Development of a Third-order Closure Turbulence Model With Subgrid-scale Condensation

Grant J. Firl and David A. Randall

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Model Description

- Predicts 10 second-order moments: 3 TKE components, 4 vertical fluxes, 3 thermodynamic variances/covariances
- Diagnoses 28 third-order moments algebraically
- Diagnoses cloud water and cloud fraction using a SGS condensation scheme
  - diagnosed clouds interact with turbulence through the buoyancy terms

What makes it unique?

Many standard parameterization techniques are used (e.g. dissipation and pressure correlation terms), but at least 2 aspects are nonstandard:

- diagnostic third-order moments
- SGS condensation scheme

Second-order Moments	Third-order Moments
	$\overline{w'^3}, \overline{w'u'^2}, \overline{w'v'^2}, \overline{w'^2u'}, \overline{w'^2v'}$,
	$\overline{u'^2\theta_l'}, \overline{v'^2\theta_l'}, \overline{w'^2\theta_l'}, \overline{u'^2q_t'}, \overline{v'^2q_t'}, \overline{w'^2q_t'}$,
$\overline{u'^2}, \overline{v'^2}, \overline{w'^2}$,	$\overline{w'u'\theta_l'}, \overline{w'u'q_t'}, \overline{w'v'\theta_l'}, \overline{w'v'q_t'}$,
$\overline{w'u'}, \overline{w'v'}, \overline{w'\theta_l'}, \overline{w'q_t'}$,	$\overline{u'\theta_l'^2}, \overline{v'\theta_l'^2}, \overline{w'\theta_l'^2}, \overline{u'q_t'^2}, \overline{v'q_t'^2}, \overline{w'q_t'^2}$,
$\overline{\theta_l'^2}, \overline{\theta_l'q_t'}, \overline{q_t'^2}$	$\overline{u'\theta_l'q_t'}, \overline{v'\theta_l'q_t'}, \overline{w'\theta_l'q_t'}$,
	$\overline{\theta_l'^3}, \overline{\theta_l'^2q_t'}, \overline{\theta_l'q_t'^2}, \overline{q_t'^3}$

Model Description

Third-order Moments (TOMs)

All TOMS are diagnosed using the method of Cheng et al. (2005):

1. Dynamic predictive equations for TOMs are derived
2. Unclosed terms are parameterized
   - Fourth-order moments are parameterized as

$$\overline{a'b'c'd'} = \underbrace{\left(\overline{a'b'} * \overline{c'd'} + \overline{a'c'} * \overline{b'd'} + \overline{a'd'} * \overline{b'c'}\right)}_{\text{“quasi-normal” assumption}} + \left(\overline{a'b'c'd'}\right)_{NG}$$

“Non-Gaussian” part
- determined from LES
- simplifies TOMs
- improves behavior relative to quasi-normal assumption

3. Tendency terms are neglected, and diagnostic relations are obtained by analytically solving a system of linear equations

$$\begin{aligned}\frac{\partial \overline{u_i'u_l'\theta_l'}}{\partial t} = & -\overline{u_j'u_i'u_l'}\frac{\partial \overline{\theta}_l}{\partial x_j} - \overline{u_j'u_l'\theta_l'}\frac{\partial \overline{u}_i}{\partial x_j} - \overline{u_j'u_i'\theta_l'}\frac{\partial \overline{u}_l}{\partial x_j} - \frac{\partial \overline{u_j'u_i'u_l'\theta_l'}}{\partial x_j} \\ & + \frac{g_i}{\theta_{v_0}}\overline{u_l'\theta_l'\theta_v'} + \frac{g_l}{\theta_{v_0}}\overline{u_i'\theta_l'\theta_v'} - \frac{1}{\rho_0}\left(\overline{u_l'\theta_l'\frac{\partial p'}{\partial x_i}} + \overline{u_i'\theta_l'\frac{\partial p'}{\partial x_l}}\right) \\ & + \overline{u_i'u_l'}\frac{\partial \overline{u_j'\theta_l'}}{\partial x_j} + \overline{u_l'\theta_l'}\frac{\partial \overline{u_i'u_j'}}{\partial x_j} + \overline{u_i'\theta_l'}\frac{\partial \overline{u_j'u_l'}}{\partial x_j} \\ & + \nu_{\theta_l}\overline{u_i'u_l'\frac{\partial^2\theta_l'}{\partial x_j^2}} + \nu\overline{u_l'\theta_l'\frac{\partial^2 u_i'}{\partial x_j^2}} + \nu\overline{u_i'\theta_l'\frac{\partial^2 u_l'}{\partial x_j^2}}\end{aligned}$$

$$\begin{aligned}\overline{w'^2\theta_l'} = & -A_{2.3}\frac{\partial \overline{w'^2}}{\partial z} - A_{2.6}\frac{\partial \overline{w'\theta_l'}}{\partial z} - A_{2.7}\frac{\partial \overline{w'q_t'}}{\partial z} - A_{2.8}\frac{\partial \overline{\theta_l'^2}}{\partial z} \\ & - A_{2.9}\frac{\partial \overline{\theta_l'q_t'}}{\partial z} - A_{2.10}\frac{\partial \overline{q_t'^2}}{\partial z} + L_2\end{aligned}$$

Cheng et al. (2005)	Current Model
6 TOMs; no moisture variables	28 TOMs; includes moisture

Model Description

SGS Condensation

SGS condensation scheme is needed to provide 3 things:

- cloud fraction and cloud water (for radiation and microphysics calculations)
- second- and third-order correlations involving cloud water

buoyancy terms can be written $\overline{\chi'\theta_v'} = \overline{\chi'\theta_l'} + C_{T_0}\overline{\chi'q_t'} + D(z)\overline{\chi'q_l'}$

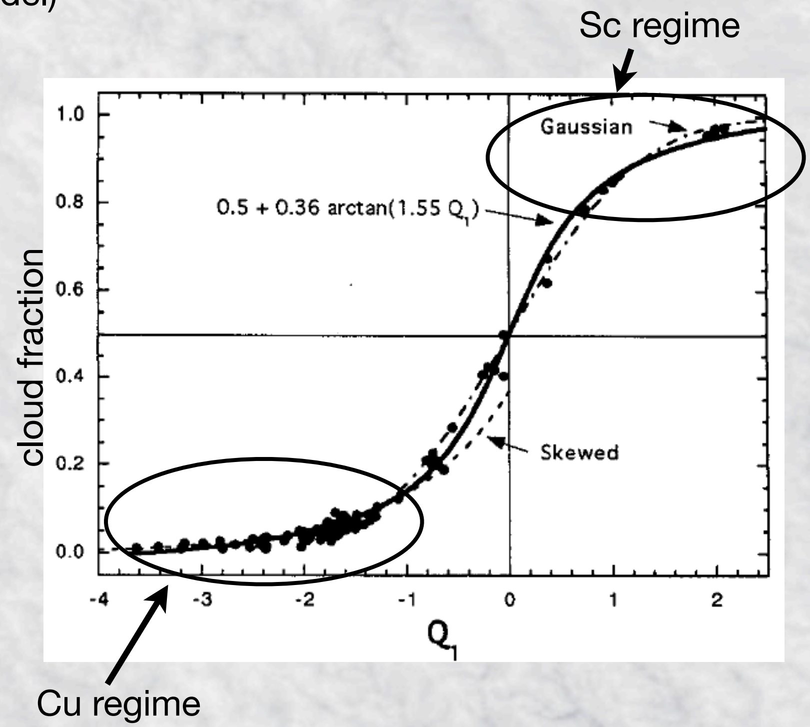
✓ ✓ (calculated in model) — need to parameterize

Cloud fraction and water are calculated from general functions of Cuijpers and Bechtold (1995)

- they are functions of Q_1, the "normalized saturation deficit"

Cloud water correlations are cloud regime dependent

- Gaussian relations of Mellor (1977) for Sc
- Positively skewed relations from Bougeault (1981) for Cu
- linearly interpolate based on Q_1 for intermediate regimes



Tests

Single Column Model (SCM)

- 5 standard test cases
  1. clear convective BL (Wangara) ✓
  2. smoke filled BL ✓
  3. nocturnal drizzling stratocumulus (DYCOMS)
  4. non-precipitating trade-wind cumulus (BOMEX)
  5. precipitating trade-wind cumulus (RICO) ✓

} GCSS

Case	# of LES participants
Smoke	13
DYCOMS	11
BOMEX	10
RICO	15

Turbulence Parameterization in 3D VVM

- 2 standard test cases
  1. nocturnal drizzling stratocumulus (DYCOMS)
  2. non-precipitating trade-wind cumulus (BOMEX)

New Model
LES mean

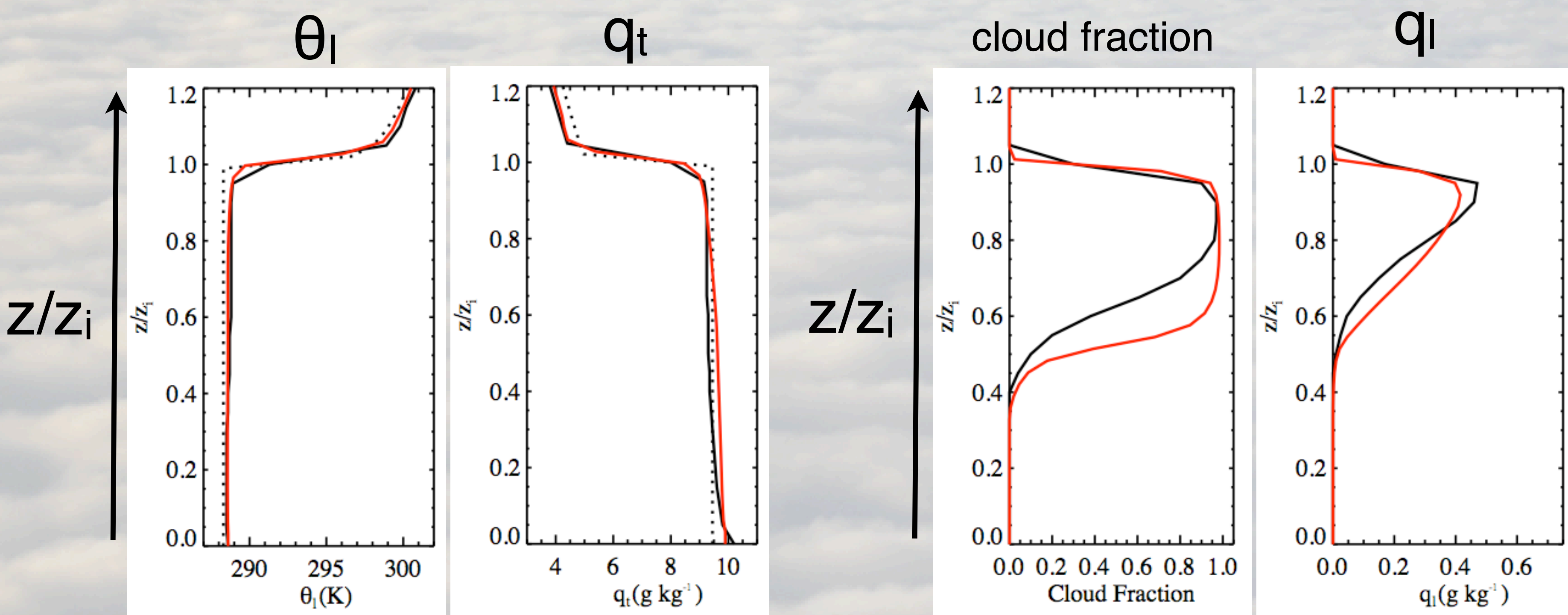
Nocturnal Drizzling Stratocumulus Case (DYCOMS II RF02)

<u>Features</u>

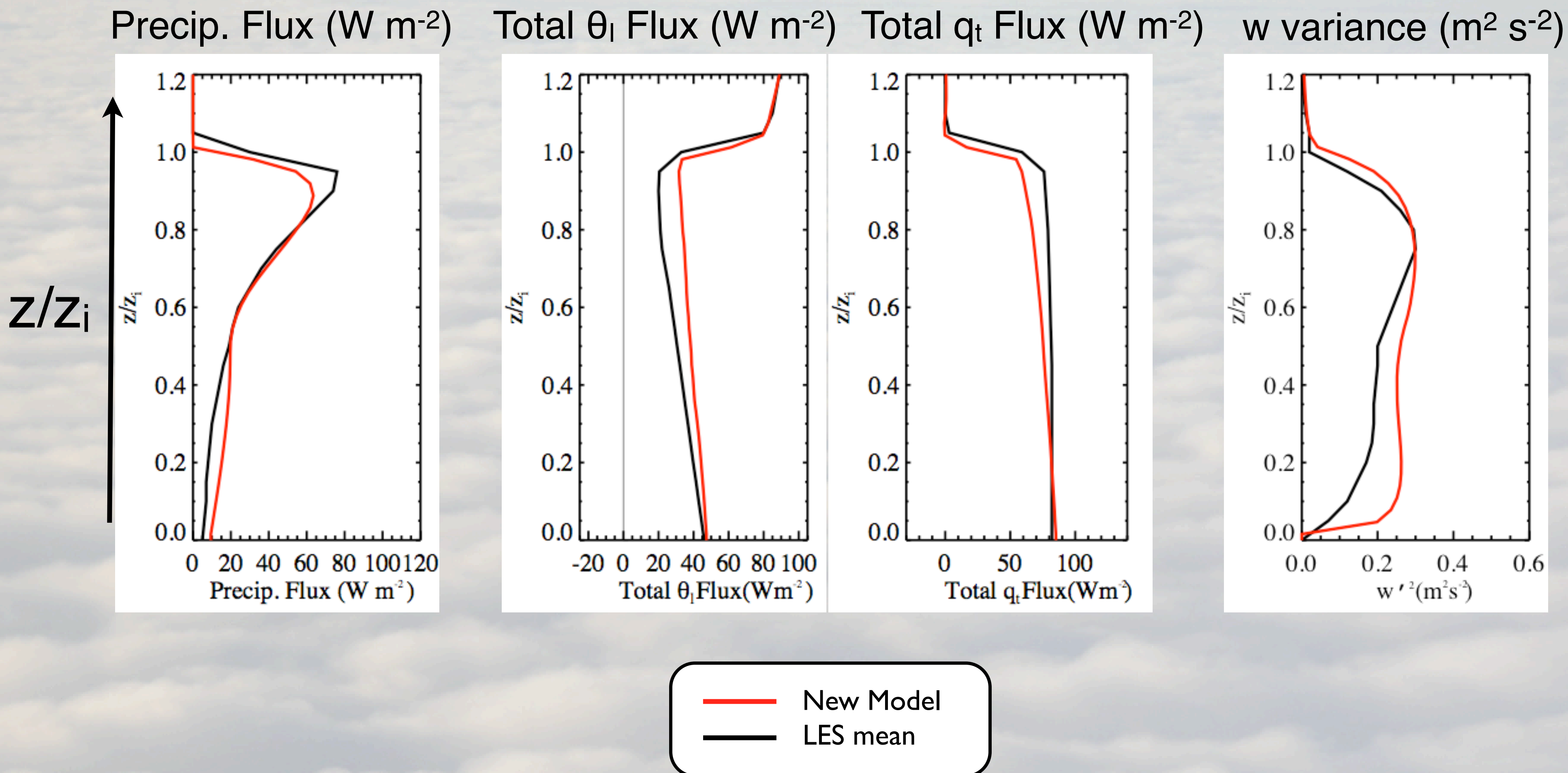
- sharp inversion
- constant surface fluxes
- forcings: subsidence, large-scale PGF, net LW forcing (q_l),cloud droplet sedimentation

<u>Goal</u>

Test complete model for a drizzling stratocumulus regime



Nocturnal Drizzling Stratocumulus Case (DYCOMS II RF02)



Nonprecipitating Shallow Trade-wind Cumulus Case (BOMEX)

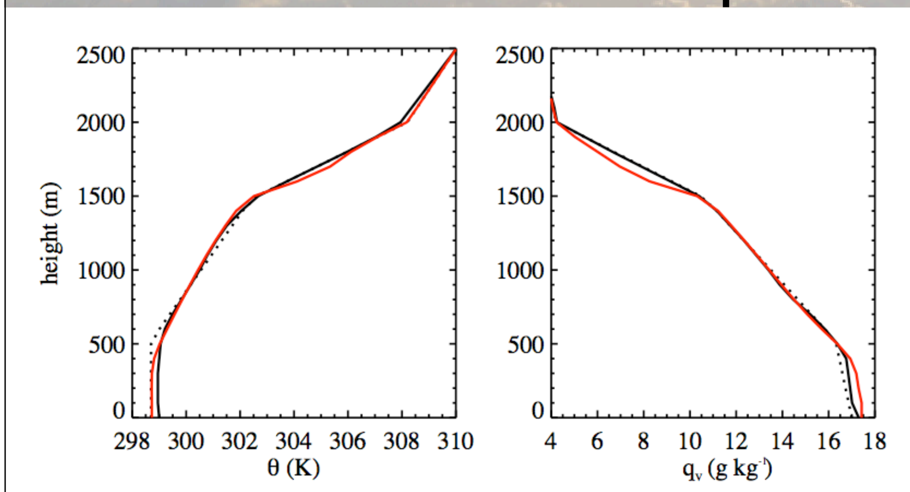
Features

- conditionally unstable profile
- ~5% cloud fraction; ~1 km deep cumuli
- constant surface fluxes
- forcings: subsidence, large-scale PGF, radiative cooling, large-scale moisture advection

Goal

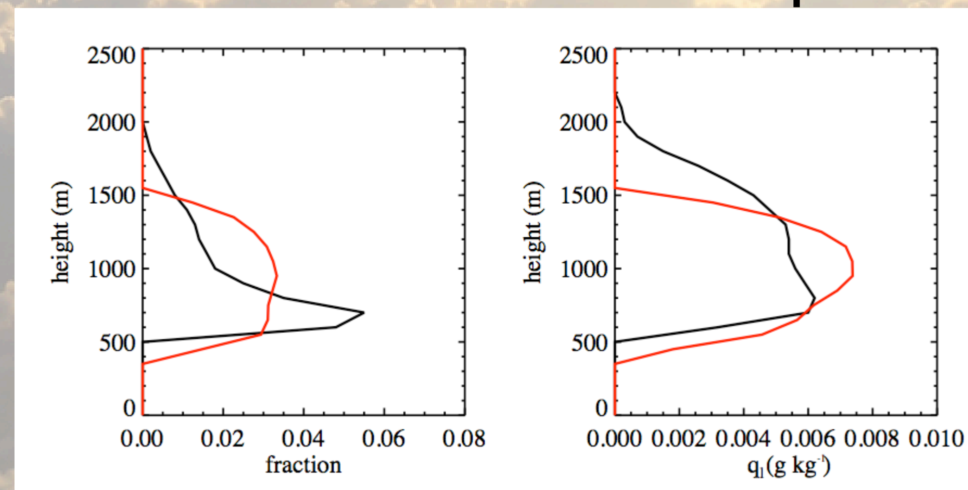
Test complete model for a nonprecipitating low cloud fraction cumulus regime.

θ $\quad$ q_v



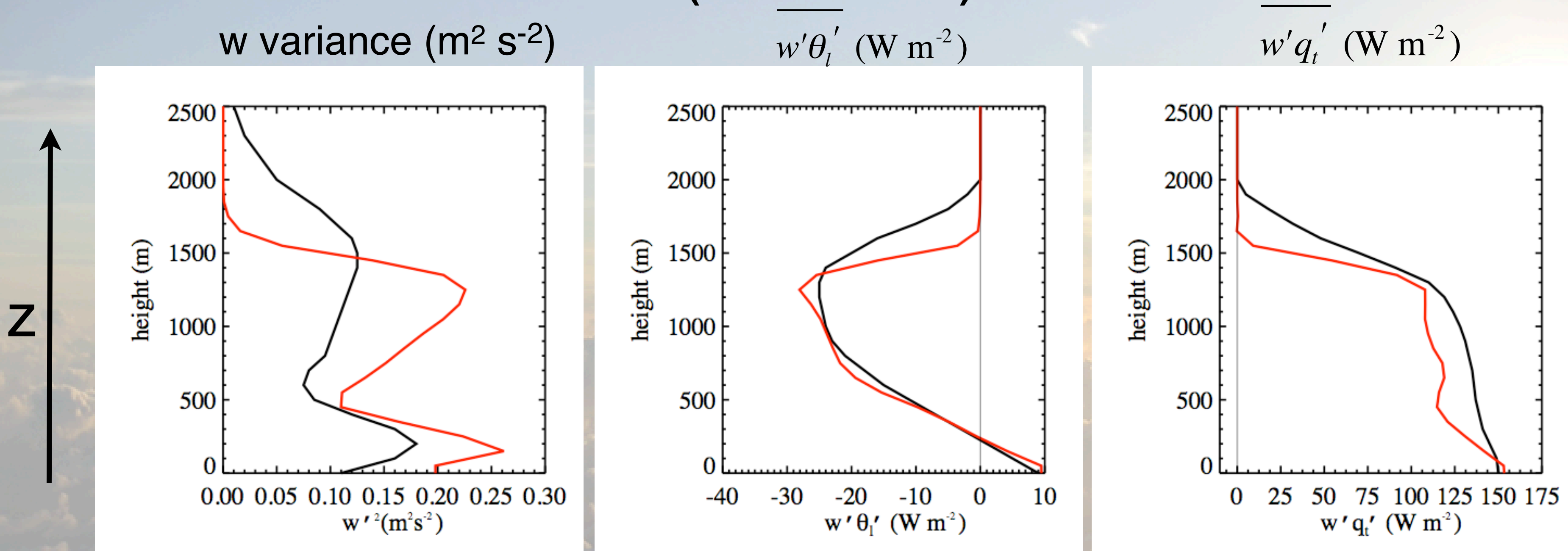
z

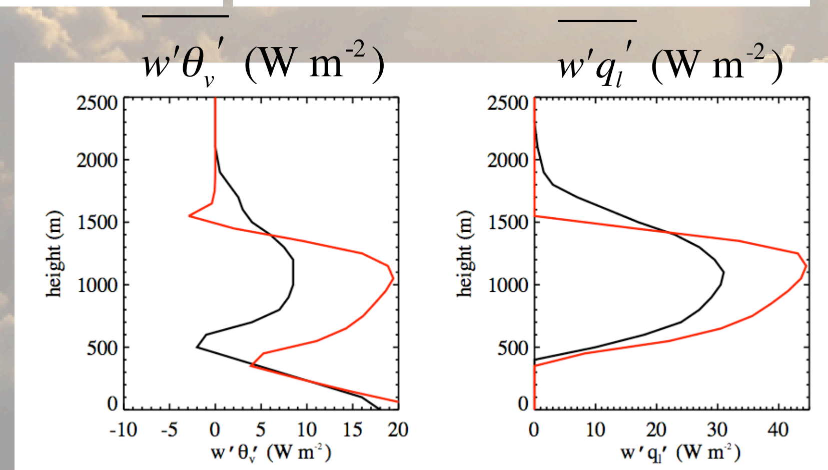
cloud fraction $\quad$ q_l



New Model
LES mean

Nonprecipitating Shallow Trade-wind Cumulus Case (BOMEX)



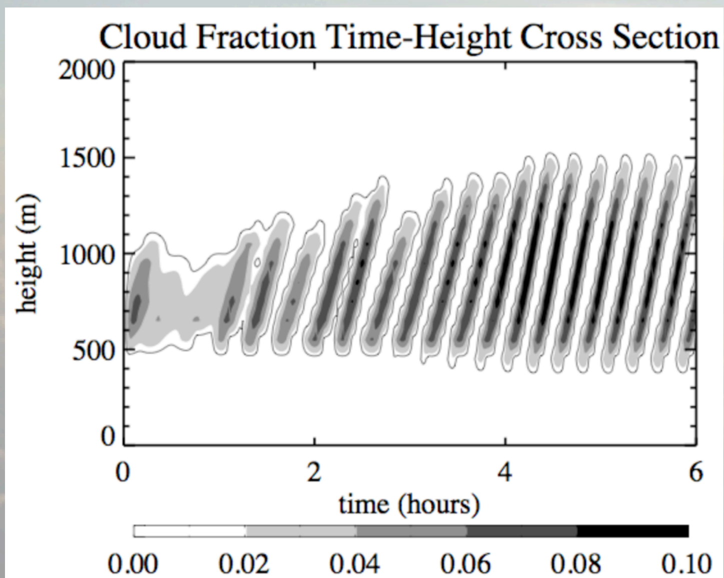


$$\frac{\partial \overline{w'^2}}{\partial t} = -\frac{\partial \overline{w'^3}}{\partial z} - \frac{c_4}{\tau_1}\left(\overline{w'^2} - \frac{2}{3}\bar{e}\right) + \left(2 - \frac{4c_5}{3}\right) g\alpha\overline{w'\theta_v'} - c_1\frac{\overline{w'^2}}{\tau_1}$$

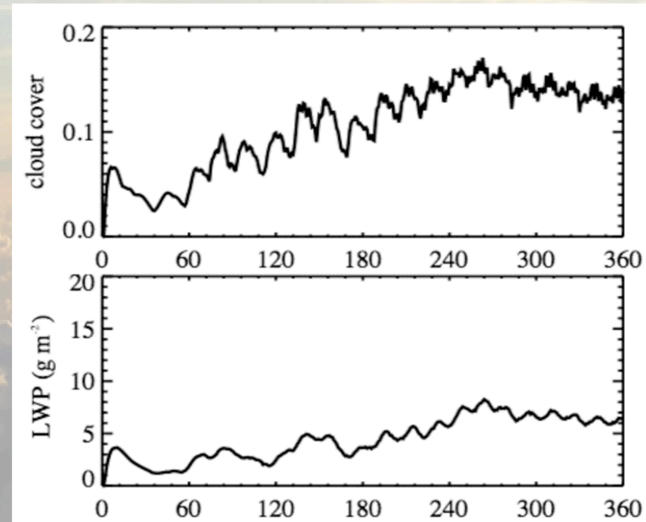
$$\overline{w'\theta_v'} = \overline{w'\theta_l'} + C_{T_0}\overline{w'q_t'} + D(z)\overline{w'q_l'}$$

New Model
LES mean

Nonprecipitating Shallow Trade-wind Cumulus Case (BOMEX)

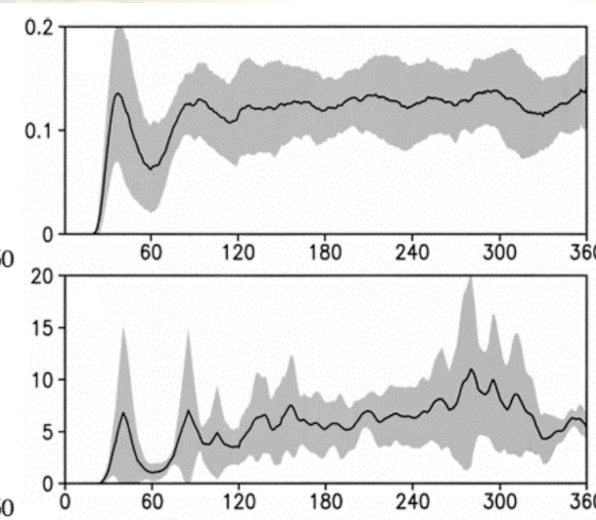


New Model



time (minutes)

LES ensemble



time (minutes)

New Model
LES mean

Tests in 3D Vector Vorticity Model (VVM)

Modifications to VVM include:

- thermodynamic variables
- turbulence scheme
- microphysics scheme

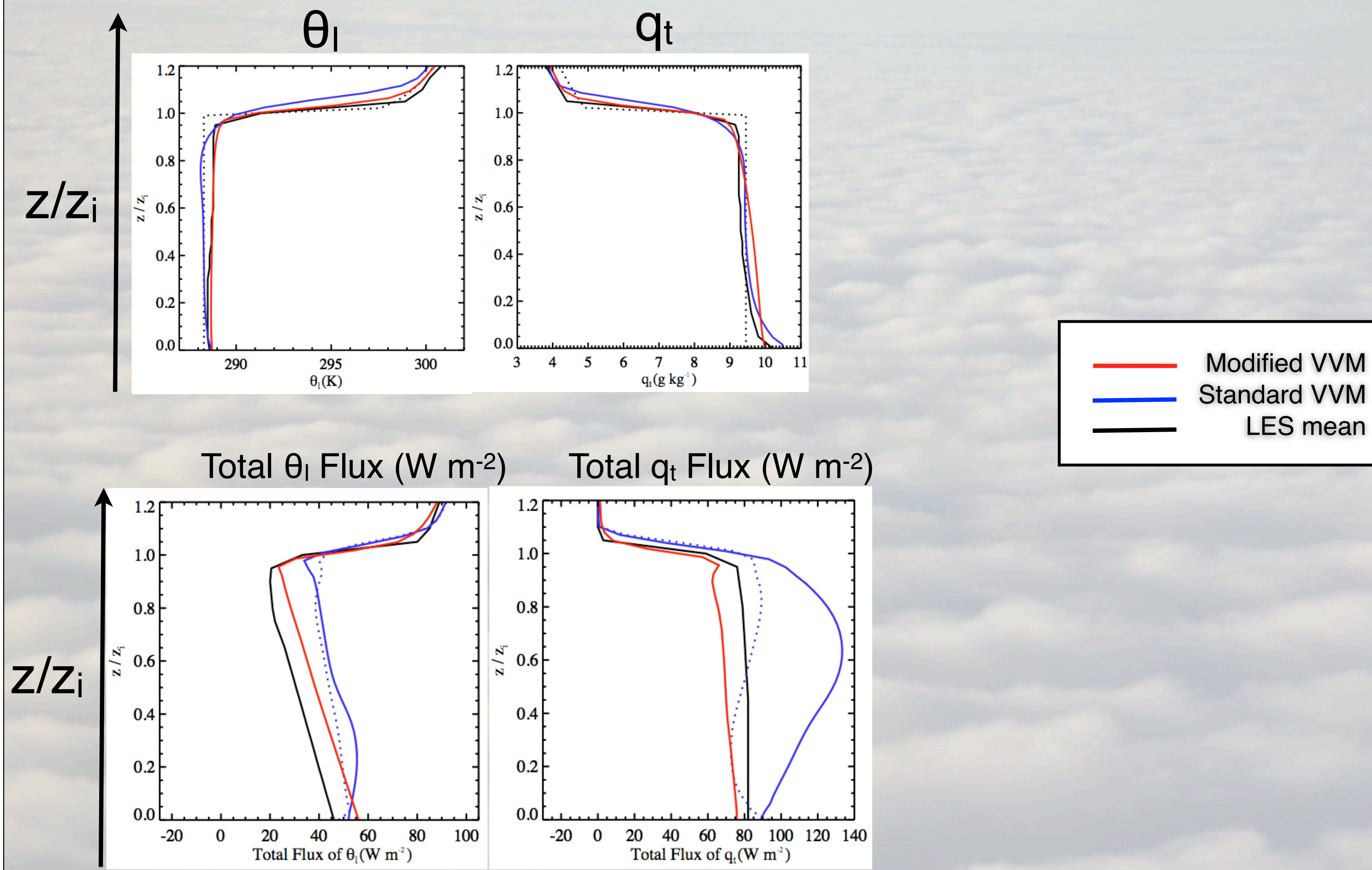
The horizontal grid spacing is 2 km.

The modified VVM uses about 10% more computer time than the control version.

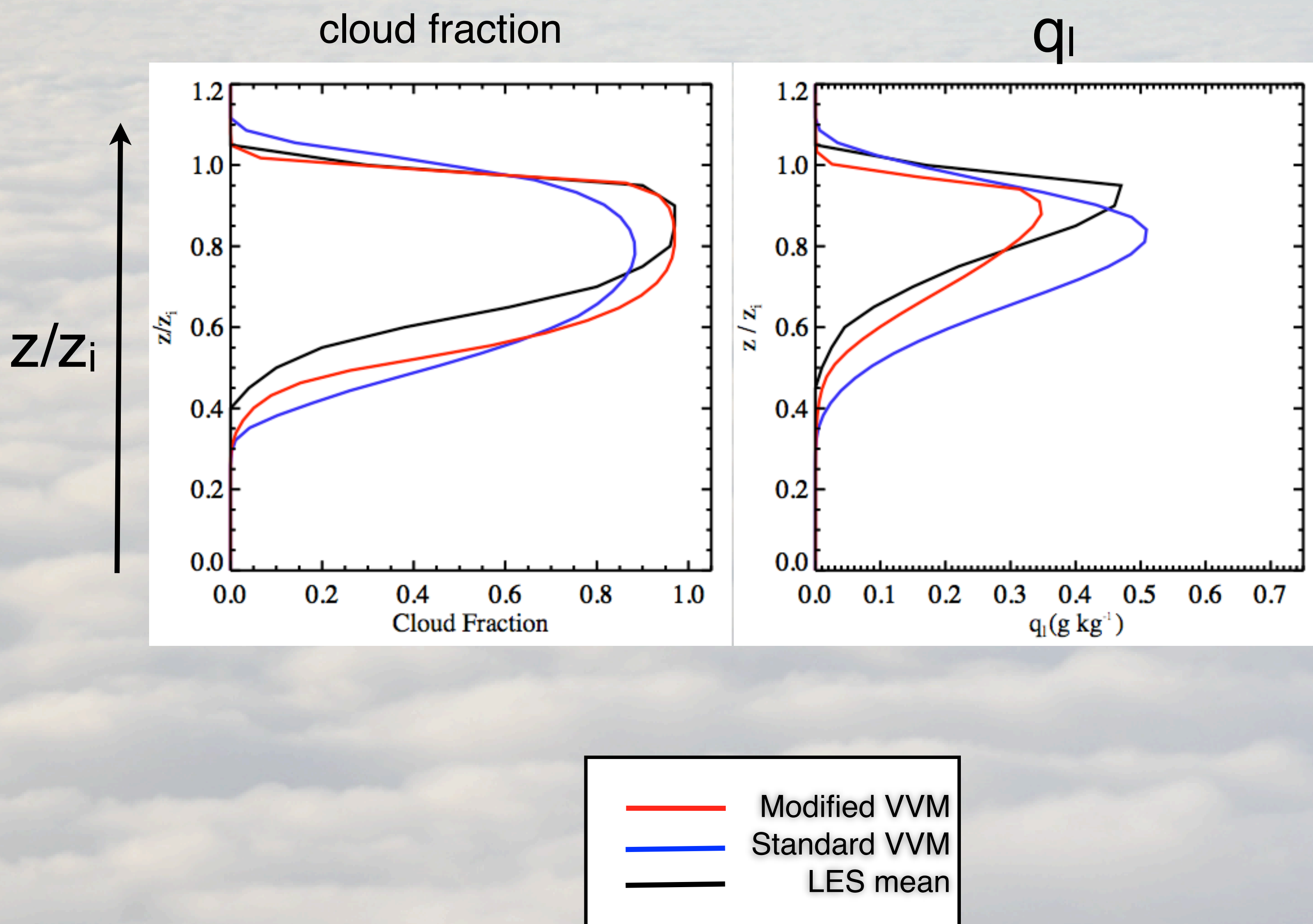
	Standard VVM	Modified VVM
Thermodynamic Vars.	θ, q_v, q_c, q_i, q_r, q_s, q_g,	θ_l, q_t, 2 rain water (cloud water diag.)
Turbulence	1st order scheme (Ri-dependent K)	New 3^{rd}-order closure model
Microphysics	Bulk Model including ice Lin et al. (1983); Lord et al. (1984); Krueger et al. (1995)	Khairoutdinov and Randall (2003) modified for SGS partial cloudiness

Modified VVM
Standard VVM
LES mean

Nocturnal Drizzling Stratocumulus Case (DYCOMS II RF02)

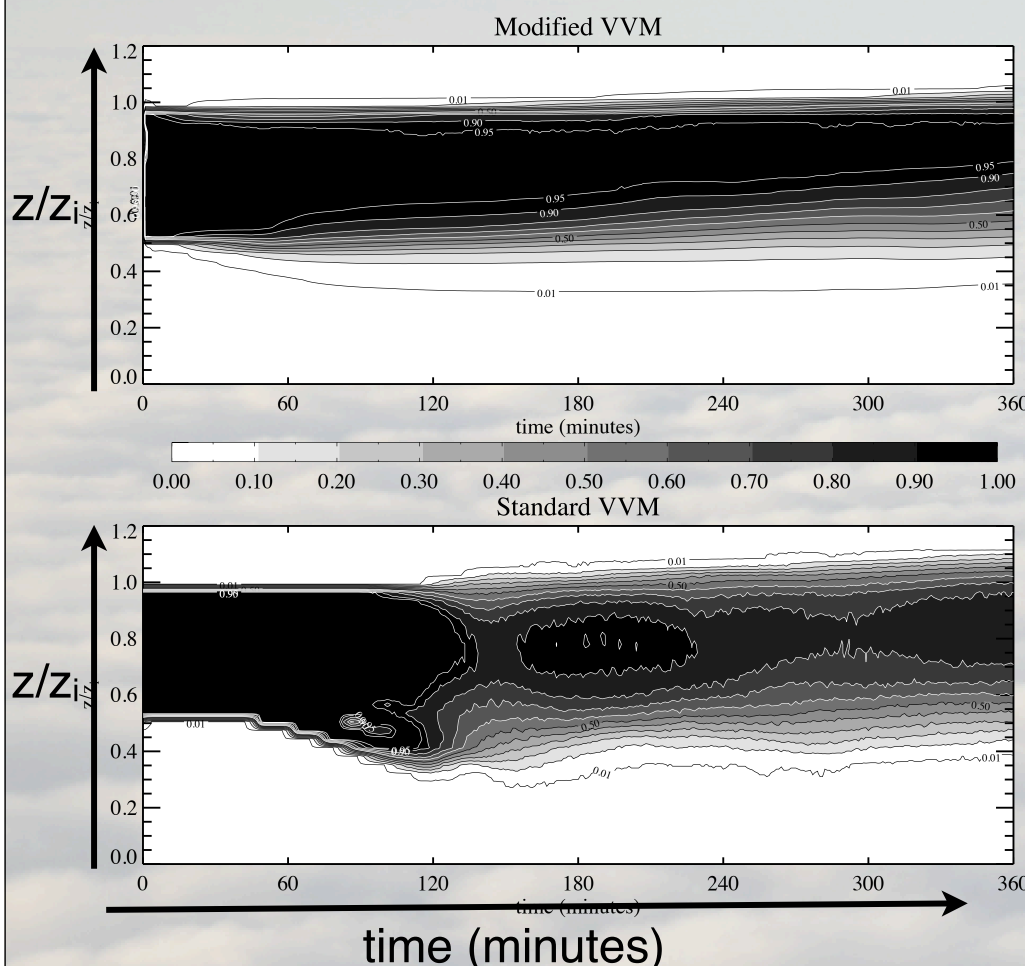


Nocturnal Drizzling Stratocumulus Case (DYCOMS II RF02)

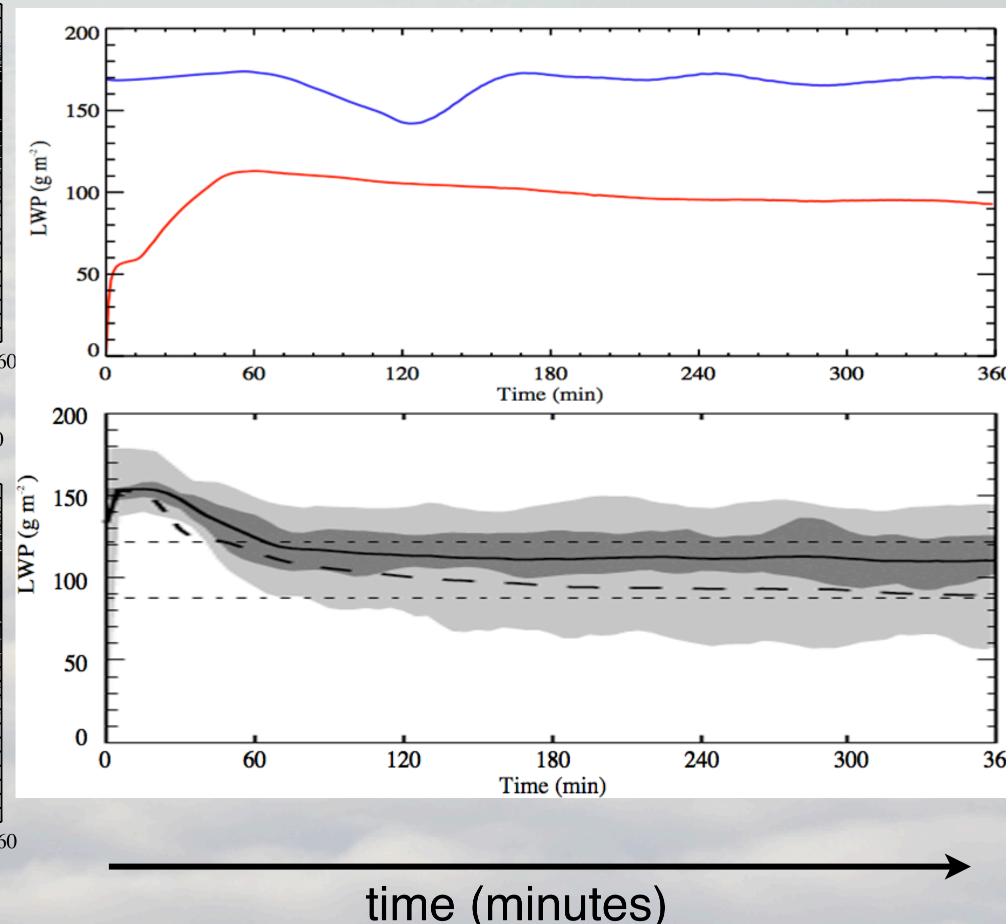


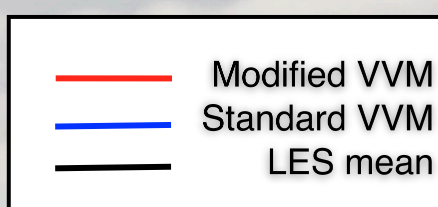
Nocturnal Drizzling Stratocumulus Case (DYCOMS II RF02)

cloud fraction

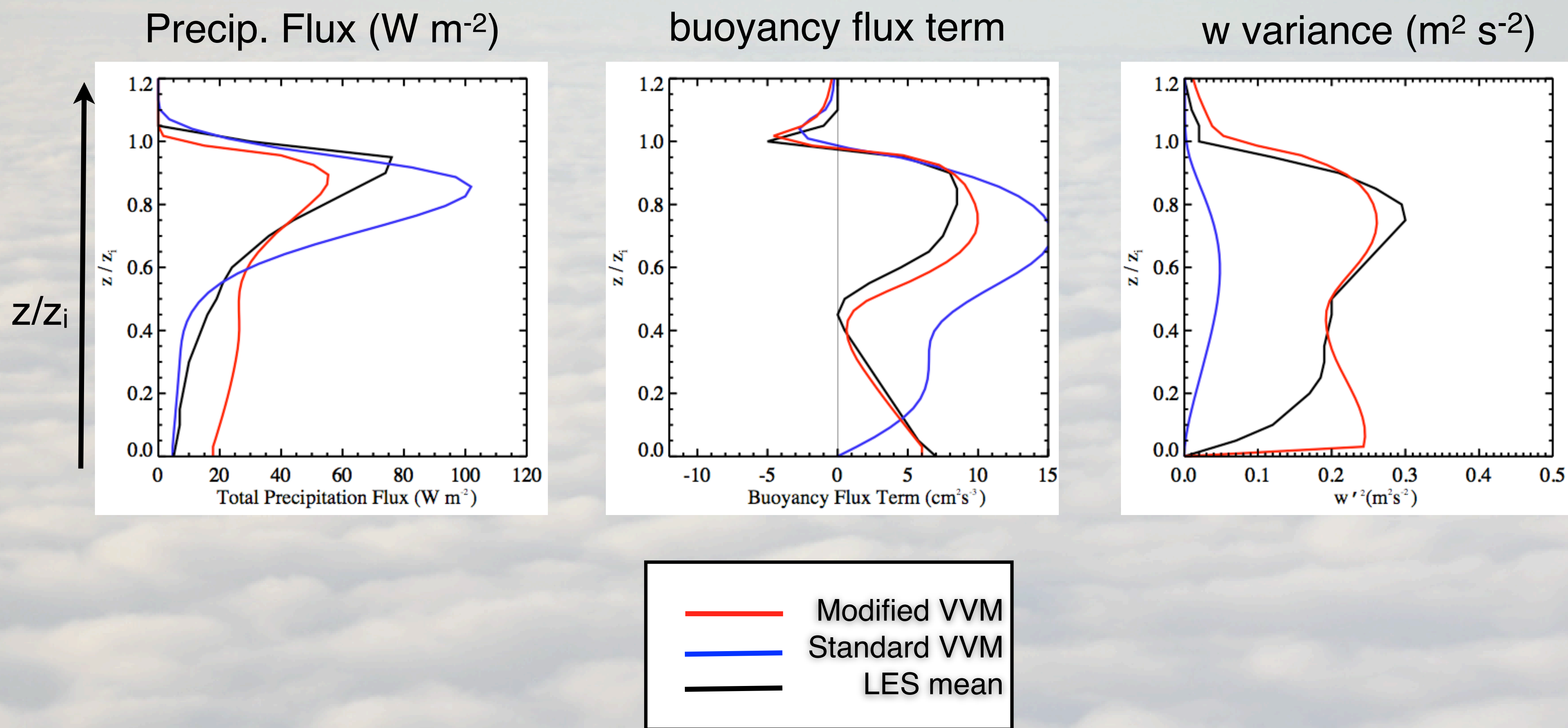


Liquid Water Path (g m^{-2})

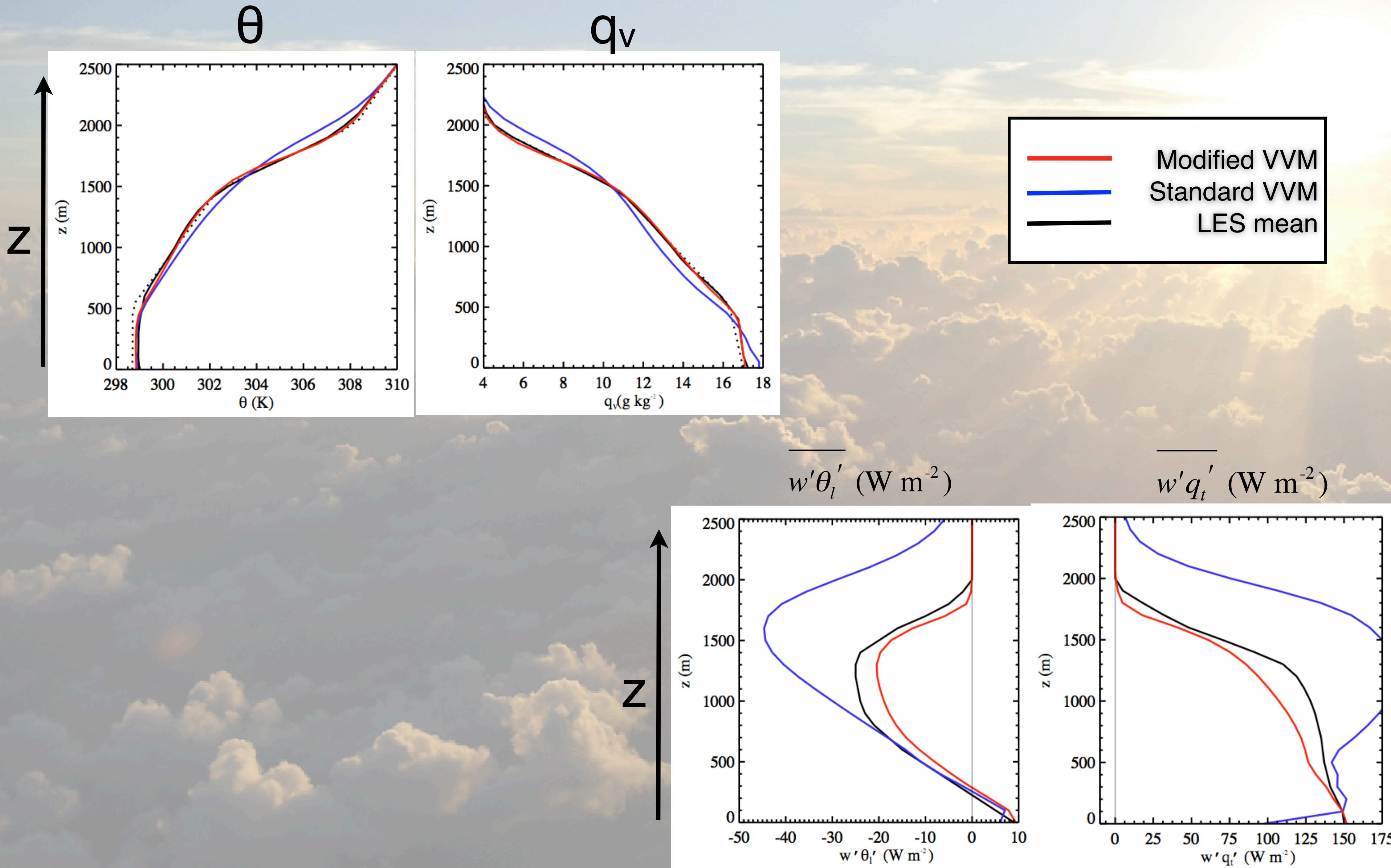




Nocturnal Drizzling Stratocumulus Case
(DYCOMS II RF02)



Nonprecipitating Shallow Trade-wind Cumulus Case (BOMEX)



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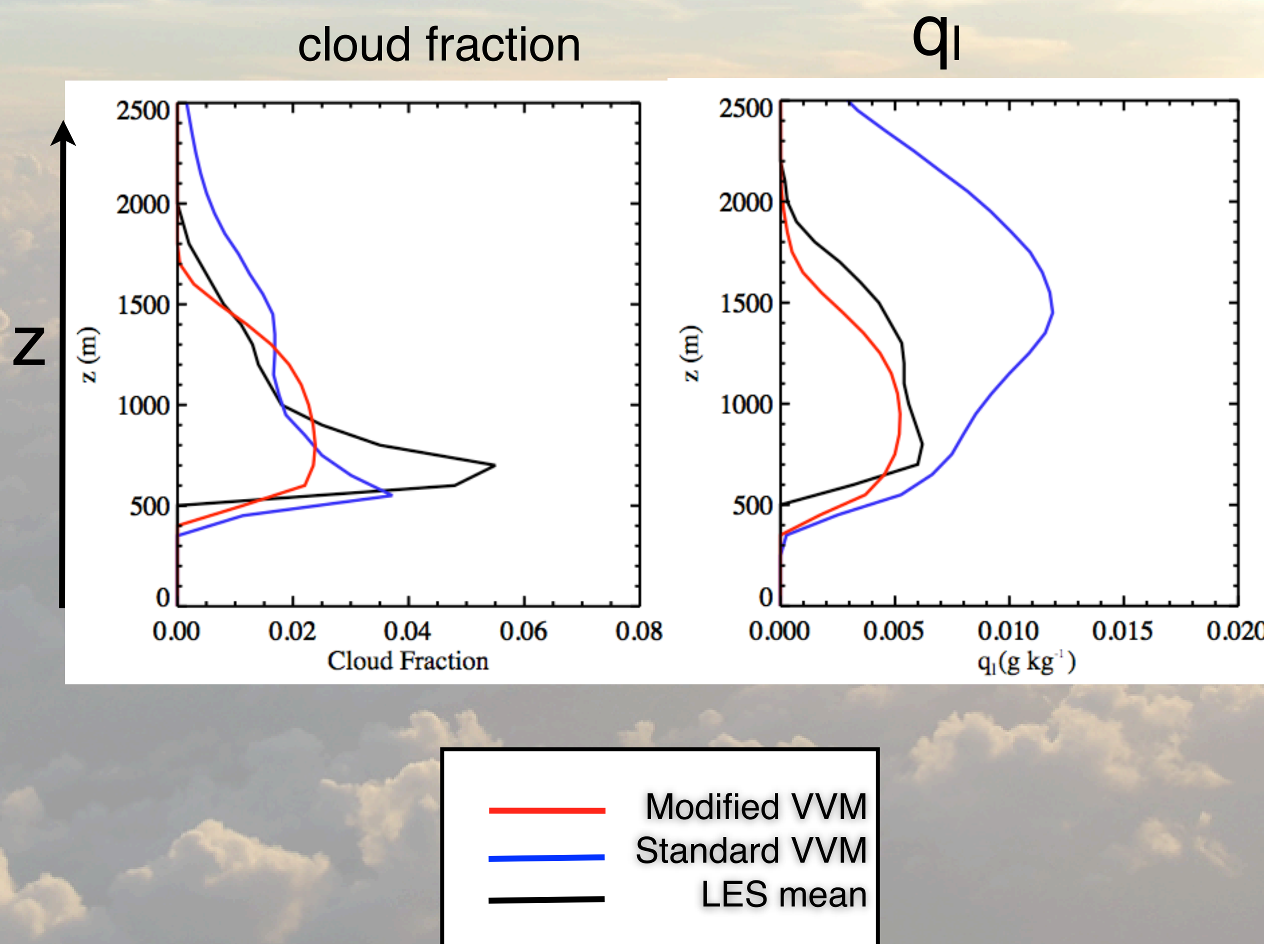
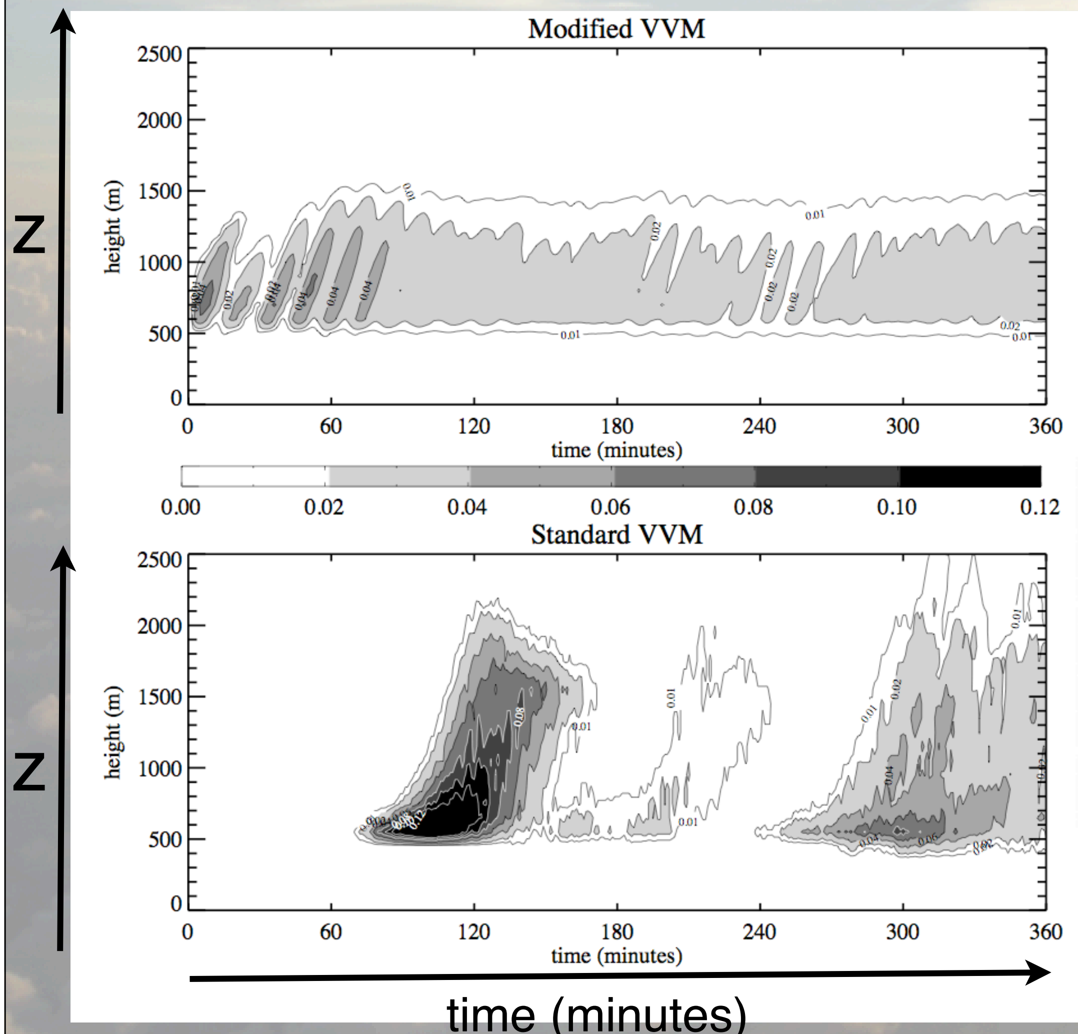


Nonprecipitating Shallow Trade-wind Cumulus Case (BOMEX)

cloud fraction



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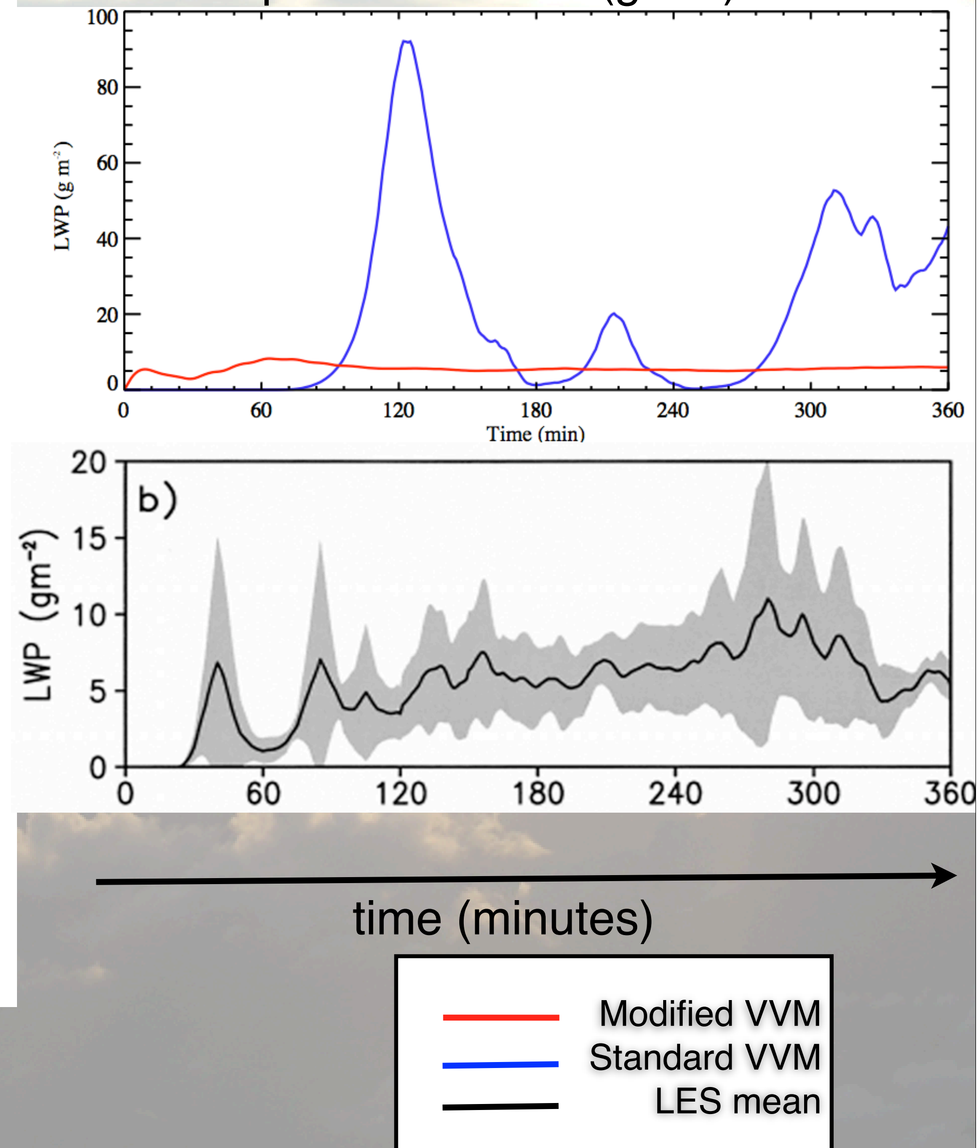
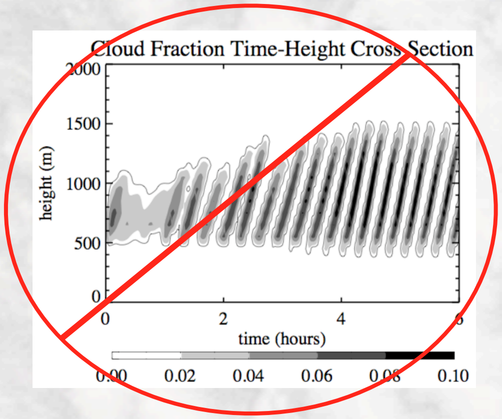


Ongoing Work



Goal: eliminate spurious cloud water oscillation

- Cheng, Xu, and Golaz (2004) studied this oscillation
- recommendation: improve parameterization of the liquid water correlations in the buoyancy terms (particularly for TOMs)

$$\overline{\chi'\theta_v'} = \overline{\chi'\theta_l'} + C_{T_0}\overline{\chi' q_t'} + D(z)\overline{\chi' q_l'}$$

Method: parameterize buoyancy terms according to Lewellen and Lewellen (2004)

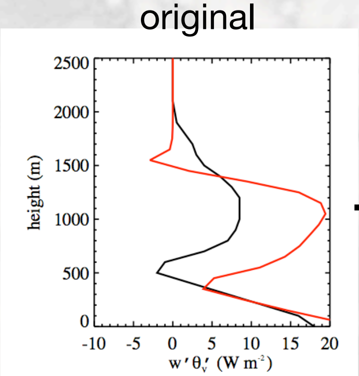
- buoyancy terms are parameterized as interpolation between clear and cloudy limits:

$$\overline{w'\theta_v'} = \left(1-\hat{R}\right)\overline{w'\theta_v'}_{CLEAR} + \hat{R}\,\overline{w'\theta_v'}_{CLOUD}$$

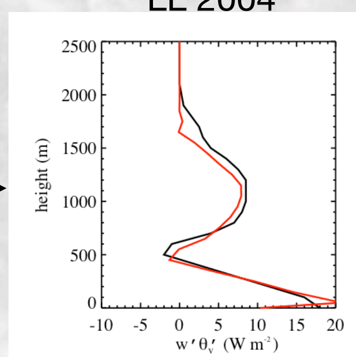
where $\hat{R}$ is the "effective cloud fraction" obtained from a mass-flux approach

Early Testing:

original



LL 2004



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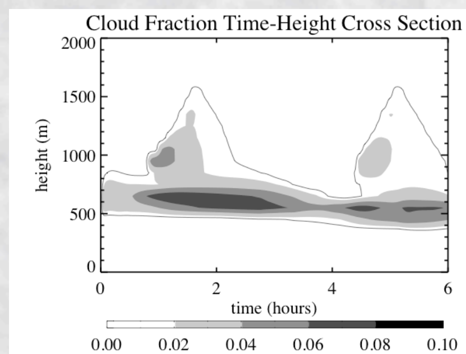

Improvements

- better buoyancy flux
- oscillation gone
- better cloud fraction profile

Needs work

- weak TOMs

Conclusions

- Developed a new third-order closure turbulence model
  - Diagnostic TOMs, non-Gaussian FOMs
  - SGS condensation
  - Microphysics scheme that accounts for SGS cloudiness
- 5 SCM cases
  - Wangara
  - Smoke Cloud
  - DYCOMS II
  - BOMEX & RICO
- 2 3-D cases
  - modified version performs better than standard version with small computational penalty

Future Work

- Eliminate cloud water oscillation
- Reduce # of SOMs, TOMs
- Run more test cases
- Port model to SAM
- Test in GCM