Estimating entrainment from cloud radar

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November 5, 2013

Estimating entrainment using the "bulk-plume" approximation

Define a cloud indicator function: $\mathcal{A} = \begin{cases} 1 & \text{inside cloud} \\ 0 & \text{outside cloud} \end{cases}$

Denote the average over x,y,t by an overbar.

Pick a conserved tracer ϕ.

Apply bulk-plume approximation.

Then, the entrainment profile $\bar{e}$ is given by:

$$\boxed{\bar{e} = \frac{M \partial_z \phi_c}{\phi_e - \phi_c}} \propto \frac{\text{in-cloud } \partial_z \phi}{\text{outside } \phi \text{ - inside } \phi}$$

Calculating entrainment using "direct measurement"

Define a cloud indicator function: $\mathcal{A} = \begin{cases} 1 & \text{inside cloud} \\ 0 & \text{outside cloud} \end{cases}$

Write down continuity equation for "cloudy air":

$$\partial_t(\rho\mathcal{A}) + \vec{\nabla} \cdot (\rho\mathcal{A}\vec{u}) = e - d$$

Define entrainment e and detrainment d such that:

$$e \geq 0\,,\; d \geq 0\,,\; ed = 0$$

Then, it immediately follows that:

$$\boxed{e = \max\left[0\,,\; \partial_t(\rho\mathcal{A}) + \vec{\nabla} \cdot (\rho\mathcal{A}\vec{u})\right]}$$

Pros and Cons

Bulk-plume entrainment rate

Con:

Depends on the tracer being used

Sometimes negative

Pro:

Easy to measure

Directly measured entrainment rate

Pro:

Independent of any tracer

Never negative

Con:

Difficult to measure -- or is it?

There are 3 ways to directly measure entrainment in LES

1. Eulerian measurement at the grid-cell level
   (Romps, 2010)

2. Eulerian measurement at the sub-grid-cell level
   (Dawe and Austin, 2011)

3. Lagrangian particles
   (Yeo and Romps, 2013)

But, 0 ways to directly measure entrainment from obs

Recall: $\mathcal{A}$ is the indicator function for cloud, and a bar denotes an average over x, y, and t.

Direct measurement in LES uses:

$$e = \max\left[0\,,\ \partial_t(\rho\mathcal{A}) + \vec{\nabla}\cdot(\rho\mathcal{A}\vec{u})\right]$$

With some approximations:

$$\boxed{\bar{e} = \overline{\max\left[0\,,\ \mathcal{A}\partial_z(\rho w)\right]}}$$

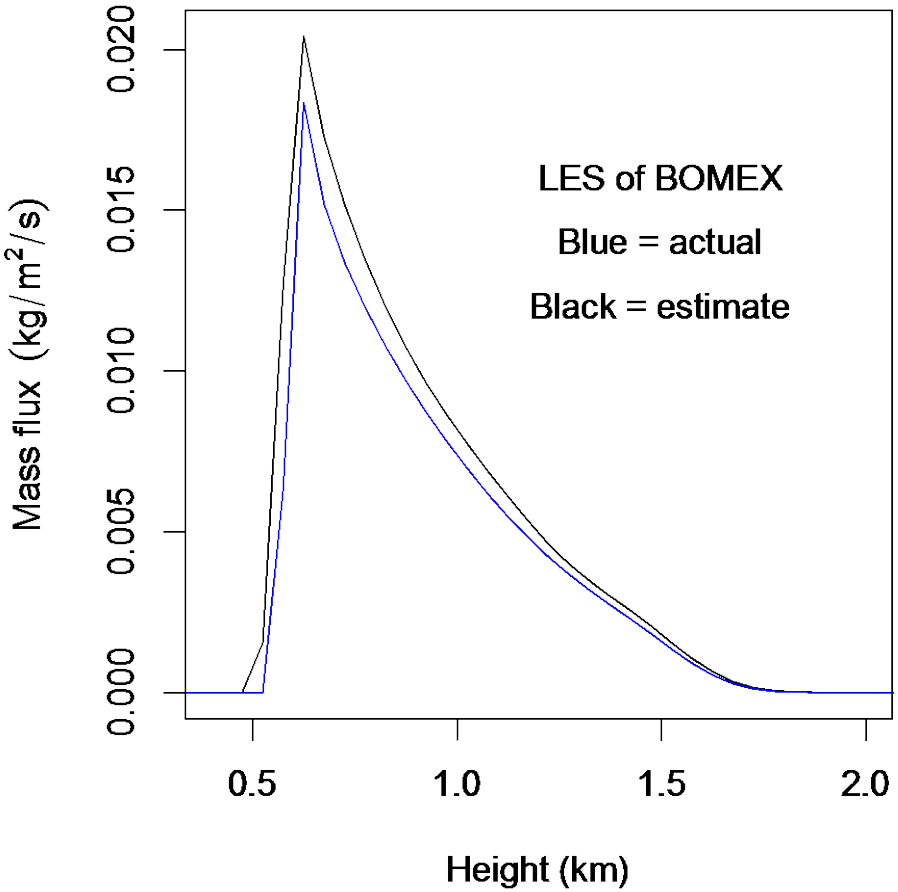
This can be used on cloud radar data!

How good is this approximation? Test with LES of **shallow clouds**

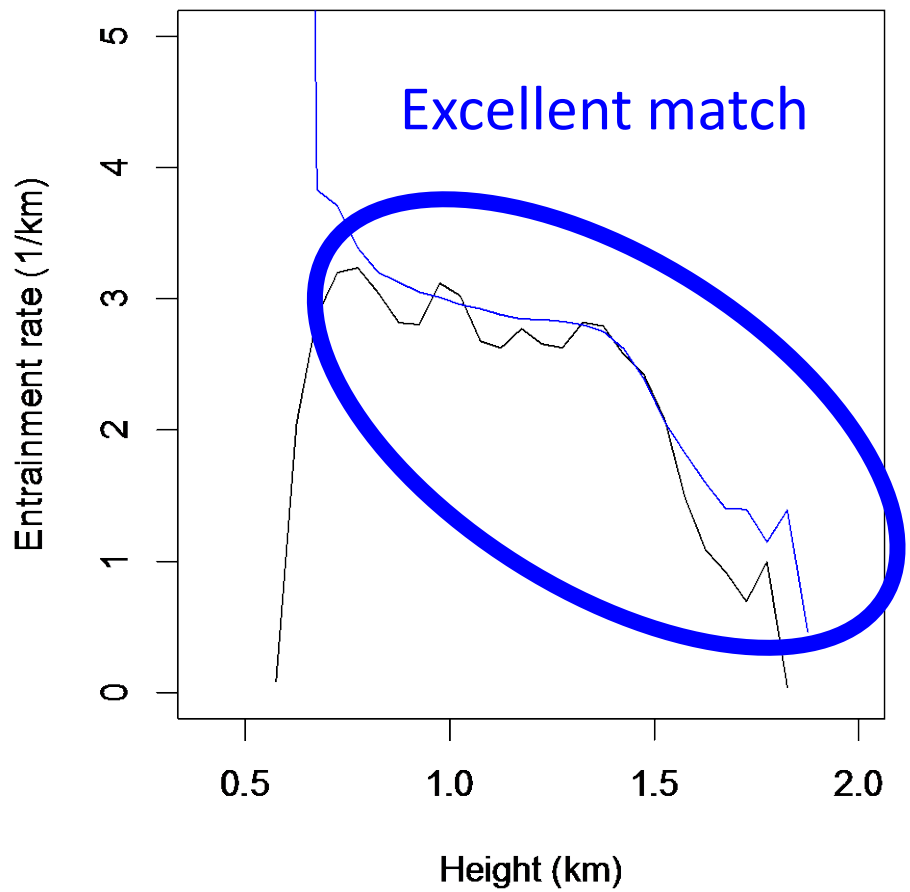
blue = direct measurement

black = the approximation

Mass flux



Entrainment

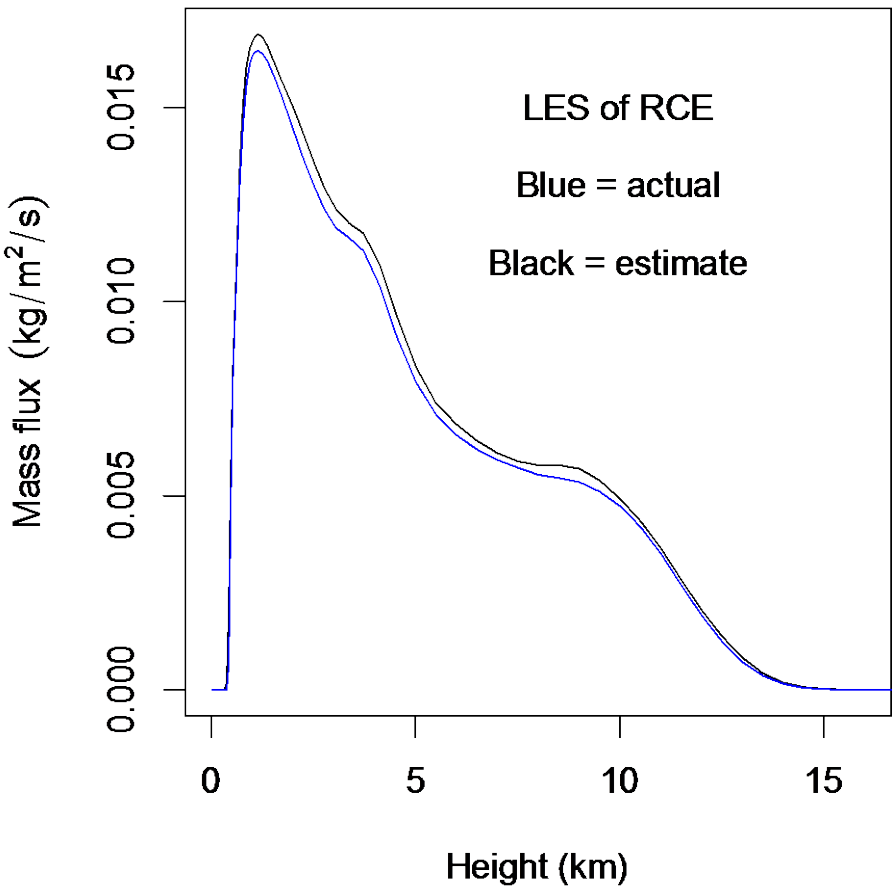


How good is this approximation? Test with LES of **deep clouds**

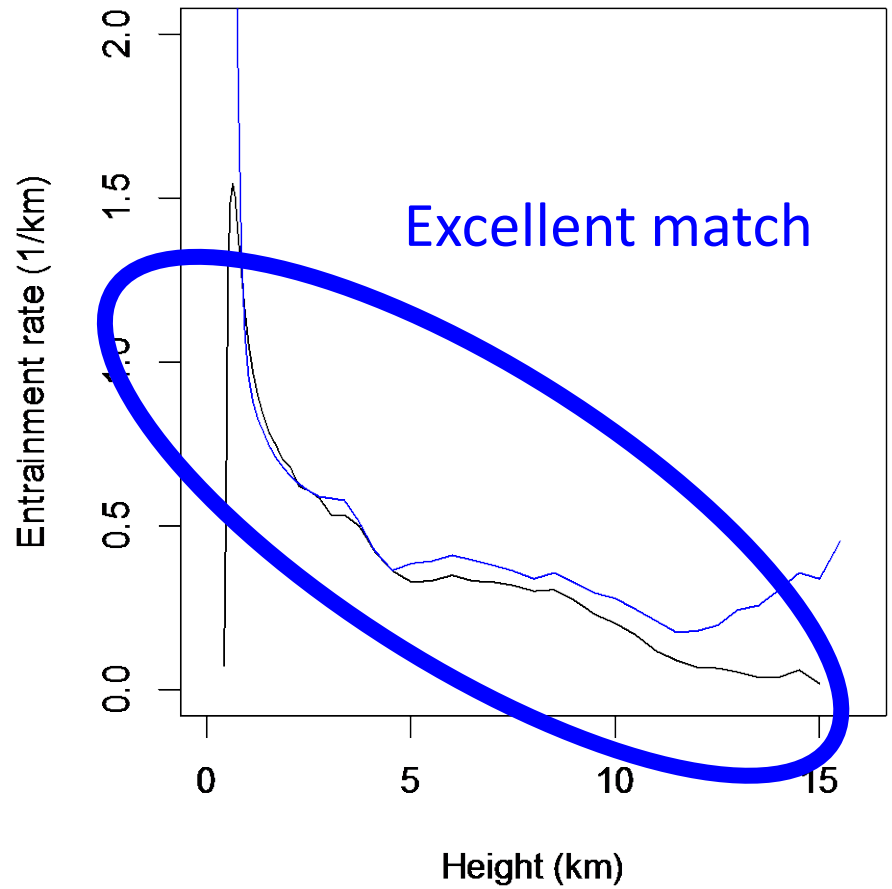
blue = direct measurement

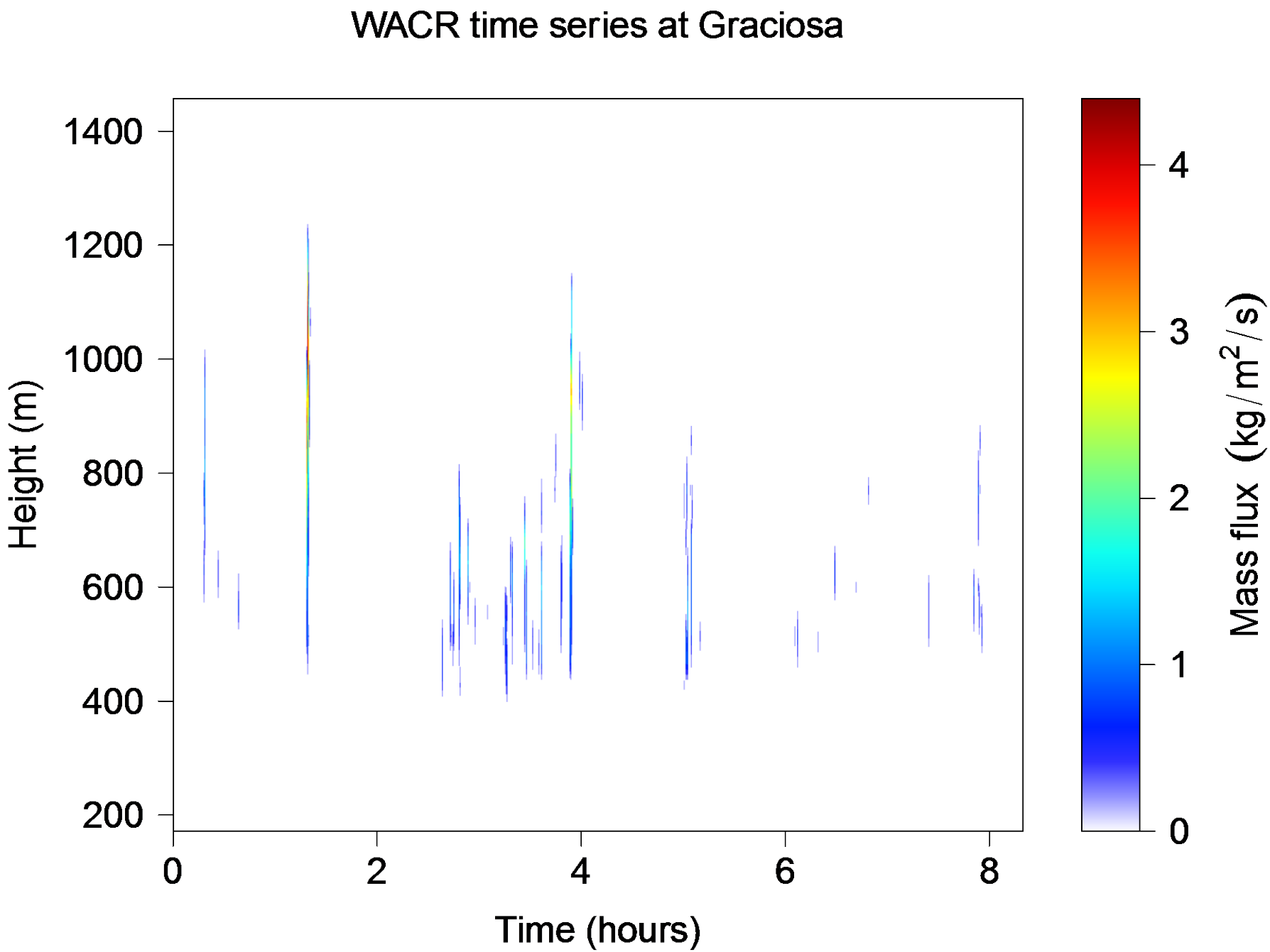
black = the approximation

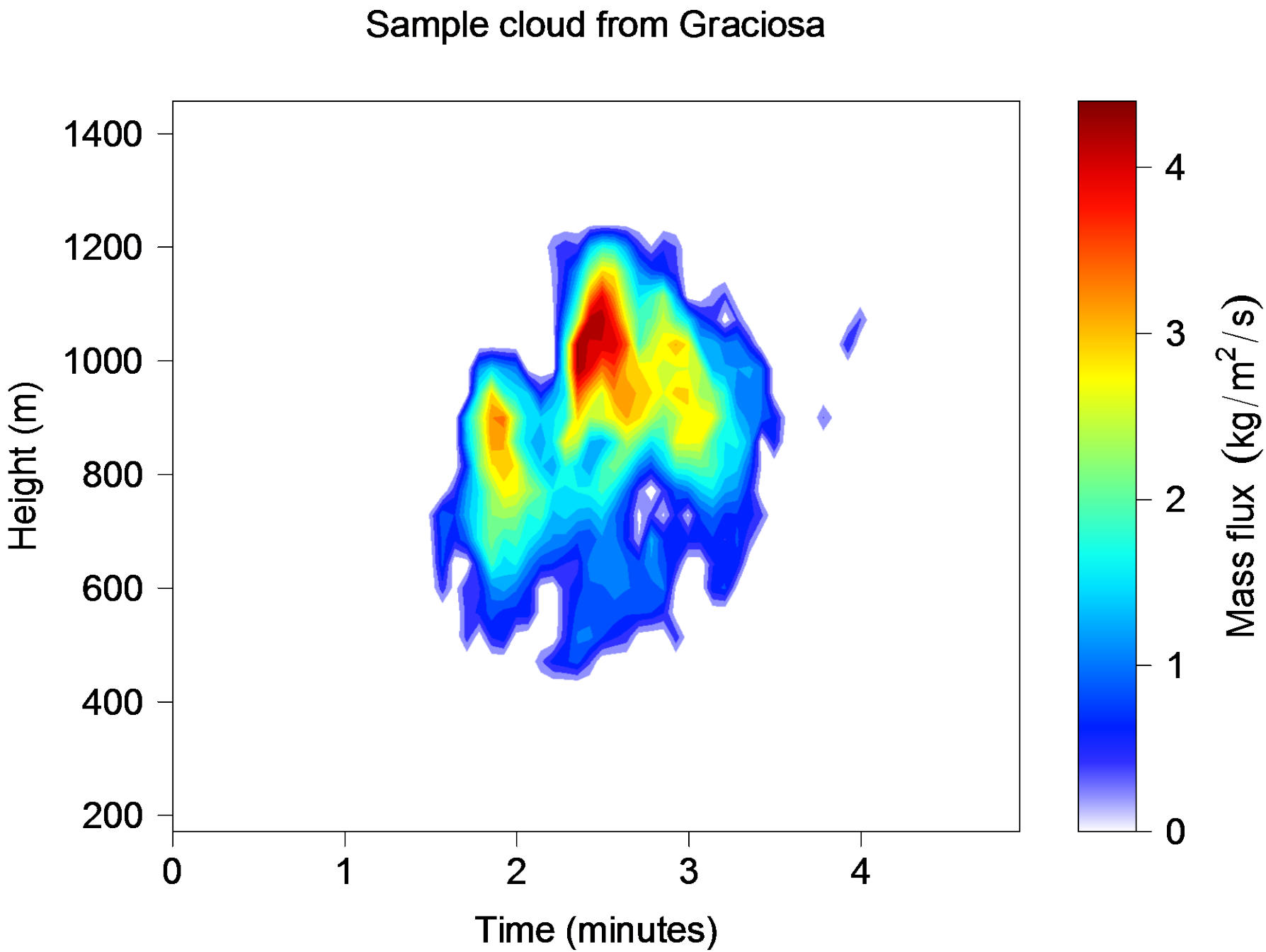
Mass flux



Entrainment



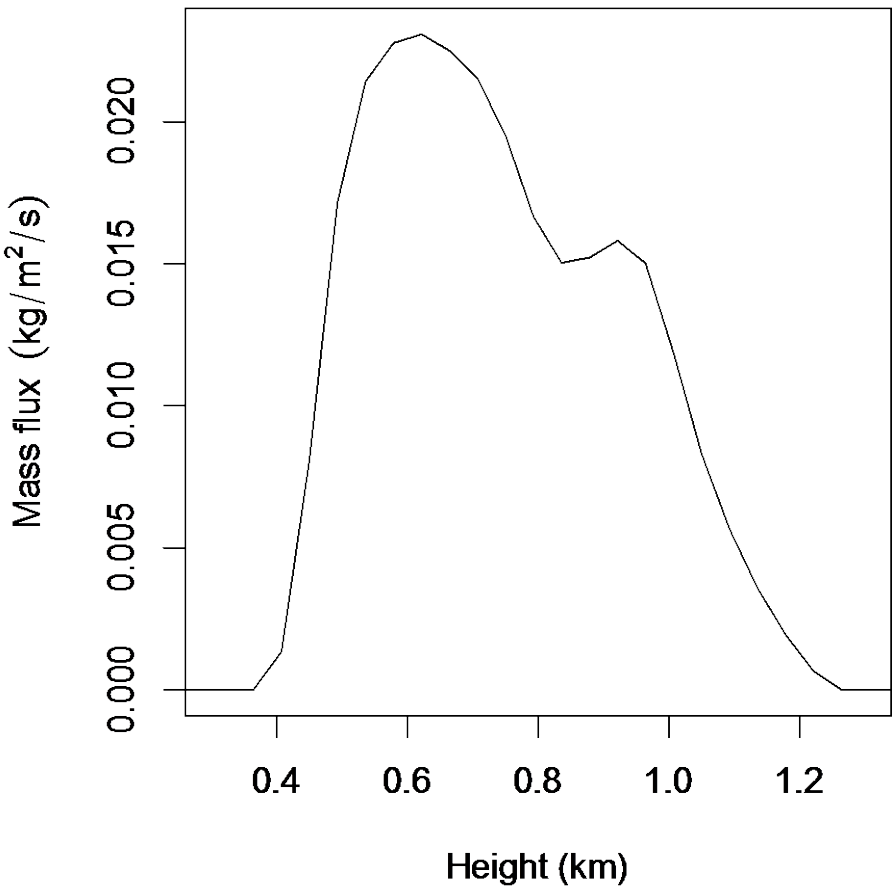

WACR time series at Graciosa
Height (m)
1400
1200
1000
800
600
400
200
0
2
4
6
8
Time (hours)
4
3
2
1
0
Mass flux (kg/m2/s)


Sample cloud from Graciosa
Height (m)
1400
1200
1000
800
600
400
200
0
1
2
3
4
Time (minutes)
Mass flux (kg/m2/s)
4
3
2
1
0

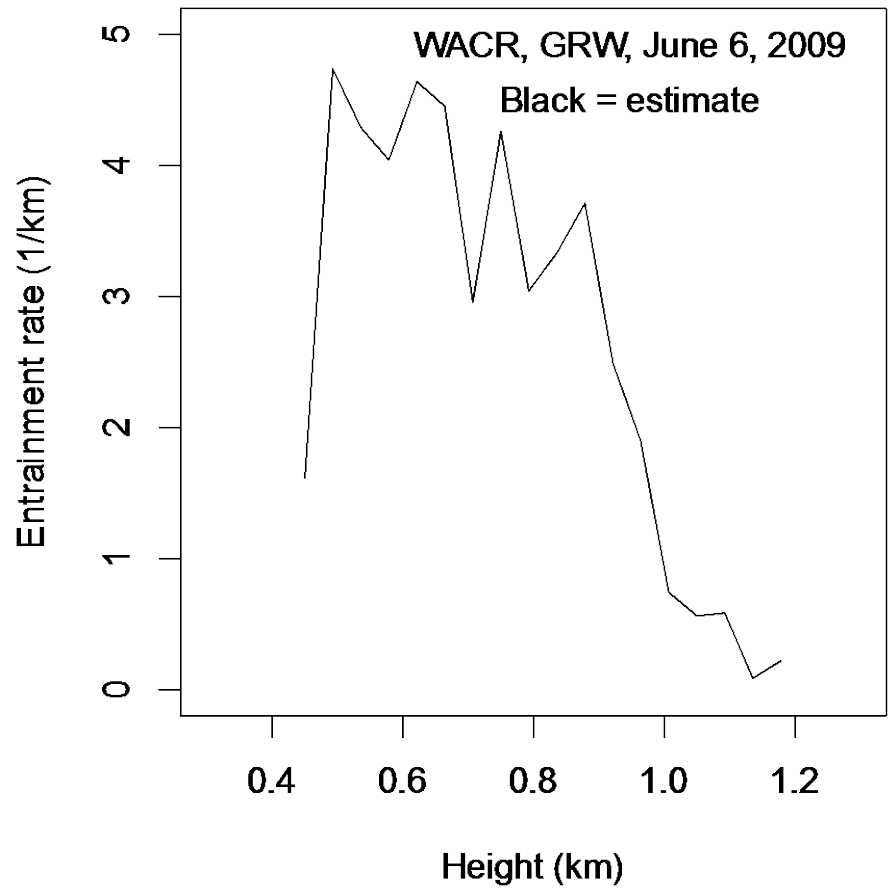
Apply this approximation to WACR data

black = the approximation applied to 8 hours of WACR data on shallow cumuli at Graciosa

Mass flux



Entrainment



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Now, 1 way to directly measure entrainment from obs

1. Cloud radar