Surface-based observations of the fractional entrainment rate

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Entrainment Impacts Cumulus

We know that entrainment affects the characteristics of cumulus clouds:

- Decreased liquid water paths
- Reduced droplet sizes
- Shorter heights
- etc…

Can we observe these impacts and work backwards to get the fractional entrainment rate λ?

$$\lambda = \frac{1}{m}\frac{dm}{dt}$$

An inversion problem

This is the classic inversion problem: retrieving variables that can't be directly measured from ones that can.

In this case, we can measure things like effective radius and liquid water path.

We can also model the impact of entrainment on these characteristics.

Similar to thermodynamic retrievals

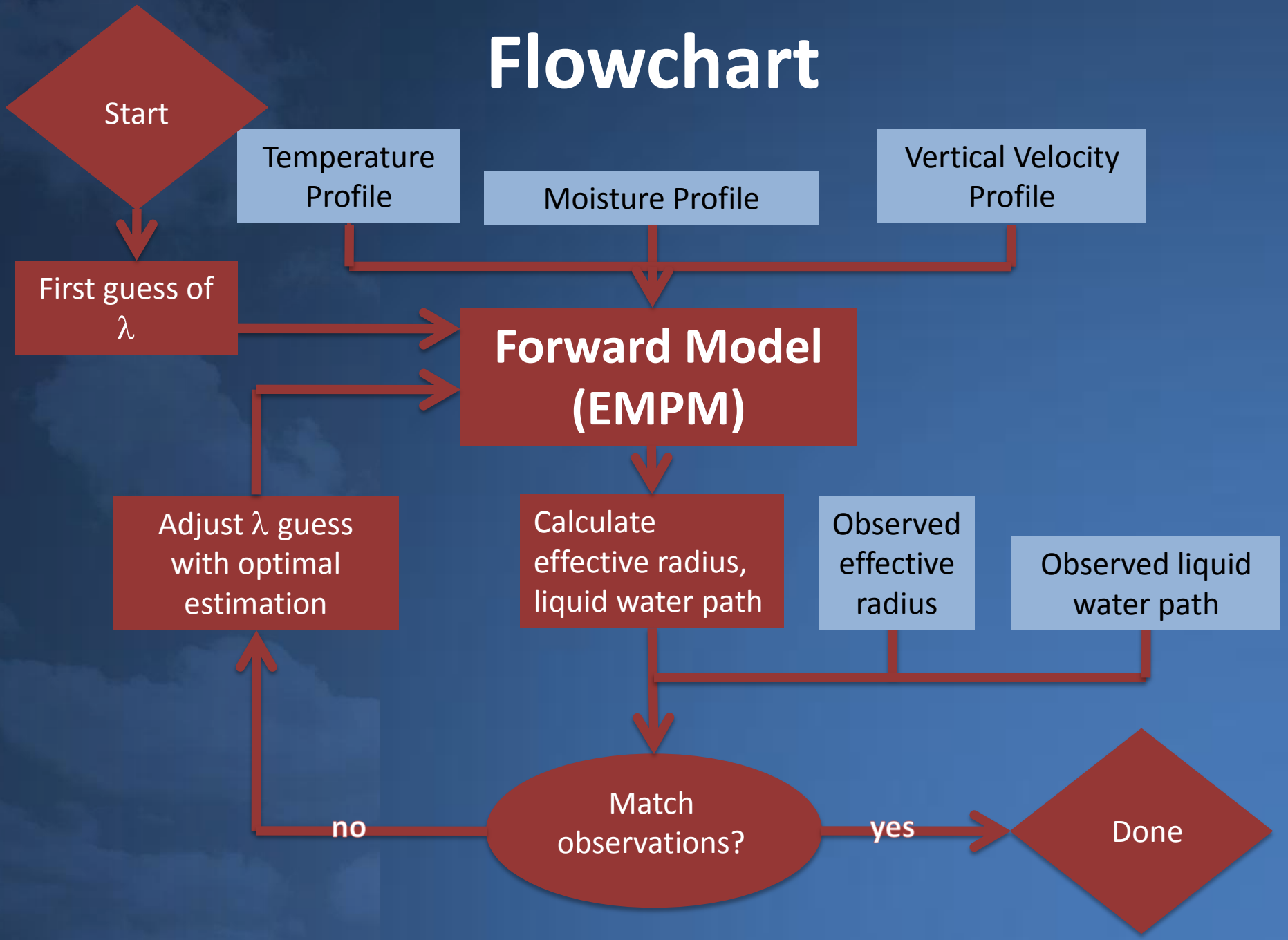
- Use a cloud model instead of an RTM

ERICA

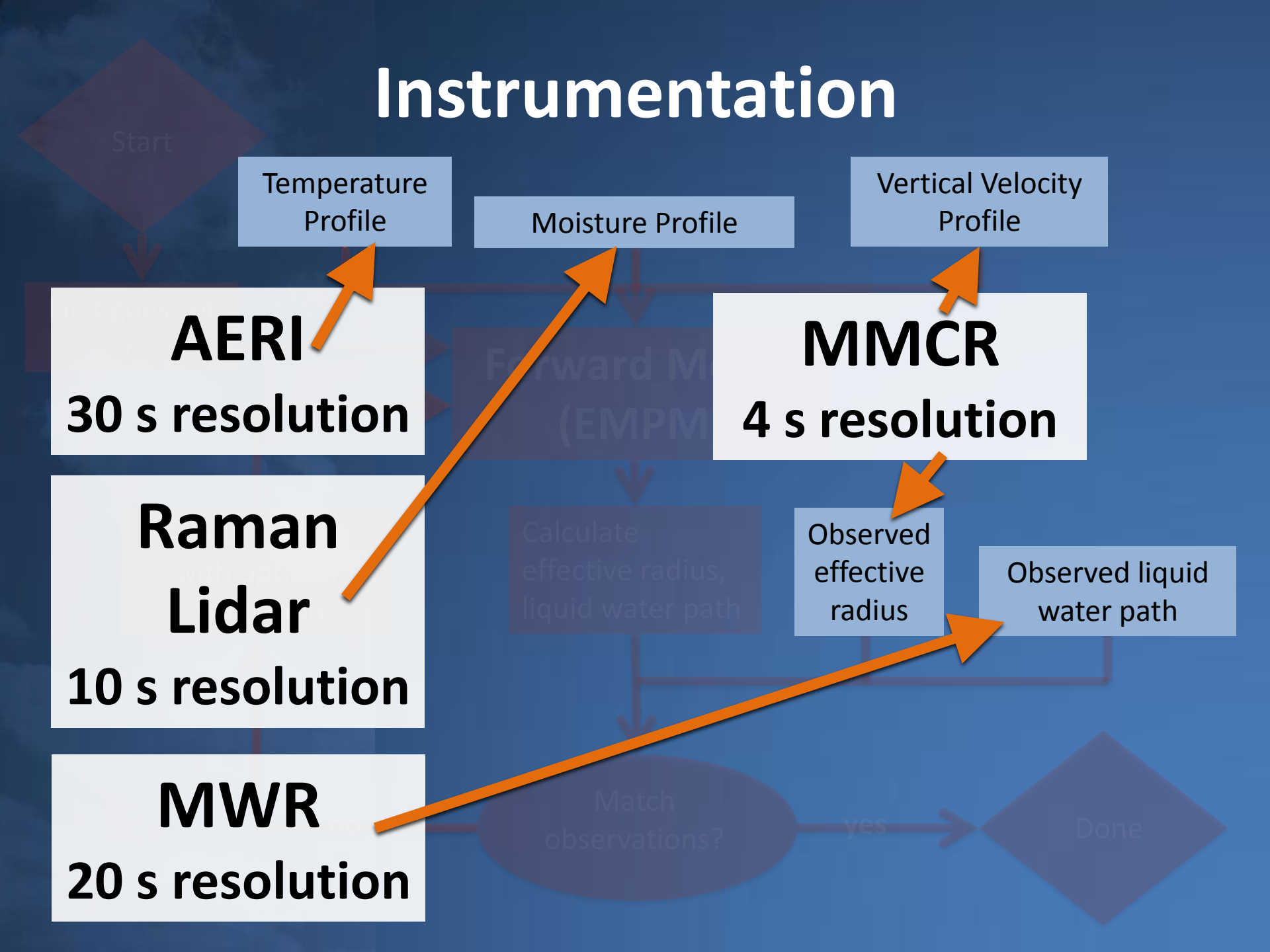
ERICA: Entrainment Rate In Cumulus Algorithm

- Use ground-based observations in a cloud model
- Assume a guess for entrainment rate
- Run the model
- Calculate quantities that can be observed from model output
- Adjust the guesses using optimal estimation
- Iterate until observations match model output

Flowchart


Start
Temperature Profile
Moisture Profile
Vertical Velocity Profile
First guess of λ
Forward Model (EMPM)
Adjust λ guess with optimal estimation
Calculate effective radius, liquid water path
Observed effective radius
Observed liquid water path
Match observations?
no
yes
Done

Instrumentation



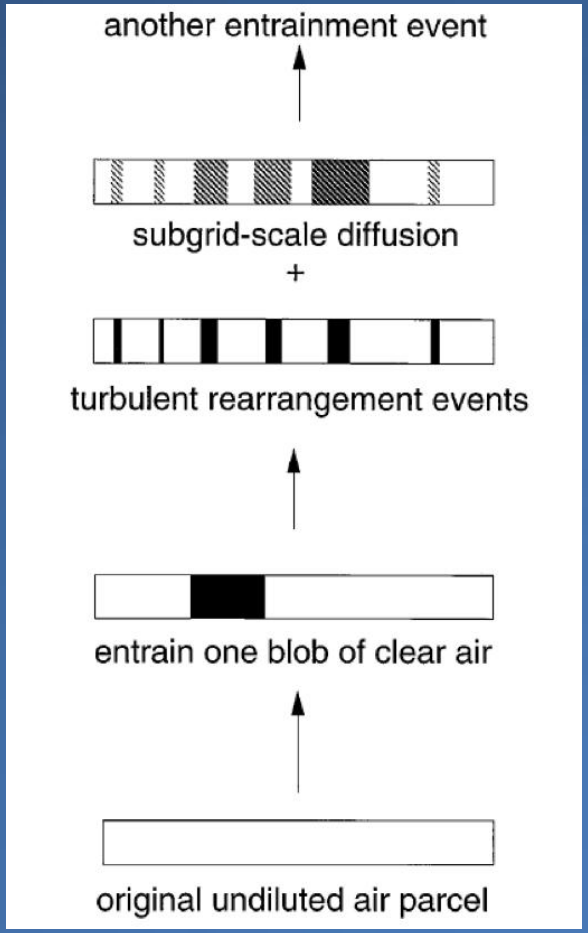
Forward model: EMPM

- Explicit Mixing Parcel Model (Krueger et al. 1997) simulates rising cumulus parcels.
- Explicitly calculates droplet microphysics (Su et al. 1998)
- Incorporates:
  - Entrainment
  - Vertical motion
  - Turbulent mixing
  - Droplet growth
- The physics of the problem are encapsulated in the model

Forward model: EMPM

EMPM calculations begin at cloud base:

- Cloudy air rises from cloud base.
- Droplets grow
- Blobs of environmental (dry) air are entrained intermittently.
- These dry blobs replace a section of the parcel so that parcel size remains constant throughout ascent.
- Turbulent deformation and molecular diffusion rearrange the air inside the parcel.



From Krueger et al. (1997)

ERICA needs observations

The cloud model needs observations of:

- Temperature profile
- Moisture profile
- Vertical velocity
- Cloud base height/temperature/moisture

The algorithm also needs observations of cloud characteristics

- Effective Radius
- Liquid water path

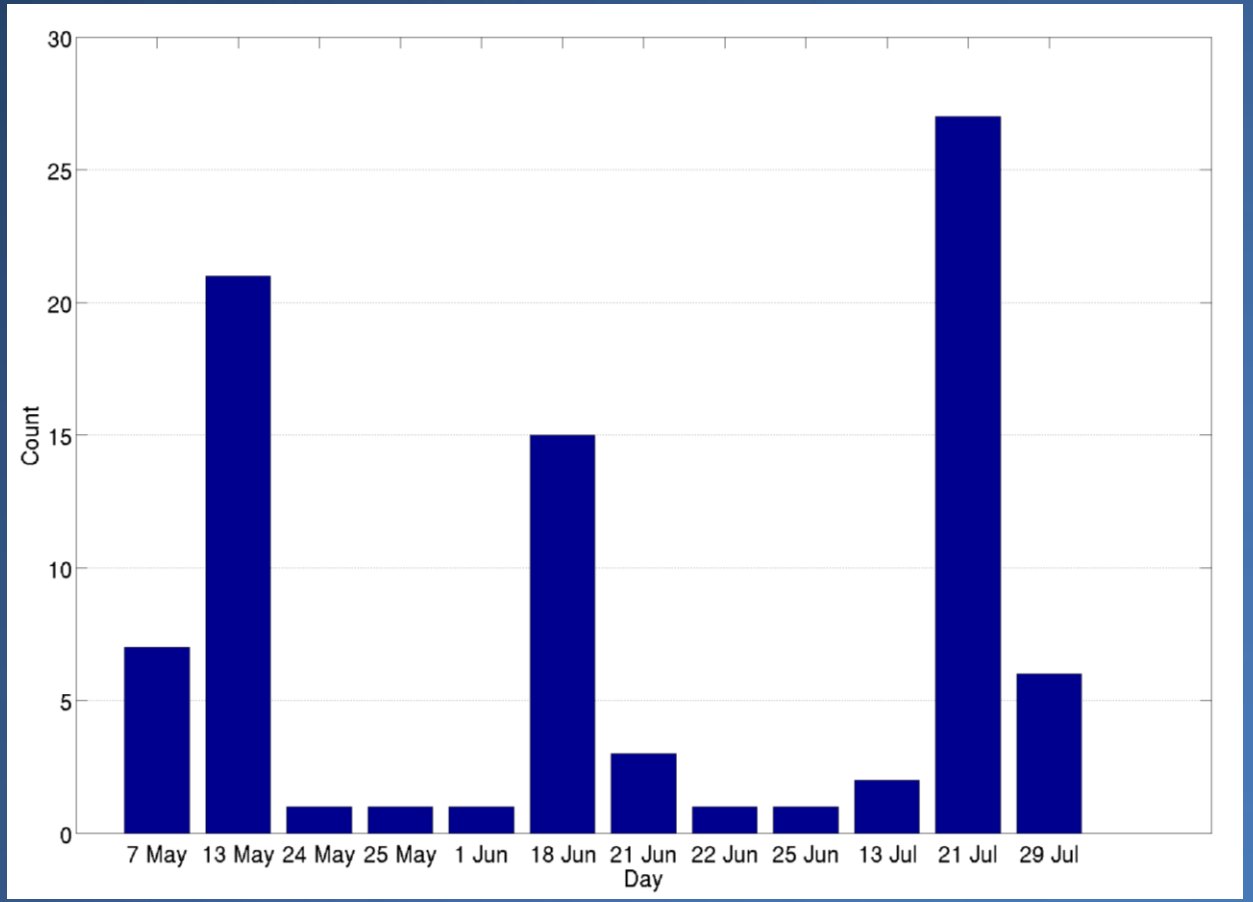
ARM SGP site has everything we need!

Short-term climatology

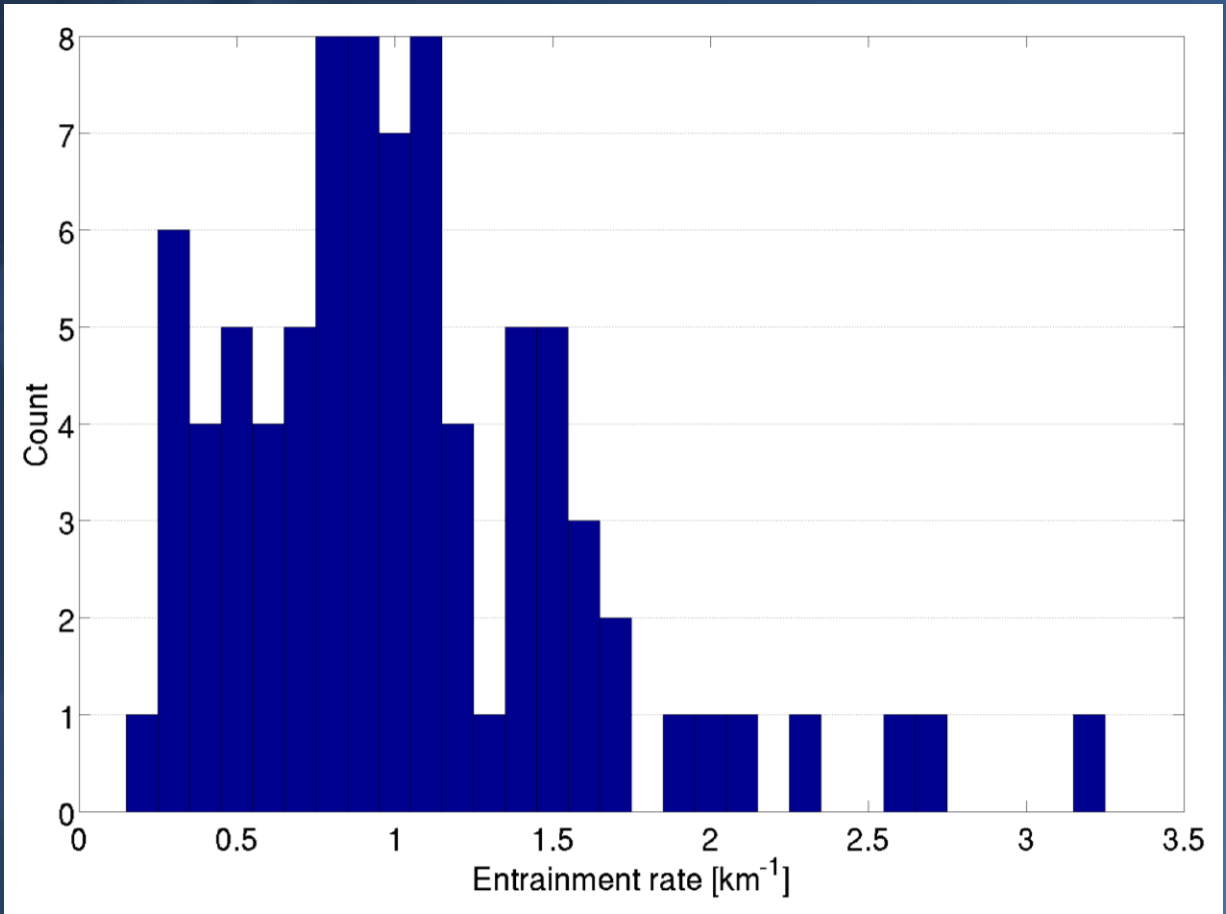
ERICA was used to process three months of cumulus events over SGP:

May-July 2009 dataset contains 86 retrievals over the course of 12 days.

A priori λ was set to 1.5 +/- 1 km^{-1}.



Entrainment rate distribution



Mean λ: 1.05
+/-0.13 km^{-1}

Std. dev.: 0.57 km^{-1}

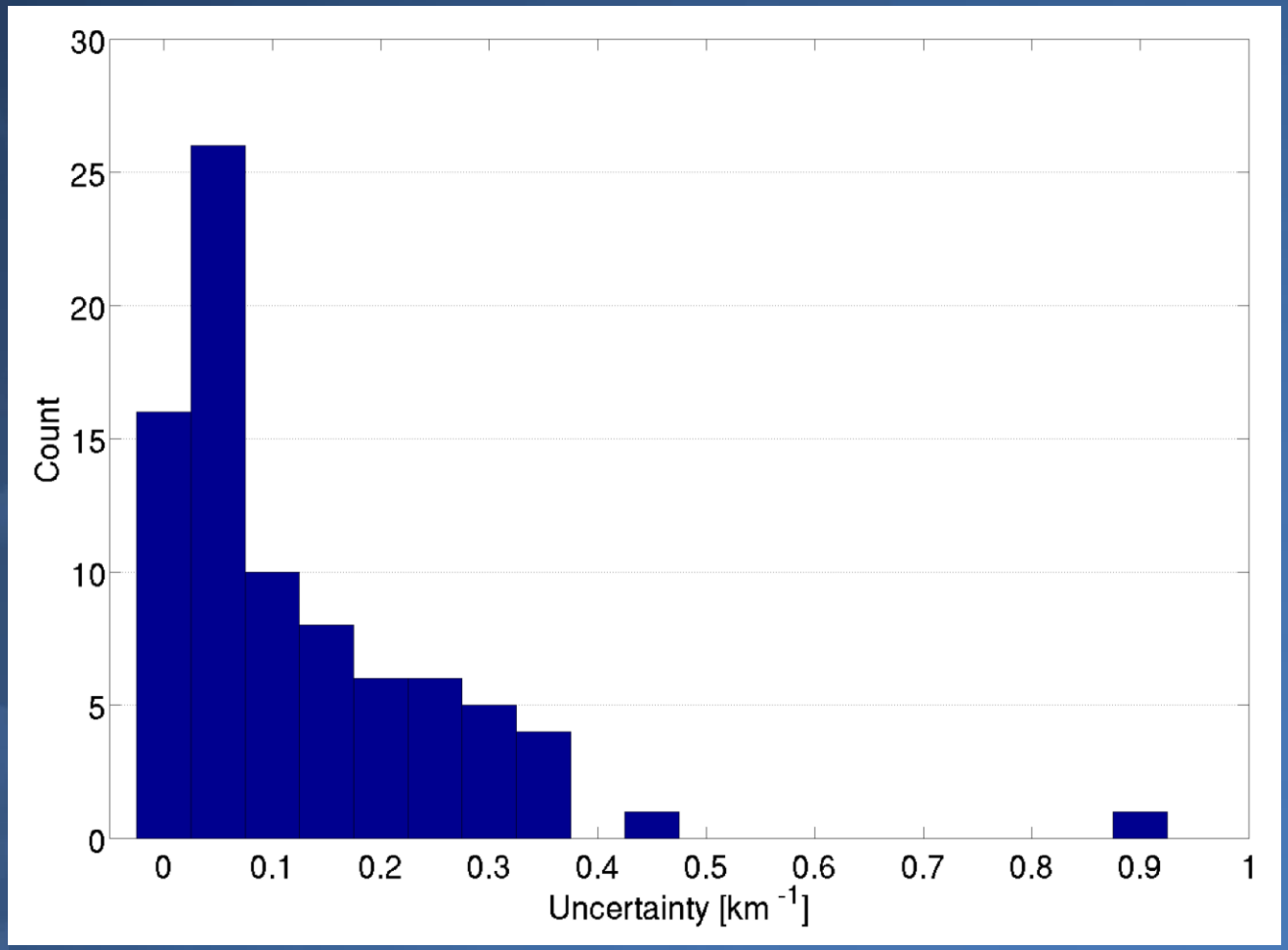
Median λ: 0.96 km^{-1}

Uncertainties

Mean: 0.13 km^{-1}

Std. dev.: 0.14 km^{-1}

Median : 0.07 km^{-1}



Degrees of Freedom

Optimal Estimation also returns the degrees of freedom of the signal:

- What is the information content?
- What observations are contributing to the retrieval?
- What retrieved variables have the most support?

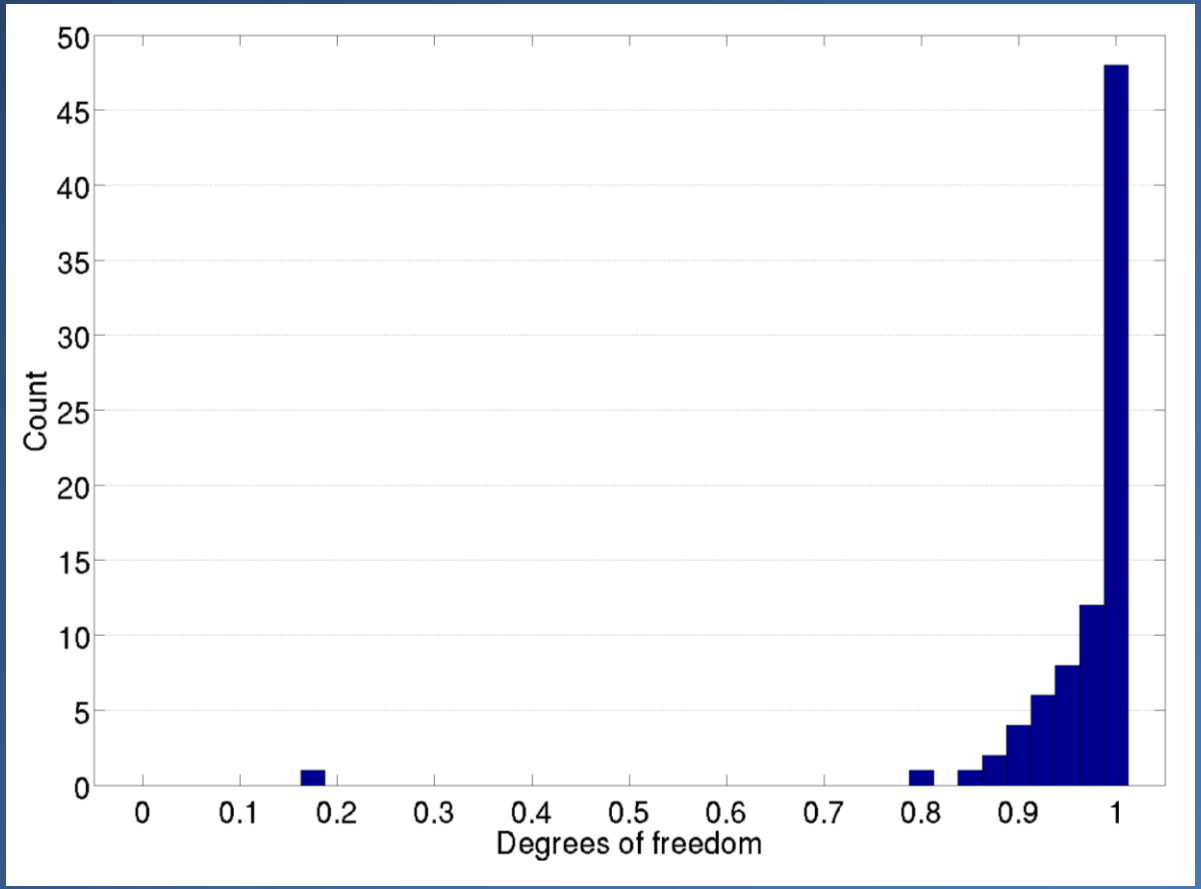
This tells us how confident we can be that our retrieved result is what we think it is.

Degrees of Freedom

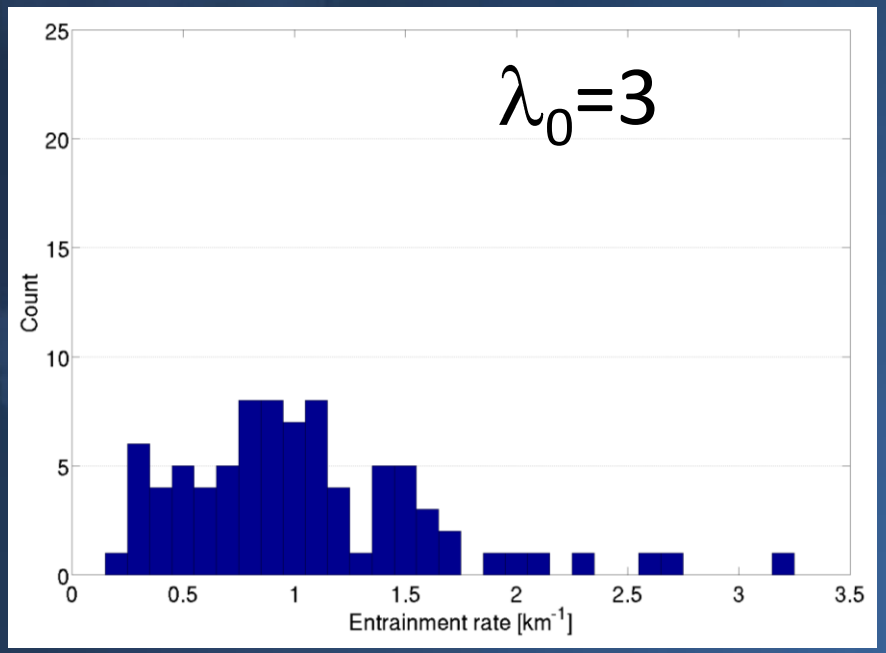
Mean: 0.964

25th percentile: 0.956
50th percentile: 0.995
75th percentile: 0.999

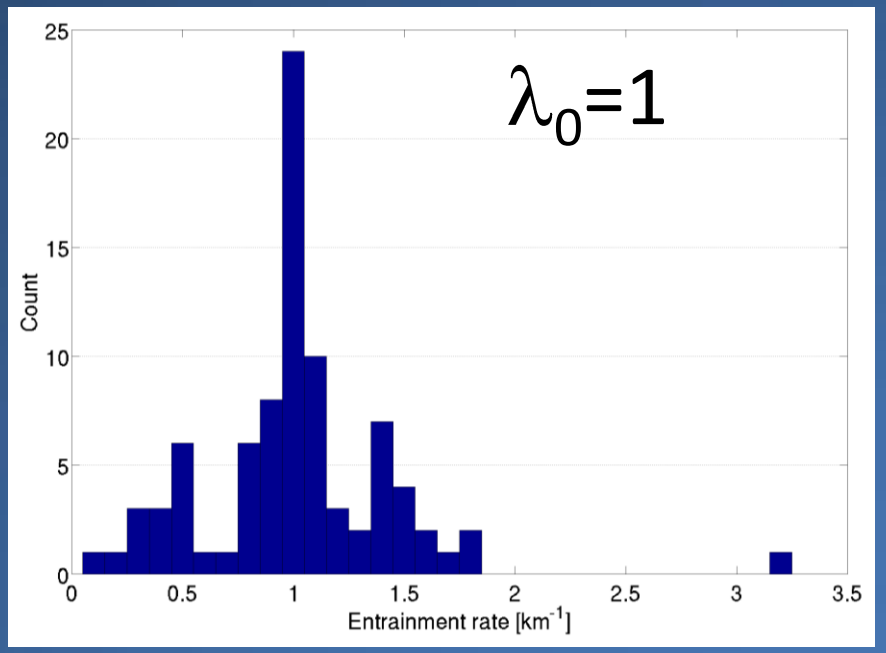
ERICA is sensitive to the entrainment rate and is returning robust results.



First Guess Impact

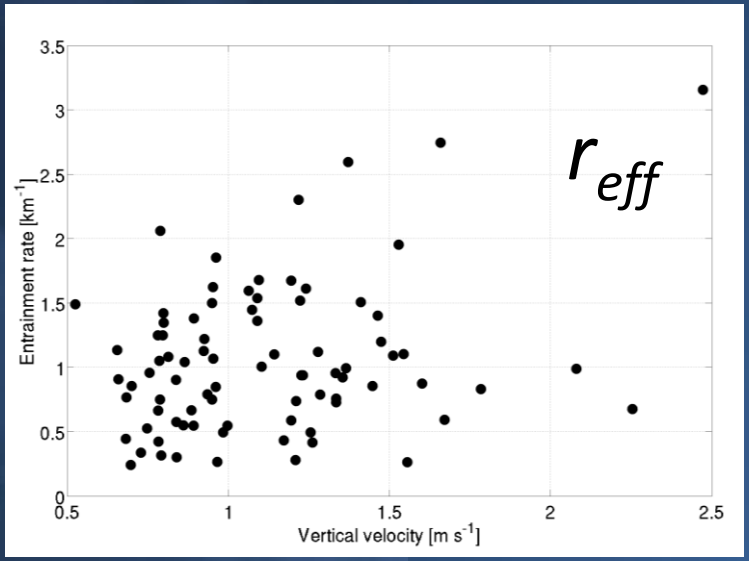


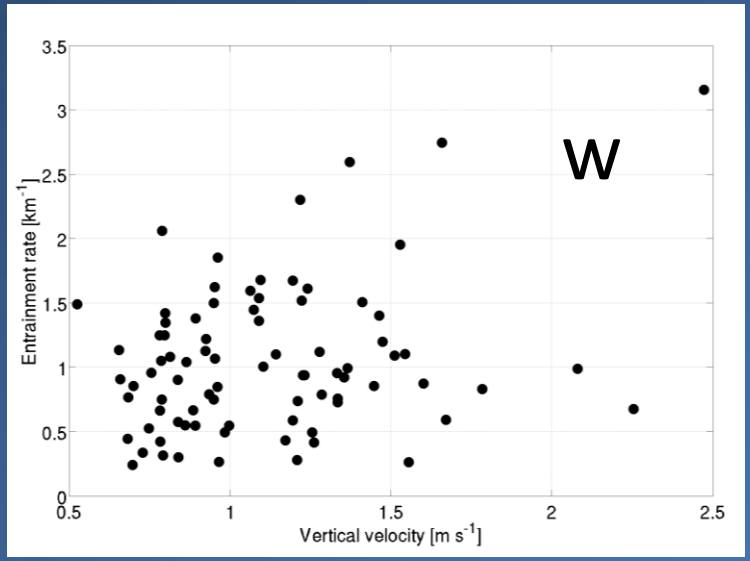
Mean = 1.05
Std. dev. = 0.57

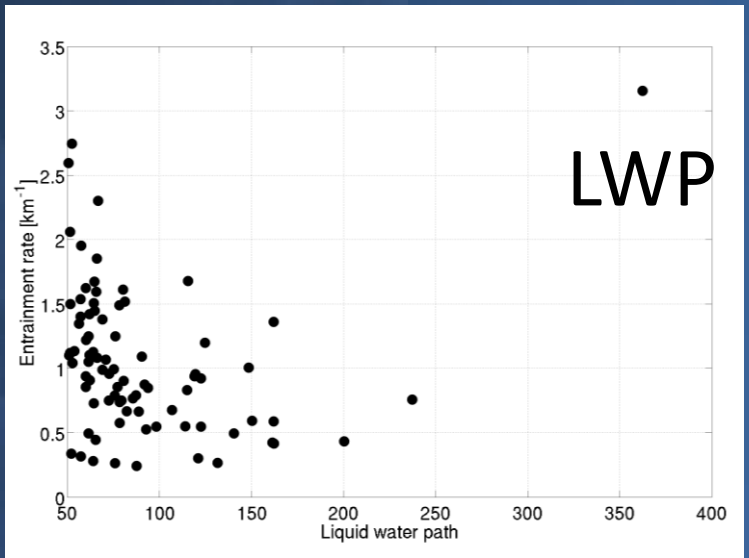


Mean = 1.03
Std. dev. = 0.44

Entrainment vs. cloud characteristics



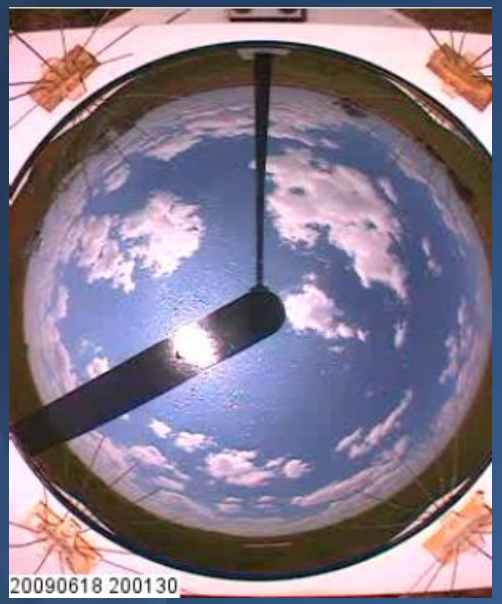


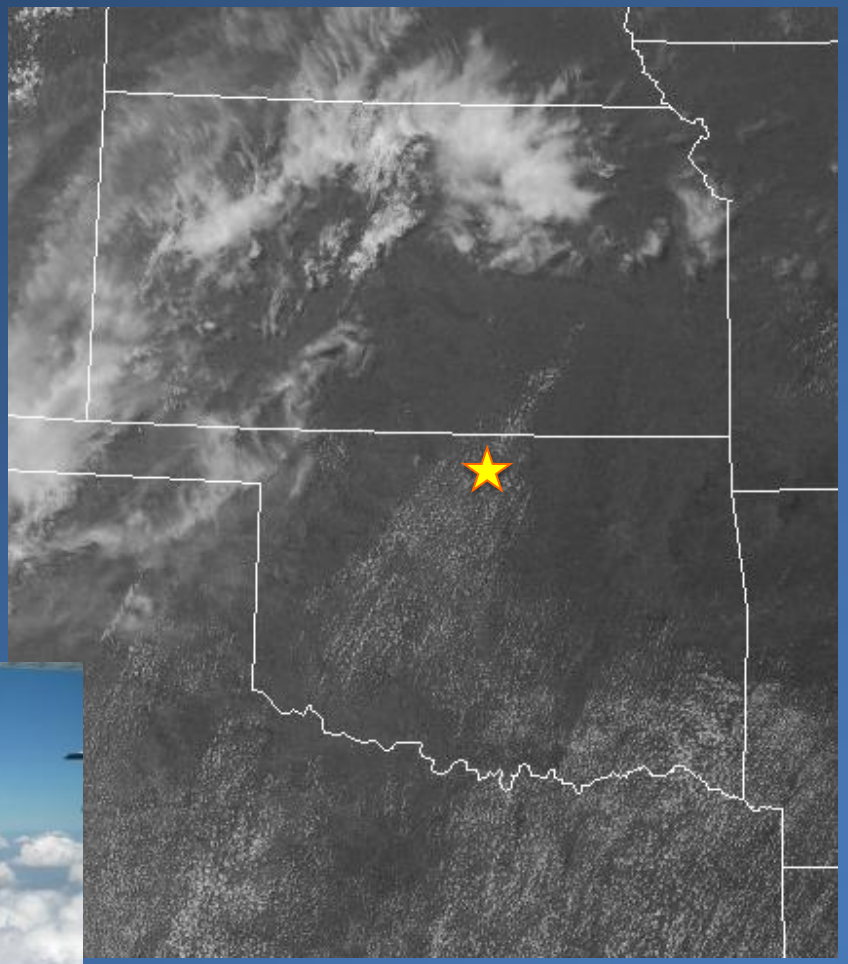


Correlation coefficients

r_{eff} : -0.15
LWP: -0.02
w: 0.29

Case Study: 18 June 2009





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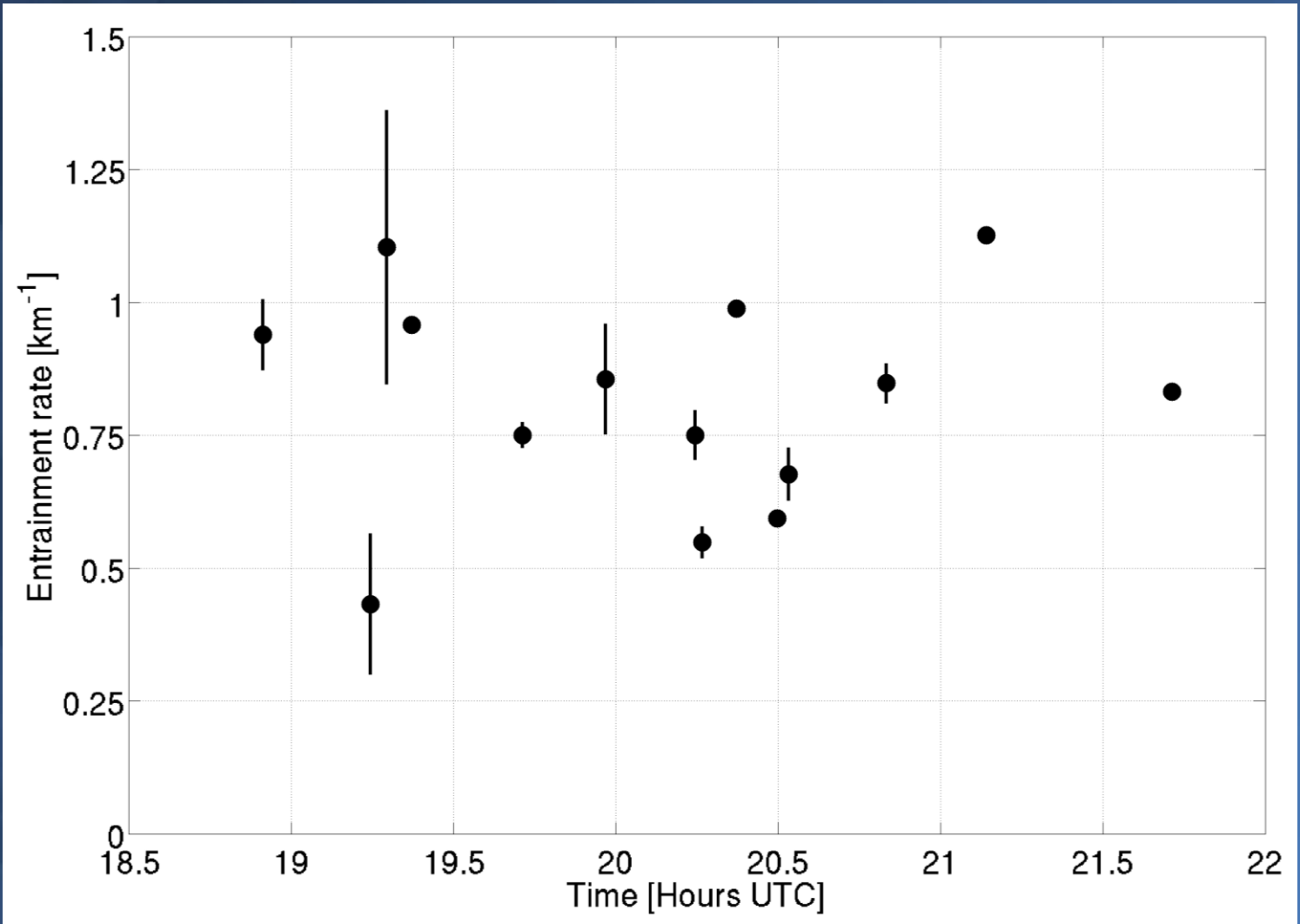
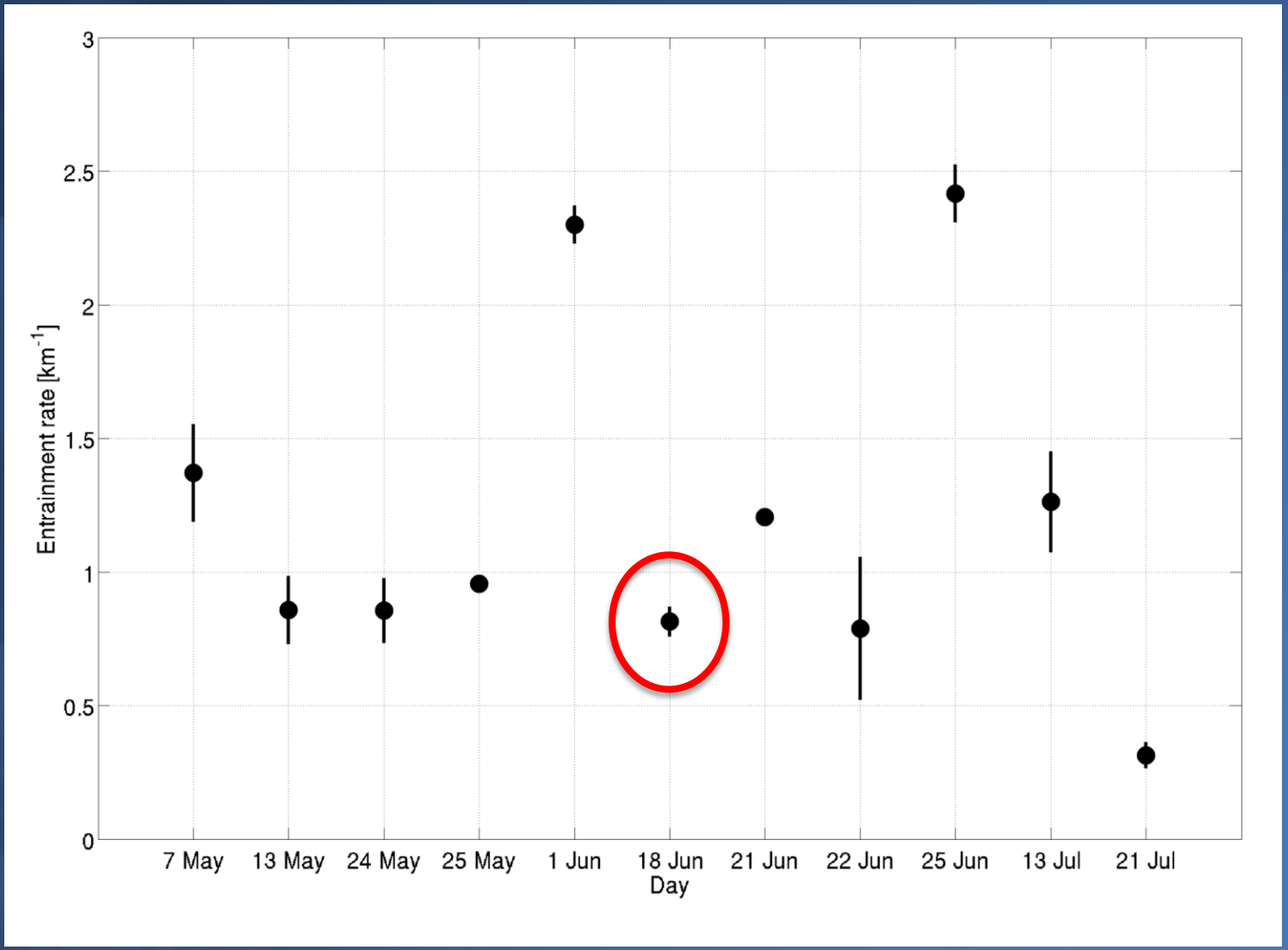


Entrainment rate by day



Summary and Conclusions

A working remote-sensing algorithm has been achieved.

Observations in short-term climatology match well with existing understanding of magnitude.

Retrievals show high information content, small uncertainties, and little tendency to fall back to the a priori value, which implies in a robust product.

Entrainment rate varies from day to day and even from one cloud to the next.

Future Avenues

Years of data available to process.

Validate against synthetic retrievals.

Produce a long-term climatology of entrainment at Southern Great Plains.

With addition of new instruments to ARM TWP, start investigating entrainment in tropical deep convection.

Discussion.

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