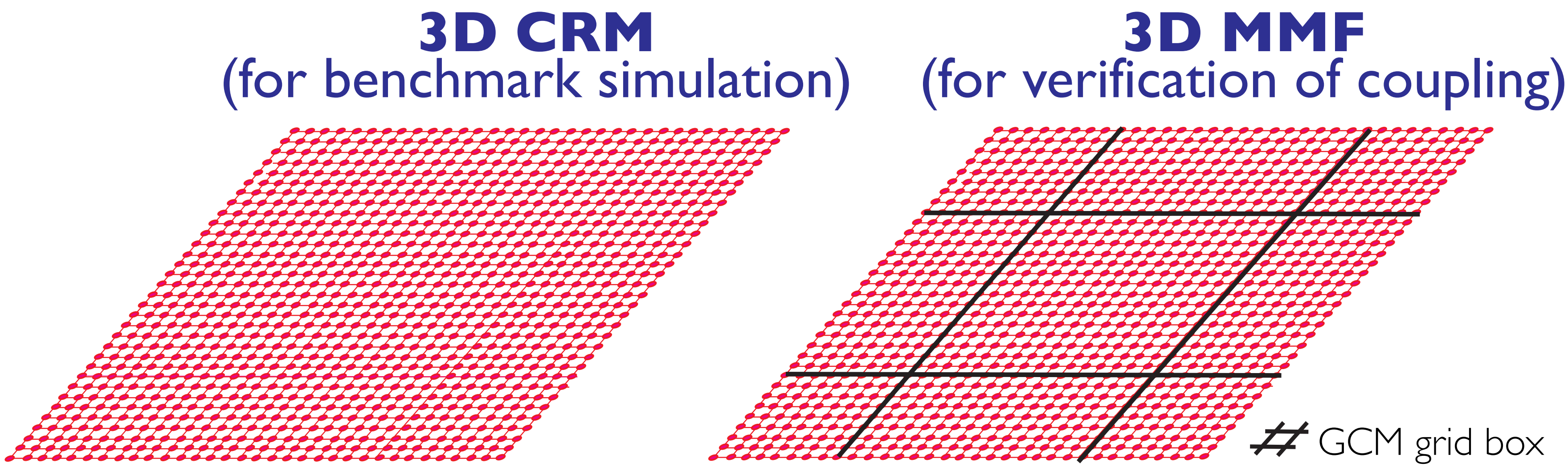
Verification of Various formulations of Coupling Using a 3D MMF

(ongoing work)

Experimental Strategy



- Construct a 3D MMF in which a 3D CRM is coupled with an idealized GCM.
- Compare the results of 3D MMF with those of the straightforward application of the 3D CRM.

Vector Vorticity Cloud Model (VVCM)

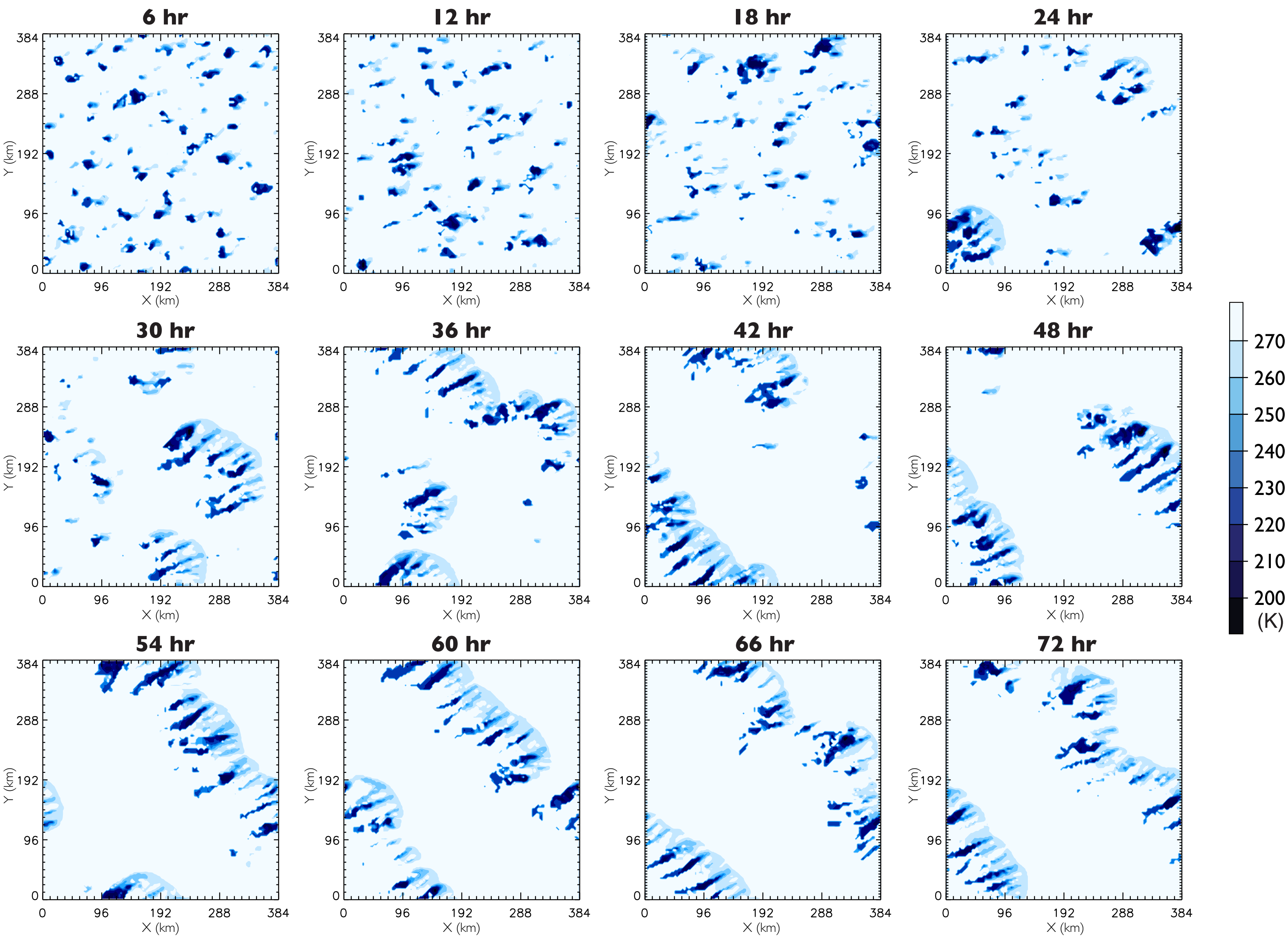
A Three-Dimensional Anelastic Model Based on the Vorticity Equation
Joon-Hee Jung and Akio Arakawa, 2008, *Mon. Wea. Rev.*, **136**, 276-294.

- Nonhydrostatic anelastic 3D model
- Prognostic variables:
  - Horizontal components of vorticity
  - Vertical component of vorticity (*at a certain height*)
  - *Horizontally uniform* part of horizontal velocity (*at a certain height*)
  - Potential temperature
  - Mixing ratios of various phases of water
- 3D elliptic (or parabolic) equation is solved for vertical velocity
- Physics:
  - Bulk ice-phase microphysical parameterization
  - Radiation parameterization
  - Turbulence parameterization (1st-order closure)

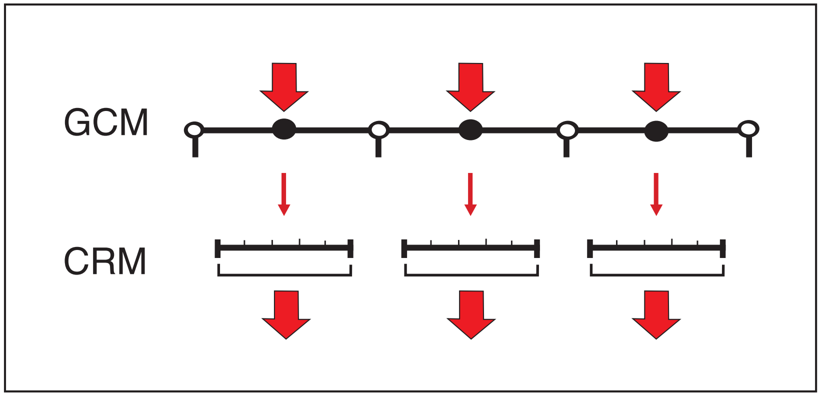
Benchmark Simulation with VVCM

- Domain size: 384 km x 384 km x 18 km
- Horizontal resolution: 3 km
- Vertical resolution: 34 layers with a stretched vertical grid
- Lower boundary: ocean surface with a fixed temperature
- Idealized tropical condition: based on a GATE Phase-III mean sounding and a wind profile during TOGA COARE
- Large-scale forcing: prescribed cooling and moistening tendencies
- Perturbation: random temperature perturbations into the lowest layer

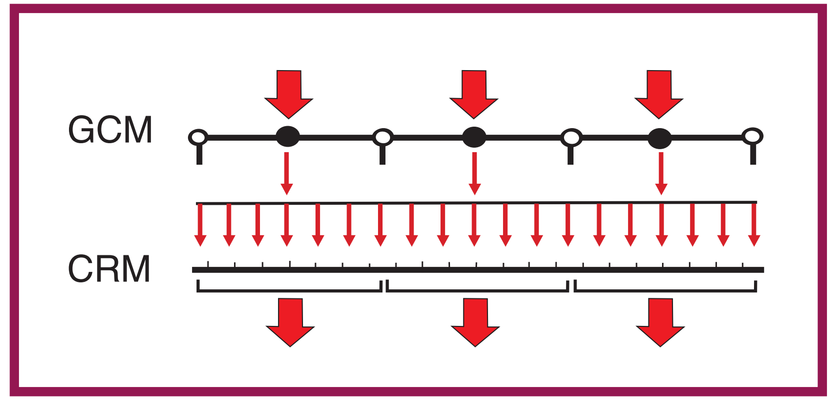
BENCHMARK SIMULATION
Cloud Top Temperature



PROTOTYPE COUPLING
(as originally suggested)



3D MMF COUPLING



Approach A:* *Explicit formulation of GCM/CRM effects

Approach B:* *Mutual adjustments of prognostic variables

Approach C:* *Hybrid of A and B

- Approach A includes an ad hoc way of eliminating the double counting.
- Horizontal resolution of GCM: 96 km

EXPERIMENTS 1 AND 2

- For thermodynamic variables

Approach A

$$\begin{cases} \dfrac{\partial q_C}{\partial t} = S_C + \hat{S}_G \\ \dfrac{\partial q_G}{\partial t} = S_G + \langle S_C \rangle \end{cases}$$

- For vorticity components

Approach B

$$\begin{cases} \dfrac{\partial q_C}{\partial t} = S_C - \dfrac{1}{\tau}\left(q_C - \hat{q}_G\right) \\ \dfrac{\partial q_G}{\partial t} = S_G - \dfrac{1}{\tau}\left(q_G - \langle q_C \rangle\right) \end{cases}$$

EXP 1

Approach A

$$\begin{cases} \dfrac{\partial q_C}{\partial t} = S_C + \hat{S}_G \\ \dfrac{\partial q_G}{\partial t} = S_G + \langle S_C \rangle \end{cases}$$

EXP 2

Approach A

$$\begin{cases} \dfrac{\partial q_C}{\partial t} = S_C + \hat{S}_G \\ \dfrac{\partial q_G}{\partial t} = S_G + \langle S_C \rangle^* \end{cases}$$

EXP 2a

$\langle S_C \rangle^*$ *includes only the tendency due to turbulence and surface flux.*

Relative Error of a 3D-MMF Simulation (EXP 1)

Mass-Weighted Vertical mean of thermodynamic variables

Gross RH *	1 %
Cloud liquid water	17 %
Cloud ice	5 %

Surface precipitation -2 %

Surface fluxes

Evaporation	-29 %
Sensible heat	-25 %

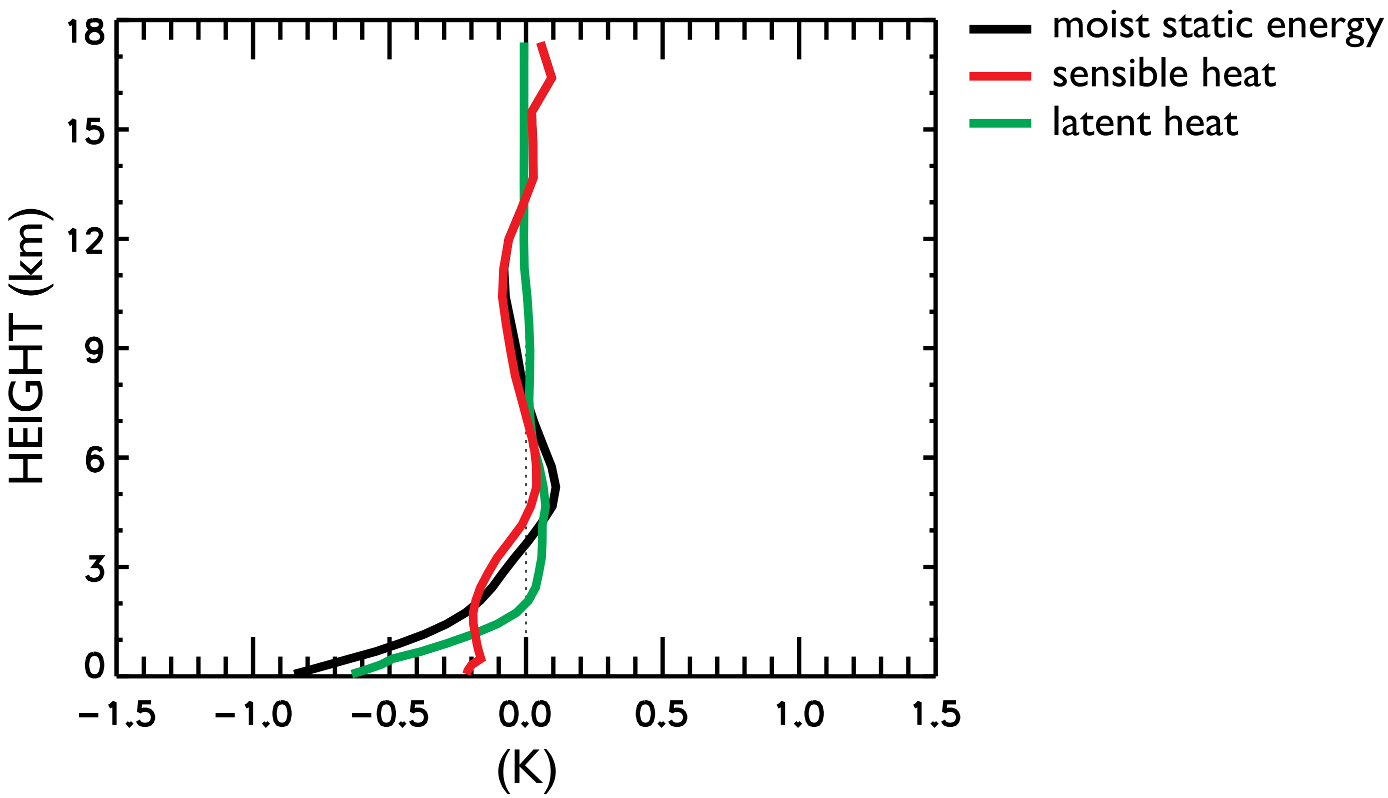
Mass-weighted vertical mean of variances

$\xi'\xi'$	-57 %
$\eta'\eta'$	-57 %
$\zeta'\zeta'$	-59 %
u'u'	-33 %
v'v'	-57 %
w'w'	-24 %

* *From the mass-weighted vertical averages of water vapor mixing ratio and its saturated value.*

(EXP 1)

Domain-Time Averaged Vertical Profiles of Errors



The underestimation of the surface fluxes is the cause for this, not the result.

Relative Error of a 3D-MMF Simulation (EXP 1)

Mass-Weighted Vertical mean of thermodynamic variables

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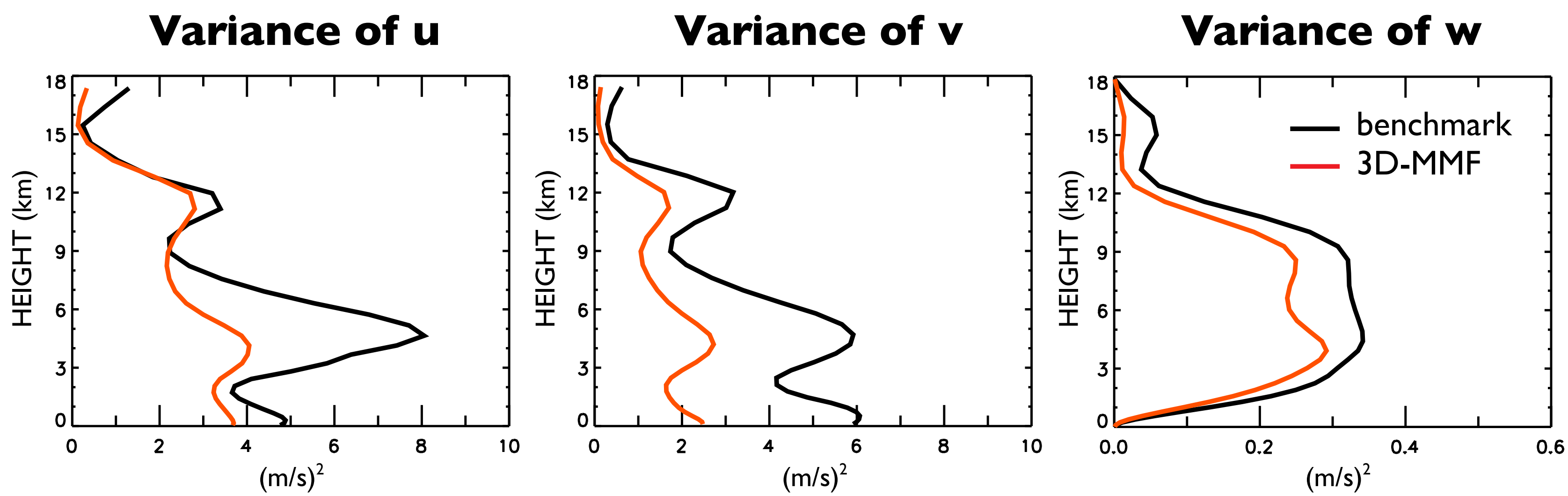
(EXP 1)

Domain-Time Averaged Vertical Profiles



Errors are quantitative rather than qualitative.

Relative Error of a 3D-MMF Simulation (EXP 2 and 2a)

Mass-Weighted Vertical mean of thermodynamic variables

EXP:	2	2a
Gross RH *	0 %	0 %
Cloud liquid water	-22 %	-22 %
Cloud ice	2 %	3 %

Surface precip.	-4 %	-4 %

Surface fluxes

Evaporation	-67 %	-66 %
Sensible heat	-66 %	-65 %

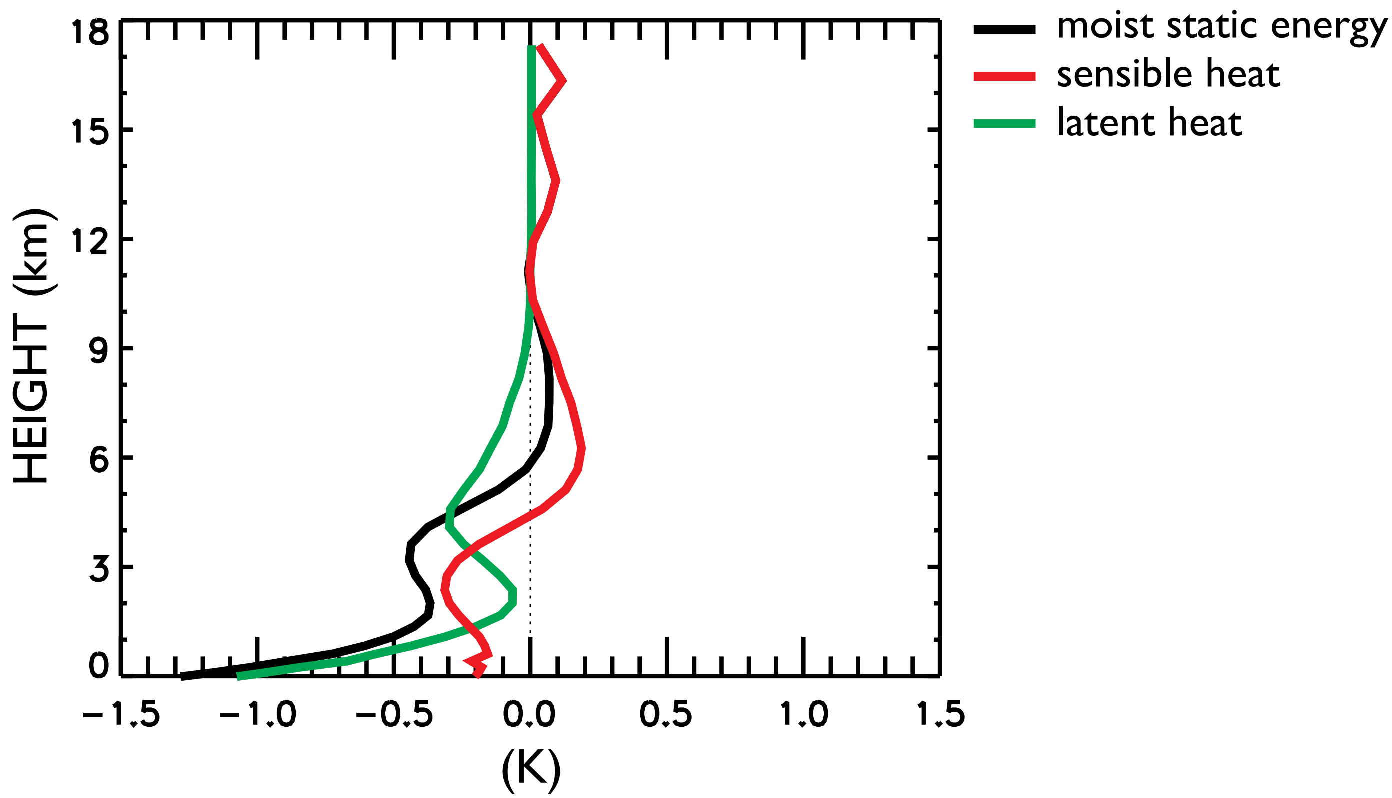
Mass-weighted vertical mean of variances

EXP:	2	2a
$\xi'\xi'$	-71 %	-70 %
$\eta'\eta'$	-68 %	-67 %
$\zeta'\zeta'$	-21 %	-20 %
$u'u'$	-63 %	-62 %
$v'v'$	-67 %	-66 %
$w'w'$	15 %	14 %

* *From the mass-weighted vertical averages of water vapor mixing ratio and its saturated value.*

(EXP 2)

Domain-Time Averaged Vertical Profiles of Errors



Again, the underestimation of the surface fluxes is the cause for this.

EXP2a is practically the same.

EXPERIMENT 3

For both thermodynamic variables and vorticity components

Approach B

$$\begin{cases} \dfrac{\partial q_C}{\partial t} = S_C - \dfrac{1}{\tau_C}\left(q_C - \hat{q}_G\right) \\ \dfrac{\partial q_G}{\partial t} = S_G - \dfrac{1}{\tau_G}\left(q_G - \langle q_C \rangle\right) \end{cases}$$

τ_C : time scale for the response of convection to large-scale forcing
τ_G : time scale for the adjustment of the large-scale fields by convection

- *Ambiguities in formulating forcing and feedback do not exist.*
- *Since q_C tends to be adjusted to $\hat{q}_G$, q_C may be excessively damped.*

Relative Error of a 3D-MMF Simulation (EXP 3)

Variance of w

	t_C = 0.5 hr	t_C = 1 hr	t_C =2 hr	t_C = 4 hr
t_G = 0.5 hr	-59 %	-72 %	-81 %	-86 %
t_G = 1 hr	-22 %	-52 %	-70 %	-78 %
t_G = 2 hr	42 %	-11 %	-47 %	-64 %
t_G = 4 hr	141 %	48 %	-12 %	-46 %

Convective activity is sensitive to the choice of the time scales.

Over-prediction when $\tau_G \;\square\; \tau_C$

Under-prediction when $\tau_G \leq \tau_C$

Relative Error of a 3D-MMF Simulation (EXP 3)

Mass-Weighted Vertical mean of thermodynamic variables

τ:	0.5 hr	4 hr
Gross RH *	11 %	12 %
Cloud liquid water	1 %	-22 %
Cloud ice	-13 %	-25 %
Surface precip.	-40 %	-43 %
Surface fluxes		
Evaporation	-36 %	-12 %
Sensible heat	-26 %	-10 %

Mass-weighted vertical mean of variances

τ:	0.5 hr	4 hr
$\xi'\xi'$	-83 %	-76 %
$\eta'\eta'$	-85 %	-78 %
$\zeta'\zeta'$	-75 %	-80 %
u'u'	-3 %	-73 %
v'v'	-67 %	-77 %
w'w'	-59 %	-46 %

* *From the mass-weighted vertical averages of water vapor mixing ratio and its saturated value.*

EXPERIMENT 4

Approach C

- For thermodynamic variables

$$\begin{cases} \dfrac{\partial q_C}{\partial t} = S_C + \hat{S}_G \\ \dfrac{\partial q_G}{\partial t} = \left\langle \hat{S}_G \right\rangle + \left\langle S_C \right\rangle - \dfrac{1}{\tau_T}\left(q_G - \left\langle q_C \right\rangle \right) \end{cases}$$

- For vorticity components

$$\begin{cases} \dfrac{\partial q_C}{\partial t} = S_C + \hat{S}_G \\ \dfrac{\partial q_G}{\partial t} = \left\langle \hat{S}_G \right\rangle + \left\langle S_C \right\rangle - \dfrac{1}{\tau_V}\left(q_G - \left\langle q_C \right\rangle \right) \end{cases}$$

Relative Error of a 3D-MMF Simulation (EXP 4)

$\tau_v = 1$ hr

Mass-Weighted Vertical mean of thermodynamic variables

τ_T :	0 hr	2 hr
Gross RH	0 %	0 %
Cloud liquid water	-22 %	-22 %
Cloud ice	2 %	1 %
Surface precip.	-4 %	-5 %
Surface fluxes		
Evaporation	-67 %	-67 %
Sensible heat	-66 %	-66 %

Mass-weighted vertical mean of variances

τ_T :	0 hr	2 hr
$\xi'\xi'$	-71 %	-72 %
$\eta'\eta'$	-68 %	-69 %
$\zeta'\zeta'$	-19 %	-20 %
$u'u'$	-63 %	-63 %
$v'v'$	-67 %	-67 %
$w'w'$	14 %	14 %

Summary and Conclusion

- Errors of the MMF are sensitive to formulation of the coupling.
- The variances of horizontal winds are under-predicted in all experiments.
- Consequently, the surface heat fluxes are under-predicted. The low-level temperature and humidity tend to be low.
- Finding a proper way of the coupling should be one of the central problems in MMF development. This is especially true for horizontal momentum and cloud-microphysical variables.

Revised Approach B (to be tested)

Predictor Step:

$$\begin{cases} \dfrac{q_G^* - q_G^n}{\Delta t} = S_G + \langle P_C \rangle \\ \dfrac{q_C^* - q_C^n}{\Delta t} = S_C + \hat{P}_G \end{cases}$$

P represents sources/sinks ***due to physics***.

Adjustment Step:

$$\begin{cases} \dfrac{q_G^{n+1} - q_G^*}{\Delta t} = -\dfrac{1}{\tau}\left(q_G - \langle q_C \rangle\right) \\ \dfrac{q_C^{n+1} - q_C^*}{\Delta t} = -\dfrac{1}{\tau}\left(\langle q_C \rangle - \langle \hat{q}_G \rangle\right) \end{cases}$$

- Implementation of the source/sink terms and mutual adjustment are performed sequentially.
- No local damping of q_C.
- Sources/sinks due to physics are compatible between the GCM and CRM.