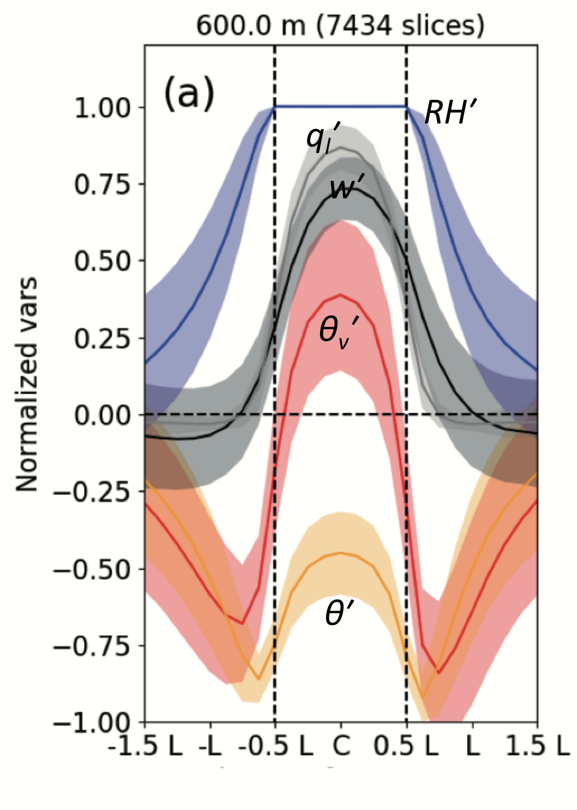
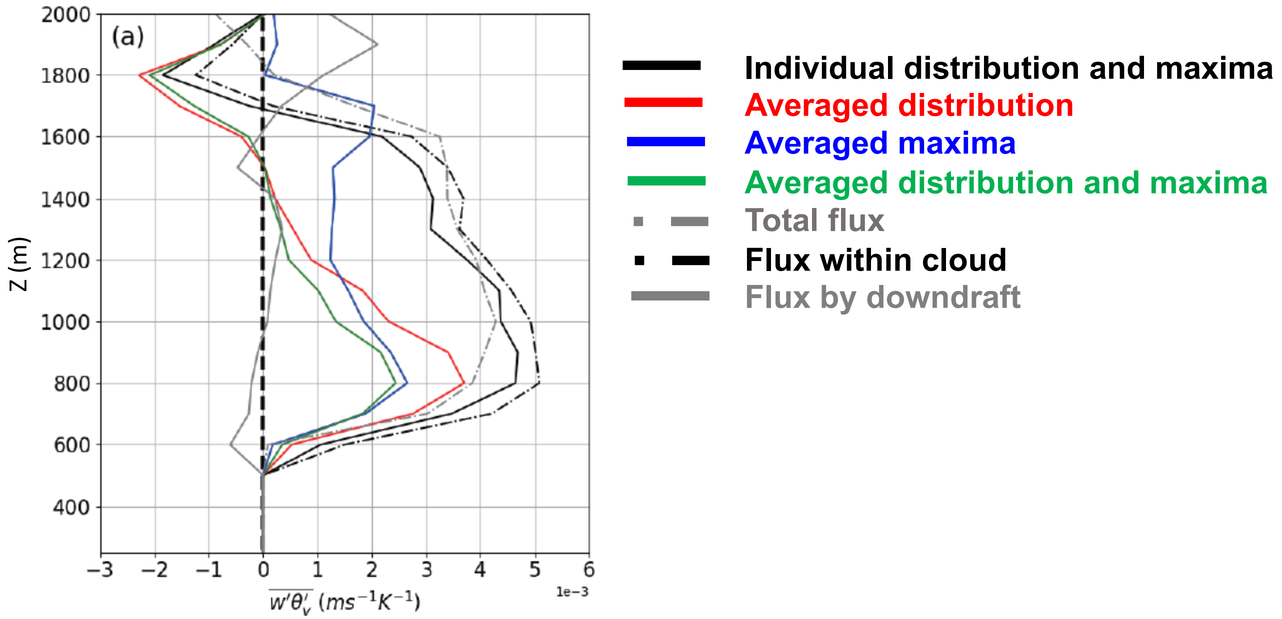
Composited structure of non-precipitating shallow cumulus clouds

Chris Holloway, Jian-Feng Gu, Bob Plant and Todd Jones University of Reading

- Internal cloud structures are critical for understanding cloud dynamics and for convection parameterization.
- 25-m MONC simulations of BOMEX and ARM cases are investigated.





- Composited distributions of shallow cumulus share similar general features, with a maximum near the centre and decreasing outward.
- Differences appear near cloud edge, with a transition zone just inside, a cloud shell just outside, and a moist buffering region further outward.
- Possible power law distributions of vertical velocity are proposed for 2D and 3D symmetric clouds.
- To represent vertical heat and water fluxes, the transition zone, uncertainties in maxima, and cloud top downdrafts are all important.

Gu et al, "Composited structure of non-precipitating shallow cumulus clouds", submitted to *QJRMS*

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Motivation

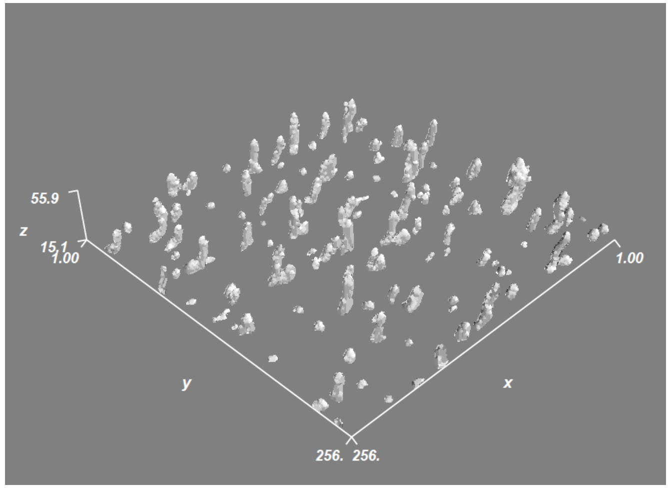
- Internal structures of dynamical and thermodynamic variables within shallow cumulus clouds are critical for our understanding of cloud dynamics and application in convection parameterization.
- Reasonable estimates of vertical transport for both heat and moisture fluxes are important in convection parameterization. Bulk plume models do not consider inhomogeneous distribution of vertical motions and transported variables within clouds, leading to underestimation of vertical fluxes.
- No consensus of the shapes of distributions has been achieved. Some parameterizations (‘parabolic distribution’: Leger et al. 2019) use assumed internal distributions that are different from observations (‘triangular distribution’, at least for deep convection: Zipser and LeMone 1980, Wang et al. 2020).
- What factors need to be considered in a parameterization when the scheme uses assumed distributions?

Large eddy simulations

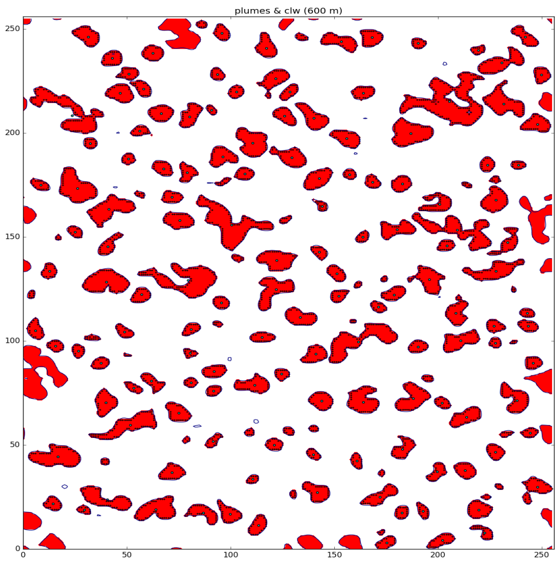
- **Met Office-NERC Cloud (MONC) model**
- **Oceanic case (BOMEX)**
  - 15 km × 15 km × 3 km @ 25 m resolution (both horizontal and vertical)
  - Most configurations follow the inter-comparison study of BOMEX (Siebesma et al. 2003)
  - 3D Smagorinsky turbulence scheme
  - 6 hour simulation, last hour simulation (equilibrium state, 10 min output frequency) is taken for analysis
- **Continental case with diurnal cycle (ARM)**
  - 6.4 km × 6.4 km × 5 km @ 25 m resolution (both horizontal and vertical)
  - Most configurations follow the inter-comparison study of ARM (Brown et al. 2002)
  - 24 hour simulation, 6 hours output centred around the time of maximum surface fluxes (equilibrium state, 15 min output frequency) is taken for analysis

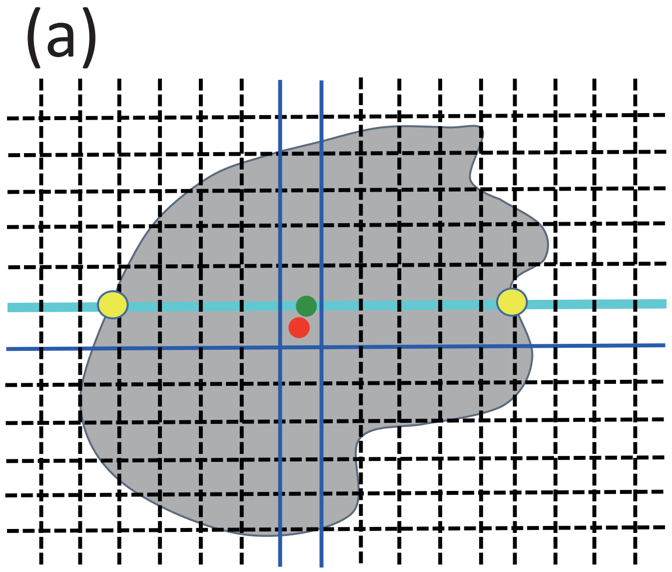
General features of composited structures in BOMEX and ARM are consistent at different levels (cloud base, middle of cloud layer and cloud top). Thus only results from BOMEX are presented.

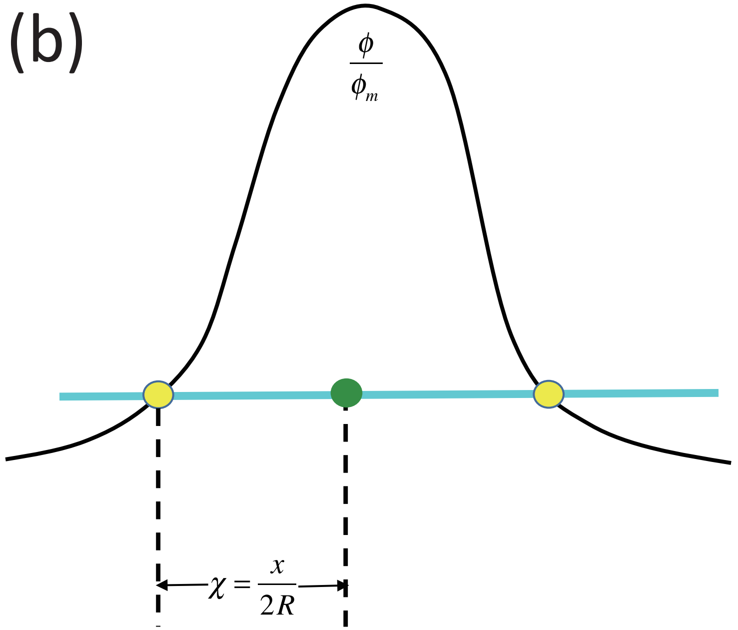
Composite Algorithm



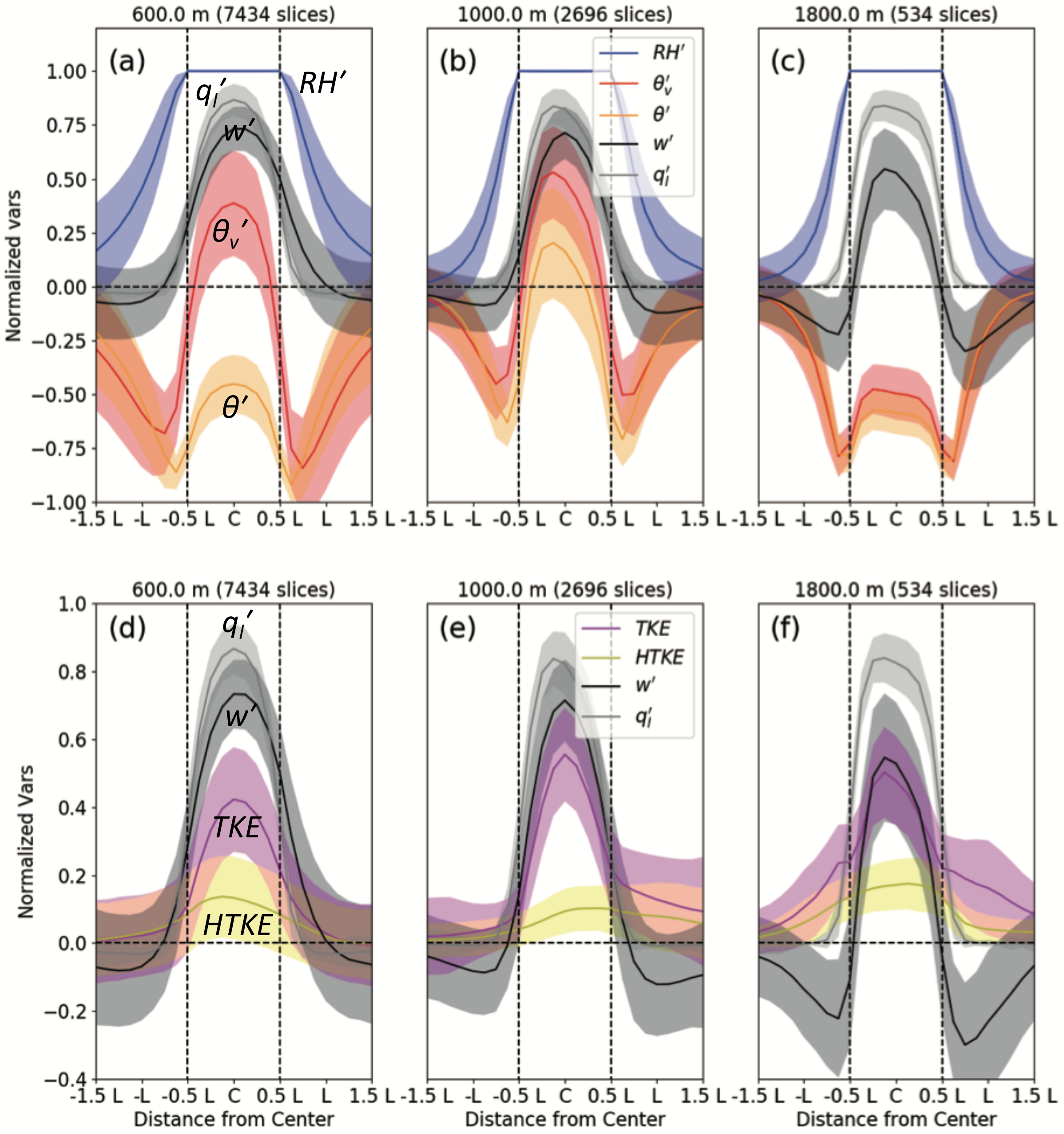
1. Identify cloud objects using q_l at single level.
2. Find the object centre.
3. Take four slices across the objects near cloud centre.
4. Interpolate the variables onto slices.
5. Normalize variables both in magnitude (by max. in object) and distance from the centre.
6. Average over slices.



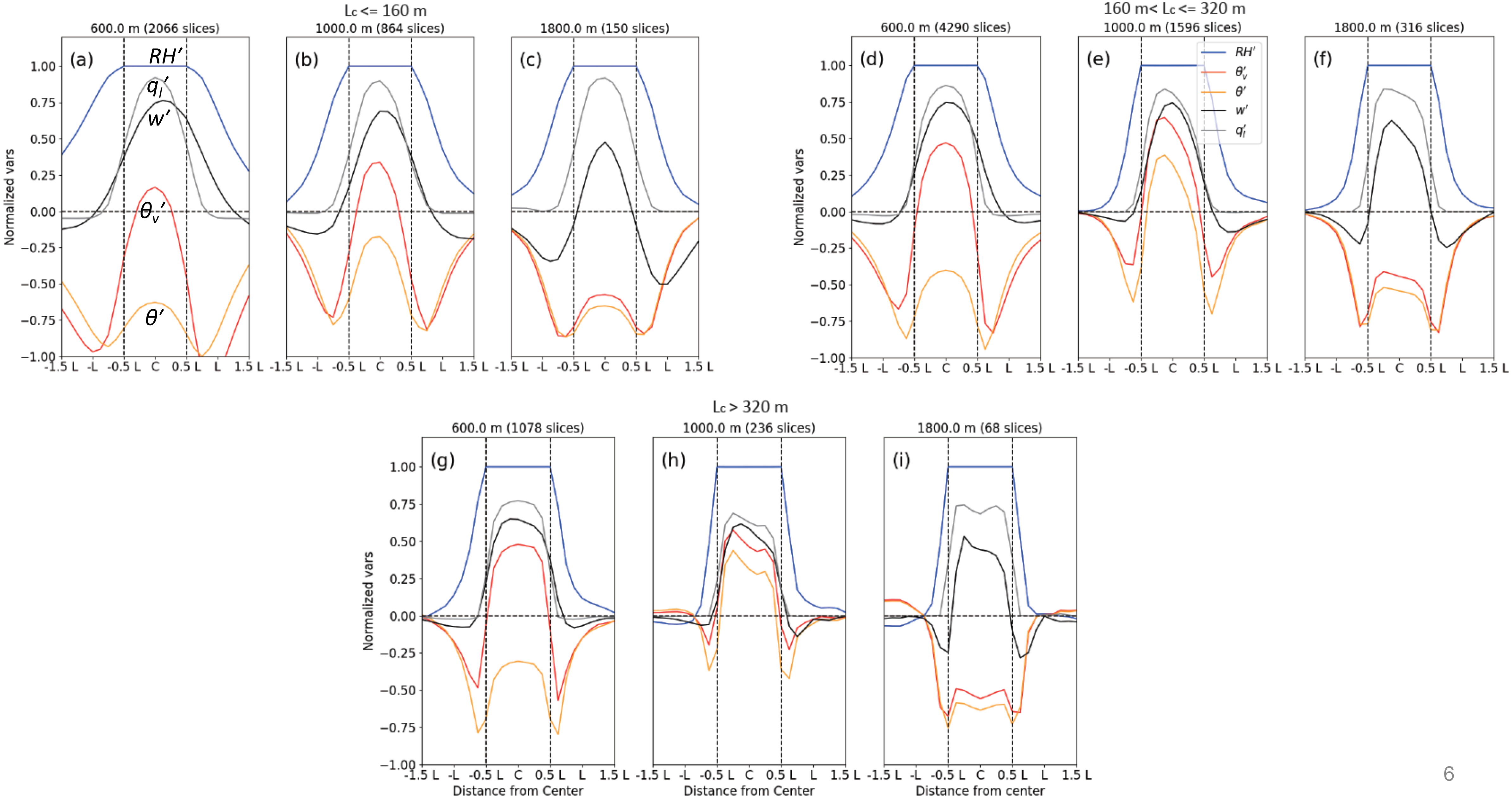




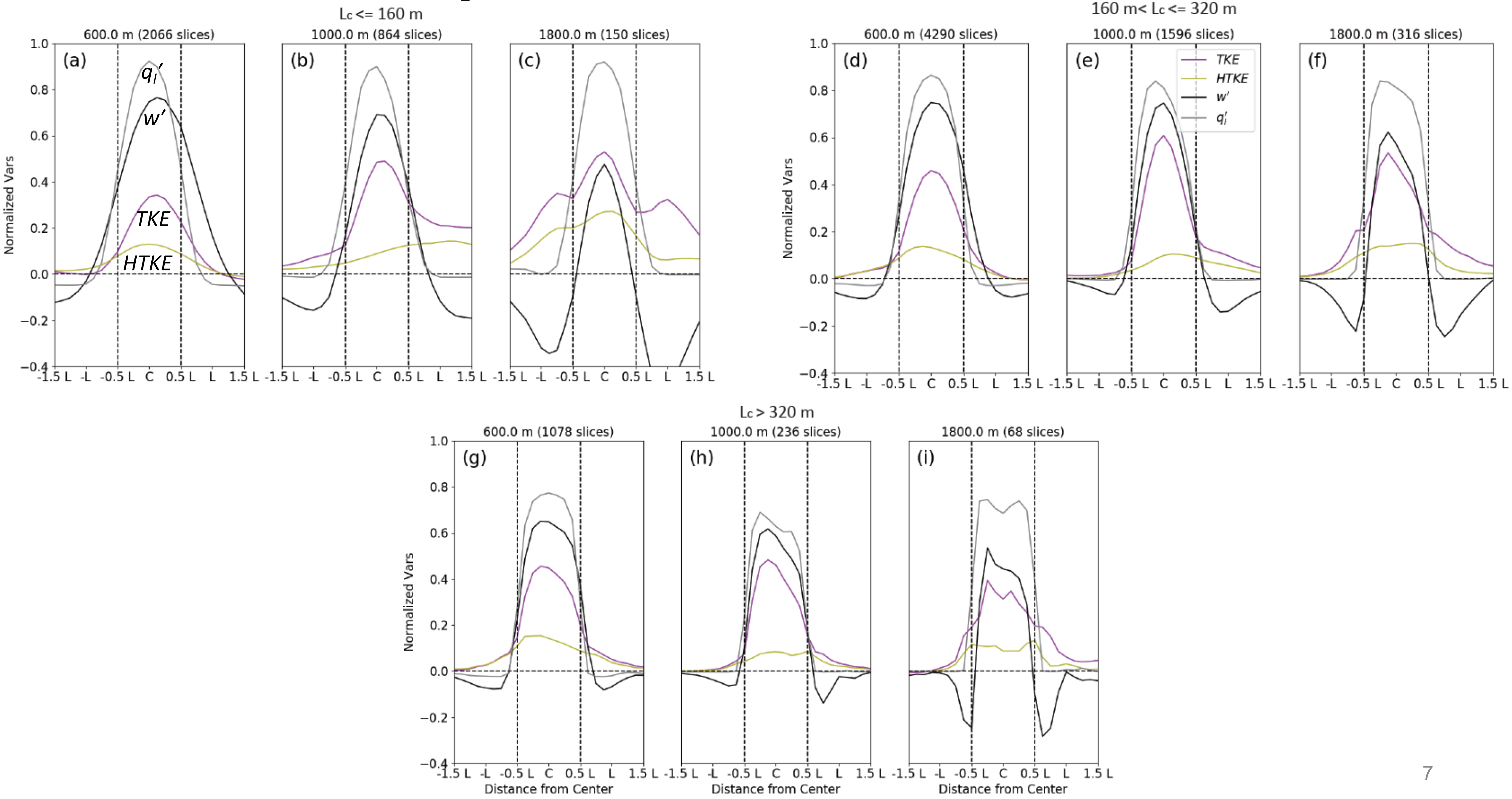
Composited distributions



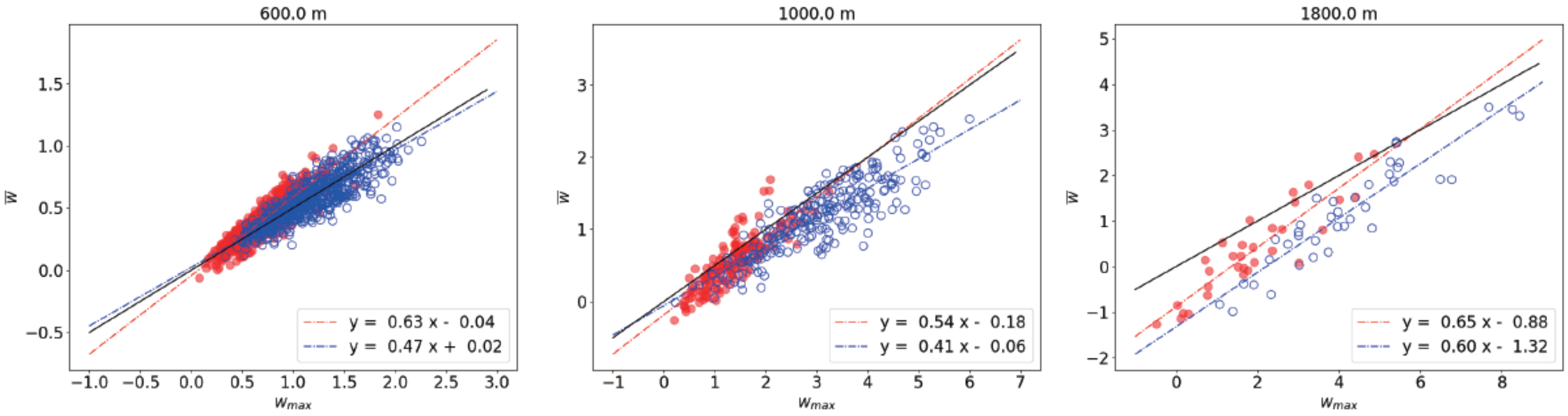
Dependence on cloud size



Dependence on cloud size



Relationship between w_m and w_{max}



Possible power law distribution

We assume the normalized distribution $f(r/R)$ for vertical motion takes a form of power law distribution:

$$f(r/R) = a_0 + a_1(r/R)^m$$

(1) For a 2D symmetric cloud,

$$\overline{w} = \frac{\int_0^R w_m f\left(\frac{r}{R}\right) dr}{\int_0^R dr} = \frac{w_m}{R} \int_0^R f\left(\frac{r}{R}\right) dr$$

Using α to denote the ratio of $\overline{w}$ to w_m, we have:

$$\int_0^R f\left(\frac{r}{R}\right) dr = \alpha R,$$

(2) Similarly, for a 3D axisymmetric cloud, at each vertical level, we have

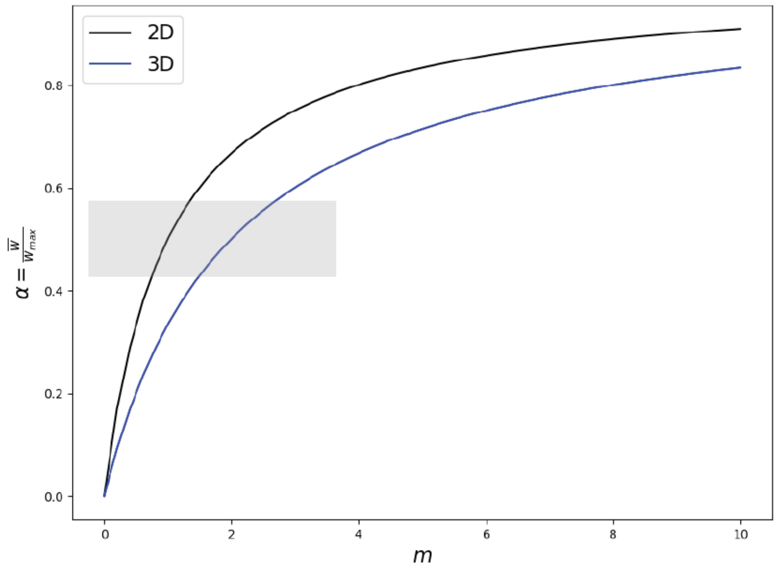
$$\int_0^{2\pi} \int_0^R f\left(\frac{r}{R}\right) r\,dr\,d\theta = \alpha \pi R^2$$

$f(0) = 1.0$

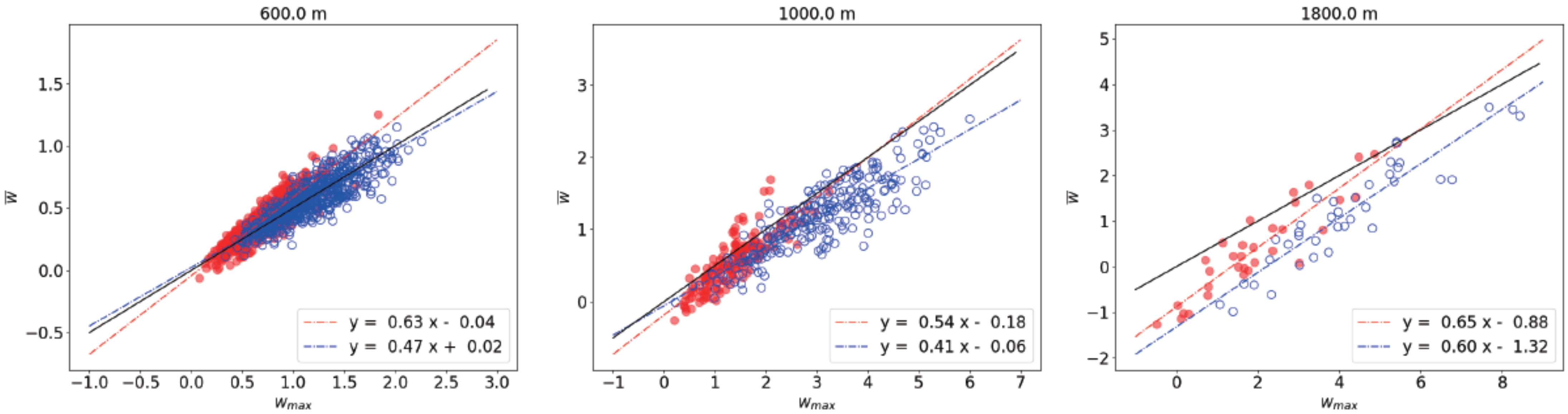
$f(1) = 0$

$$\alpha = \frac{m}{m+1} \quad \text{(2D cloud)}$$

$$\alpha = \frac{m}{m+2} \quad \text{(3D cloud)}$$



Relationship between w_m and w_{max}



m=1 for 2D clouds (consistent with observations)
m=2 for 3D clouds (consistent with Leger et al. 2019)

These results provide motivation to reconcile observational estimates of cloud *w* distributions with LES.

Estimation of vertical fluxes with composited distribution

No averaged distributions and maxima are used

$$< w'\phi' > = \frac{2\pi}{S_{tot}} \sum_i w'_{mi} \phi'_{mi} \int_0^{r_i} f_{w_i}\left(\frac{r}{r_i}\right) f_{\phi_i}\left(\frac{r}{r_i}\right) r\,dr$$

Averaged distributions are used

$$< w'\phi' > \approx \frac{2\pi}{S_{tot}} \sum_i w'_{mi} \phi'_{mi} \int_0^{r_i} \overline{f_{w_i}\left(\frac{r}{r_i}\right)}\, \overline{f_{\phi_i}\left(\frac{r}{r_i}\right)} r\,dr$$

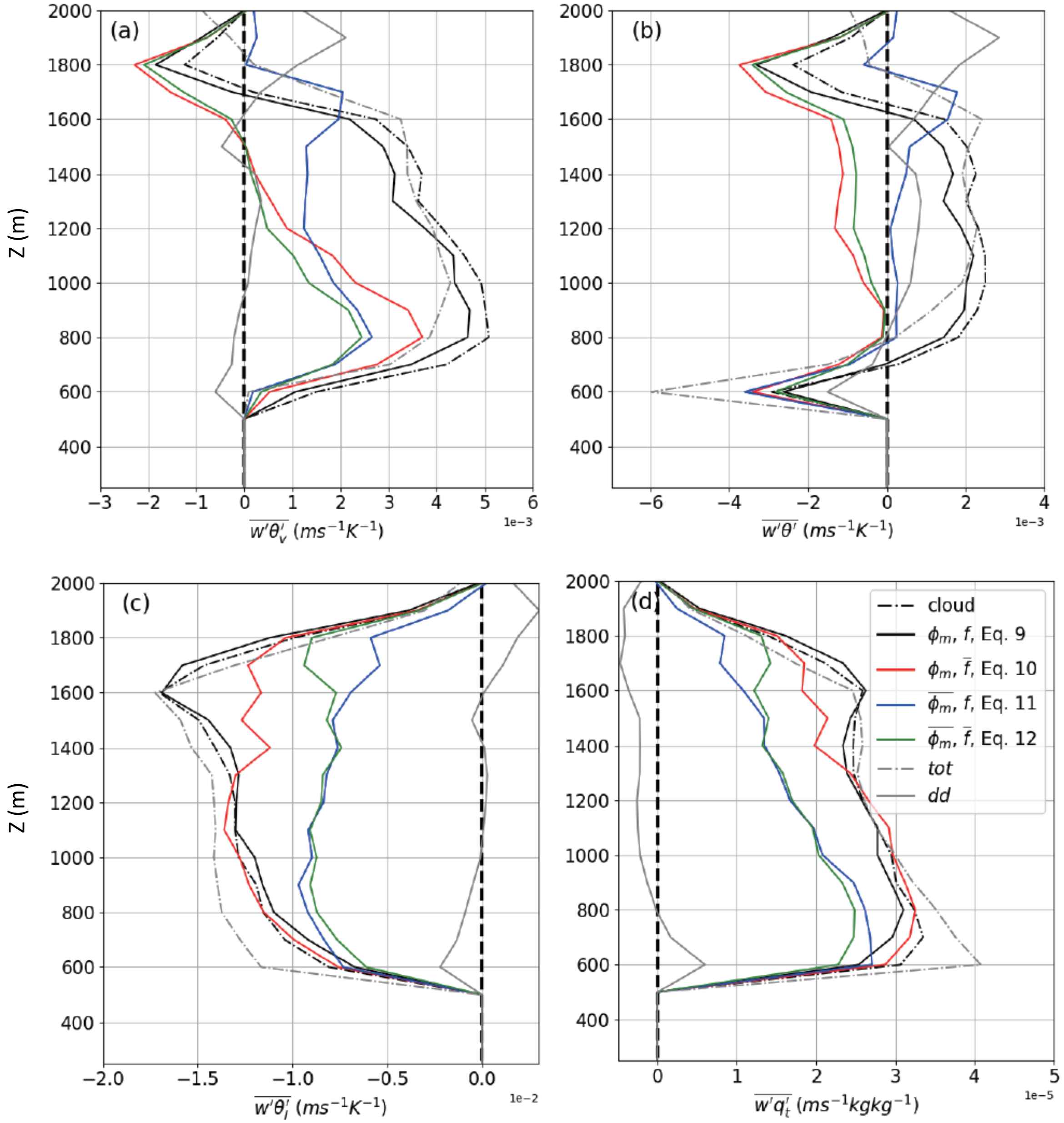
Averaged maxima are used

$$< w'\phi' > \approx \frac{2\pi}{S_{tot}} \overline{w'_{mi}}\, \overline{\phi'_{mi}} \sum_i \int_0^{r_i} f_{w_i}\left(\frac{r}{r_i}\right) f_{\phi_i}\left(\frac{r}{r_i}\right) r\,dr$$

Averaged distribution and averaged maxima are used

$$< w'\phi' > \approx \frac{2\pi}{S_{tot}} \overline{w'_{mi}}\, \overline{\phi'_{mi}} \sum_i \int_0^{r_i} \overline{f_{w_i}\left(\frac{r}{r_i}\right)}\, \overline{f_{\phi_i}\left(\frac{r}{r_i}\right)} r\,dr$$

Estimation of vertical fluxes with composited distribution



Individual distribution and maxima
Averaged distribution
Averaged maxima
Averaged distribution and maxima
Total flux
Flux within cloud
Flux by downdraft

Flux estimation using individual distribution and maxima can capture the total fluxes well.

Averaged distribution significantly underestimates heat fluxes (including opposite sign buoyancy flux) because of the inappropriate treatment of the transition zone. But it gives a reasonable estimation of θ_l and q_t fluxes.

Averaged maxima underestimates both heat and water fluxes due to the large uncertainty of maxima as shown in composited structures. But it gives the right sign of buoyancy fluxes within the cloud layer.

Averaged distribution and maxima significantly underestimates both heat and water fluxes.

Cloud top downdrafts contribute non-negligible positive heat fluxes.

Summary

Composited distributions of dynamical and thermodynamic variables in non-precipitating shallow cumulus clouds share similar general features, with maxima near the centre and decreasing outward.

Differences appear near cloud edge, with a transition zone just inside the edge, a cloud shell just outside, and a moist buffering region further outward.

Possible power law distributions of vertical velocity are proposed for 2D and 3D symmetric clouds, based on the relationship between the mean and maximum vertical velocities in cloud.

Composited distributions are used to represent the vertical heat and water fluxes. Results show that the transition zone needs to be carefully treated and the uncertainty of maxima needs to be considered. Cloud top downdrafts are also important.