Strong cloud-circulation coupling explains weak trade cumulus feedback

Raphaela Vogel*, Anna Lea Albright, Jessica Vial, Geet George, Bjorn Stevens, Sandrine Bony

*raphaela.vogel@uni-hamburg.de
the trade-cumulus cloud feedback has remained a major source of uncertainty for climate sensitivity (Bony and Dufresne 2005, Vial et al. 2013, Myers et al. 2021)

while many climate models exhibit strong trade cumulus feedbacks, satellite-derived constraints from observed natural variability (Myers et al. 2021, Cesana and del Genio 2021) & large-eddy simulations (Vogel et al. 2016, Radtke et al. 2021) suggest a rather weak feedback

In climate models, trade cumulus feedbacks are governed by changes in cloud fraction near cloud base (Vial et al. 2016, Brient et al. 2016)

high sensitivity models suggest a desiccation of the lower cloud layer with increasing lower-tropospheric mixing (Vial et al. 2016, Sherwood et al. 2014)
Mixing-desiccation mechanism – a hypothesis for a strongly positive trade cumulus feedback

- enhanced moisture transport by convection compensated by downward mixing of drier air & evaporation of clouds near cloud base.

→ \( C \propto R \propto M^\beta \), with \( \beta < 0 \)

- consistent with high-sensitivity climate models & idealized large-eddy simulations of non-precipitating trade cumuli (Sherwood et al. 2014, Rieck et al. 2012)

but.....

- \( M_{act} = Cac_{t} wac_{t} \), mostly governed by area fraction of active clouds \( C_{act} \) (~50% of total \( C \))

→ \( \beta > 0 \)

- substantial variability in \( W \) observed in the trades (Bony & Stevens 2019, George et al. 2021)

- never tested with observations

(Bony et al. 2017, Stevens et al. 2021)
Mixing-desiccation mechanism – a hypothesis for a strongly positive trade cumulus feedback

- enhanced moisture transport by convection compensated by downward mixing of drier air & evaporation of clouds near cloud base.

\[ C \propto R \propto M^\beta, \text{ with } \beta < 0 \]

- consistent with high-sensitivity climate models & idealized large-eddy simulations of non-precipitating trade cumuli \cite{Sherwood2014, Rieck2012}
**EUREC4A field campaign**  
*Bony et al. 2017, Stevens et al. 2021*

- Jan-Feb 2020  
- 4 aircraft & ships, drones, BCO...  
- goal: test mixing-desiccation hypothesis  
- Clouds @Barbados representative for entire trade-wind belt *Medeiros & Nuijens 2016*
mass flux estimation from dropsonde measurements
Mass flux estimation using EUREC4A dropsondes

\[ M = E + W - \frac{\partial h}{\partial t} \nabla h \sim M_{\text{act}} = a_{\text{act}} \, w_{\text{act}} \]

> sub-cloud layer top \( h \)
- target: max. cloud-base cloud fraction level
- definition: \( \theta_v(h) \geq \bar{\theta}_v + \epsilon \), with \( \epsilon = 0.2K \)
Mass flux estimation using EUREC4A dropsondes

\[ M = E + W - \frac{\partial h}{\partial t} \nabla h \]

\[ \sim M_{\text{act}} = a_{\text{act}} w_{\text{act}} \] (Vogel et al. 2020)

> sub-cloud layer top \( h \)
  - target: max. cloud-base cloud fraction level
  - definition: \( \theta_v(h) \geq \bar{\theta}_v + \epsilon \), with \( \epsilon = 0.2K \)

> entrainment rate \( E \): 
  \[ E = \frac{A_e w' \bar{\theta}_v'}{\Delta \theta_v} \], with \( A_e = 0.43 \) (Albright et al., 2022)

> mesoscale vertical velocity \( W \) at \( h \):
  from regression method (Bony & Stevens 2019)

>> target scale: 3-circle averages (~3h, 200 km)
First observations of convective mixing at the mesoscale

- M and E robust to changes in estimation procedure and consistent with independent data
  - on average, M~E
  - but on shorter timescales, E & W contribute almost equally to variability in M
Cloud-base cloud fraction

horizontally-staring 355nm ALIAS lidar
(Chazette et al. 2020)

horizontally-staring 94GHz BASTA Doppler radar
(Delanoë et al. 2016)

very good agreement among different instruments (Bony et al. 2022)
First observations of $M$, $C$ and RH co-variations

- $C$ is both small and highly variable
- $R$ is robustly around 86%
- 3 circle-sets with inconsistent sampling neglected
Do we find evidence for the mixing-desiccation mechanism in the EUREC4A data?
\[ C = a_M \tilde{M} + a_R \tilde{R} \]

W & E contribute equally to variability in M, but have opposing relations to R → negligible desiccation effect of M!

M alone explains 50% of C variability

dynamical control through M overwhelms thermodynamic control through R → \( a_M/a_R \sim 1.8 \)

EUREC\(^4\)A data refute mixing-desiccation mechanism
Ubiquity of SMOCS* and their influence on moisture variance in the trades 
(George et al. 2022, in review)

*Shallow Mesoscale Overturning Circulations

- anti-correlation between divergence in the sub-cloud and cloud layers
- Sub-cloud convergence correlated with moister sub-cloud and cloud-base layers
- ERA5: SMOCs are elongated features of ~100-200 km and cover ~58% of domain
How consistent is the present generation of climate models with our observations?

- 4 CMIP5 and 6 CMIP6 models (Taylor et al. 2012, Eyring et al. 2016)
- AMIP 1979-2008 & AMIP+4K (uniform warming)
- Winter months (DJFM)
- subhourly output at selected sites from CFMIP (Webb et al. 2017): BCO, BOMEX, EUREC4A, NTAS
- monthly outputs over 60W-44W, 11N-16N
Models underestimate strong cloud-circulation coupling

Magnitude, variability, and coupling of M, C and R in CFMIP models differs drastically from EUREC^4A data

Underlying fast physical processes that couple M, R and C in the models are largely time-scale invariant
Process-based constraints render strongly positive trade cumulus feedbacks implausible.

Magnitude, variability, and coupling of M, C and R in CFMIP models differs drastically from EUREC$^4$A data.

Underlying fast physical processes that couple M, R and C in the models are largely time-scale invariant.

Models with largest positive feedback represent refuted mixing-desiccation mechanism and particularly exaggerate variability of C and coupling of C to R instead of M (small $a_M/a_R$).

$\Delta CRE/\Delta T$ [Wm$^{-2}$K$^{-1}$] C [%]

Models with largest positive feedback represent refuted mixing-desiccation mechanism and particularly exaggerate variability of C and coupling of C to R instead of M (small $a_M/a_R$).

$\Delta CRE/\Delta T$ [Wm$^{-2}$K$^{-1}$] C [%]

Models with largest positive feedback represent refuted mixing-desiccation mechanism and particularly exaggerate variability of C and coupling of C to R instead of M (small $a_M/a_R$).

$\Delta CRE/\Delta T$ [Wm$^{-2}$K$^{-1}$] C [%]

Models with largest positive feedback represent refuted mixing-desiccation mechanism and particularly exaggerate variability of C and coupling of C to R instead of M (small $a_M/a_R$).

$\Delta CRE/\Delta T$ [Wm$^{-2}$K$^{-1}$] C [%]

Models with largest positive feedback represent refuted mixing-desiccation mechanism and particularly exaggerate variability of C and coupling of C to R instead of M (small $a_M/a_R$).

$\Delta CRE/\Delta T$ [Wm$^{-2}$K$^{-1}$] C [%]

Models with largest positive feedback represent refuted mixing-desiccation mechanism and particularly exaggerate variability of C and coupling of C to R instead of M (small $a_M/a_R$).

$\Delta CRE/\Delta T$ [Wm$^{-2}$K$^{-1}$] C [%]

Models with largest positive feedback represent refuted mixing-desiccation mechanism and particularly exaggerate variability of C and coupling of C to R instead of M (small $a_M/a_R$).

$\Delta CRE/\Delta T$ [Wm$^{-2}$K$^{-1}$] C [%]

Models with largest positive feedback represent refuted mixing-desiccation mechanism and particularly exaggerate variability of C and coupling of C to R instead of M (small $a_M/a_R$).

$\Delta CRE/\Delta T$ [Wm$^{-2}$K$^{-1}$] C [%]

Models with largest positive feedback represent refuted mixing-desiccation mechanism and particularly exaggerate variability of C and coupling of C to R instead of M (small $a_M/a_R$).

$\Delta CRE/\Delta T$ [Wm$^{-2}$K$^{-1}$] C [%]

Models with largest positive feedback represent refuted mixing-desiccation mechanism and particularly exaggerate variability of C and coupling of C to R instead of M (small $a_M/a_R$).

$\Delta CRE/\Delta T$ [Wm$^{-2}$K$^{-1}$] C [%]

Models with largest positive feedback represent refuted mixing-desiccation mechanism and particularly exaggerate variability of C and coupling of C to R instead of M (small $a_M/a_R$).

$\Delta CRE/\Delta T$ [Wm$^{-2}$K$^{-1}$] C [%]

Models with largest positive feedback represent refuted mixing-desiccation mechanism and particularly exaggerate variability of C and coupling of C to R instead of M (small $a_M/a_R$).

$\Delta CRE/\Delta T$ [Wm$^{-2}$K$^{-1}$] C [%]

Models with largest positive feedback represent refuted mixing-desiccation mechanism and particularly exaggerate variability of C and coupling of C to R instead of M (small $a_M/a_R$).

$\Delta CRE/\Delta T$ [Wm$^{-2}$K$^{-1}$] C [%]

Models with largest positive feedback represent refuted mixing-desiccation mechanism and particularly exaggerate variability of C and coupling of C to R instead of M (small $a_M/a_R$).

$\Delta CRE/\Delta T$ [Wm$^{-2}$K$^{-1}$] C [%]

Models with largest positive feedback represent refuted mixing-desiccation mechanism and particularly exaggerate variability of C and coupling of C to R instead of M (small $a_M/a_R$).

$\Delta CRE/\Delta T$ [Wm$^{-2}$K$^{-1}$] C [%]

Models with largest positive feedback represent refuted mixing-desiccation mechanism and particularly exaggerate variability of C and coupling of C to R instead of M (small $a_M/a_R$).

$\Delta CRE/\Delta T$ [Wm$^{-2}$K$^{-1}$] C [%]

Models with largest positive feedback represent refuted mixing-desiccation mechanism and particularly exaggerate variability of C and coupling of C to R instead of M (small $a_M/a_R$).

$\Delta CRE/\Delta T$ [Wm$^{-2}$K$^{-1}$] C [%]

Models with largest positive feedback represent refuted mixing-desiccation mechanism and particularly exaggerate variability of C and coupling of C to R instead of M (small $a_M/a_R$).

$\Delta CRE/\Delta T$ [Wm$^{-2}$K$^{-1}$] C [%]

Models with largest positive feedback represent refuted mixing-desiccation mechanism and particularly exaggerate variability of C and coupling of C to R instead of M (small $a_M/a_R$).

$\Delta CRE/\Delta T$ [Wm$^{-2}$K$^{-1}$] C [%]

Models with largest positive feedback represent refuted mixing-desiccation mechanism and particularly exaggerate variability of C and coupling of C to R instead of M (small $a_M/a_R$).

$\Delta CRE/\Delta T$ [Wm$^{-2}$K$^{-1}$] C [%]

Models with largest positive feedback represent refuted mixing-desiccation mechanism and particularly exaggerate variability of C and coupling of C to R instead of M (small $a_M/a_R$).

$\Delta CRE/\Delta T$ [Wm$^{-2}$K$^{-1}$] C [%]

Models with largest positive feedback represent refuted mixing-desiccation mechanism and particularly exaggerate variability of C and coupling of C to R instead of M (small $a_M/a_R$).

$\Delta CRE/\Delta T$ [Wm$^{-2}$K$^{-1}$] C [%]

Models with largest positive feedback represent refuted mixing-desiccation mechanism and particularly exaggerate variability of C and coupling of C to R instead of M (small $a_M/a_R$).

$\Delta CRE/\Delta T$ [Wm$^{-2}$K$^{-1}$] C [%]

Models with largest positive feedback represent refuted mixing-desiccation mechanism and particularly exaggerate variability of C and coupling of C to R instead of M (small $a_M/a_R$).

$\Delta CRE/\Delta T$ [Wm$^{-2}$K$^{-1}$] C [%]

Models with largest positive feedback represent refuted mixing-desiccation mechanism and particularly exaggerate variability of C and coupling of C to R instead of M (small $a_M/a_R$).

$\Delta CRE/\Delta T$ [Wm$^{-2}$K$^{-1}$] C [%]
conclusions
Conclusions

By refuting the mixing-desiccation mechanism, the EUREC⁴A data...

... refute an important mechanism for a strongly positive trade cumulus feedback and thus a critical line of evidence for a large climate sensitivity (Stevens et al. 2016)

... render climate models with strong positive feedbacks implausible

... both support (Myers et al. 2021, Vogel et al. 2016) and explain at the process scale a weak trade cumulus feedback

paper accepted in Nature, preprint: https://doi.org/10.1002/essoar.10512547.1