The diurnal susceptibility of subtropical clouds to aerosols

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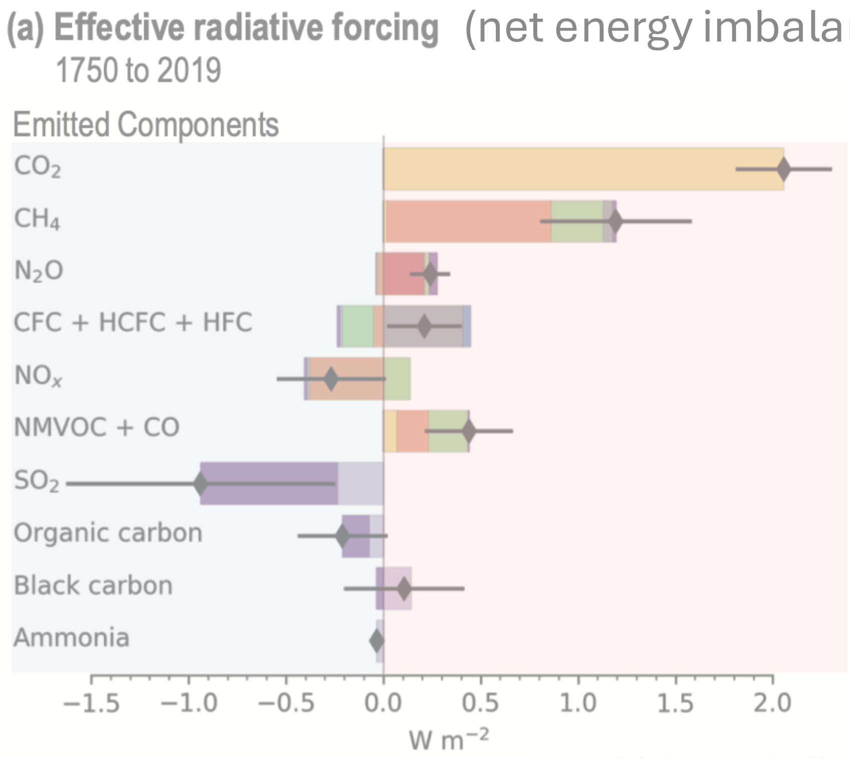
IPCC AR6

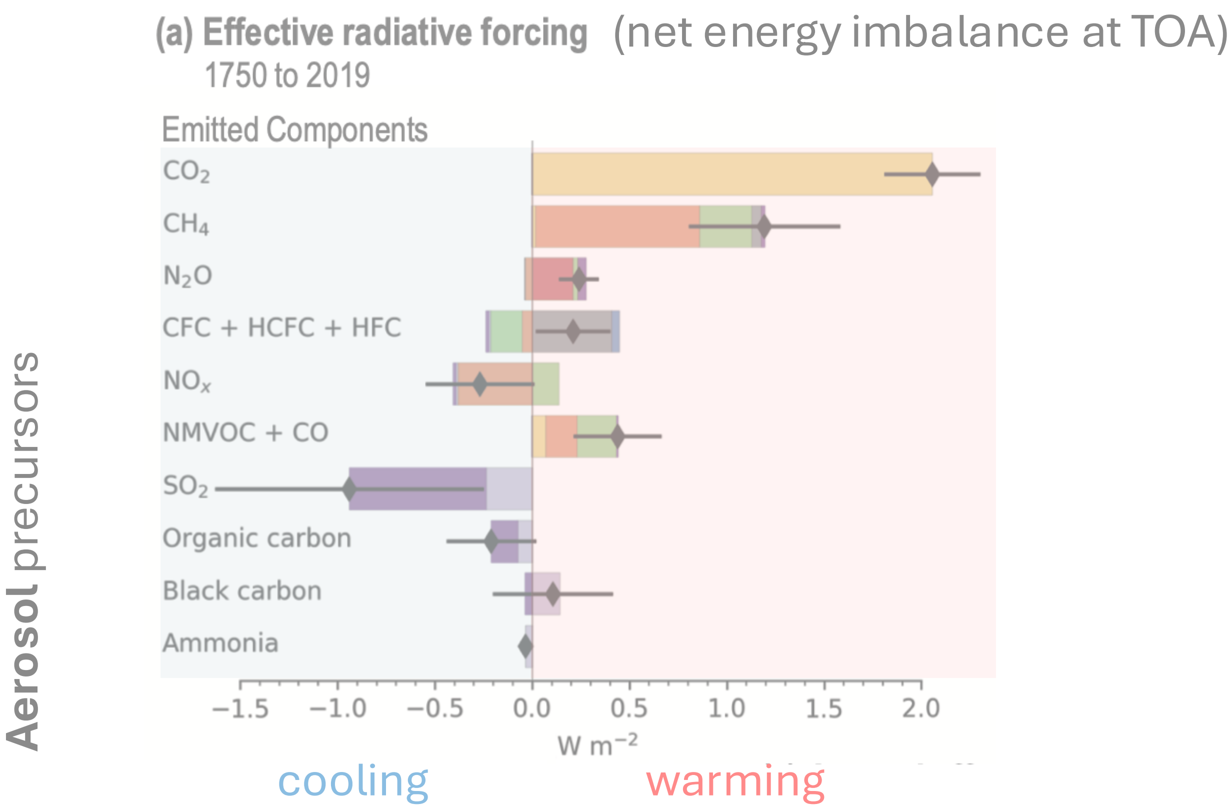


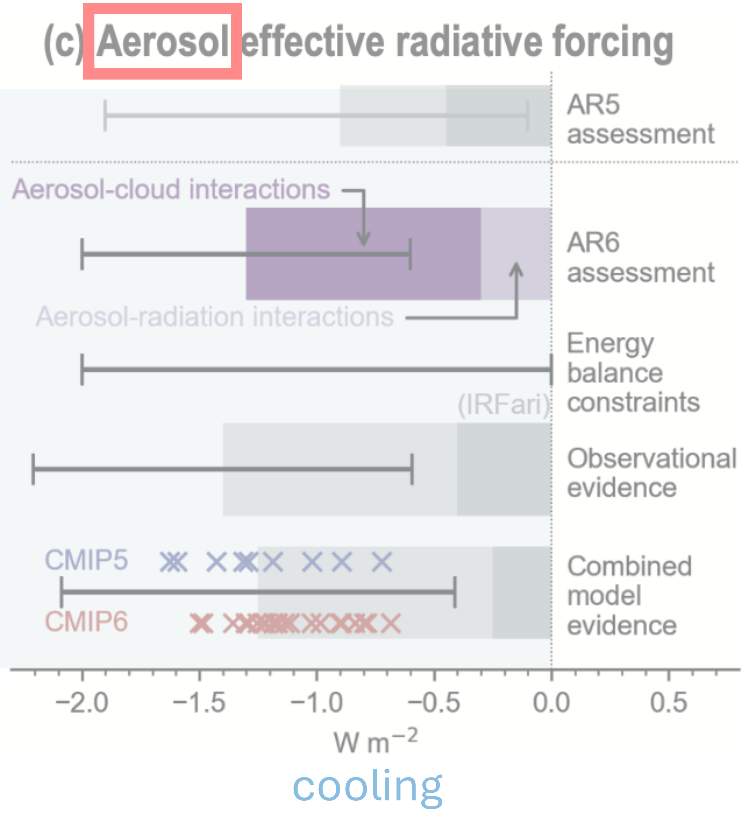
(net energy imbalance at TOA)

cooling warming

(a) ERFs for well-mixed greenhouse gases, and other atmospheric components (anthropogenic forcing)

IPCC AR6





(a) ERFs for well-mixed greenhouse gases, and other atmospheric components (anthropogenic forcing)

(c) net **aerosol** ERF for 1750–2019 from different lines of evidence.

Aerosol Effective Radiative Forcing (ERF)

From AR6:

ERFari – Effective Radiative Forcing due to aerosol–radiation interactions: scattering and absorption

ERFaci – Effective Radiative Forcing due to aerosol-cloud interactions: albedo, LWP, cloud cover

Aerosol Effective Radiative Forcing (ERF)

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ERFaci – Effective Radiative Forcing due to aerosol-cloud interactions: albedo, LWP, cloud cover

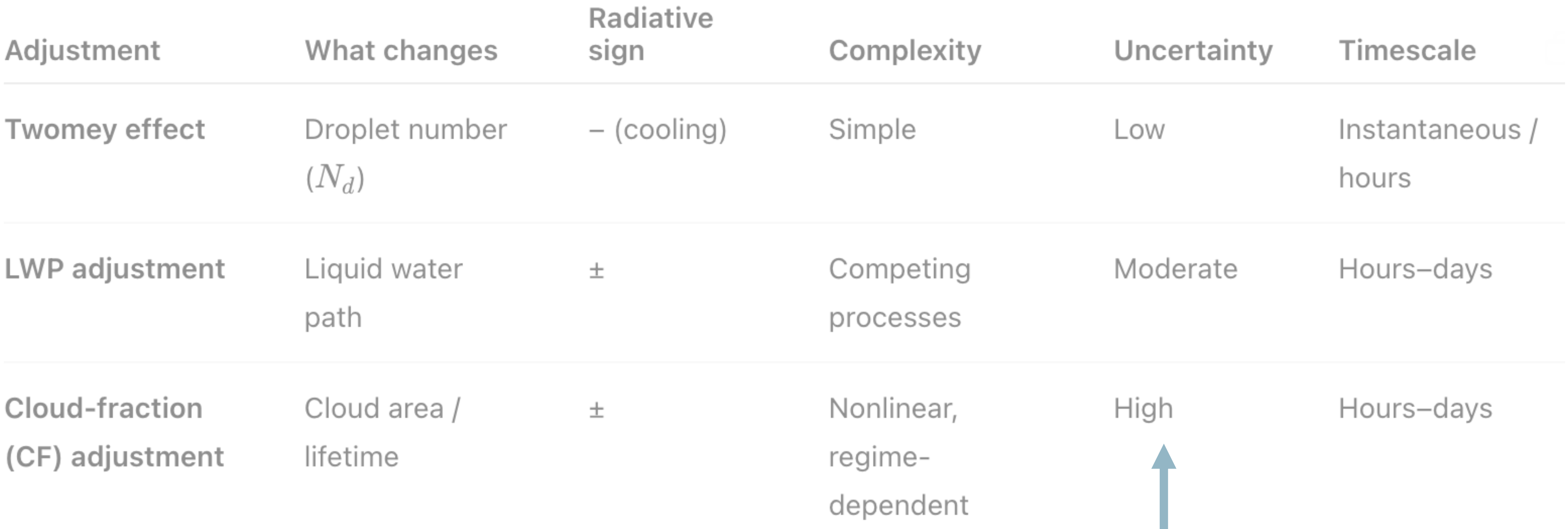
ERFaci:

- **First Indirect Effect (Twomey Effect) -** Also known as the **cloud albedo effect**. It describes how an increase in aerosols leads to a larger number of smaller cloud droplets (for a constant cloud water content), which increases the cloud's reflectivity (albedo) and reflects more solar radiation back to space.
- **Second Indirect Effect (Albrecht Effect) -** Also known as the **cloud lifetime and morphology effect**. It describes how the smaller droplets produced by more aerosols are less efficient at colliding to form raindrops, which suppresses drizzle and extends the life and fractional coverage of the cloud:

  - LWP Adjustments: Can be positive (precipitation suppression) or negative (if smaller droplets lead to faster evaporation and entrainment of dry air).
  - Cloud Fraction (CF) Adjustments: is negative when aerosols increase cloud lifetime or areal coverage by suppressing precipitation, and positive when aerosol-enhanced evaporation and entrainment cause clouds to break up and cover less of the sky.

Introduction

ERFaci:

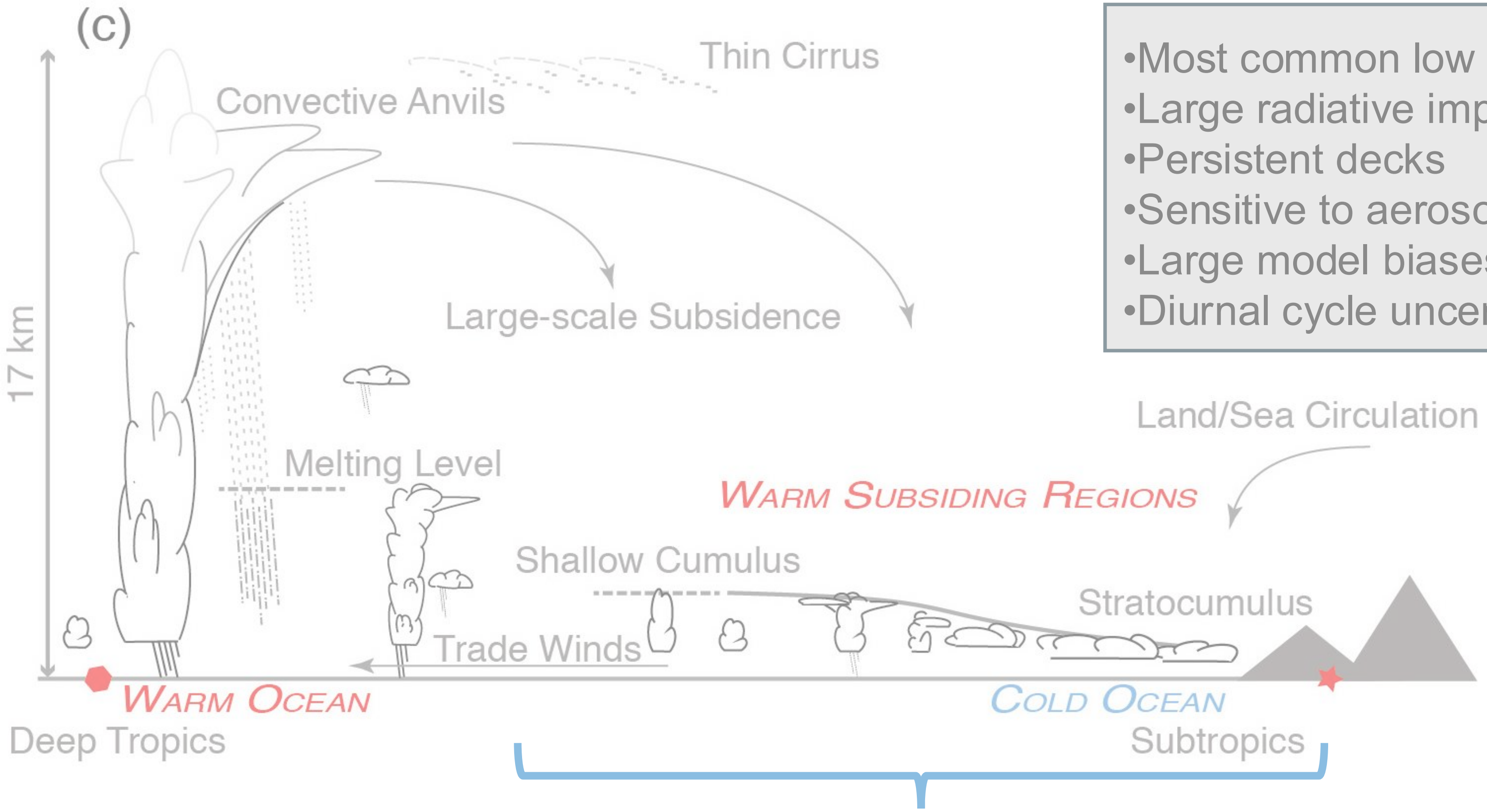


Adjustment	What changes	Radiative sign	Complexity	Uncertainty	Timescale
Twomey effect	Droplet number (N_d)	– (cooling)	Simple	Low	Instantaneous / hours
LWP adjustment	Liquid water path	±	Competing processes	Moderate	Hours–days
Cloud-fraction (CF) adjustment	Cloud area / lifetime	±	Nonlinear, regime-dependent	High	Hours–days

Cloud adjustments

High uncertainty arises from difficulties in making accurate observations

Introduction



- Most common low cloud type
- Large radiative impact
- Persistent decks
- Sensitive to aerosols
- Large model biases
- Diurnal cycle uncertainty

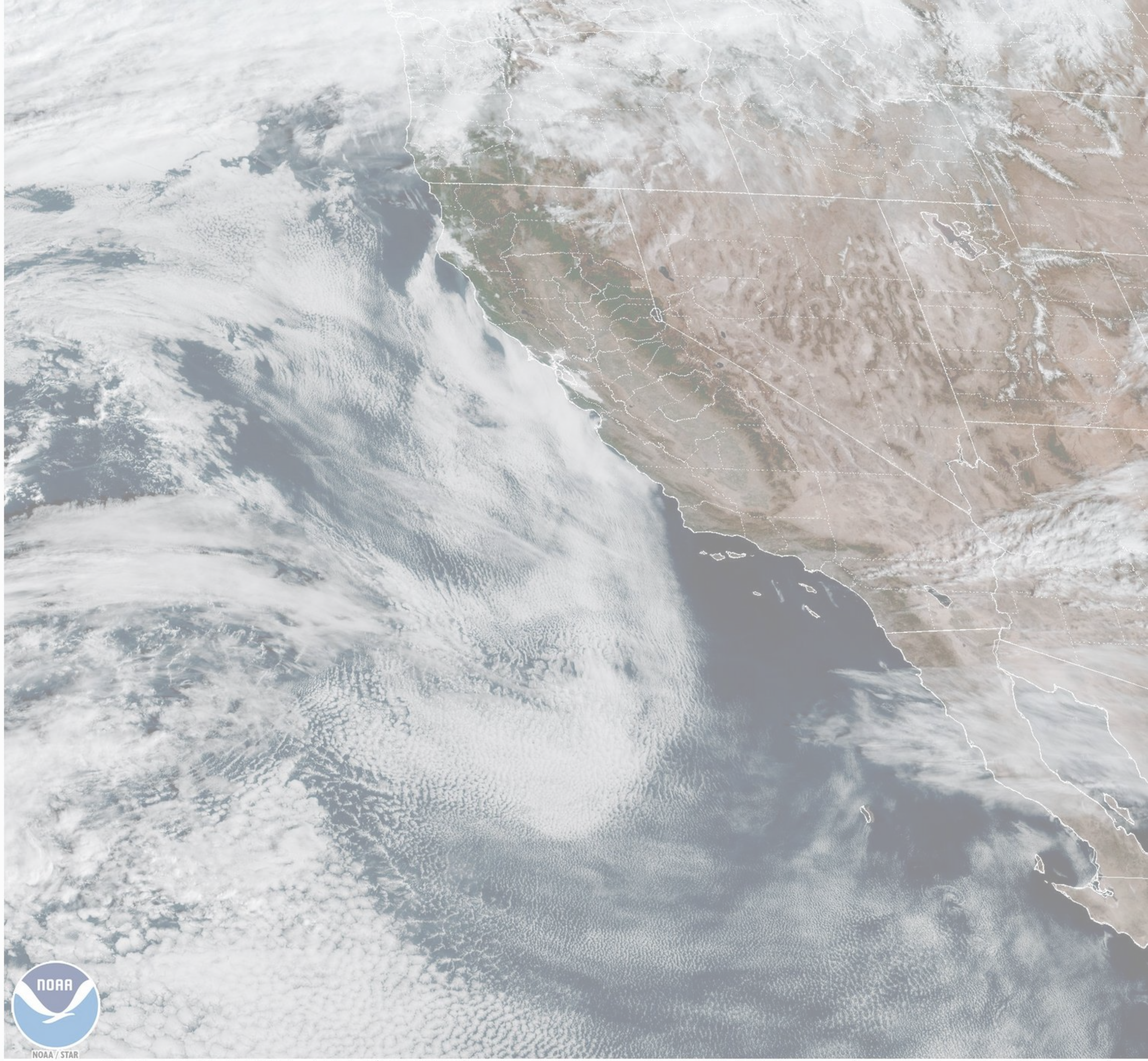
Regions where ERFaci is significant

Aerosols, Cloud Microphysics, and Fractional Cloudiness

Bruce A. Albrecht (1989)

> Likewise, the relatively complicated horizontal variations in cloud structure that are often observed in visible satellite images of marine stratocumulus (Fig. 2) often have a lifetime of several hours and in many cases are maintained by variations in the microphysical structure of the clouds and not variations in the temperature, moisture, and wind.

Aerosols as a key control of horizontal variability!



30 Oct 2022 17:20Z - NOAA/NESDIS/STAR GOES-18 - GEOCOLOR Composite - Western US Seaboard

Focus of the study

The diurnal susceptibility of subtropical clouds to aerosols:

SW outgoing radiation $\boxed{F^{\uparrow}(N_c, \mathrm{LWP}_c, f_c) \;=\; F_0\,\mu_0\,A(N_c, \mathrm{LWP}_c, f_c)}$

Susceptibility:

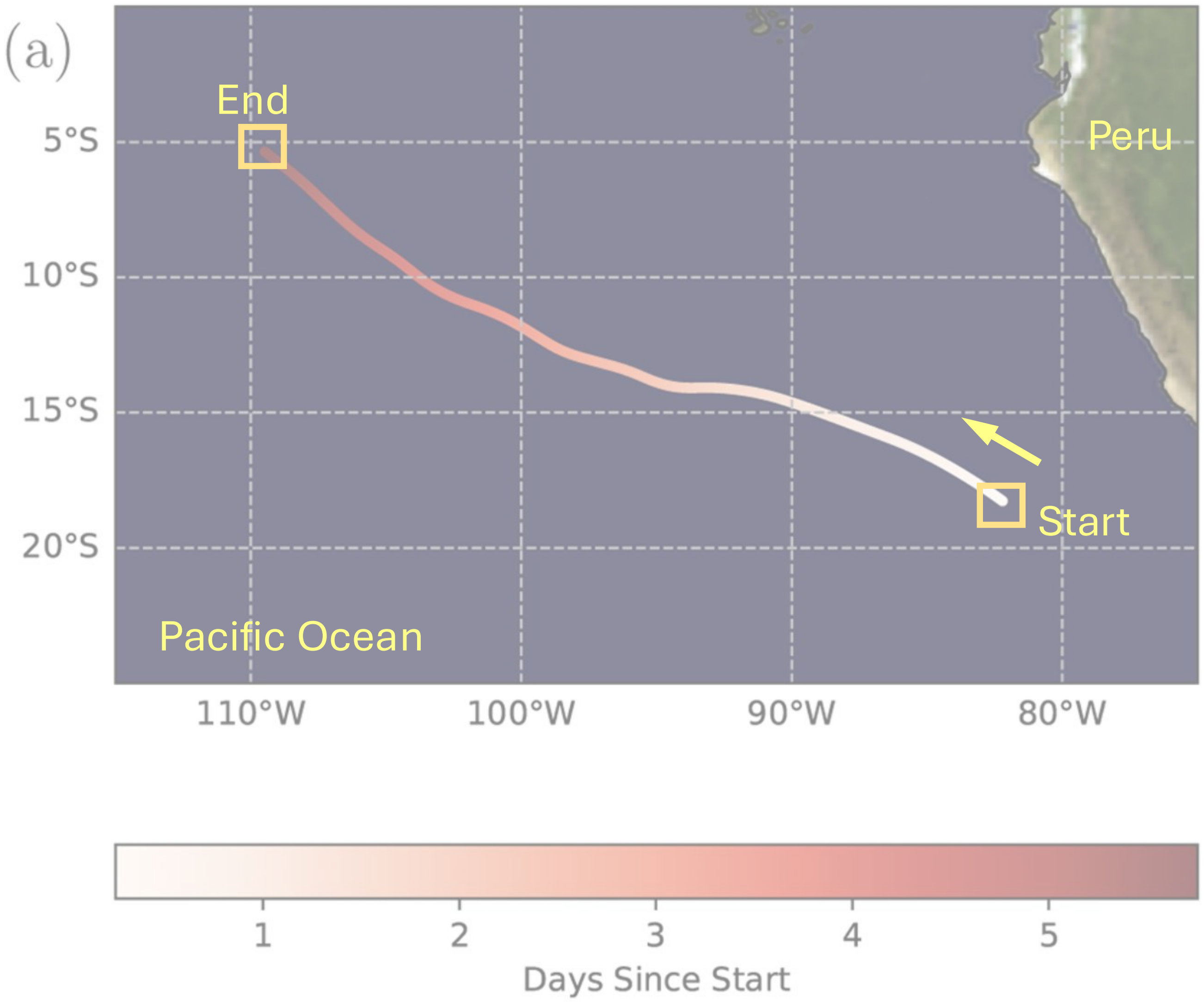
$$\frac{\mathrm{d}F^{\uparrow}}{\mathrm{d}\ln N_{\mathrm{c}}} = \underbrace{\frac{\partial F^{\uparrow}}{\partial \ln N_{\mathrm{c}}}}_{\text{Twomey Effect }(S_N)} + \underbrace{\frac{\partial F^{\uparrow}}{\partial \ln \mathrm{LWP}_{\mathrm{c}}} \cdot \frac{\mathrm{d}\ln \mathrm{LWP}_{\mathrm{c}}}{\mathrm{d}\ln N_{\mathrm{c}}}}_{\text{LWP adjustment }(S_{\mathrm{LWP}})} + \underbrace{\frac{\partial F^{\uparrow}}{\partial f_{\mathrm{c}}} \cdot \frac{\mathrm{d}f_{\mathrm{c}}}{\mathrm{d}\ln N_{\mathrm{c}}}}_{\text{Fraction adjustment }(S_f)} .$$

Cloud droplet number concentration

Region: Subtropical–tropical
Timescale: Hourly to daily (diurnal)
System: Cloud–aerosol interactions
Perturbation: Aerosol variations

Scientific gap: To our knowledge, such a decomposition has not yet been reported in the literature.

Experiment design



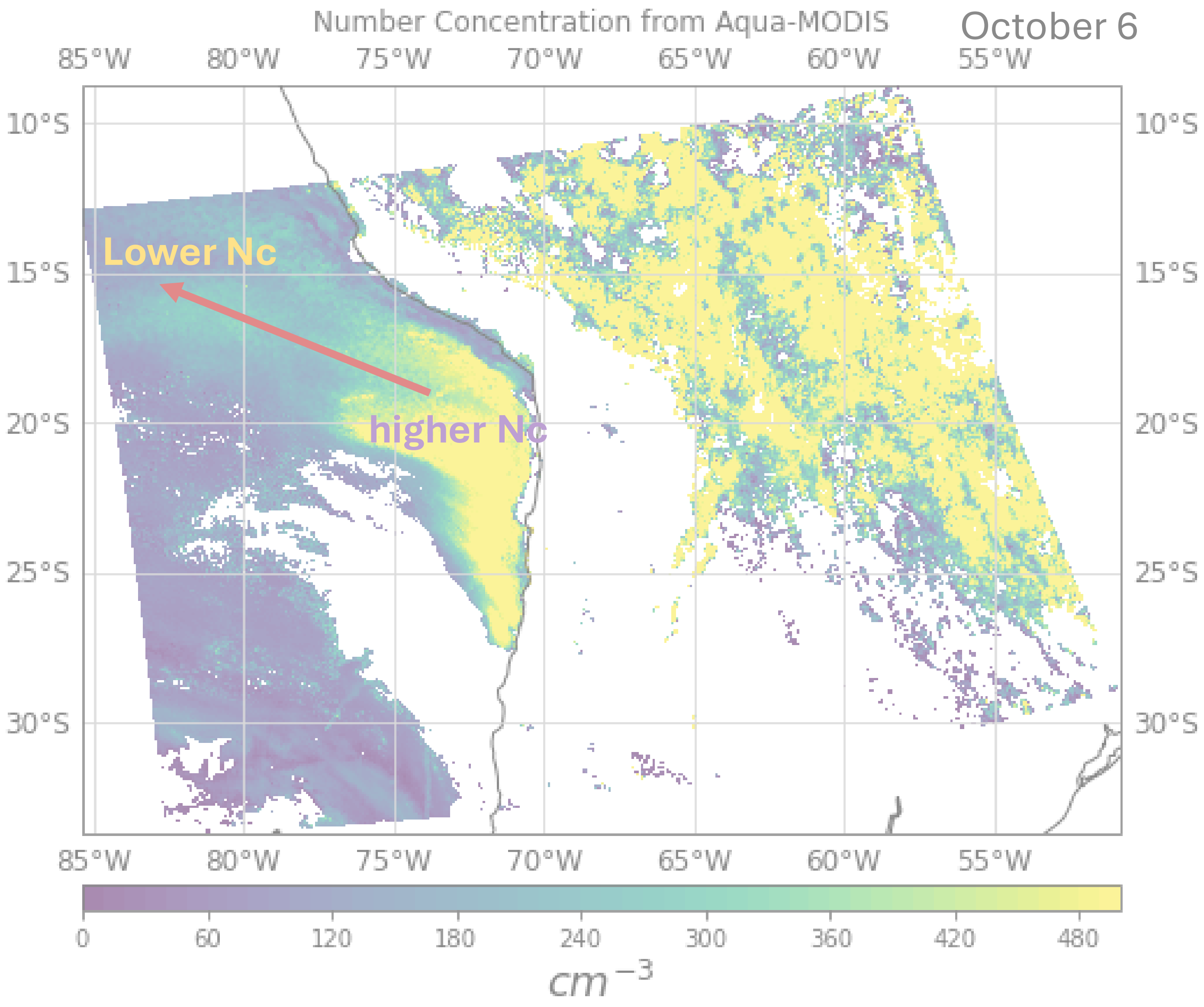
Lagrangian approach:
an air mass moving along a 6-day trajectory

Perturbation scenario:
Reference: clean air scenario
Perturbation: polluted air scenario

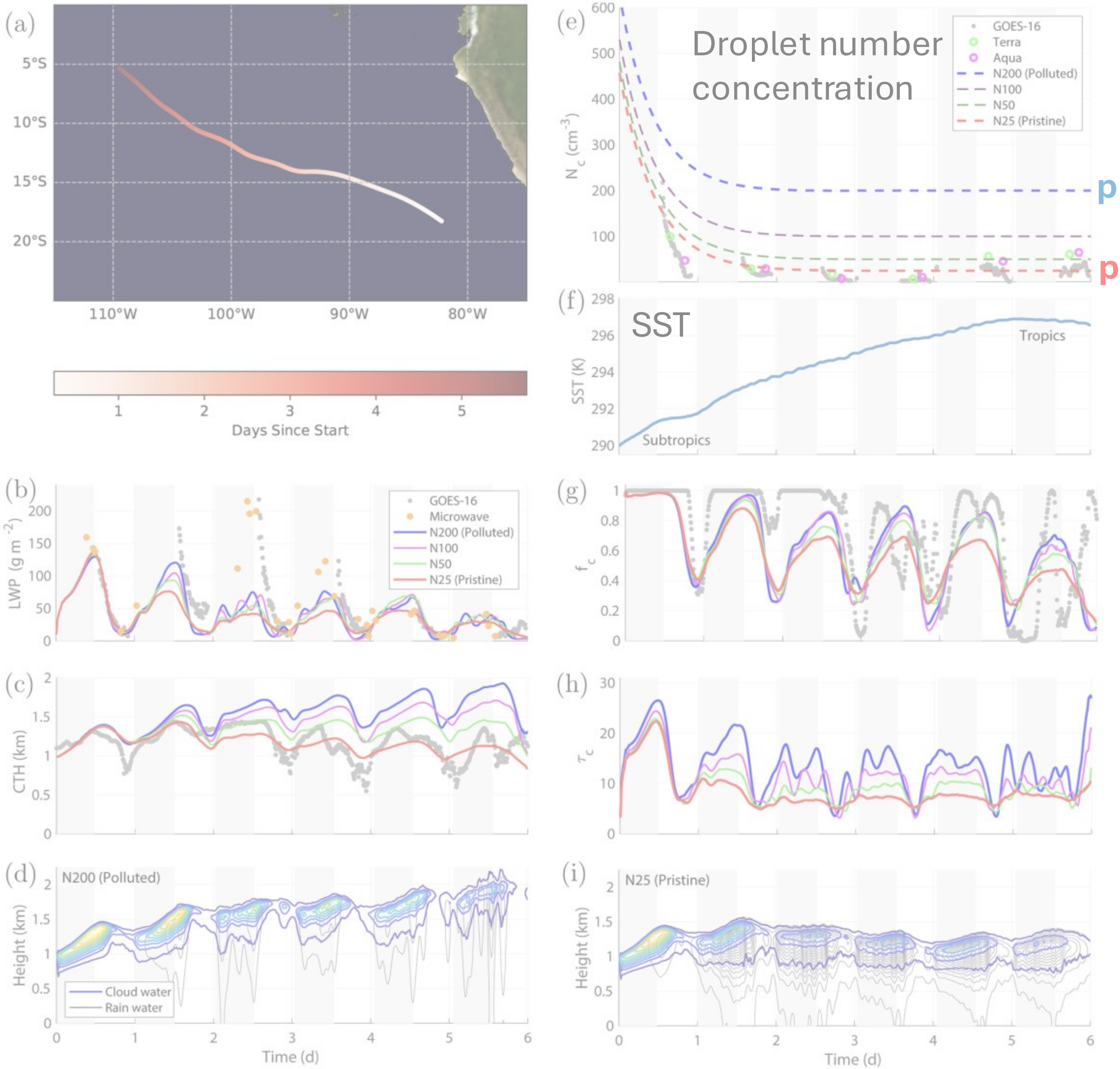
Initial/boundary conditions:
Reanalysis (MERRA-2)

Modeling tool:
Large-Eddy Simulation ▨

Experiment design



Results: Overview



polluted scenario (N200; perturb.)

pristine scenario (N25; reference)

Grid-mean LWP

Cloud fraction

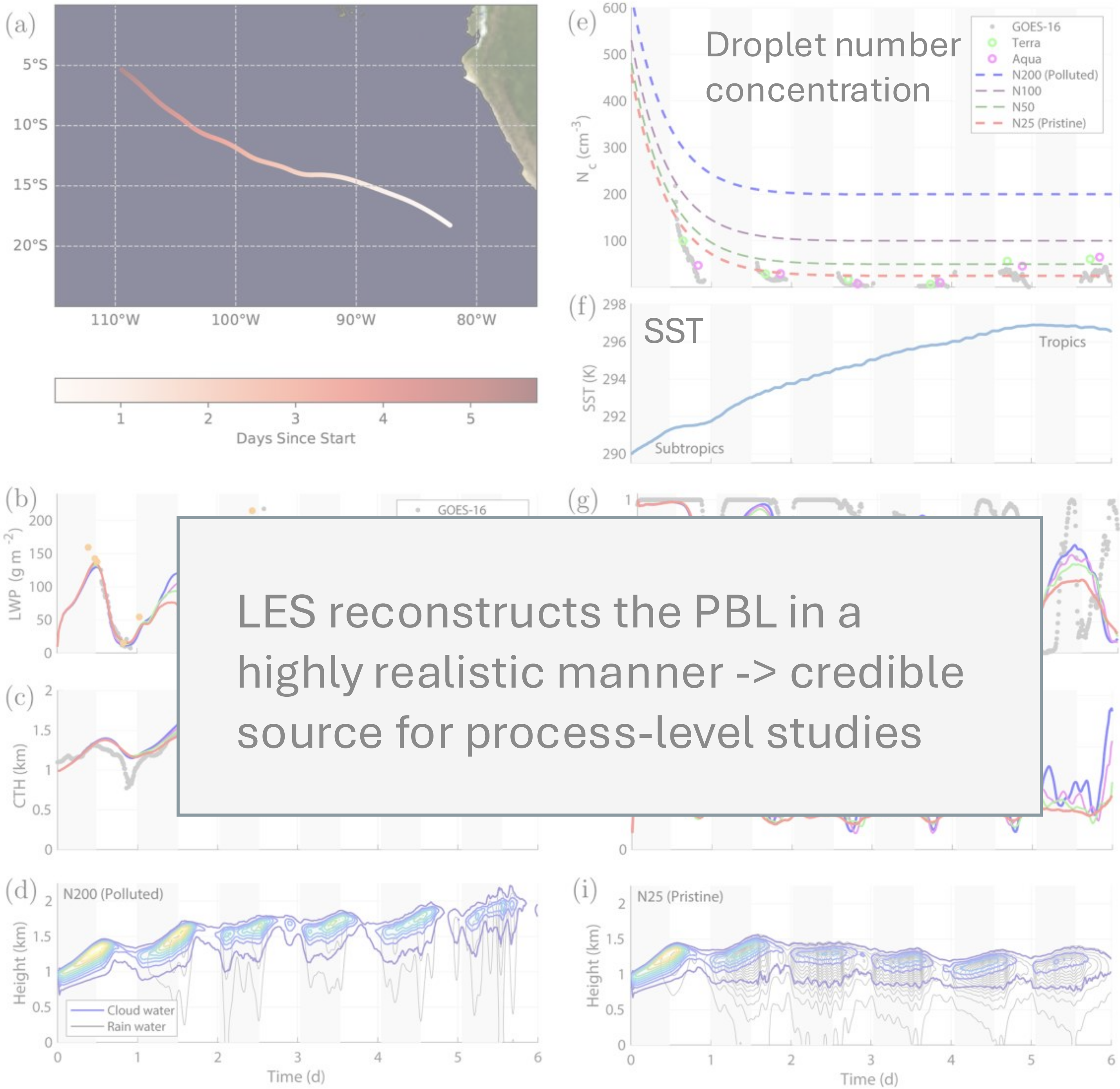
Cloud-top height

Cloud optical thickness

Cloud/rain (polluted)

Cloud/rain (pristine)

Results: Overview



LES reconstructs the PBL in a highly realistic manner -> credible source for process-level studies

polluted scenario (N200; perturb.)

pristine scenario (N25; reference)

Grid-mean LWP

Cloud-top height

Cloud/rain (polluted)

Cloud fraction

Cloud optical thickness

Cloud/rain (pristine)

Results: Sensitivity calculations

Outgoing SW:

$$\boxed{F^{\uparrow}(N_c, \mathrm{LWP}_c, f_c) \;=\; F_0\,\mu_0\,A(N_c, \mathrm{LWP}_c, f_c)}$$

Total albedo:

$$A = (1 - f_c)\alpha_{\mathrm{surf}} + f_c A_c$$

Clear-sky and cloudy

Cloud albedo:

$$A_c = \alpha_{\mathrm{cld}} + \frac{\alpha_{\mathrm{surf}}(1 - \alpha_{\mathrm{cld}})^2}{1 - \alpha_{\mathrm{surf}}\alpha_{\mathrm{cld}}}$$

Stevens et al. (1984)

$$\alpha_{\mathrm{cld}} = \frac{1}{1 + \gamma_1 \tau_c}\left(\gamma_1 \tau_c + (\beta_o - \gamma_1 \mu_o)\left(1 - \exp\left(\frac{-\tau_c}{\mu_0}\right)\right)\right)$$

Meador and Weaver (1980)
(Dependence on solar zenith angle)

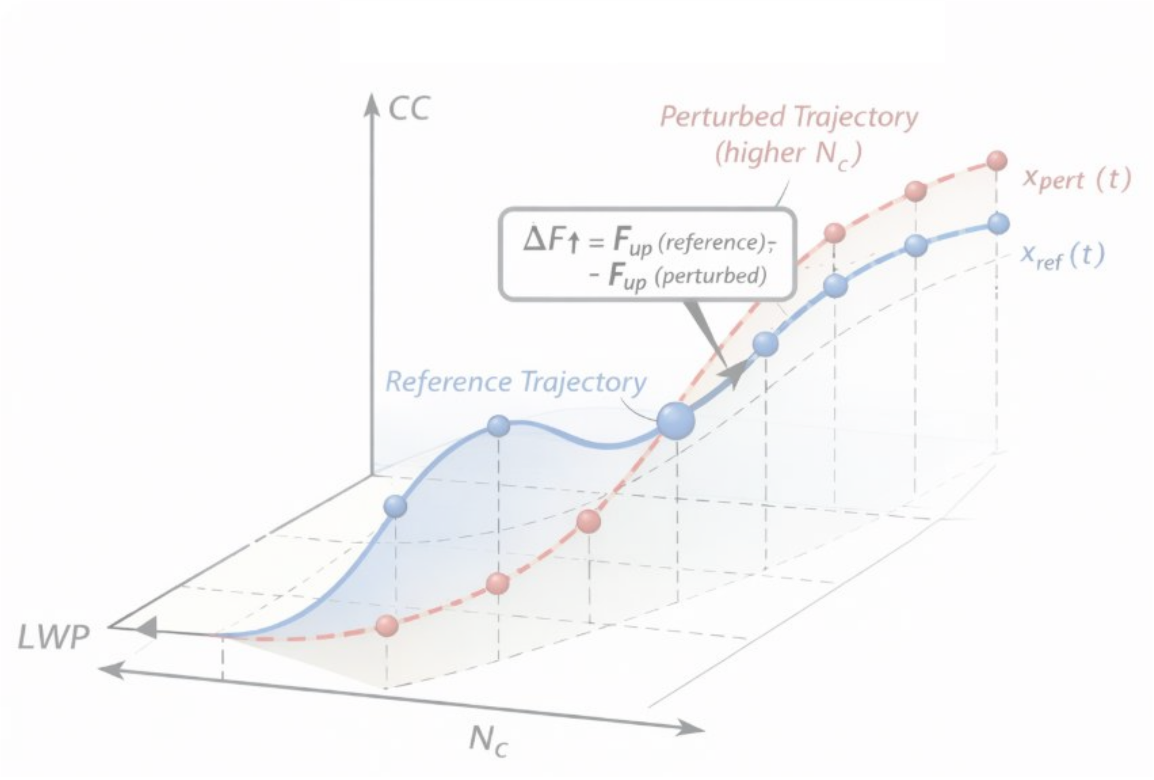
Cloud optical thickness:

$$\tau_c = 0.2\, {N_c}^{1/3} {\mathrm{LWP}_c}^{5/6}$$

Hoffman et al. (2023)

Results: Sensitivity calculations

Sensitivity analysis in phase space



State vector:

$$\mathbf{x}_{\mathrm{ref}}(t) = \left(N_c^{\mathrm{ref}}(t),\ \mathrm{LWP}_c^{\mathrm{ref}}(t),\ f_c^{\mathrm{ref}}(t)\right)$$

One-direction perturbation:

$$\mathbf{x}_{\mathrm{pert}}(t) = \mathbf{x}_{\mathrm{ref}}(t) + \left(\delta N_c,\ 0,\ 0\right)$$

Diagnosed one-direction difference:

$$\Delta F_{\uparrow}(t) = F_{\uparrow}\left(N_c^{\mathrm{ref}}(t),\ \mathrm{LWP}_c^{\mathrm{ref}}(t),\ f_c^{\mathrm{ref}}(t)\right) - F_{\uparrow}\left(N_c^{\mathrm{ref}}(t) + \delta N_c,\ \mathrm{LWP}_c^{\mathrm{ref}}(t),\ f_c^{\mathrm{ref}}(t)\right)$$

For small perturbations:

$$\Delta F_{\uparrow}(t) \approx -\left.\frac{\partial F_{\uparrow}}{\partial N_c}\right|_{\mathbf{x}_{\mathrm{ref}}(t)} \delta N_c$$

Results: Sensitivity calculations

Sensitivity analysis in phase space

From N200 trajectory

From N25 trajectory

Mean from the two trajectories

Twomey effect:

$$S_N = \frac{\partial F^{\uparrow}}{\partial \ln N_\mathrm{c}} \approx \frac{F^{\uparrow}\left(N_\mathrm{c200}, \overline{\mathrm{LWP}}_\mathrm{c}, \overline{f_\mathrm{c}}\right) - F^{\uparrow}\left(N_\mathrm{c25}, \overline{\mathrm{LWP}}_\mathrm{c}, \overline{f_\mathrm{c}}\right)}{\ln N_\mathrm{c200} - \ln N_\mathrm{c25}},$$

LWP adjustment:

$$S_\mathrm{LWP} = \frac{\partial F^{\uparrow}}{\partial \ln \mathrm{LWP}_\mathrm{c}} \cdot \frac{\mathrm{d} \ln \mathrm{LWP}_\mathrm{c}}{\mathrm{d} \ln N_\mathrm{c}} \approx \frac{F^{\uparrow}\left(\overline{N_\mathrm{c}}, \mathrm{LWP}_\mathrm{c}(N_\mathrm{c200}), \overline{f_\mathrm{c}}\right) - F^{\uparrow}\left(\overline{N_\mathrm{c}}, \mathrm{LWP}_\mathrm{c}(N_\mathrm{c25}), \overline{f_\mathrm{c}}\right)}{\ln N_\mathrm{c200} - \ln N_\mathrm{c25}}$$

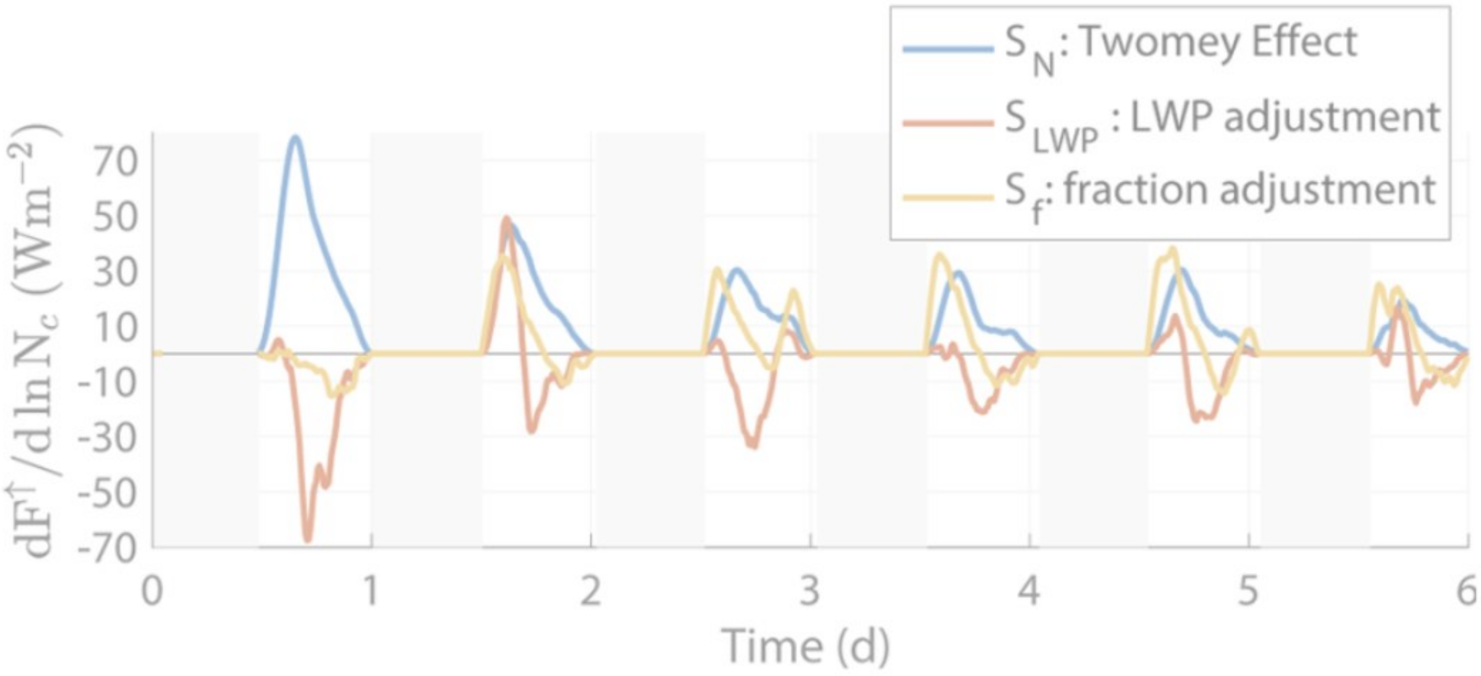
Cloud cover adjustment:

$$S_f = \frac{\partial F^{\uparrow}}{\partial \ln N_\mathrm{c}} = \frac{\partial F^{\uparrow}}{\partial f_\mathrm{c}} \cdot \frac{\mathrm{d} f_\mathrm{c}}{\mathrm{d} \ln N_\mathrm{c}} \approx \frac{F^{\uparrow}\left(\overline{N_\mathrm{c}}, \overline{\mathrm{LWP}}_\mathrm{c}, f_\mathrm{c}(N_\mathrm{c200})\right) - F^{\uparrow}\left(\overline{N_\mathrm{c}}, \overline{\mathrm{LWP}}_\mathrm{c}, f_\mathrm{c}(N_\mathrm{c25})\right)}{\ln N_\mathrm{c200} - \ln N_\mathrm{c25}}$$

Susceptibility

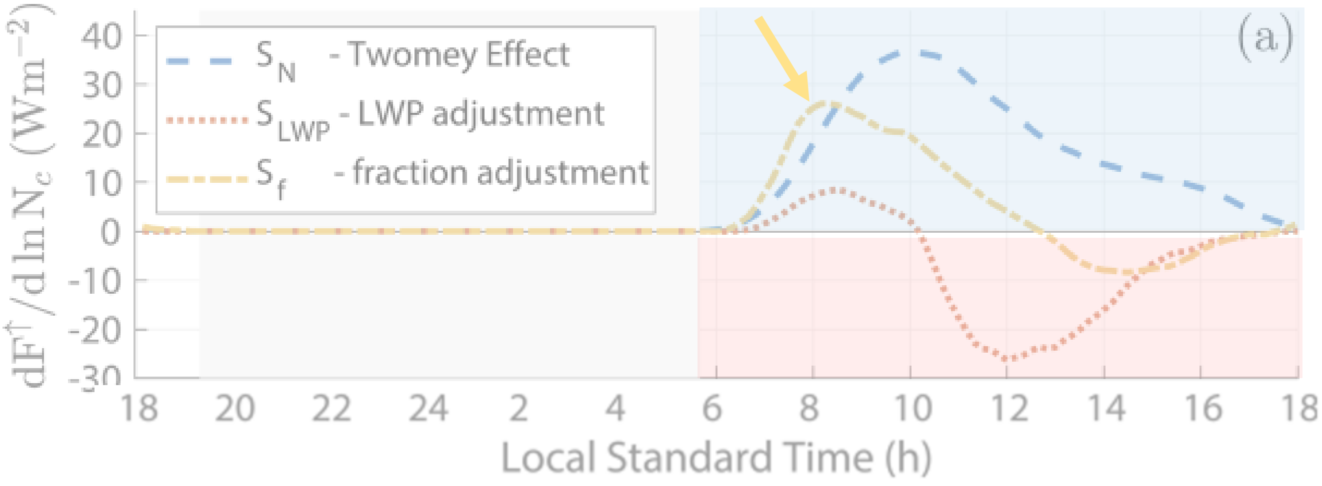
Results: Diurnal susceptibility – partial contributions

6 full diurnal cycles



Results: Diurnal susceptibility – partial contributions

Composite diurnal cycle



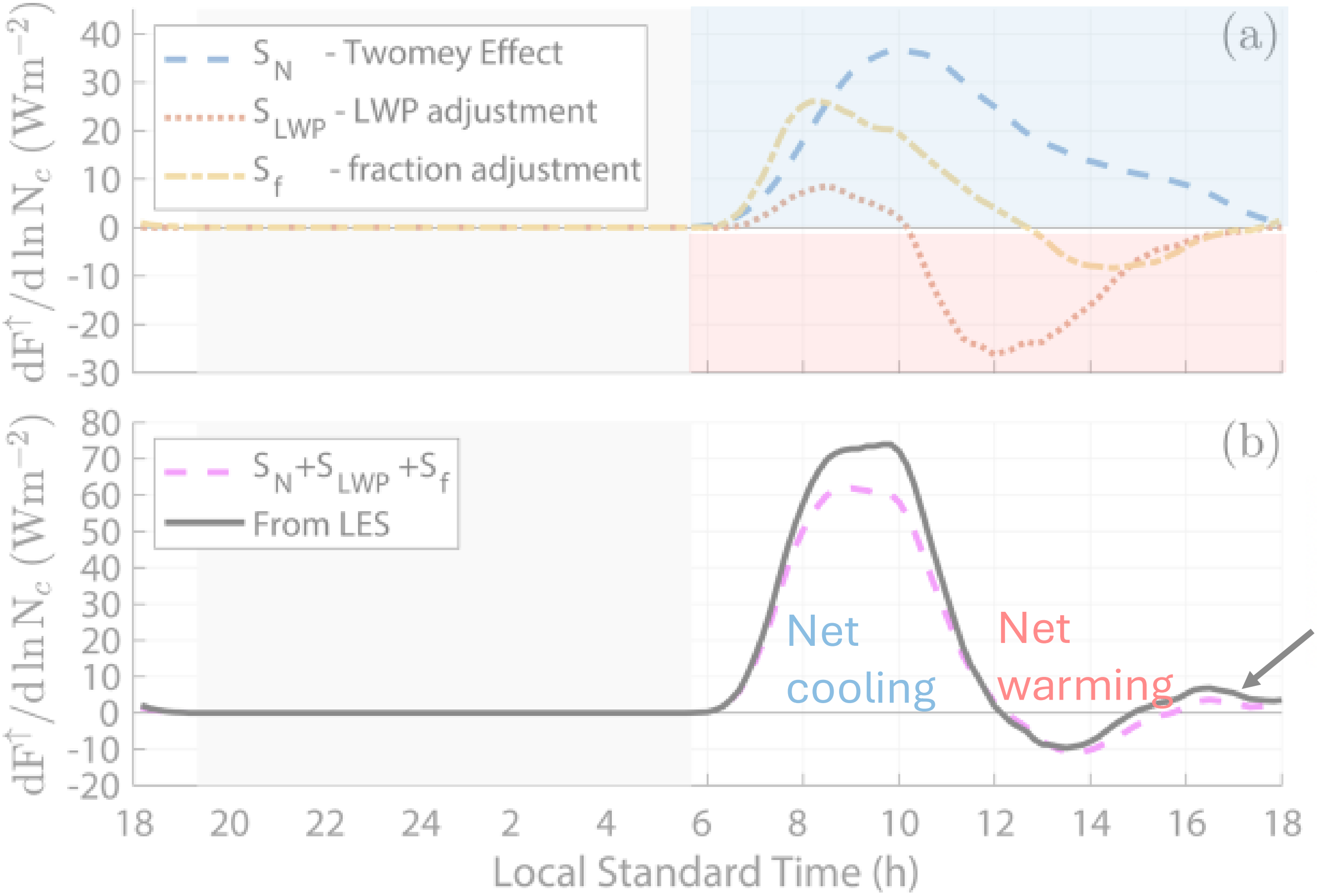
Cooling (reflecting more sunlight)

Warming

- Twomey effect: always cooling (as expected).
- Cloud adjustments (LWP, f_c (are cooling in the morning but become warming later in the day.
- LWP adjustment : the strongest warming (around noon).
- Both cloud adjustments act against the Twomey effect in the afternoon.

Results: Diurnal susceptibility – partial contributions

Composite diurnal cycle



Cooling (reflecting more sunlight)

Warming

Two different trajectories from LES:

$$S = \frac{dF^{\uparrow}}{d\ln N_c} = \frac{F^{\uparrow}(N_{c200}, \mathrm{LWP}_{c200}, f_{c200}) - F^{\uparrow}(N_{c25}, \mathrm{LWP}_{c25}, f_{c25})}{\ln N_{c200} - \ln N_{c25}}.$$

Consistency check PASSED!

$$\frac{dF_{\uparrow}}{d\ln N_c} \approx \frac{\partial F_{\uparrow}}{\partial \ln N_c} + \frac{\partial F_{\uparrow}}{\partial \mathrm{LWP}_c}\frac{d\mathrm{LWP}_c}{d\ln N_c} + \frac{\partial F_{\uparrow}}{\partial f_c}\frac{d f_c}{d\ln N_c}.$$

From LES

Results: process-level understanding

Composite diurnal cycle

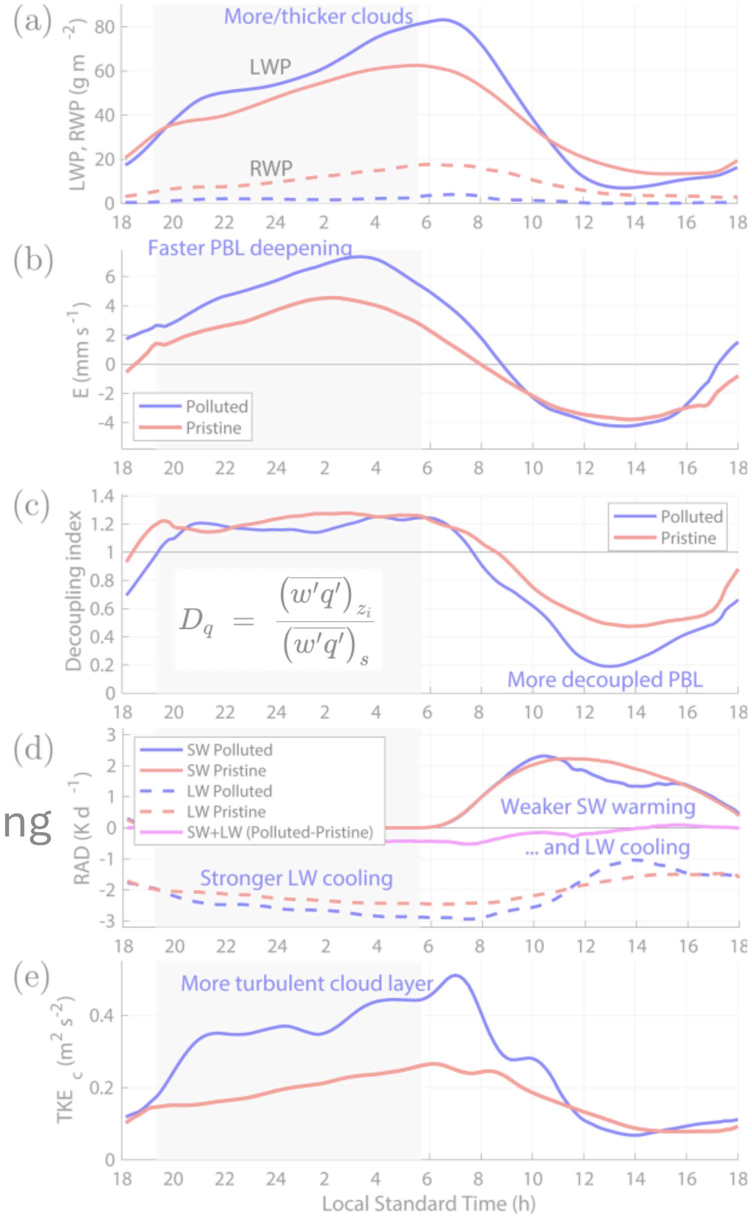
LWP, rain

Cloud-top entrainment

Decoupling

Cloud-layer LW cooling/ SW heating

Cloud-layer TKE



Results: process-level understanding

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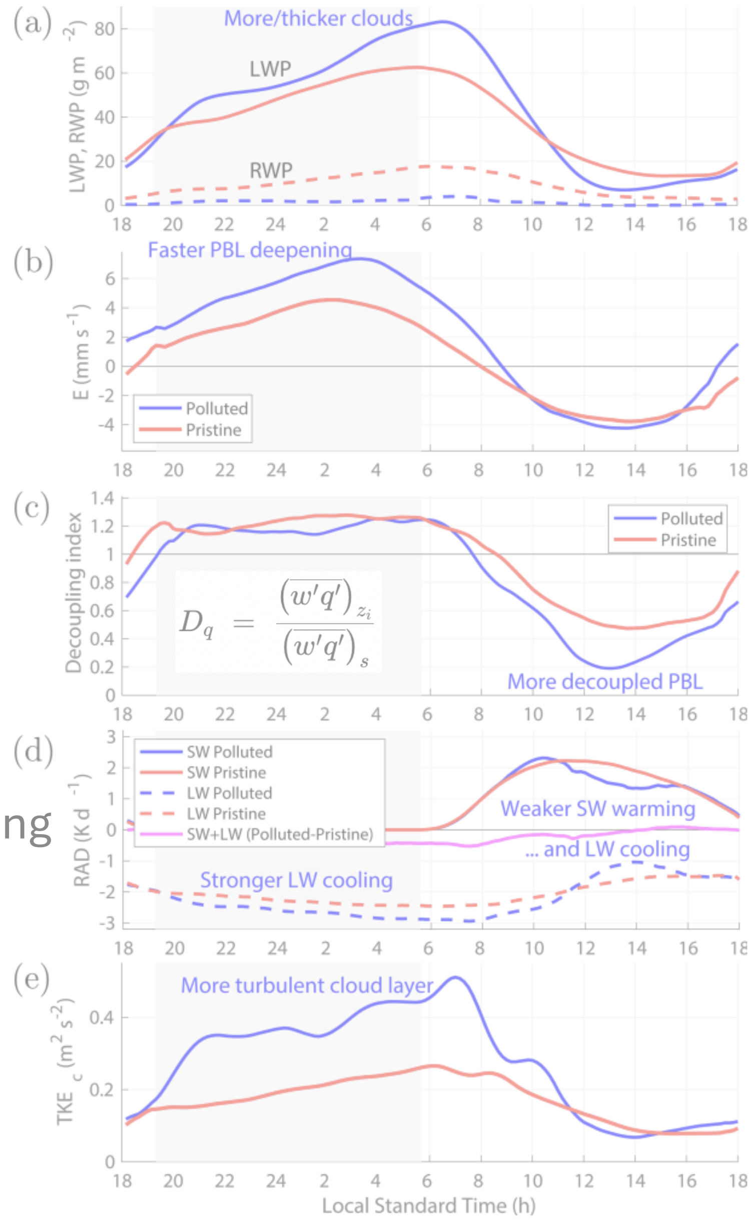

Polluted (vs. pristine) cloud layer:

- Gets thicker as PBL grows faster at night, but also collapses faster during daytime

Results: process-level understanding

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LWP, rain

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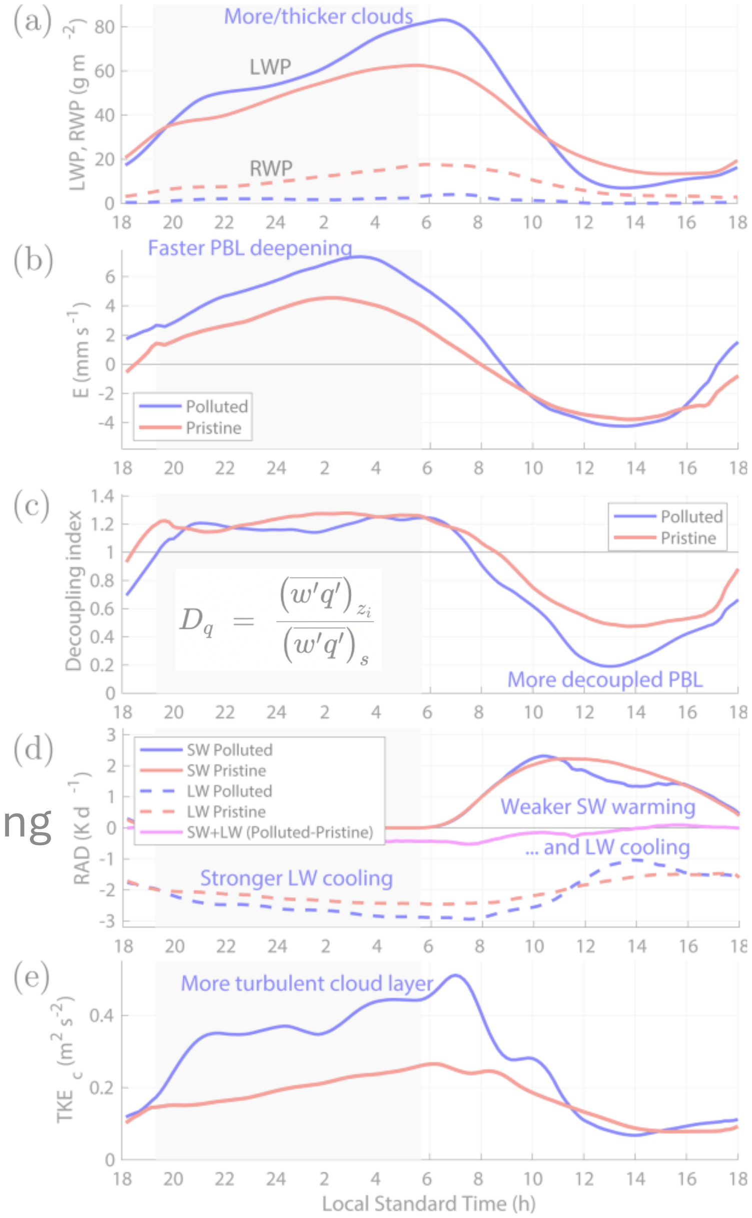

Polluted (vs. pristine) cloud layer:

- Gets thicker as PBL grows faster at night, but also collapses faster during daytime
- Is well coupled, but gets much more decoupled during daytime (overextended, more exposed to EIL)

Results: process-level understanding

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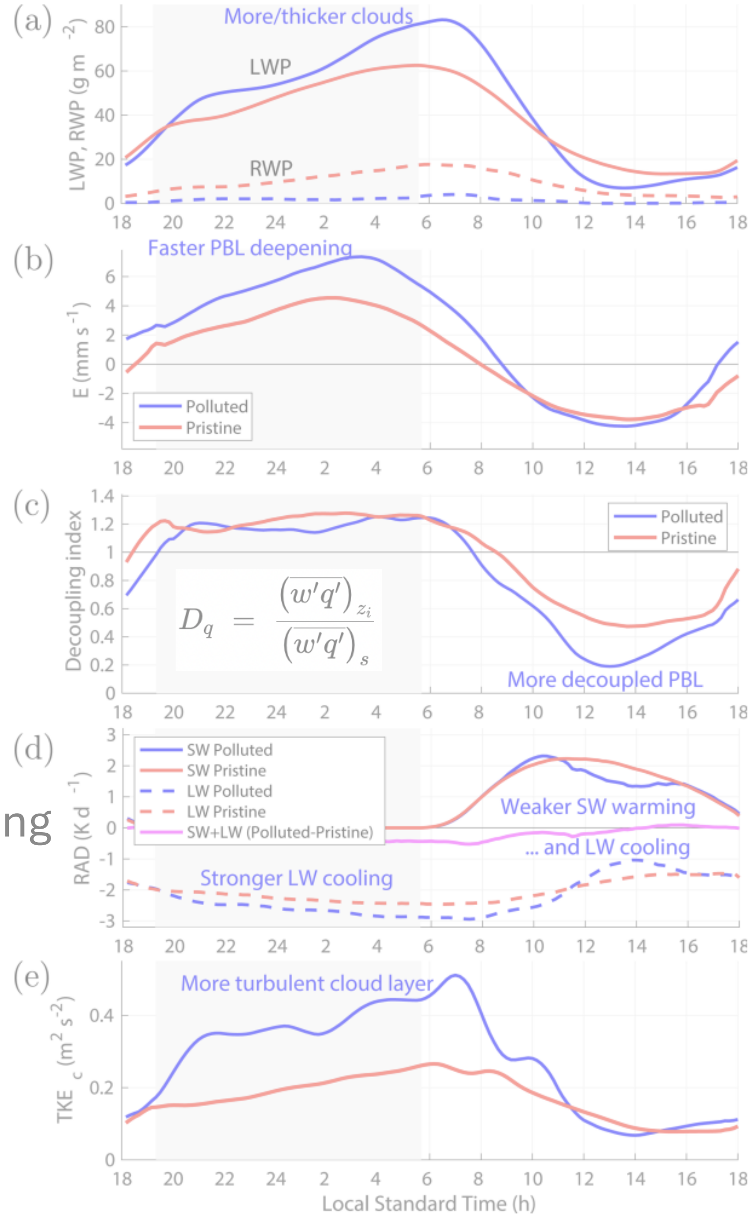


Polluted (vs. pristine) cloud layer:

- Gets thicker as PBL grows faster at night, but also collapses faster during daytime
- Is well coupled, but gets much more decoupled during daytime (overextended, more exposed to EIL)
- Experiences stronger LW cooling at night
- Experiences similar (or smaller) SW warming – contrary to suggested explanation of the collapse

Results: process-level understanding

Composite diurnal cycle

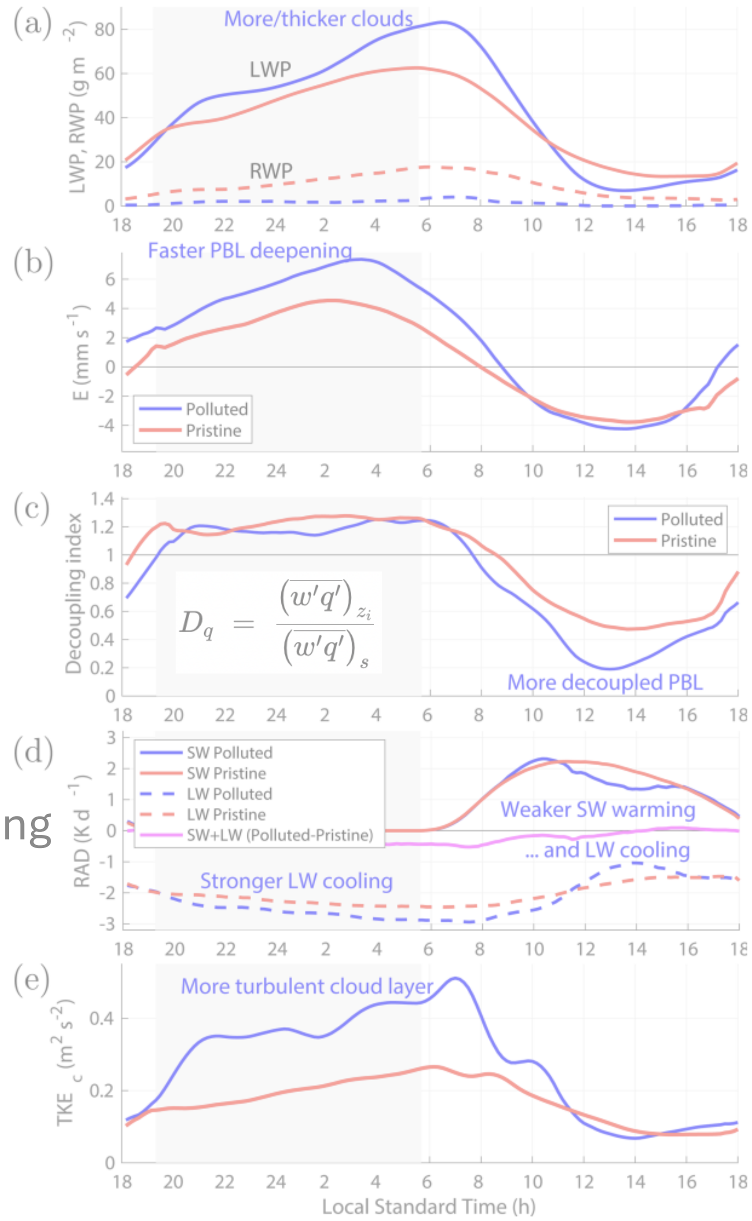
LWP, rain

Cloud-top entrainment

Decoupling

Cloud-layer LW cooling/ SW heating

Cloud-layer TKE



Polluted (vs. pristine) cloud layer:

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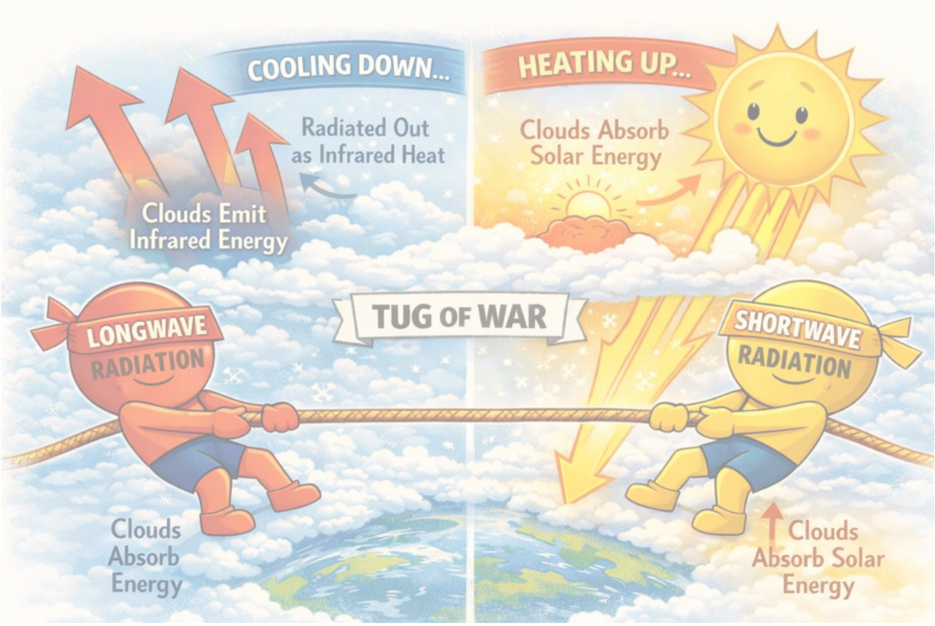
- Is well coupled, but gets much more decoupled during daytime (overextended, more exposed to EIL)
- Experiences stronger LW cooling at night
- Experiences similar (or smaller) SW warming – contrary to suggested explanation of the collapse
- Is much more turbulent at night, when deepening is faster (cloud-top-cooling driven turbulence)

Differences develop mainly at night

Results: process-level understanding

Radiation Tug of war: Longwave vs Shortwave

Why is the diurnal cycle so strong?



Results: process-level understanding

Radiation Tug of war: Longwave vs Shortwave

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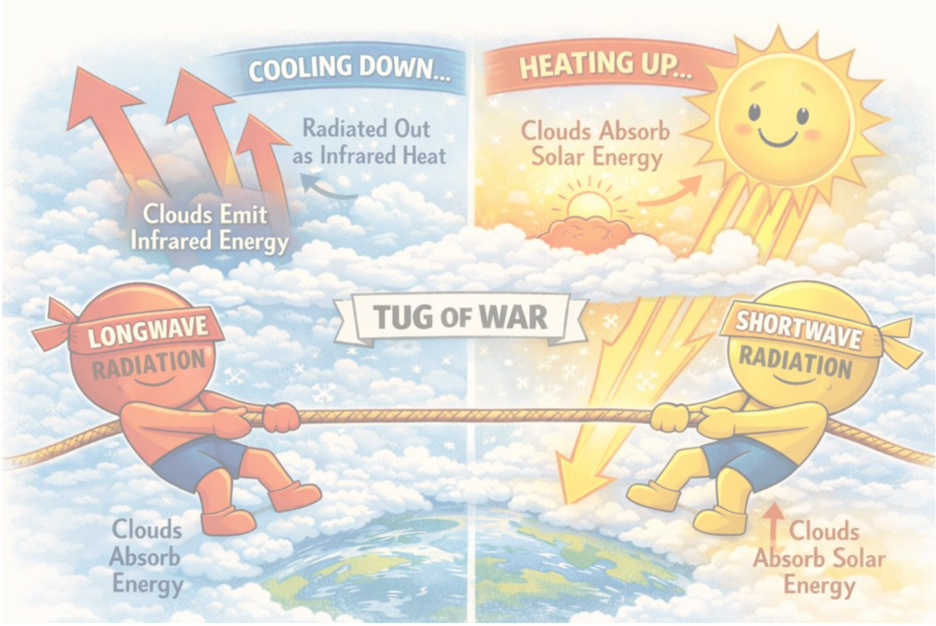
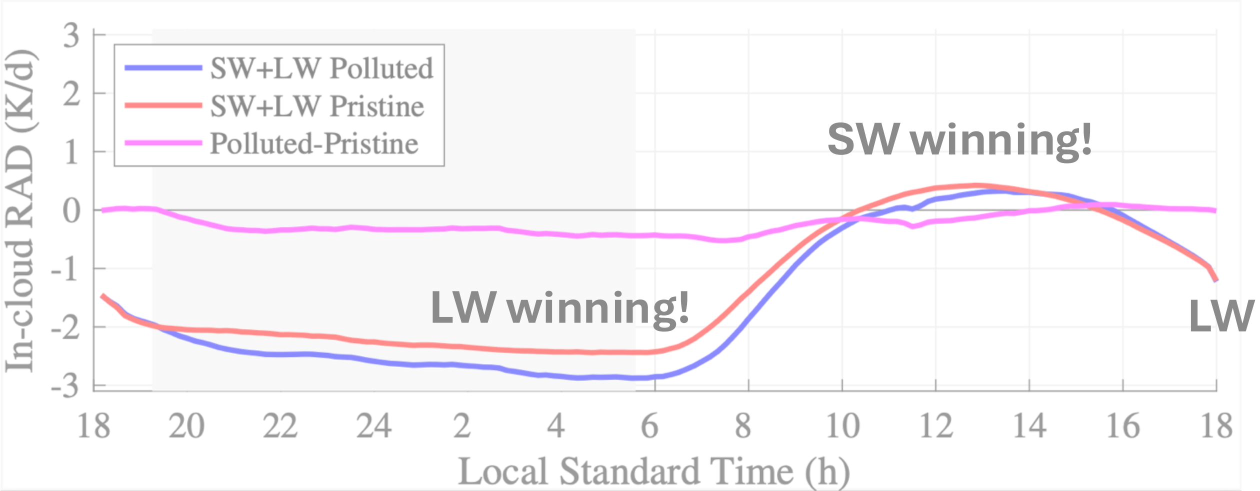


Cloud-layer-integrated radiative forcing



LW winning!

SW winning!

LW winning again!

And the cycle repeats itself...

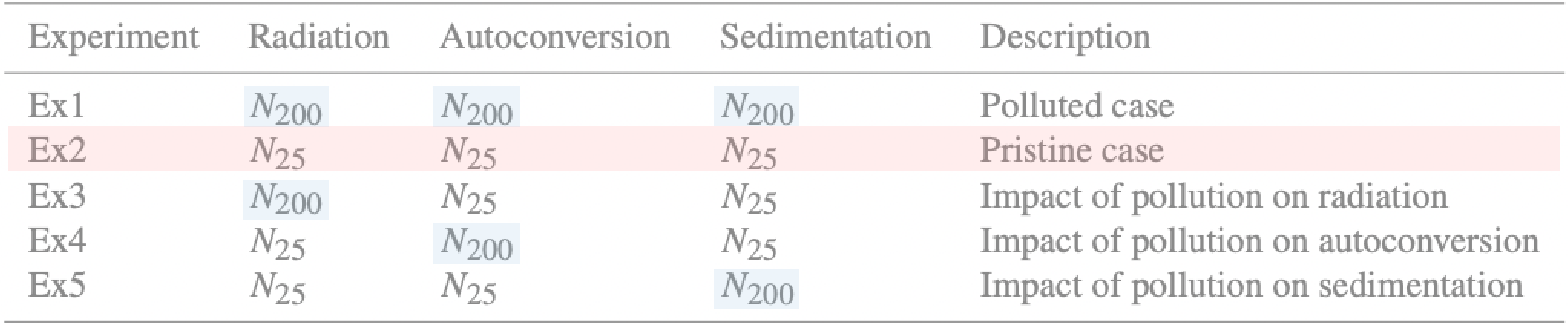
Results: sensitivity experiments

More benefits of the virtual LES lab: process-denial studies.

Idea: What if we run an LES experiment for the Pristine scenario (N25), but make one particular process interact with the Polluted component (N200)?

Results: sensitivity experiments

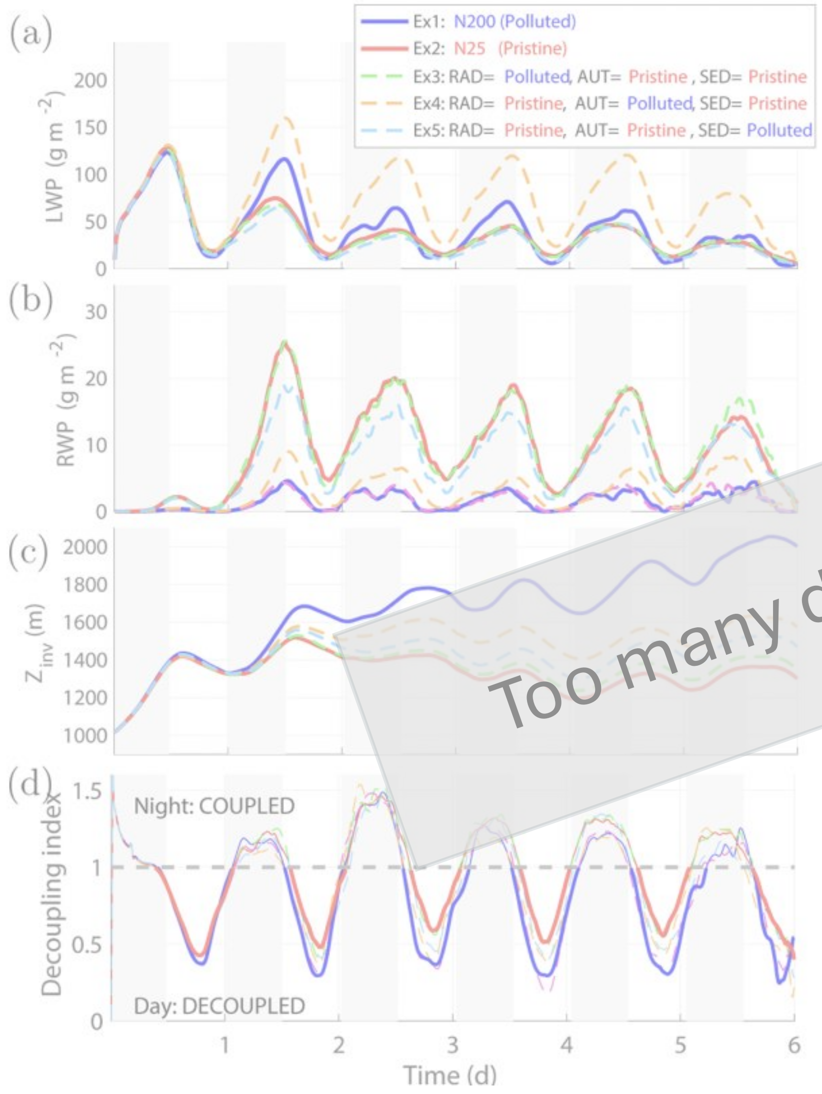
What are key controls: Radiation, Autoconversion, or Sedimentation?



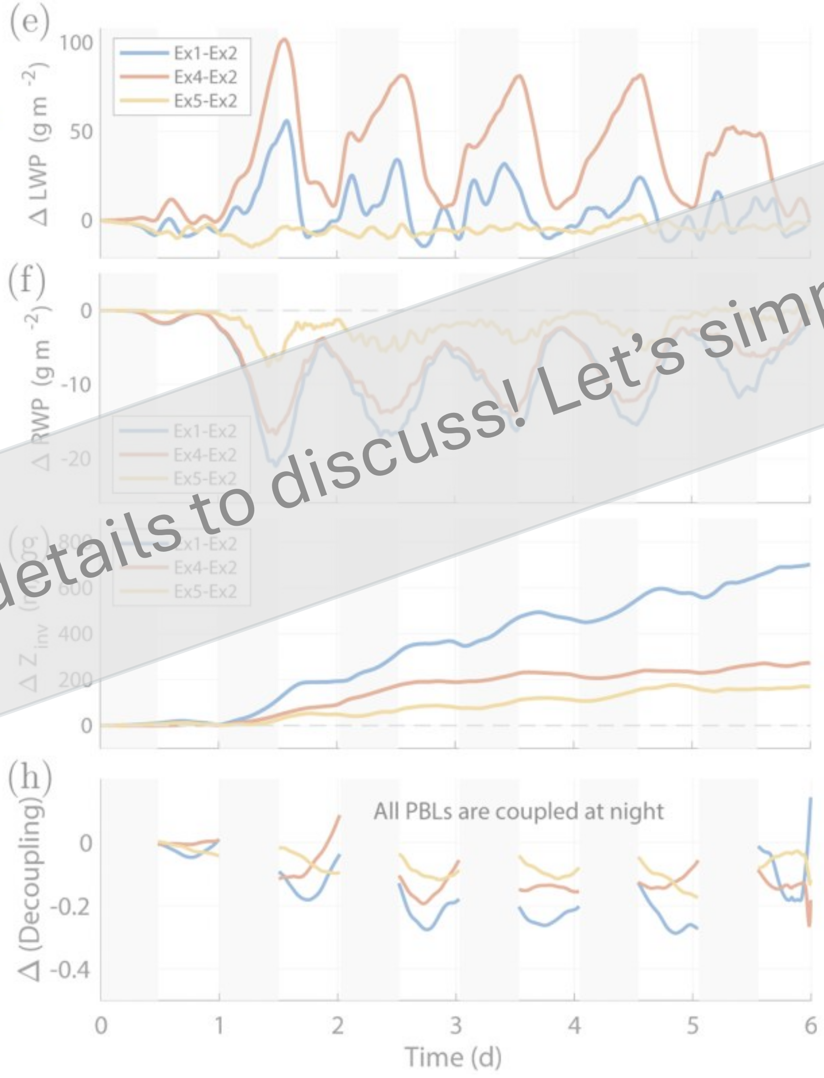
Experiment	Radiation	Autoconversion	Sedimentation	Description
Ex1	N_{200}	N_{200}	N_{200}	Polluted case
Ex2	N_{25}	N_{25}	N_{25}	Pristine case
Ex3	N_{200}	N_{25}	N_{25}	Impact of pollution on radiation
Ex4	N_{25}	N_{200}	N_{25}	Impact of pollution on autoconversion
Ex5	N_{25}	N_{25}	N_{200}	Impact of pollution on sedimentation

Very busy slide

Sensitivity experiment results



Differences wrt. pristine case

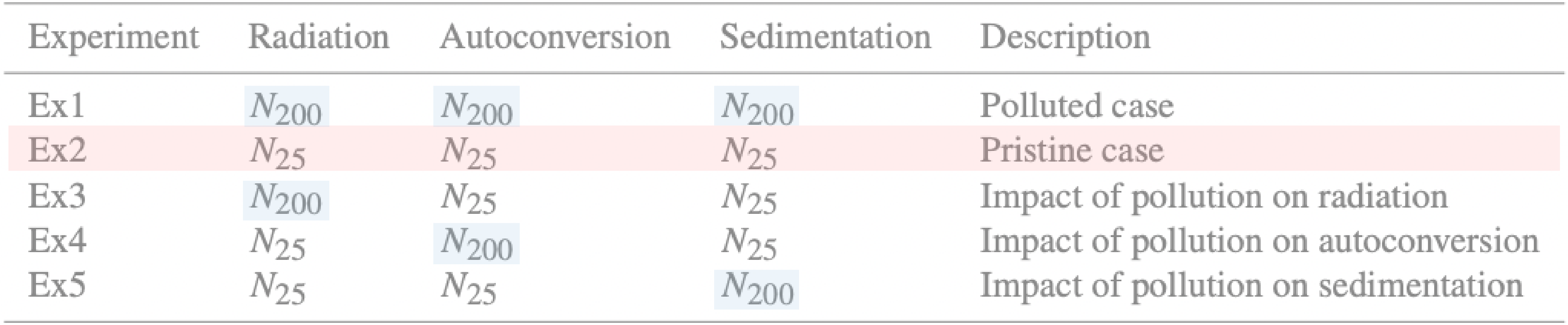


Too many details to discuss! Let's simplify!

- The influence of N_c on radiative transfer has a marginal effect on the evolution of the PBL (Ex3=Ex2)
- The autoconversion has a positive and distinctly diurnal influence on the LWP sensitivity
- Cloud water sedimentation process has a smaller, negative, and relatively constant influence (e)
- Both autoconversion and cloud water sedimentation affect the precipitation suppression mechanism
- Both autoconversion and cloud water sedimentation influence the entrainment efficiency and growth of the boundary layer.

Results: sensitivity experiments

What are key controls: Radiation, Autoconversion, or Sedimentation?



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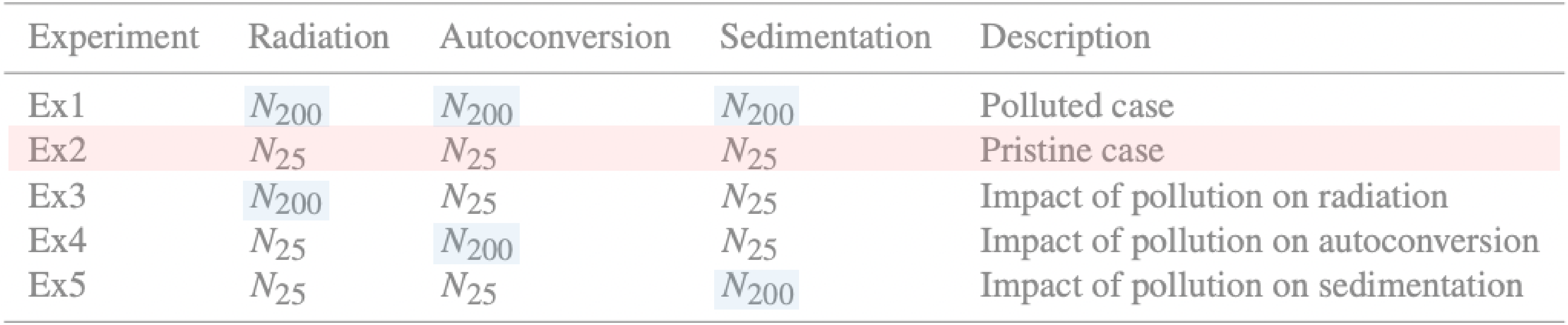
Results: sensitivity experiments

What are key controls: Radiation, Autoconversion, or Sedimentation?



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Ex3	N_{200}	N_{25}	N_{25}	Impact of pollution on radiation
Ex4	N_{25}	N_{200}	N_{25}	Impact of pollution on autoconversion
Ex5	N_{25}	N_{25}	N_{200}	Impact of pollution on sedimentation

MARGINAL

STRONG

+ LWP (diurnal)
- RWP
+Entrainment
+Decoupling

Pollution prevents water from leaving the cloud layer

WEAK

- LWP (constant)
- RWP
+Entrainment
+Decoupling

Pollution makes particles lighter and less prone to leave the entrainment layer

Summary

- Pristine and polluted scenario simulations; ERFaci decomposed into Twomey effect, and LWP and cloud fraction adjustments: Their time-dependent partial impacts were quantified for the diurnal cycle.

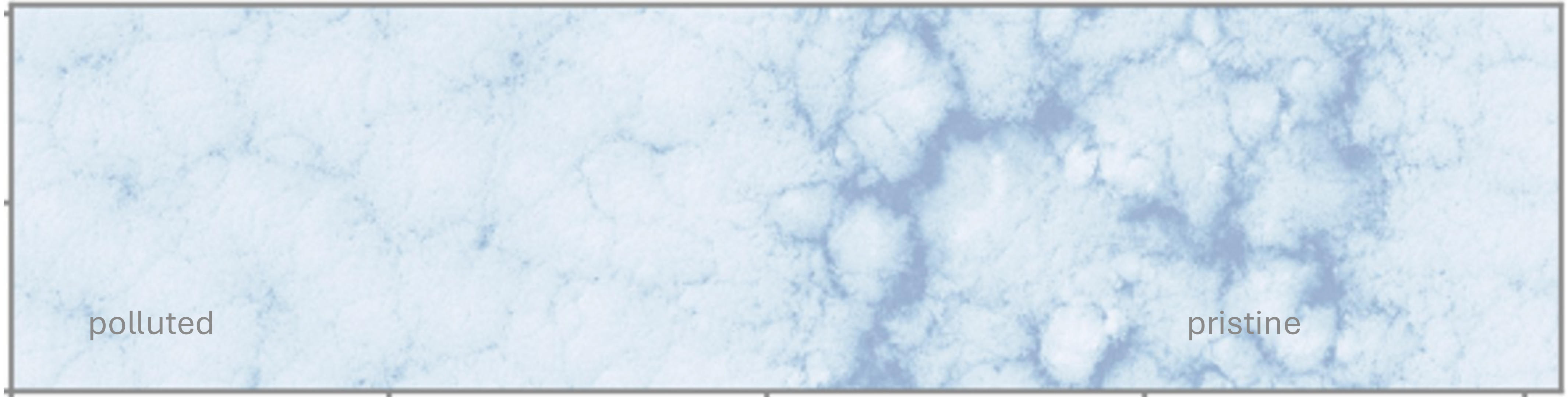
- Twomey always positive (morning peak); LWP and fc switch sign → ERFaci super-Twomey in morning (~2x stronger), near-neutral in afternoon.

- Precipitation suppression produces thicker, more turbulent clouds → enhanced LWP → stronger overnight cloud-top entrainment → deeper, drier, decoupled PBL → mid-day collapse.

- Increasing Nc amplifies diurnal cloud variability → morning/afternoon contrast.

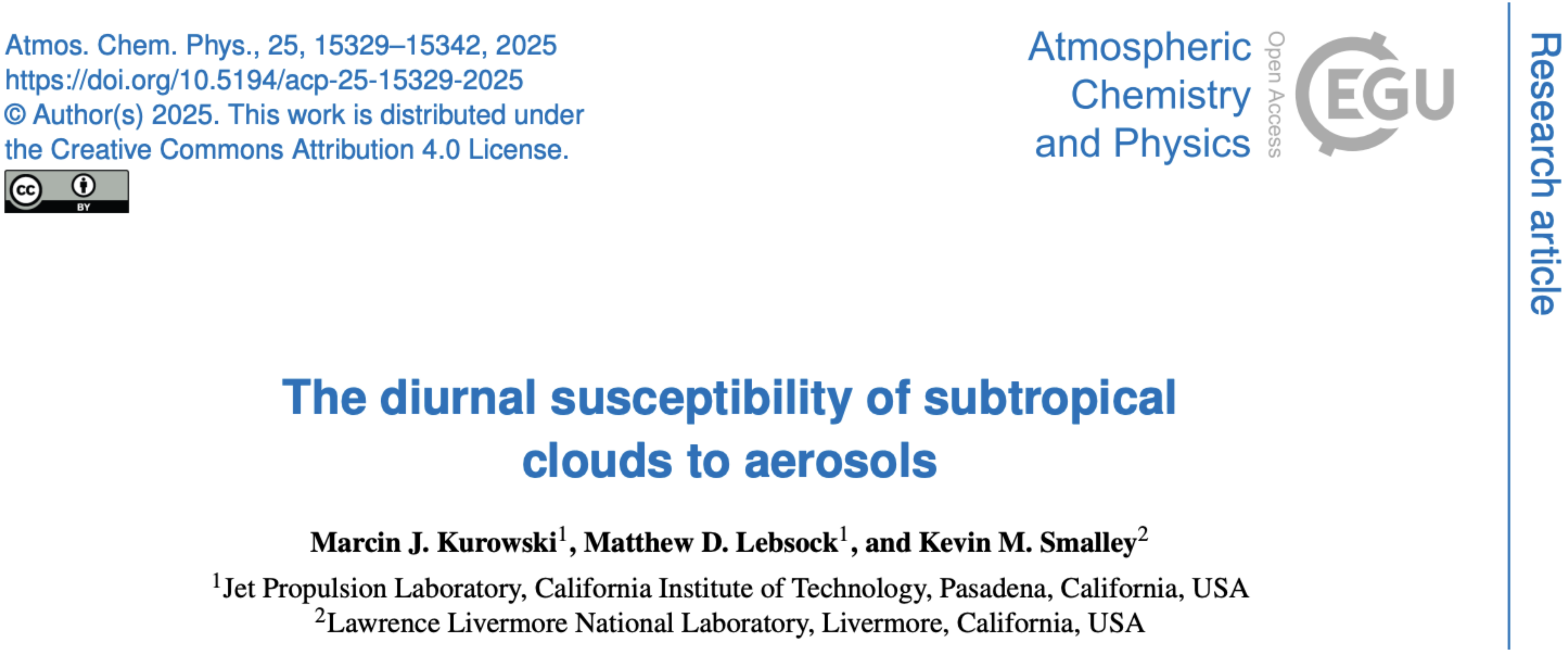
- Single LES suite; effects may differ in non-precipitating clouds.

Thank you!



Dziękuję za uwagę!

If you want to learn more...



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Research article

The diurnal susceptibility of subtropical clouds to aerosols

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