Satellite Observations of Entrainment Processes in Convective Clouds

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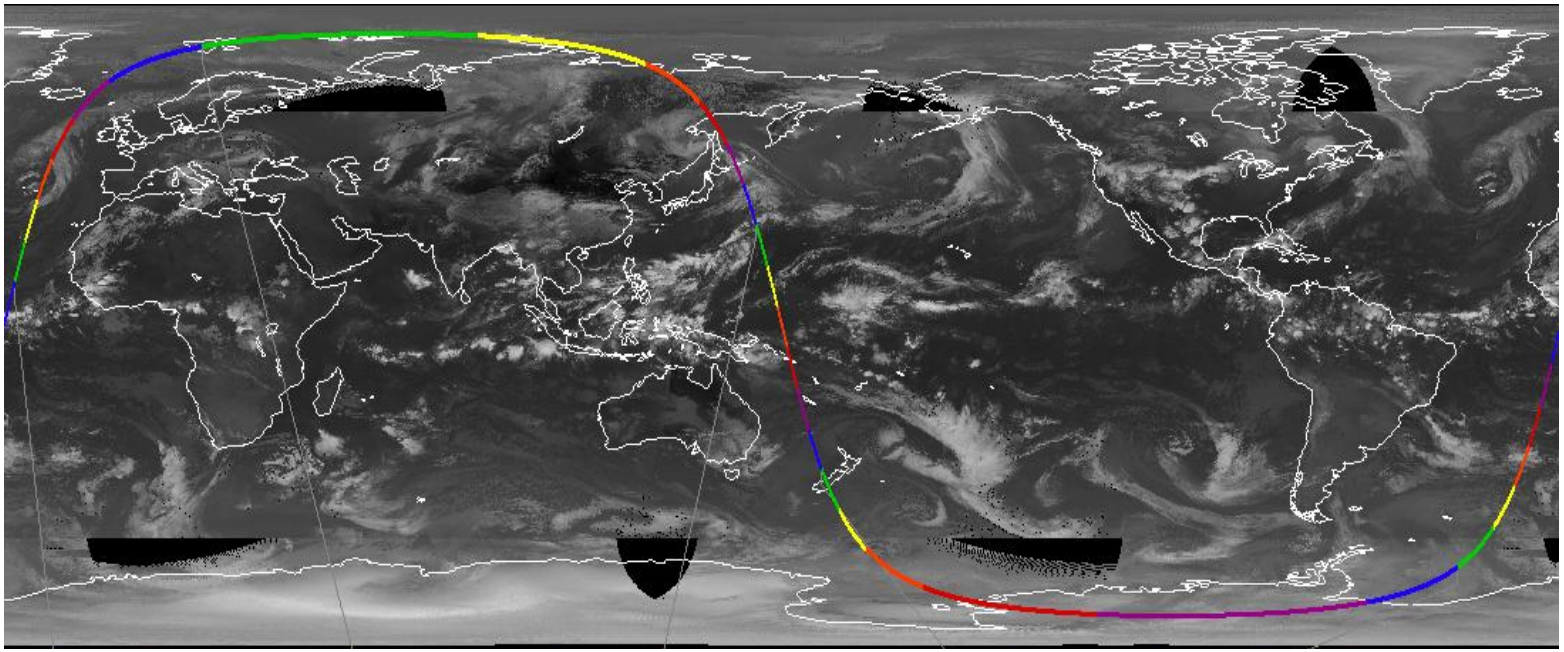

Satellite measurements are mostly used for tracking weather and deriving climatology. Study of detailed cloud dynamic processes (e.g., convective entrainment) is traditionally not considered as the “territory” of satellite, but belongs to aircraft or modeling.

Outlines

1. Using A-Train Data to Estimate Bulk Entrainment Rate & Convective Buoyancy

2. Possible Applications to DOE/ARM Measurements

3. Ozone as A Tracer to probe Convective Entrainment

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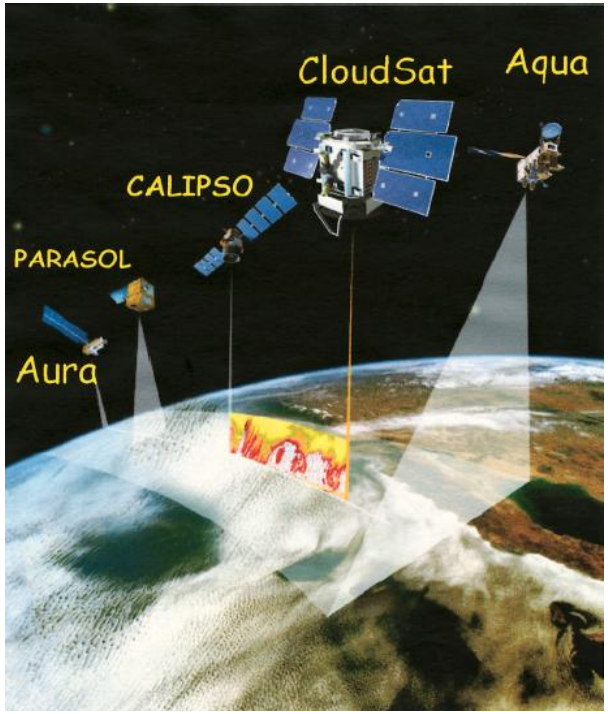
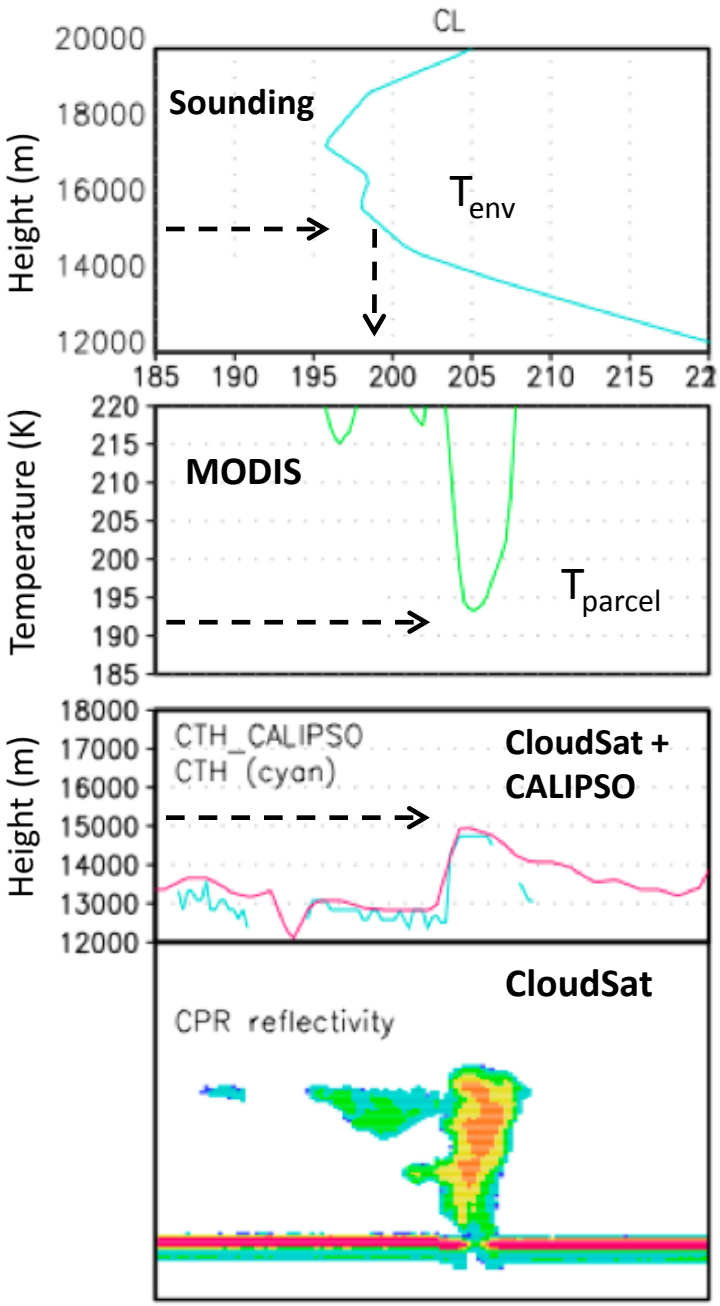
A-Train to study convection



Aqua: MODIS, AIRS, AMSR-E, CERES

CloudSat: a 94-GHz cloud profiling radar

CALIPSO: dual-channel lidar + IR radiometer



$$B = g\frac{T_{parcel} - T_{env}}{T_{env}}$$

(water vapor and hydrometer effects on B are incorporated, but they are small terms near convective top)

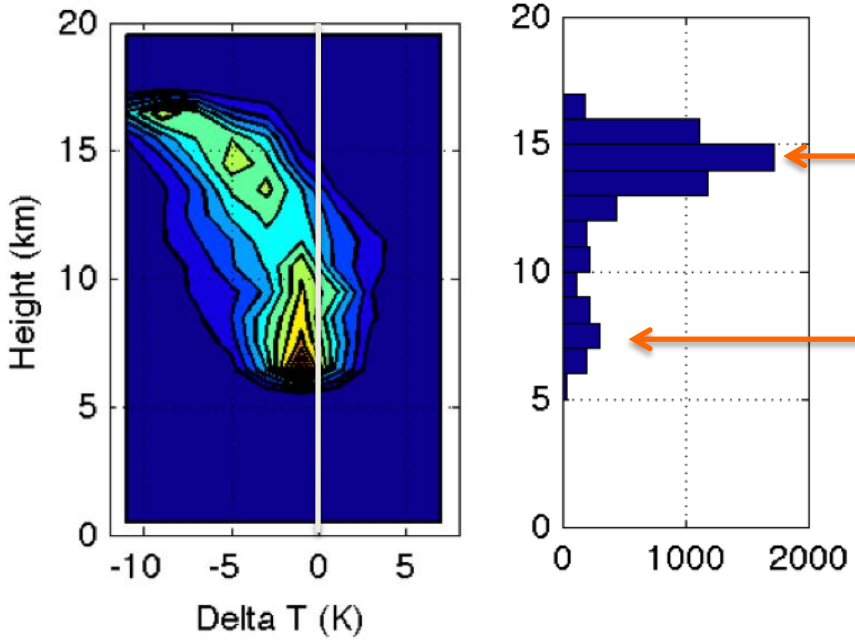
T_{parcel}=193 K; T_{env}=198 K

Negatively buoyant!

(*We corrected for the non-black effect near cloud top using CALIPSO lidar*)

The key is to have independent measurements of 1) *cloud-top height (CTH)* and 2) *cloud-top temperature (CTT)*, plus identification of convective tower.

Initial Results

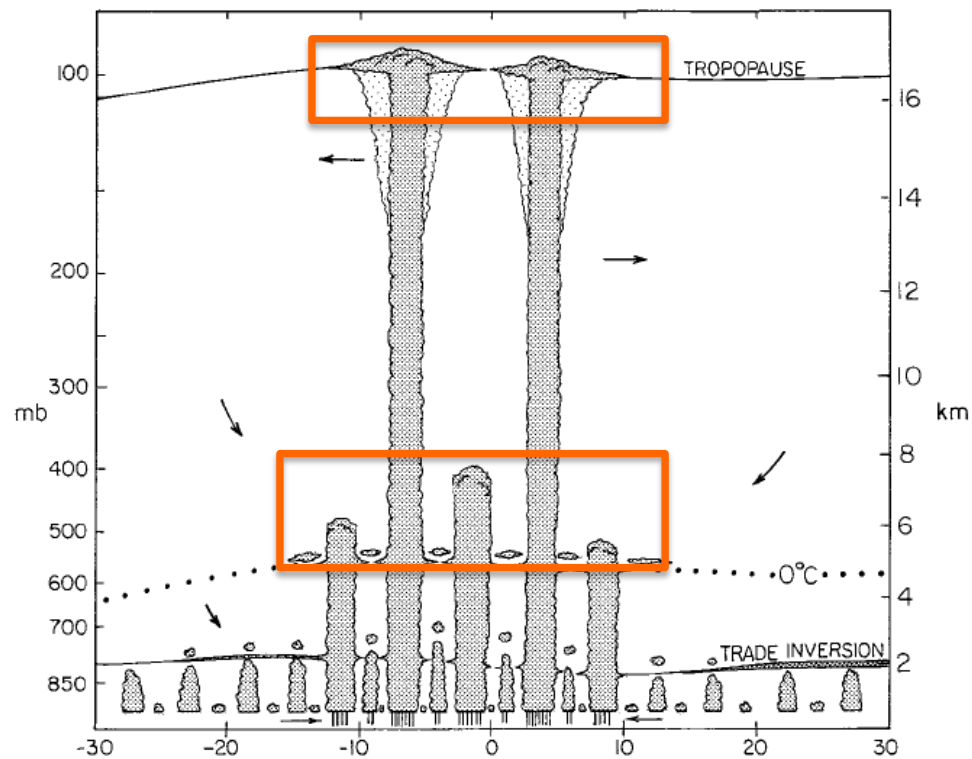


Overshooting convection

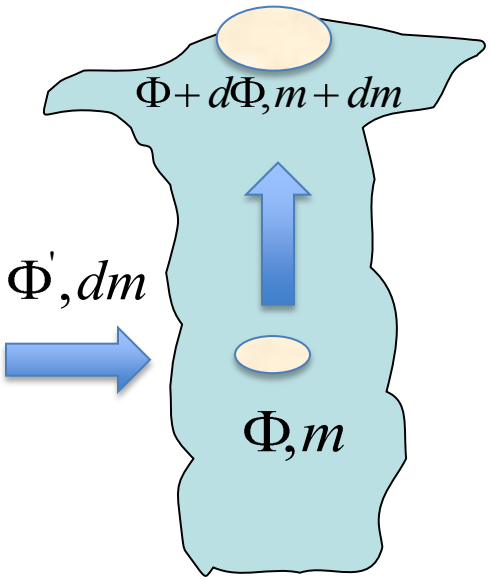
(Apparent) cumulus congestus

$$\Delta T \equiv T_{parcel} - T_{env}$$

We exclude shallow convection for now



We selected ~ 6000 convective towers with well-defined cloud tops over 15S-15N



Φ is any conserved, intensive quantity (e.g., moist static energy)

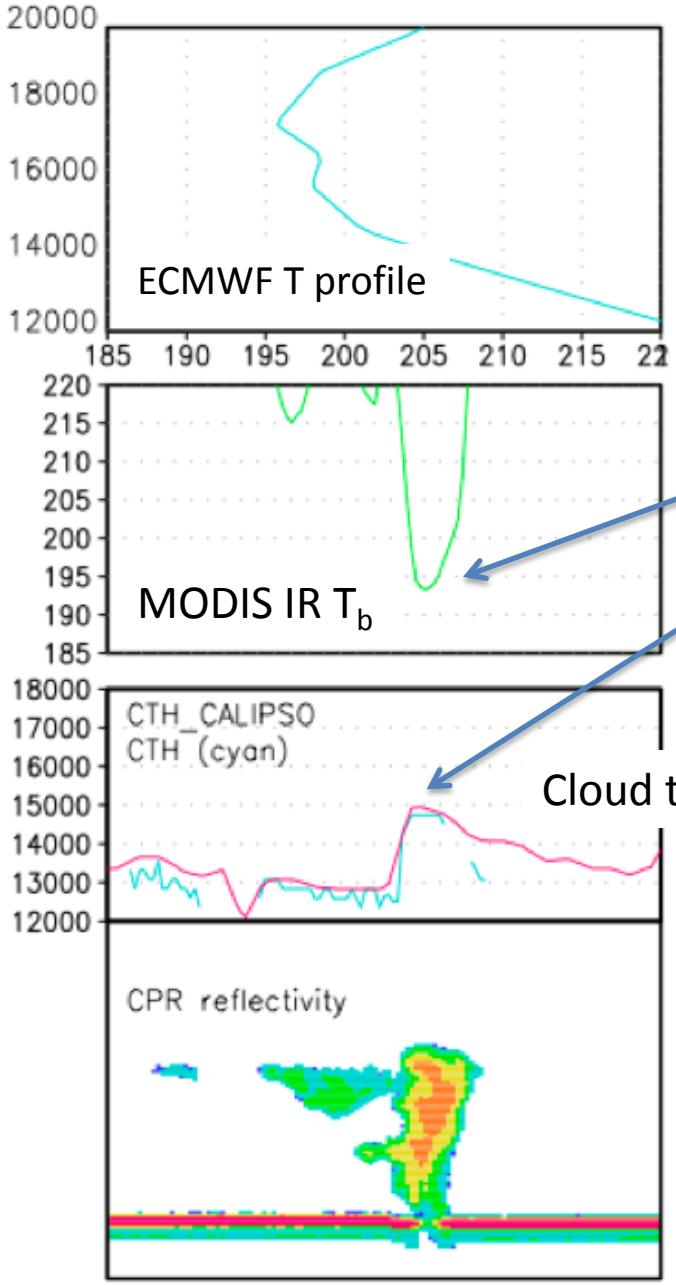
$$\frac{d\Phi}{dz} = \frac{d\ln m}{dz}(\Phi' - \Phi) \qquad where\ \lambda \equiv \frac{d\ln m}{dz}$$, entrainment rate

Moist Static Energy (MSE) = $C_p T + gz + L_v q$

If CloudSat (together with other ancillary data) can give us an estimate of

1) MSE of the convective tower,
2) MSE of the environment

We may be able to use this simple model to estimate the *magnitude of dilution* the convective tower has gone through.



$$C_pT + gz + L_vq$$

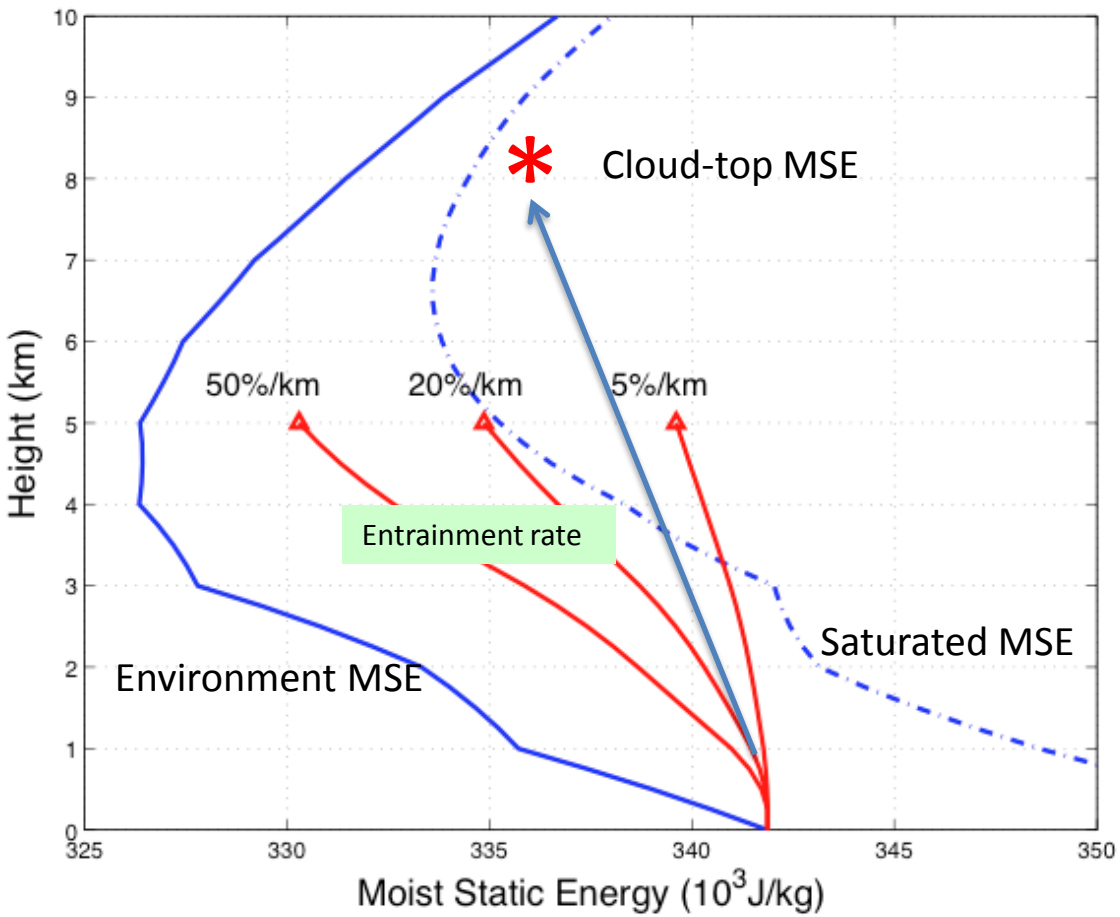
Cloud top height

Cloud-top MSE
(T_b has been corrected for non-blackbody effect)

Luo et al. (2010)

Integrate this equation from the PBL upward to the observed cloud top height. Iterate λ until the calculated MSE matches the observed MSE.

$$\frac{d\Phi}{dz} = \lambda(\Phi' - \Phi)$$



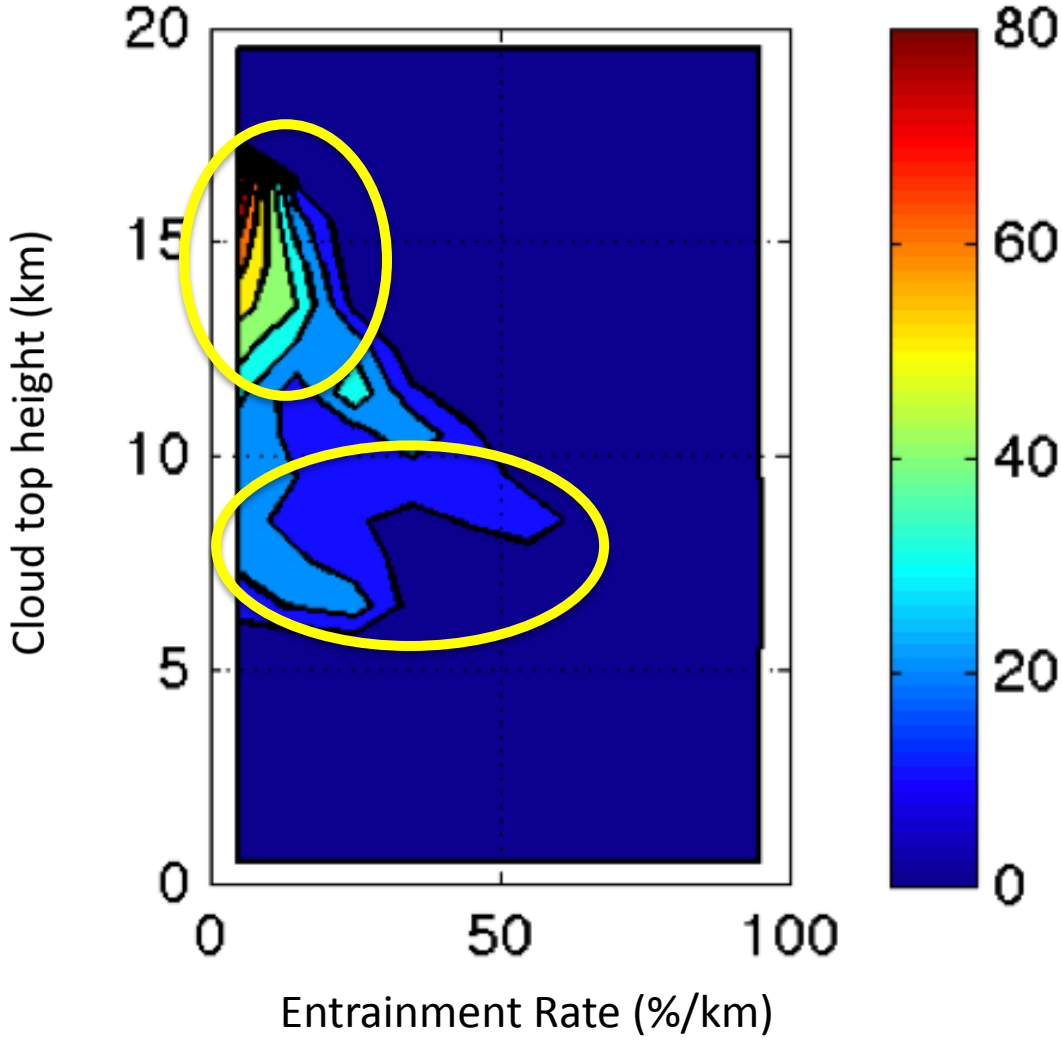
Caveat: 1) Assuming the environment MSE represents that of the cloud base, 2) using the bulk entraining plume model

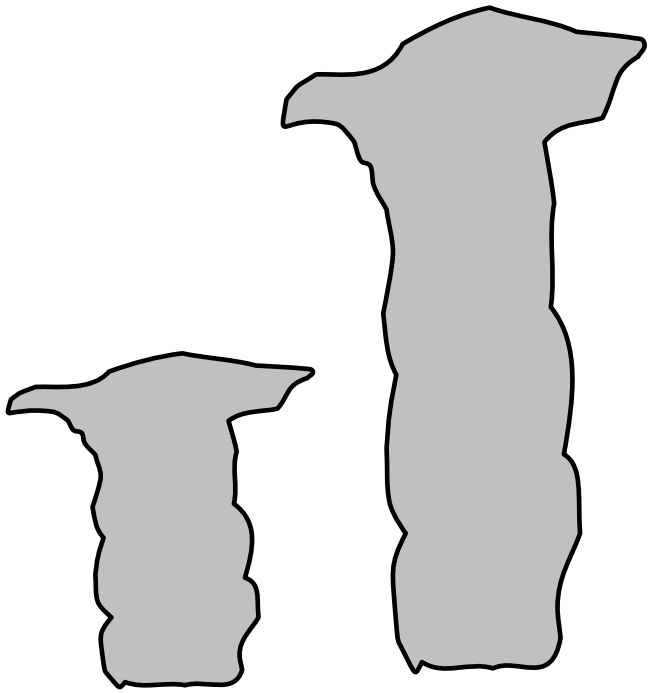
Energy boost from ice nucleation is ignored for now, but could be included using CloudSat IWC product

Luo et al. (2010)

Histogram of λ as a function of CTH

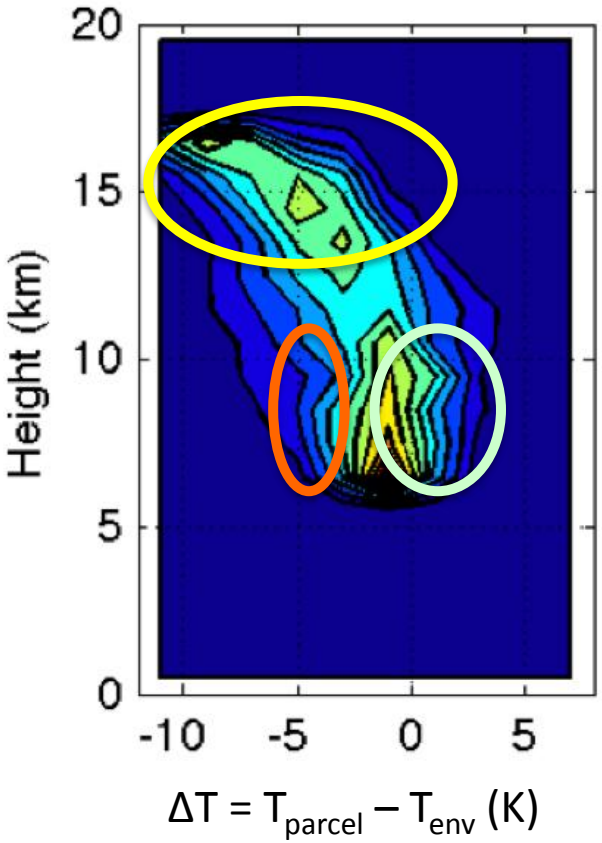
Entrainment rate



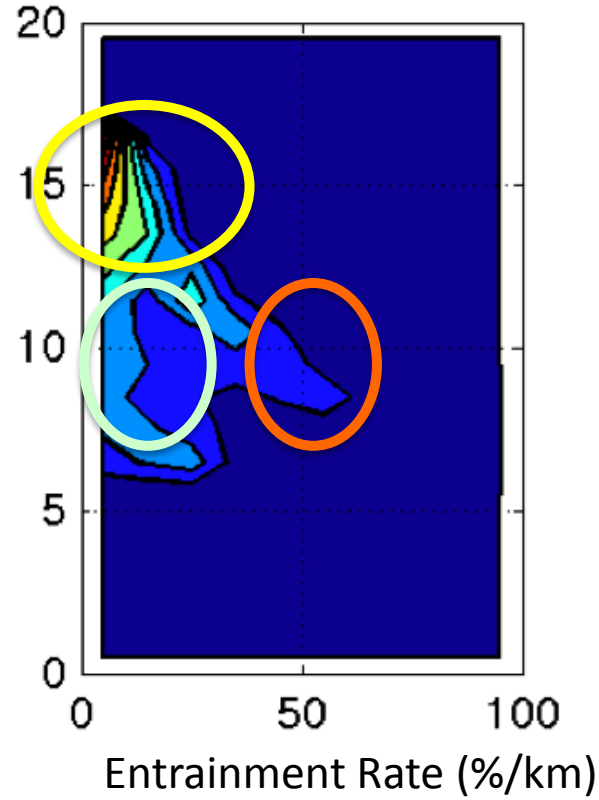


Luo et al. (2010)

Buoyancy



Entrainment rate



Deep convection:
B <0 & λ < 10%/km

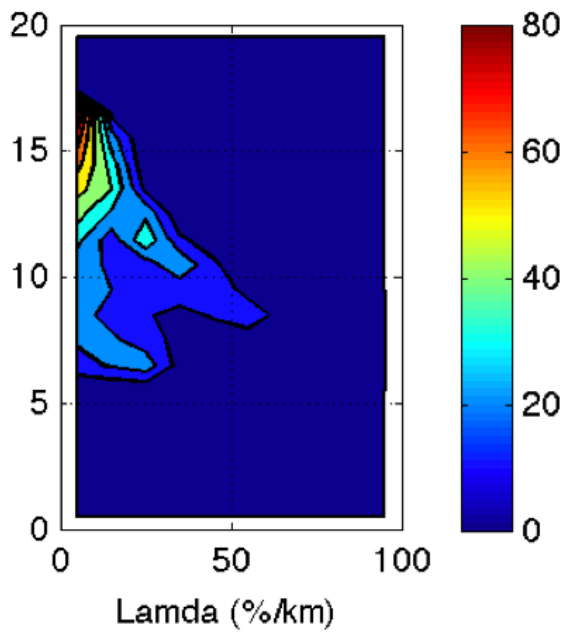
"Terminal" cumulus congestus:
B < 0 & λ up to 50%/km

"Transient" cumulus congestus:
B > 0 & λ ~ 10%/km

Luo et al. (2010)

Sensitivity tests on entrainment rate estimated (% km^{-1})

	Control	Cloud top MSE +3 kJ/kg	Cloud top MSE -3 kJ/kg	PBL MSE +3 kJ/kg	PBL MSE -3 kJ/kg	RH +15%	RH -15%
Case #1: DC	10	4	21	12	6	12	8
Case #2: Cg	17	8	31	21	11	24	13



Source of errors:

1. Cloud-top MSE
2. PBL inhomogeneity
3. Ambient MSE (mostly RH)

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Factors Limiting Convective Cloud-Top Height at the ARM Nauru Island Climate Research Facility

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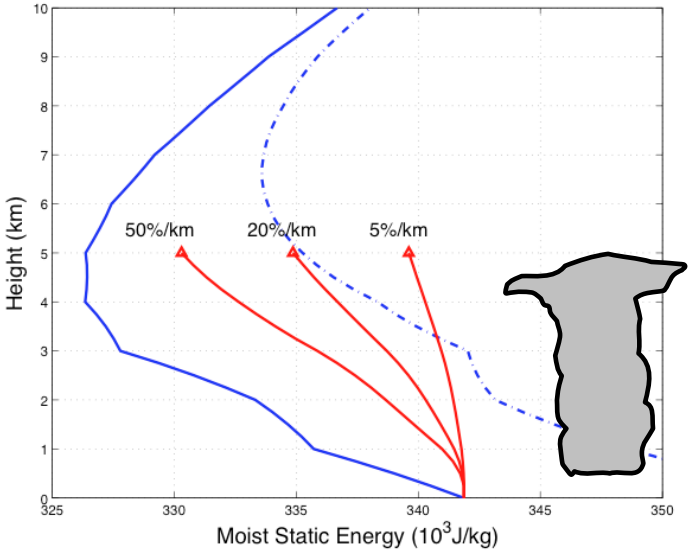
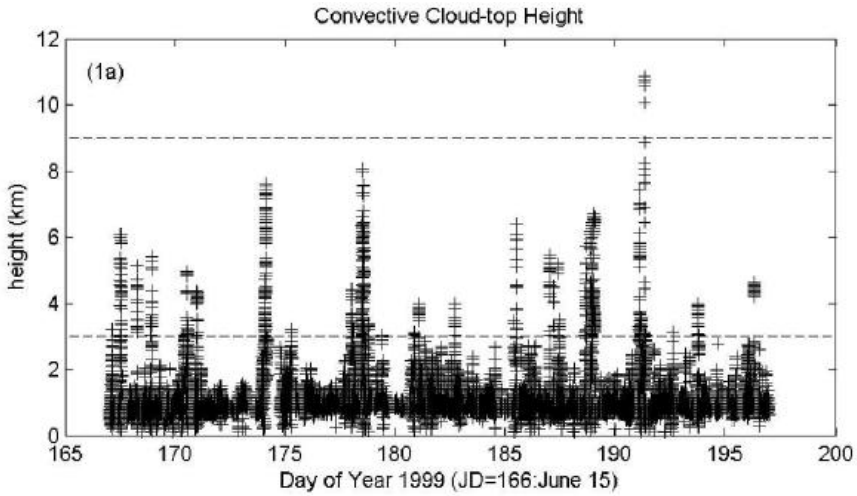
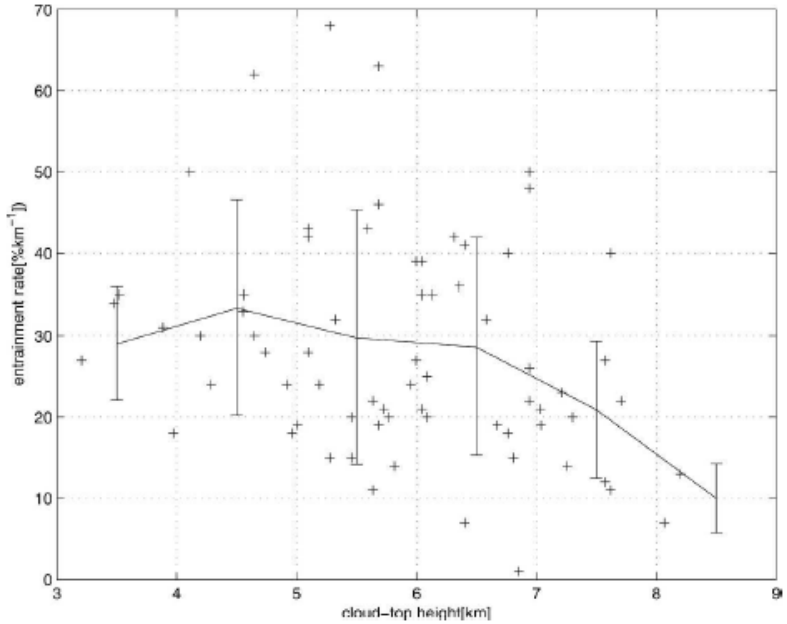
ABSTRACT

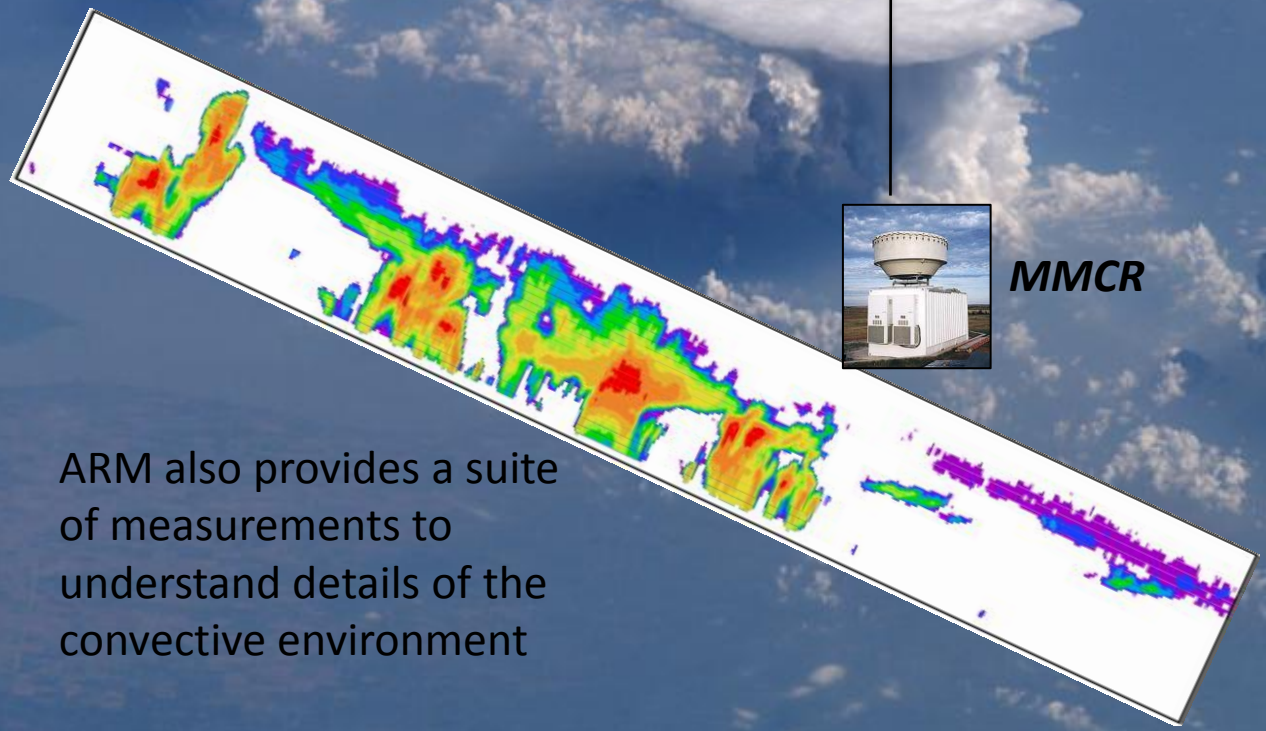




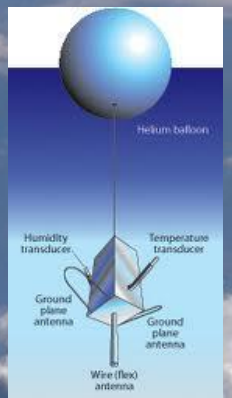


Geostationary satellite

$$C_p T + gz + L_v q$$

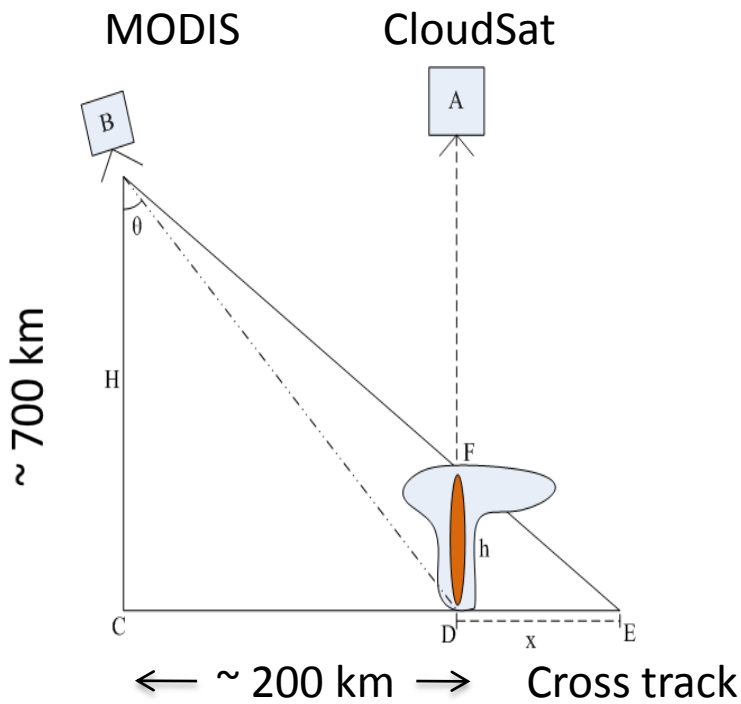


MMCR

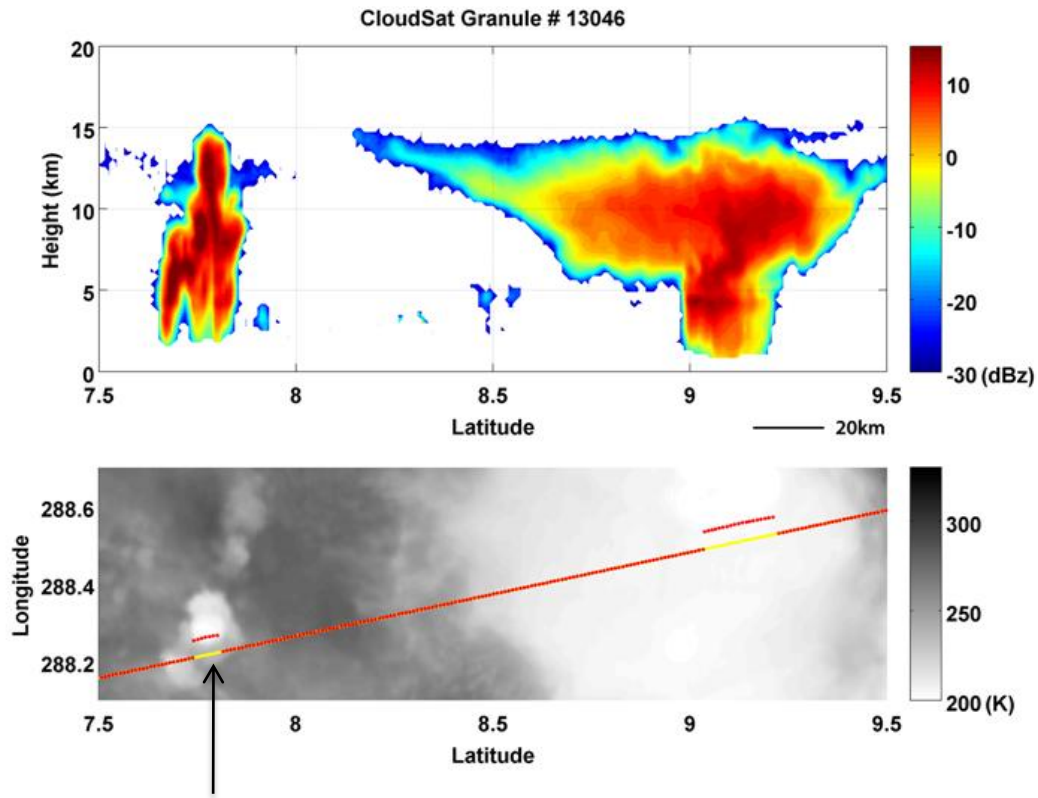


Radiosonde

ARM also provides a suite of measurements to understand details of the convective environment



Parallax Problem



~ 50 K difference in brightness temperature

Wang, Luo and Huang (2011), In press

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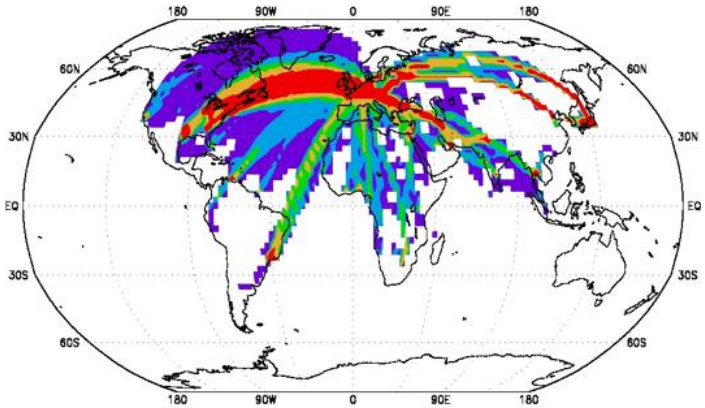
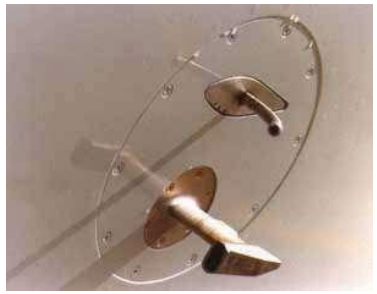
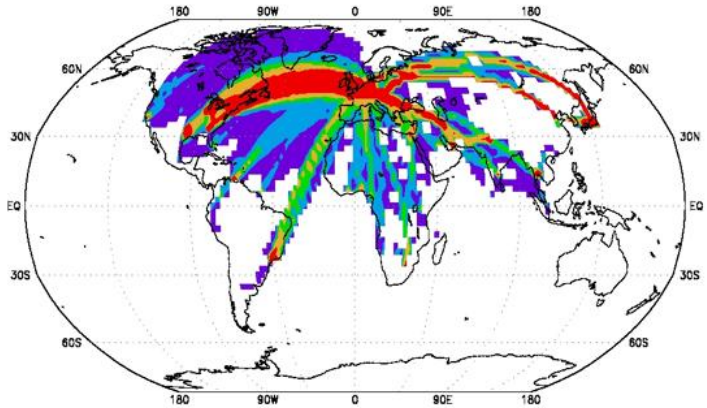
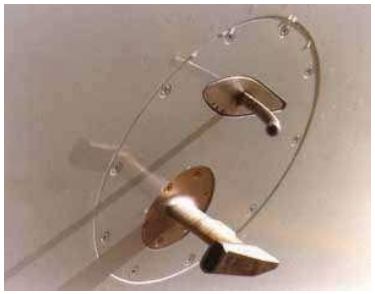




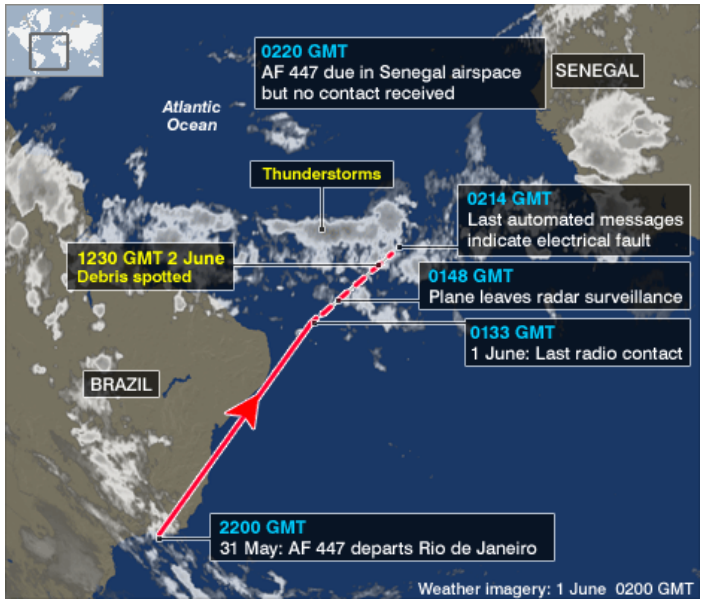
Measurements of OZone and wAter vapour by Airbus In-Service airCraft (MOZAIC)



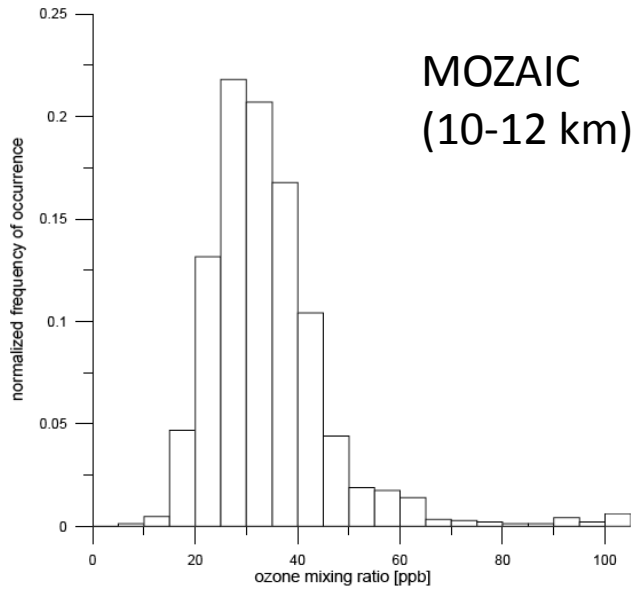


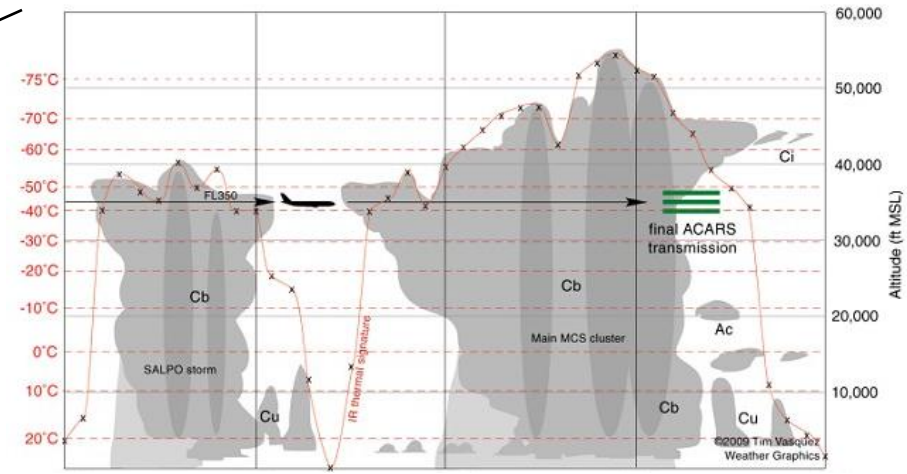
Measurements of OZone and wAter vapour by Airbus In-Service airCraft (MOZAIC)

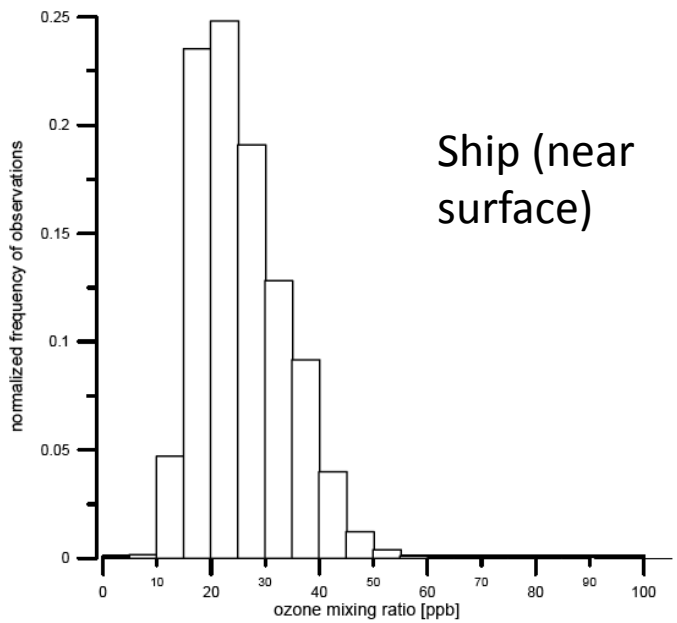
Air France 447 crash (June 1 2009)



We only focus on flights within convective clouds



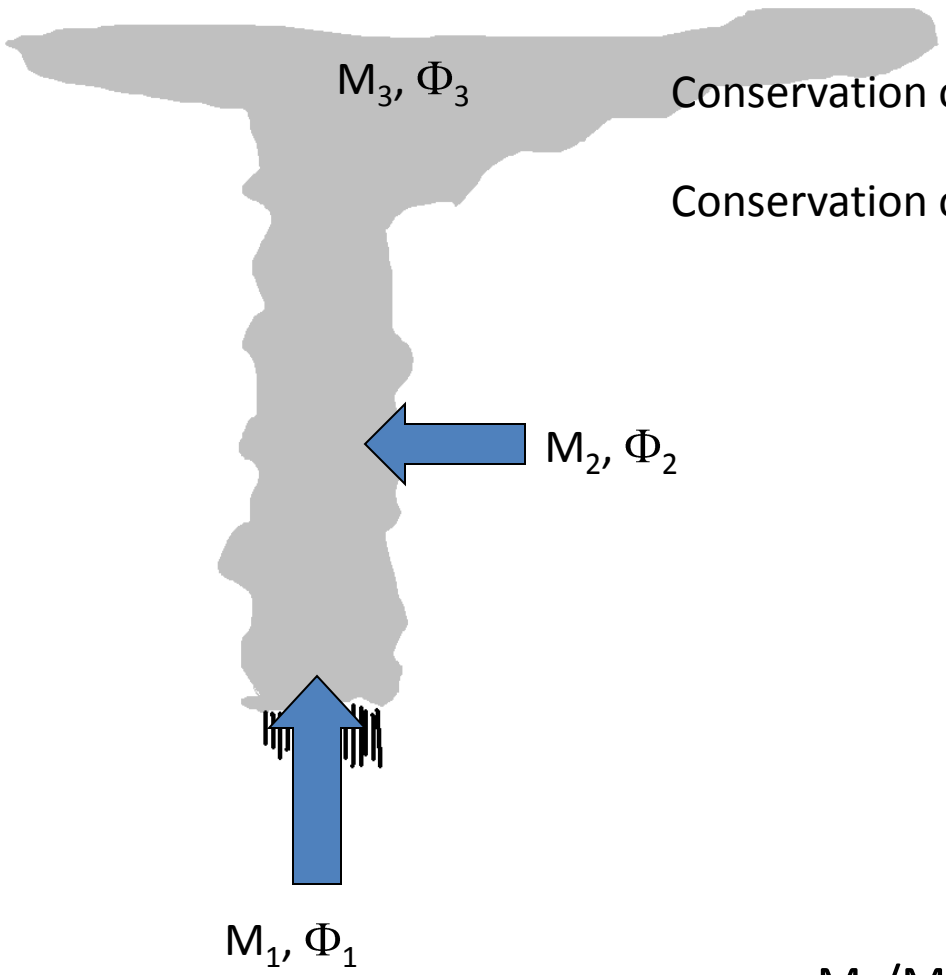




Based on 4-years of aircraft (N~5000) and ship (N~2000) measurements, O_3 near deep convective outflow level is ~ 7 ppb (~ 30%) higher than that at the MBL.

But O_3 is a quasi-conservative quantity at convective time scale: production of O_3 is only a few ppb/day.

Cumulus ensemble model (not an individual plume)



Conservation of mass $M_3=M_1+M_2$ (1)

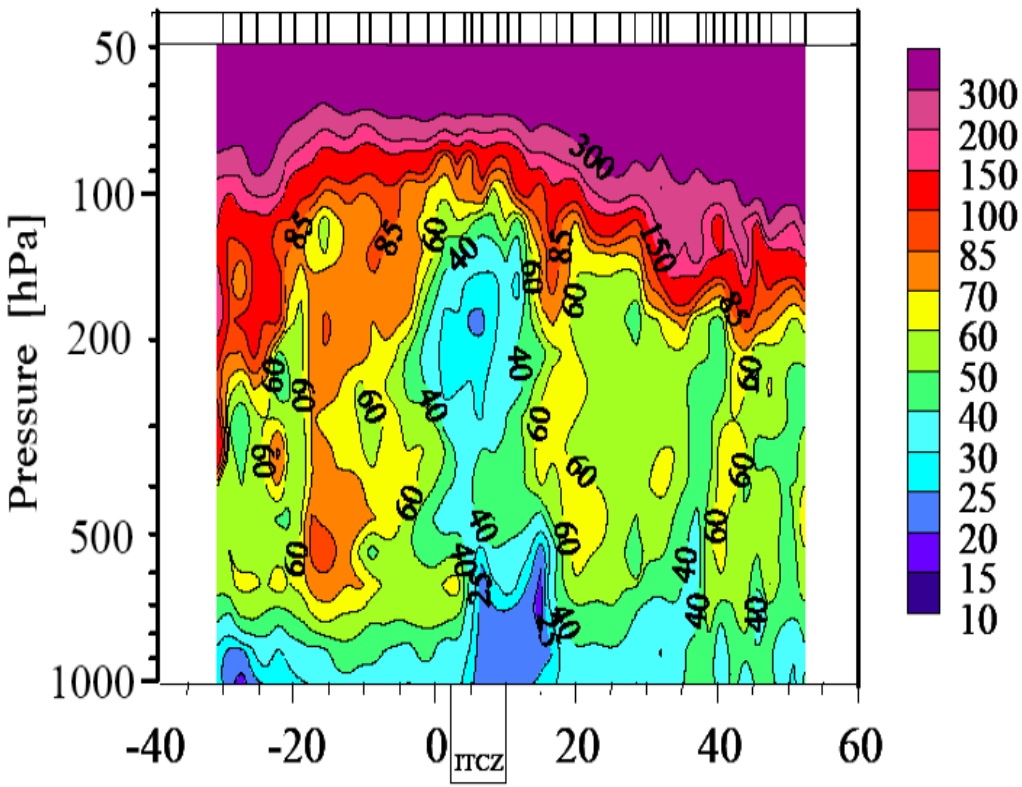
Conservation of O_3 $M_3\Phi_3= M_1\Phi_1+M_2\Phi_2$ (2)

$$\boxed{\frac{M_2}{M_1}=\frac{\Phi_3-\Phi_1}{\Phi_2-\Phi_3}}$$

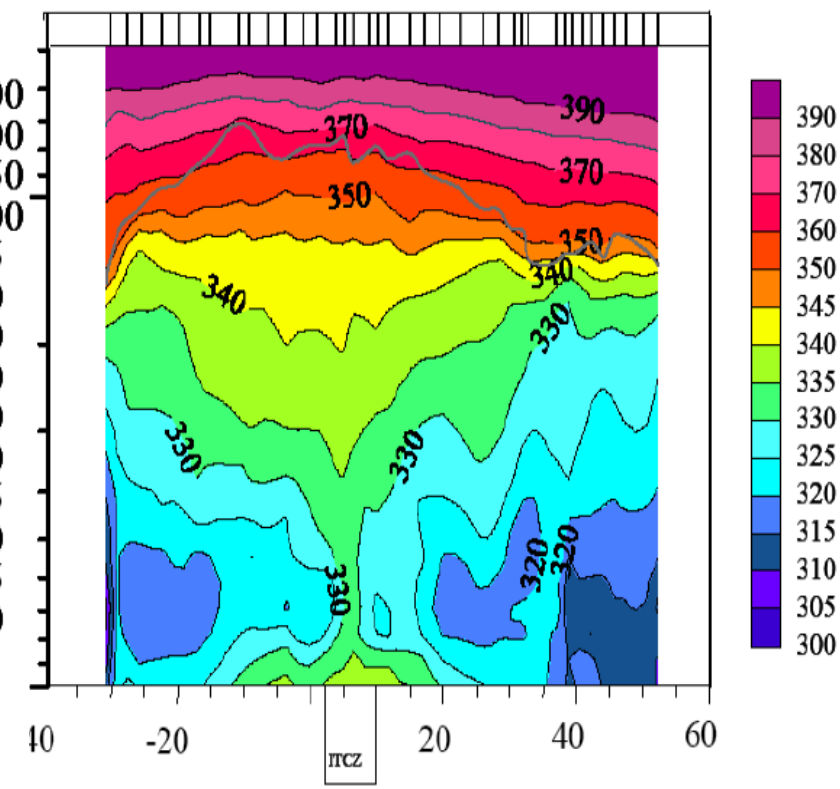
$M_2/M_1=(34-27)/(48-34)=0.5$

Ozone & θ_e cross section along an Atlantic cruise (PolarStern)

O_3 cross section



θ_e cross section



Summary

1. Simultaneous measurements of convective CTH and CTT, aided by ambient sounding, enables us to use the entraining plume model to estimate bulk entrainment rate (and cloud-top buoyancy) of convective towers.

1. This method has been applied to A-Train data, but can be easily adopted to ARM measurements. ARM provides rich information about the convective environment, which enables a detailed study of convective entrainment

2. Ozone is actually a better tracer to probe convective entrainment than MSE. Satellite application of the ozone approach should be promising.

References

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Thank You!