Daytime variation in aerosol indirect effect for warm boundary layer clouds in the Eastern North Atlantic (ENA) using cloud retrievals from Meteosat-11

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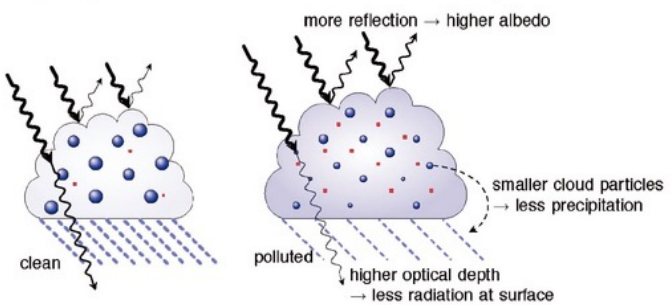
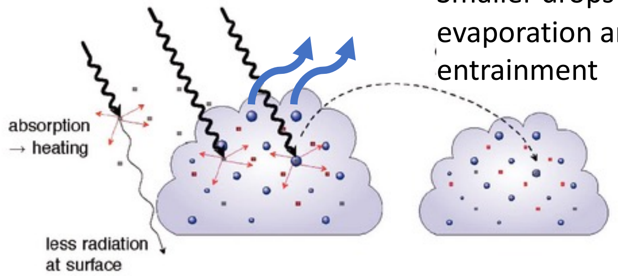
Background: challenges in estimating aerosol indirect effect (AIE)

1. Both sign and magnitude of the AIE depend on cloud state.





In precipitating clouds: aerosols decrease droplet size and inhibit precipitating → **increase** cloud water and cloud amount → **More** TOA reflected radiation from higher LWP, CF, and smaller droplets .

In non-precipitating clouds: smaller droplets increase the evaporation rate → **increases** cloud top entrainment → **decreases** cloud water and amount → the net changes in TOA reflected radiation is a balance between the Twomey effect and cloud adjustment effect.

2. The confounding factors make determine the causality challenging.

- Meteorological factors, such as relative humidity, PBL height, and stability, influence both aerosol and cloud properties.
- Cloud processes, such as coalescence, accretion, and scavenge, influence Nd, LWP, and CF.

3. Inferring process from snapshots of observations.

Observations, whether from satellites, in-situ, or ground-based, provide snapshots of the aerosol-cloud system. Most previous studies assume a Markovian system, where processes are related to current state of the system and have no memory of the past state. *However, this assumption contradicts the inherent nature of cloud systems.*

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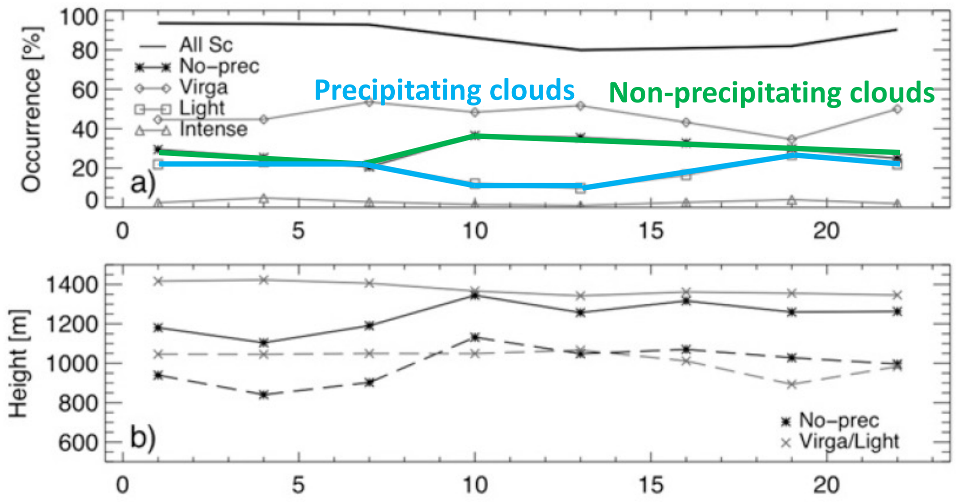
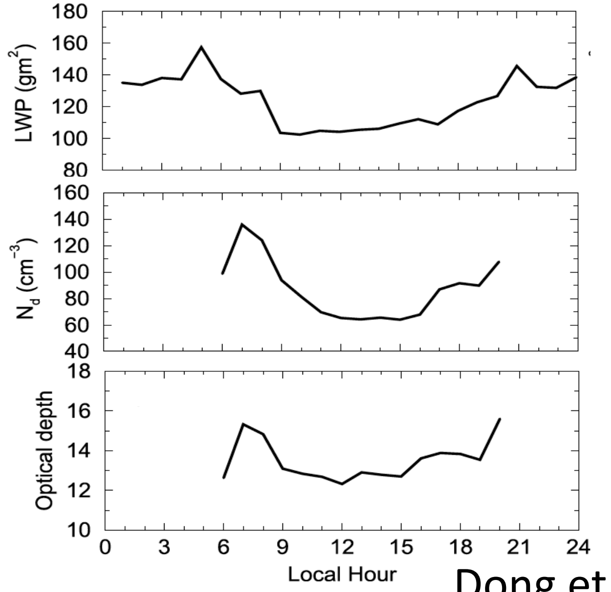
Motivation: why we expect a diurnal variation in AIE in the ENA?

Diurnal variation of cloud states from ARM:



Remillard et al . (2012)

Diurnal variation of cloud properties from ARM



Dong et al. (2014)

- Boundary layer clouds in the ENA region exhibit significant diurnal variation in cloud state and properties in summer.
- Given the sign and magnitude of the AIE depend on cloud state and properties, we would expect a notable diurnal variation in AIE.
- ***However, the diurnal variation in AIE has not been quantified in observational studies.***

In this study, we will quantify the responses of cloud LWP, cloud albedo, and cloud fraction to Nd perturbations and their **daytime variations** using cloud retrievals from the **Meteosat-11**.

Dataset and methodology:

Dataset:

- Pixel-level Meteosat- 11 cloud retrievals, 3km and a half-hourly resolution.
- Cloud properties are retrieved from the Spinning Enhanced Visible InfraRed Imager (SEVIRI) using the Satellite ClOud and Radiation Property retrieval System (SatCORPS) algorithms.
- Focus on the Eastern North Atlantic (ENA) region (33-43°N, 23-33°W) during July 2018-2021.

Methodology:

- Focus on warm boundary layer clouds with 90% cloud tops < 3km and a liquid phase.
- **Include both overcast and broken clouds** to quantify the response of cloud fraction to N_d perturbations.
- To minimize the confounding meteorological impact, cloud susceptibility is quantified in a 1°×1° grid box at each time step as $dln(X)/dln(N_d)$
- Filter pixels with r_e >$3\mu m$, τ > 3, SZA< 65°, and remove cloud edge for each cloud object.
- To reduce impacts from cloud heterogeneity and co-variability, smooth the pixel data to 0.25°

Dependence of AIE on cloud states:

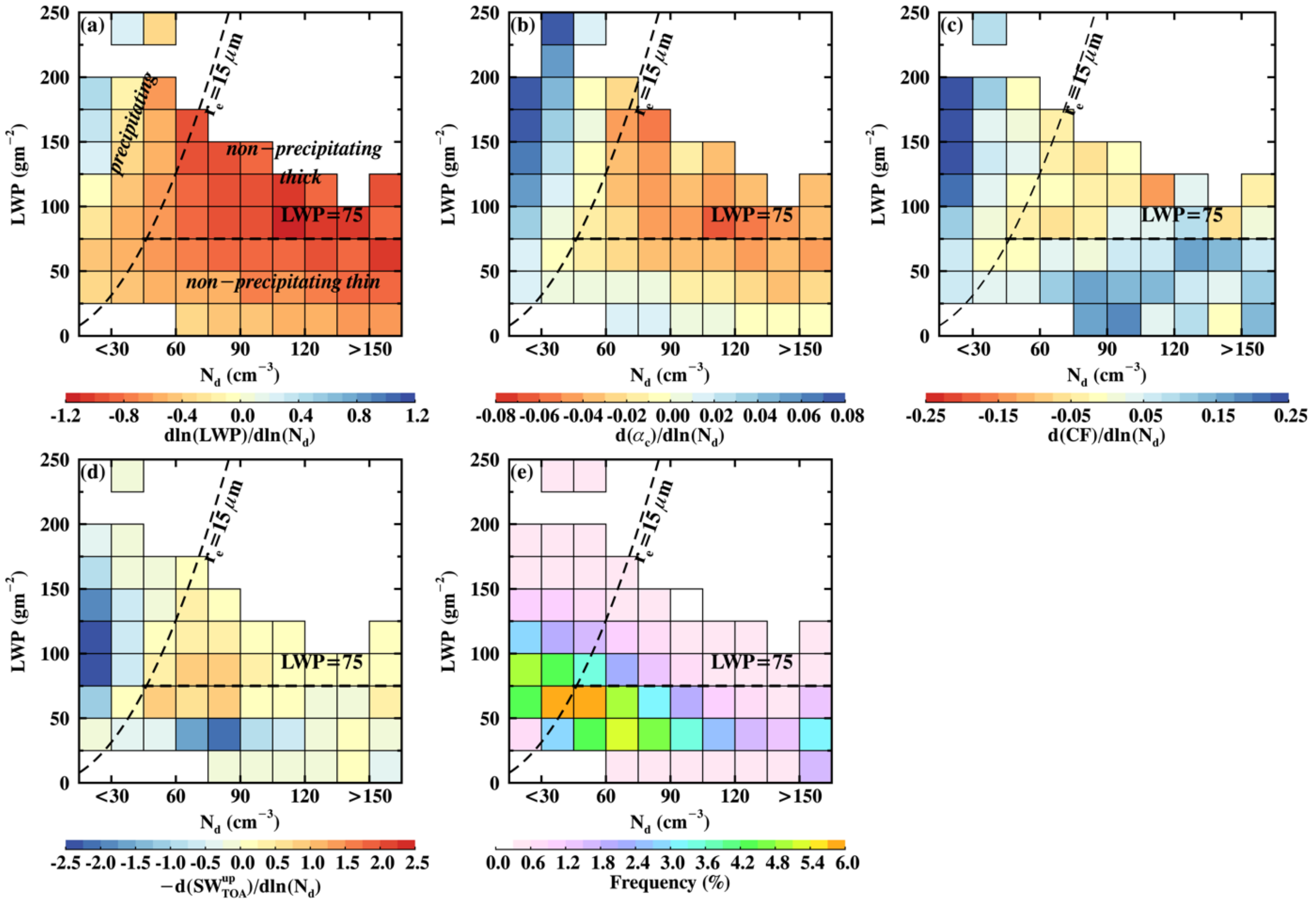


Fig. 1 Daytime mean of the aerosol indirect effect for different cloud states

- Classify three cloud state: **precipitating clouds** ($r_e > 15\mu m$), **non-precipitating thin clouds** ($r_e <$ 15μm, LWP < 75 gm^{-2}), and **non-precipitating thick clouds** ($r_e <$ 15μm, LWP > 75 gm^{-2}).

- **Sign and magnitude of cloud susceptibilities depends on cloud states**: precipitating clouds exhibit a net cooling effect at the surface, non-precipitating thick clouds have a warming effect, and non-precipitating thin clouds have a cooling effect.

Daytime variation in AIE

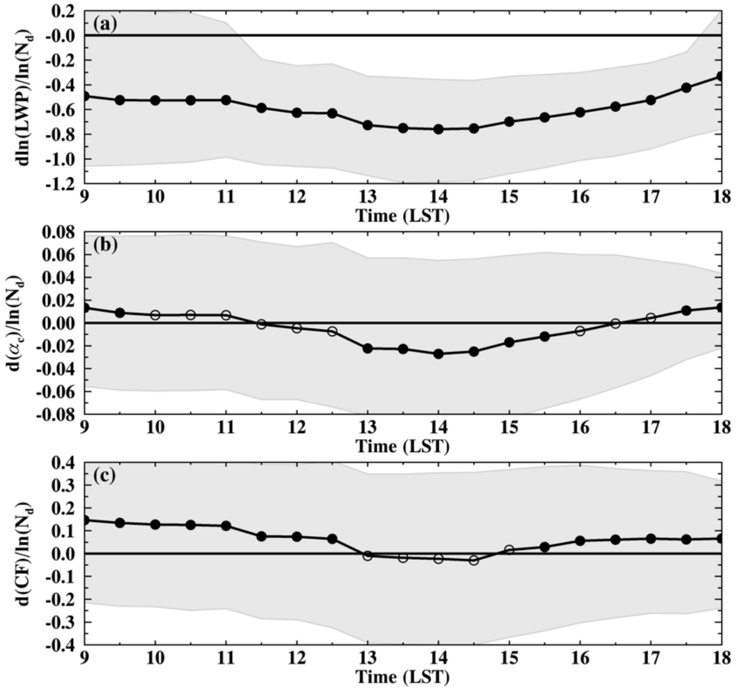


Fig. 2 Daytime variation in AIE for all cloud states.

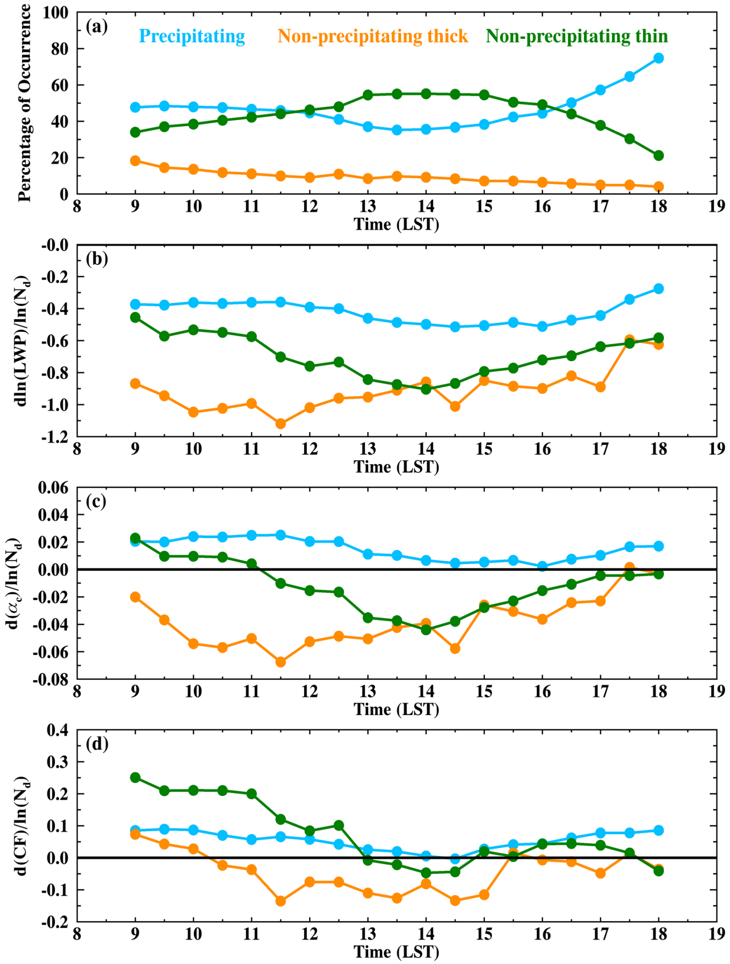


Fig. 3 Daytime variation in AIE for different cloud states.

- **A "U-shaped" diurnal variations** in AIE: clouds are ***more susceptible* at noon** and ***less susceptible*** in the **morning and evening**

- Different cloud states exhibit distinct diurnal variation pattern:
- Non-precipitating thin clouds show a similar **"U-shaped"** diurnal variation in LWP and albedo susceptibilities.
- Precipitating clouds have **minimal diurnal variation** in AIE.
- Thick clouds exhibit increasing LWP and albedo susceptibilities from noon to afternoon.

Impact of cloud memory on daytime variation in AIE

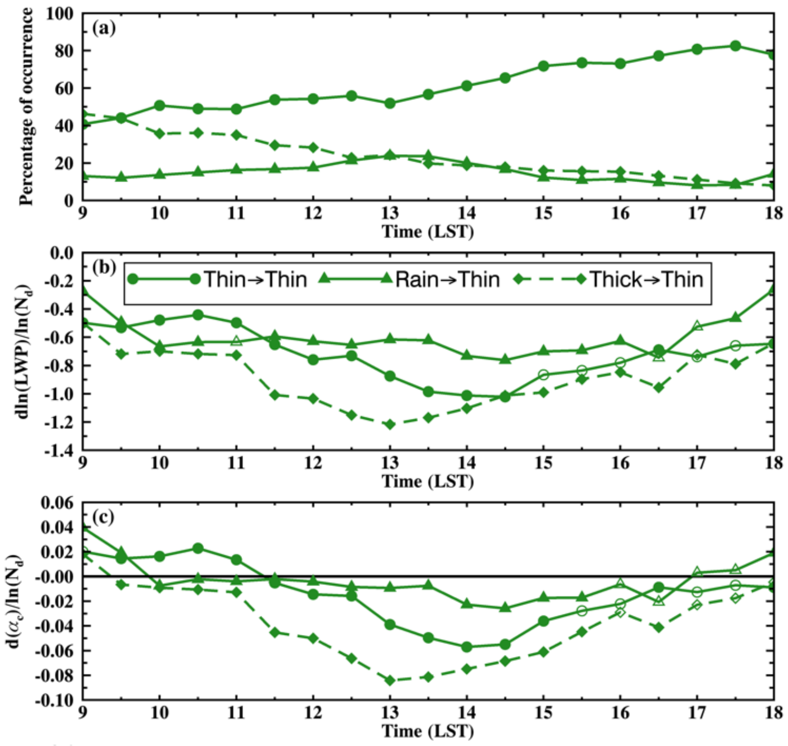
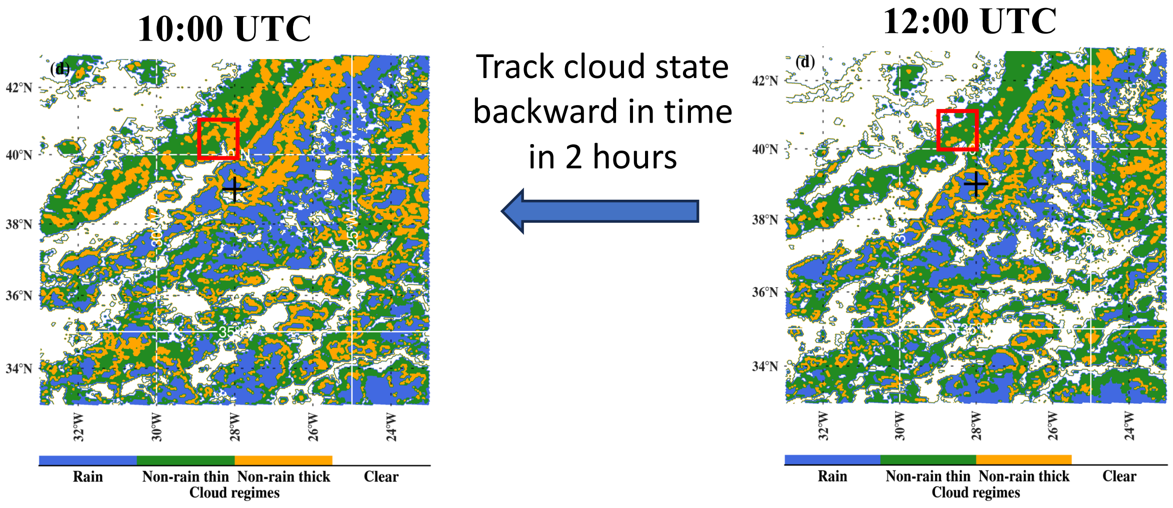


Fig. 4 Daytime variation in AIE for non-precipitating thin clouds transition from different states.



- At 9am, ~50% of thin clouds originate from thick clouds in previous hours; in the afternoon, ~80% thin clouds are from thin clouds (Fig. 4a).
- Non-precipitating thin clouds that transition from thick clouds have significantly more negative LWP and albedo susceptibilities than thin clouds that are previously thin or precipitating (Fig. 4b-c).

→ **clouds retain the memory of LWP response in the previous state.**

Impact of cloud memory on daytime variation in AIE

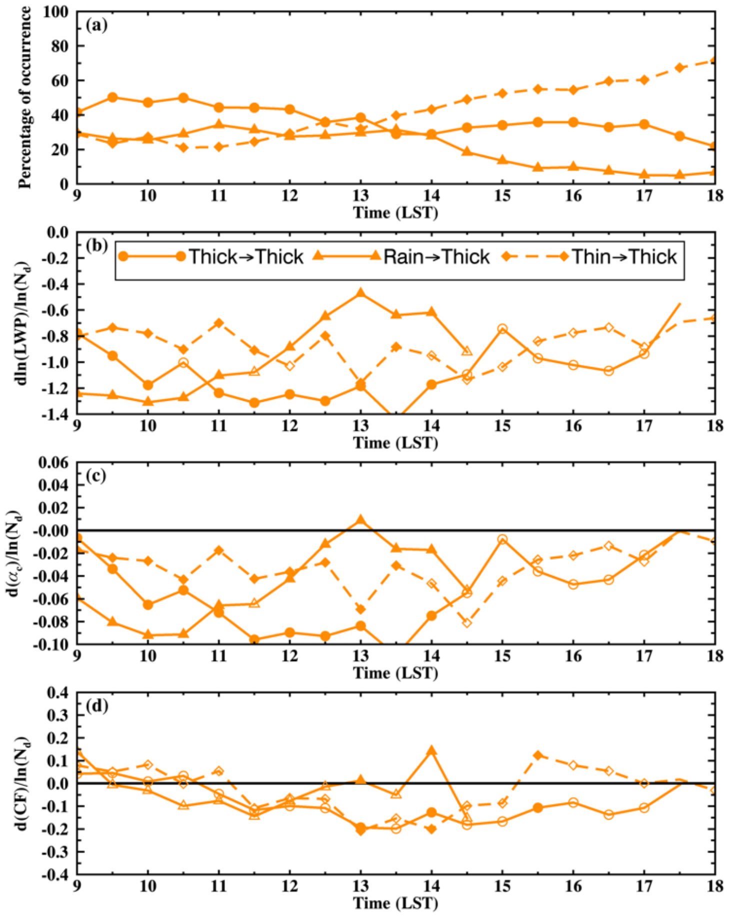


Fig. 5 Daytime variation in AIE for non-precipitating thick clouds transition from different states.

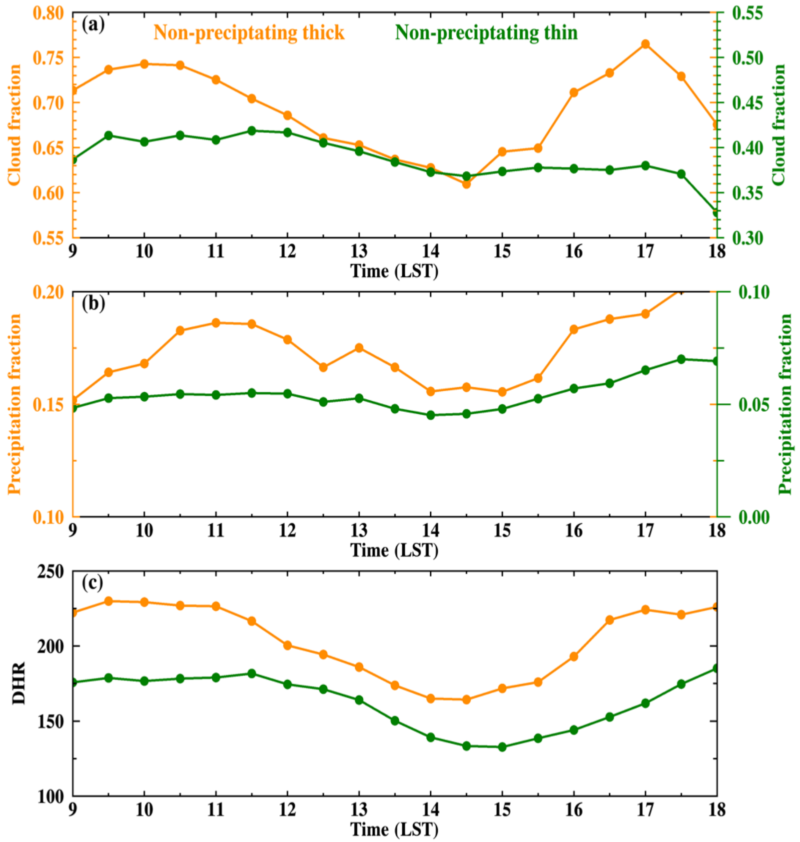
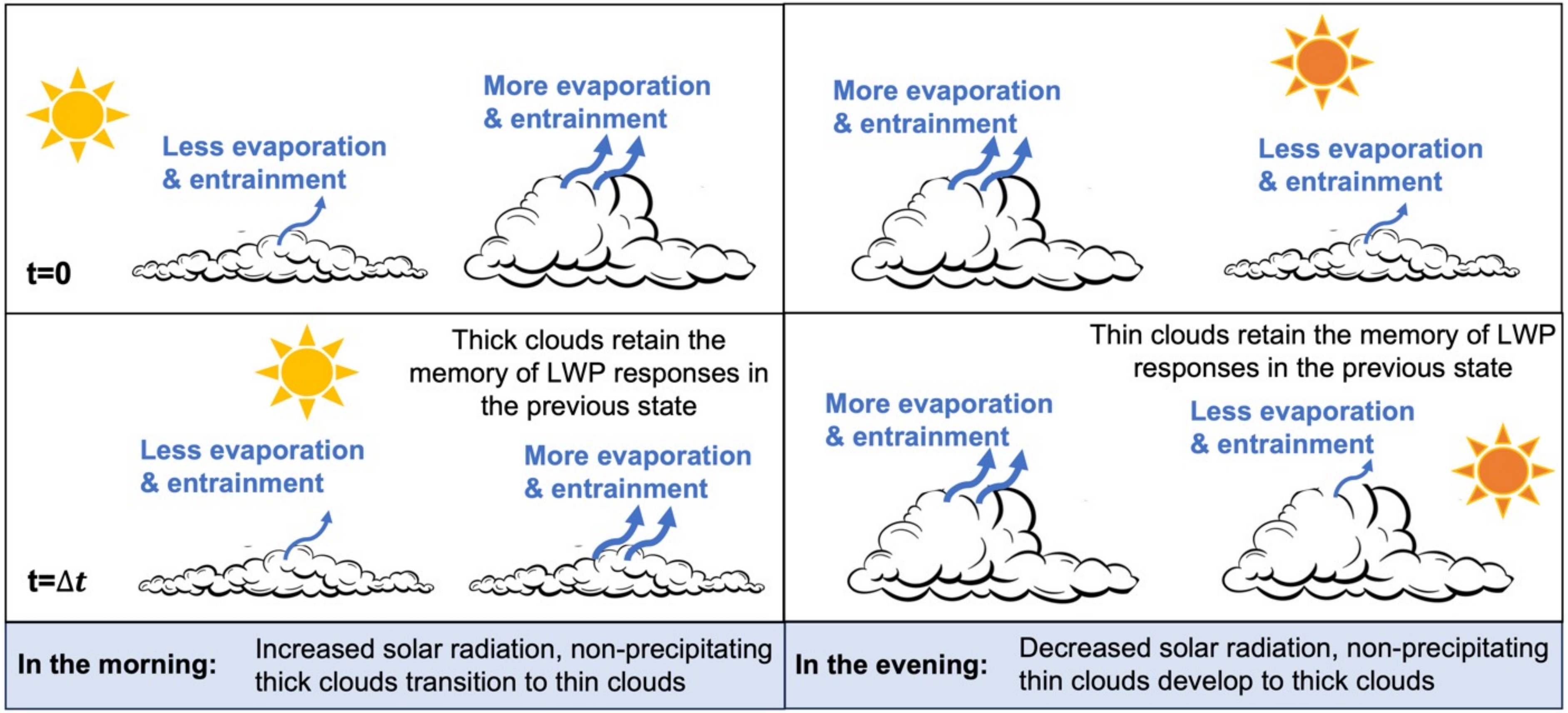


Fig. 6 Daytime variation in AIE for non-precipitating thick clouds transition from different states.

- Thick clouds that developed from thin clouds have significantly less negative responses in LWP and albedo than thick clouds that remained thick (Figs. 5b-d).
- Diurnal variation in CF susceptibility cannot be explained by transition in cloud state (Fig. 5d).
- Instead, it's due to thick clouds break up from morning to noon and change back to overcast clouds in the afternoon (Fig. 6)



- In the morning, non-precipitating thick clouds transition to thin clouds. Clouds retain the memory of the large negative LWP response to N_d perturbations and lead to a decrease in LWP susceptibility for thin clouds.
- In the afternoon, non-precipitating thin clouds develop to thick clouds while retaining the less negative LWP response and lead to an increase in LWP susceptibility.

Can polar-orbiting satellite capture the daytime variation in AIE?

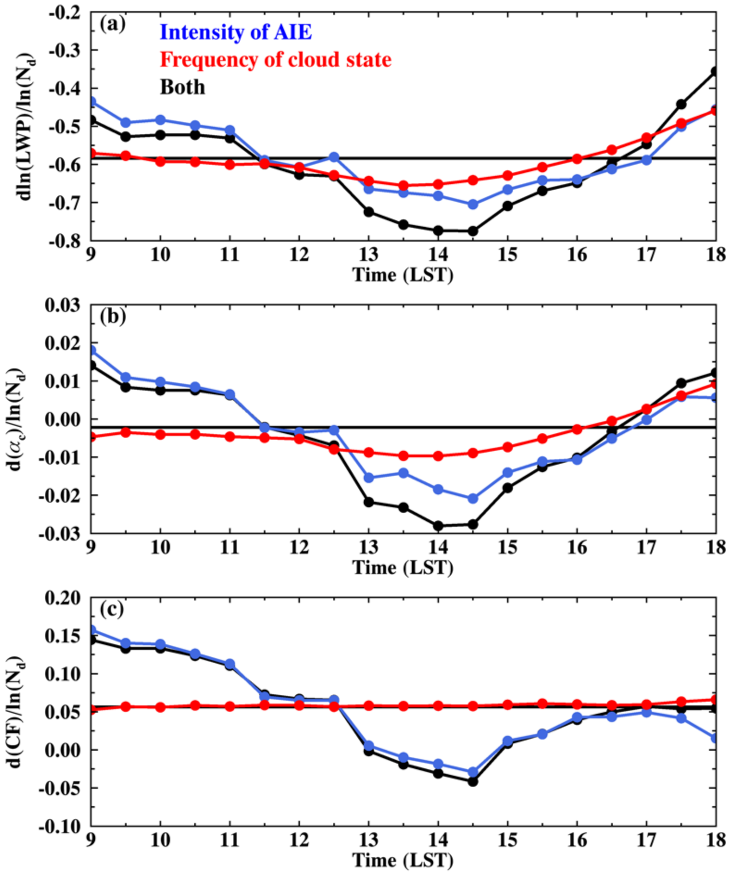
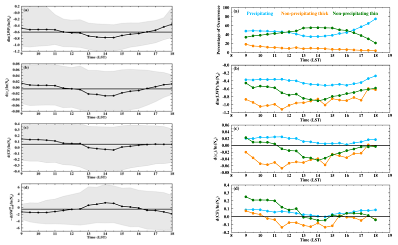


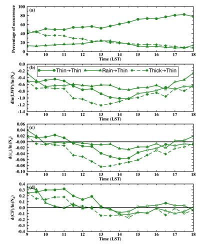
Fig. 7 Daytime variation in AIE contributed from the variability in the intensity of cloud susceptibility and in the frequency of occurrence of cloud states.

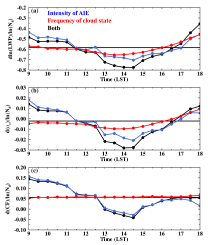
- Blue line is calculated by weighting the half-hourly cloud susceptibility with the daytime mean frequency of occurrence of cloud state.
- Red line is calculated using the daytime mean cloud susceptibility weighted by the half-hourly frequency of occurrence of cloud states.
- Diurnal variation in aerosol indirect effect is mostly caused by the diurnal variability in intensity of aerosol-cloud interaction (blue line).
- *Polar-orbiting satellites cannot capture the daytime variation in AIE. With its overpass time at 13:30 LST, it underestimate the daytime mean values of cloud susceptibility.*

Concluding remarks

1. Warm boundary layer clouds in the Eastern North Atlantic region demonstrate a significant **"U-shaped" diurnal variation,** indicating a higher susceptibility to N_d perturbations at noon and lower susceptibility in the morning and evening.
2. Different cloud states show distinct patterns of diurnal variation in AIE.
3. Diurnal variation in AIE is influenced by the diurnal transition between non-precipitating thick and thin clouds and the "lagged" cloud responses to N_d perturbations.
4. *Polar-orbiting satellites* with overpass time at 13:30 LST *underestimate* the average daytime magnitude of the aerosol indirect effect.







Qiu et al. (2024) ACP, https://doi.org/10.5194/acp-24-2913-2024