A new conceptual picture of the trade-wind transition layer*

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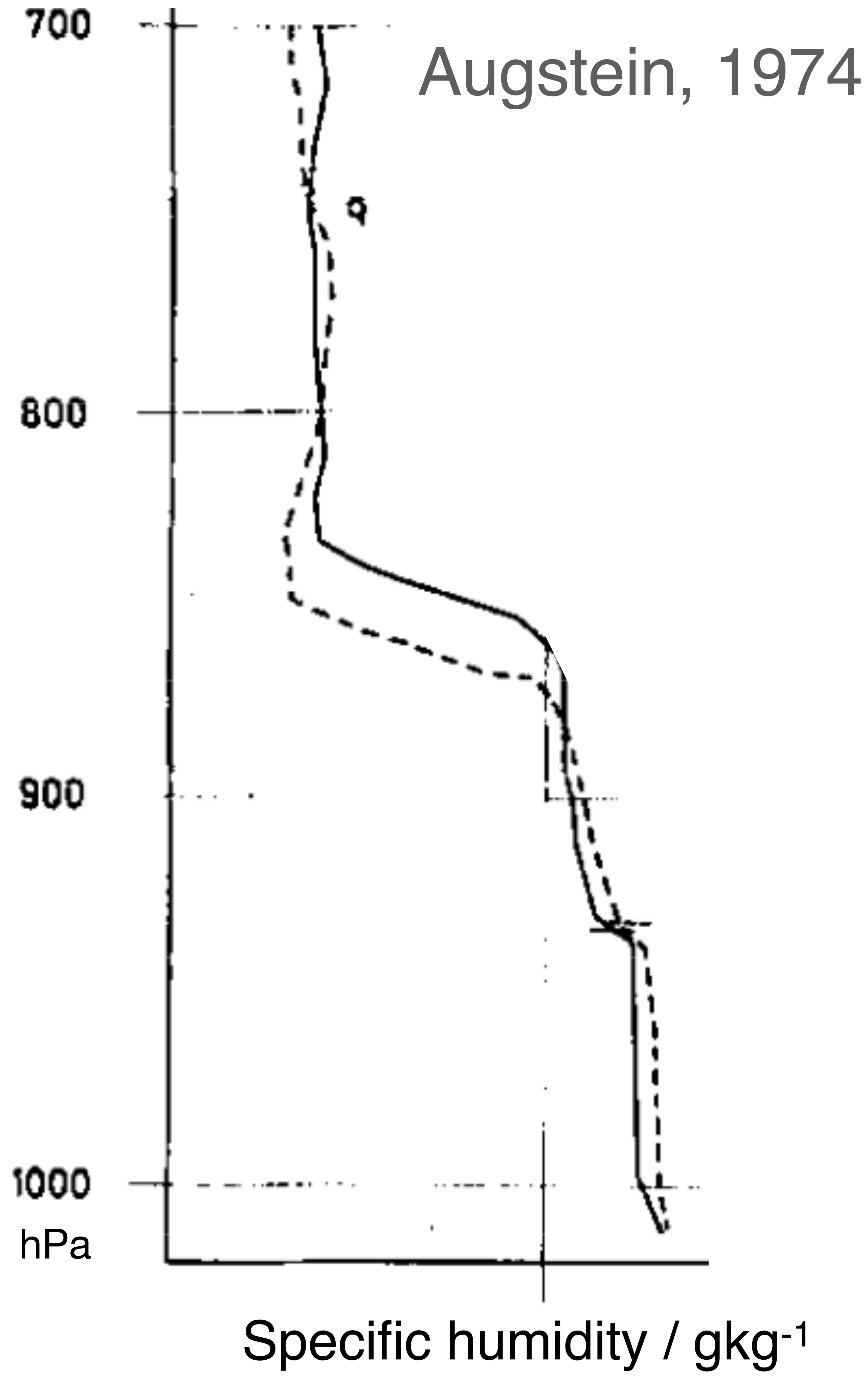
Trade-wind atmosphere has characteristic vertical structure

e.g., Malkus, 1958, Augstein, 1974, Yin & Albrecht, 2000



Studying vertical structure teaches us about physical processes producing this structure

Mark Rothko, Blue and Grey (1962)

Free troposphere

~ 2-3 km

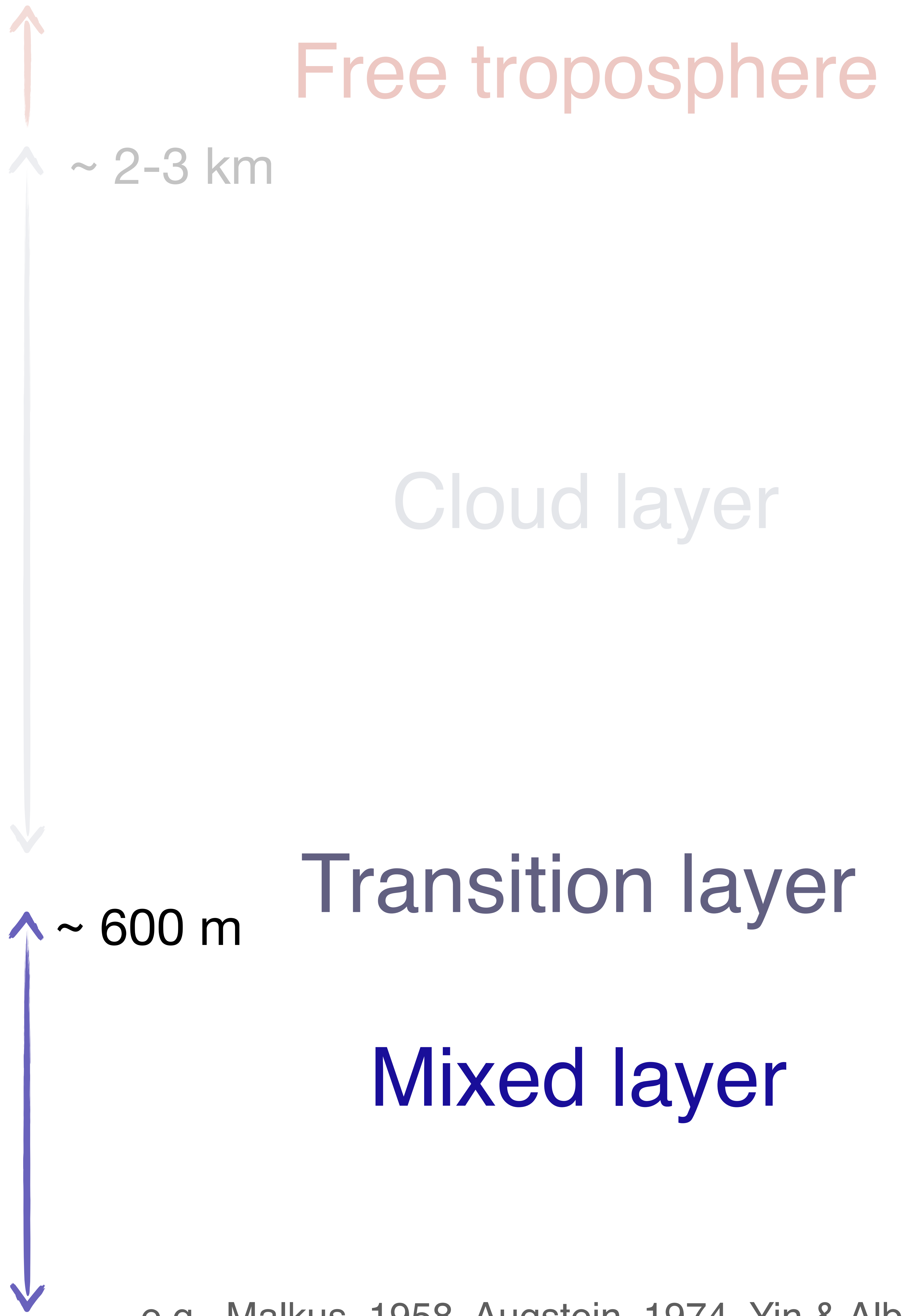
Cloud layer

~ 600 m

Mixed layer

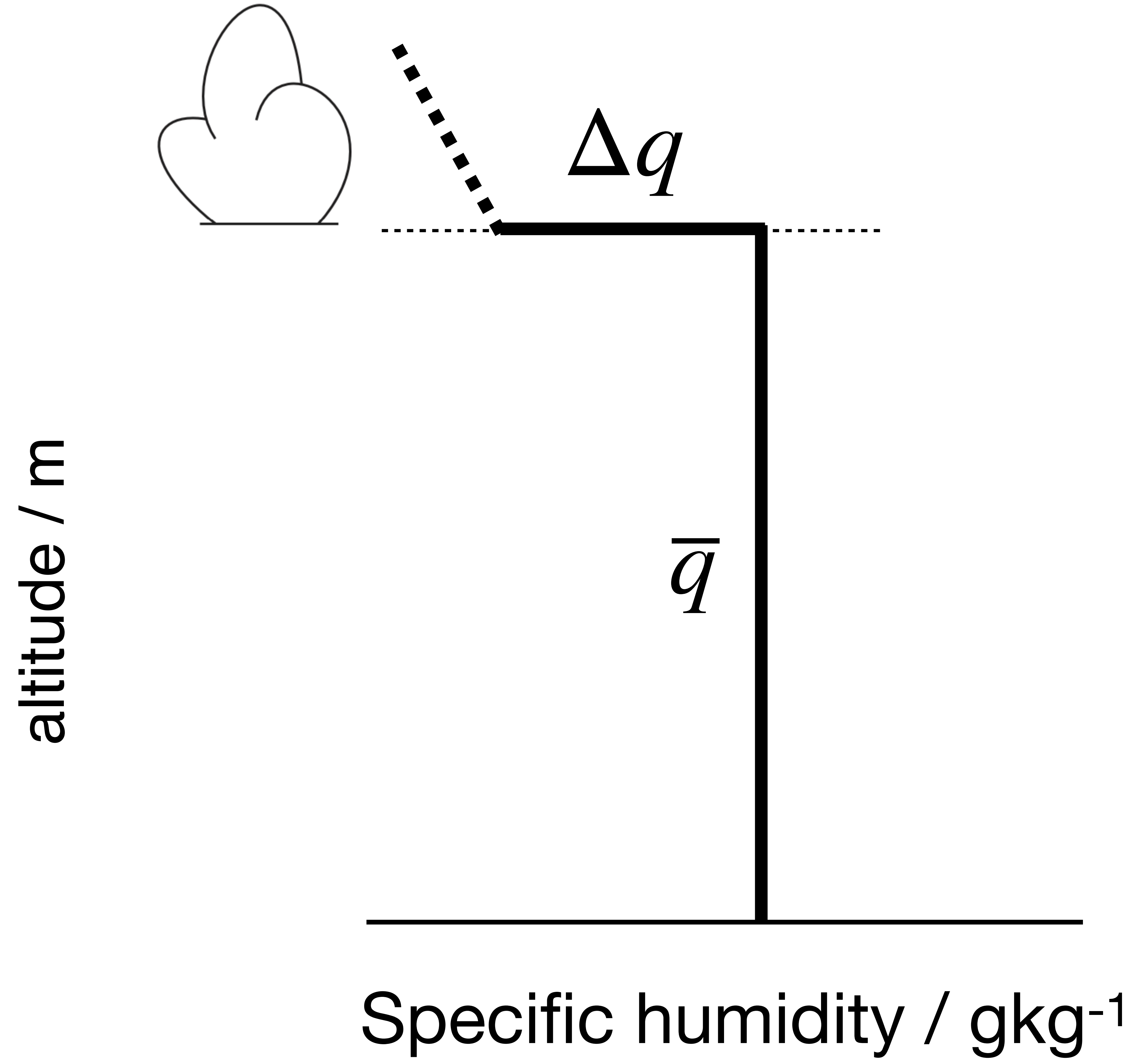
e.g., Malkus, 1958, Augstein, 1974, Yin & Albrecht, 2000

Mark Rothko, Blue and Grey (1962)

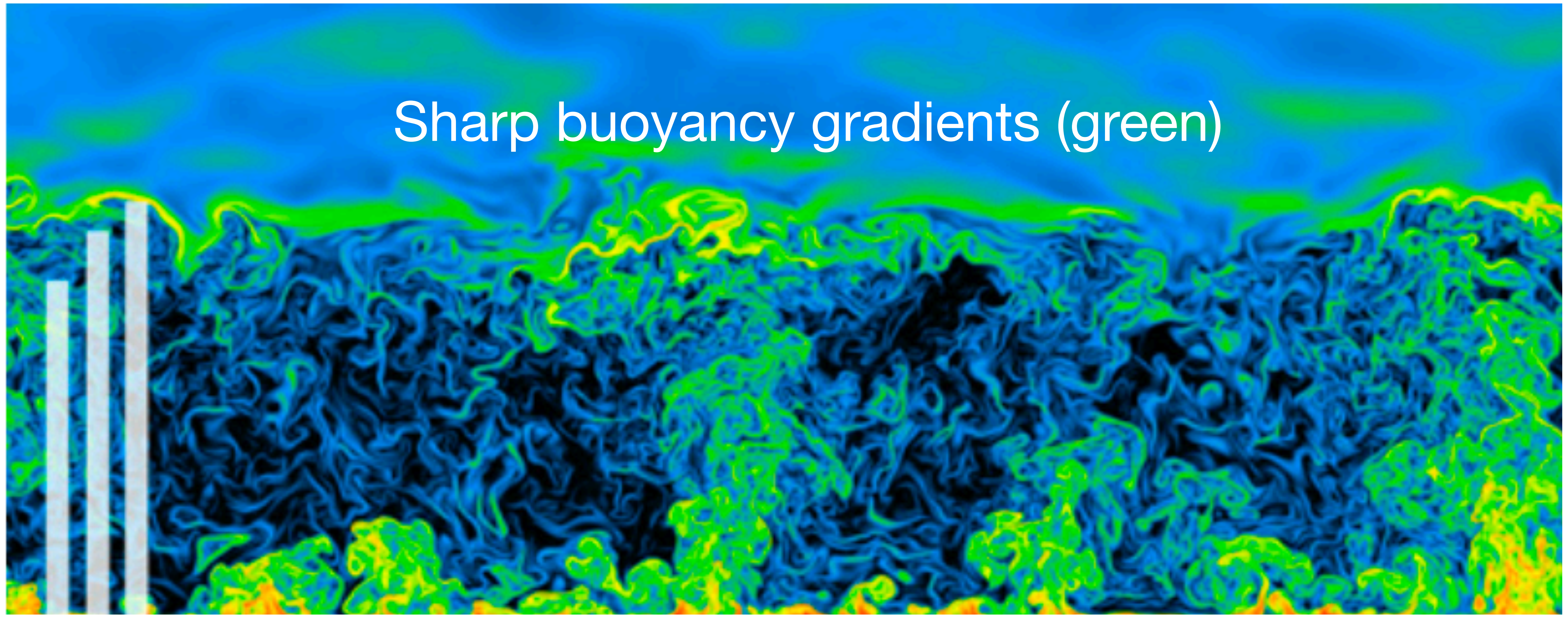


e.g., Malkus, 1958, Augstein, 1974, Yin & Albrecht, 2000

Common transition layer idealization (sharp gradients),
In analogy with StCu regimes or dry convective layers

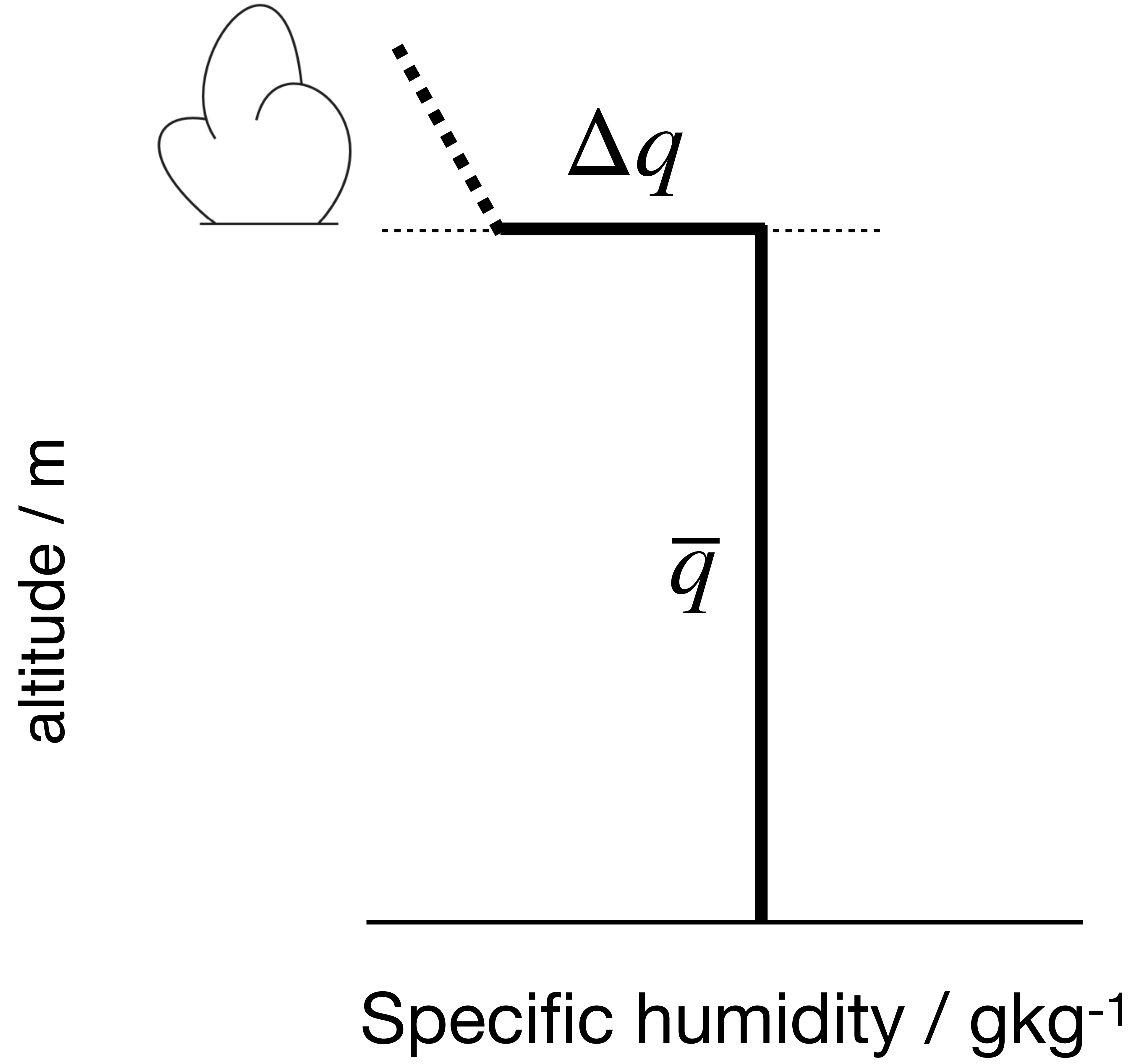


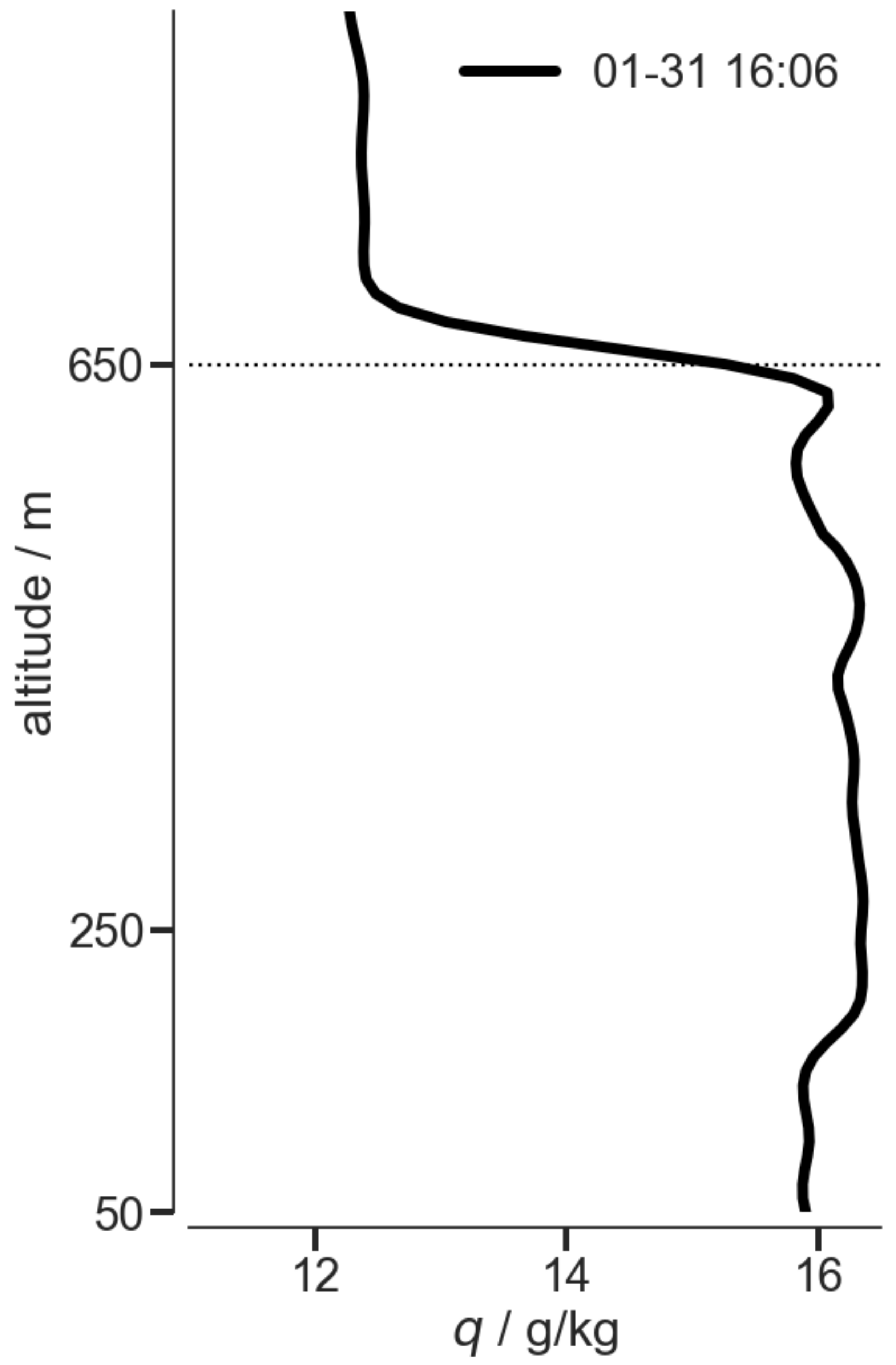
e.g., idealizations made in Lilly, 1968, Arakawa, Schubert, 1974, Betts, 1976, Albrecht, 1979, Stevens 2006



Direct numerical simulation results reproduced from Garcia & Mellado, 2014

How representative is this cloud-free structure?



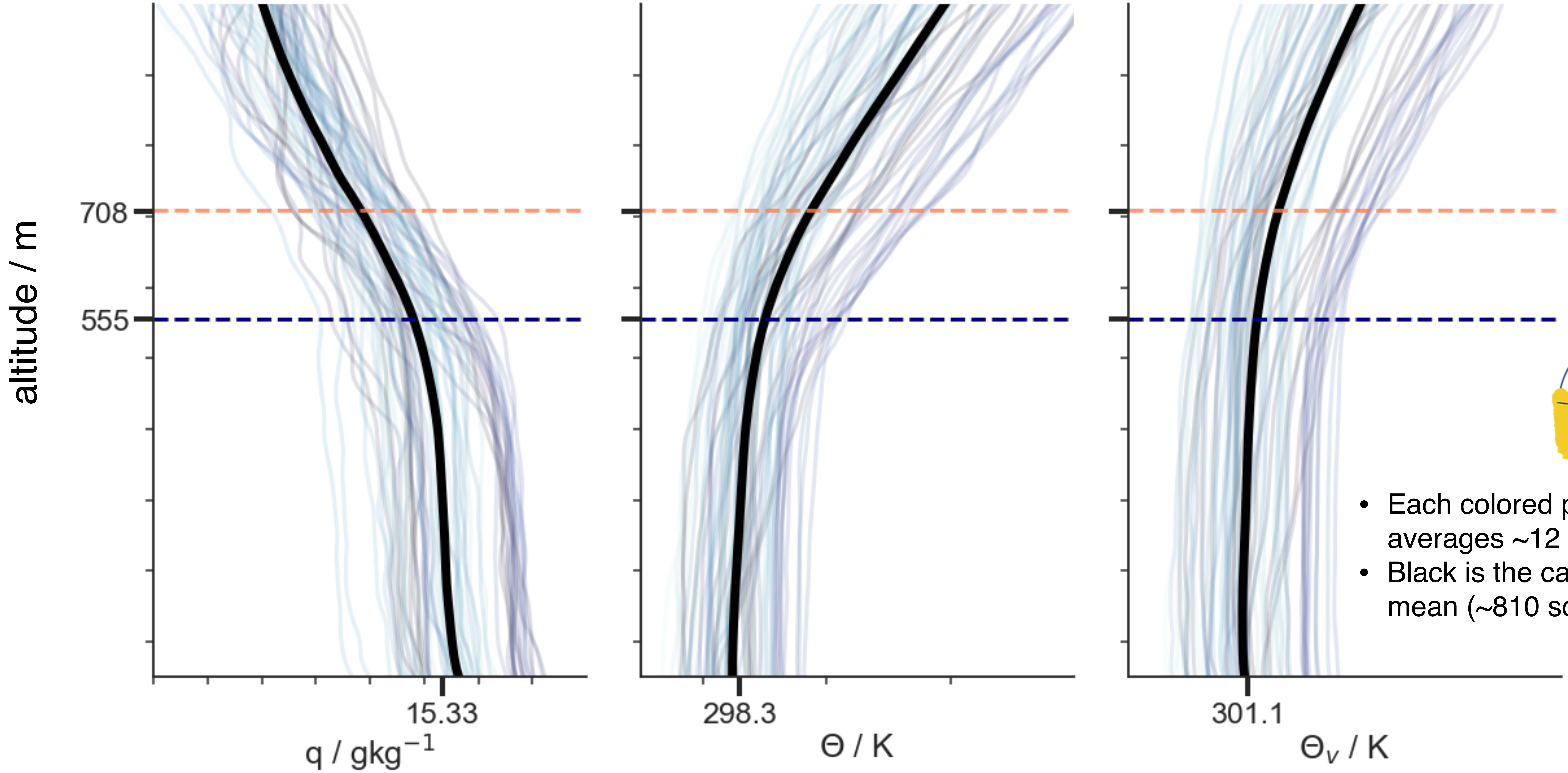


Single dropsonde sounding from EUREC^{4}A

Cloud-base cloud fraction measured from a lidar-radar synergy is small, 5.3±3.2% (Bony et al., 2022), so it appears reasonable that cloud-free transition layer structure could be the baseline

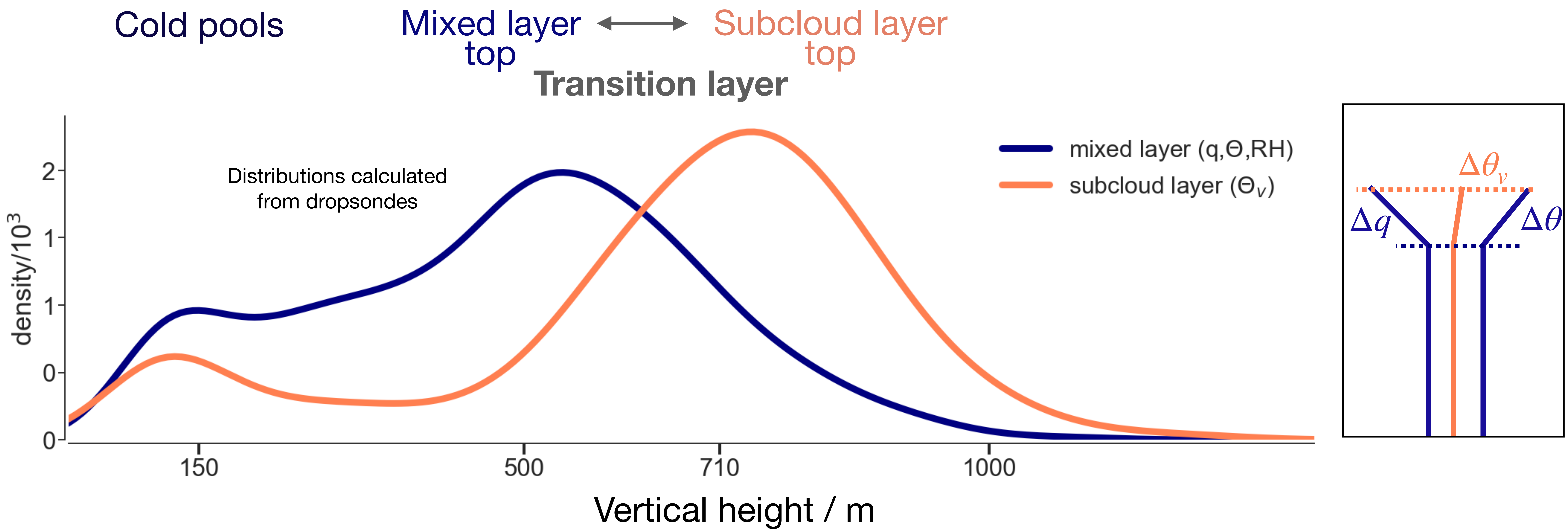
Most of the time, vertical gradients are smoother.
How to define transition layer from profiles?

Apply height definitions, e.g., Canut et al., 2012, to observed thermodynamic profiles



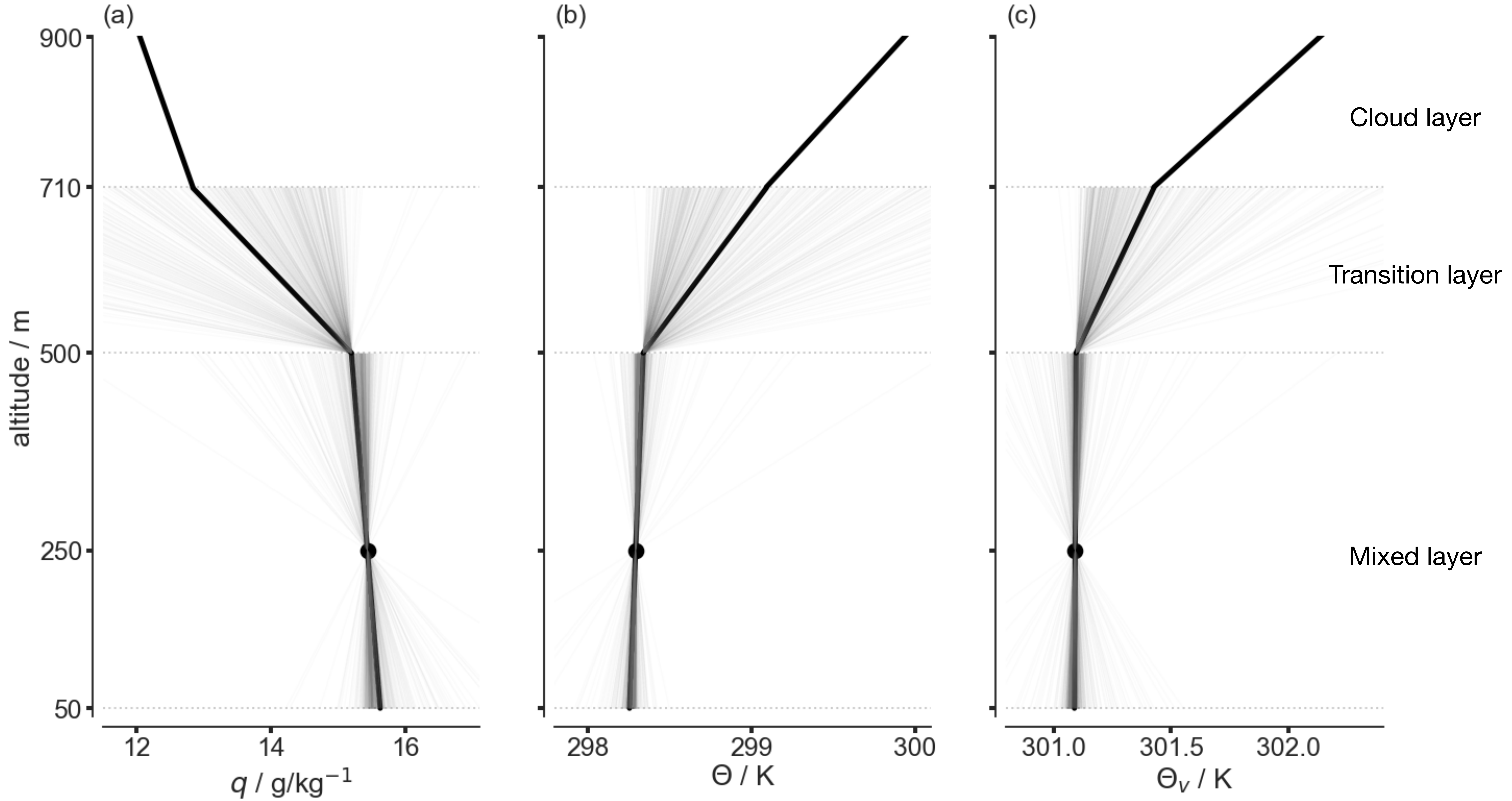
- Each colored profile averages ~12 dropsondes
- Black is the campaign-mean (~810 sondes)

Evidence for ~150-200 m thick transition layer between mixed and subcloud layer tops



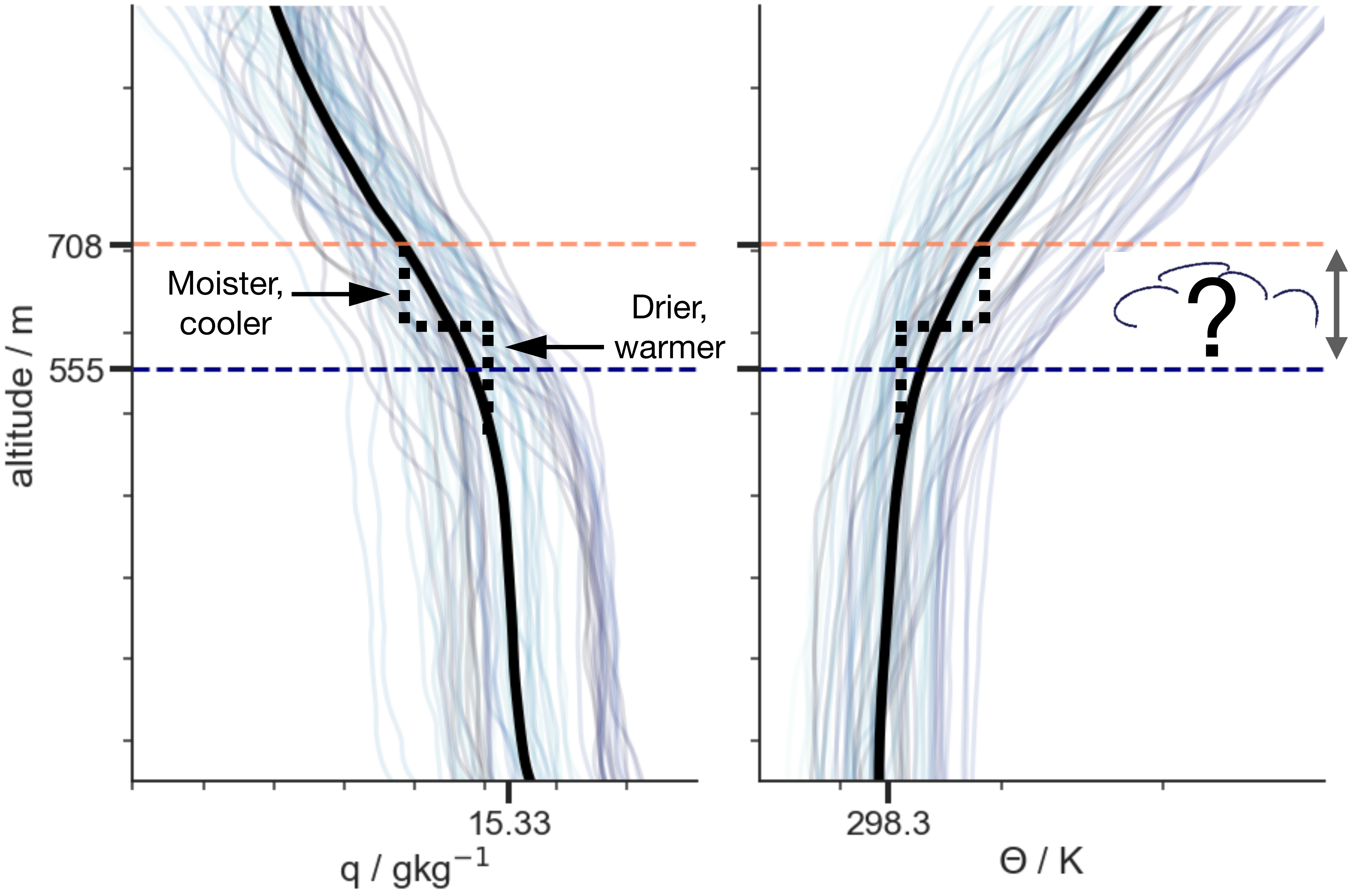
- Associate region between mixed layer and subcloud layer tops — that is better-mixed in θ_v than q, θ individually — with transition layer
- Methodology for identifying transition layer given in Albright et al., Observed subcloud layer moisture and heat budgets in the trades, JAS, 2022, + implications for modeling subcloud layer thermodynamics

Transition layer thermodynamic gradients differ from those in mixed and cloud layers (810 dropsonde profiles composited by layer; mean depths)



What produces the observed transition layer structure — thicker and with smoother gradients — compared to jump structure?

Does life cycle (condensation-evaporation dipole) of very small clouds smooth vertical gradients in transition layer?



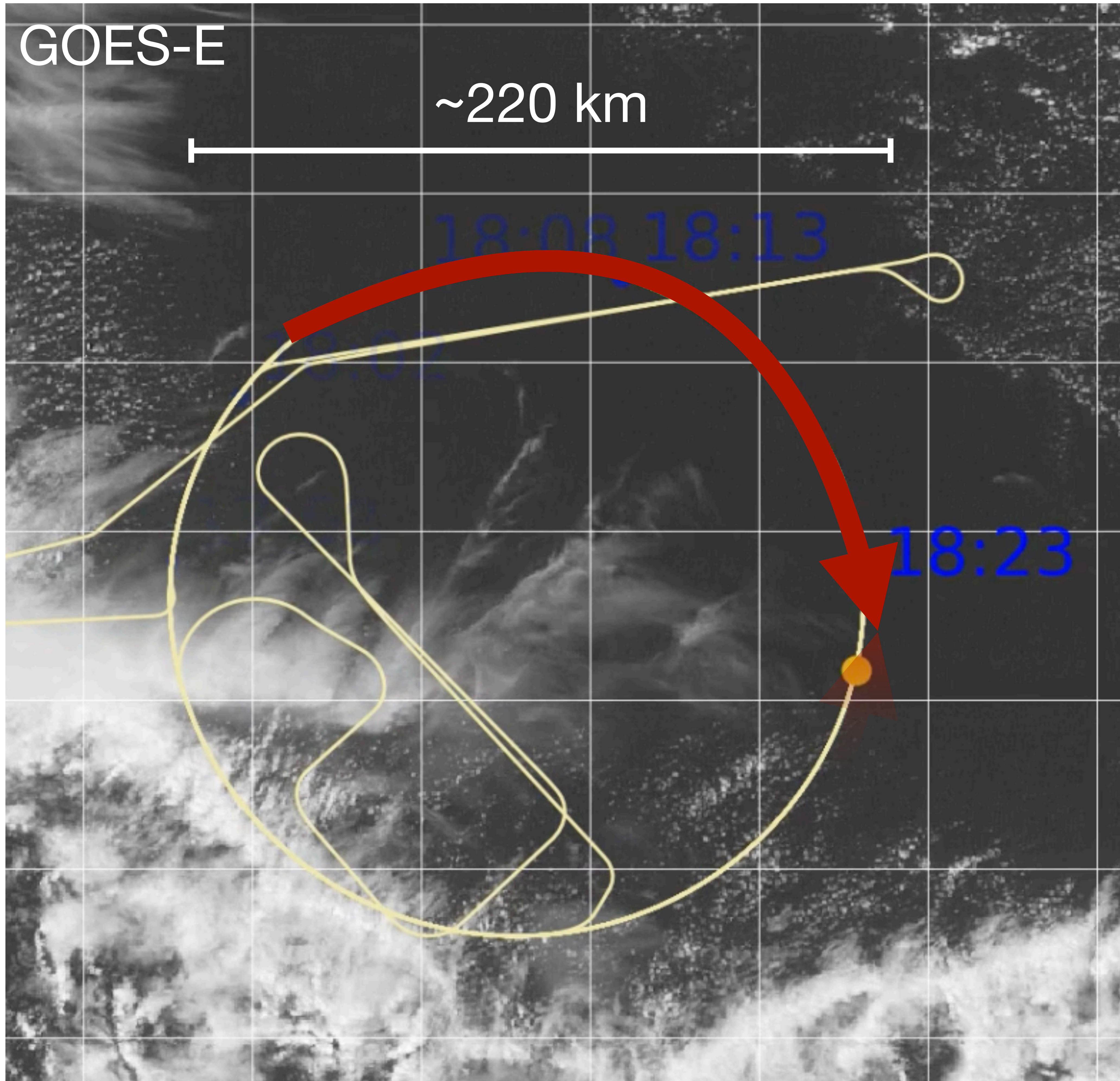
- About 60% of cloud bases (three-hourly ceilometer data) and ~75% LCLs (from sondes) below transition layer top
- Another way of defining the transition layer is between cloud base and maximum cloud-base cloudiness level (cf. Vogel et al., 2022)

Cf. cloud based above the transition layer in Malkus, 1958; Augstein, 1974; but within transition layer in Neggers et al., 2009, Gentine et al., 2013

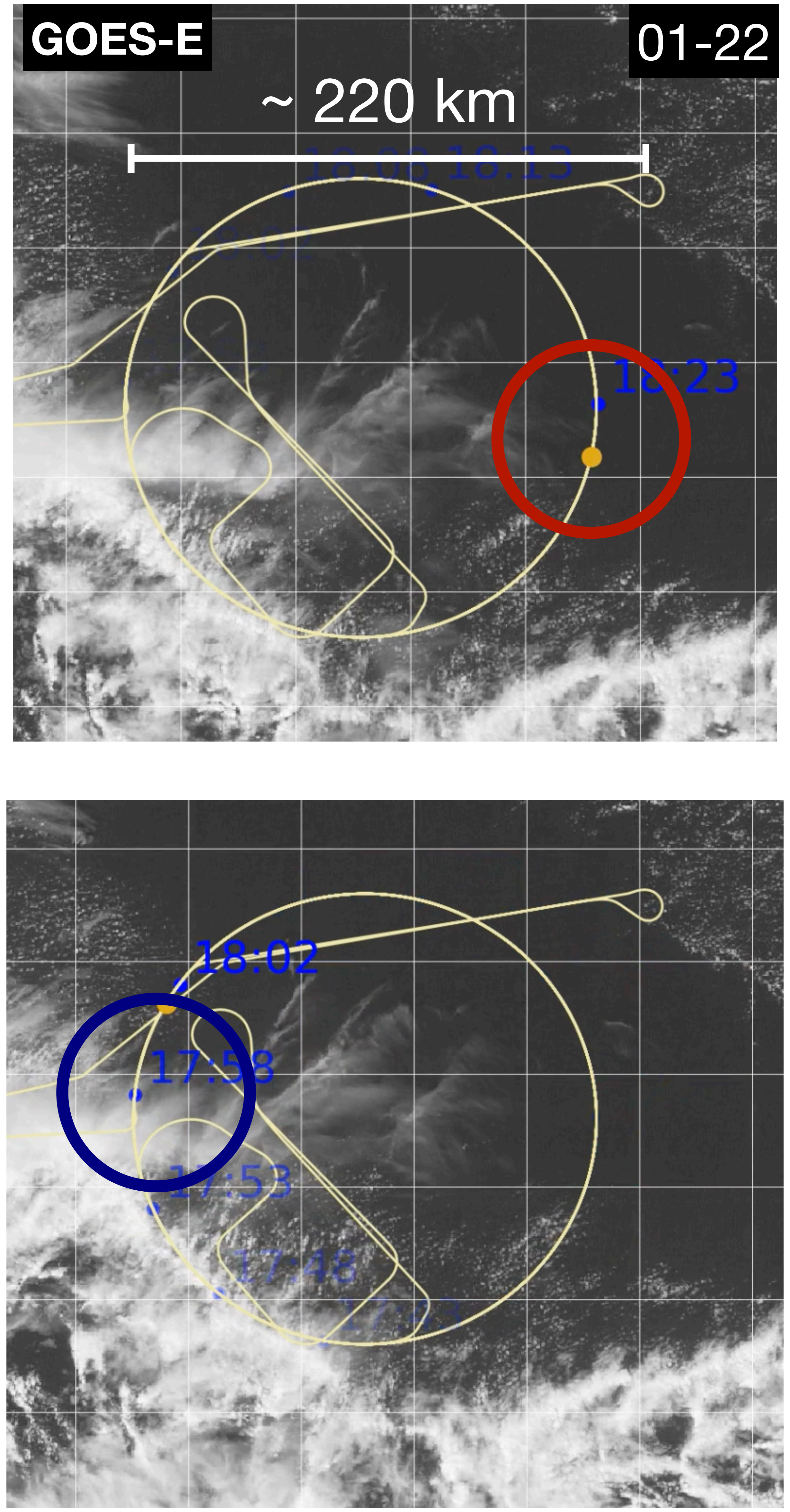
Test using denial of mechanism — examine transition layer structure in **large clear-sky areas**

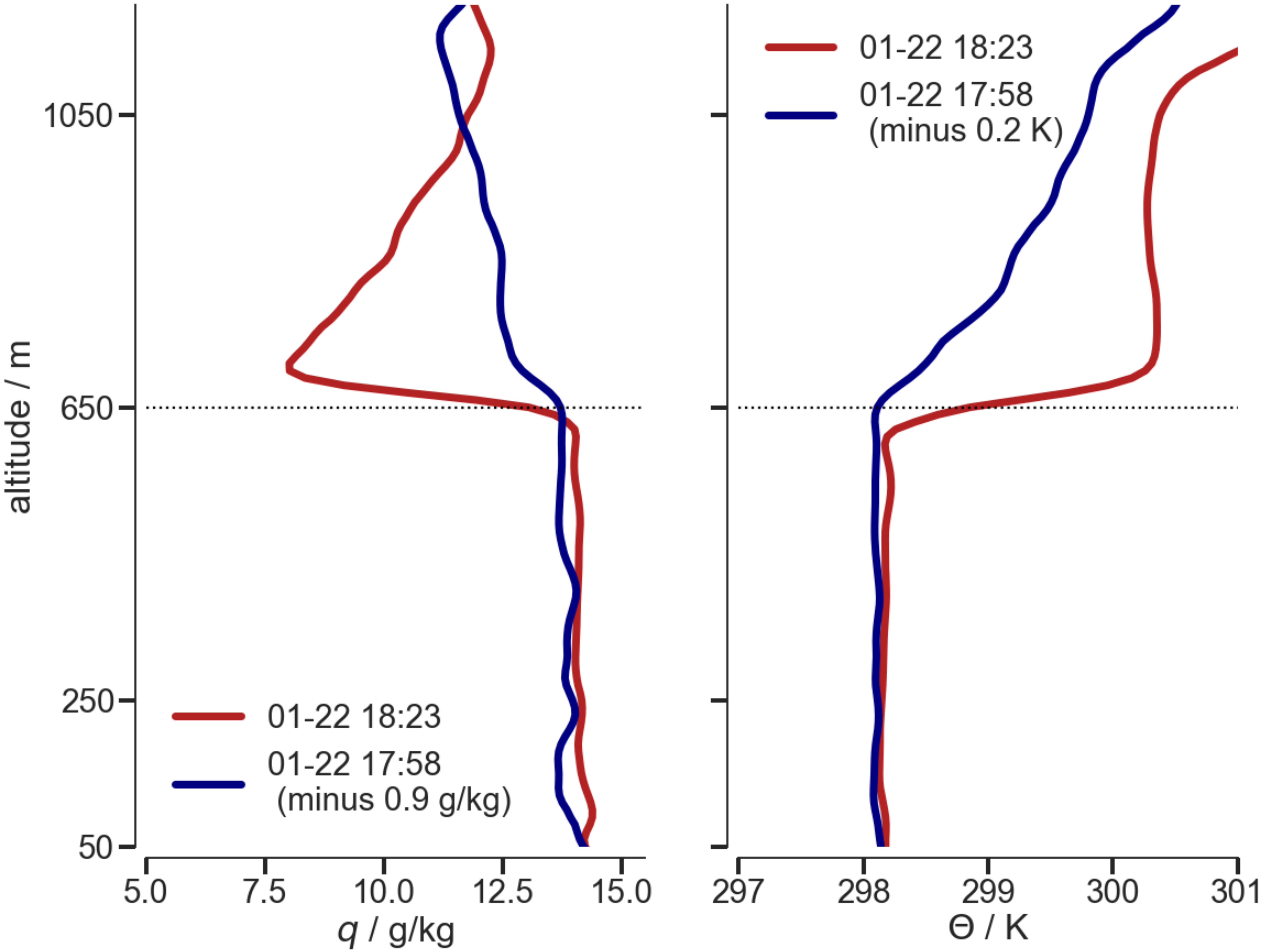
defined:

1. by eye, within patterns of cloud organization, identified from satellite images
2. as cloud-free over ~200 km of flight path (15 minutes of flying) using cloud flags and cloud top heights from WALES lidar
3. using large-eddy simulation output from Dauhut et al., 2022



Sharp gradients exist, but rarely, and in large clear-sky areas





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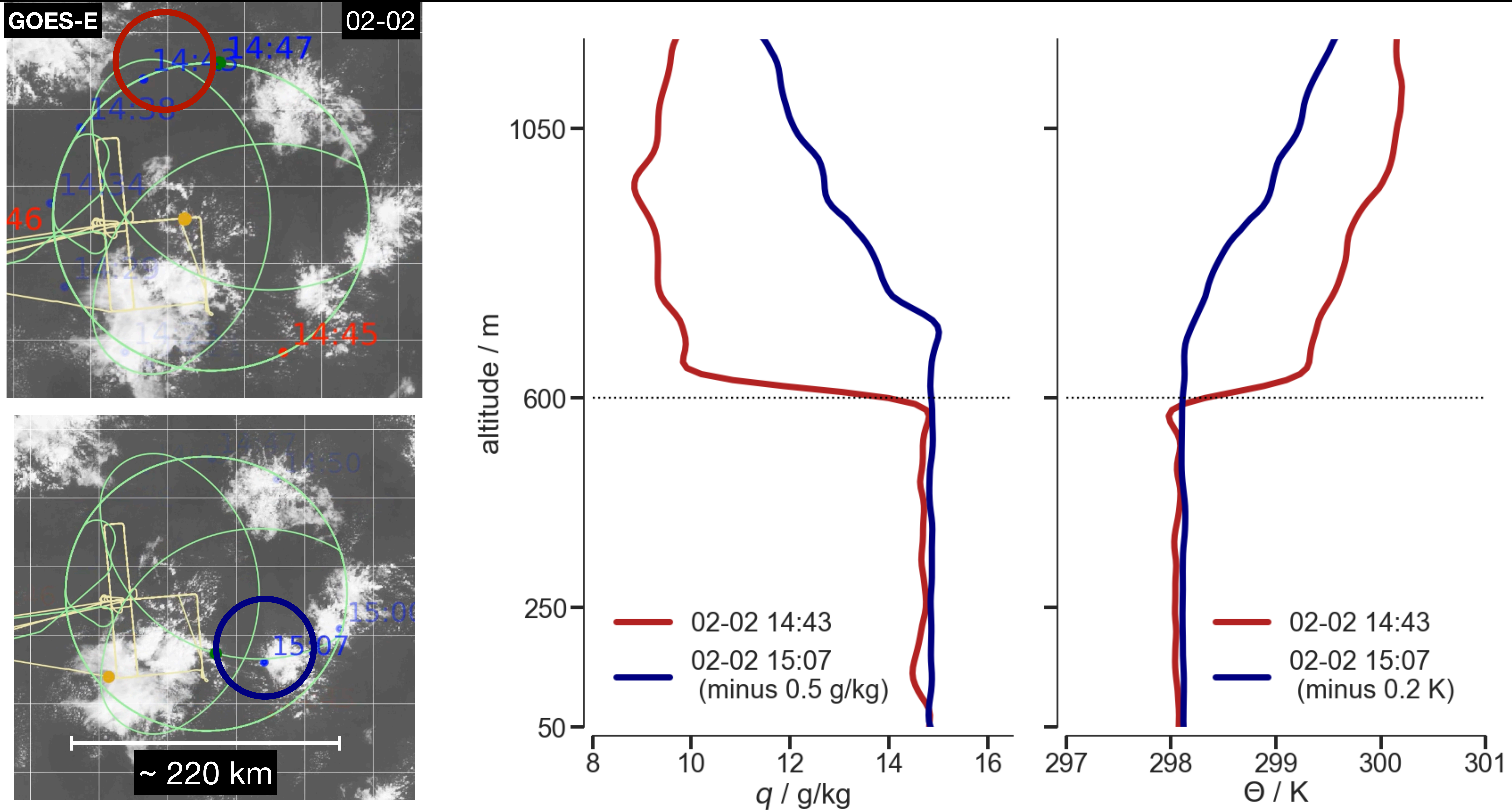
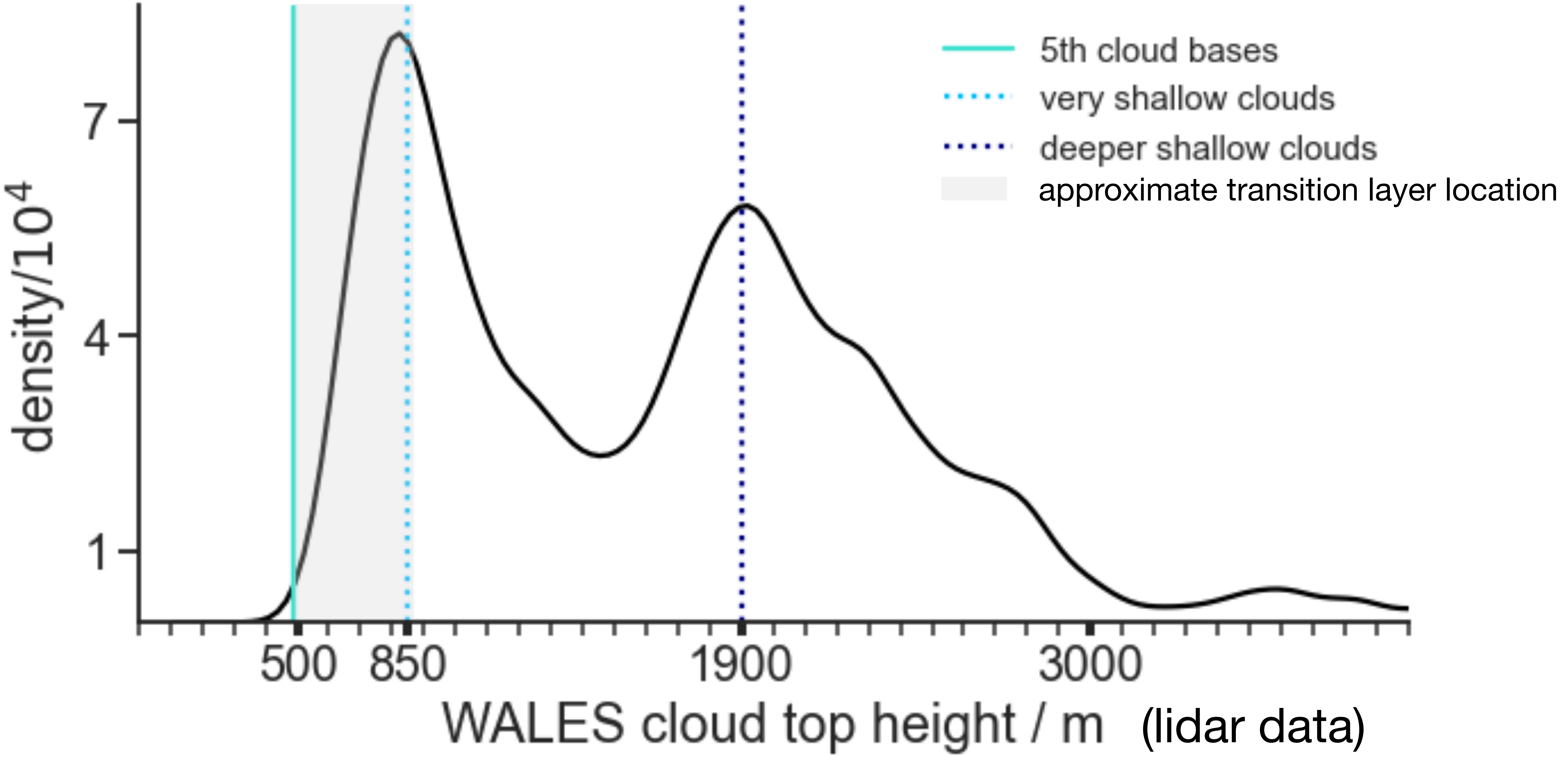


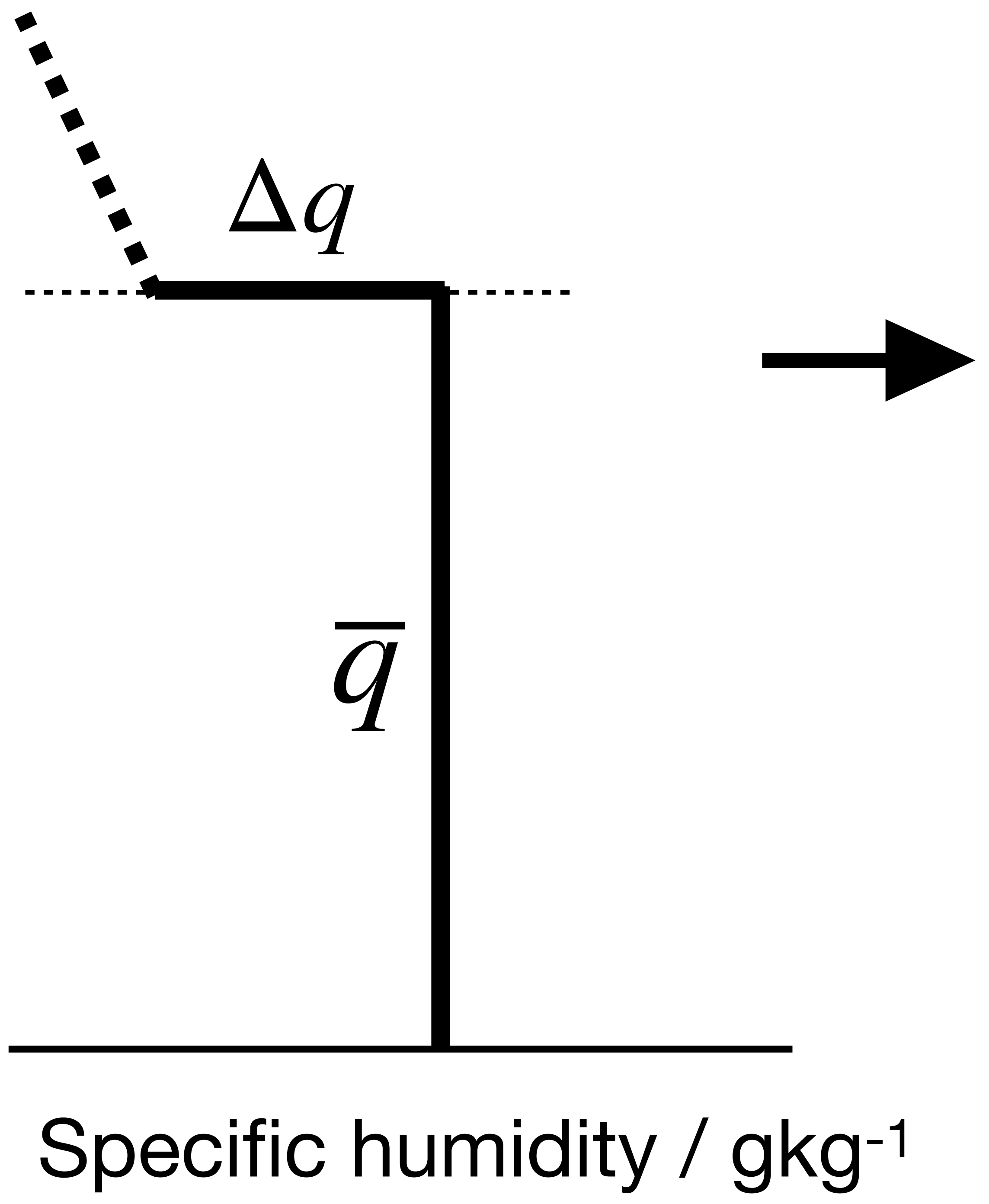
Very shallow clouds are ubiquitous.
Are they associated with smoother gradients?



Two cloud populations seen in satellite retrievals (e.g., Genkova et al. 2012, Leahy et al., 2012, Mieslinger et al., 2019), but with ~250-500 m observational uncertainties. Cf. also Vial et al, 2023

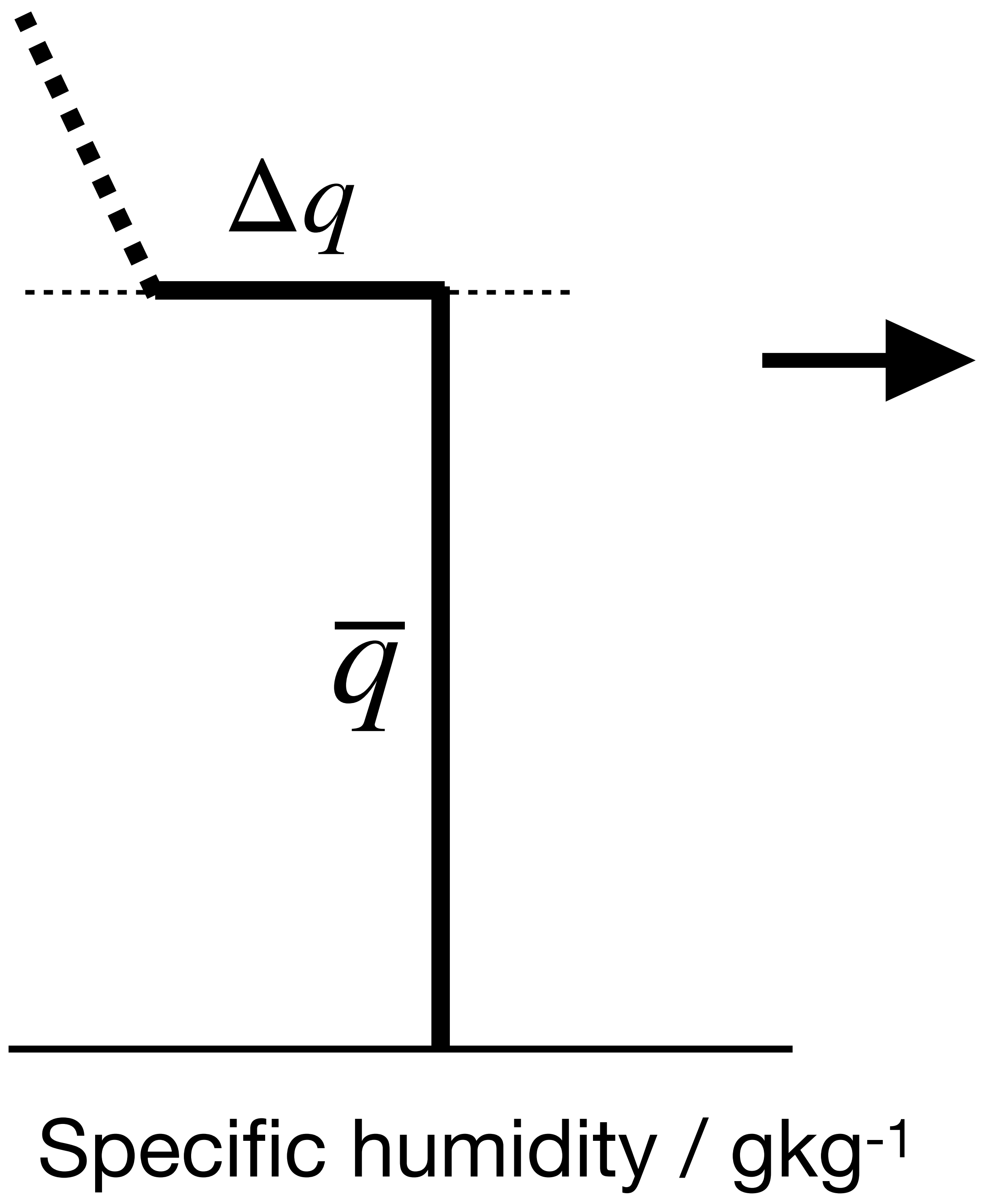
Proxy for transition layer structure

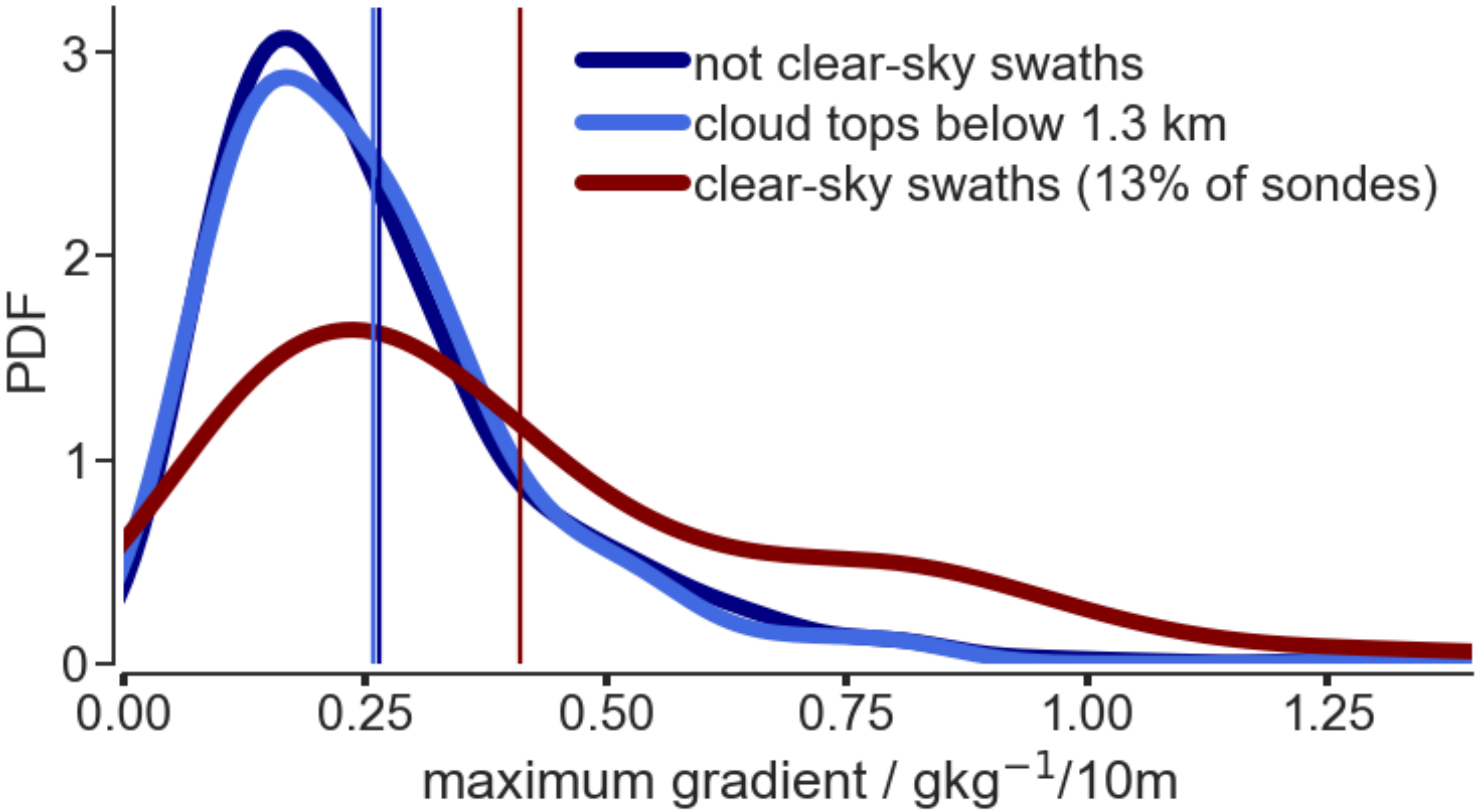
Select sharpest vertical gradient b/t 300-800 m



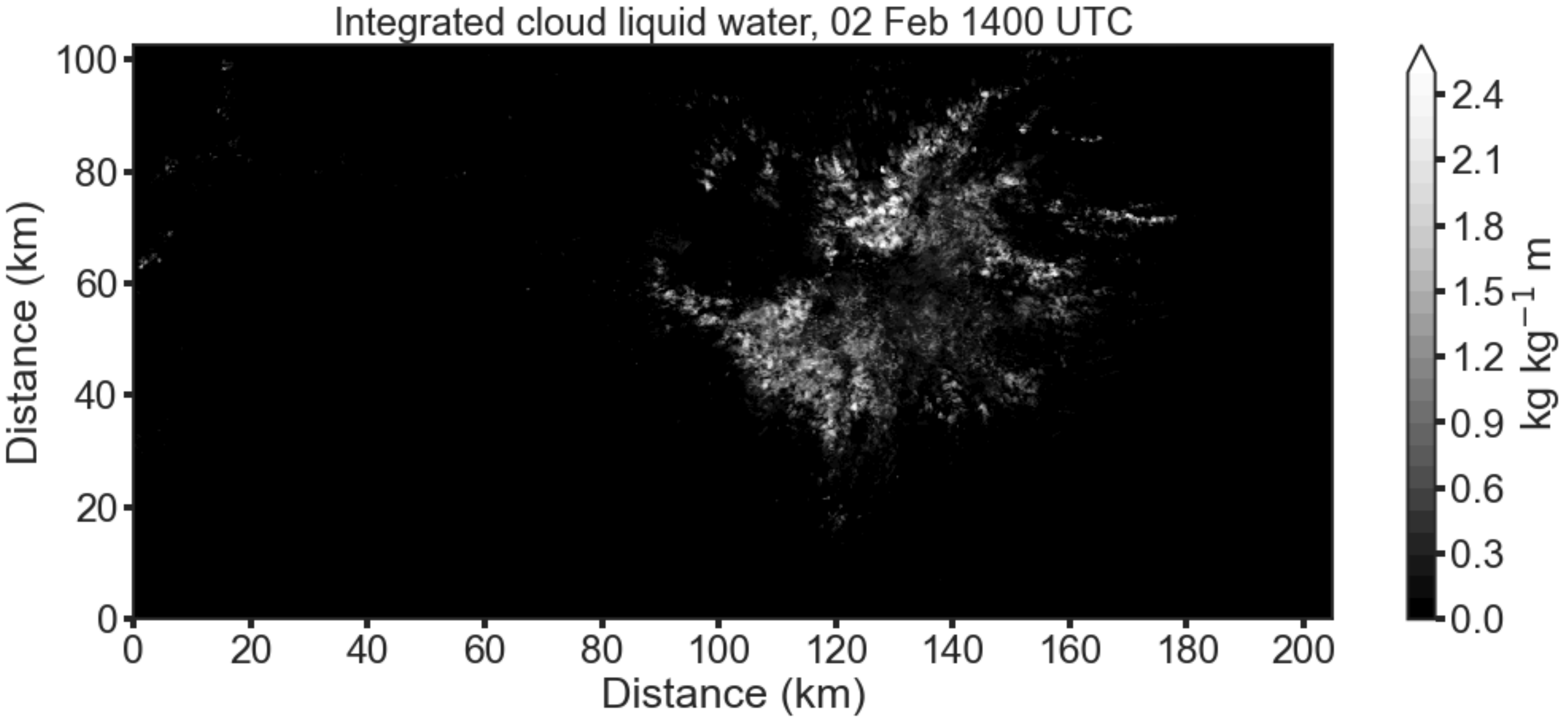
Large clear-sky areas (red) exhibit stronger vertical gradients

Select sharpest vertical gradient b/t 300-800 m





A similar picture in large-eddy simulation output



LES simulation output from Dauhut et al., 2022 QJRMS,
100 m (horizontal); 40 m (vertical)

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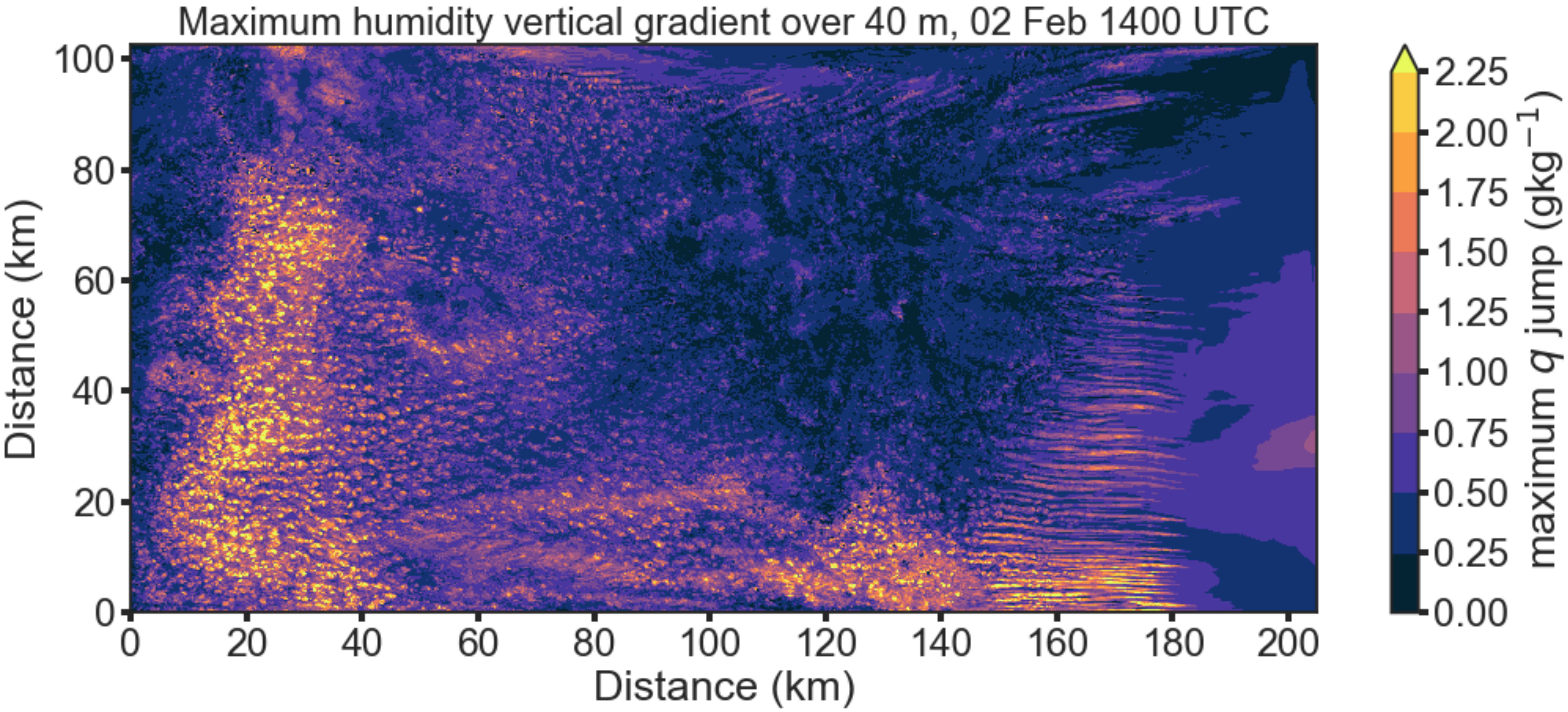
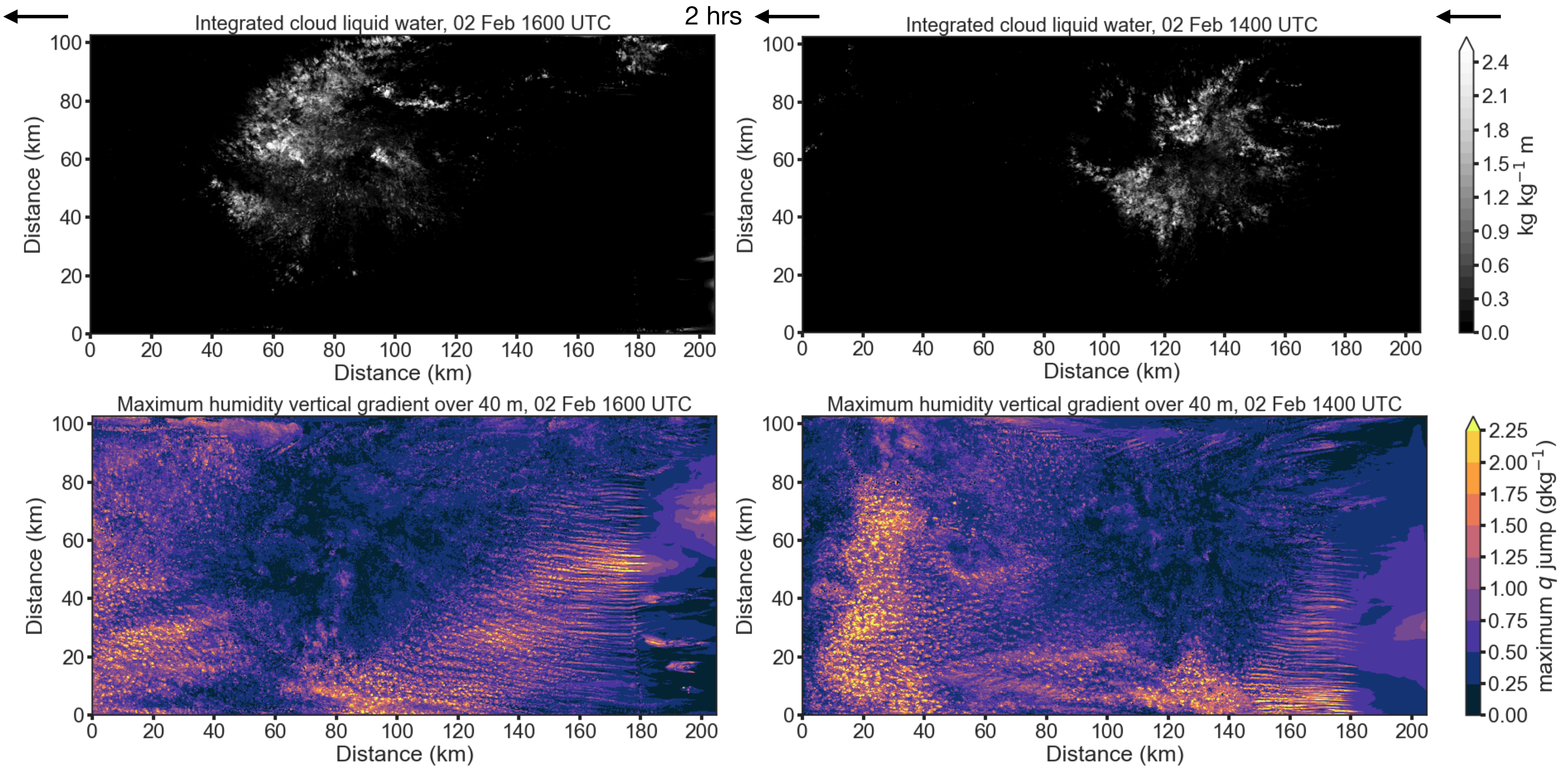


LES simulation output from Dauhut et al., 2022 QJRMS,
100 m (horizontal); 40 m (vertical)

Find weak correlation b/t transition layer gradients & mesoscale subsidence (max. r~0.3 with ω_{2km})

Larger transition layer gradients with distance to cloud center of mass, evolving over time; confirmed by random forest analysis



Inferences from EUREC^{4}A observations and LES

1. Jump-like transition layer structure found in large (O(200 km)) cloud-free areas

2. Strength of transition layer gradients only weakly associated with subsidence strength, maximizing at 2 km (r~0.3)

3. Shallow population of clouds creates transition layer structure by a condensation-evaporation dipole — **active role for very shallow clouds** that is missing from our previous conceptualization

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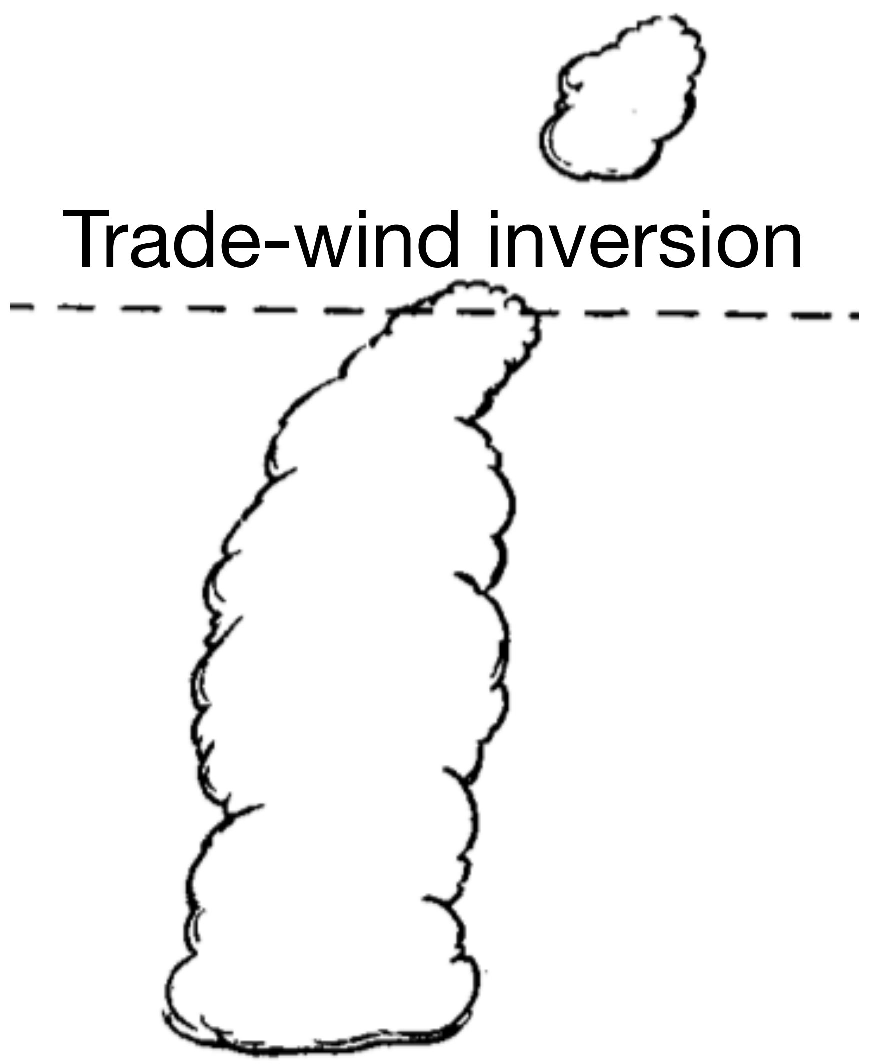
4. Inferences from mixed layer theory and mixing diagrams suggest that differences in cloud-free and cloudy transition layer structures do not affect the rate of entrainment mixing, but rather the properties of the air incorporated into the mixed layer, primarily as a moistening (not shown)

Connections to cloud organization and shallow to deep cloud transition

1. **Interplay between very shallow and deeper shallow clouds**, with each population growing its own layer (cf. Riehl, 1951, Stevens, 2007). Do smaller clouds make it easier for larger clouds to form (cf. Neggers et al, 2015) and organize, and on what timescale?



Riehl et al, 1951

Photo by Frédéric Batier, 2020

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2. **Contribution to the energetics of entrainment mixing**:
   - Additional contribution to entrainment mixing based on ability to detrain condensate into the overlying stable layer, in addition to surface buoyancy fluxes, wind shear, radiative cooling
   - Cloud-free mixed layer theory, such as for entrainment rate closures, is still skillful with appropriate modifications reflecting finite-thickness transition layer (cf. Albright et al., 2022)

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Thank you

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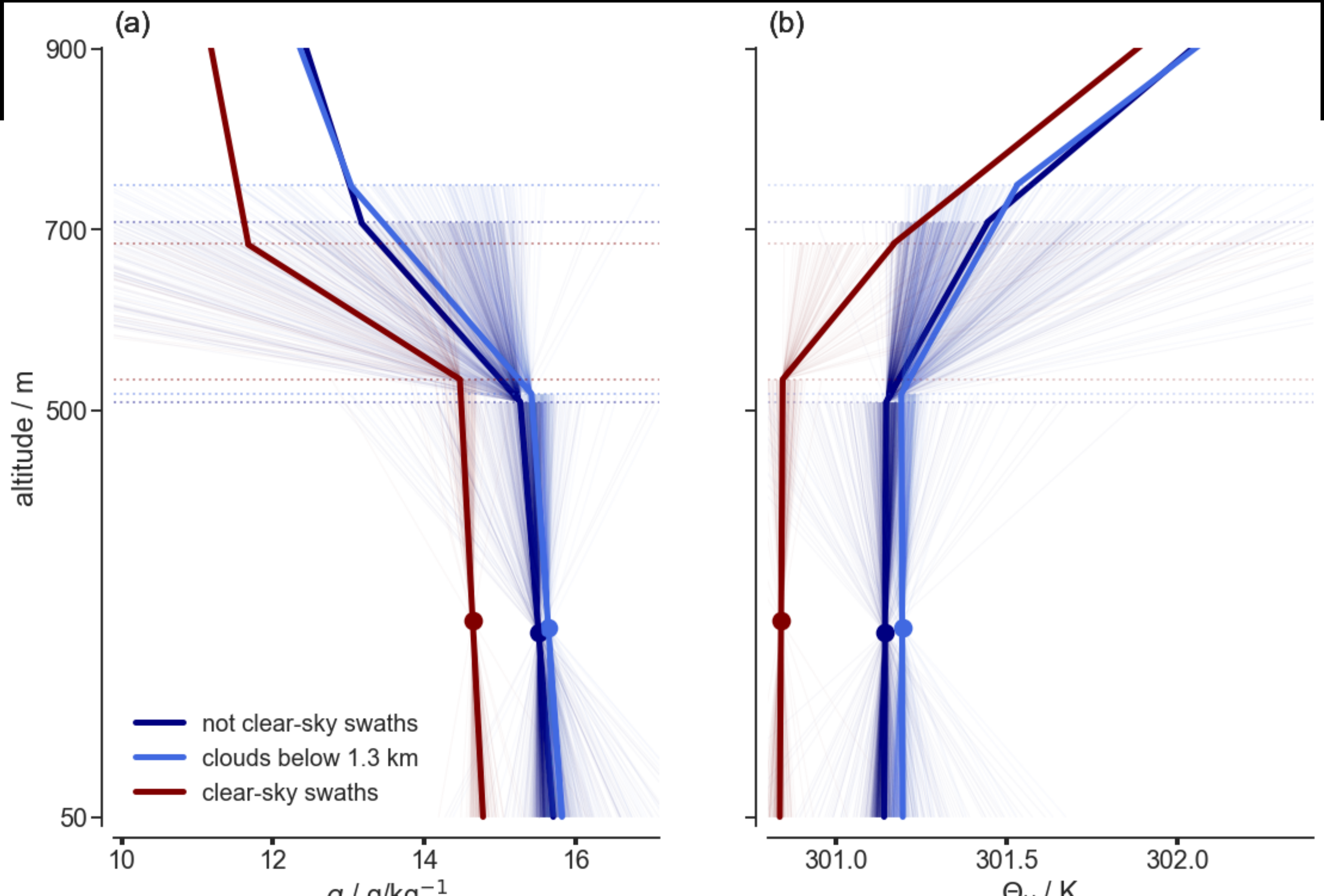
Related personal references

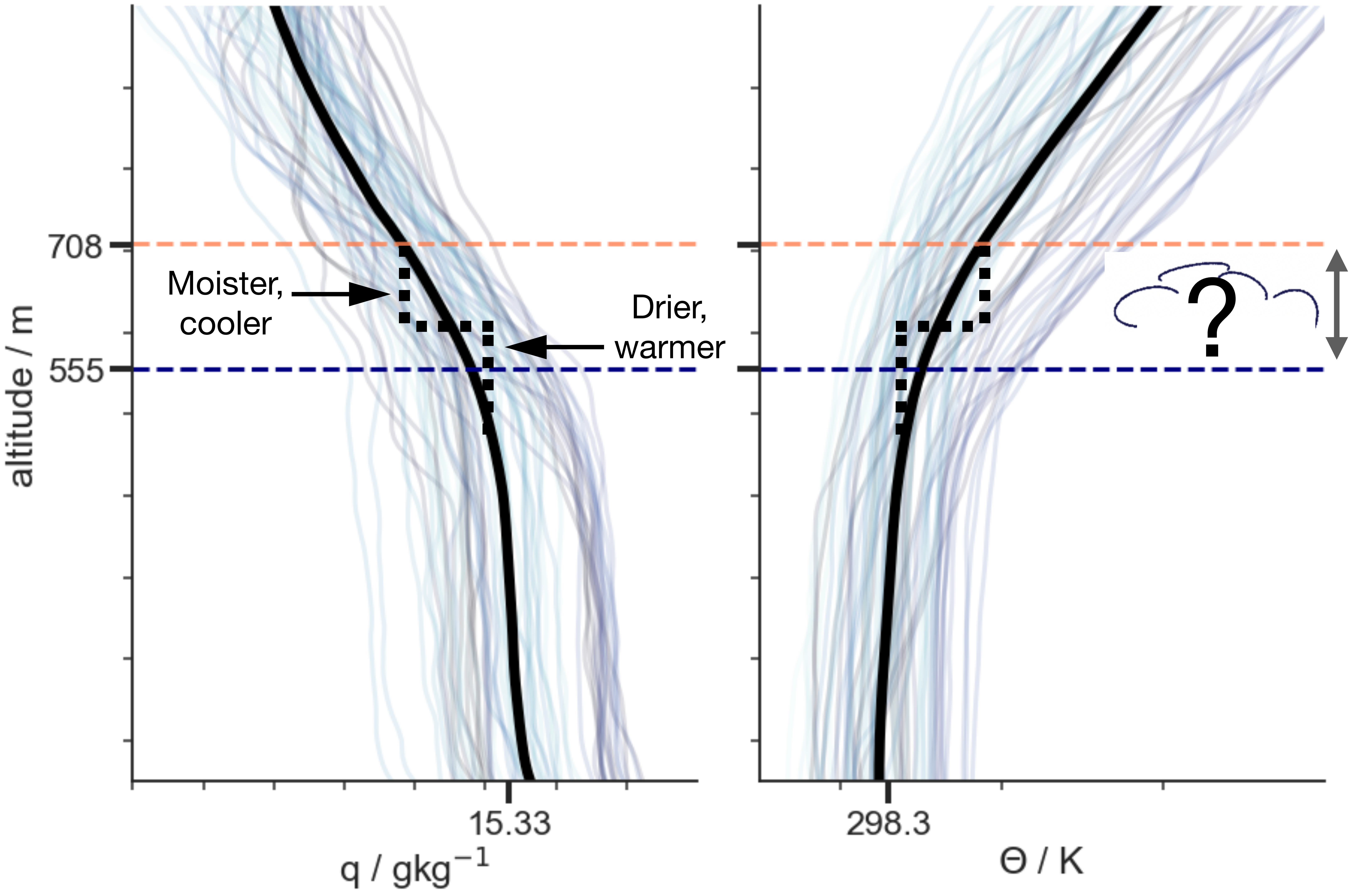
Albright, A. L., Fildier, B., Touzé-Peiffer, L., Pincus, R., Vial, J., & Muller, C. (2021). Atmospheric radiative profiles during EUREC4A. Earth System Science Data, 13(2), 617-630
Albright, A. L., Bony, S., Stevens, B., & Vogel, R. (2022). Observed subcloud layer moisture and heat budgets in the trades. Journal of the Atmospheric Sciences
Albright, A. L., Stevens, B., Bony, S., & Vogel, R (2023). A new conceptual picture of the trade-wind transition layer. Journal of the Atmospheric Sciences

Additional slides



(a)
(b)
900
700
500
50
altitude / m
10
12
14
16
301.0
301.5
302.0
not clear-sky swaths
clouds below 1.3 km
clear-sky swaths

Does life cycle (condensation-evaporation dipole) of very small clouds smooth vertical gradients in transition layer?



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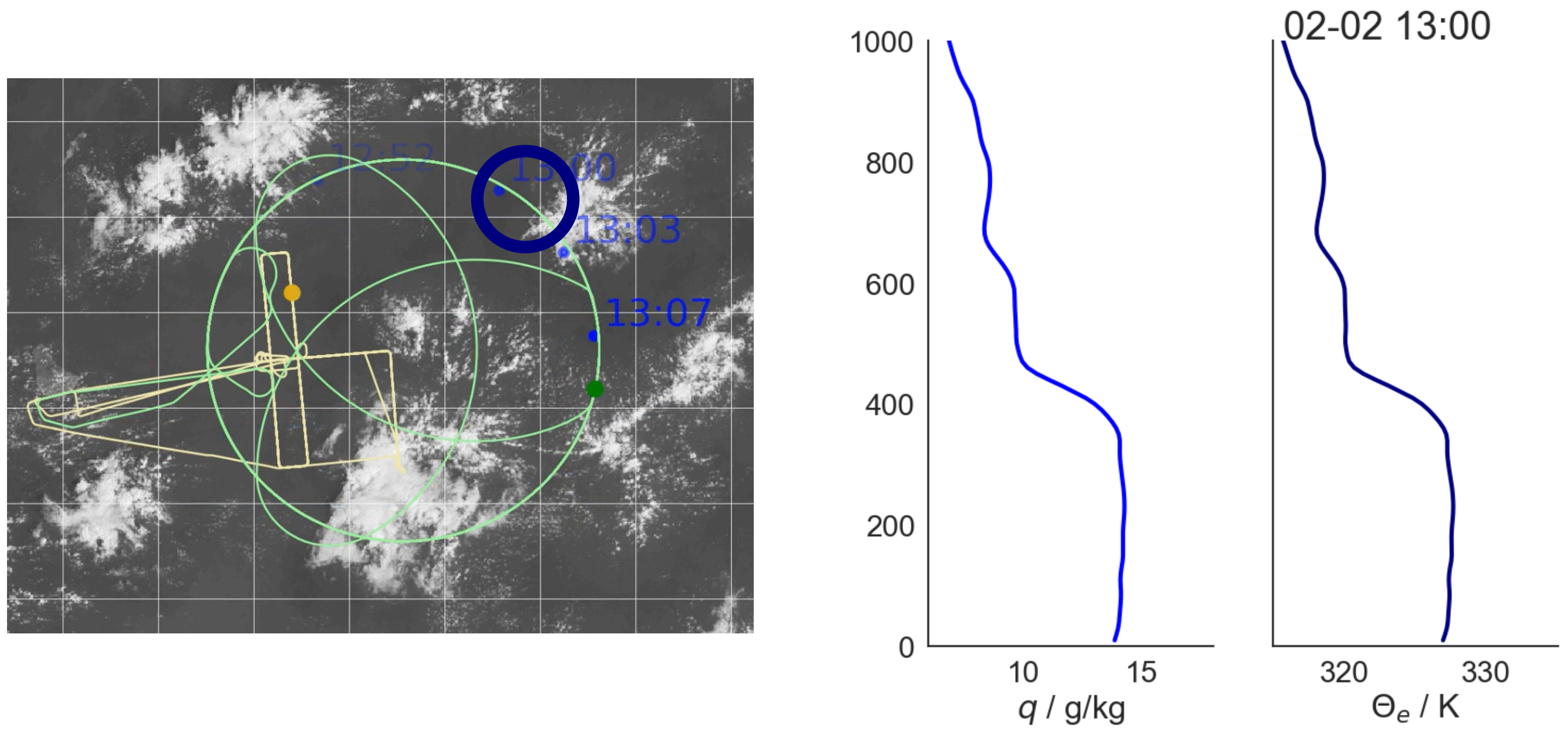
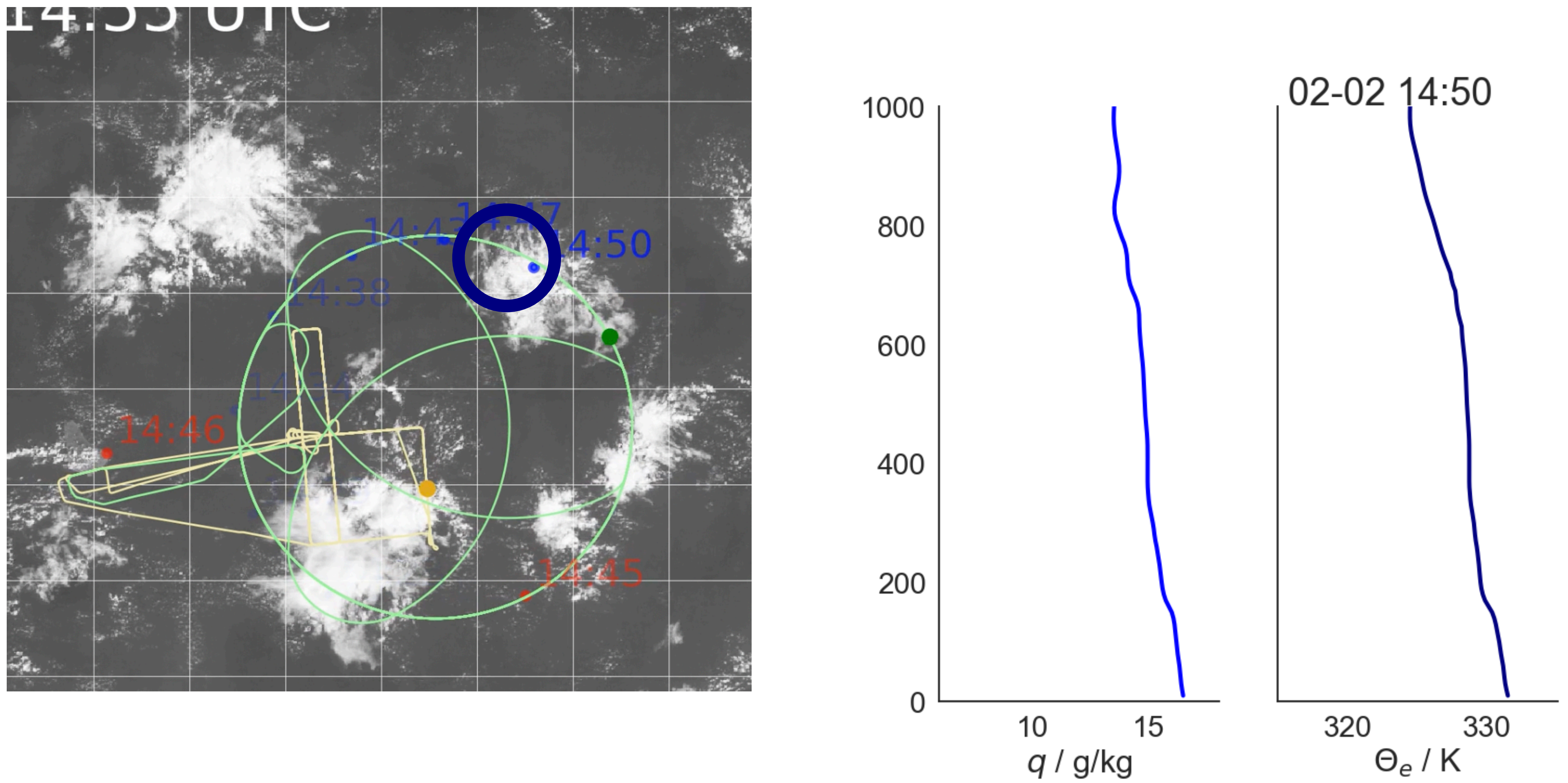
Cf. cloud based above the transition layer in Malkus, 1958; Augstein, 1974; but within transition layer in Neggers et al., 2009, Gentine et al., 2013

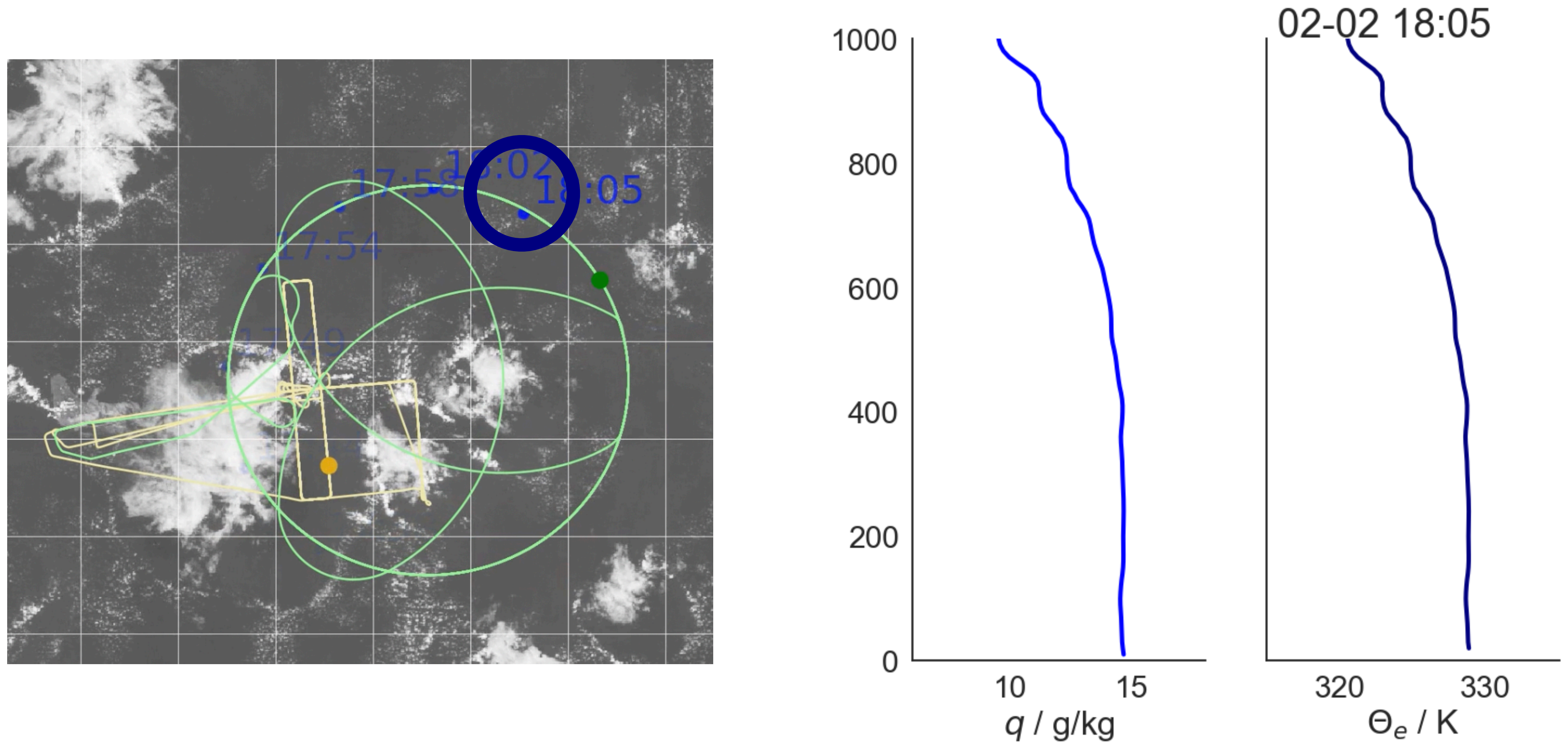
(1) Cloud-free boundary layer



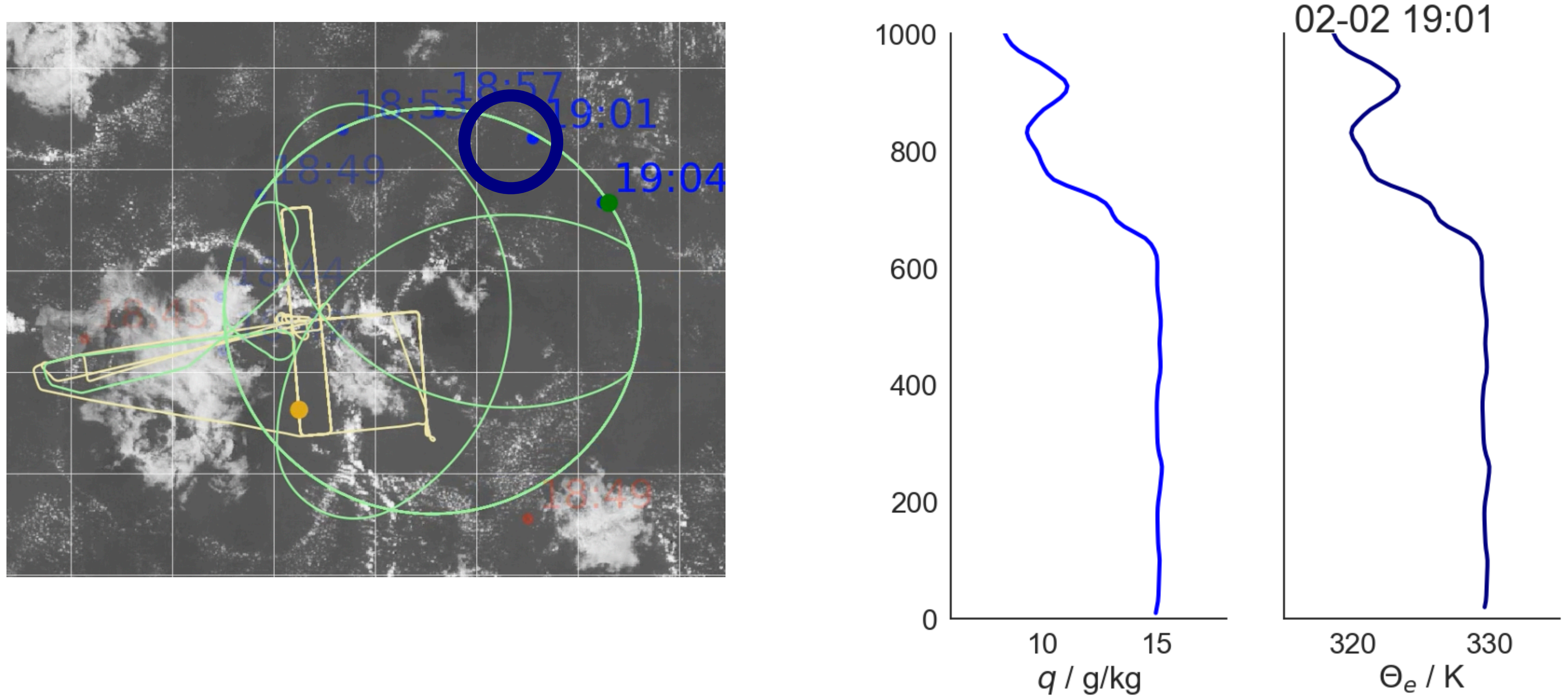
(2) Cloudy convective boundary layer



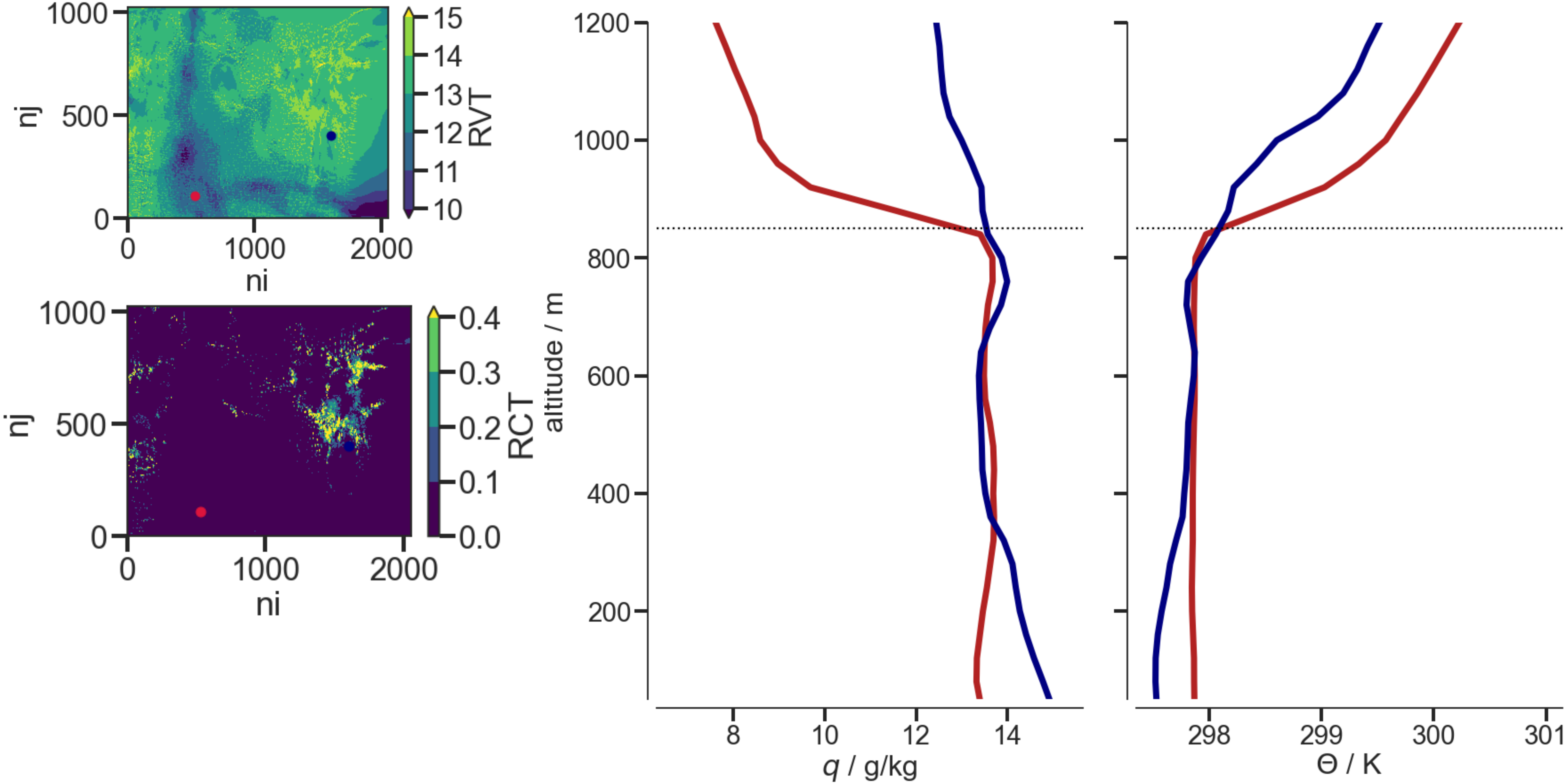
(3) No longer cloudy, but influenced by dissipated clouds



(4) Restoration towards cloud-free boundary layer



Jumps in Thibaut's LES



Do differences in transition layer structure matter for mixed layer state & surface fluxes?

- Inferences from mixed layer theory and mixing diagrams (not shown, following Paluch, 1979) suggest that the observed transition layer structure does not strongly affect the **rate of entrainment mixing**
- Rather, it influences the **properties** of the air incorporated into the mixed layer, primarily as a **moistening**

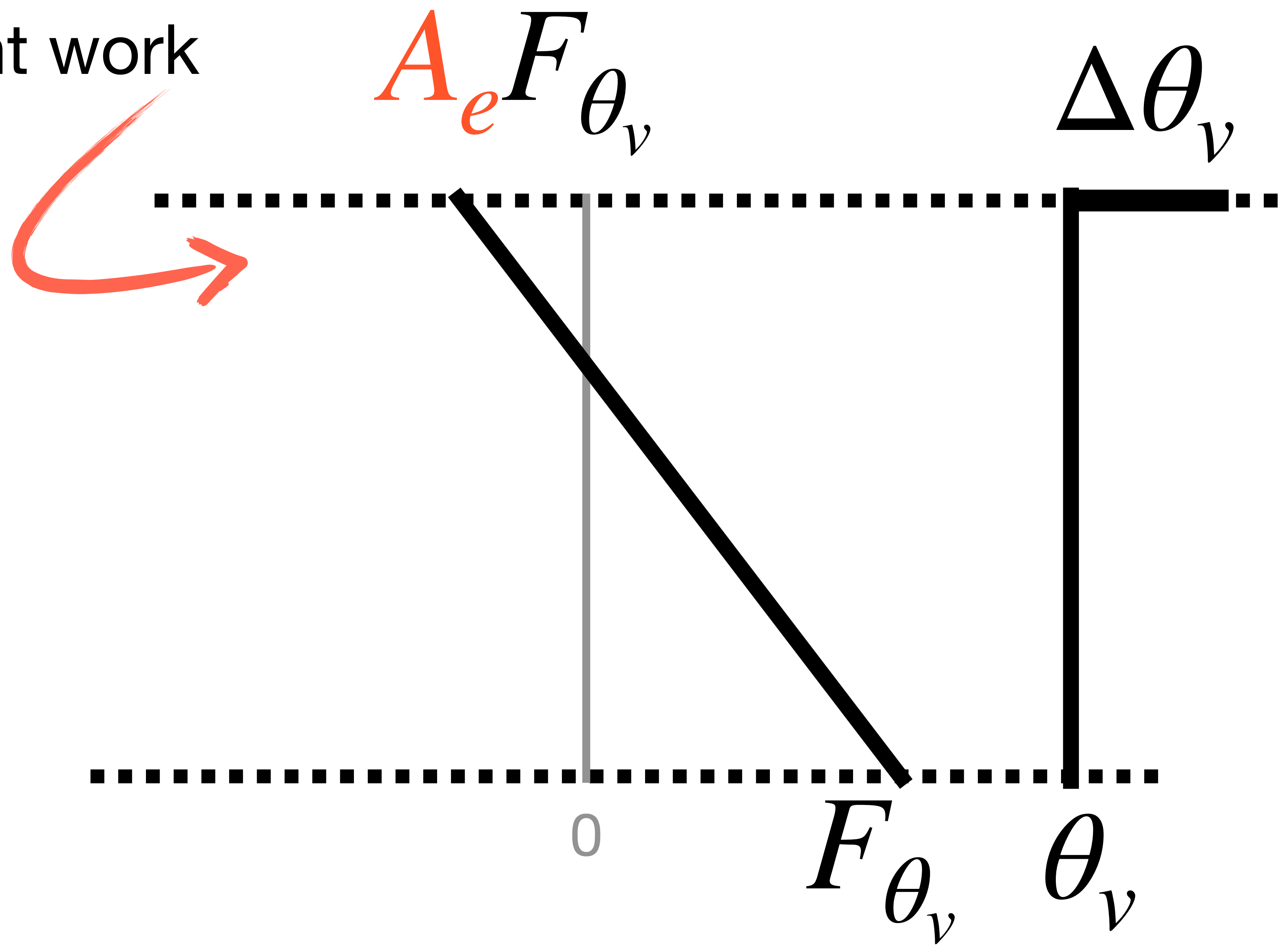
Contributions to energetics of entrainment mixing

$$E = \frac{dh}{dt} = \frac{A_e F_{\theta_v}}{\Delta_1 \theta_v}$$

Convert turbulence energy to potential energy

e.g., Ball, 1960, Lilly, 1968, Betts, 1973, Tennekes, 1973, Deardorff, 1974, Stull, 1976, Stevens 2006

‘Harvesting’ some portion of surface turbulence flux to do entrainment work



Surface turbulence flux

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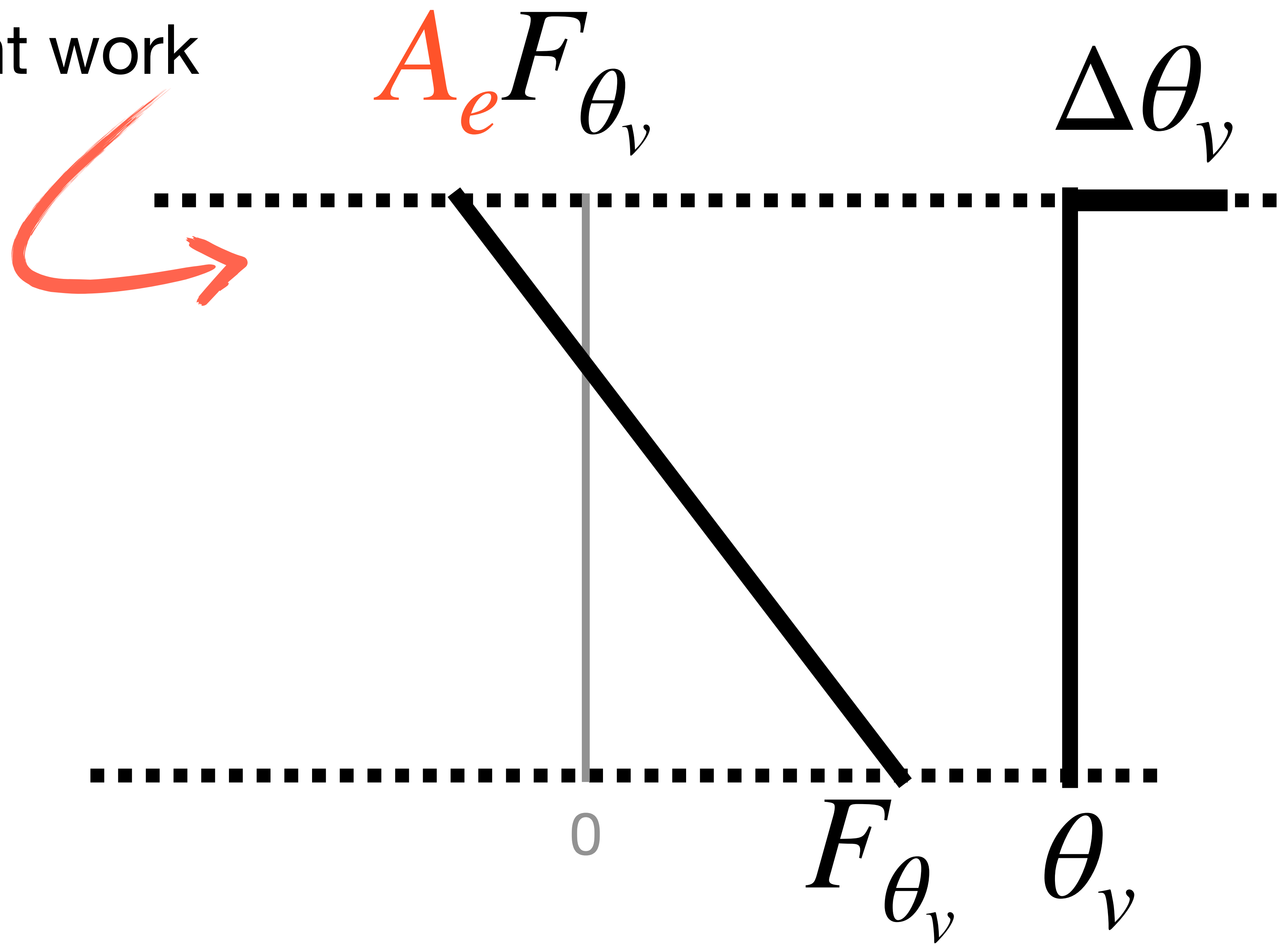

Surface turbulence flux

A_e: entrainment efficiency of surface turbulence source (constant)

A_e=0.2? 0.4?

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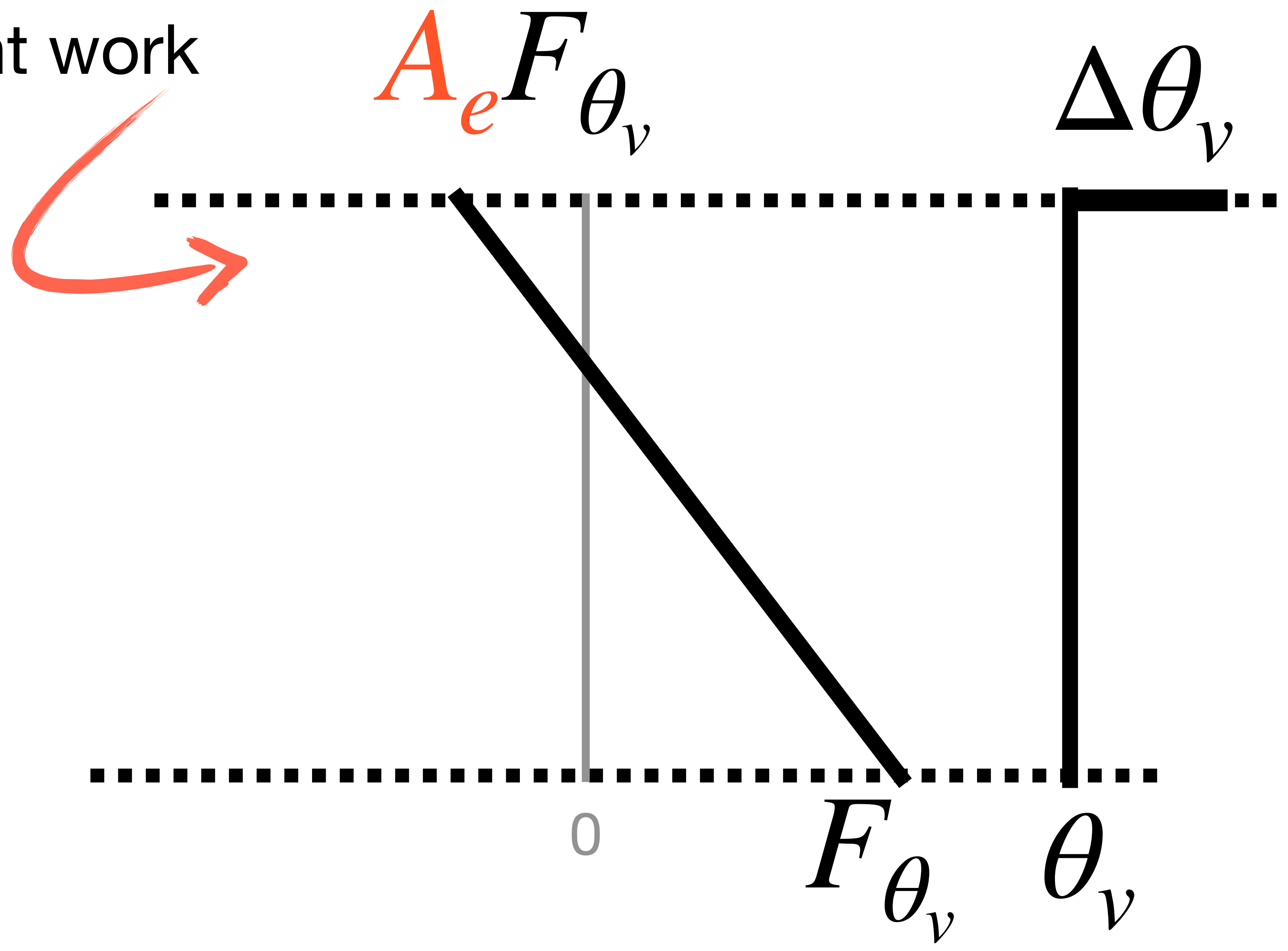


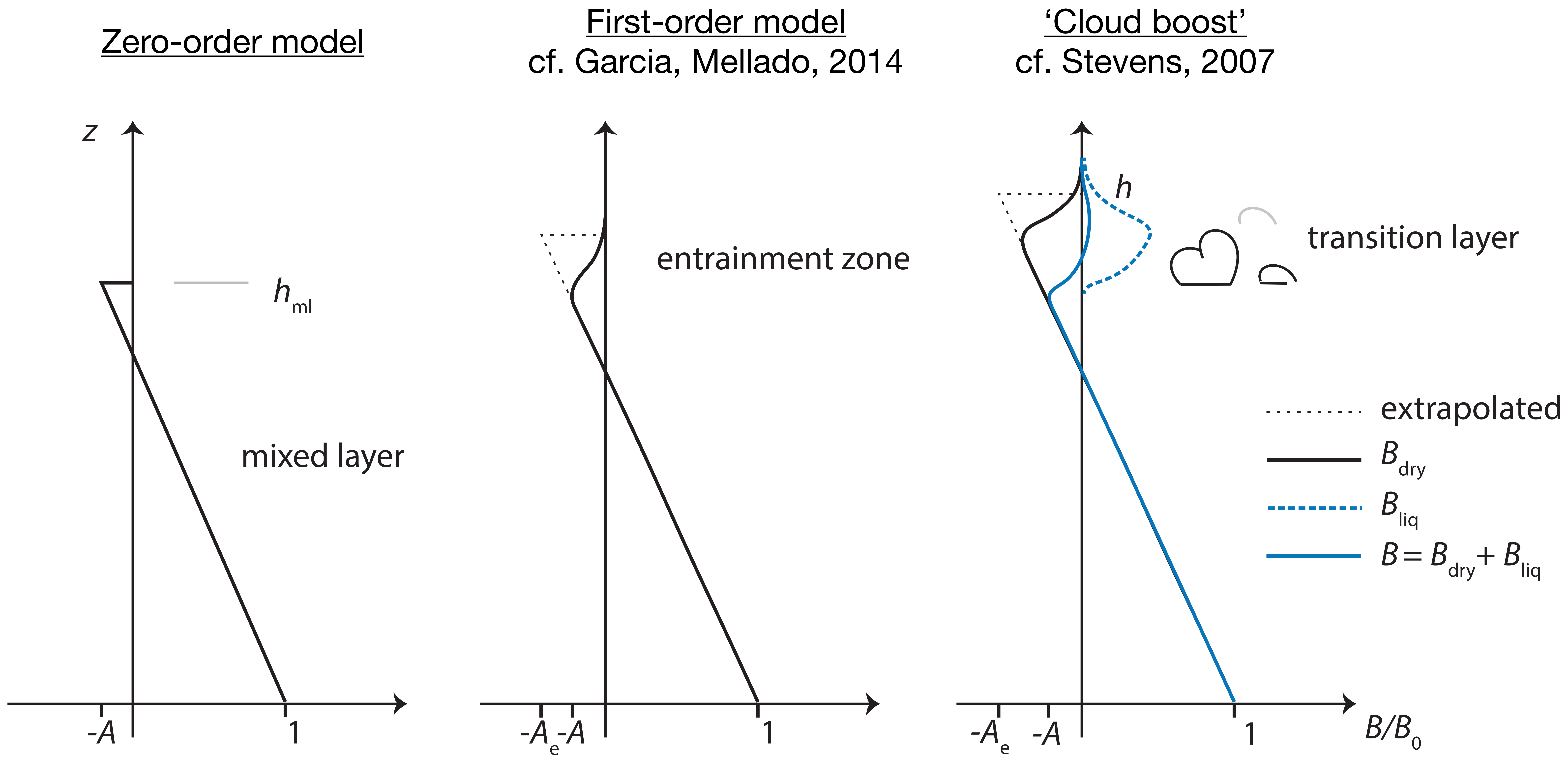
Surface turbulence flux

A_e: entrainment efficiency of surface turbulence source (constant)

A_e=0.43*

*Albright, A. L., Bony, S., Stevens, B., & Vogel, R. (2022). Observed subcloud layer moisture and heat budgets in the trades. JAS 2022.

Cloud liquid water flux contribution to $A_e \sim 0.4$

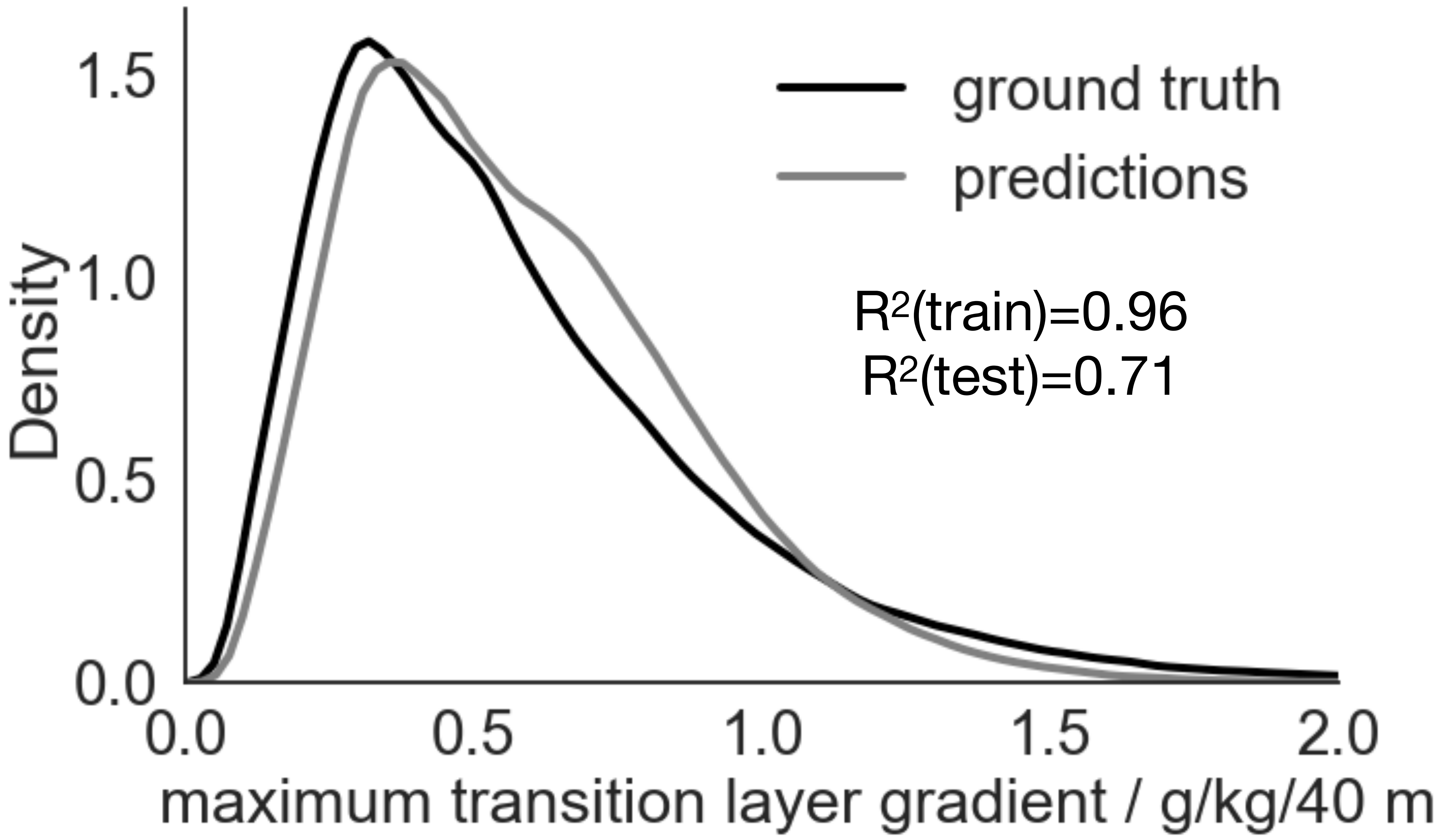


A short side project

Can we predict transition layer gradients based upon environmental variables?

- **9 variables considered:** {q, θ, wind speed in mixed layer; vertical velocity at different altitudes; integrated cloud liquid water content; distance to cloud 'center of mass', cloud base height, cloud top height}
- **Random forest** or XGBoost (machine learning) algorithms

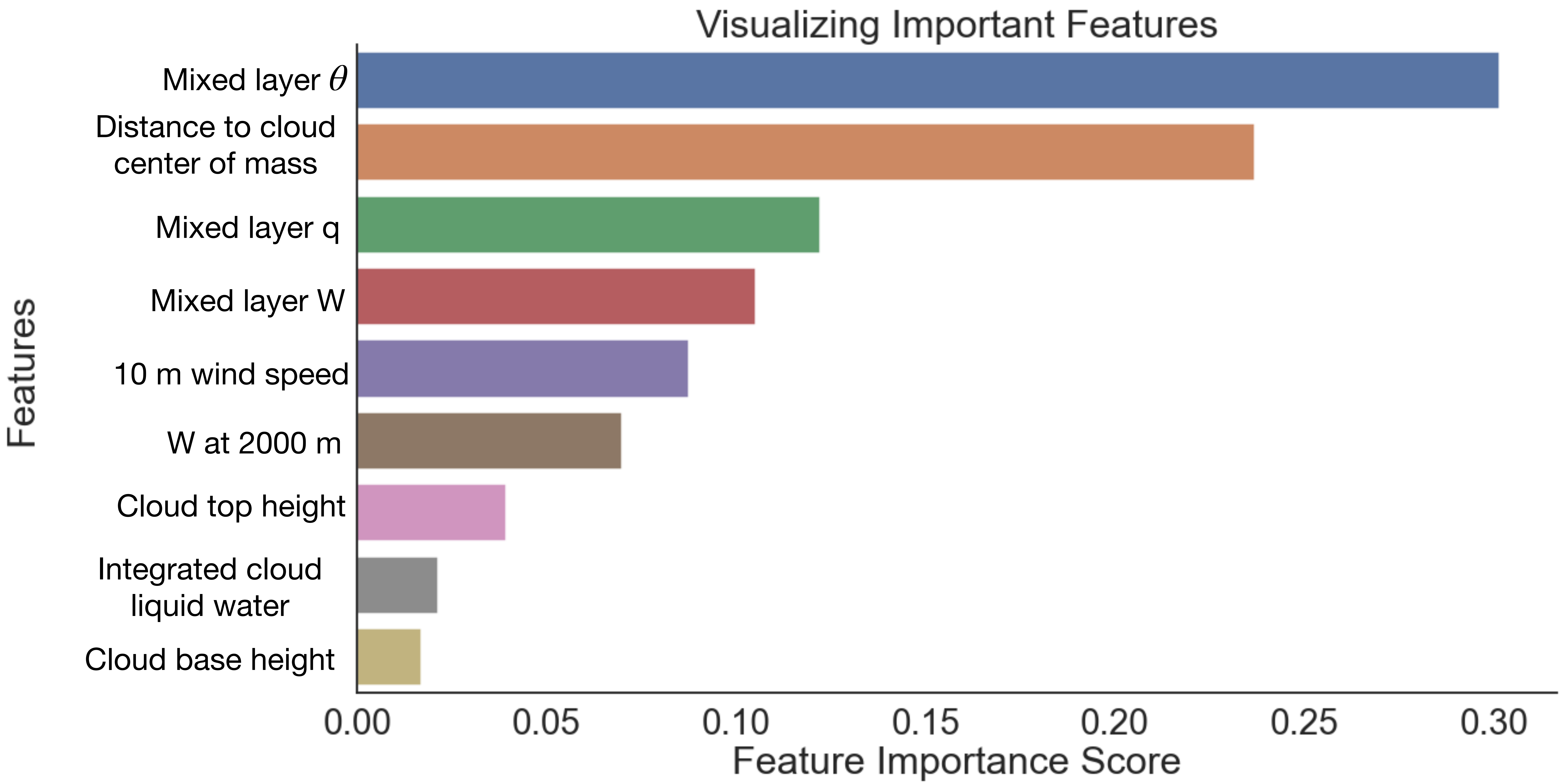
100 m (horizontal); 40 m (vertical) model output



R^2(train)=0.96
R^2(test)=0.71

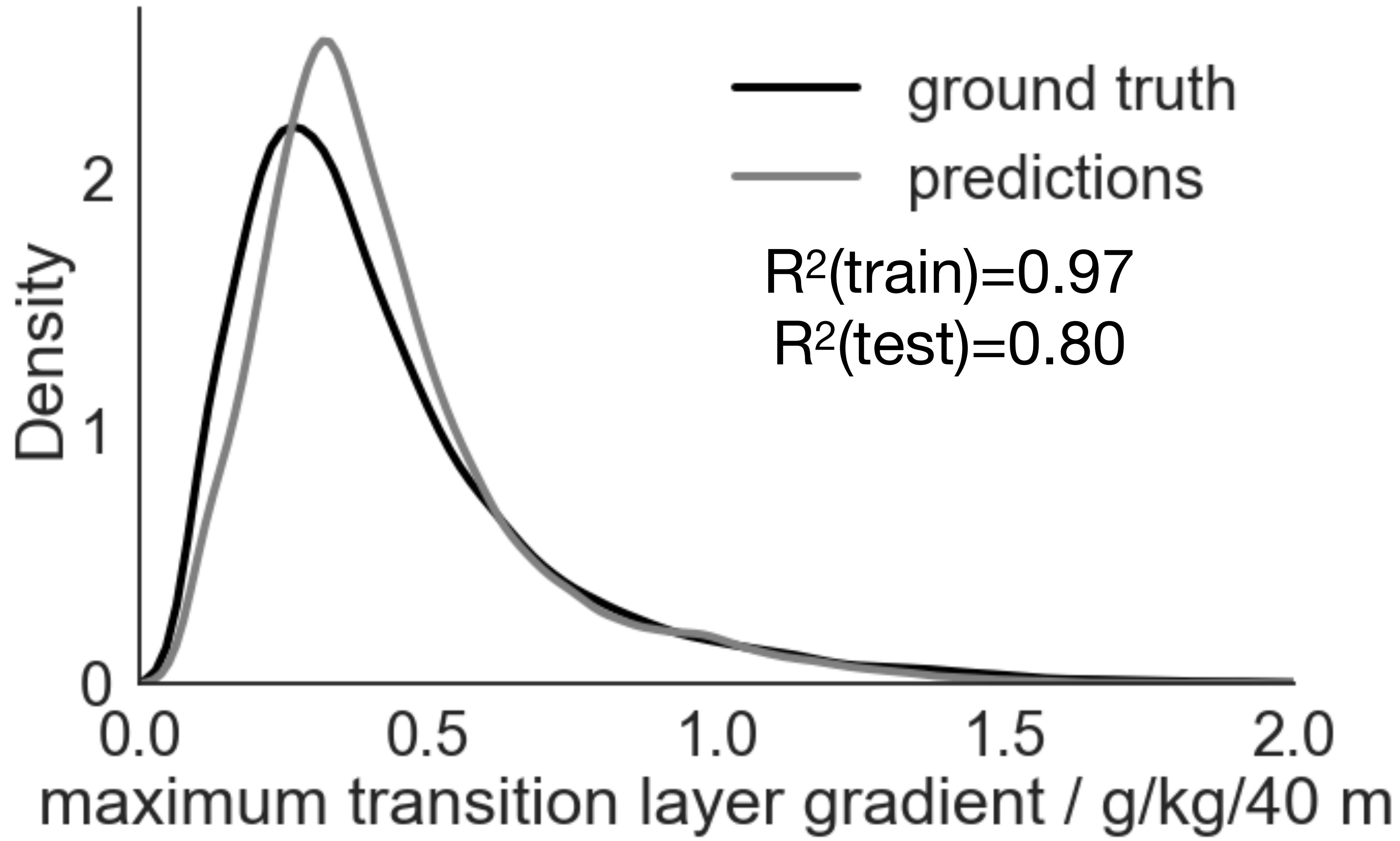
Preliminary take-away:
Algorithm has some predictive skill for maximum transition layer vertical gradient

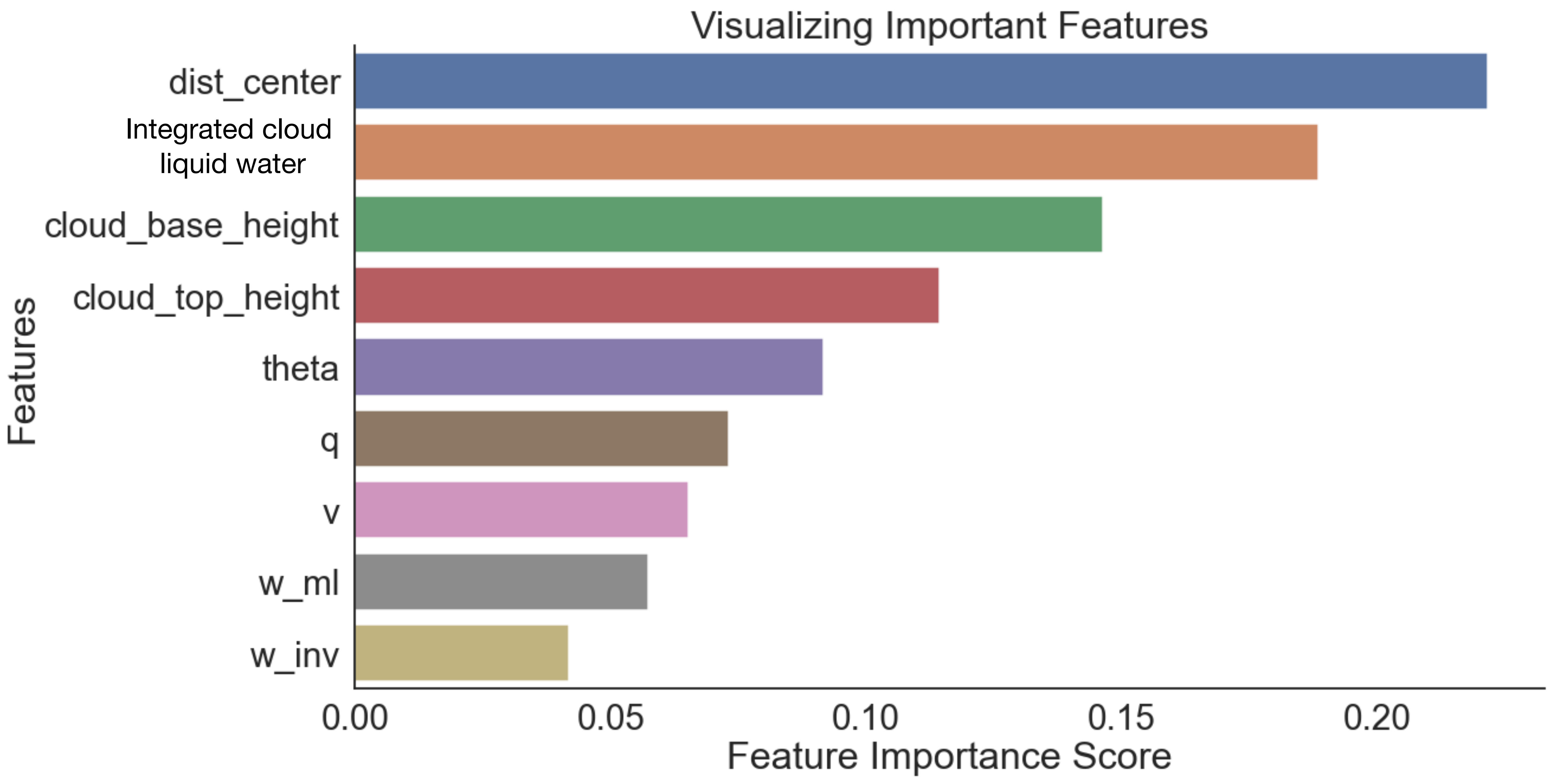
Most important environmental variables:
but, a cold pool imprint rather than a predictive feature?



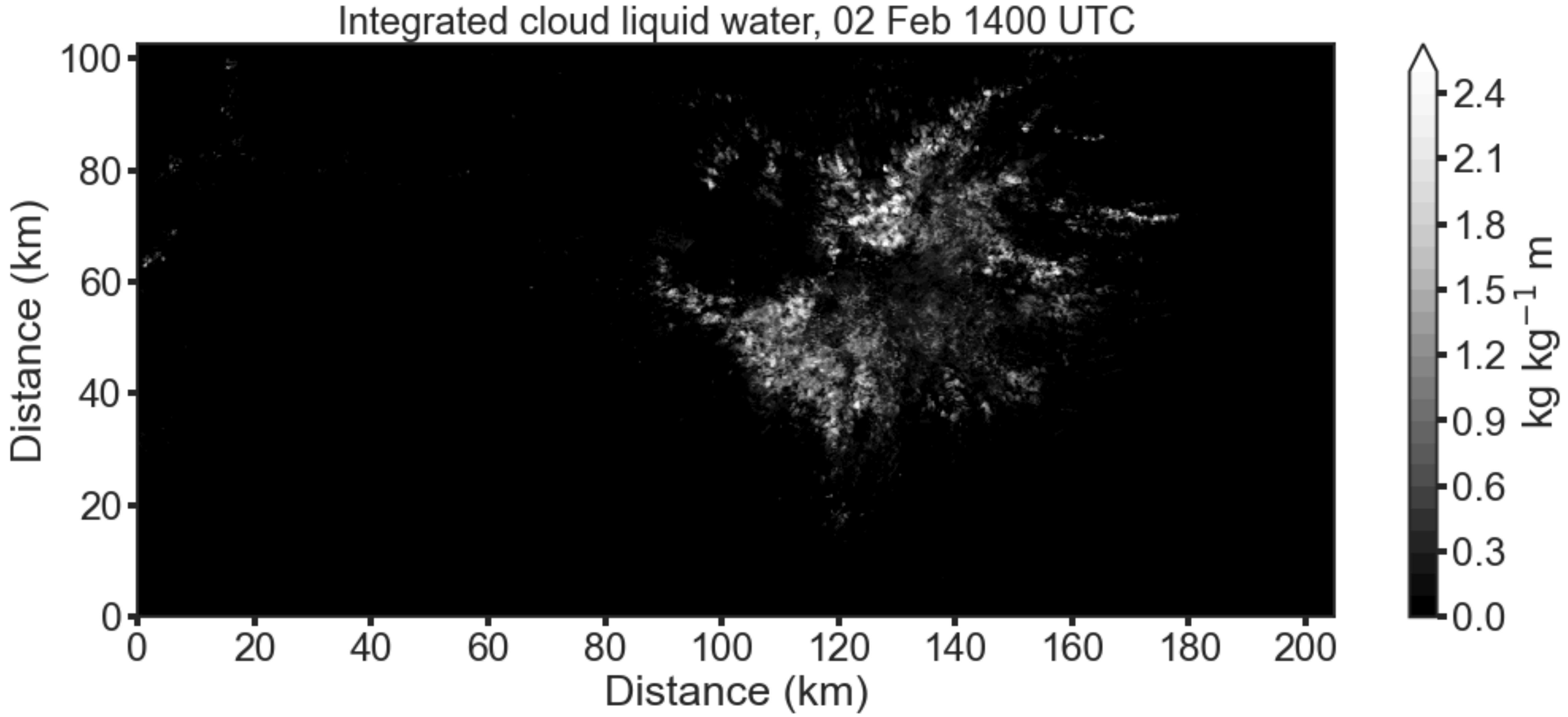
Cold pool signature? Regions $\theta \leq 297.5$ in contours

Skill increases when re-running analysis outside cloud region, and distance to cloud center of mass is most important variable

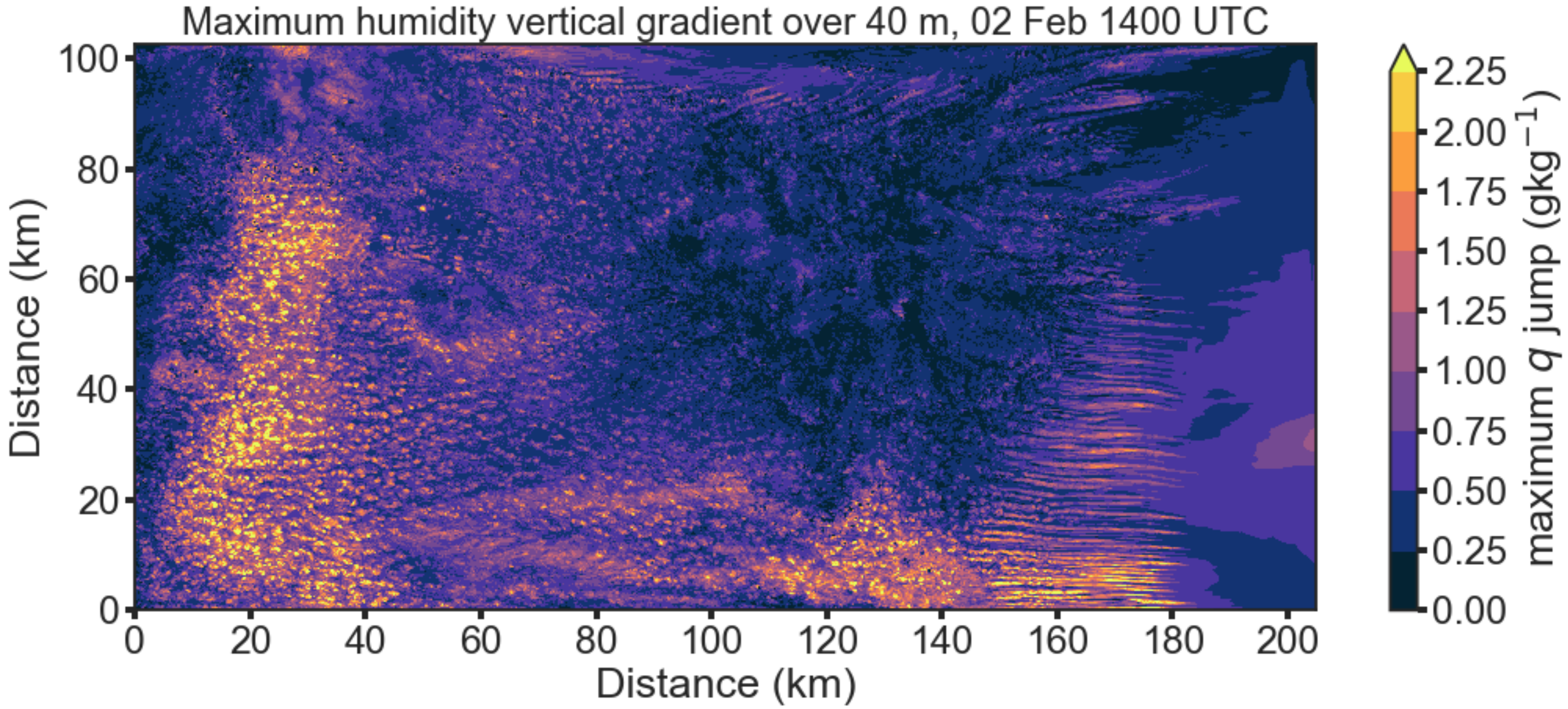




Q: Can we use machine learning techniques to identify important features associated with transition layer gradients?

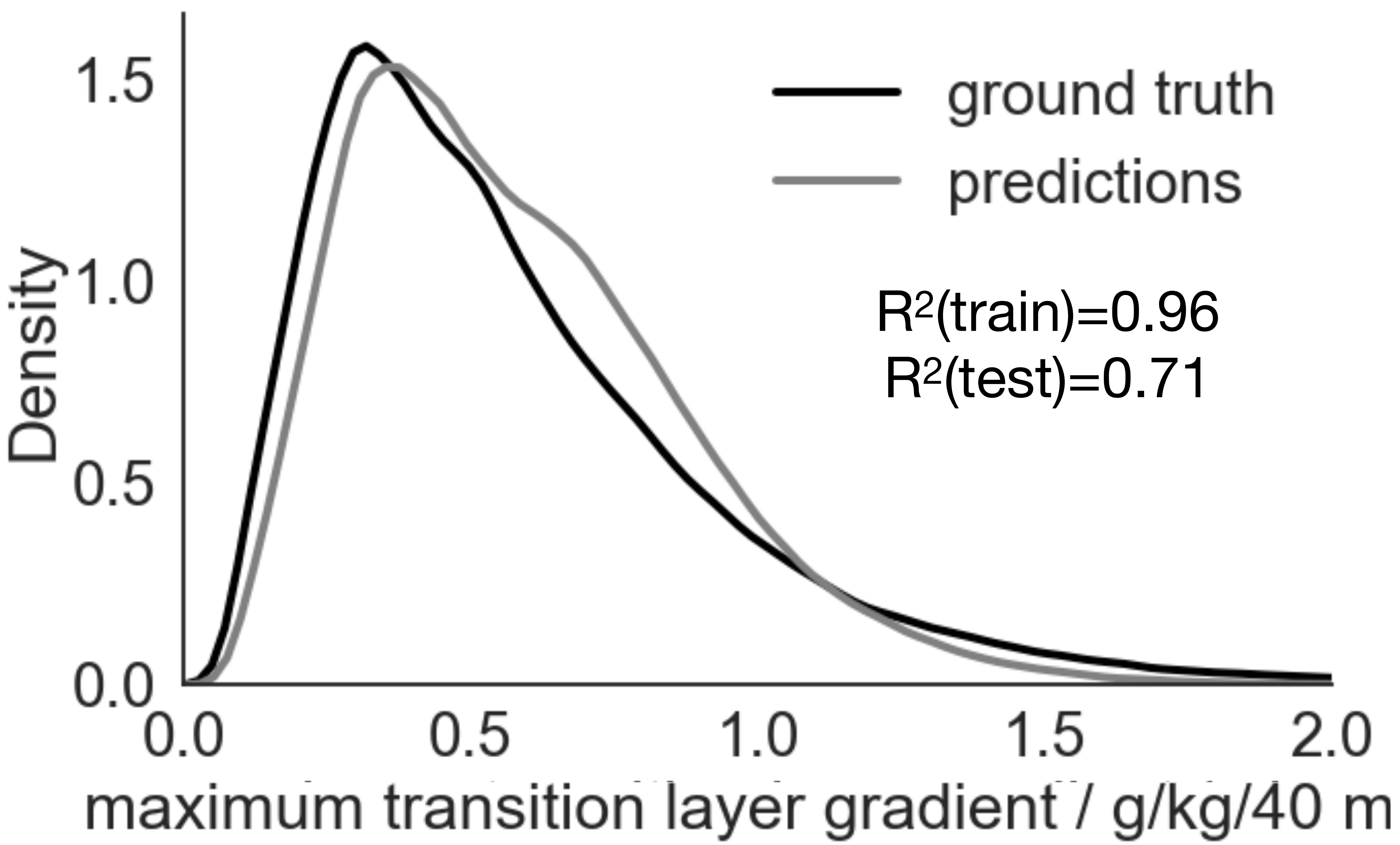


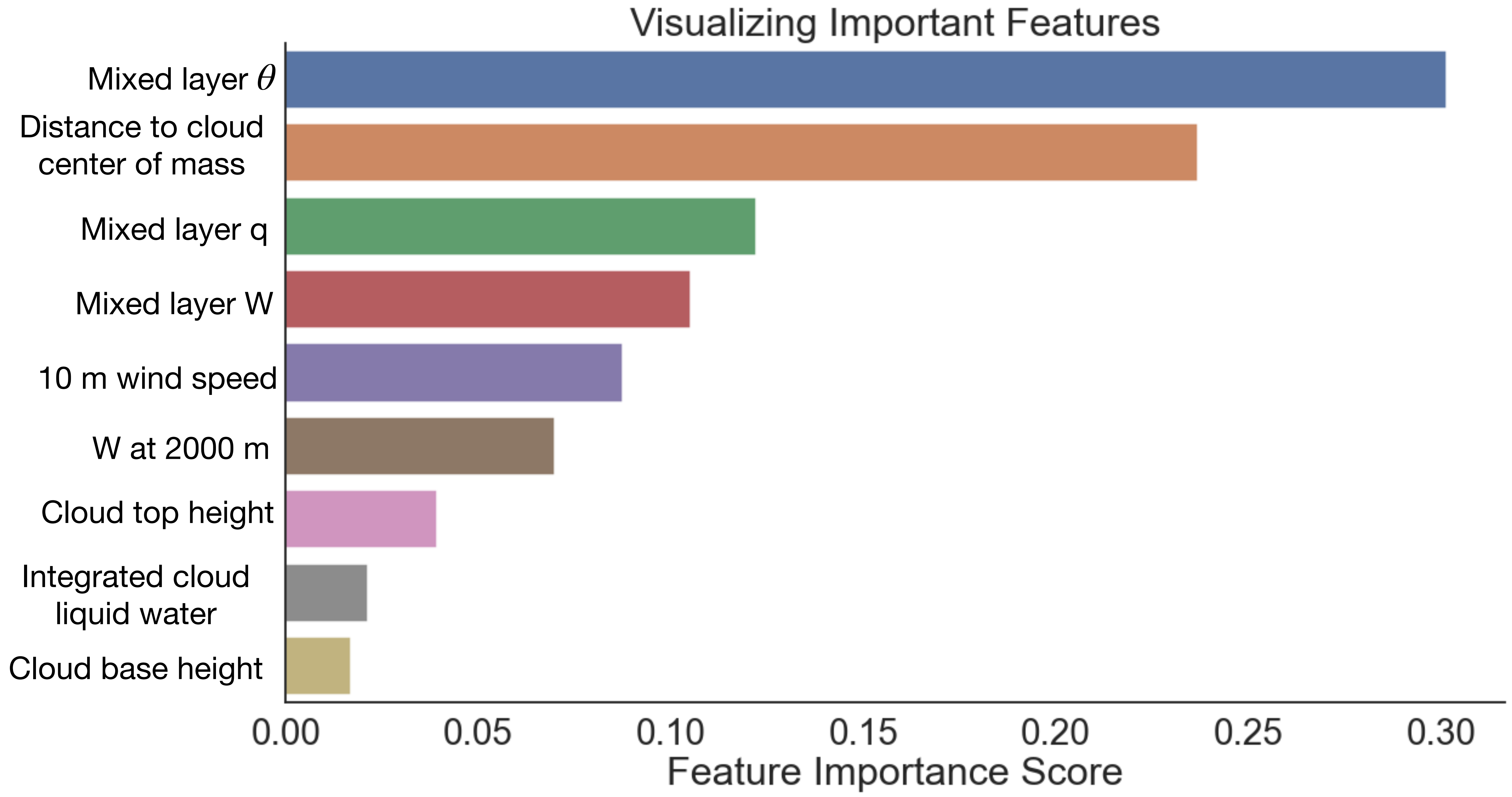
- **LES simulation** output: 100 m (horizontal), 40 m (vertical) Dauhut et al., 2022 QJRMS
- **Target**: transition layer gradient, quantified as maximum first difference (over 40 m) b/t 400-1000 m
- **9 features considered:** q, θ, wind speed at 500 m; vertical velocity at 500 m or 2km; integrated cloud liquid water content; distance to cloud 'center of mass', cloud base height, cloud top height
- **Random forest** or XGBoost (machine learning) algorithms used because they are more interpretable than deep learning, and allow for nonlinear relationships unlike multiple linear regression



Initial approach has predictive skill, but feature importance reflects cold pool signature, rather than meaningful predictor

100 m (horizontal); 40 m (vertical) model output





Distance to cloud emerges as most important feature when considering areas outside cold pools*, and skill improves

*Considered, simply, areas where $\theta_{500m} \leq 297.5$ (white contours) as those influenced by precipitation and cold pools