

Tracking Parcels That Are Entrained Across Cloud Tops

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Cloud-top entrainment



POST

Free atmosphere
(clear, warm, dry, laminar)

Z_{B+}

Inversion layer

Z_B

Mixed layer
(cloudy, cool, moist, turbulent)

Cloud-top entrainment



POST

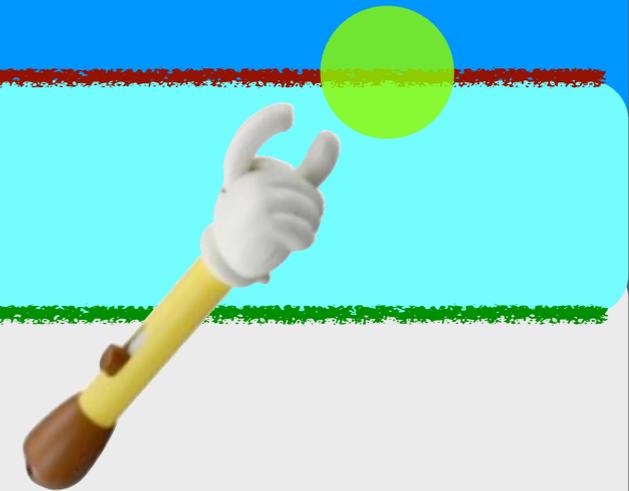
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During entrainment

- Parcels are cooled and moistened.
- Cooling is due to infrared radiation, evaporation, mixing.
- Parcels could become negatively buoyant by buoyancy reversal through evaporation.

Cloud-top entrainment



POST

Entrainment evaporates cloud.

➔ Cloud cover may change.

➔ Climate may change.

Free atmosphere
(clear, warm, dry, laminar)

Z_{B+}

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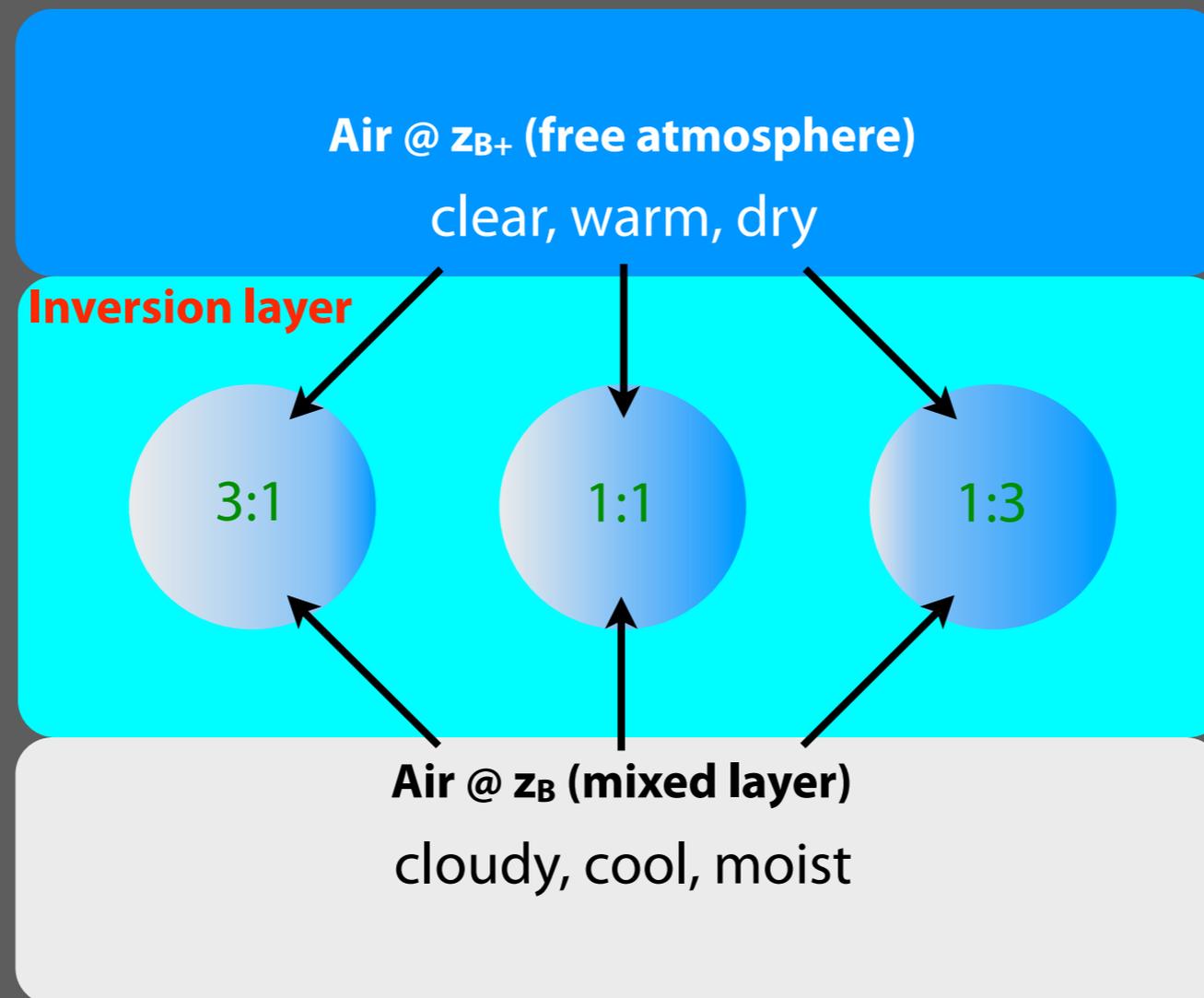
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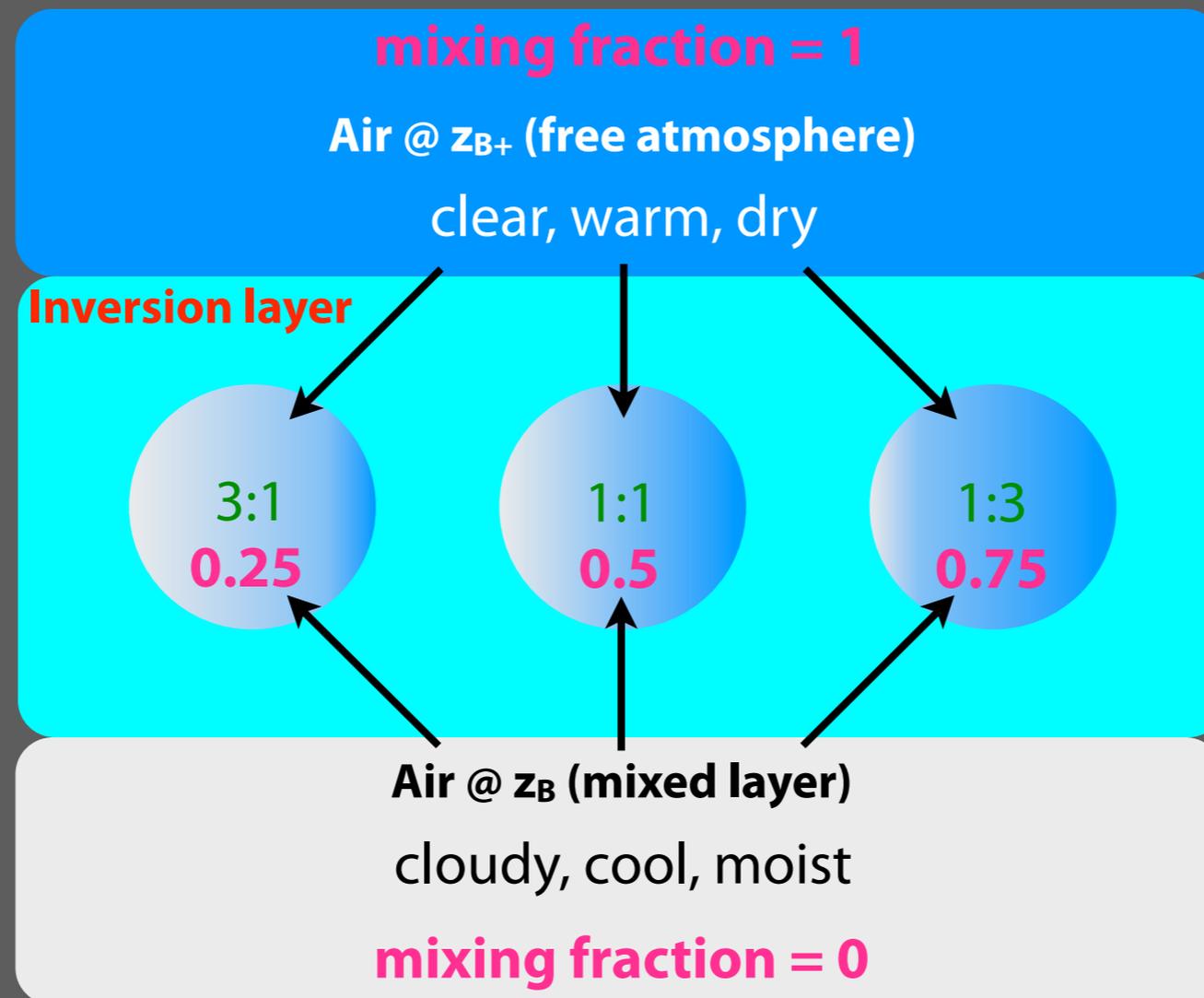
During entrainment

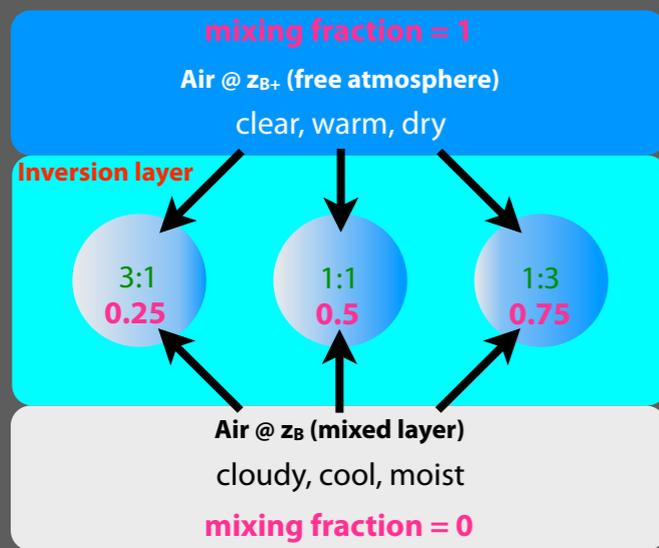
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Buoyancy reversal



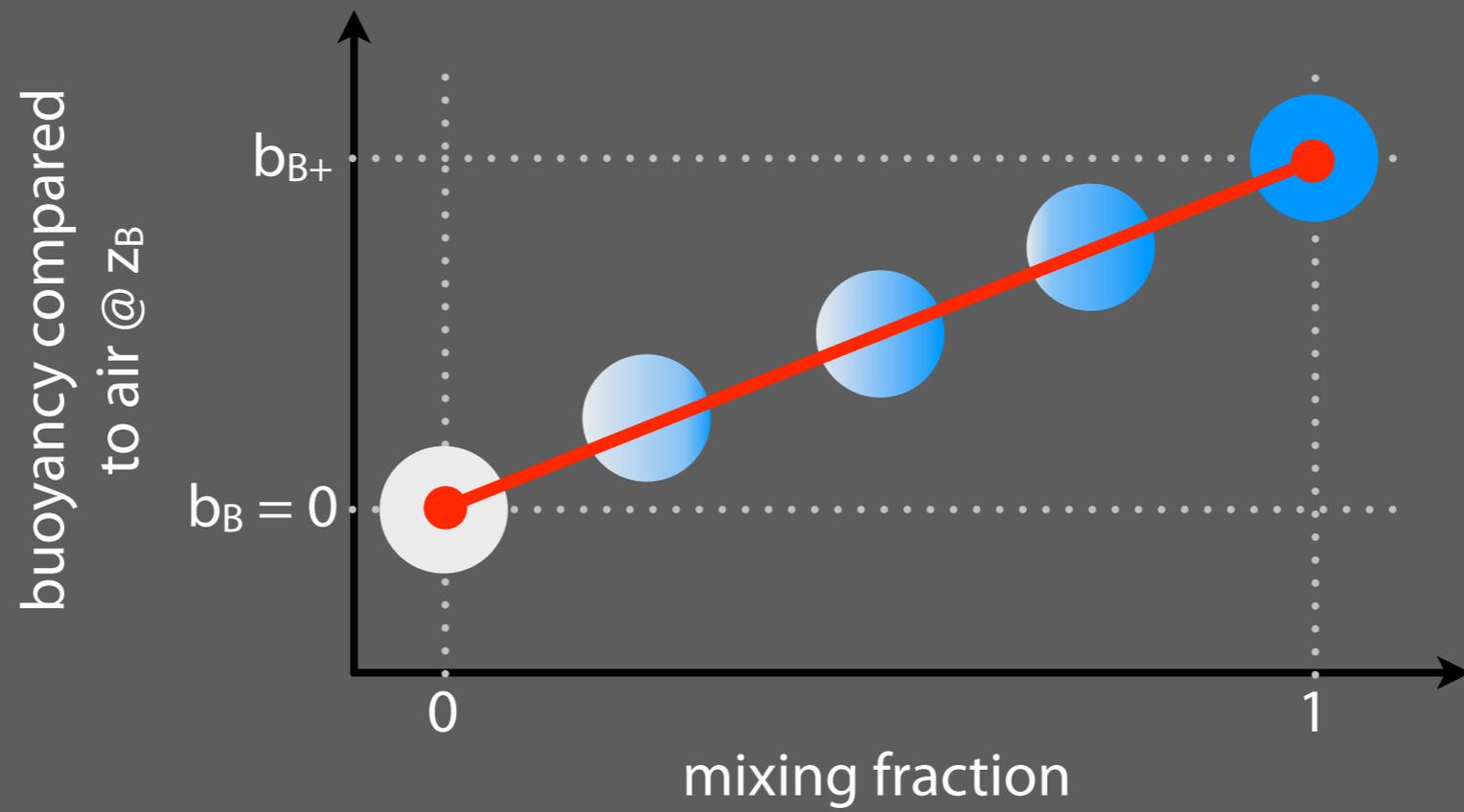
Buoyancy reversal





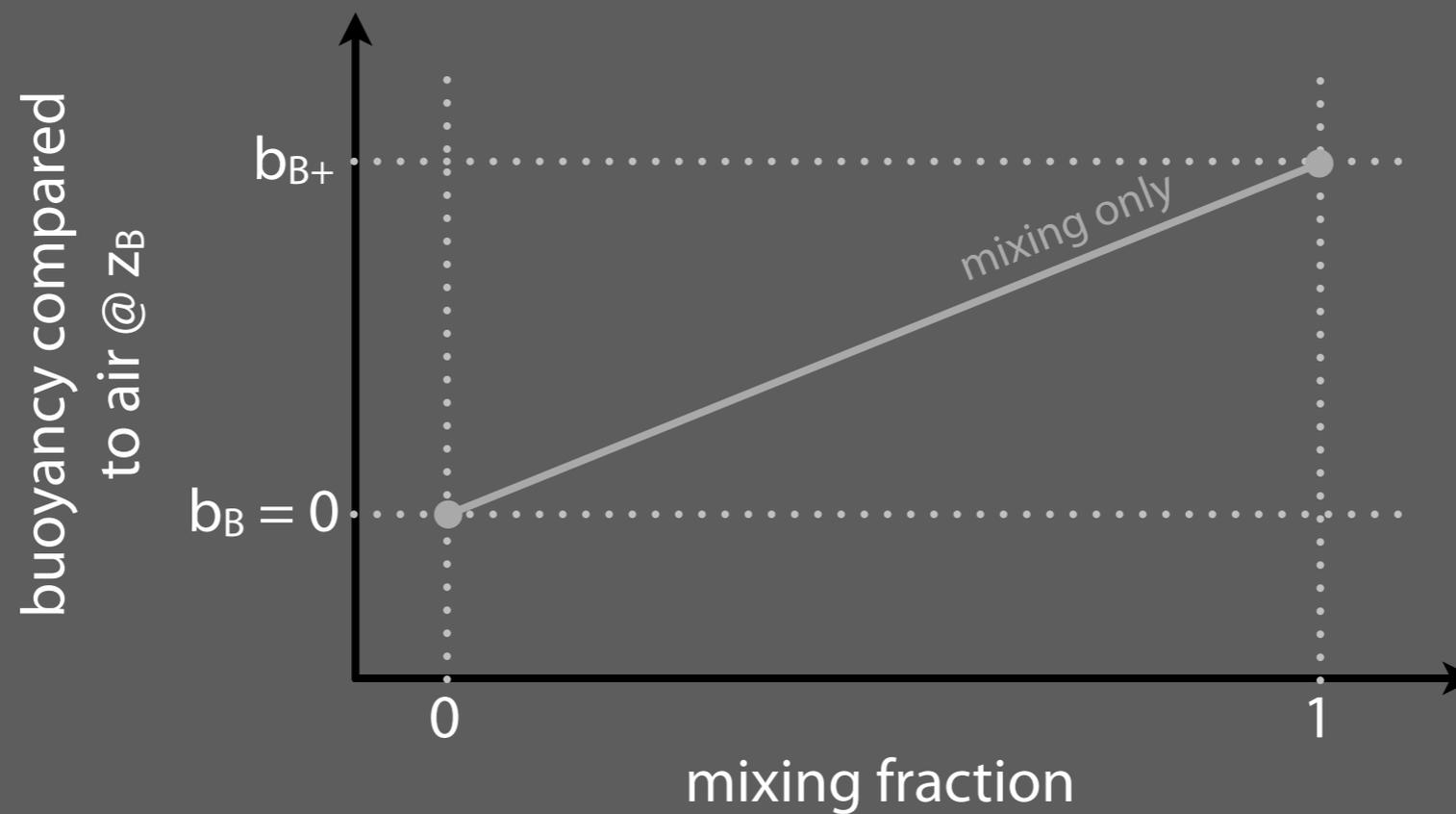
Buoyancy reversal

Mixing only



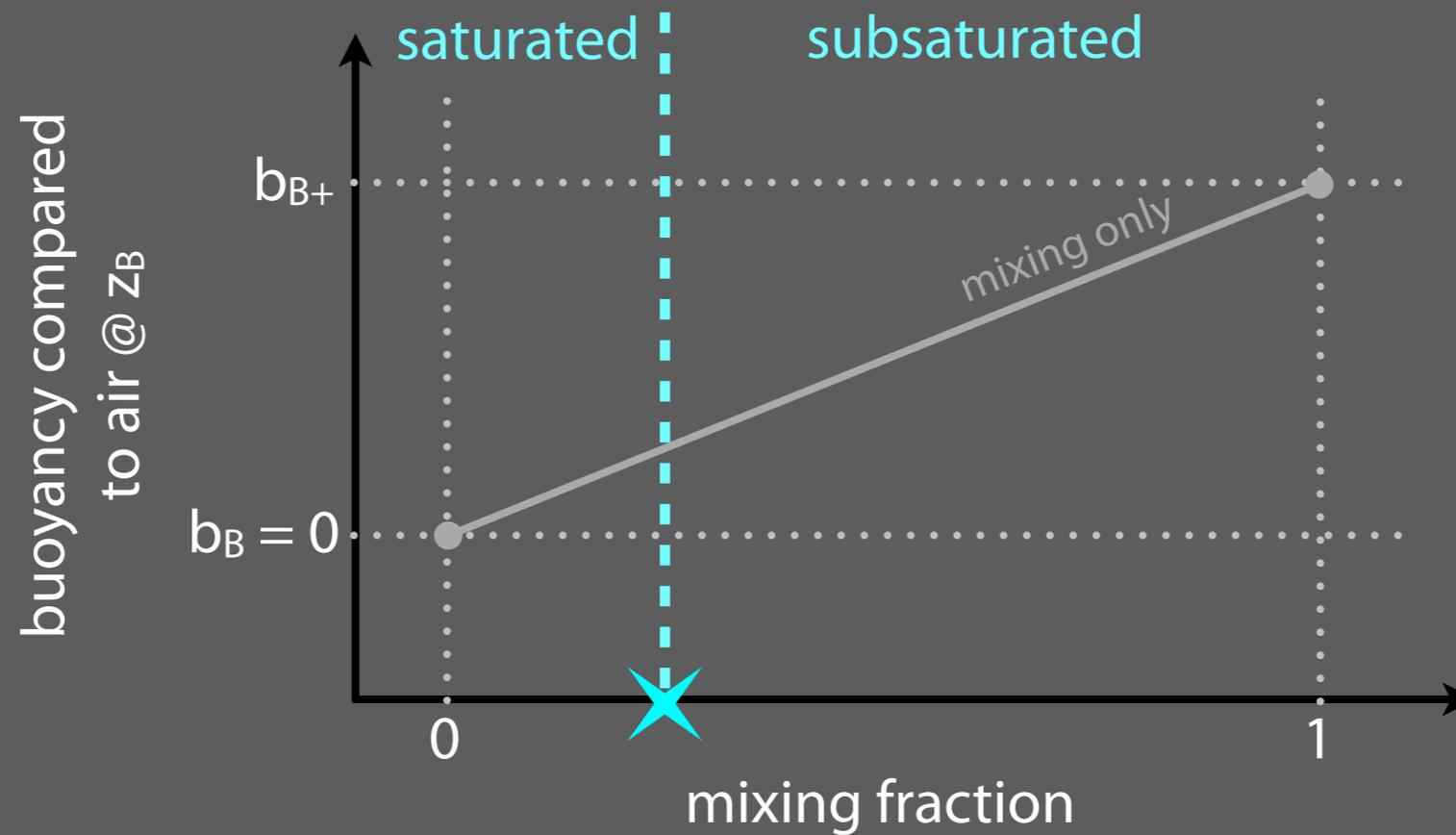
Buoyancy reversal

Mixing + evaporation



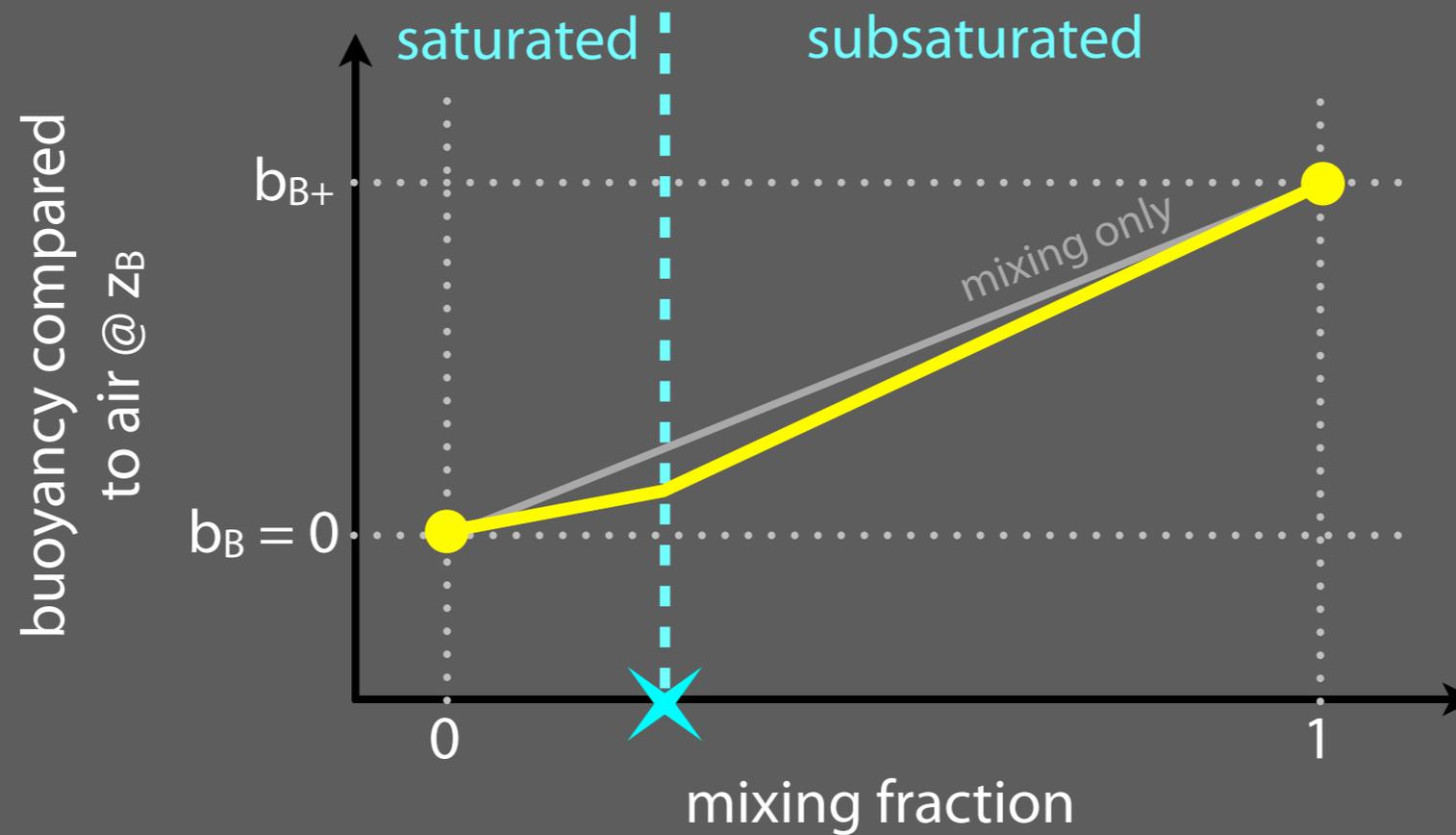
Buoyancy reversal

Mixing + evaporation



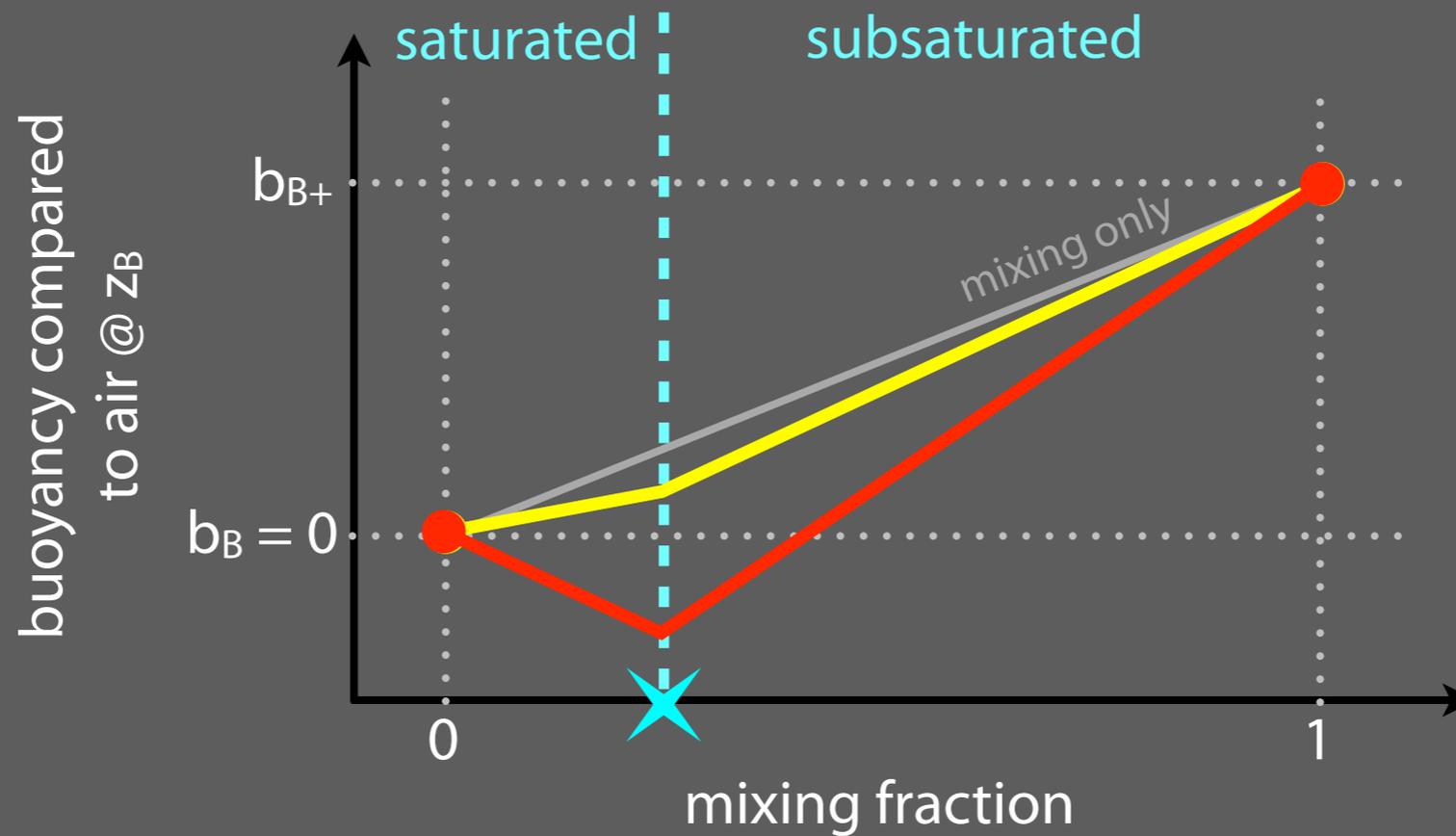
Buoyancy reversal

Mixing + evaporation



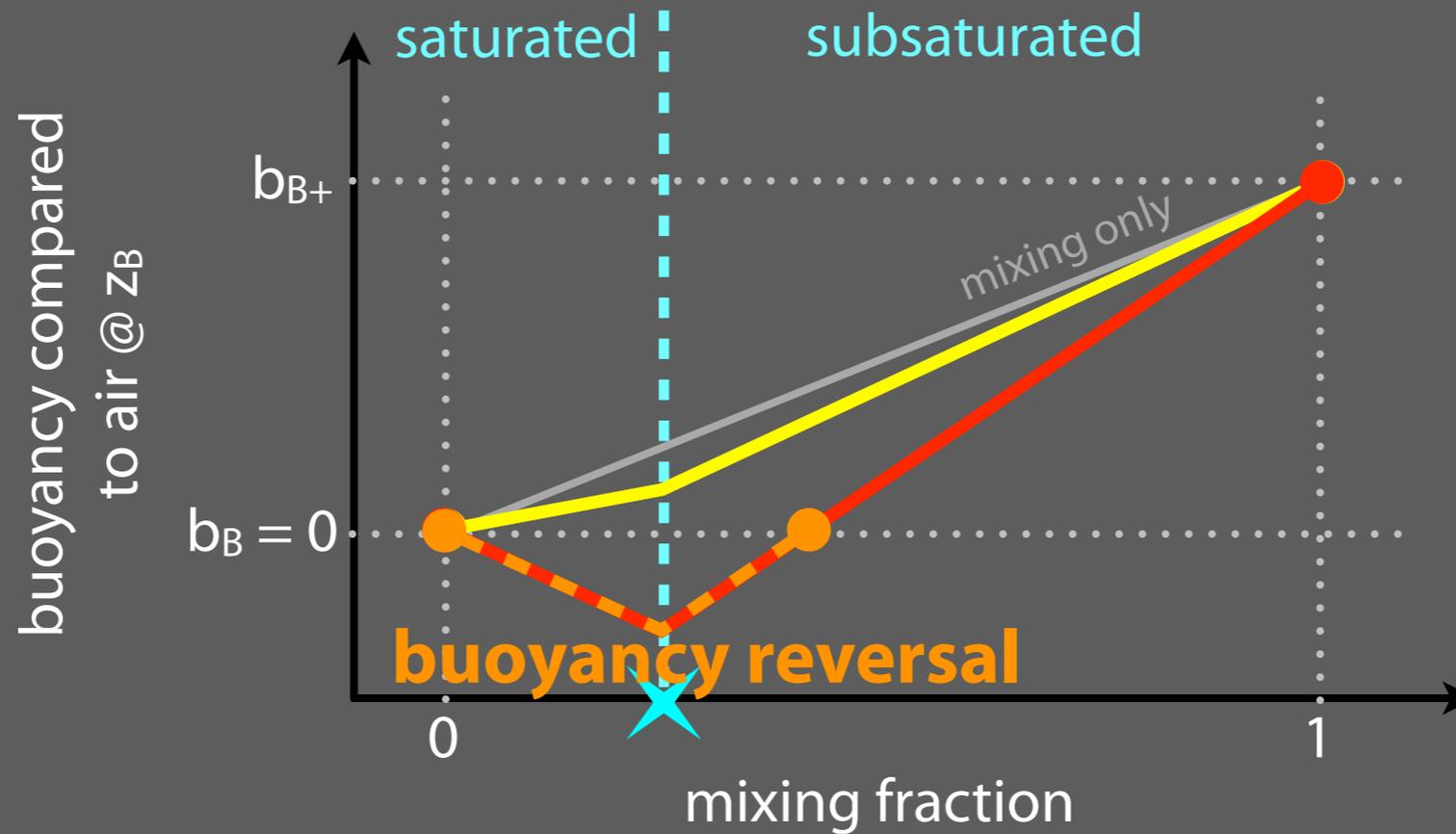
Buoyancy reversal

Mixing + evaporation



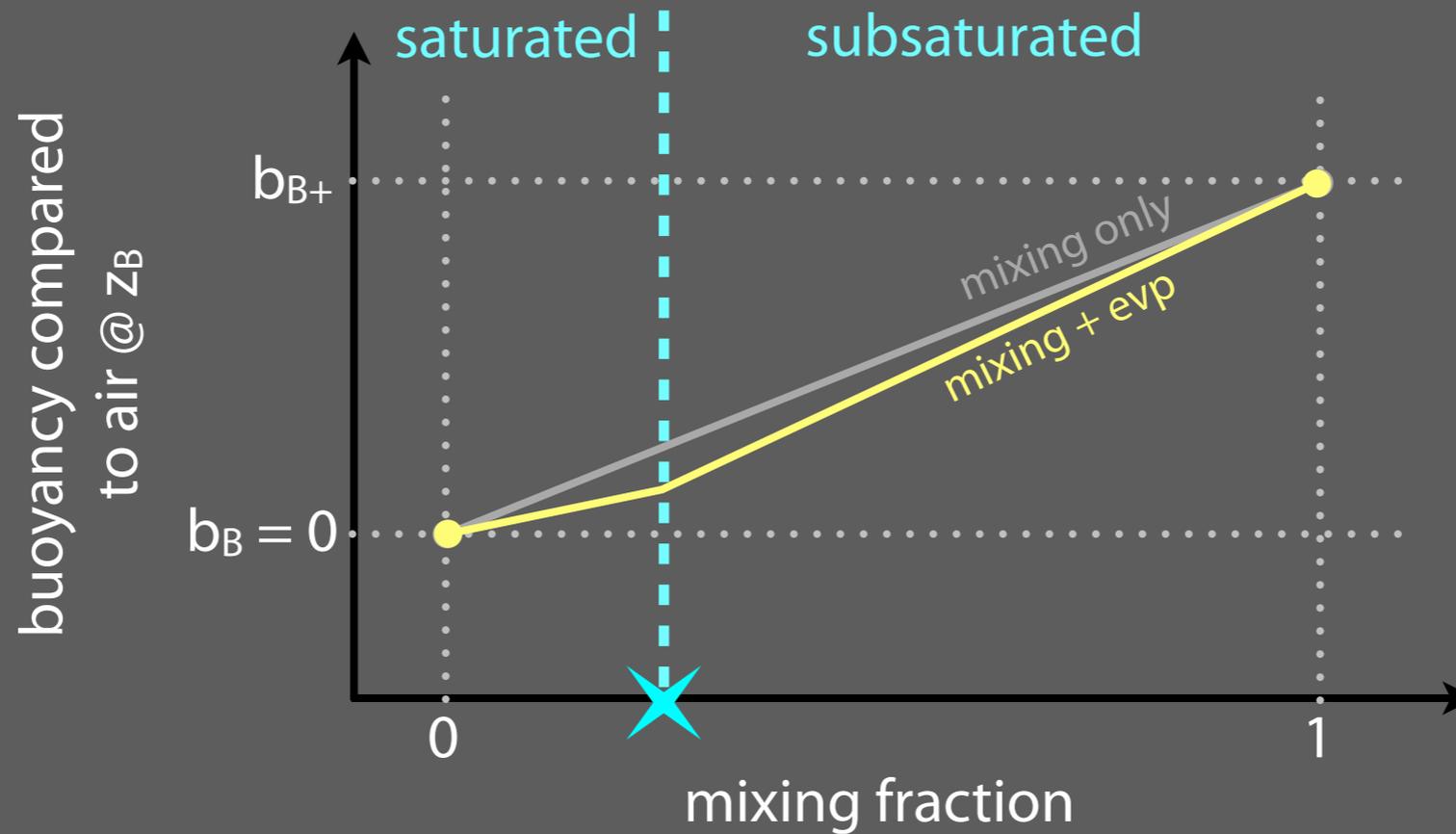
Buoyancy reversal

Mixing + evaporation



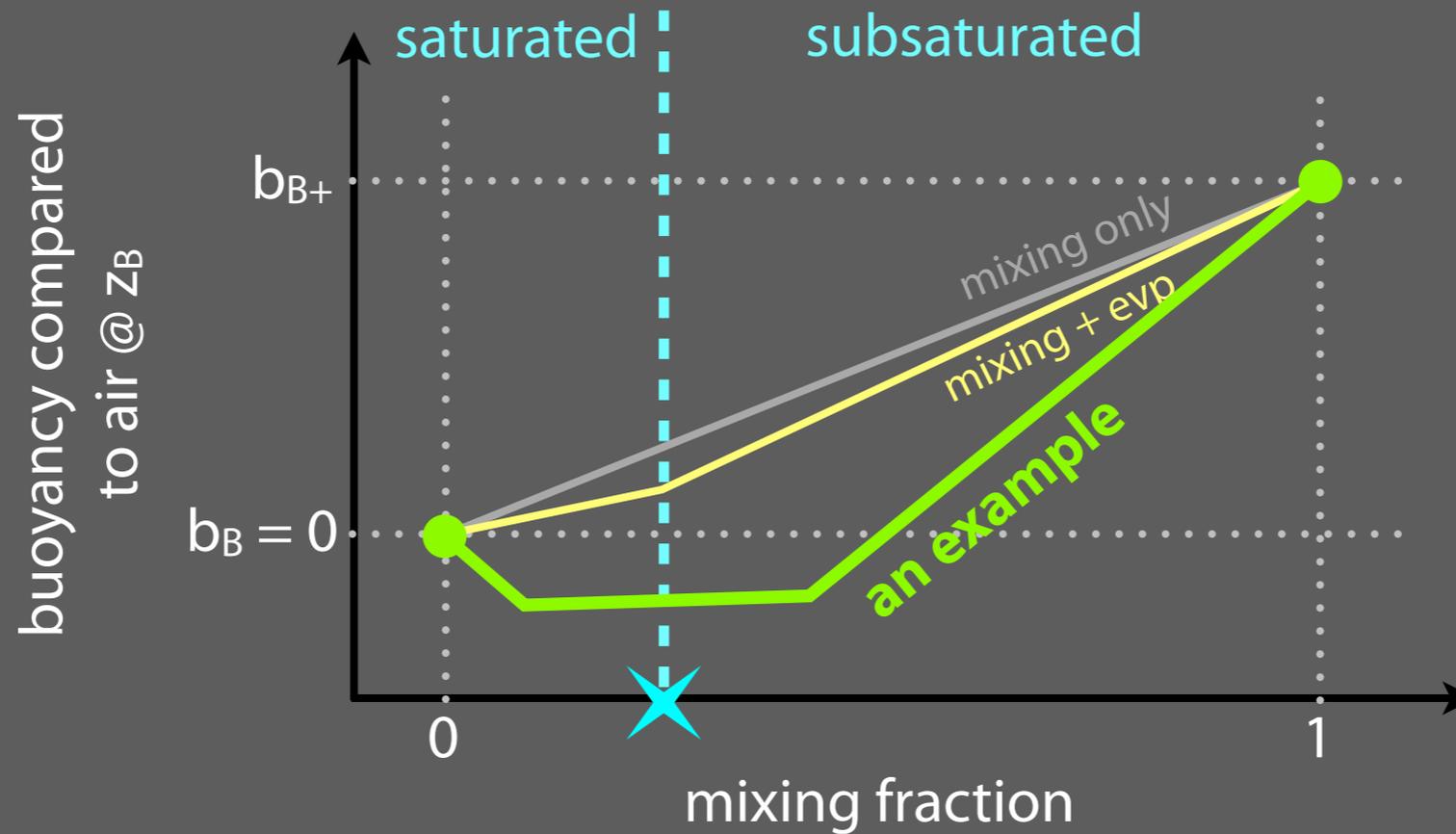
Buoyancy reversal

Mixing + evaporation + infrared cooling



Buoyancy reversal

Mixing + evaporation + infrared cooling



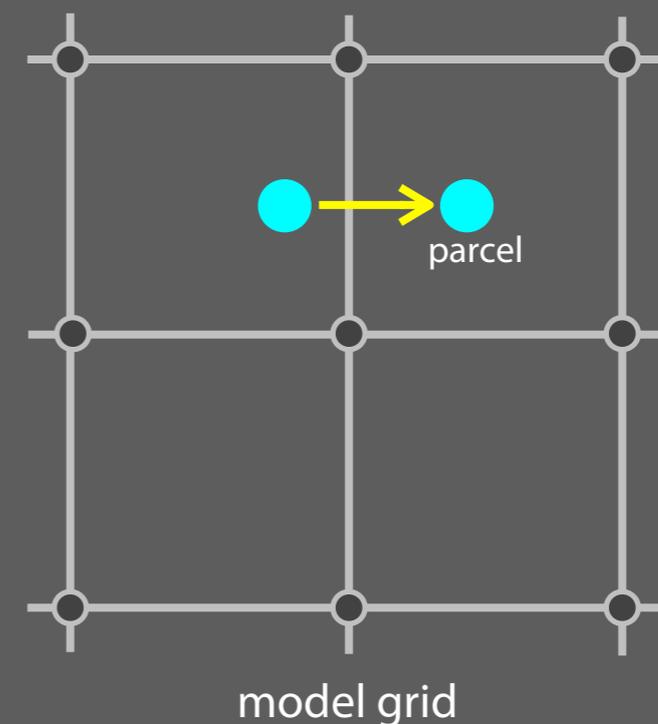
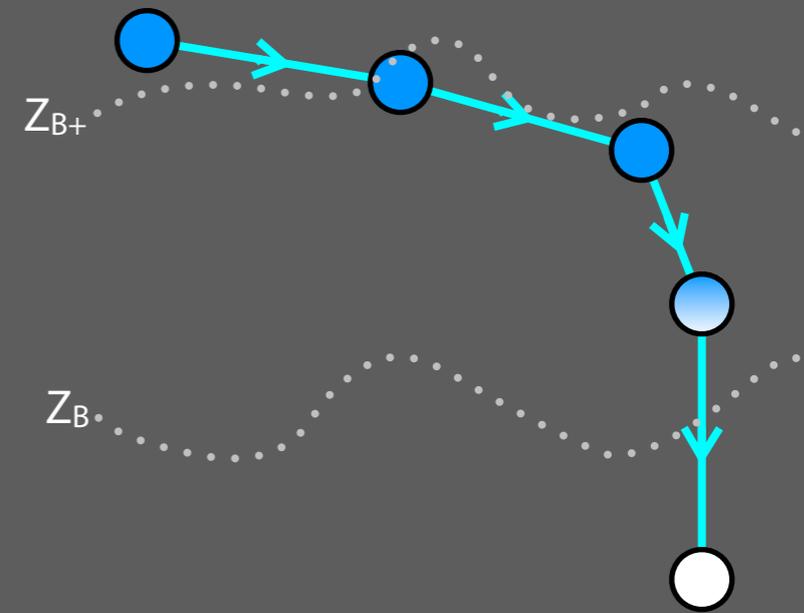
Questions

- Where, how does entrainment happen?
- Which most strongly cools entrained air, radiative cooling, evaporative cooling, or mixing?
- Does buoyancy reversal happen?



Strategy - Lagrangian tracking and LES

- Observation: Tracking individual entrained parcels is impossible.
- Lagrangian parcel tracking model (LPTM)
 - ▶ Parcel position is predicted with diagnosed parcel velocity from LES.
 - ▶ Output is diagnosed at parcel position.
 - ▶ LPTM is implemented in our LES model, SAM.

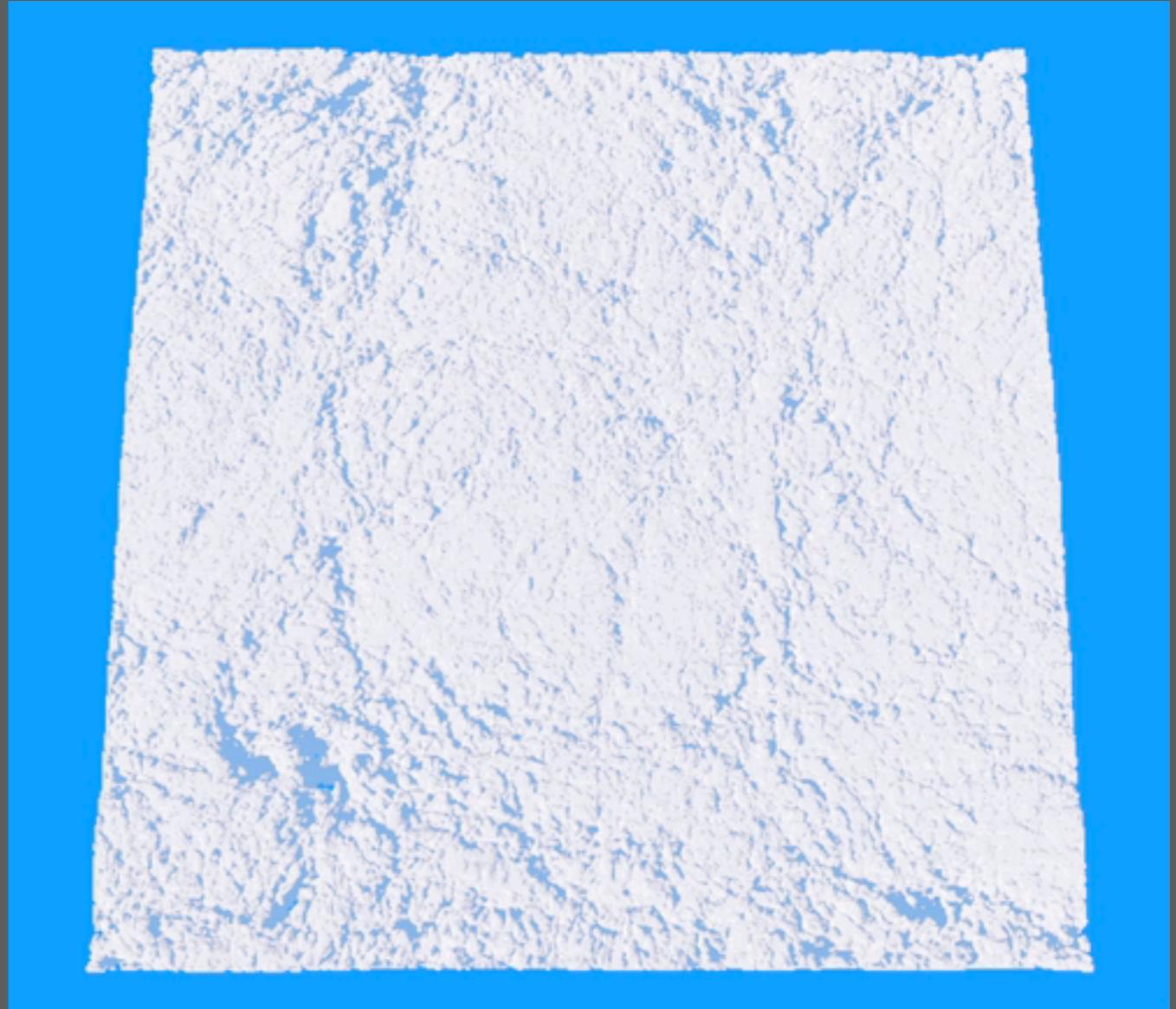
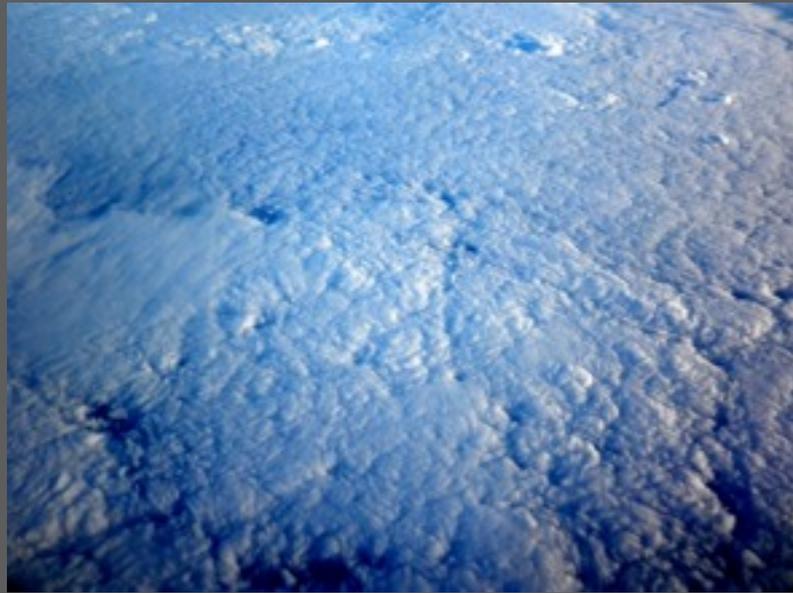


DYCOMS-II simulation



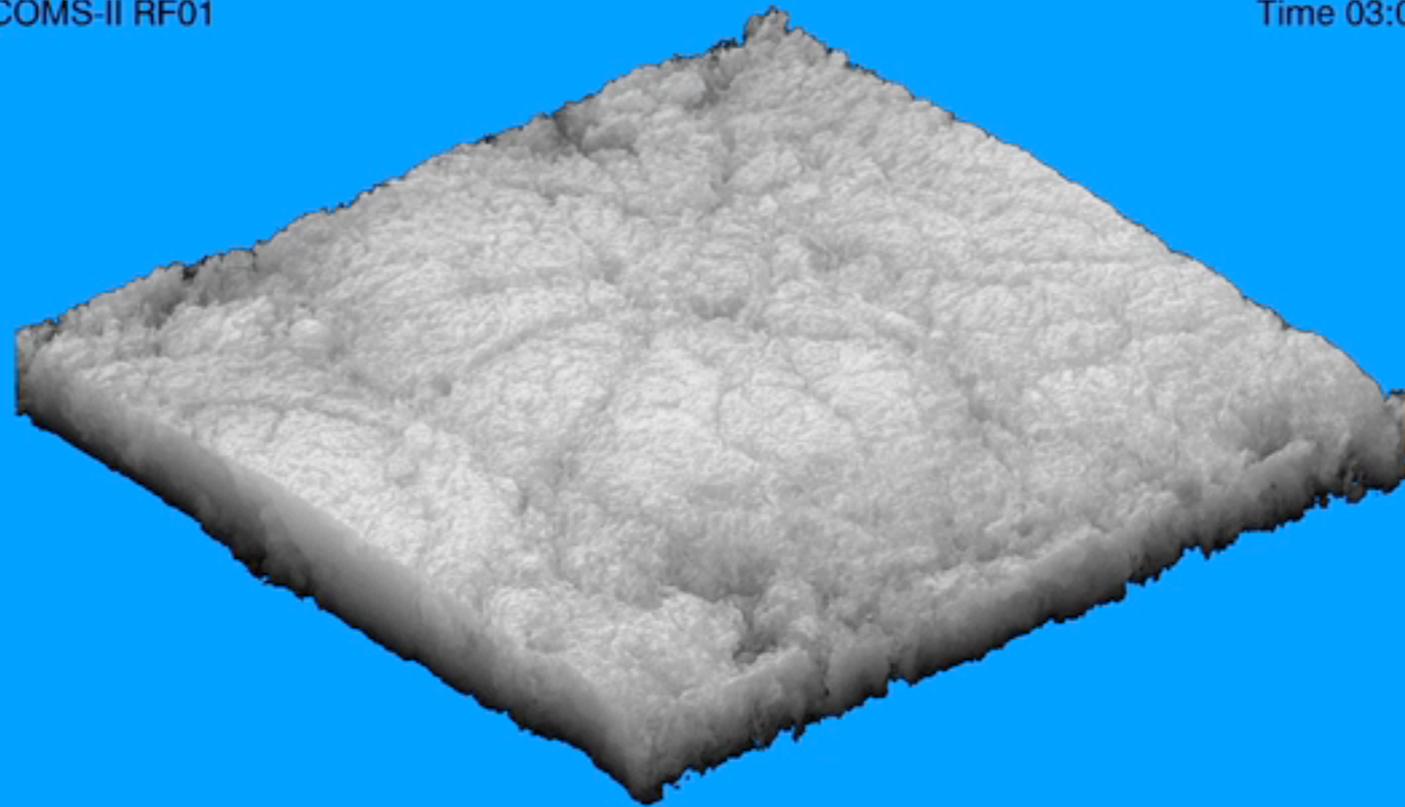
DYCOMS-II

- Based on Stevens et al. (2005)
- Configuration
 - ▶ $\Delta x = 5, \Delta z = 2.5$ m
 - ▶ Resolution: 640x640x640
 - ▶ RRTM longwave code
 - ▶ Computed surface fluxes
 - ▶ Prescribed mean wind
 - ▶ Four-hour duration
 - ▶ LPTM: 40 million parcels for last hour

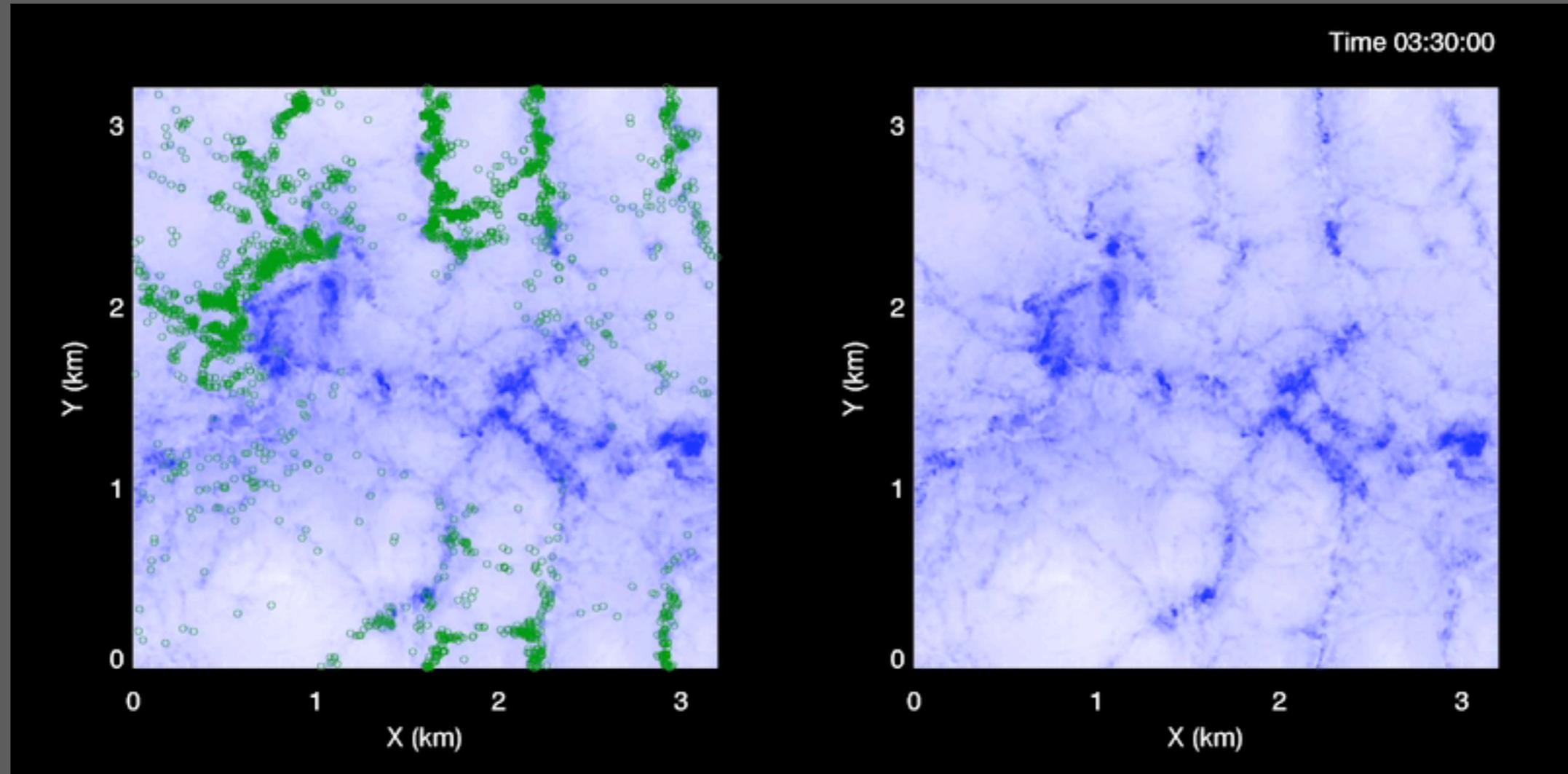


DYCOMS-II RF01

Time 03:00:00

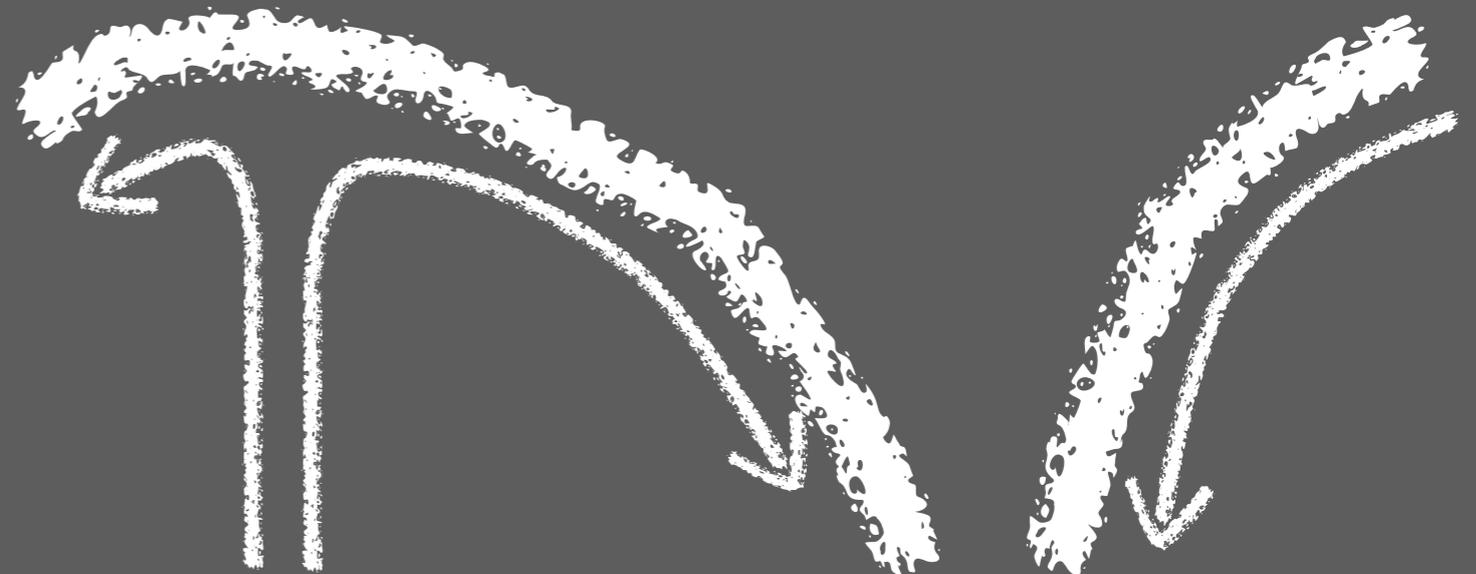
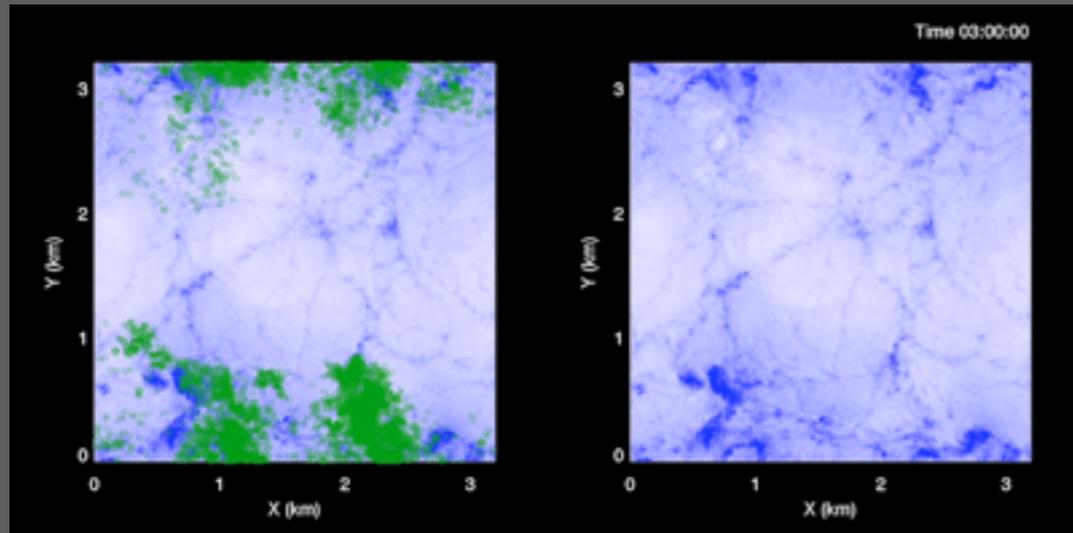


Where does entrainment happen?



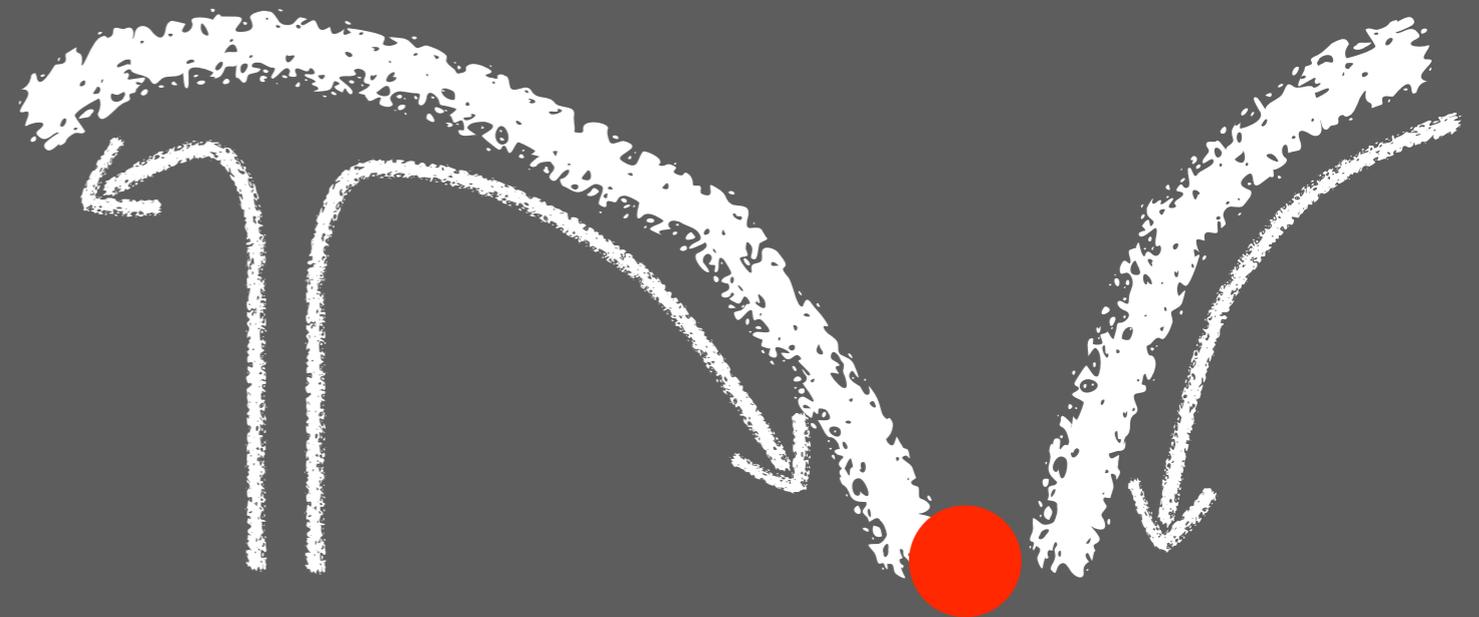
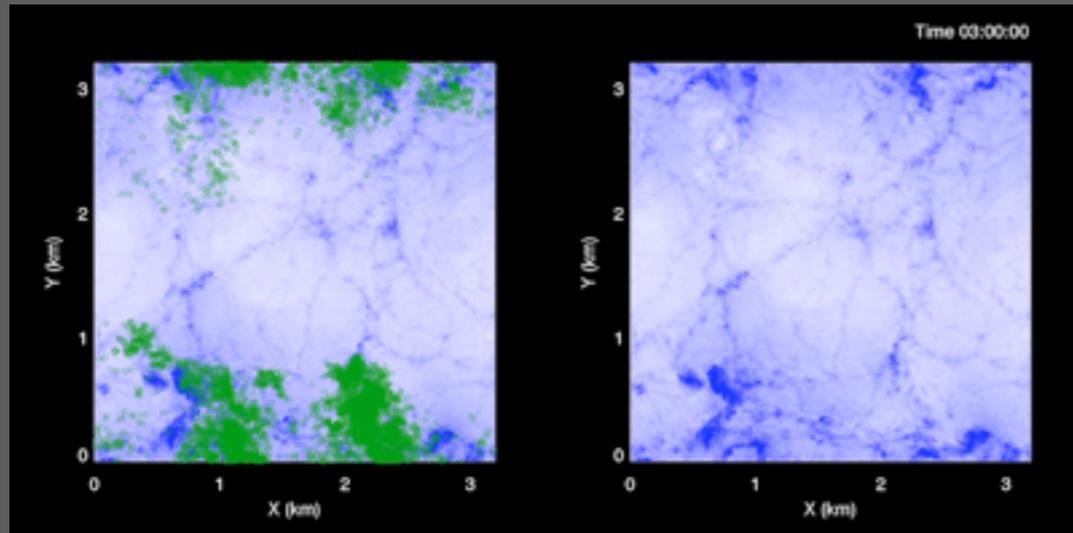
Locations of entrained parcels at z_B are shown.

Parcels captured at 03:45



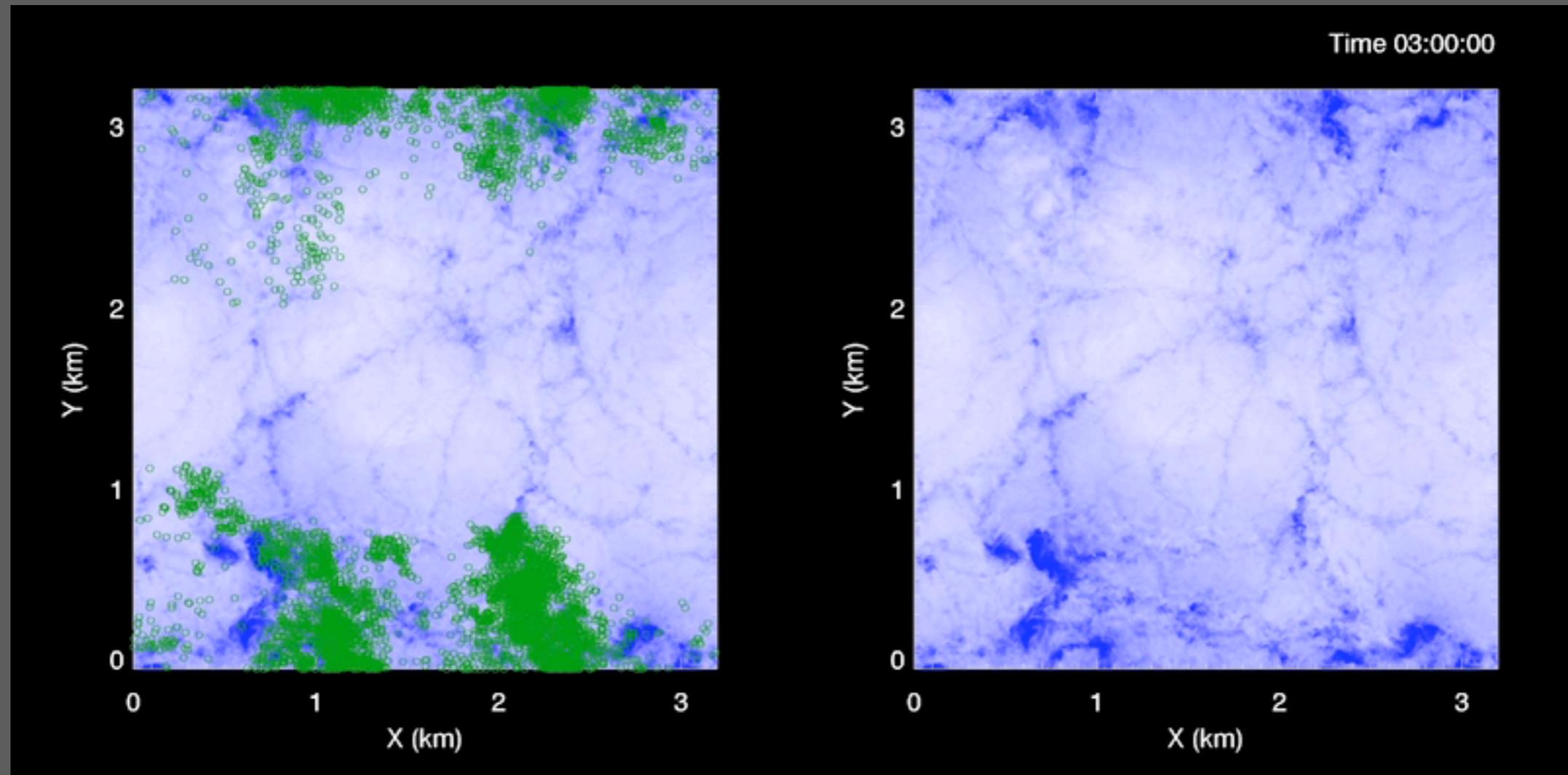
- Parcels entrained at 3:45 are shown.
- Parcels decent. (imagine)
- Red parcels contain cloud water.

Parcels captured at 03:45



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Parcels captured at 03:45



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Partitioning of cooling

$$\delta s_l = \chi \Delta s_l + (\delta s_l)_{\text{RAD}}$$
$$\delta s_v = \chi \Delta s_v + (\delta s_v)_{\text{EVP}} + (\delta s_v)_{\text{RAD}}$$



$$(s_{l_0})_{B+} = s_{l_0}(t_{B+}), (s_{l_0})_B = s_{l_0}(t_B)$$
$$(s_{v_0})_{B+} = s_{v_0}(t_{B+}), (s_{v_0})_B = s_{v_0}(t_B)$$
$$\Delta s_l = (s_{l_0})_{B+} - (s_{l_0})_B$$
$$\Delta s_v = (s_{v_0})_{B+} - (s_{v_0})_B$$

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$$(\delta s_l)_{\text{RAD}}(t) = \Sigma (Q_r \Delta t) \text{ from } t_{B+} \text{ to } t$$

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$$(\delta s_l)_{\text{RAD}}(t) = \sum (Q_r \Delta t) \text{ from } t_{B+} \text{ to } t$$

$$(\delta s_v)_{\text{EVP}}(t) = \delta s_v - \chi(t) \Delta s_v - (\delta s_v)_{\text{RAD}}(t)$$

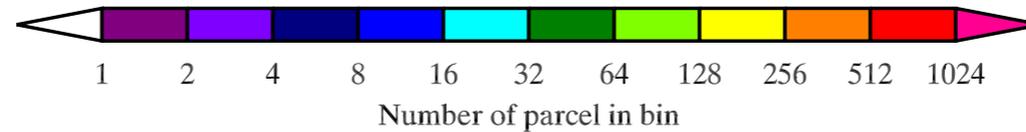
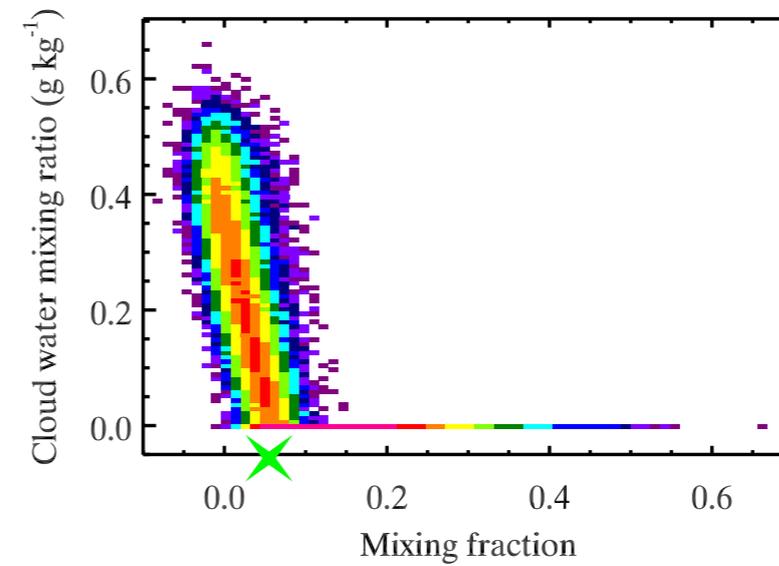
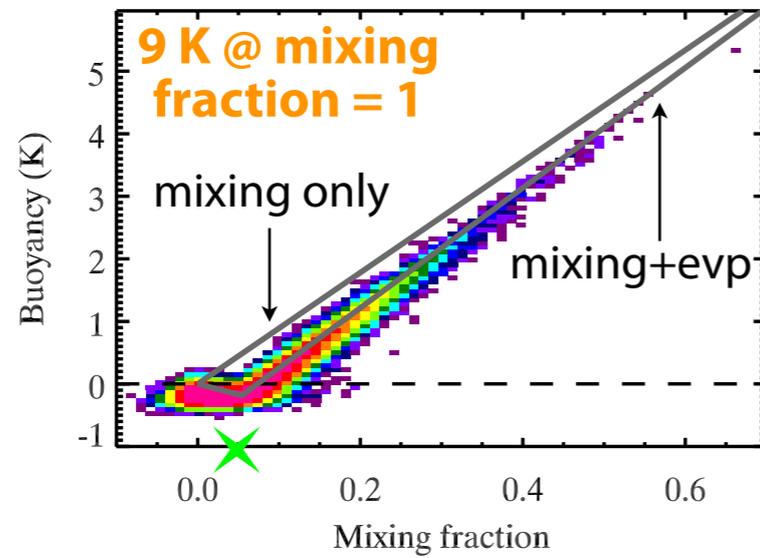
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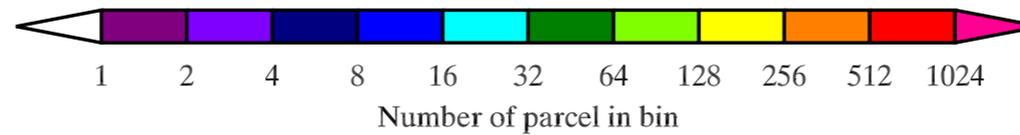
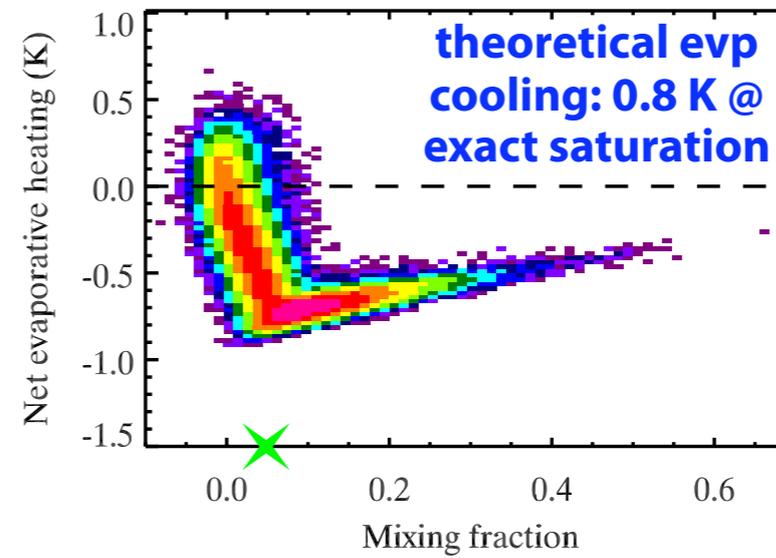
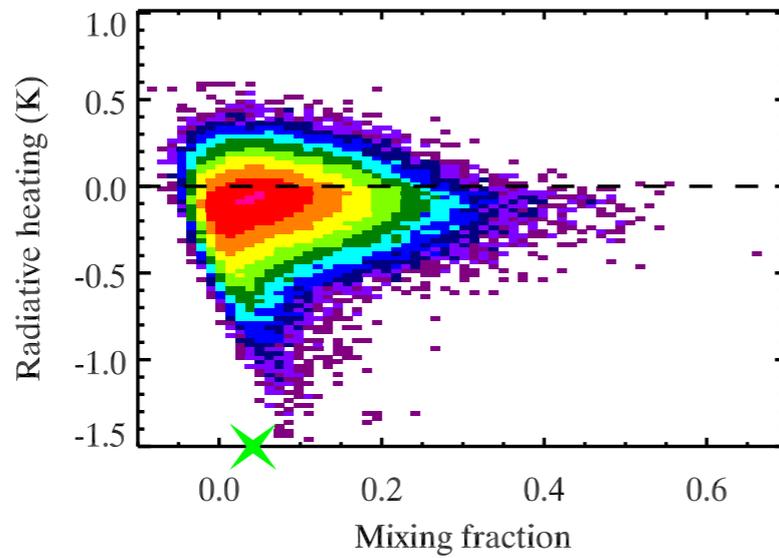
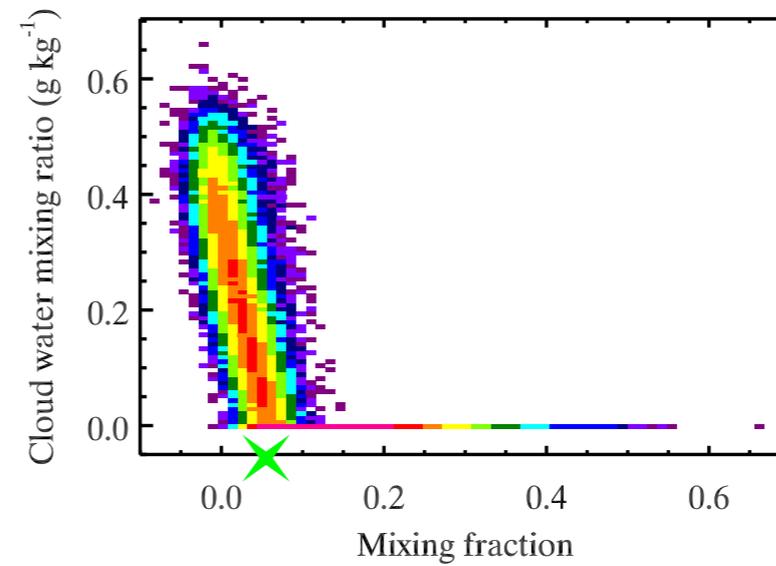
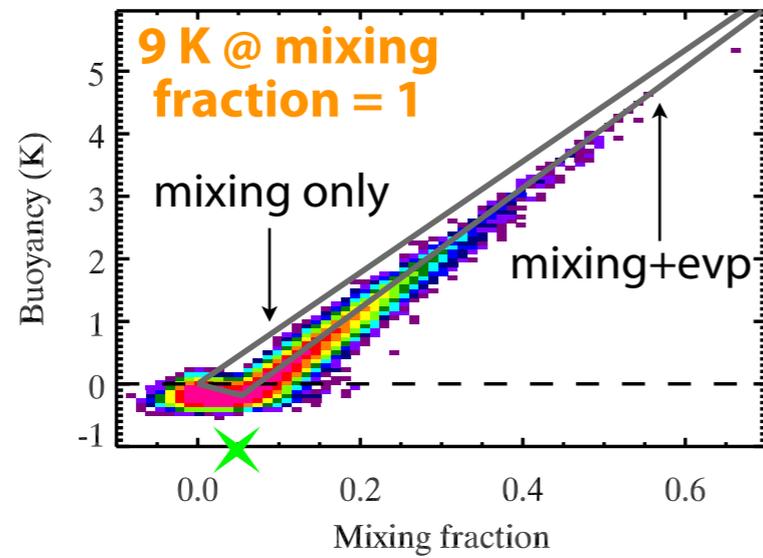
Mixing fraction analysis

$t = t_B$



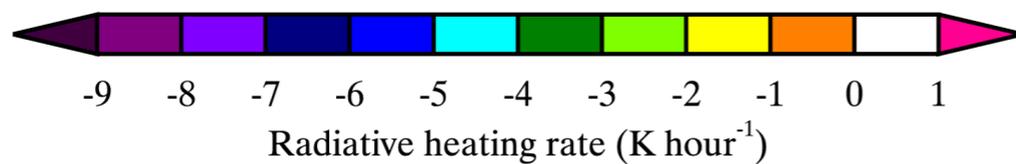
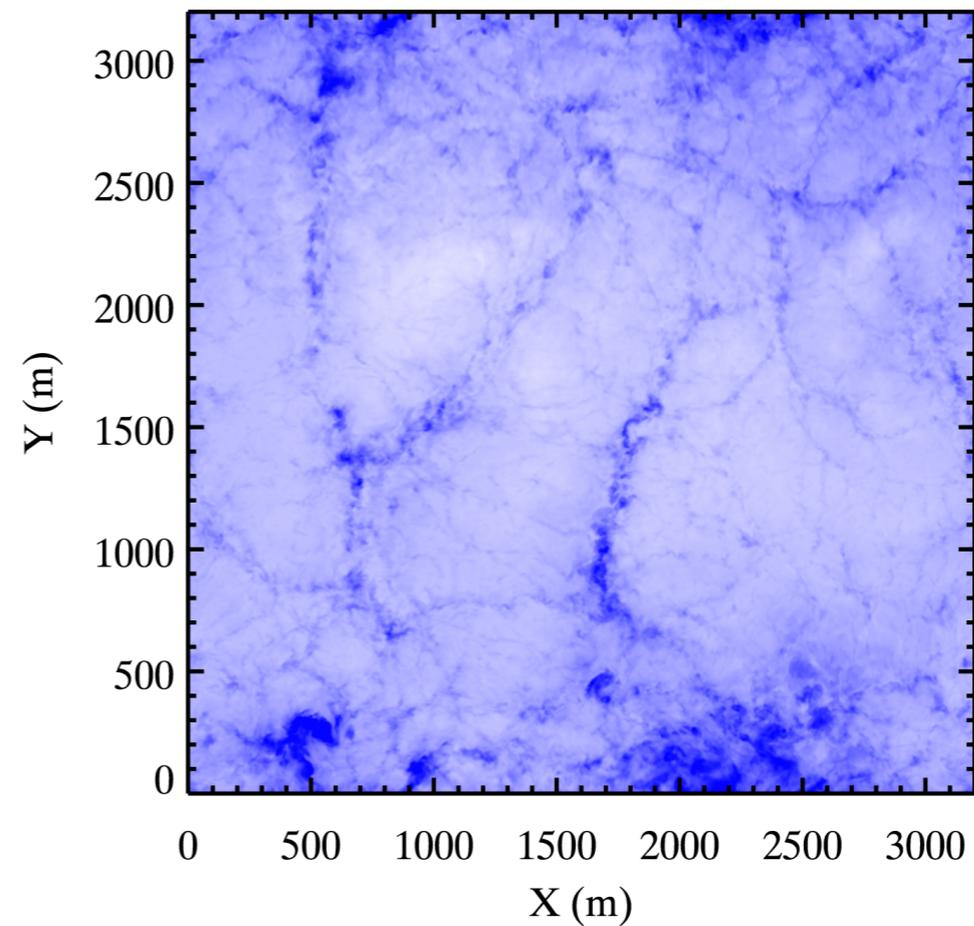
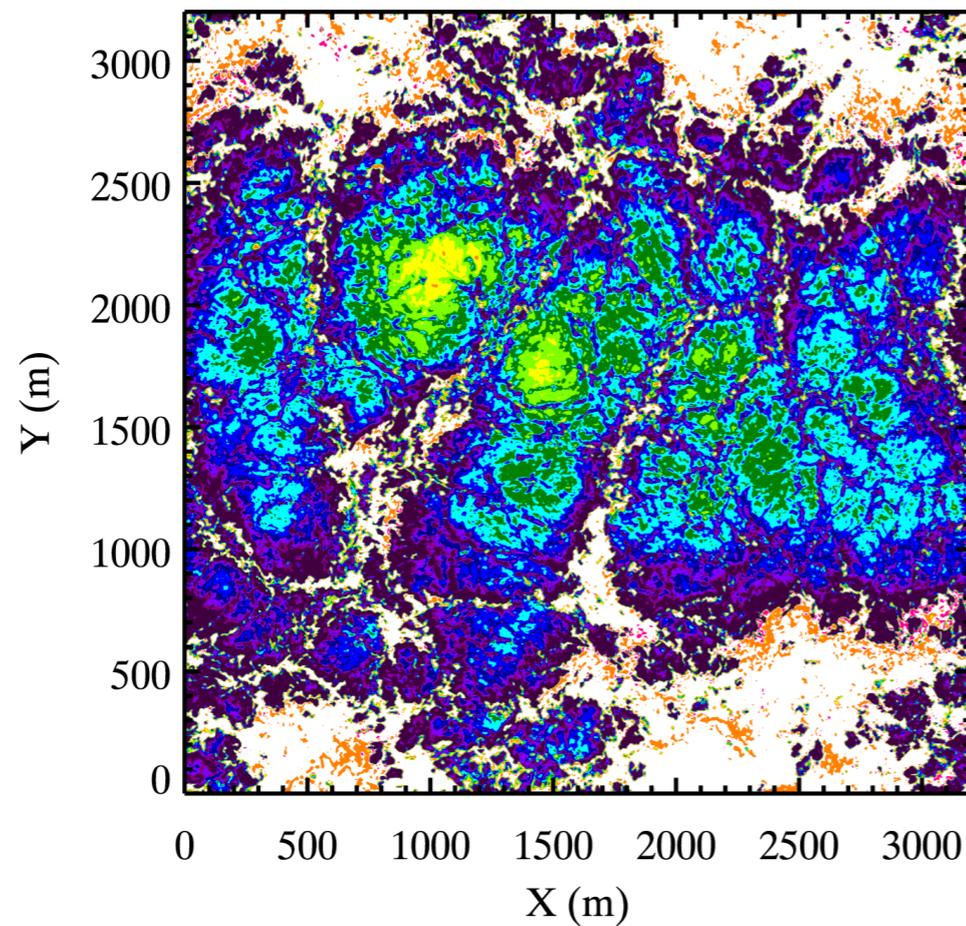
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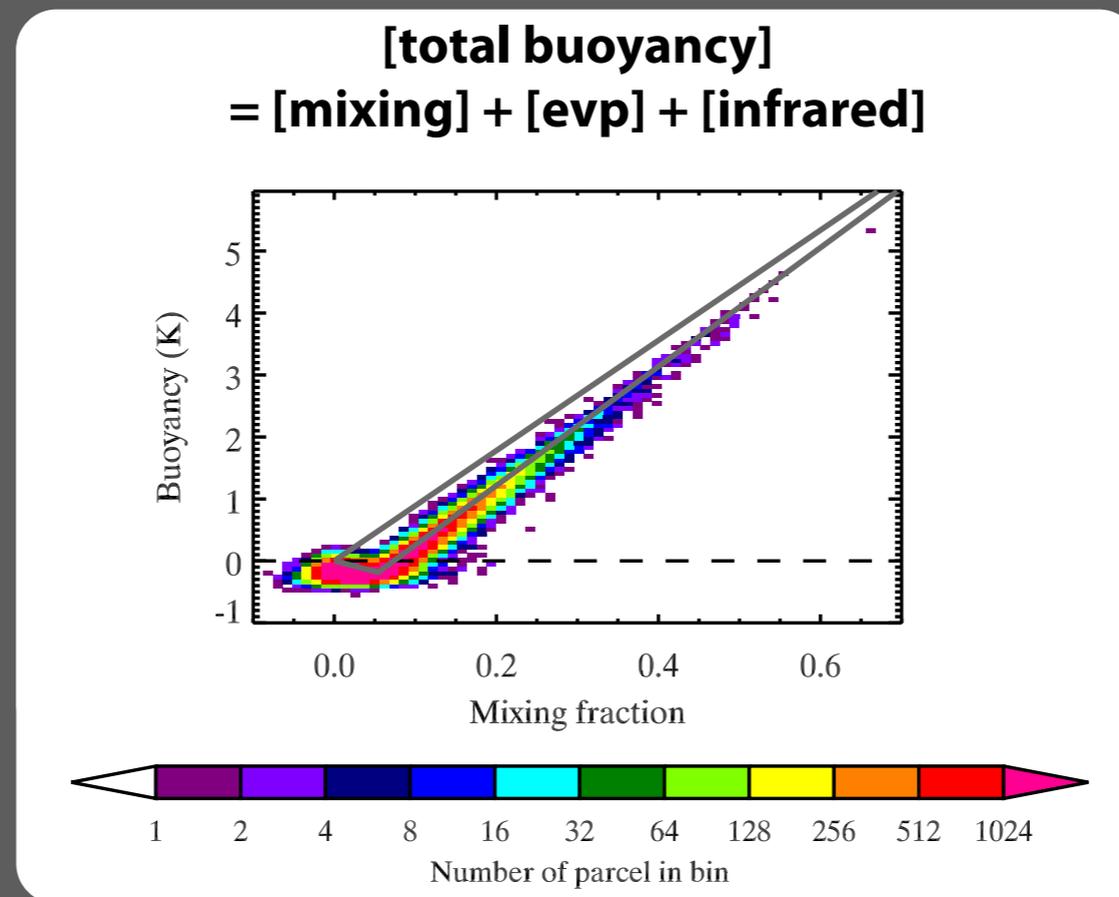


Why is radiative cooling small?

$z = 846$ m, level of the maximum radiative cooling rate at four hours
~ just above z_B

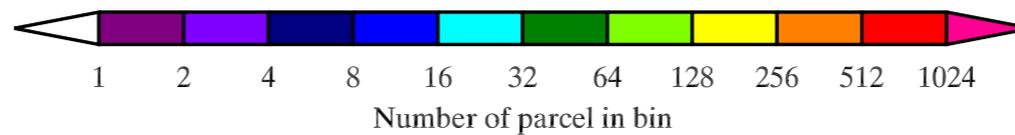
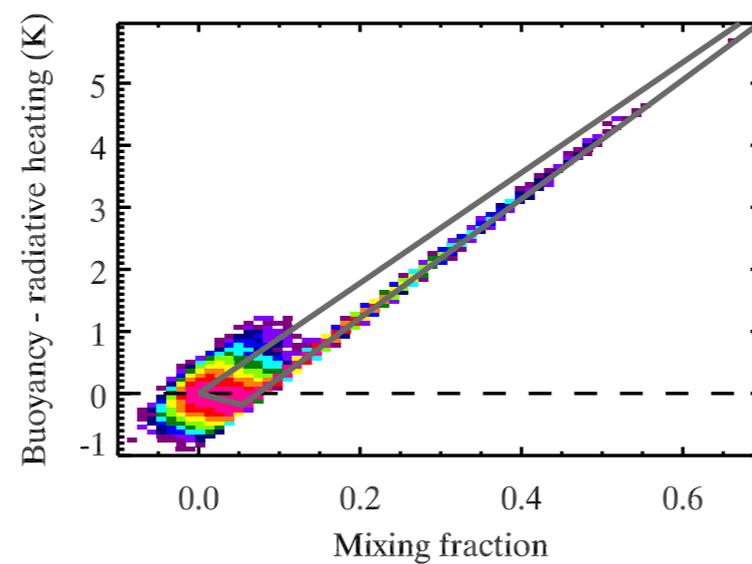


Mixing and evaporation make sufficient negative buoyancy.



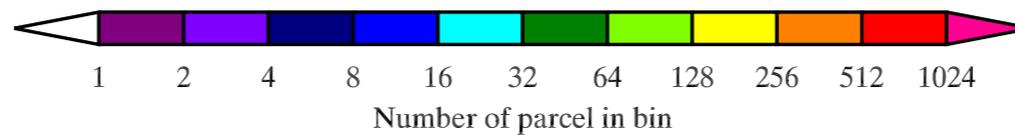
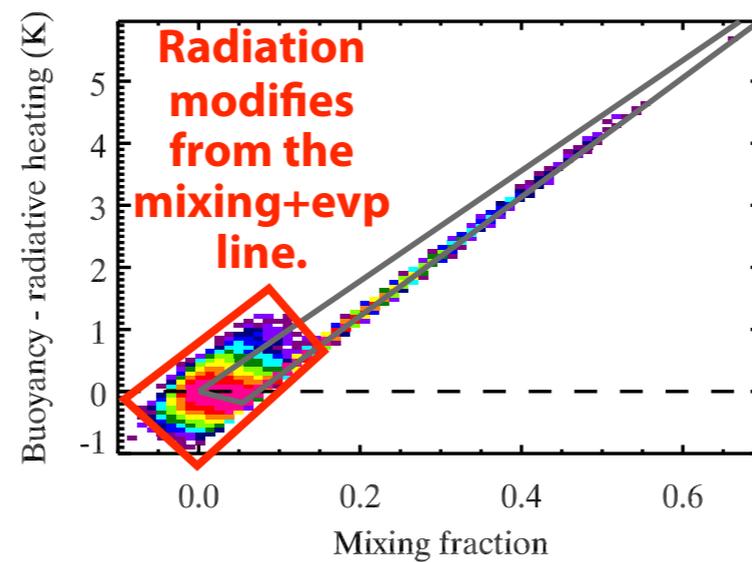
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**[buoyancy contribution due to mixing+evp]
= [total buoyancy] - [infrared]**



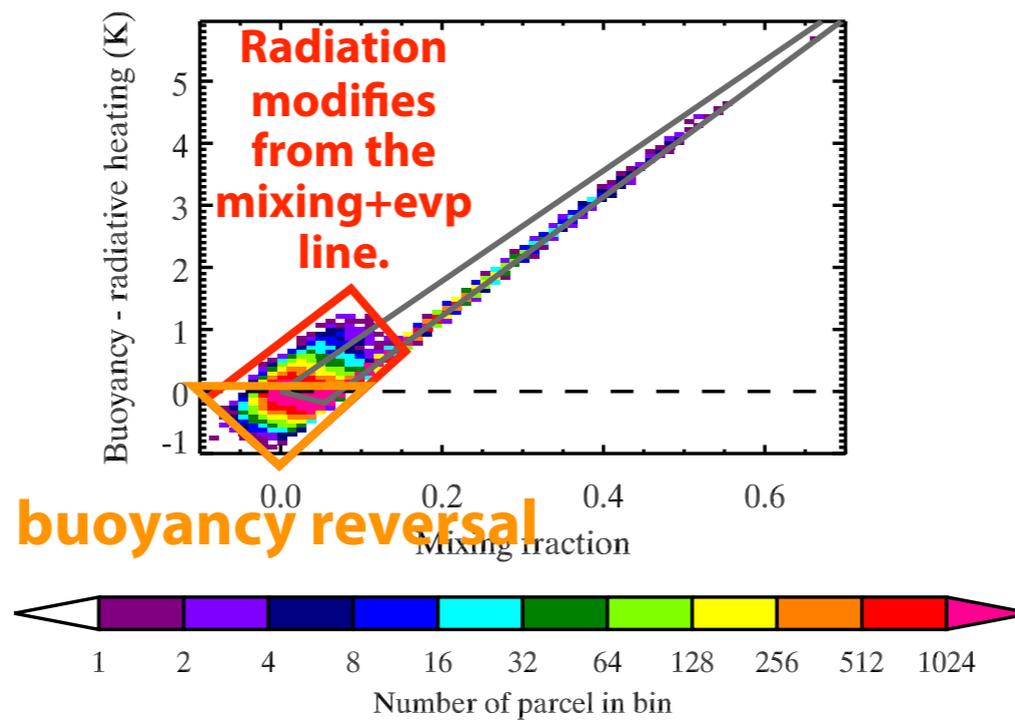
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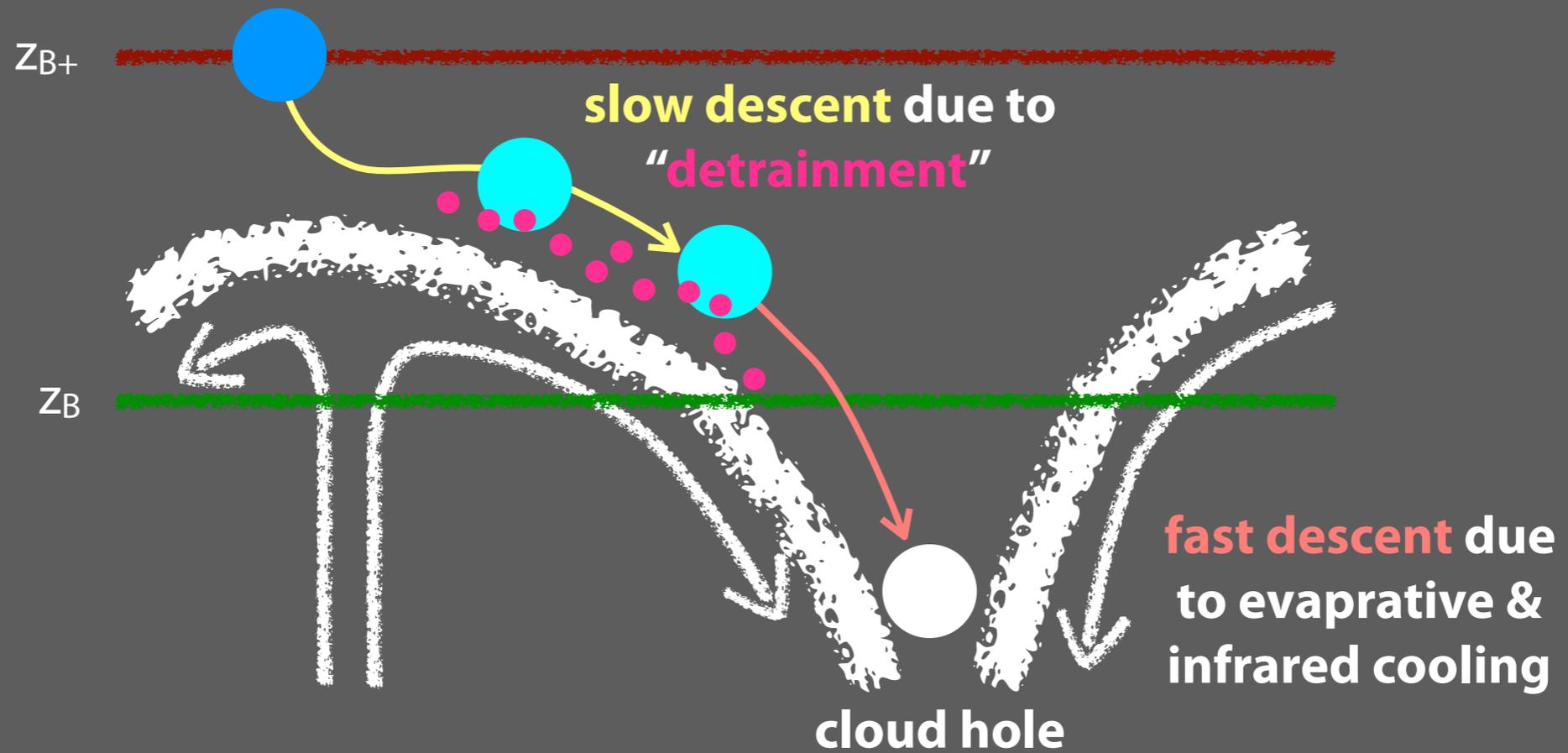


Mixing and evaporation make sufficient negative buoyancy.

**[buoyancy contribution due to mixing+evp]
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Cloud-top entrainment



Summary



- Entrainment takes place in and near the cloud holes.
- Evaporative cooling is at least as strong as radiative cooling for our simulation.
- Mixing is dominant.
- Buoyancy reversal occurs.

Questions?

