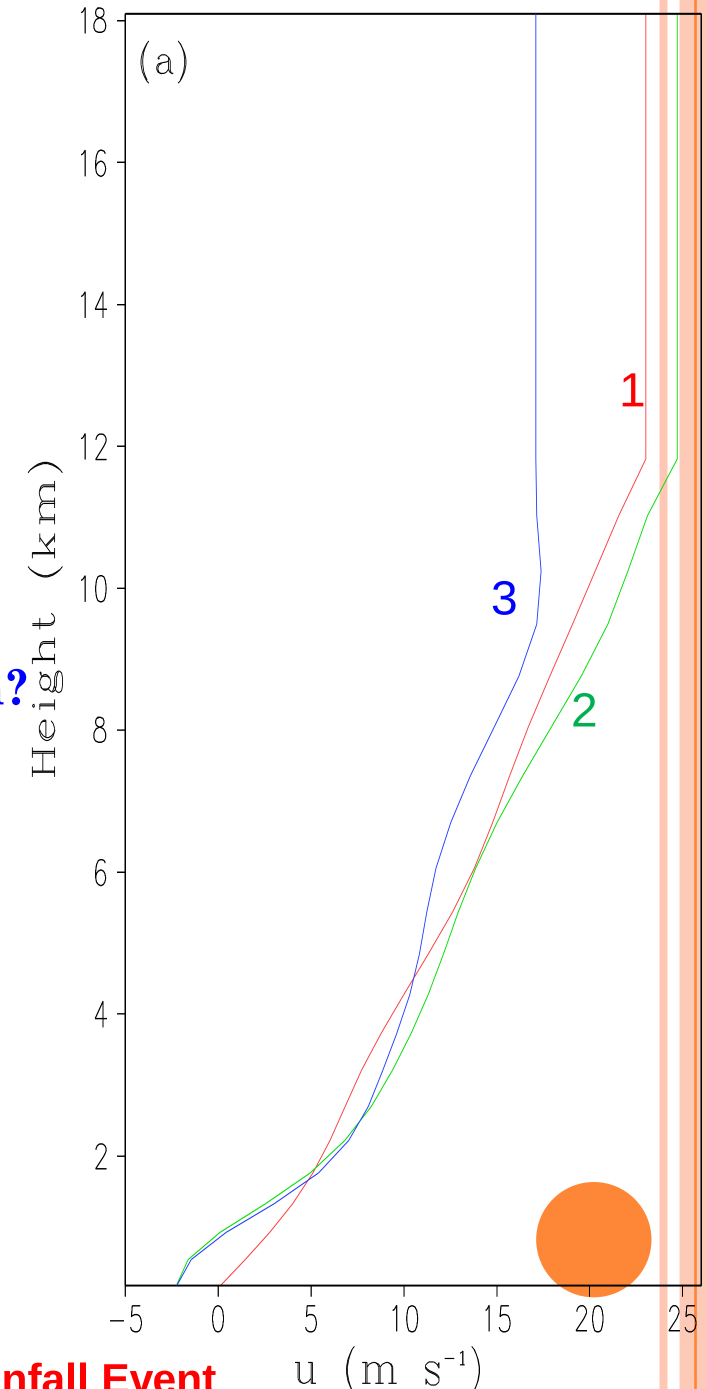
Motivation

Convective development results from the release of unstable energy. While the baroclinic conversion from perturbation available potential energy to perturbation kinetic energy forms a major source for the convective development, the barotropic conversion from the mean kinetic energy to perturbation kinetic energy could be an important source/sink that impacts the change in perturbation kinetic energy.



What controls barotropic conversion?

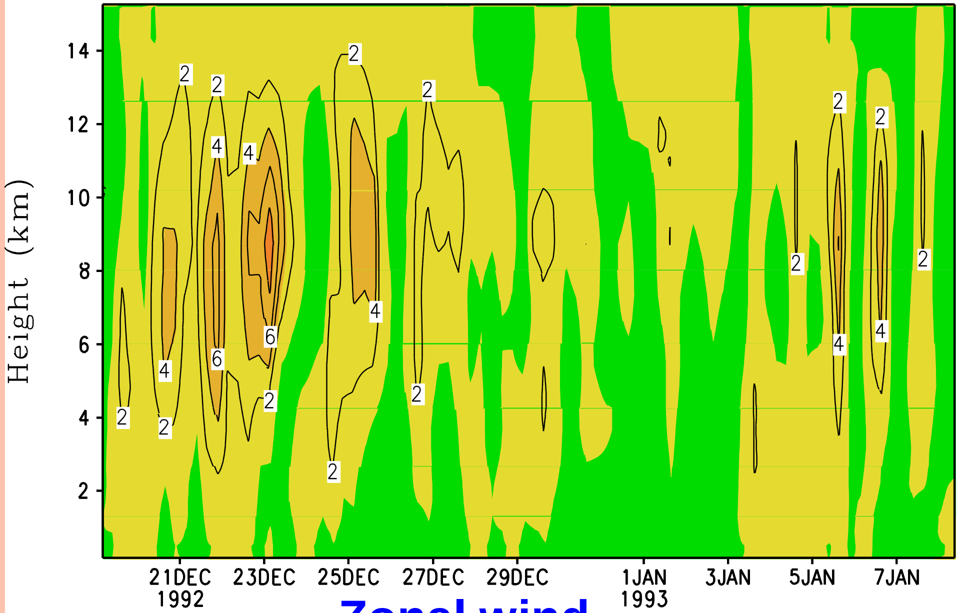


Meiyu Rainfall Event

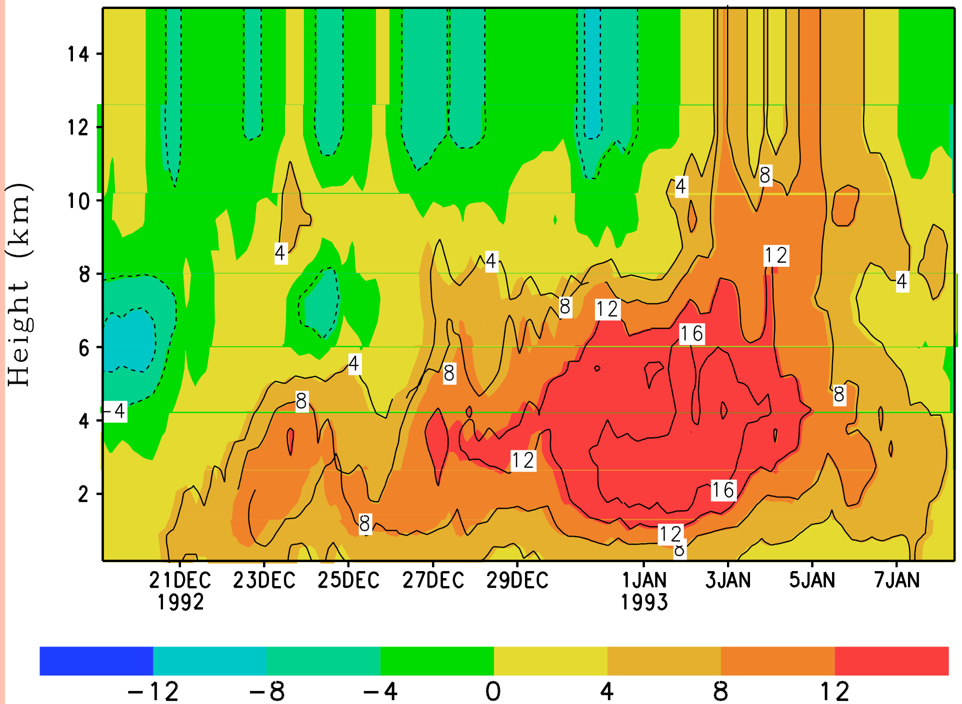
Cloud Resolving Model

- Non-hydrostatic and Anelastic (Tao and Simpson 1993)
- Prognostic equations for T, qv, qc, qr, qi, qs, qg
- Radiation (Chou and Suarez 1994, Chou et al. 1998)
- Cloud Microphysics (Rutledge and Hobbs 1983 1984, Lin et al. 1983, Tao et al. 1989, Krueger et al. 1995)
- Turbulence Closures
- Imposed spatial-uniform large-scale vertical velocity, zonal wind, surface flux, horizontal temperature and moisture advections
- Two dimension (x-z); Domain (768 km); Horizontal Resolution (1.5 km); 33 vertical levels; Time step (12 Seconds)

Vertical velocity



Zonal wind



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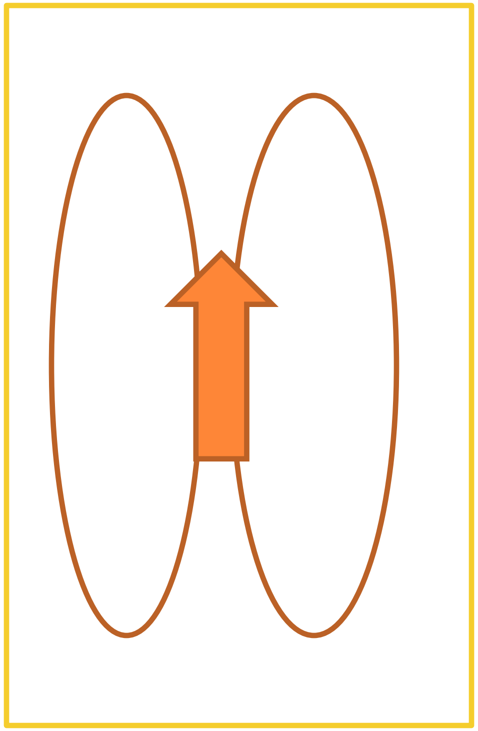
Perturbation Kinetic-Energy Budget



$$\frac{\partial K'}{\partial t} = C_u(\overline{K}, K') + C_w(\overline{K}, K') + C(P', K') + G_{qv}(K') + G_{ql}(K'),$$

$$K' = [\frac{\overline{(u')^2 + (w')^2}}{2}],$$

perturbation kinetic-energy

$$C_u(\overline{K}, K') = -[\overline{u'w'}\frac{\partial \overline{u}^{\,0}}{\partial z}],$$

$$C_w(\overline{K}, K') = -[\overline{w'w'}\frac{\partial \overline{w}^{\,0}}{\partial z}] \approx 0,$$

barotropic conversions

$$\overline{K} \leftrightarrow K'$$

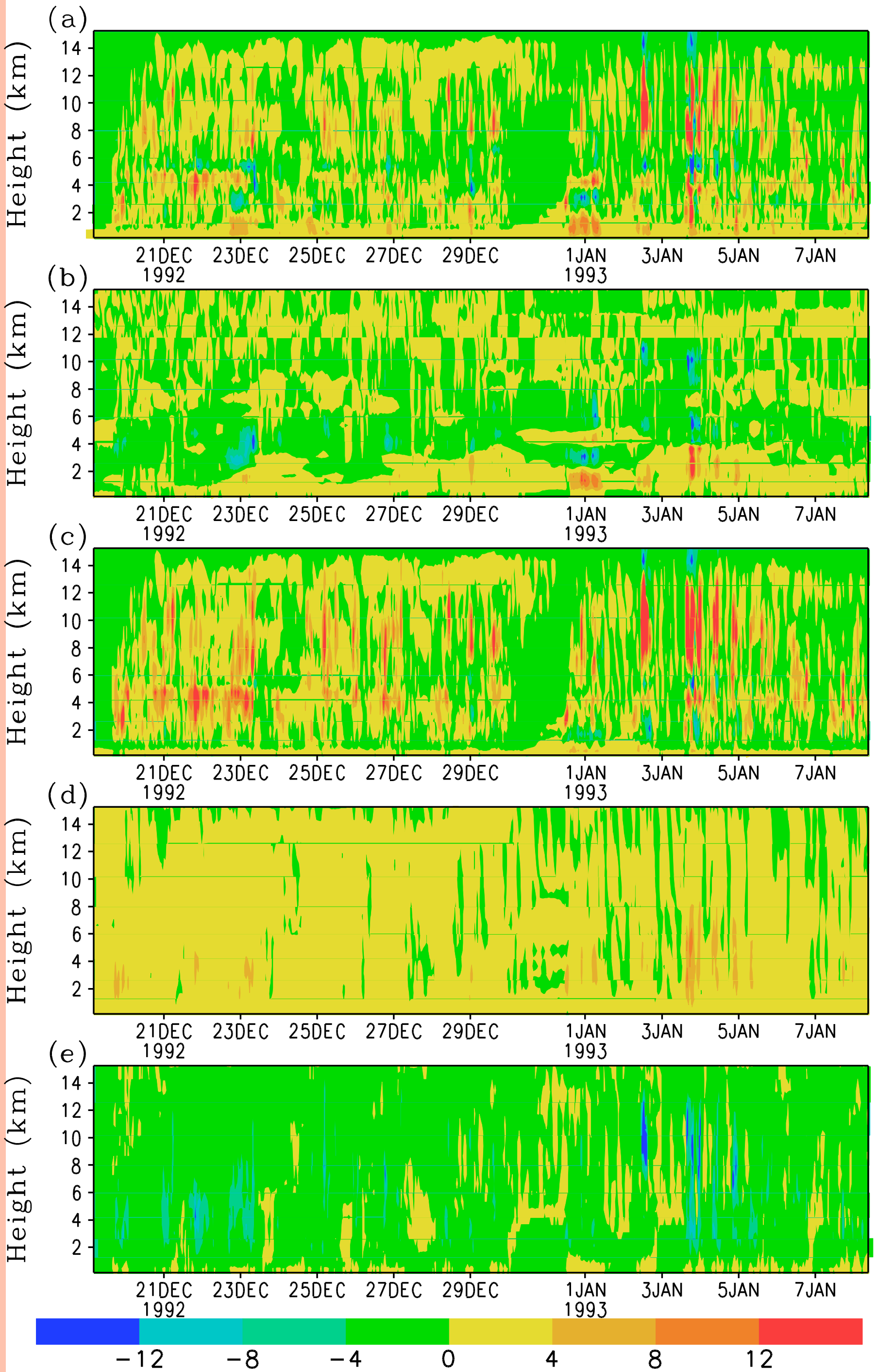
$$C(P', K') = [g\frac{\overline{w'T'}}{T_b}],$$

$$G_{qv}(K') = [0.61g\overline{w'q_v'}],$$

$$G_{ql}(K') = -[g\overline{w'q_l'}],$$

baroclinic conversions

$$[()] = \int_{z_b}^{z_t} \overline{\rho}()dz$$



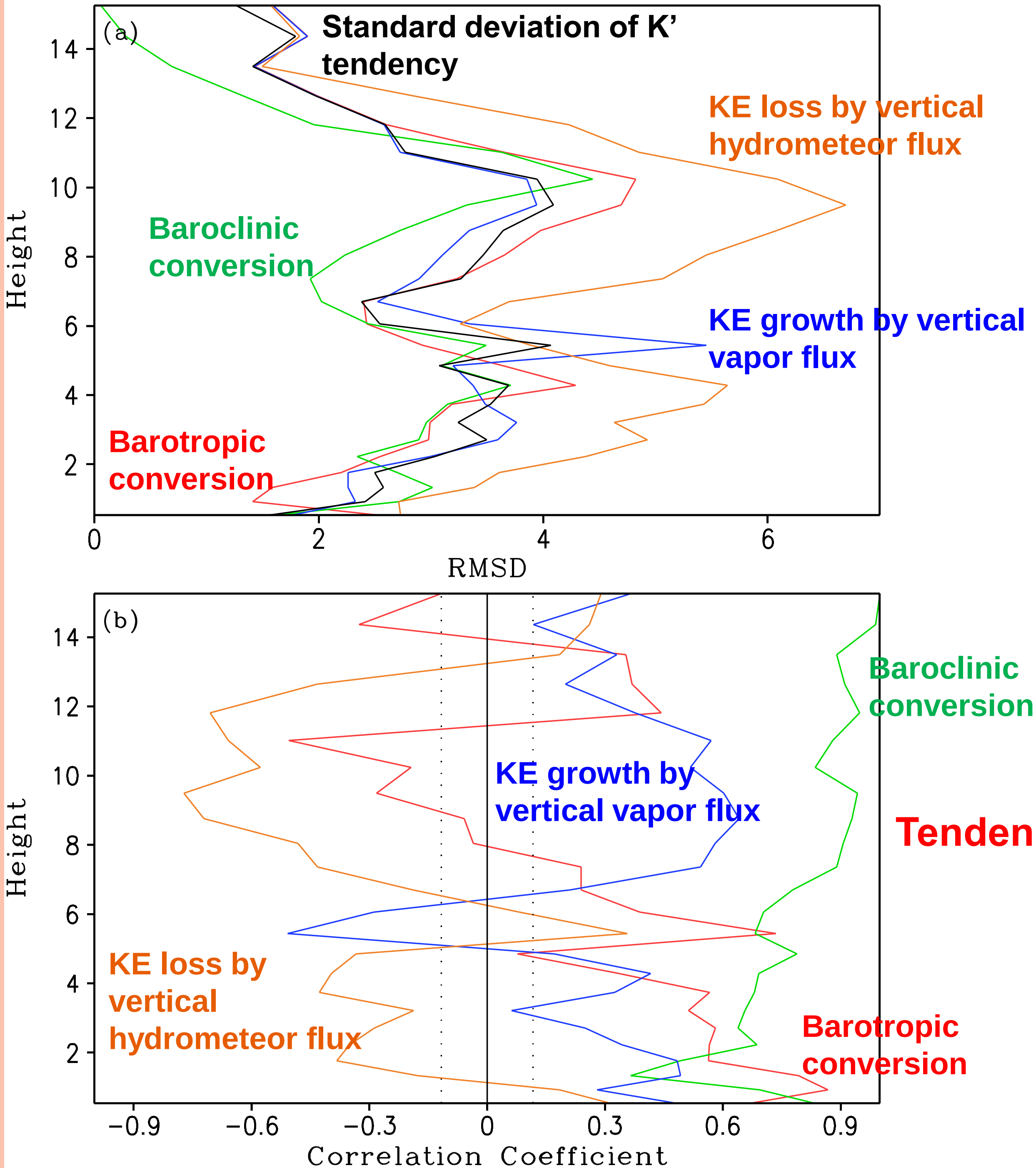
$$\frac{\partial K'}{\partial t}$$ Tendency of K'

$$C_u(\overline{K}, K')$$ Barotropic conversion between mean and perturbation kinetic energy

$$C(P', K')$$ Baroclinic conversion between perturbation available potential energy and kinetic energy due to vertical heat flux

$$G_{qv}(K')$$ Growth of kinetic energy due to vertical vapor flux

$$G_{ql}(K')$$ Loss of kinetic energy due to vertical hydrometeor flux



Tendency of K' vs. K' budget term

Barotropic Kinetic-Energy Conversion （BKEC）

$$C_u(\overline{K}, K') = -[\overline{u'w'}\frac{\partial \overline{u}^o}{\partial z}]$$

$$= -\int_{z_b}^{z_t}(\overline{\rho}\,\overline{u'w'}\frac{\partial \overline{u}^o}{\partial z})dz$$

$$= -\int_{z_b}^{z_t}\overline{\rho}\,\overline{u'w'}\,d\overline{u}^o$$

C_u is calculated by vertically integrating BKEC or adding BKEC for vertical layers in our calculations.

$$K' \Rightarrow \overline{K}$$

- A dynamically stable system

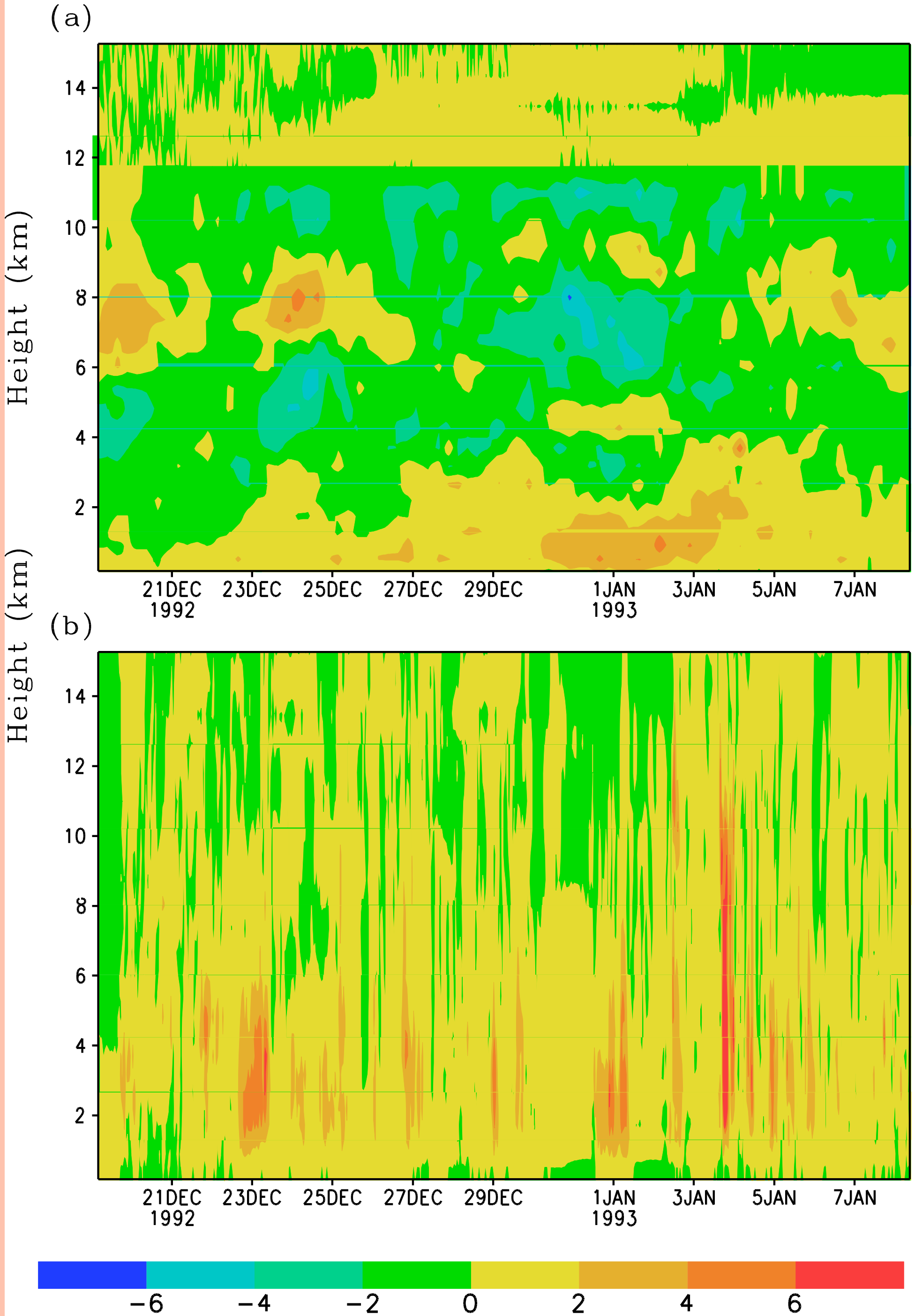
$$\overline{K} \Rightarrow K'$$

A dynamically unstable system

$$BKEC = BKEC1 * \mathrm{BKEC2}$$

$$\mathrm{BKEC1} = d\overline{u}^o$$

$$BKEC2 = -\overline{\rho}\,\overline{u'w'}$$



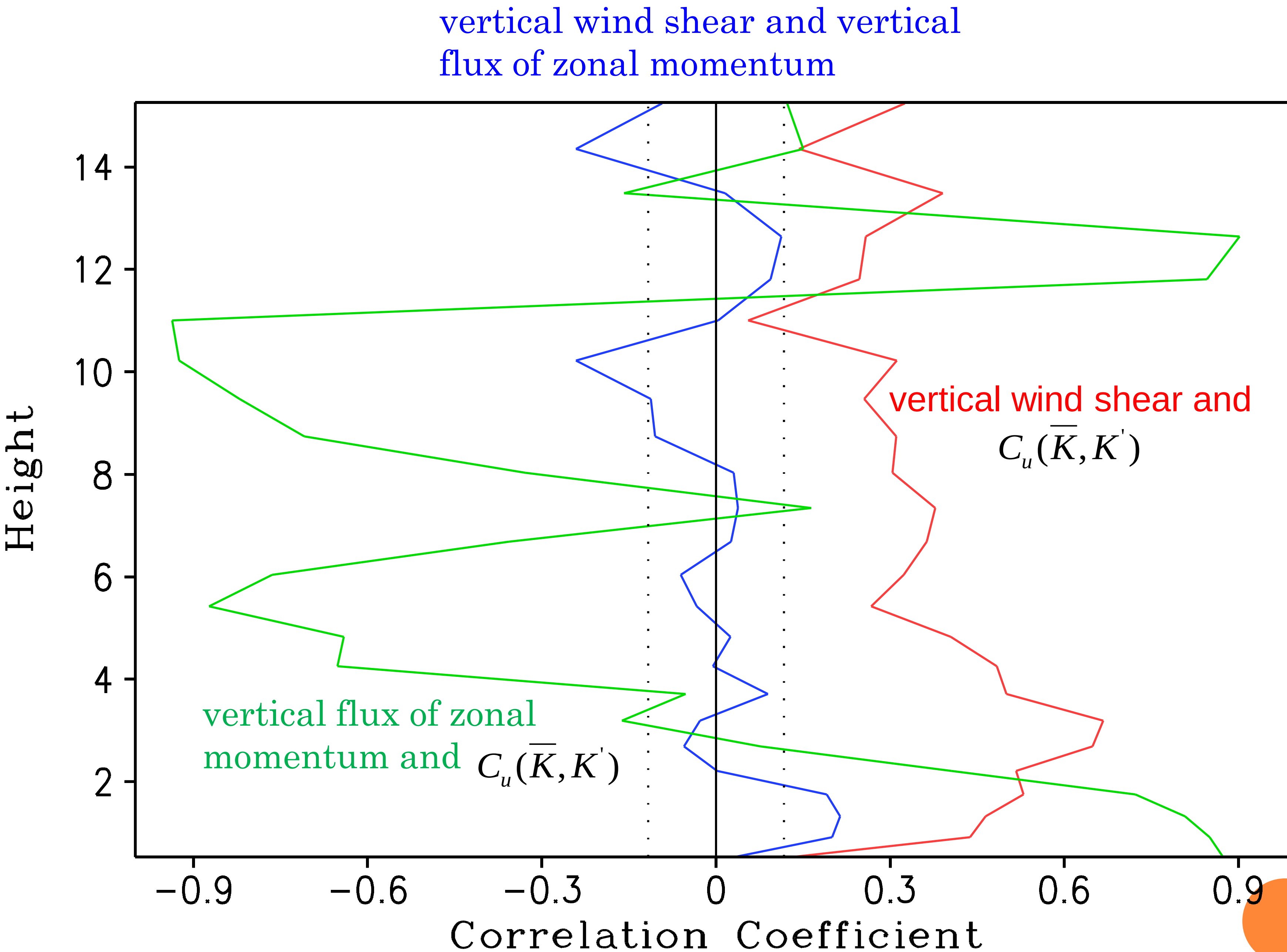
BKEC1:Imposed zonal-wind difference in vertical layer

BKEC2: Vertical flux of zonal momentum

$$BKEC = BKEC1 * \mathrm{BKEC2}$$

$$\mathrm{BKEC1} = d\bar{u}^{o}$$

$$BKEC2 = -\overline{\rho}\,\overline{u'w'}$$


vertical wind shear and vertical
flux of zonal momentum
vertical wind shear and
$C_u(\overline{K},K^{'})$
vertical flux of zonal
momentum and $C_u(\overline{K},K^{'})$
Height
14
12
10
8
6
4
2
−0.9
−0.6
−0.3
0
0.3
0.6
0.9
Correlation Coefficient

Budget of Vertical Transport of Horizontal Momentum

$$\frac{\partial u'}{\partial t} = -\frac{\partial}{\partial x}(2u'\bar{u}^o + u'u') - \frac{1}{\bar{\rho}}\frac{\partial}{\partial z}\bar{\rho}(w'\bar{u}^o + \bar{w}^o u' + w'u' - \overline{w'u'}) - c_p \frac{\partial(\bar{\theta}\pi')}{\partial x}$$

$$\frac{\partial w'}{\partial t} = -\frac{\partial}{\partial x}(u'\bar{w}^o + \bar{u}^o w' + u'w') - \frac{1}{\bar{\rho}}\frac{\partial}{\partial z}\bar{\rho}(2w'\bar{w}^o + w'w' - \overline{w'w'}) - c_p \frac{\partial(\bar{\theta}\pi')}{\partial z} + g(\frac{\theta'}{\theta_o} + 0.61 q_v' - q_l')$$

$$-\bar{\rho}w' \times (a) - \bar{\rho}u' \times (b)$$

Taking model domain mean

$$\frac{\partial}{\partial t}(-\bar{\rho}\overline{u'w'}) = \bar{\rho}\overline{w' \frac{\partial}{\partial x}(2u'\bar{u}^0 + u'u')} + \overline{w' \frac{\partial}{\partial z}\bar{\rho}(w'\bar{u}^0 + \bar{w}^0 u' + w'u')}$$

$$+ \bar{\rho}\overline{u' \frac{\partial}{\partial x}(u'\bar{w}^0 + \bar{u}^0 w' + u'w')} + \overline{u' \frac{\partial}{\partial z}\bar{\rho}(2w'\bar{w}^0 + w'w')}$$

$$+ c_p \bar{\rho}\overline{w' \frac{\partial(\bar{\theta}\pi')}{\partial x} + u' \frac{\partial(\bar{\theta}\pi')}{\partial z}}$$

$$- \bar{\rho}g\overline{u' \frac{\theta'}{\theta_0}} - 0.61\bar{\rho}g\overline{u'q_v'} + \bar{\rho}g\overline{u'q_l'}$$

$$\pi = (p/p_o)^\kappa$$

$$\kappa = R/c_p$$

Budget of Vertical Transport of Horizontal momentum

Tendency of vertical flux of zonal momentum

Dynamics term

$$
\frac{\partial}{\partial t}\left(-\bar{\rho}\,\overline{u'w'}\right) = \bar{\rho}\,\overline{w'\frac{\partial}{\partial x}\left(2u'\bar{u}^{0} + u'u'\right)} + \overline{w'\frac{\partial}{\partial z}\bar{\rho}\left(w'\bar{u}^{0} + \bar{w}^{0}u' + w'u'\right)}
$$

$$
+\bar{\rho}\,\overline{u'\frac{\partial}{\partial x}\left(u'\bar{w}^{0} + \bar{u}^{0}w' + u'w'\right)} + \overline{u'\frac{\partial}{\partial z}\bar{\rho}\left(2w'\bar{w}^{0} + w'w'\right)}
$$

Pressure-gradient term

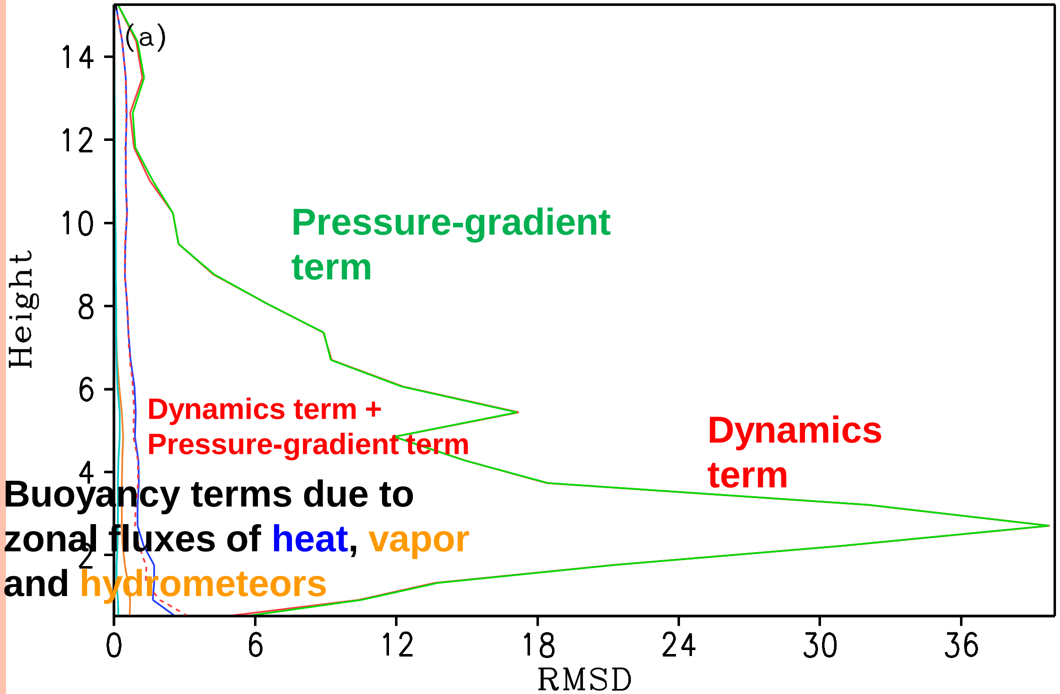
$$
+c_p\,\bar{\rho}\,\overline{w'\frac{\partial(\bar{\theta}\pi')}{\partial x} + u'\frac{\partial(\bar{\theta}\pi')}{\partial z}}
$$

Buoyancy term due to zonal heat flux

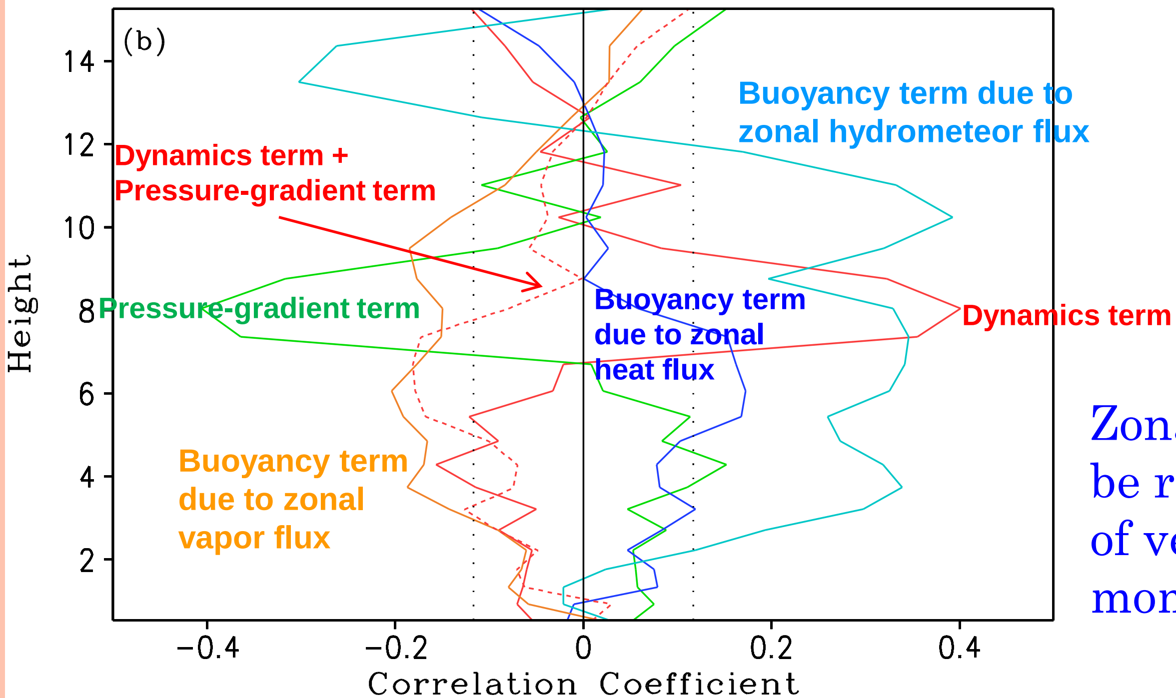
$$
-\bar{\rho}g\,\overline{u'\frac{\theta'}{\theta_0}} - 0.61\bar{\rho}g\,\overline{u'q_v'} + \bar{\rho}g\,\overline{u'q_l'}
$$

Buoyancy term due to zonal vapor flux

Buoyancy term due to zonal hydrometeor flux



Dynamics and pressure-gradient terms are largely cancelled out, and sum of dynamics and pressure-gradient terms are also largely cancelled out by buoyancy term due to zonal heat flux



Zonal flux of hydrometeor may be responsible for the tendency of vertical transport of zonal momentum

Summary

- The analysis of the budget shows that while baroclinic conversion from perturbation available potential energy to perturbation kinetic energy plays an important role in convective development.

- The impacts of vertical flux of zonal momentum on the evolution of barotrpic conversion are stronger than those of vertical wind shear. The vertical wind shear does not have any impacts on the tendency of vertical flux of zonal momentum.

- The analysis of the root-mean-squared difference and correlation shows that zonal flux of hydrometeor may be responsible for the tendency of vertical flux of zonal momentum.

THANK YOU!