On the Role of Wind Shear and Cloud Droplet Sedimentation on Entrainment in Stratocumulus

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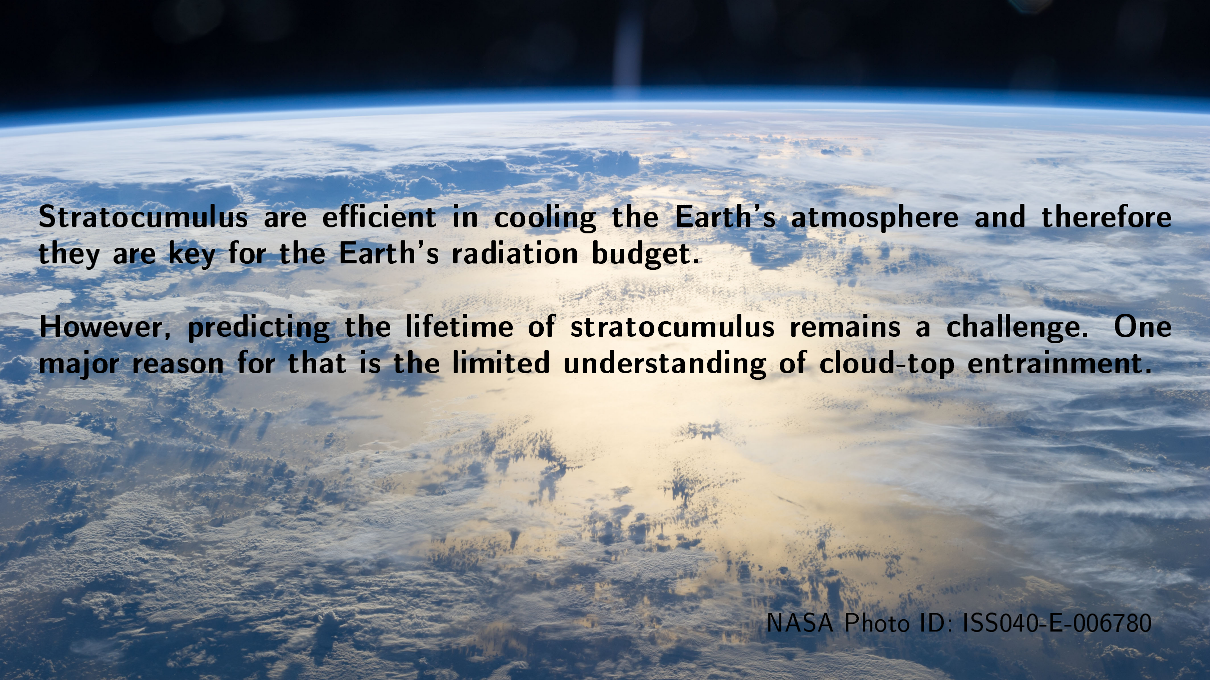

Stratocumulus are efficient in cooling the Earth's atmosphere and therefore they are key for the Earth's radiation budget.

However, predicting the lifetime of stratocumulus remains a challenge. One major reason for that is the limited understanding of cloud-top entrainment.

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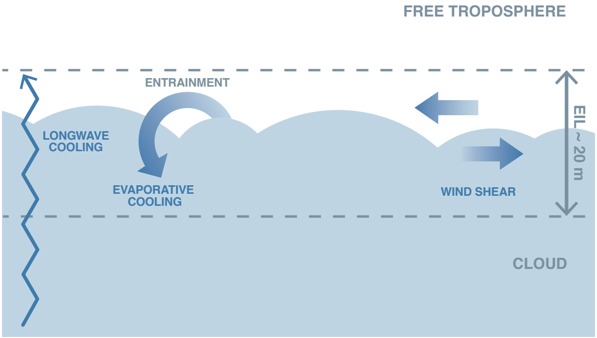
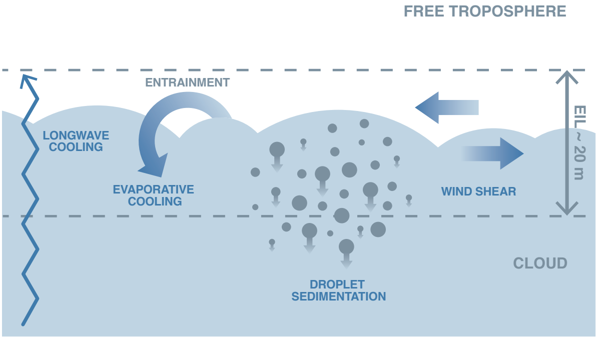
Quantifying wind-shear effects remains a challenge



The EIL is a transition layer between the cloud and the free troposphere.

- Wind shear can substantially enhance entrainment and thicken the entrainment interfacial layer (EIL).
- At which minimal shear strength does shear start to enhance entrainment?
- The magnitude of shear enhancement remains highly uncertain.

Quantifying droplet-sedimentation effects remains a challenge



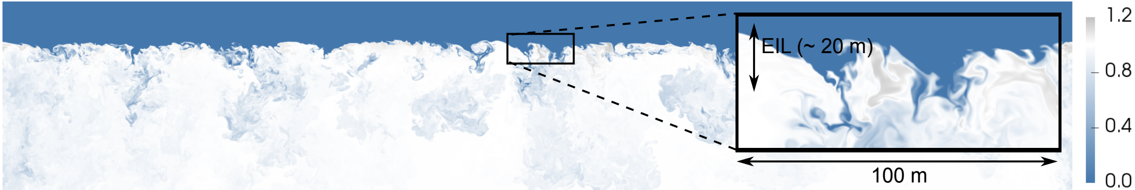
The EIL is a transition layer between the cloud and the free troposphere.

- Droplet sedimentation can substantially weaken entrainment.
- The magnitude of sedimentation weakening remains highly uncertain (entrainment weakens by $5 - 40\%$ *).
- To what extent can sedimentation and shear effects compensate each other?
- How do sedimentation and shear effects compensate each other?

* *Bretherton, Blossey, and Uchida 2007; Ackerman et al. 2009; Hill, Feingold, and Jiang 2009 Lozar and Mellado 2017*

Direct numerical simulations resolve mixing processes in the EIL

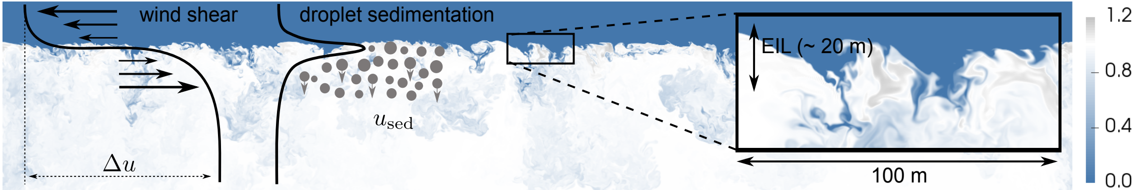
Simulation snapshot showing the normalized liquid water field:

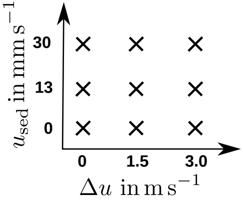


- Direct numerical simulations of a nocturnal stratocumulus cloud-top are performed.
- Neglecting surface fluxes, drizzle, and solar heating allows us to reach submeter-scale resolution, i.e. $\Delta x = \Delta y = \Delta z \simeq 20\,\mathrm{cm}$.
- Match all atmospheric parameters of subtropical clouds (RF01 DYCOMS-II), except the Reynolds number. However, a certain degree of Reynolds number similarity is observed.

Systematic study of wind-shear and droplet-sedimentation effects

Simulation snapshot showing the normalized liquid water field:





- The cloud-top velocity jump Δu is varied.
- The bulk sedimentation velocity u_{sed} is varied.
- $u_{\mathrm{sed}} = u_{\mathrm{sed}}(d, \sigma_{\mathrm{gc}})$ is a function of the mean droplet diameter d and of the geometric standard deviation σ_{gc} of the log-normal droplet size distribution *.

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* *By doing so we follow previous work of Bretherton, Blossey, and Uchida 2007; Ackerman et al. 2004.*

Research questions – Outline

In general:
Direct numerical simulations are employed to better understand how wind shear and droplet sedimentation alter cloud-top entrainment.

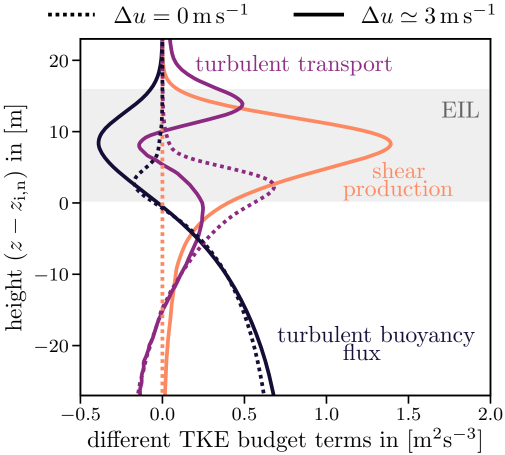
In particular:

(1) **At which minimal shear strength does shear start to enhance entrainment?**

(2) To what extent can sedimentation and shear effects compensate each other?

(3) How do sedimentation and shear compensate each other?

Two competing processes determine cloud-top entrainment



The budget of turbulent kinetic energy (TKE) in a quasi-steady state:

$$0 \simeq -\partial_z T + P + B - \epsilon\,.$$

- $\Delta u = 0\,\mathrm{m\,s^{-1}}$: the turbulent transport term $-\partial_z T$ dominates.
- $\Delta u \simeq 3\,\mathrm{m\,s^{-1}}$: the shear production term P dominates.

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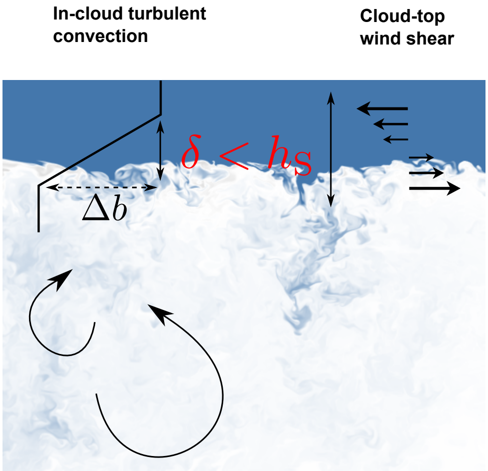
$z_{\mathrm{i,n}}$ is the height of neutral mean buoyancy

Two competing processes determine cloud-top entrainment



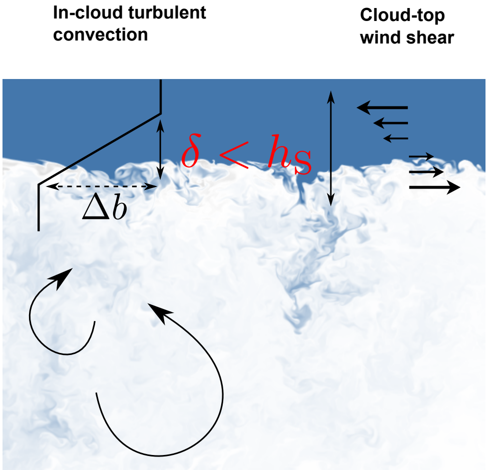
Δb is the cloud-top buoyancy jump

1. Penetrations of in-cloud turbulent convection into the stably stratified EIL are characterized by the penetration depth δ.
2. Shear driven turbulence is characterized by the shear layer thickness $h_S = (\Delta u)^2/(3\Delta b)$.

Convection dominates for: $\delta \gg h_S$
Shear dominates for: $\delta \ll h_S$

This suggests to define $h_S = \delta_{crit}$ as a critical value.

Shear enhances cloud-top entrainment only for $\Delta u > (\Delta u)_{\mathrm{crit}}$



Δb is the cloud-top buoyancy jump

But how to estimate δ ? Balance of potential and kinetic energy:

$$E_{\mathrm{pot}} = E_{\mathrm{kin}}$$

$$\delta \frac{\delta \Delta b}{h_S} = \alpha_1 w_*^2 + \alpha_2 \left(\delta \frac{\Delta u}{h_S} \right)^2$$

$$\Longrightarrow \quad \delta = \sqrt{\frac{\alpha_1}{3(2 - 3\alpha_2)}} \frac{\Delta u w_*}{\Delta b}$$

$$\delta \simeq 1.4 \frac{\Delta u w_*}{\Delta b} \ ,$$

where the *convective velocity scale* w_* characterizes the strength of in-cloud turbulence and $h_S = (\Delta u)^2 / (3\Delta b)$.

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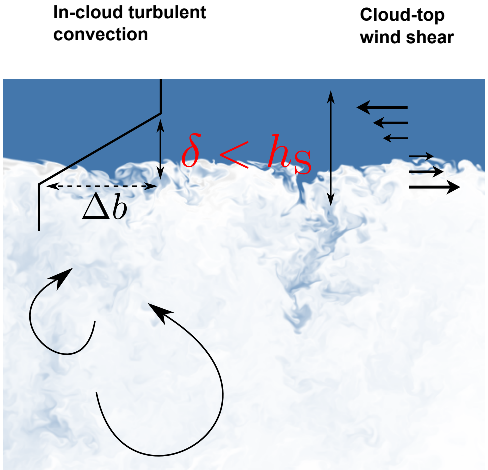
w_* is the convective velocity scale. * *Wood 2012*

Shear enhances cloud-top entrainment only for $\Delta u > (\Delta u)_{\text{crit}}$



Δb is the cloud-top buoyancy jump

$\delta \simeq 1.4(\Delta u w_*)/\Delta b$ and $h_S = (\Delta u)^2/3\Delta b$

Substituting these expressions in the threshold condition $h_S = \delta_{\text{crit}}$ yields

$$(\Delta u)_{\text{crit}} \simeq 4 w_*,$$

which implies for $w_* \simeq 0.18 - 0.92\,\text{m}\,\text{s}^{-1}$ *

$$(\Delta u)_{\text{crit}} \simeq 1 - 4\,\text{m}\,\text{s}^{-1}\,.$$

w_* *is the convective velocity scale.* * *Wood 2012*

Can wind shear weaken in-cloud turbulence w_*?

Definition of $(\Delta u)_{\mathrm{crit}} \simeq 4w_*$ suggests that w_* is independent of Δu.
However, previous studies* indicate that wind shear can weaken in-cloud turbulence w_*.

Basic idea: Shear enhanced evaporation reduces the liquid-water specific humidity q_ℓ, which reduces the net radiative cooling R_0 and weakens in-cloud turbulence w_*.

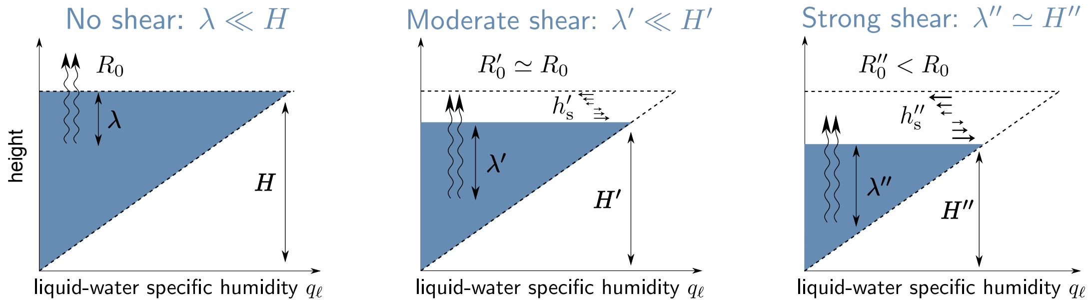
Shear enhanced evaporation does not necessarily weaken in-cloud turbulence.

* *Wang, Zheng, and Jiang 2012; Kopec, Malinowski, and Piotrowski 2016*

Only a shear with $\Delta u > (\Delta u)_{\mathrm{dep}}$ weakens in-cloud turbulence

Redefined idea:

R_0 net radiative cooling, λ extinction length, H cloud depth. Moreover $\lambda \sim q_{\ell,\max}^{-1} d_0$



Formalizing this line of argumentation yields a depletion velocity jump of
$(\Delta u)_{\mathrm{dep}}(H) \simeq 4 - 10\,\mathrm{m\,s^{-1}}$.

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d_0 is the mean droplet diameter

Research questions – Outline

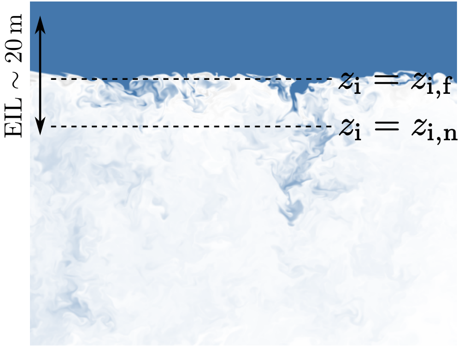
(1) At which minimal shear strength does shear start to enhance entrainment?

- Only a cloud-top wind shear with $\Delta u > (\Delta u)_{\mathrm{crit}} \simeq 1 - 4\,\mathrm{m\,s^{-1}}$ enhances entrainment.
- Only a wind shear with $\Delta u > (\Delta u)_{\mathrm{dep}} \simeq 4 - 10\,\mathrm{m\,s^{-1}}$ weakens in-cloud turbulence.

(2) **To what extent can sedimentation and shear effects compensate each other?**

(3) How do sedimentation and shear compensate each other?

Definition of the entrainment velocity w_e



The entrainment velocity

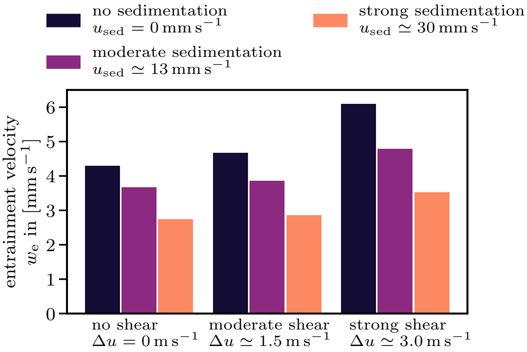
$$w_e = \frac{dz_i}{dt}$$

quantifies the rate of mixing between cloudy and free-tropospheric air.

- Different definitions of the reference height z_i are used.

* *Faloona et al. 2005; Stevens et al. 2003*

Sedimentation and shear effects can compensate each other



- Droplet sedimentation weakens entrainment by up to 40%. (LES studies typically report $5 - 25\%$ *.)
- A strong shear exceeding $(\Delta u)_{\mathrm{crit}} \simeq 2.5\,\mathrm{m\,s^{-1}}$ enhances entrainment by up to 40%.

> Entrainment can be equally sensitive towards changes in wind shear and towards changes in the droplet size distribution.

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* *Bretherton, Blossey, and Uchida 2007; Ackerman et al. 2009; Hill, Feingold, and Jiang 2009*

Entrainment can be equally sensitive towards changes in wind-shear and in the droplet size distribution

Implications:

- Changes in the droplet size distribution can substantially affect cloud lifetimes not only because of its effect on rain formation, but also because of its effect on cloud-top entrainment.
- A better characterization of the droplet size distribution is needed to accurately represent mixing effects on cloud lifetimes.

Research Questions – Summary

(1) At which minimal shear strength does shear start to enhance entrainment?

- Only a cloud-top wind shear with $\Delta u > (\Delta u)_{\mathrm{crit}} \simeq 1 - 4\,\mathrm{m\,s^{-1}}$ enhances entrainment.
- Only a wind shear with $\Delta u > (\Delta u)_{\mathrm{dep}} \simeq 4 - 10\,\mathrm{m\,s^{-1}}$ weakens in-cloud turbulence.

(2) To what extent can sedimentation and shear effects compensate each other?

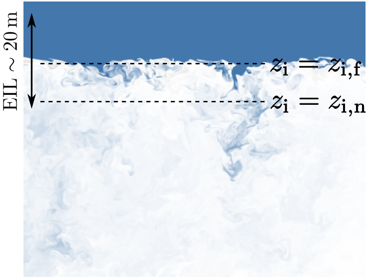
- Sedimentation weakening can cancel shear enhancement, indicating that entrainment can be equally sensitive to changes in shear and to changes in the droplet size distribution.

(3) **How do sedimentation and shear compensate each other?**

The entrainment rate equation

The entrainment velocity $w_\mathrm{e} = dz_\mathrm{i}/dt$ can be analytically decomposed into six contributions:

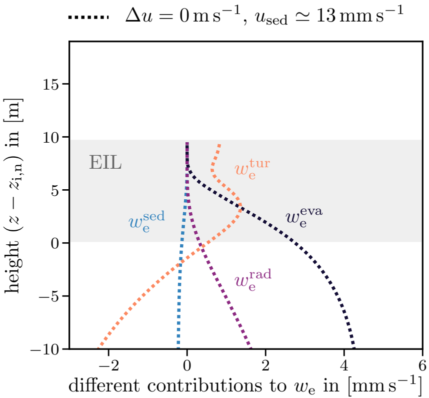
$$w_\mathrm{e} = w_\mathrm{e}^\mathrm{tur} + w_\mathrm{e}^\mathrm{eva} + w_\mathrm{e}^\mathrm{sed} + w_\mathrm{e}^\mathrm{rad} + w_\mathrm{e}^\mathrm{mol} + w_\mathrm{e}^\mathrm{def} \ .$$



- The turbulent buoyancy flux contribution $w_\mathrm{e}^\mathrm{tur} \sim -\langle w'b' \rangle_{z_\mathrm{i}}$.
- The evaporative cooling contribution $w_\mathrm{e}^\mathrm{eva} \sim (E_0 - \langle E \rangle_{z_\mathrm{i}})$.
- The sedimentation buoyancy flux contribution $w_\mathrm{e}^\mathrm{sed} \sim -\langle \mathbf{j}_\mu g \cdot \mathbf{k} \rangle_{z_\mathrm{i}}$.
- The radiative cooling contribution $w_\mathrm{e}^\mathrm{rad} \sim \beta(R_0 - \langle R \rangle_{z_\mathrm{i}})$.

with the sedimentation flux $\mathbf{j}_\mu = -q_\ell^\mathrm{c} u_\mathrm{sed} (q_\ell / q_\ell^\mathrm{c})^{5/3} \mathbf{k}$

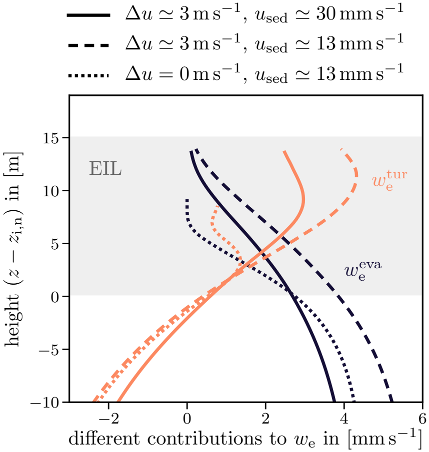
The different contributions to w_e vary strongly with height



$$w_\mathrm{e} = w_\mathrm{e}^\mathrm{tur} + w_\mathrm{e}^\mathrm{sed} + w_\mathrm{e}^\mathrm{eva} + w_\mathrm{e}^\mathrm{rad} + w_\mathrm{e}^\mathrm{mol} + w_\mathrm{e}^\mathrm{def}$$

- Strong dependence on the reference height z_i.
- Contributions of $w_\mathrm{e}^\mathrm{rad}$ and $w_\mathrm{e}^\mathrm{sed}$ are small.
- However, total radiative cooling R_0 remains comparable to total evaporative cooling E_0.

Sedimentation and shear compensate each other due to their opposing effects on w_e^{tur} and w_e^{eva}

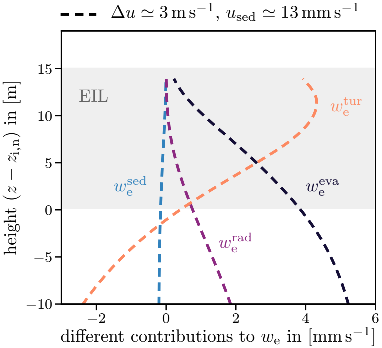


$$w_e = w_e^{tur} + w_e^{sed} + w_e^{eva} + w_e^{rad} + w_e^{mol} + w_e^{def}$$

- Shear amplifies w_e^{tur} & Shear enhanced entrainment amplifies w_e^{eva}.
- Sedimentation induced thickening of the EIL weakens w_e^{tur} & Sedimentation removes liquid water from the EIL, which weakens w_e^{eva}.

> The way sedimentation and shear compensate each other depends strongly on height.

Three implications for entrainment velocity parametrizations



$$w_e = w_e^{\mathrm{tur}} + w_e^{\mathrm{sed}} + w_e^{\mathrm{eva}} + w_e^{\mathrm{rad}} + w_e^{\mathrm{mol}} + w_e^{\mathrm{def}}$$

Mixed-layer models need accurate parameterizations of the entrainment velocity.

Implications:

1. Entrainment velocity parametrizations should pay equal attention to shear and sedimentation effects.
2. Separate contributions to w_e should be estimated at the same reference height z_i, even though different definitions of z_i only differ by a few meters.
3. Parameterizing w_e^{eva} and w_e^{tur} has priority (compared to w_e^{rad} and w_e^{sed}).

Research Questions – Summary

(1) At which minimal shear strength does shear start to enhance entrainment?

- Only a cloud-top wind shear with $\Delta u > (\Delta u)_{\mathrm{crit}} \simeq 1 - 4\,\mathrm{m\,s^{-1}}$ enhances entrainment.
- Only a wind shear with $\Delta u > (\Delta u)_{\mathrm{dep}} \simeq 4 - 10\,\mathrm{m\,s^{-1}}$ weakens in-cloud turbulence.

(2) To what extent can sedimentation and shear effects compensate each other?

- Sedimentation weakening can cancel shear enhancement, indicating that entrainment can be equally sensitive to changes in shear and to changes in the droplet size distribution.

(3) How do sedimentation and shear compensate each other?

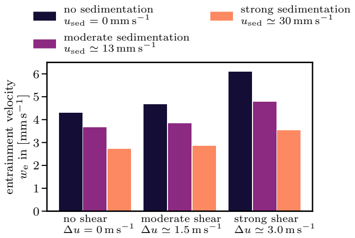
- Shear and sedimentation effects on w_{e} compensate each other due to their opposing effects on $w_{\mathrm{e}}^{\mathrm{tur}}$ and $w_{\mathrm{e}}^{\mathrm{eva}}$. Changes in $w_{\mathrm{e}}^{\mathrm{sed}}$ and $w_{\mathrm{e}}^{\mathrm{rad}}$ are less important.
- Different contributions to w_{e} depend strongly on the choice of the reference height z_{i}.

Take-home messages

Understanding and quantifying wind-shear and droplet-sedimentation effects on cloud-top entrainment is important but remains a challenge.

Conclusions:

1. Only a strong wind shear with $\Delta u > (\Delta u)_{\mathrm{crit}} \simeq 4w_*$ enhances entrainment.
2. Entrainment reduction by droplet sedimentation can completely compensate entrainment enhancement by wind shear.
3. Shear and sedimentation effects on w_e compensate each other due to their opposing effects on w_e^{tur} and w_e^{eva}. Even small variations of the reference height z_i matter.



w_* *is the convective velocity scale.*

Bibliography I

- Bretherton, CS, Peter N Blossey, and Junya Uchida (2007). "Cloud droplet sedimentation, entrainment efficiency, and subtropical stratocumulus albedo". In: *Geophysical research letters* 34.3.
- Ackerman, Andrew S et al. (2009). "Large-eddy simulations of a drizzling, stratocumulus-topped marine boundary layer". In: *Monthly Weather Review* 137.3, pp. 1083–1110.
- Hill, Adrian A, Graham Feingold, and Hongli Jiang (2009). "The influence of entrainment and mixing assumption on aerosol–cloud interactions in marine stratocumulus". In: *Journal of the Atmospheric Sciences* 66.5, pp. 1450–1464.
- Lozar, Alberto de and Juan Pedro Mellado (2017). "Reduction of the entrainment velocity by cloud droplet sedimentation in stratocumulus". In: *Journal of the Atmospheric Sciences* 74.3, pp. 751–765.
- Ackerman, Andrew S et al. (2004). "The impact of humidity above stratiform clouds on indirect aerosol climate forcing". In: *Nature* 432.7020, p. 1014.

Bibliography II

Wood, Robert (2012). "Stratocumulus clouds". In: *Monthly Weather Review* 140.8, pp. 2373–2423.

Wang, S, X Zheng, and Q Jiang (2012). "Strongly sheared stratocumulus convection: an observationally based large-eddy simulation study". In: *Atmospheric Chemistry and Physics* 12.11, pp. 5223–5235.

Kopec, Marta K, Szymon P Malinowski, and Zbigniew P Piotrowski (2016). "Effects of wind shear and radiative cooling on the stratocumulus-topped boundary layer". In: *Quarterly Journal of the Royal Meteorological Society* 142.701, pp. 3222–3233.

Faloona, Ian et al. (2005). "Observations of entrainment in eastern Pacific marine stratocumulus using three conserved scalars". In: *Journal of the atmospheric sciences* 62.9, pp. 3268–3285.

Stevens, Bjorn et al. (2003). "On entrainment rates in nocturnal marine stratocumulus". In: *Quarterly Journal of the Royal Meteorological Society* 129.595, pp. 3469–3493.