Entrainment, detrainment, and dilution of dry and moist convective thermals

Hugh Morrison

National Center for Atmospheric Research

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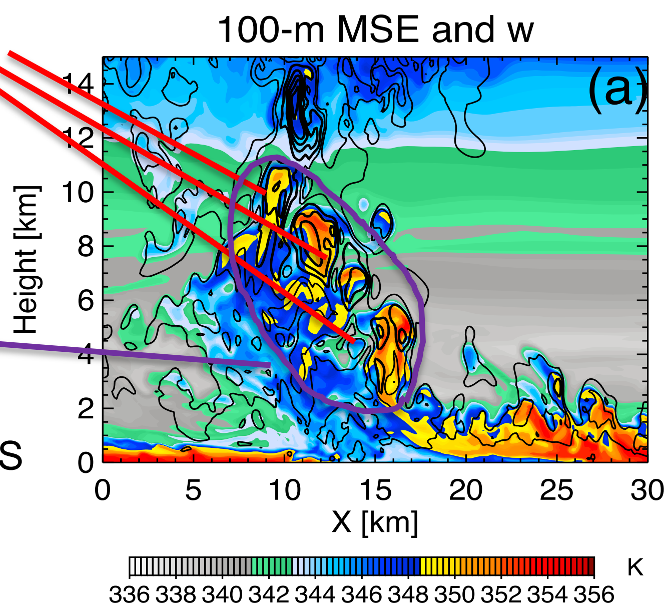
- **Observations and large-eddy simulations (LES) show that moist convection often comprises one or more distinctive large (cloud-scale) thermal structures each with their own circulations.**

- **Important to understand dynamics of these thermals because they contain relatively undilute cloud air → thus, key to understanding cloud ascent and cloud top height.**

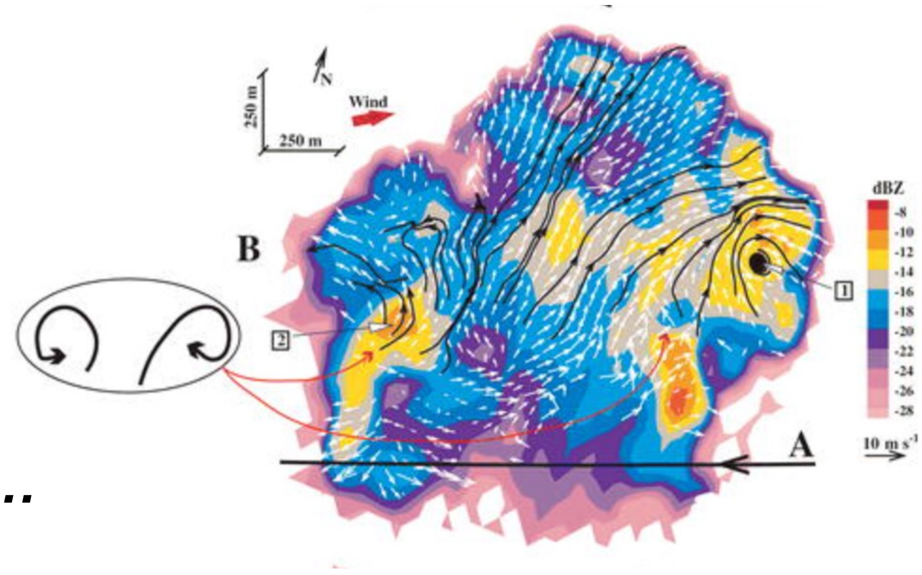
Individual updraft-scale thermals

Broader updraft structure consisting of successive rising thermals

Varble et al. (2014) LES



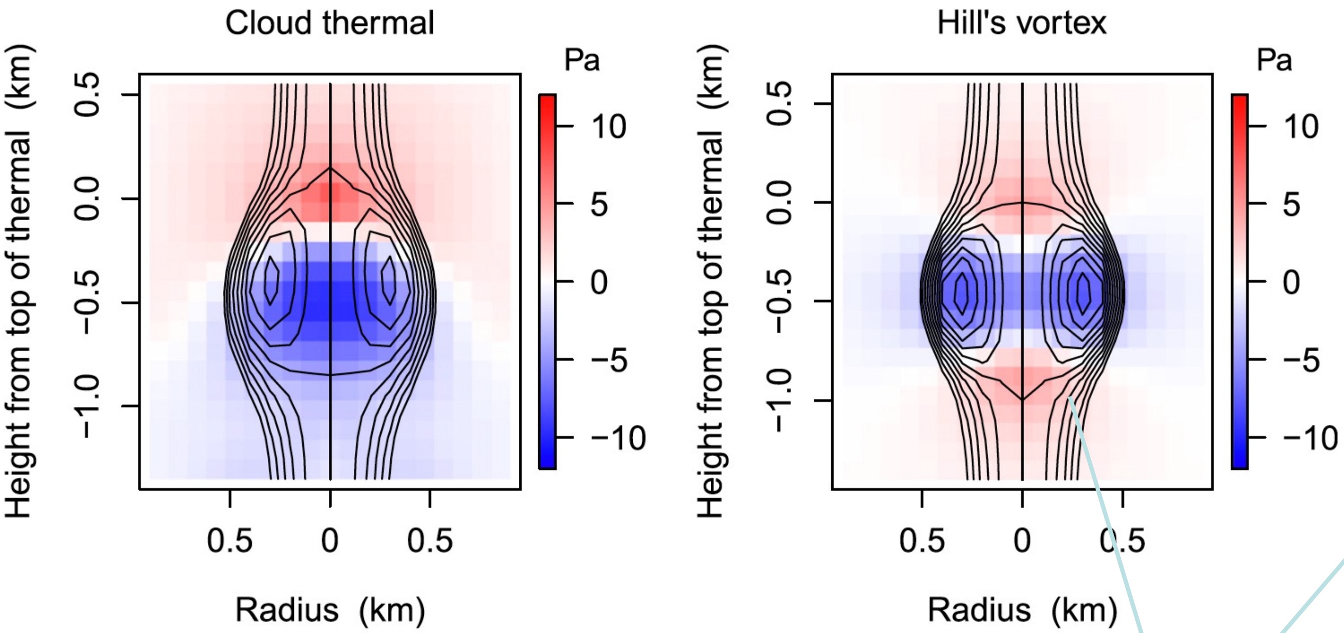
Damiami and Vali (2007), airborne cloud radar observations of large thermals in cumulus congestus

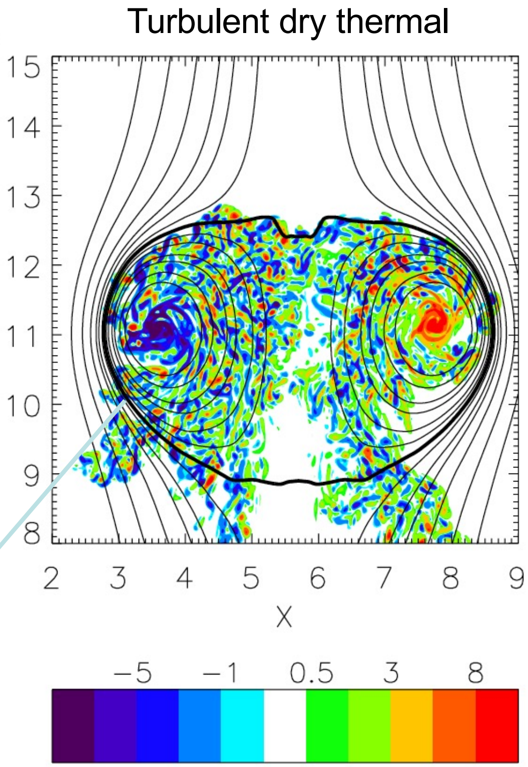


Large thermals drive the bus…

- **Overall flow structure of moist thermals is similar to dry thermals and strongly resembles a ring vortex (esp. Hill's analytic spherical vortex)**

(e.g., Sherwood et al. 2013; Romps and Charn 2015; Morrison et al. 2021)





Streamlines (lines) and perturbation pressure (colors)

Romps and Charn (2015)

Vortex or thermal boundaries defined by streamfunction calculated from azimuthally-averaged flow

Streamlines (lines) and vorticity (non-dimensional)

Morrison et al. (2022a)

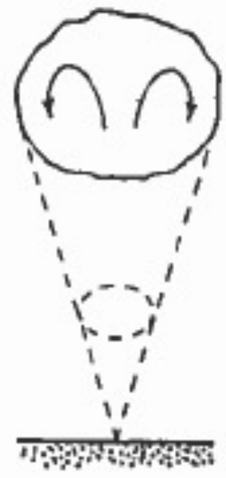
The dynamics of dry thermals are relatively well understood...

Can this inform our understanding of moist thermals?

(NOTE: there is a long history of studies on dry convective dynamics informing convection parameterizations, e.g., plume models)

The key dynamics of dry thermals:

- ***Entrain and spread with constant dR/dz (consistent with dimensional analysis, laboratory and numerical modeling studies)***
- ***Spreading rate dR/dz depends on initial shape; initially spherical thermals have dR/dz ~0.15 (incompressible, unstratified)***
- ***Entrain mainly by engulfing fluid from below the thermal, turbulent mixing plays a limited role (Turner 1957; Lecoanet and Jeevanjee 2019)***
- ***Nearly zero or slightly negative dynamic pressure drag (Morrison et al. 2022a)***
- ***Very little detrainment (Lecoanet and Jeevanjee 2019)***



Turner (1973)

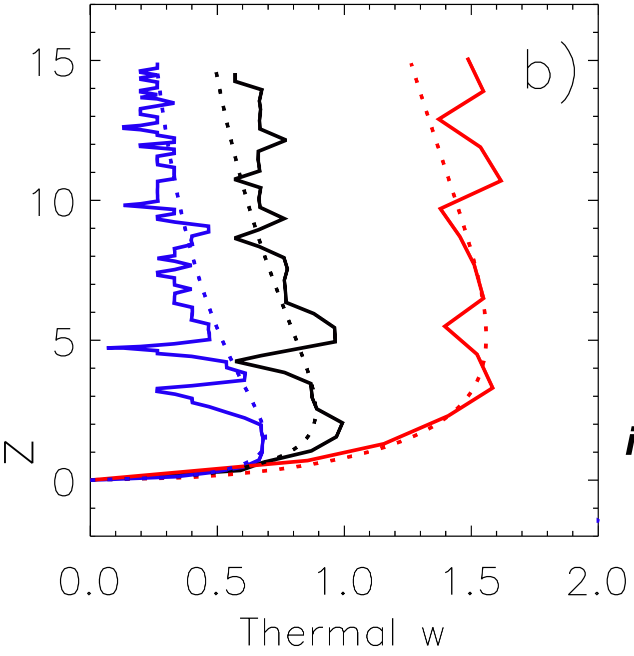
Entrainment in dry thermals

- **Fractional entrainment rate is closely related to the thermal spreading rate, *dR*/*dz* (*R* = radius, *z* = height); detrainment is negligible. Spreading rate depends strongly on initial thermal aspect ratio (aspect ratio of the initial buoyancy perturbation).**

- **Thermal growth rate *(α = dR/dz)* and ascent rate *(w)* can be well represented by an analytic model:**

Morrison et al. (2023)

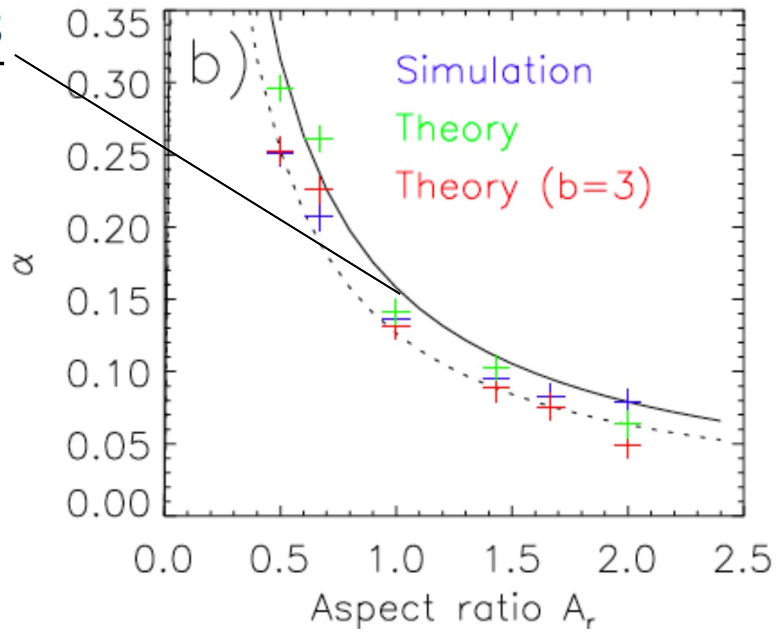
$$\alpha \approx \frac{\left(3^{\frac{1}{4}}-1\right)}{2A_r} \approx \frac{0.158}{A_r}$$



Solid lines (simulated w)

Dotted lines (analytic w)

Results shown for various initial thermal aspect ratios A_r.

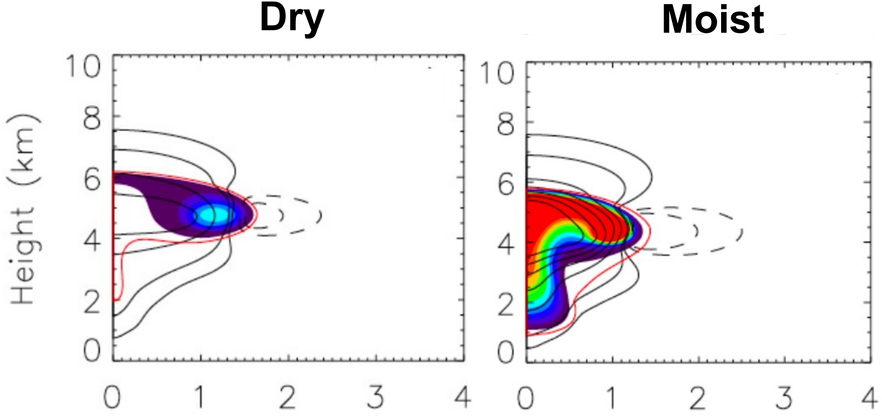


This provides a fairly complete picture of entrainment in dry thermals…

What about moist thermals?

A comparison of entrainment in dry versus moist (cloud) thermals

Buoyancy (color) and w (contour lines)

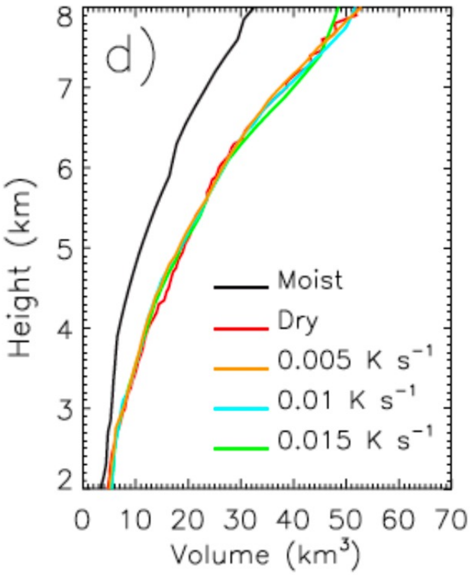


Thermal tracking algorithm similar to Romps and Charn (2015)

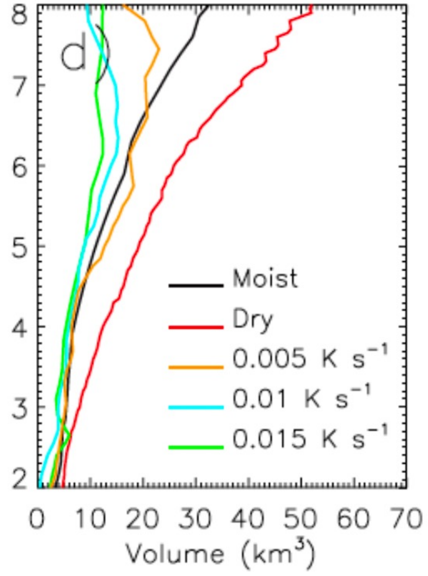
Morrison et al. (2021)

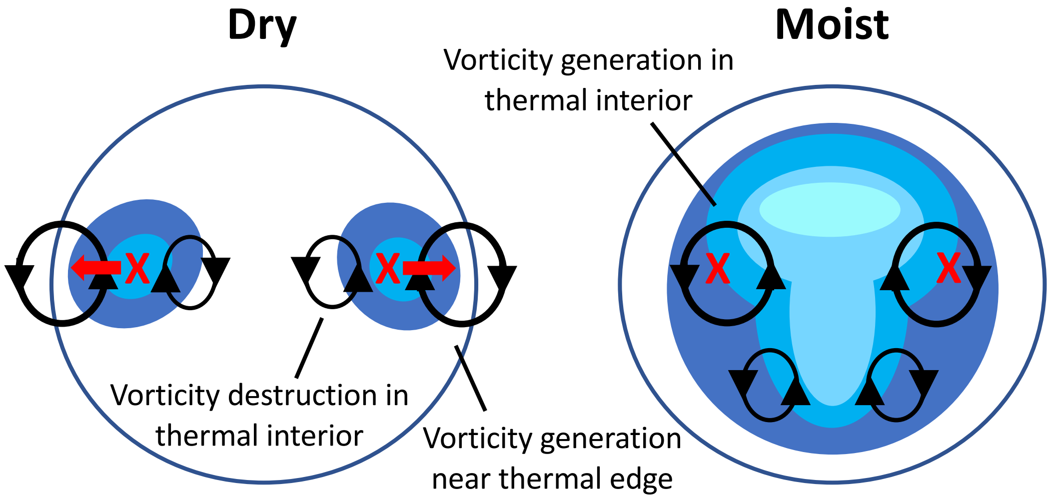
Thermal spreading rate is factor of ~2 smaller for moist thermals compared to dry owing to their different distribution of buoyancy and thus baroclinic generation of vorticity…

Volume growth with heating spread throughout thermal

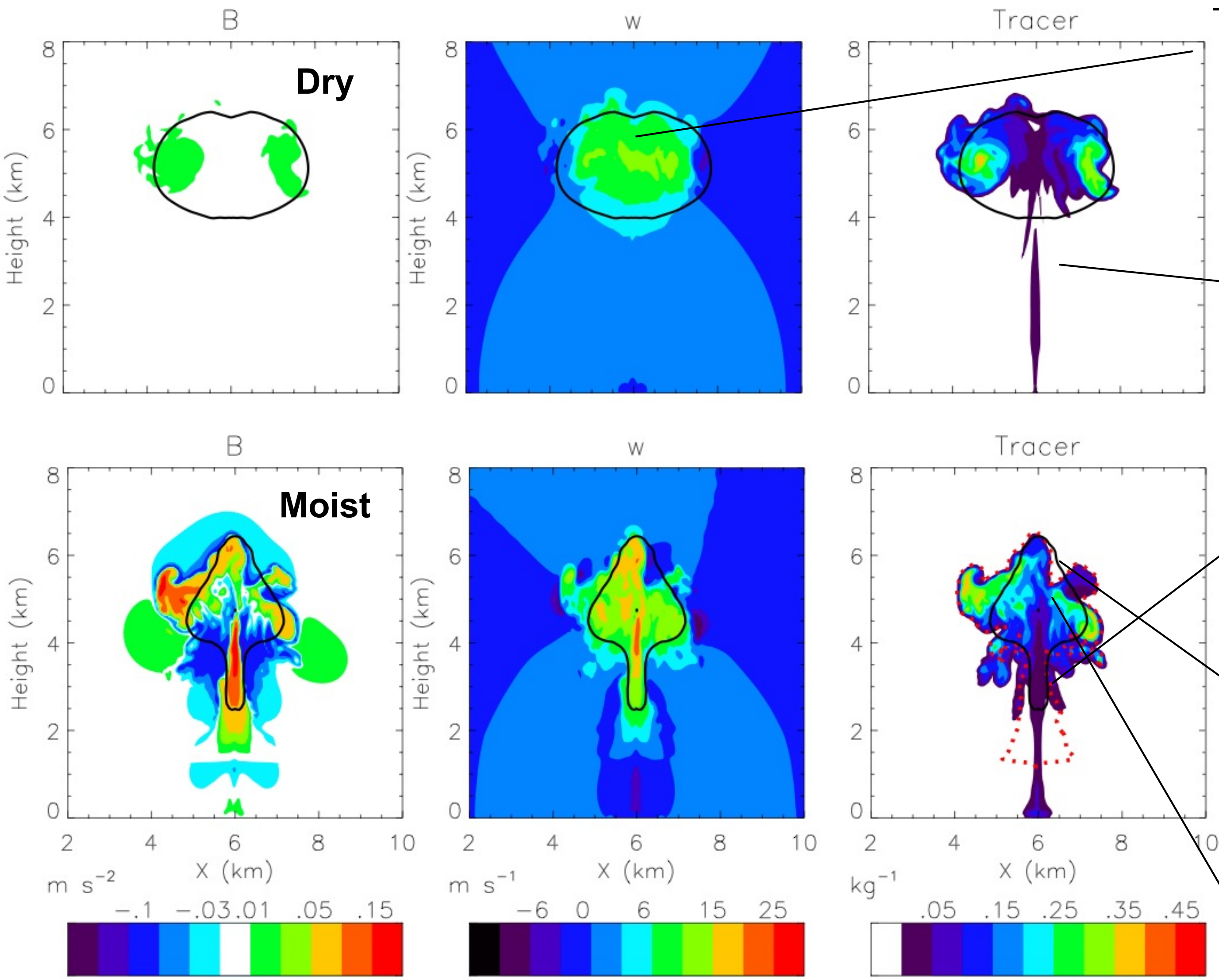


Volume growth with heating only in thermal core





What about turbulent thermals…



<u>Greater spreading rate</u> and flattening of dry thermals, 3.3 x volume of moist

<u>Very little detrainment</u> in dry thermals

<u>Substantial detrainment</u> in wake of moist thermals

<u>Cloud-environment interface instability</u> → increases mixing of cloud and environmental air

Tracer more uniformly spread in core of moist thermals

Results for moist thermals are (surprisingly) insensitive to env. static stability

Main initial findings:

While overall flow structure is similar between dry and moist thermals, their entrainment, detrainment, and dilution behavior is different → dry thermals are a poor approximation of moist thermal behavior.

Helps explain why cloud thermals do not expand much as they rise (e.g., Hernandez-Deckers and Sherwood 2016; Peters et al. 2020), yet are substantially diluted.

Thank you!

Questions?

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