Estimates of the vertical profile of entrainment rate from millimeter-wavelength radar observations

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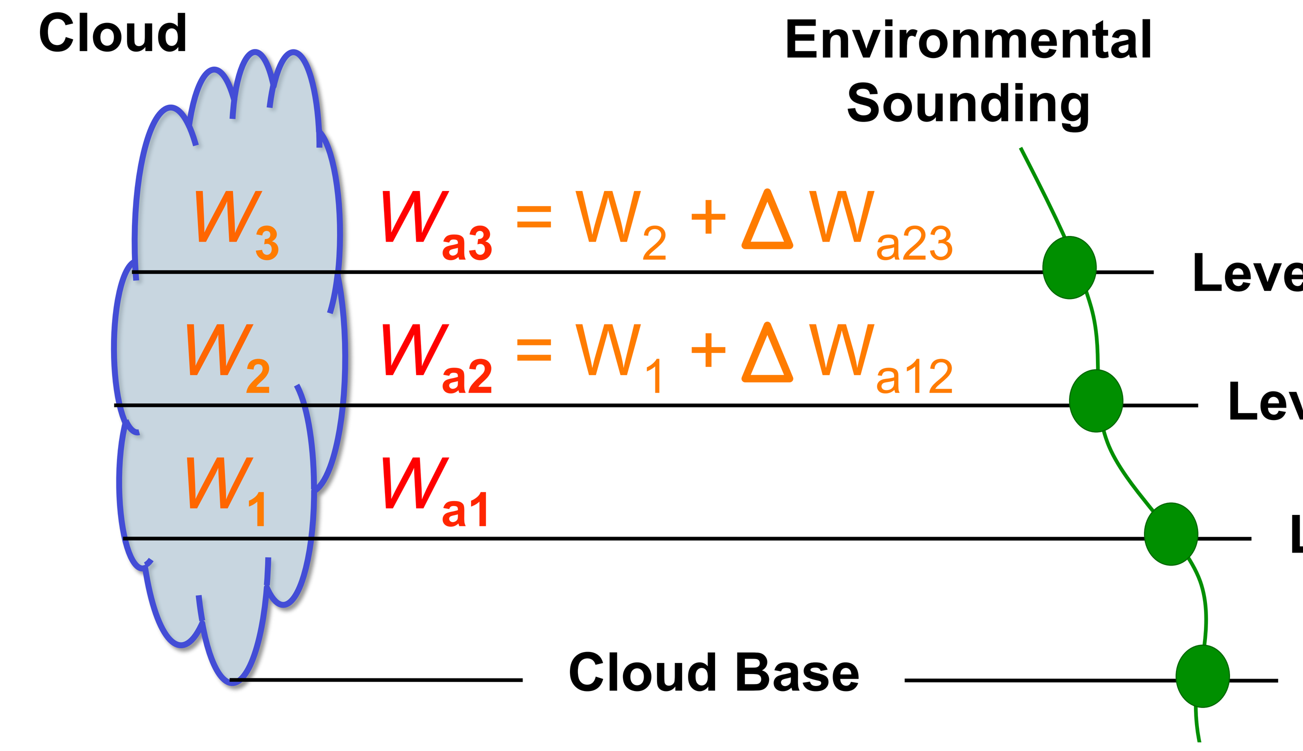
Abstract: **Mixing of environmental air with buoyant plumes has important implications on cloud lifecycle and subsequent impacts on atmospheric energy and water budgets. This mixing is notoriously difficult to measure particularly via remote sensing.**

We introduce a technique using velocity profiles from an ARM vertically-pointing, millimeter-wavelength cloud radar and estimates of the cloud adiabaticity in order to estimate the vertical profile of entrainment rate for shallow cumulus clouds.

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

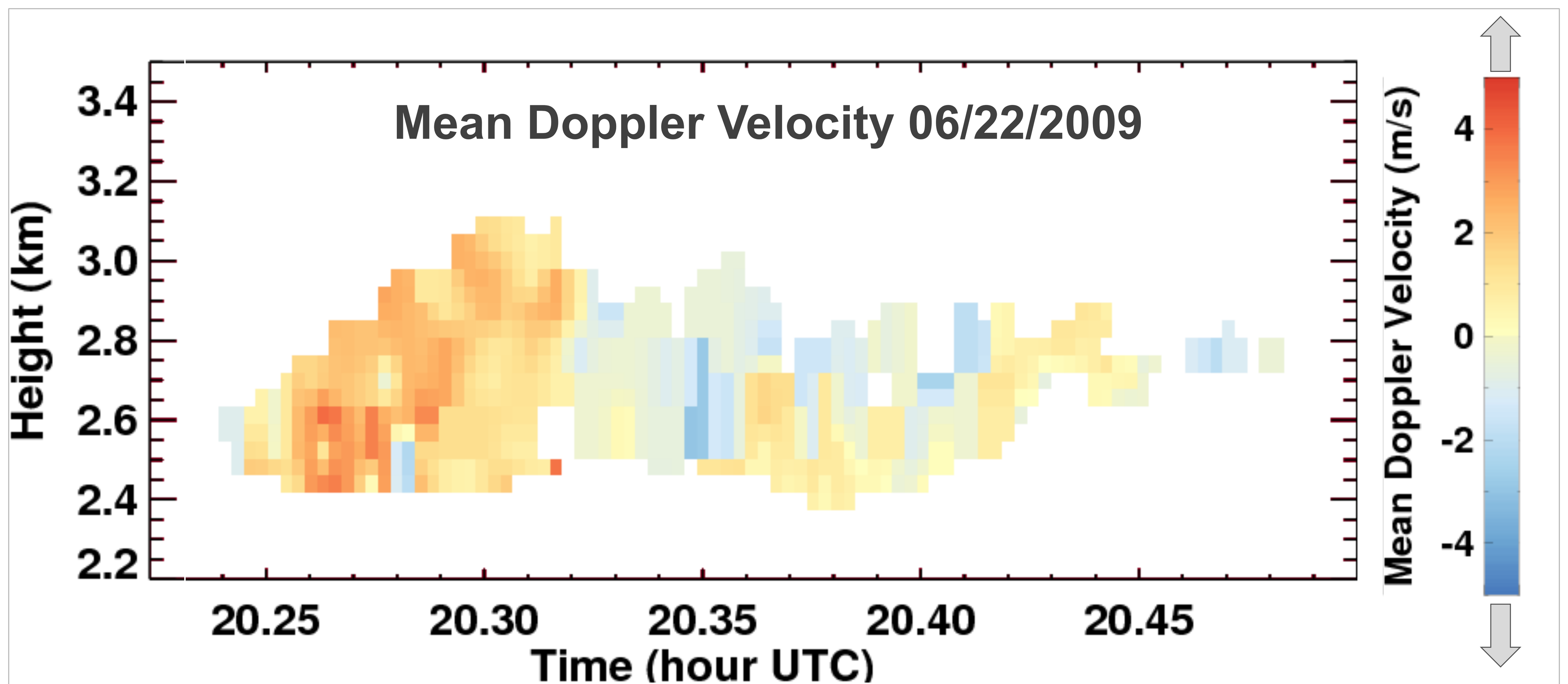
χ^* = mixing fraction of cloudy air during entrainment mixing process

W_2 = radar measured vertical velocity

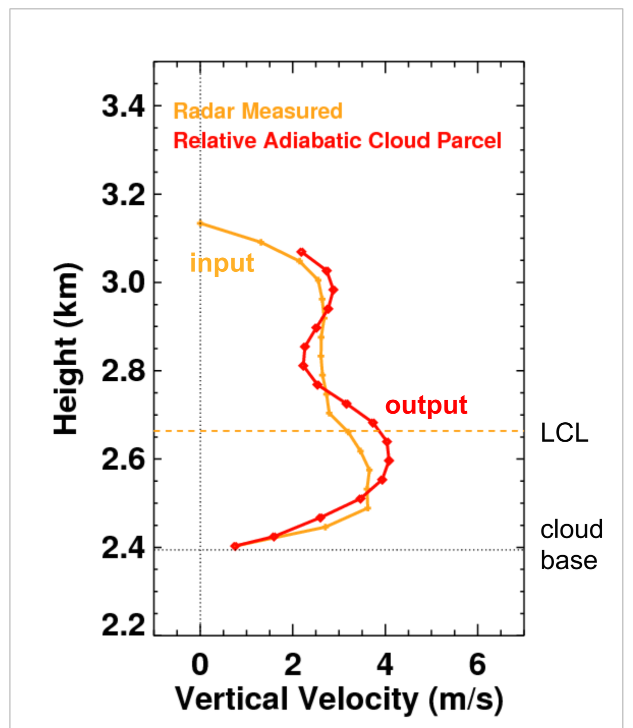
L_v = latent heat
c_p = specific heat capacity at constant pressure
g = acceleration due to gravity

2. Data:

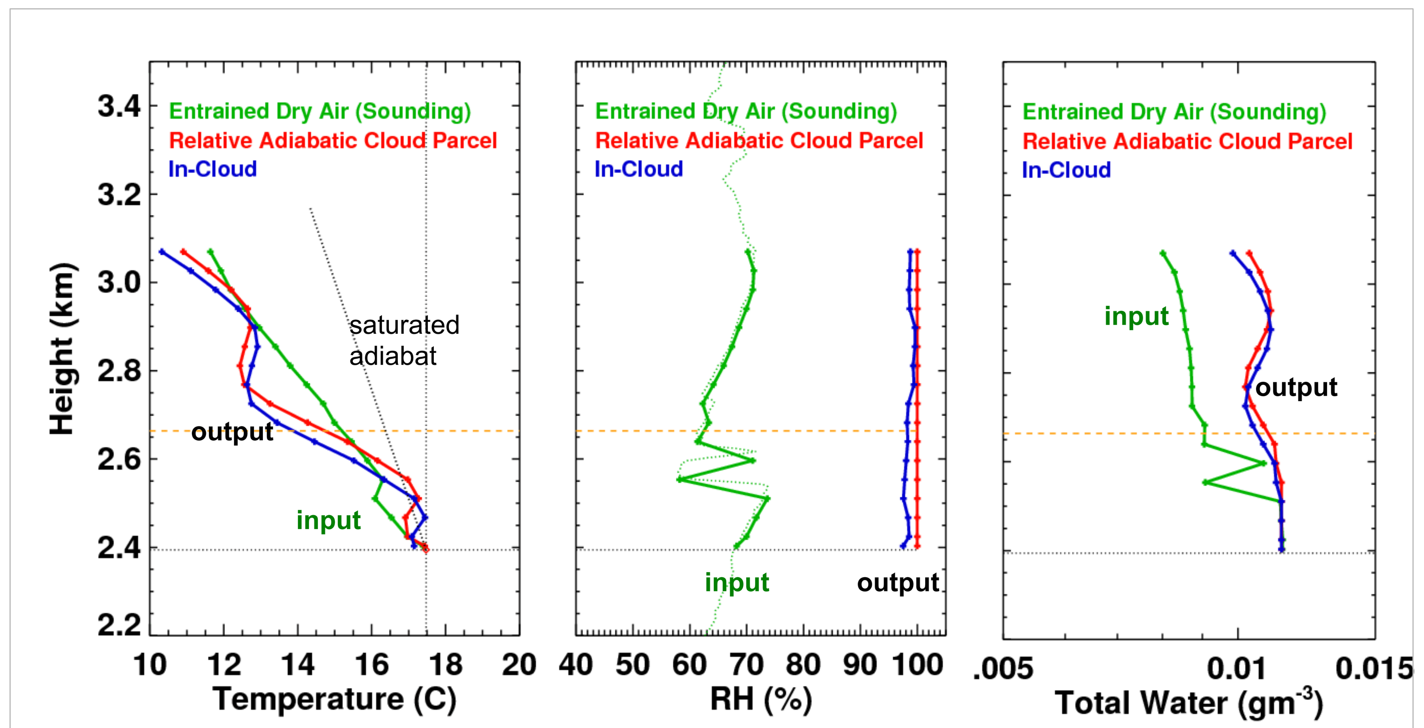
Shallow cumulus on June 22, 2009 at the Southern Great Plains, during the RACORO campaign, provided an opportunity to implement the method using ARM Millimeter-wavelength Cloud Radar (MMCR) and radiosonde observations.



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



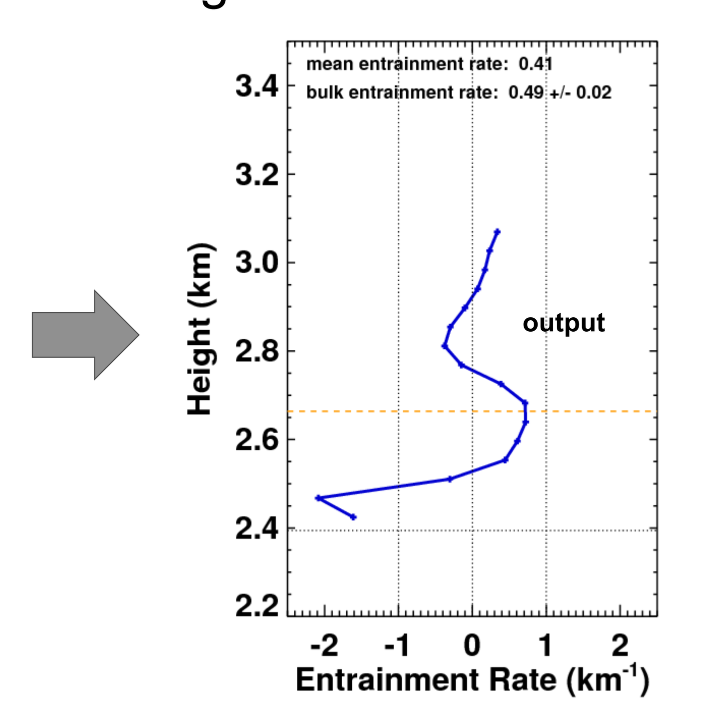
A smoothed maximum MMCR mean doppler velocity profile is used as the radar measured vertical velocity input.



The sounding nearest to the cloud is used. For this case, observations from the 6/22/2009, 23:31 UTC sounding are applied, however profiles from the previous sounding, as well as from AERI+RAMAN Lidar were compared to determine the appropriateness of the 23:31 sounding.

3. Results:

Profile of entrainment rate is a function of mixing fraction



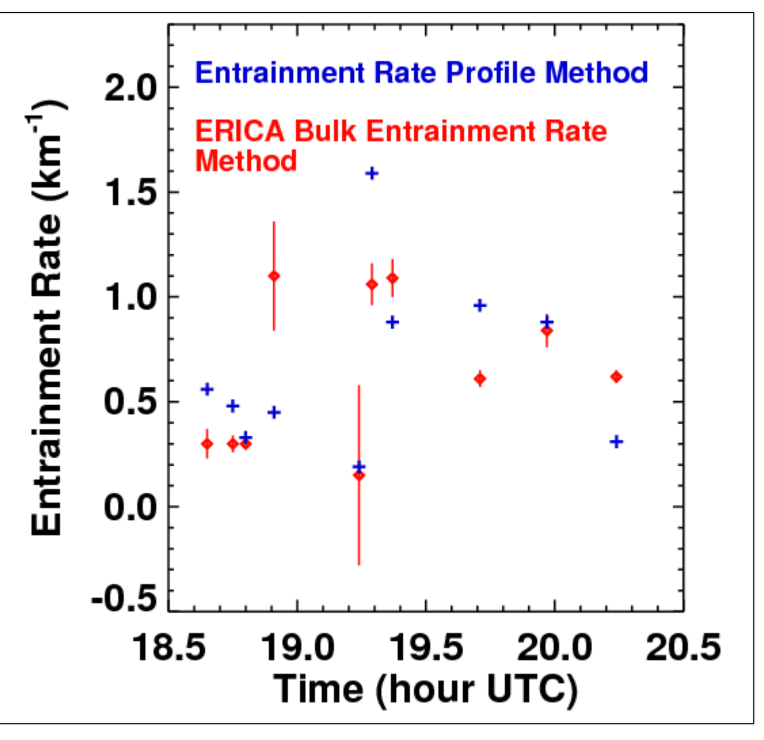
Mean entrainment rate from profile method: 0.41 km^{-1}

ERICA bulk entrainment rate: 0.49 +/- .02 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), for the cloud shown above, and for about two hours of shallow cumulus on 6/18/2009 at SGP (shown in figure).

Further analysis is needed, but some of the discrepancies can be attributed to differing cloud identification and selection methods.



5. Future Work

- Comparison to other remote sensing and in situ techniques
- Extension to additional convective cloud types (e.g., congestus, deep convection)
- Extension to other ARM sites, particularly Azores and tropical sites

6. References:

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.

A.M. Vogelmann et al., 2012. RACORO extended-term, aircraft observations of boundary-layer clouds, Bulletin Amer. Meteor. Soc.