Entrainment Rates in Non-Precipitating Cumulus from Cloud Radar Observations

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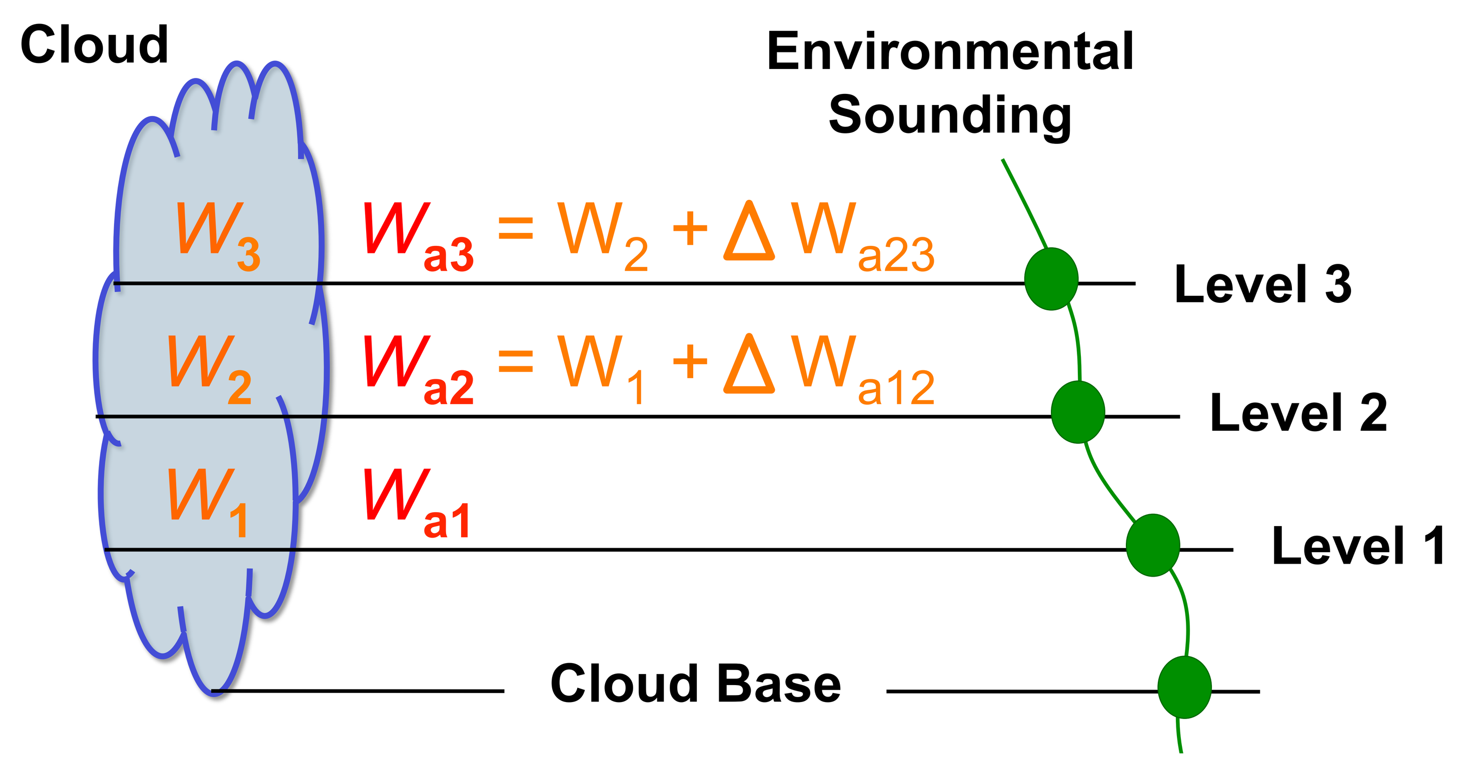
Abstract: The mixing of environmental air across the cloud interface plays a significant role in the lifecycle of the cloud system and the subsuquent influences on the hydrological and energy cycles. Despite its importance, the entrainment process remains poorly understood and its measurement and quantification are extremely difficult. We present a remote sensing technique that builds upon previous aircraft in situ based techiques (Lu et al. 2012) in order to estimate the vertical profile of entrainment rate. This mixing is notoriously difficult to measure, particularly via remote sensing. The profile of vertical velocity observed by the vertically pointing Millimeter Wavelength Cloud Radar (MMCR) is used with an adiabatic parcel model that incorporates conservation of total water and energy in the retrieval algorithm. This initial study concentrates on five years of non-precipitating shallow cumulus observations over the ARM SGP site, where radar-based observations of mean Doppler velocity are a reasonable proxy for the in-cloud air motion. A preliminary application of the methodology has shown reasonable agreement with simple bulk entrainment estimates using an entraining plume model (Jensen and Del Genio 2006), as well as in comparison to a more complex method that uses a full cloud model and multiple ARM remote sensors (Wagner et al. 2013).

1. Method:

- The cloud grows adiabatically from cloud base and then experiences the first entrainment event and isobaric mixing at Level 1.
- After a new saturation is achieved during isobaric mixing, the cloud ascends adiabatically without entrainment from Level 1 to Level 2.
- It then experiences the second entrainment event and isobaric mixing at Level 2.
- The process is repeated for Level 3 and higher levels.



Mixing Equations:

Acceleration of the relative adiabatic parcel, which is used to determine its vertical velocity	$a = g * (Tv - Tv_e) / Tv_e$
Mixing fraction determined from radar-measured vertical velocity and calculated vertical velocity of the relative adiabatic parcel	$\chi^* = W_2 / W_{a2}$
In-cloud temperature solved iteratively	$c_p T = c_p T_a \chi^* + c_p T_e (1-\chi^*) - L_v (q_{La} \chi^* - q_L)$
Solve for in-cloud liquid water mixing ratio	$q_L + q_{vs}(T) = \chi^* [q_{vs}(T_a) + q_{La}] + (1-\chi^*) q_{ve}$

In-Cloud
T = temperature
Tv = virtual temperature
q_L = liquid water mixing ratio
$q_{vs}(T)$ = saturation vapor mixing ratio

Entrained Dry Air (Sounding)
T_e = temperature
Tv_e = virtual temperature
q_{ve} = water vapor mixing ratio

Relative Adiabatic Cloud Parcel
T_a = temperature
a = acceleration
W_a = vertical velocity
q_{La} = liquid water mixing ratio
$q_{vs}(T_a)$ = saturation vapor mixing ratio

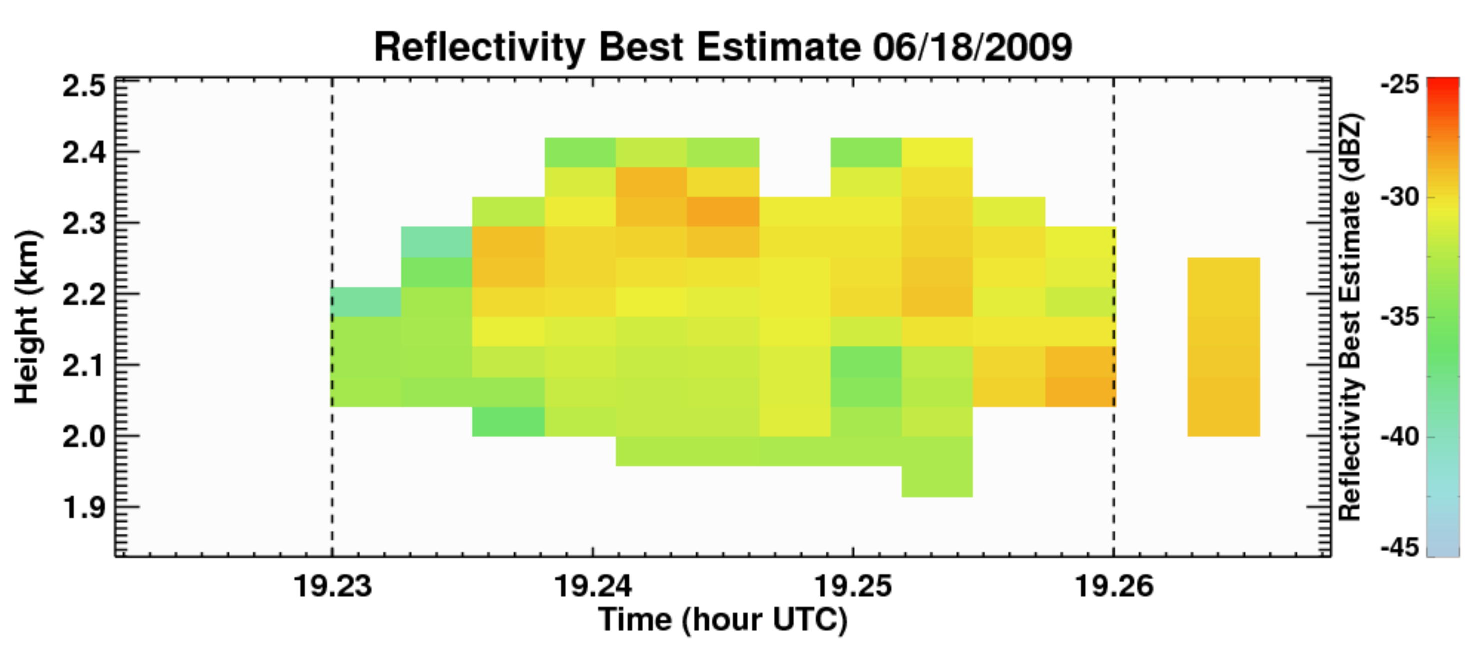
χ^* = mixing fraction of cloudy air during entrainment mixing process

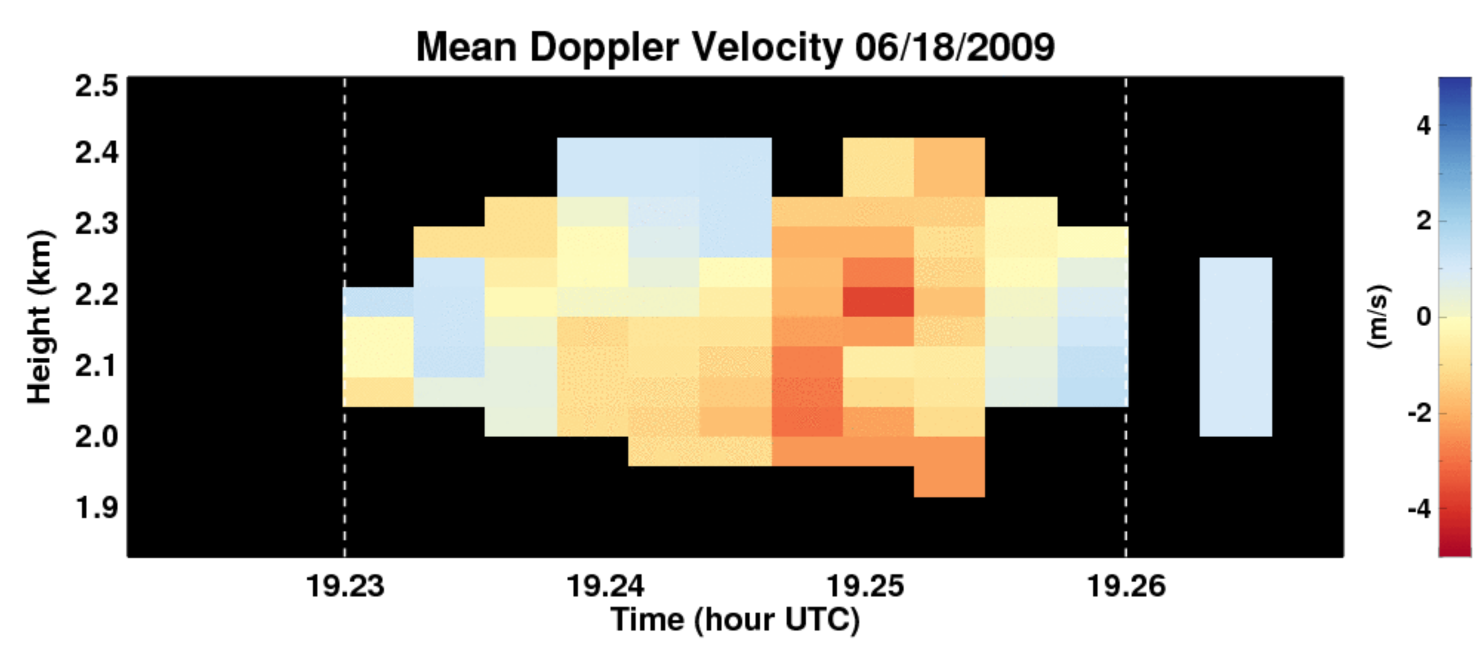
W_2 = radar measured vertical velocity

L_v = latent heat
c_p = specific heat capacity at constant pressure
g = acceleration due to gravity

2. Data:

Shallow cumulus on June 18, 2009 at the Southern Great Plains, during the RACORO campaign, provided an opportunity to implement the method using ARM Millimeter-wavelength Cloud Radar (MMCR) and radiosonde observations.



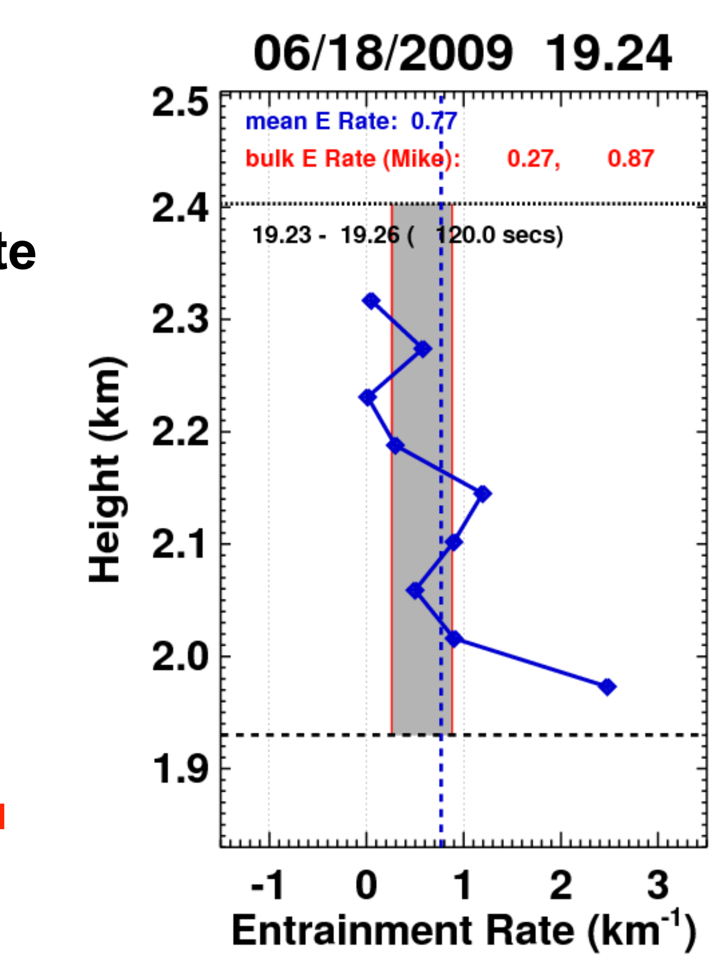


MMCR vertical velocity profile limited to reflectivity >= -40 dBZ.

3. Results:

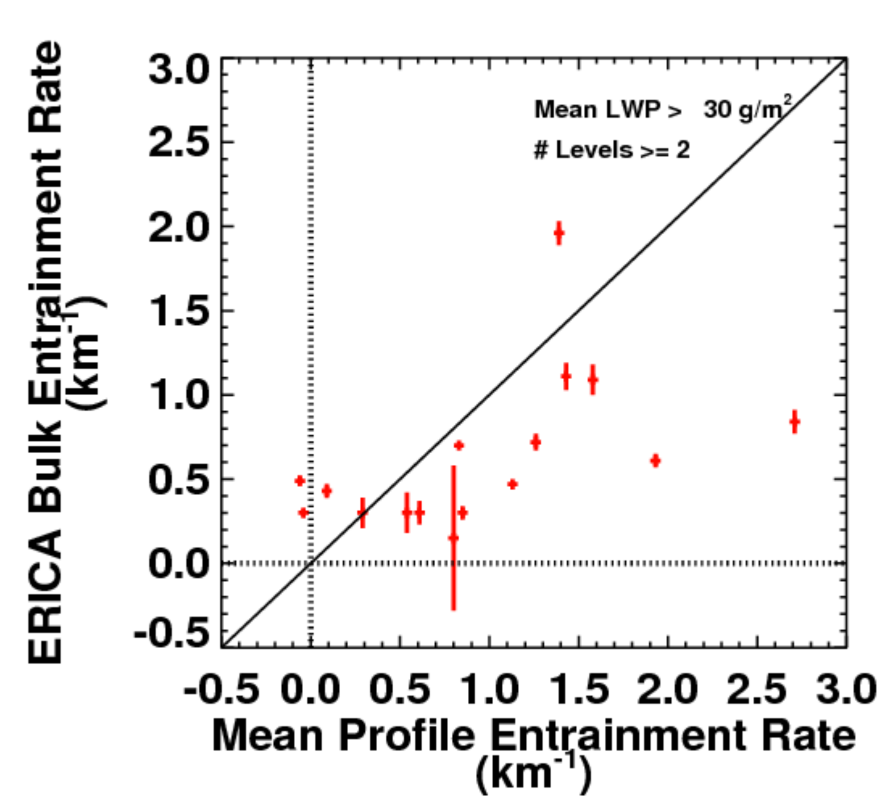
Mean entrainment rate from profile method:
0.77 km^{-1}

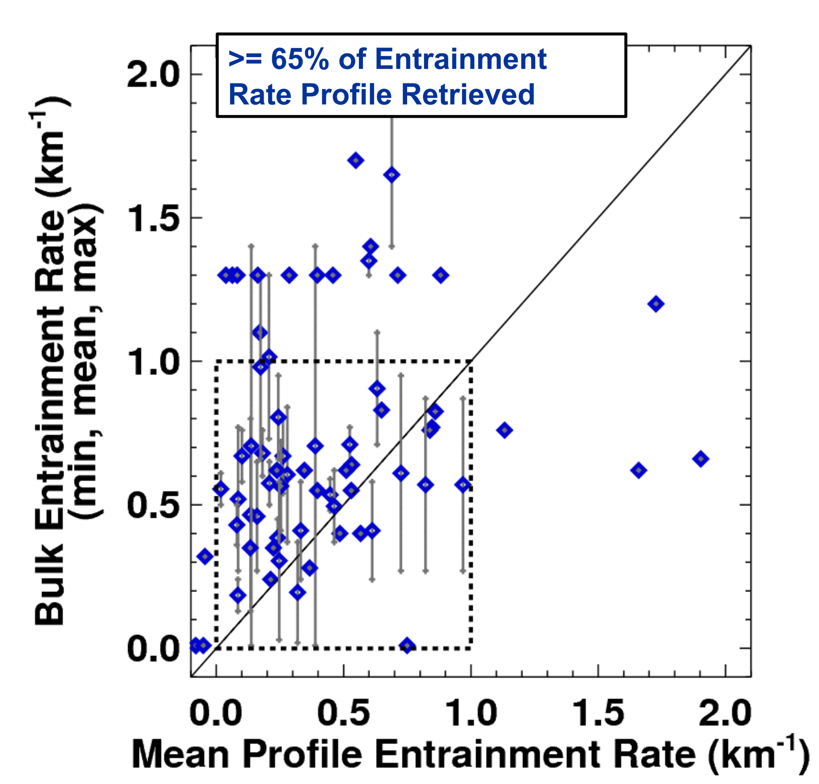
Jensen bulk entrainment rate:
0.27 – 0.87 km^{-1}



4. Evaluation:

Mean entrainment rates from the observation-based profile method presented here were evaluated against the Entrainment Rate In Cumulus Algorithm (ERICA), an observation-based bulk entrainment rate retrieval method (Wagner et al., 2013), and the simple entraining plume model method from Jensen and Del Genio (2006).





5. References:

Jensen, M. P. and Del Genio, A. D., 2006:Factors limiting convective cloud top height at the ARM Nauru Island climate research facility. *J. Climate*, 19, 2105-2117.

C. Lu, Y. Liu, S. Soo Yum, S. Niu, S. Endo, 2012. A new approach for estimating entrainment rate in cumulus clouds, Geophysical Research Letters.

T.J. Wagner et al., 2013. Ground-based remote retrievals of cumulus entrainment rates, Journal of Atmospheric and Oceanic Technology, Early Online Release.