Following Clouds: Seeking Causal Relationships in Aerosol-Cloud Interactions

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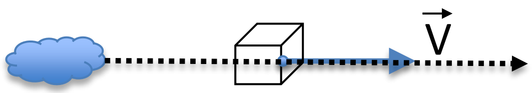
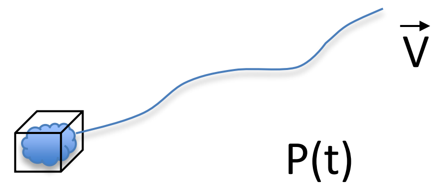
Following Clouds

Eulerian



P(x,y,z,t)

Lagrangian



P(t)

Lagrangian Observational Technique

- Tracer quantities become a function of **time only**.
  - Budgets can be formulated without the use of hard-to-measure advective terms
  - Temporal constraints on ACI can be constructed
- Cloud regime shifts are difficult to quantify from a Eulerian perspective
- **History** of the environment can be linked to the development of cloud.
  - Upstream conditions impact local cloud properties
  - Monthly cloud amounts are better correlated with SST 24-30 h upstream than with the local surface temperature (Klein et al. 1995).

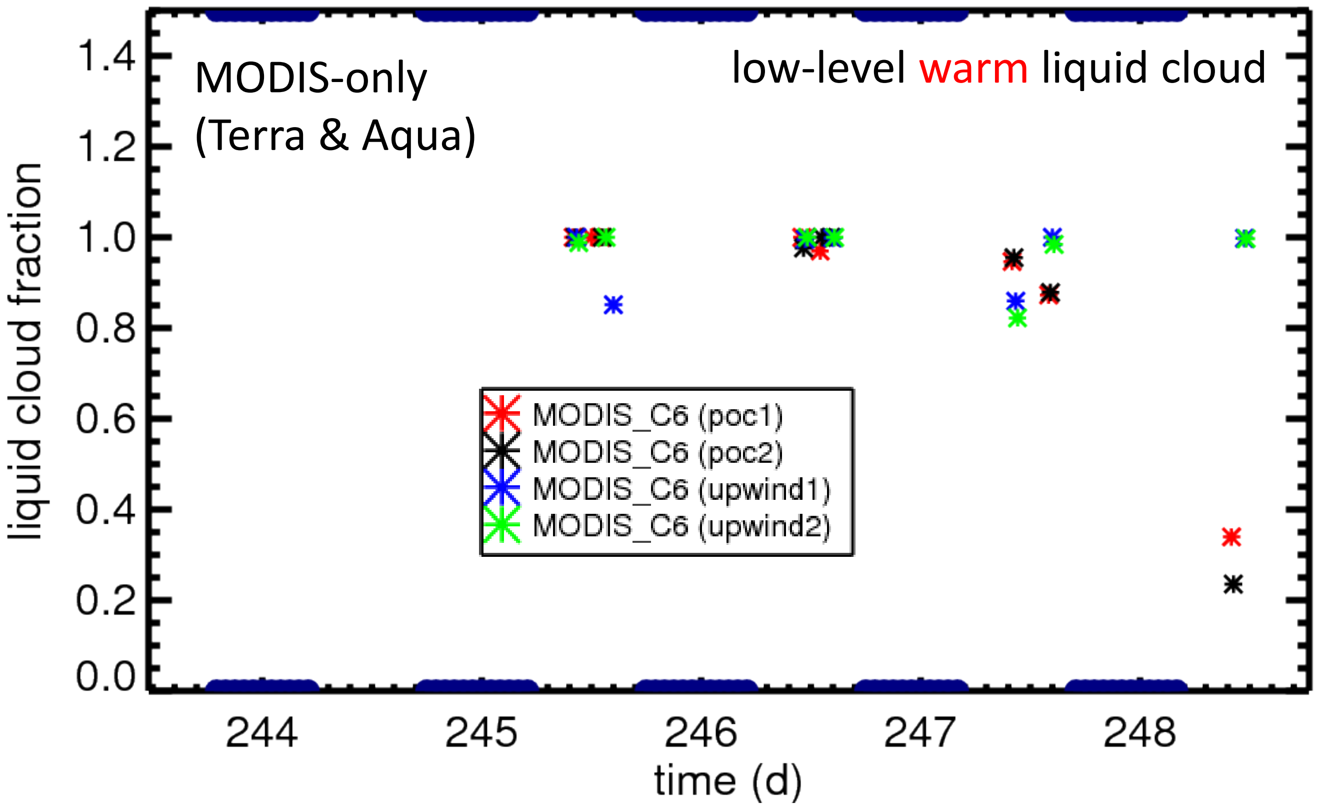
<u>Method</u>

Run **NOAA HYSPLIT** model

Aggregate **SEVIRI** observations over a 1°×1° degree region averaged over 1hr intervals.

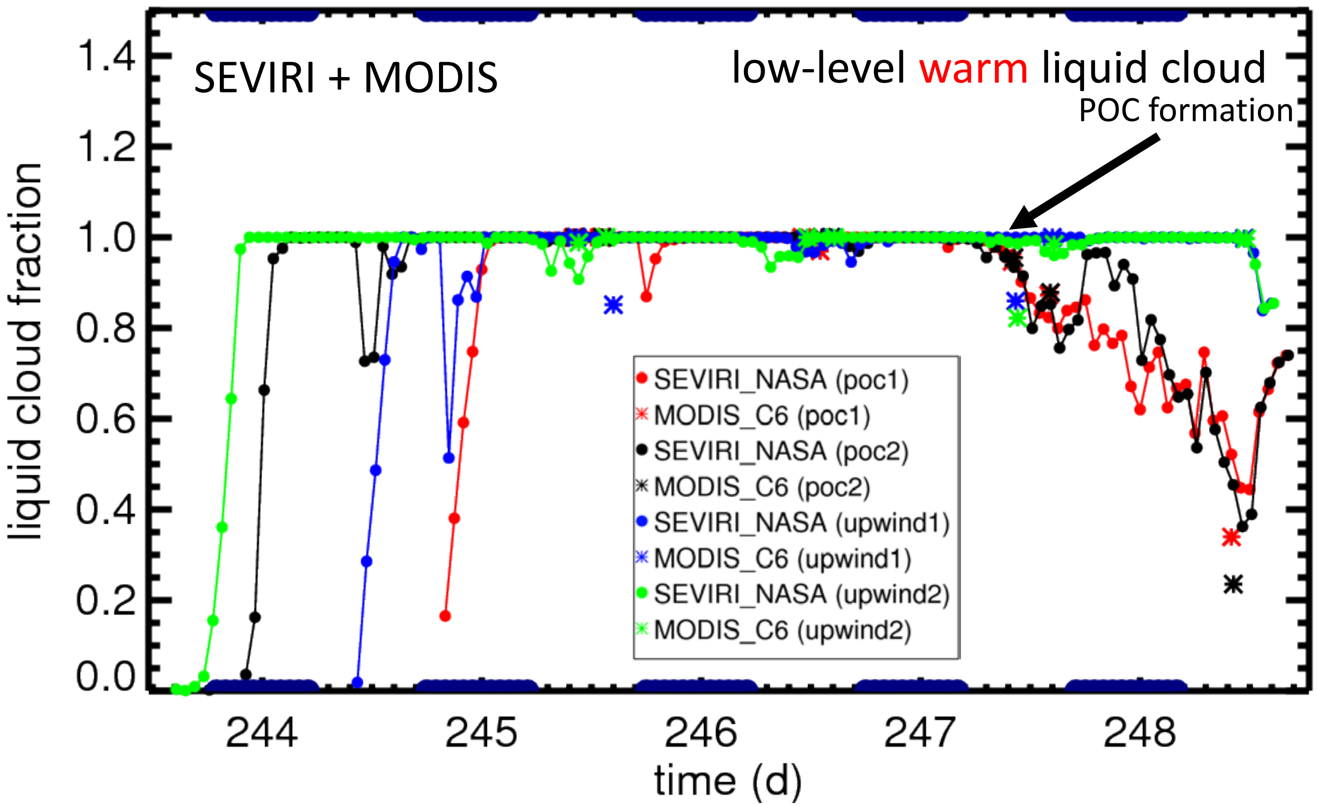
Average **MODIS** and precipitation measurements from GPM and IMERG.

Liquid Cloud Fraction



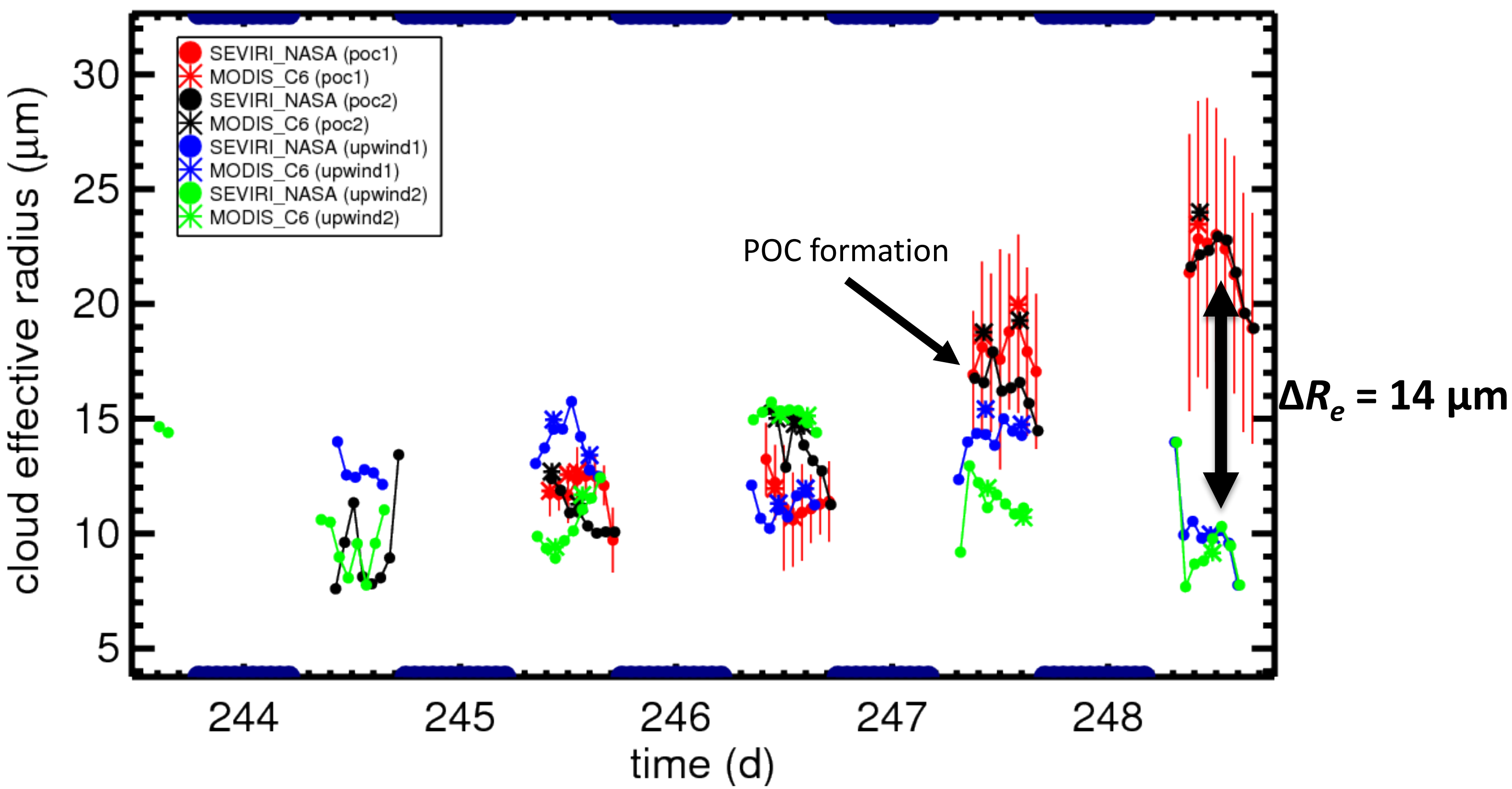
- Cloud fraction significantly lower in the POC (**red & black**) on day 248.
  - *Difficult to see transition when only MODIS data is used.*

Liquid Cloud Fraction



- Cloud fraction begins to decrease rapidly in POC cases (**red & black**) during early morning hours on day 247.
- MODIS collection 6 product agrees well with SEVIRI NASA product.

Droplet Effective Radius (daytime only)



- Nighttime retrieval screened by solar zenith angle greater than 60°.
- Clear separation between POC and control on final day of trajectory.
- MODIS collection 6 LUT's saturate at R_e = 30 μm, aircraft observations provided by Steve Able show the effective radii are actually about twice this value (not shown).

Lagrangian Stratus-to-Cumulus Transition

Question 1: **Can aerosols influence cloud properties along this transition?**
Question 2: **Do we observe evidence for cloud lifetime effects?**
Question 3: **How do Twomey, LWP and Cloud fraction radiative effects change along trajectories?**

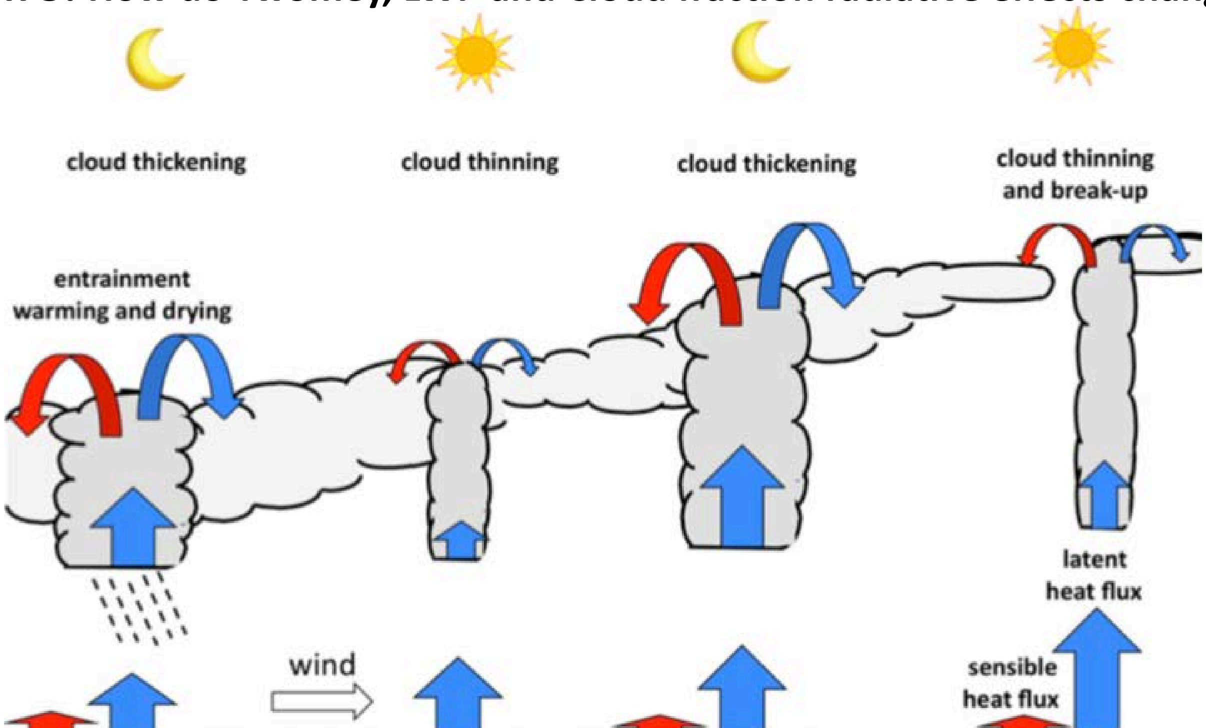


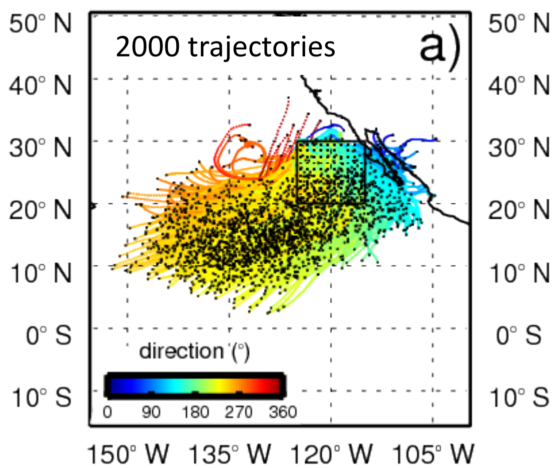
Figure: De Roode et al. (2016), *JAS*

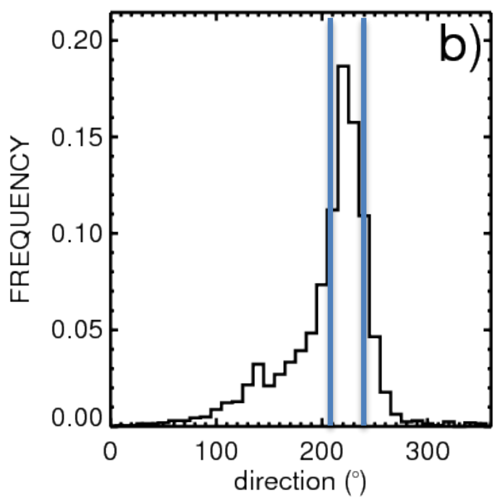
$$\Delta F_{TOA} = -F^{\downarrow} C \alpha_c (1-\alpha_c) \Delta \ln N_d \left(\frac{1}{3} + \frac{5}{6} \frac{\Delta \ln \mathcal{L}}{\Delta \ln N_d} + \frac{\Delta \ln C}{\Delta \ln N_d} \right)$$

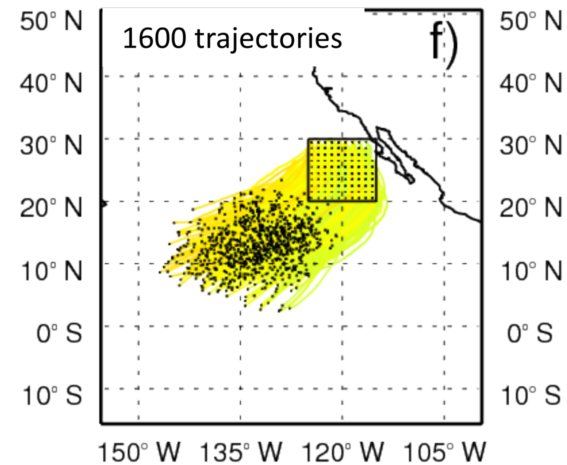
Radiative effect derivation from Quaas et al. 2008, JGR

ΔF_{TOA}: radiative effect
C: cloud fraction;
α_c: cloud albedo
$\mathcal{L}$: liquid water path
N_d: droplet concentration

Regional Analysis Procedure







Method:

- **Parcel model: HYSPLIT**
- **Duration**: *forward* 80 hours
- **Height:** middle of the PBL
- **Period:** 2016 – 2017

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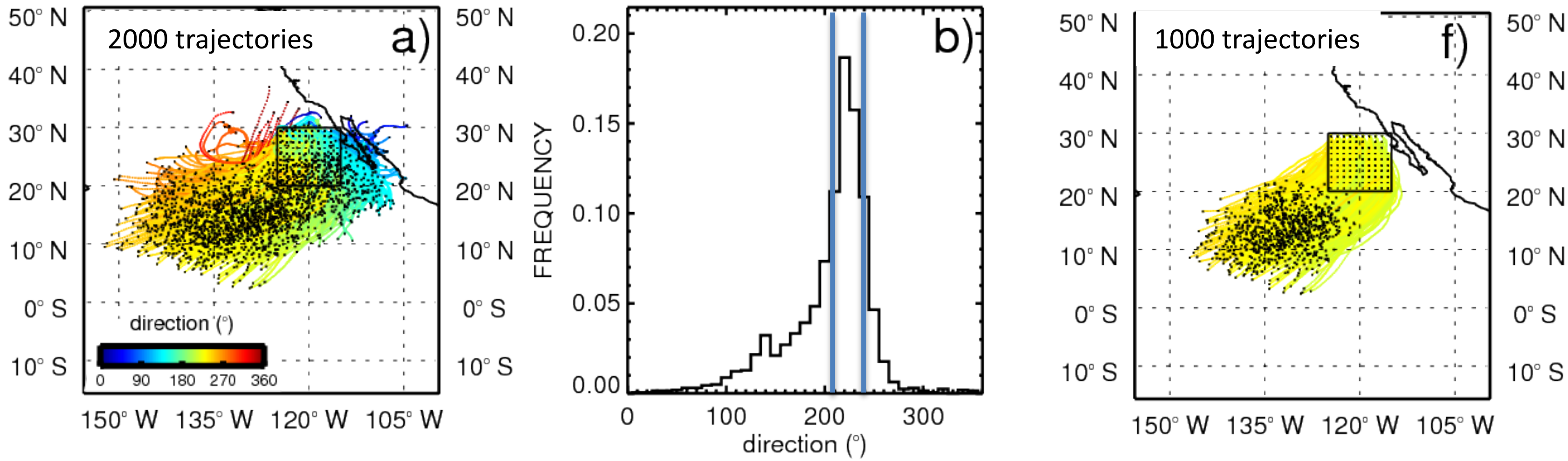

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Screening Procedure:

- MODIS 1° (MOD08_D3)
- High-clouds (less than 5 hour integrated occurrence)
- Confident clear grid-boxes at ***start of trajectory***

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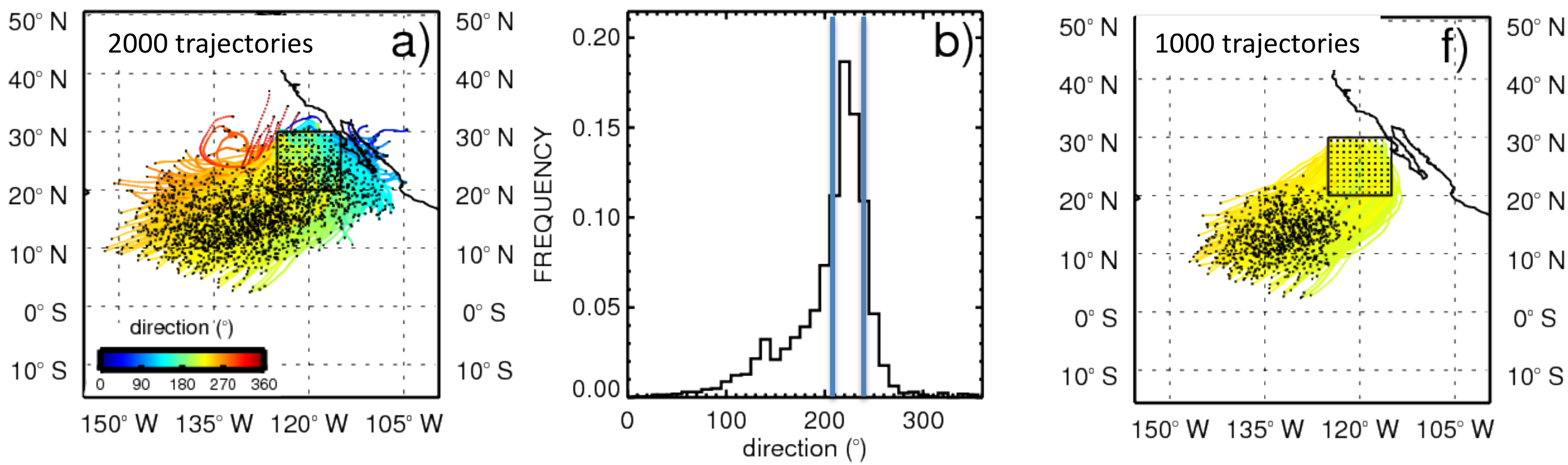

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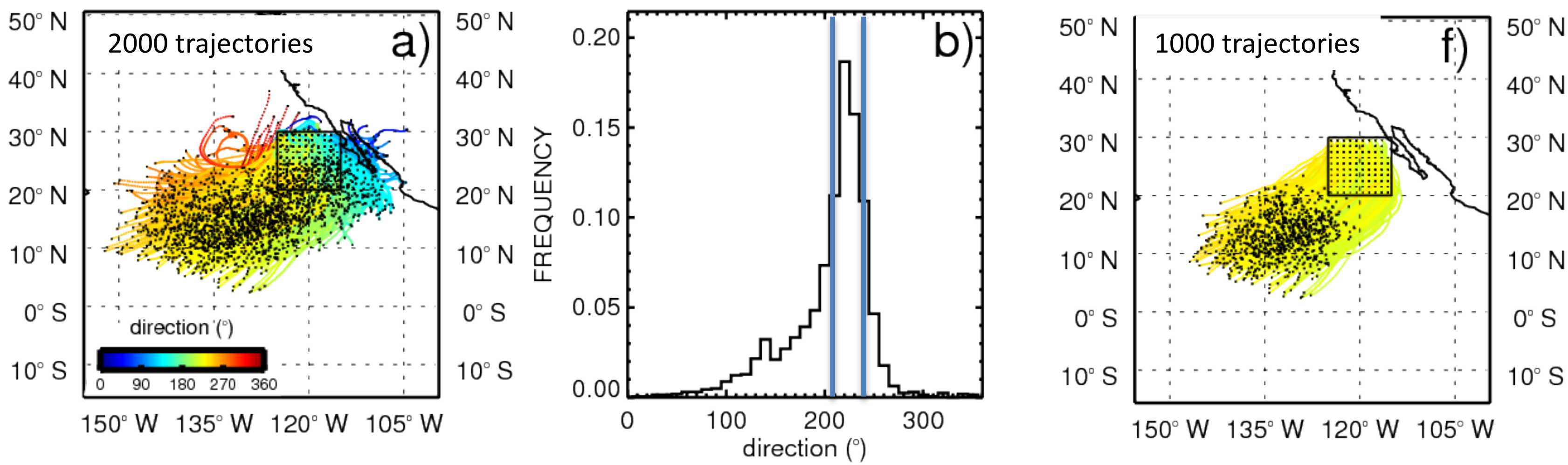
Why start in clearsky?

1. Accurate baseline aerosol optical depth.
2. History of aerosol connection to cloud.
3. Baseline cloud radiative effect
4. Quantify Timescale of cloud formation/dissipation
5. Sort trajectories between clean and polluted.

Regional Analysis Procedure



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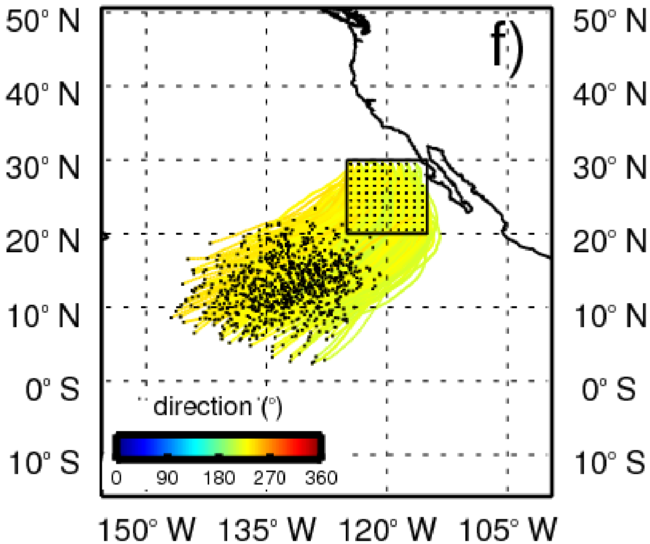
Data:

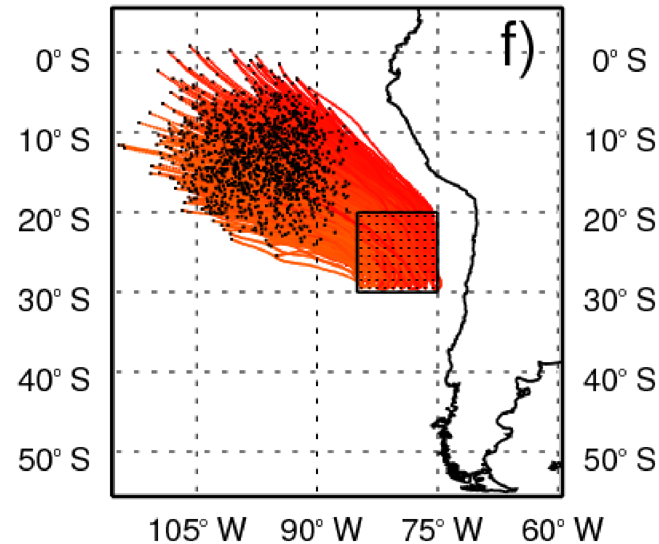
- **Aerosol**: MODIS (MYD04) and CAMS
- **Cloud/Radiation:** CERES SYN hourly 1° Edition 4
- **Reanalysis data**: ECMWF ERA-Interim

Regional Analysis Procedure

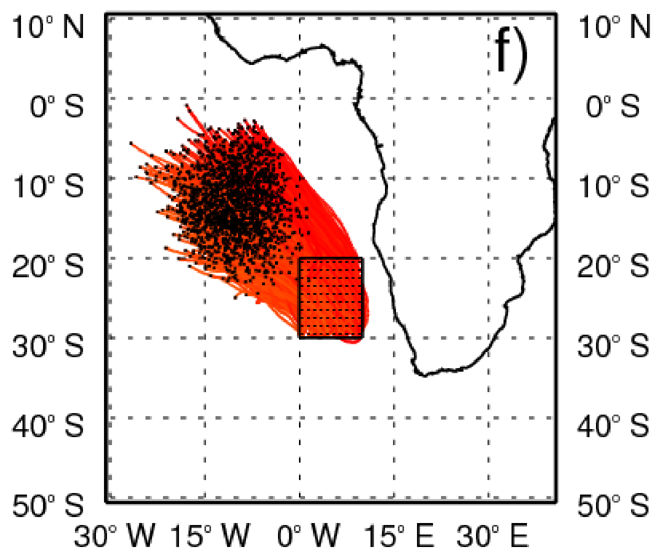
Baja Californian



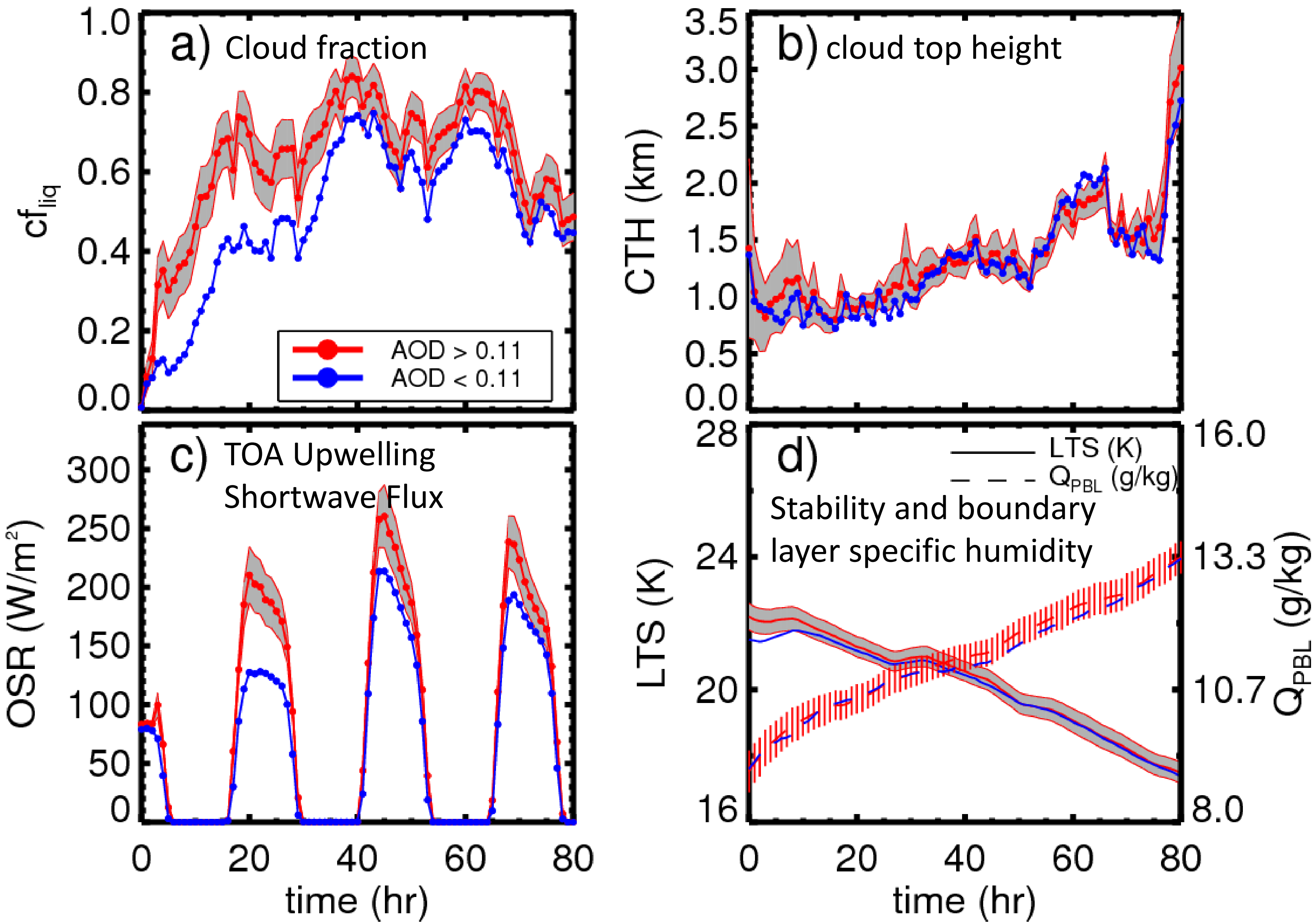
Chilean



Namibian

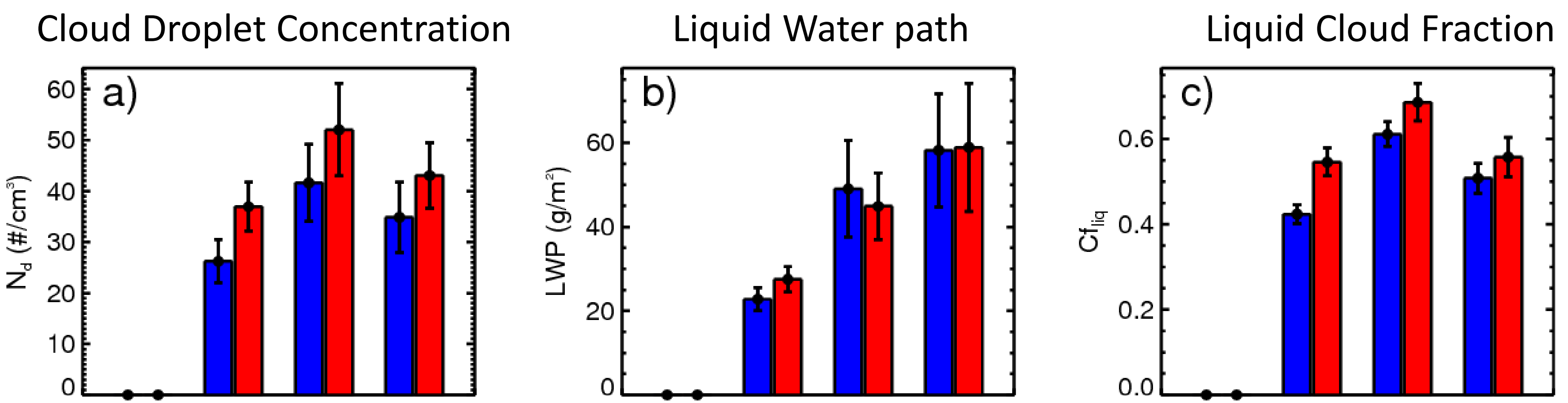


Baja California Stratocumulus



Baja California Stratocumulus

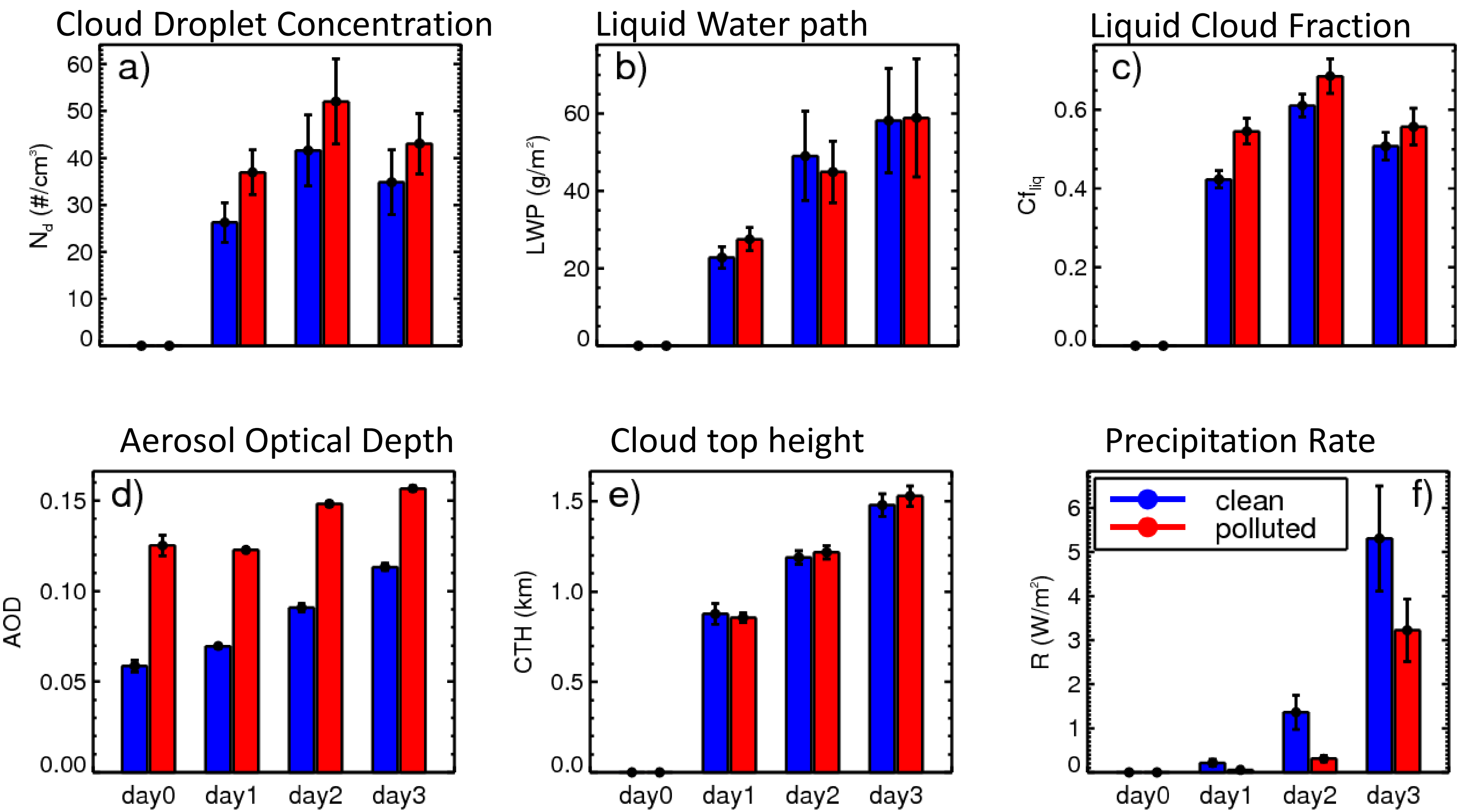
daytime averages (9am – 4pm local time)



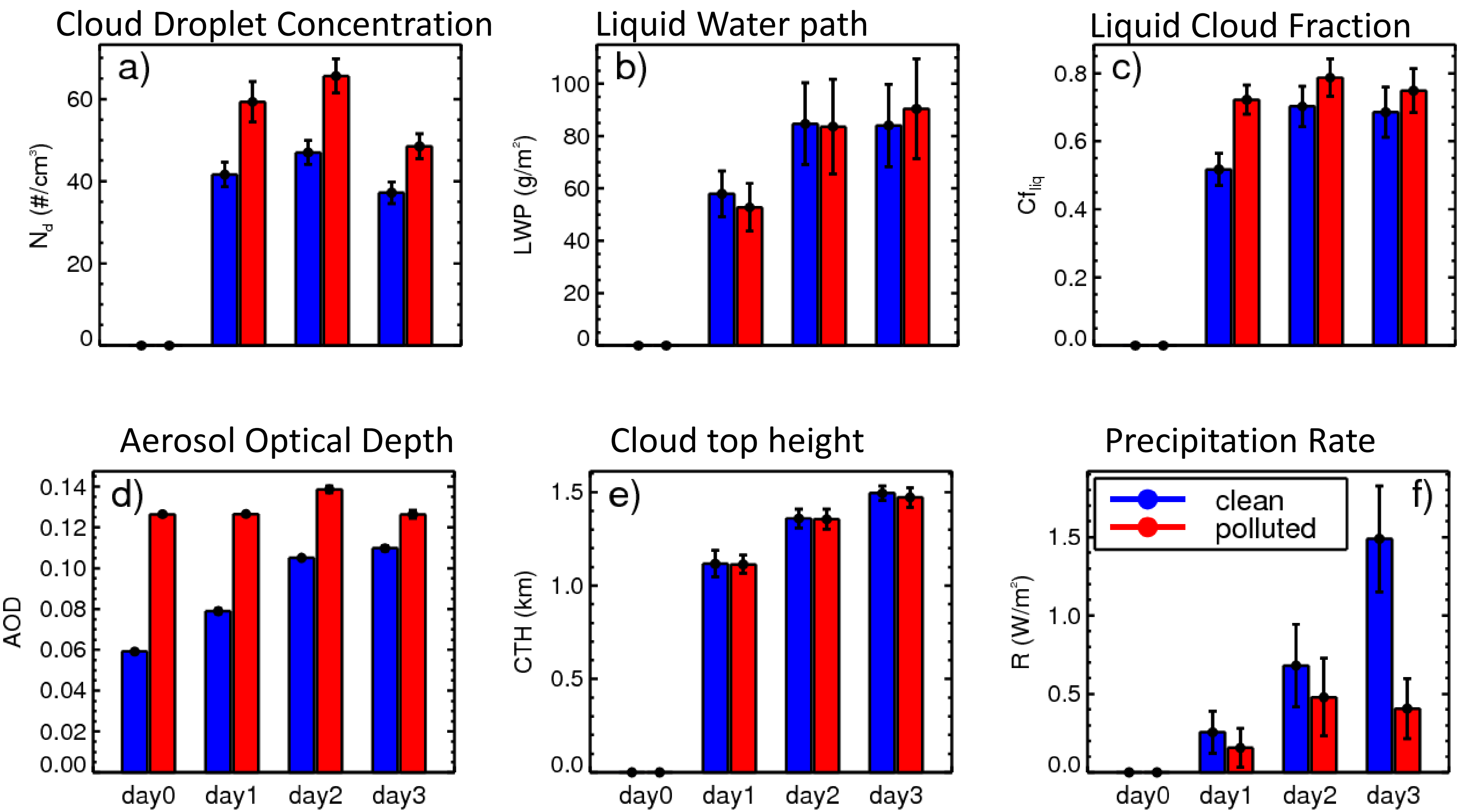
<u>Daytime averages</u>

- Cloud droplet concentration is larger in polluted trajectories.
  - Clouds forming in polluted airmass have more numerous cloud droplets (Twomey, 1974).
- Cloud fraction is larger under polluted conditions
  - aerosols suppress precipitation (AMSR and IMERG show this) causing cloud water path and areal extent to increase.
- Cloud property differences between polluted and clean trajectories diminish along the trajectory.

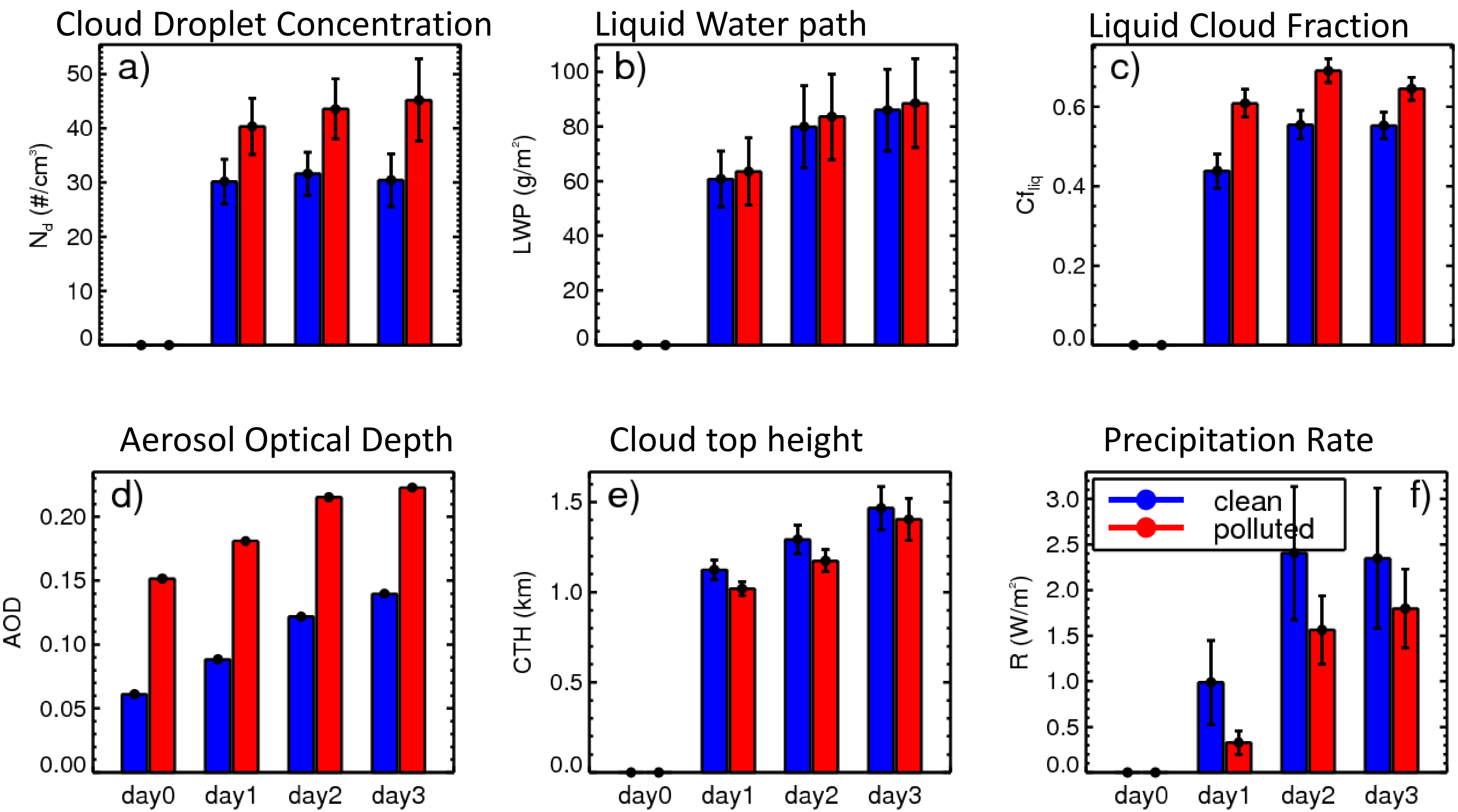
Baja California Stratocumulus



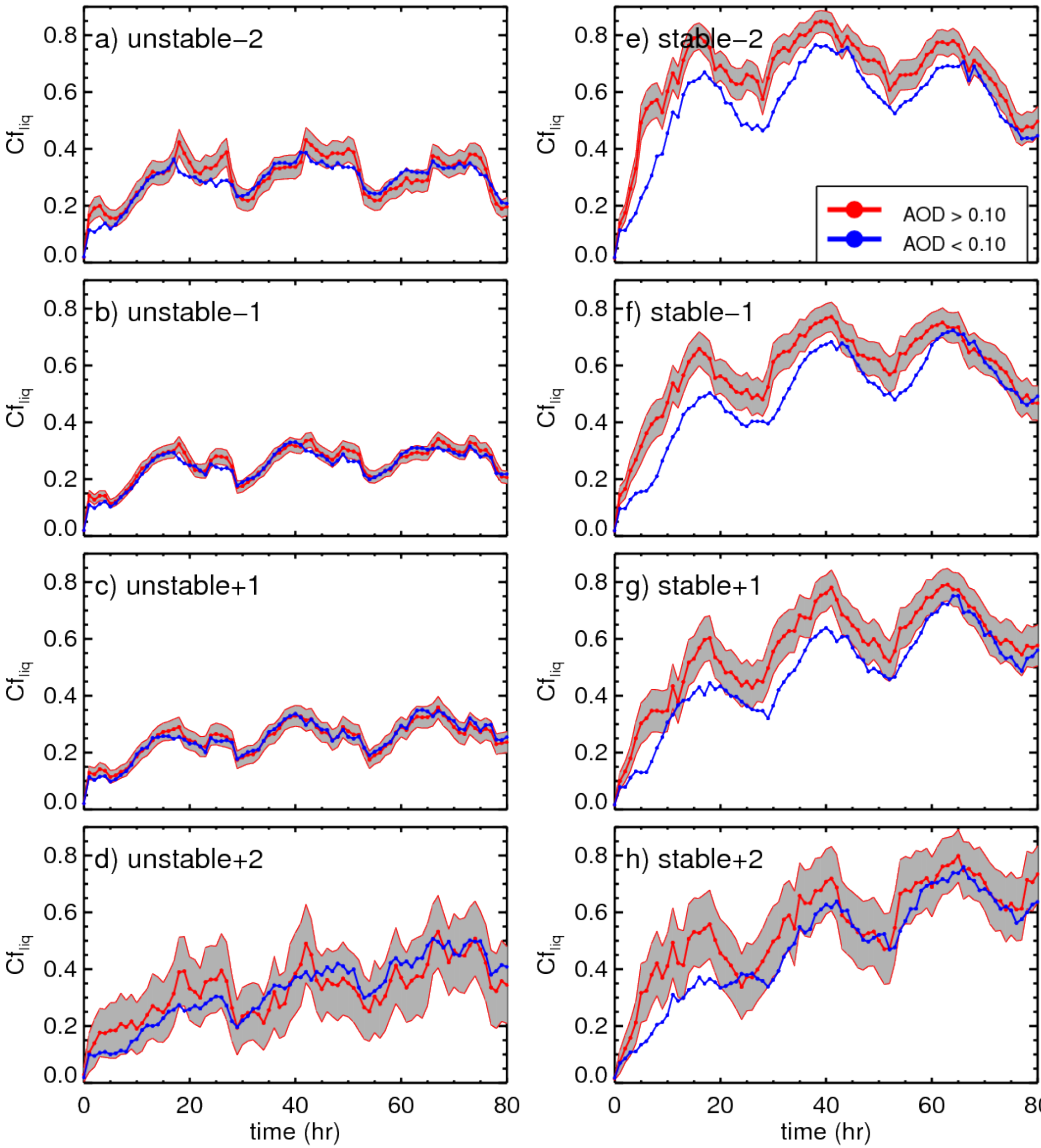
Chilean Stratocumulus



Namibian Stratocumulus

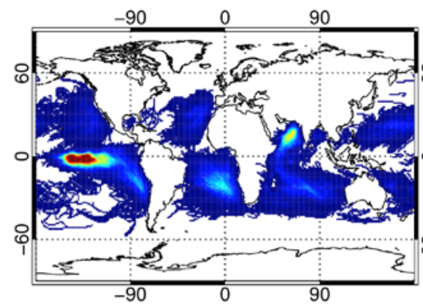


- Black carbon AOD is 3x larger in the Namibian region.
  - minor influence on CDNC and cloud fraction overall.

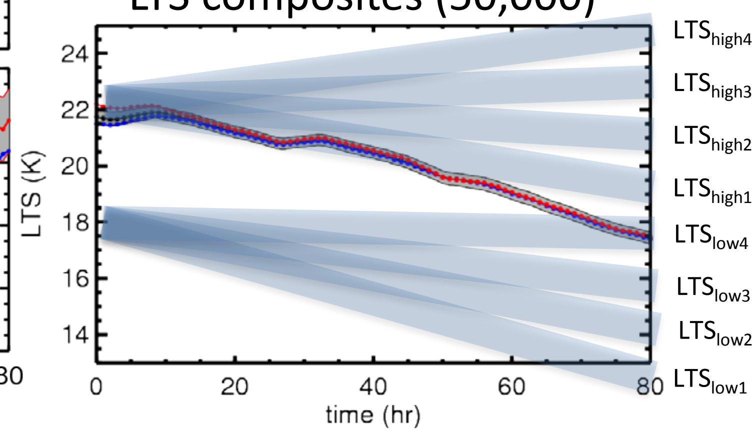


Cloud Fraction

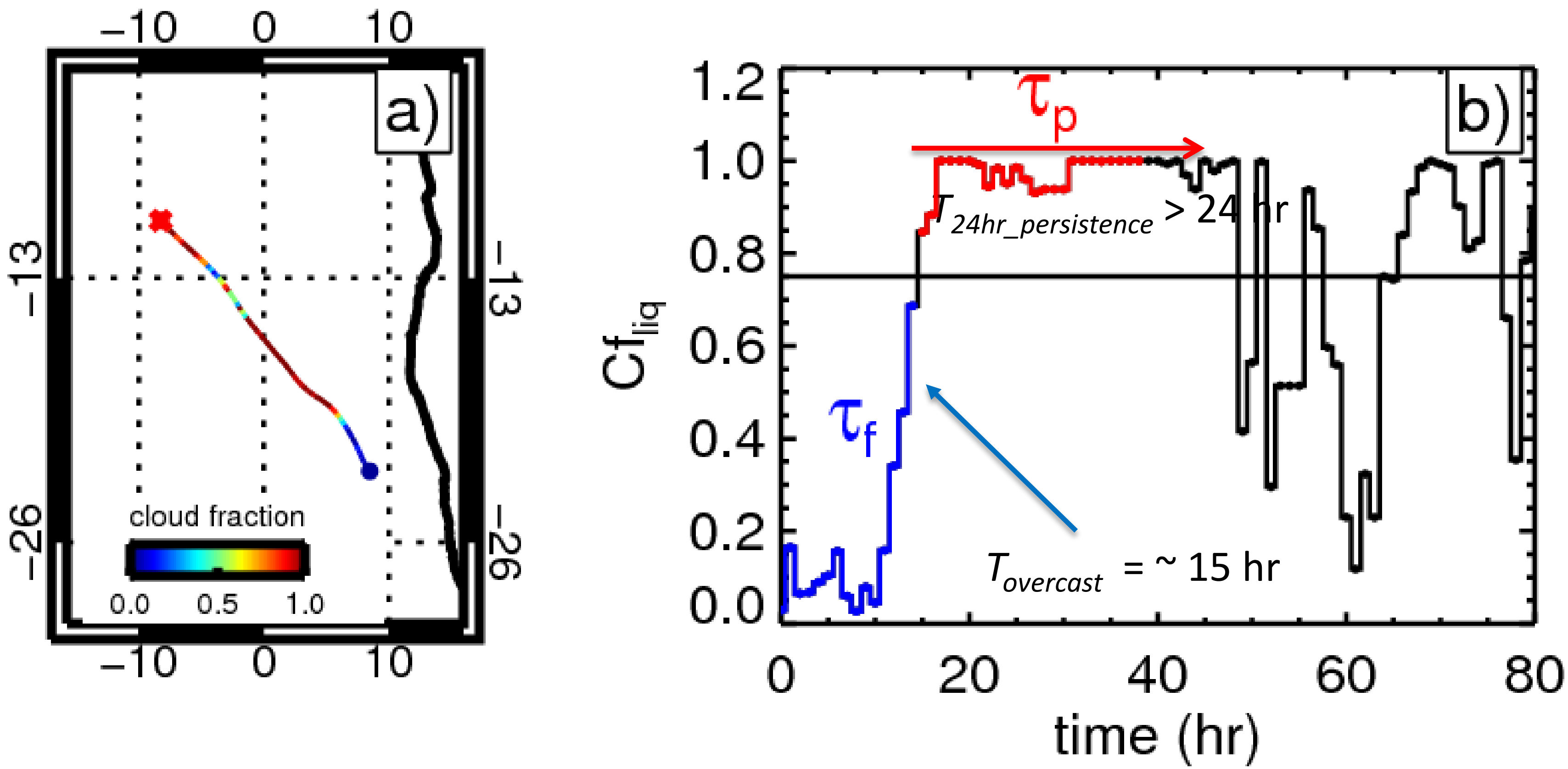
- Cloud fraction increase is largest under stable atmospheric conditions.
  - Vertical development limited to depth of boundary layer.
  - Unstable atmospheric conditions are very dry



LTS composites (50,000)



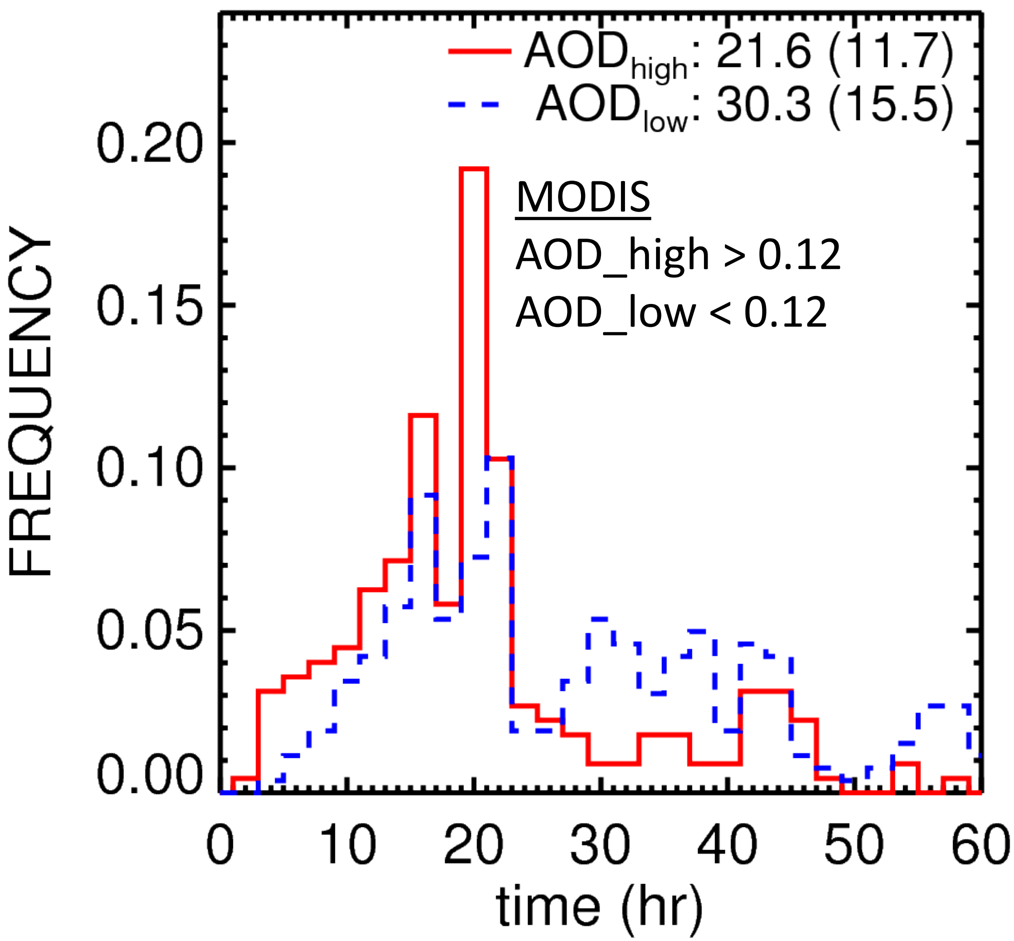
Aerosol-Cloud Lifetime Effect



- All trajectories start off with cloud fraction less than 25%.
- $T_{overcast}$: timescale for cloud fraction to increase to 75%
- $T_{24hr\_persistence}$: timescale for cloud fraction to return below 75%

Low-Cloud Onset (Formation)

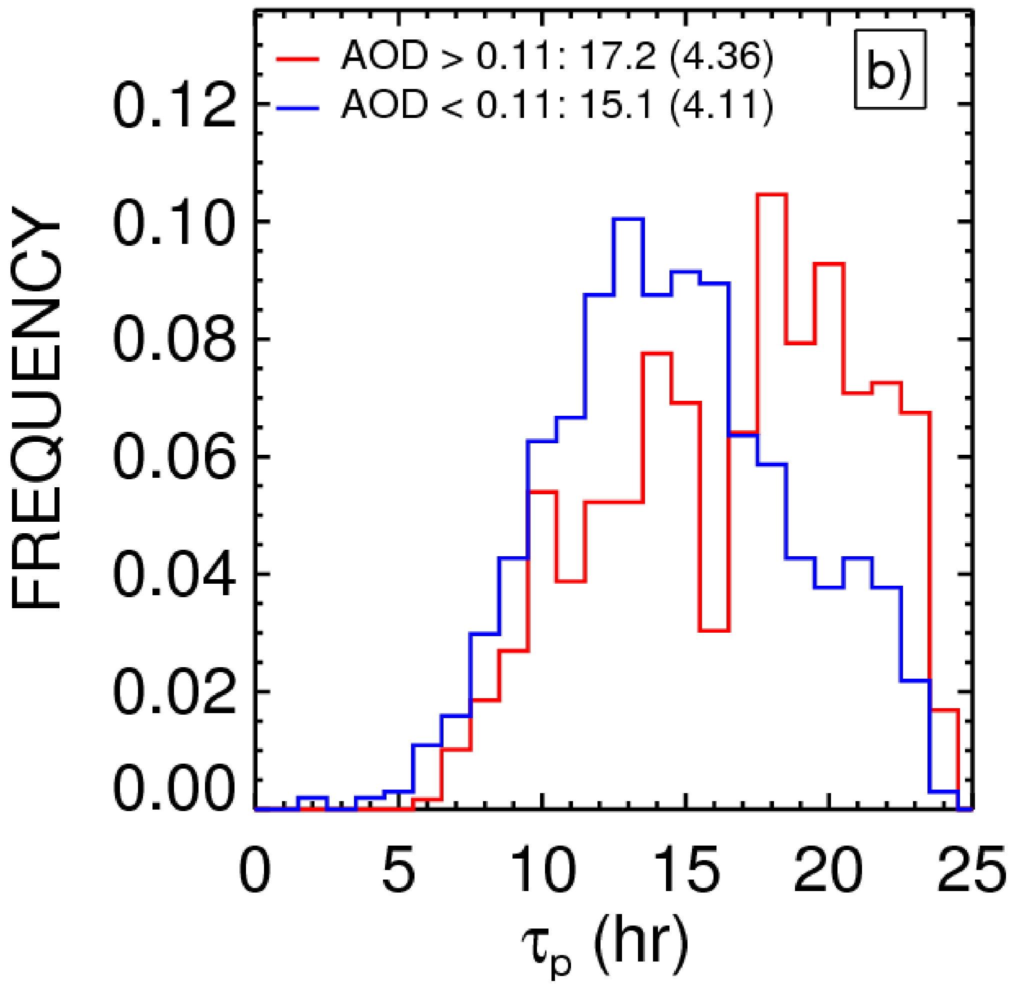
- *Formation* (T_f): timescale of trajectory grid box reaching 75%



- On average it takes approximately 30 hours for the cloud fraction to increase from nearly zero to 75%.
- 13.2% of cases never exceed C_f=.75.
- It takes 9 hours longer for the airmass to become cloudy when the aerosol optical depth is low.

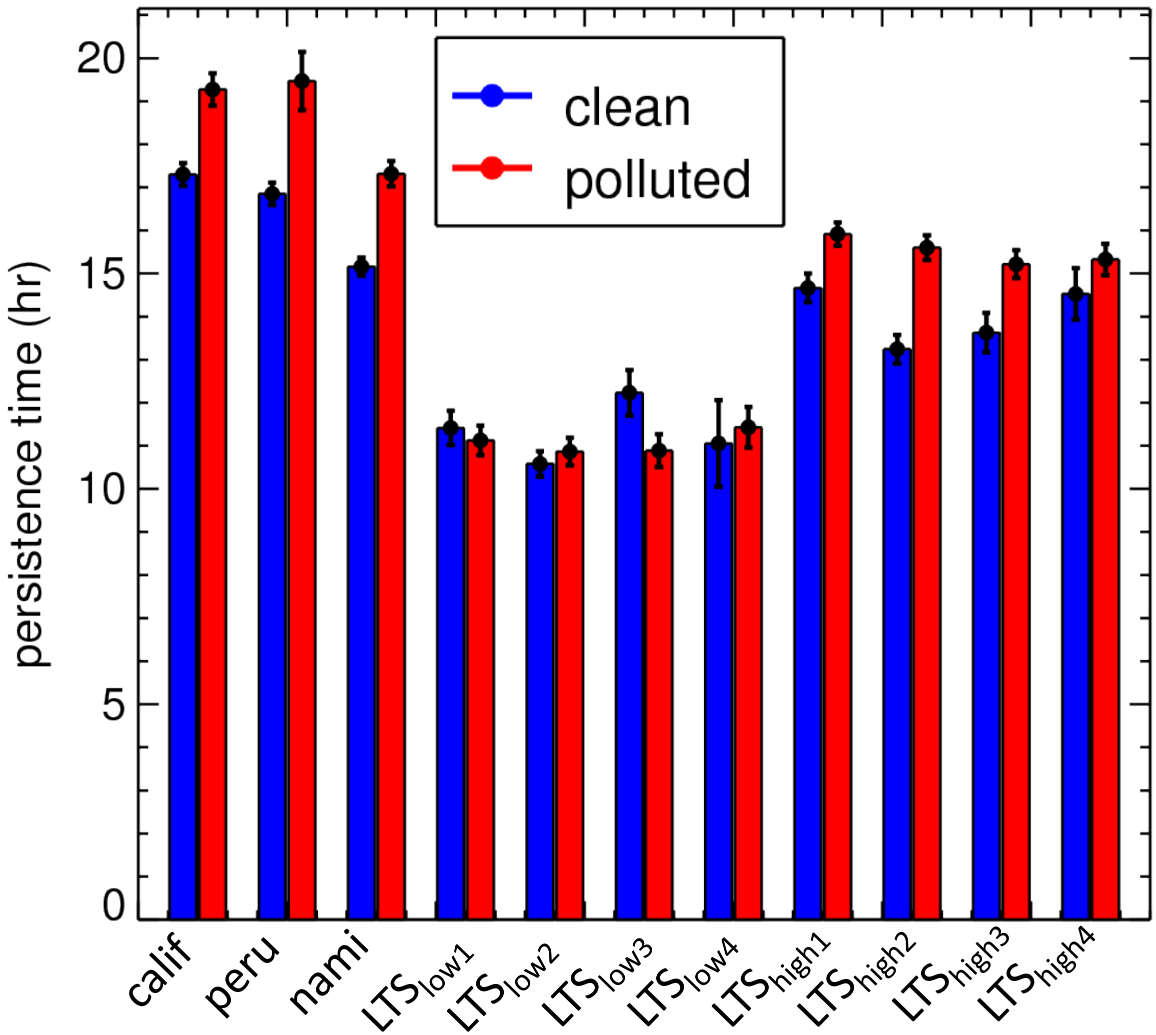
Low-Cloud Persistence

- *Persistence* (T_p): number of overcast hours along trajectory in a 24 hour period after formation



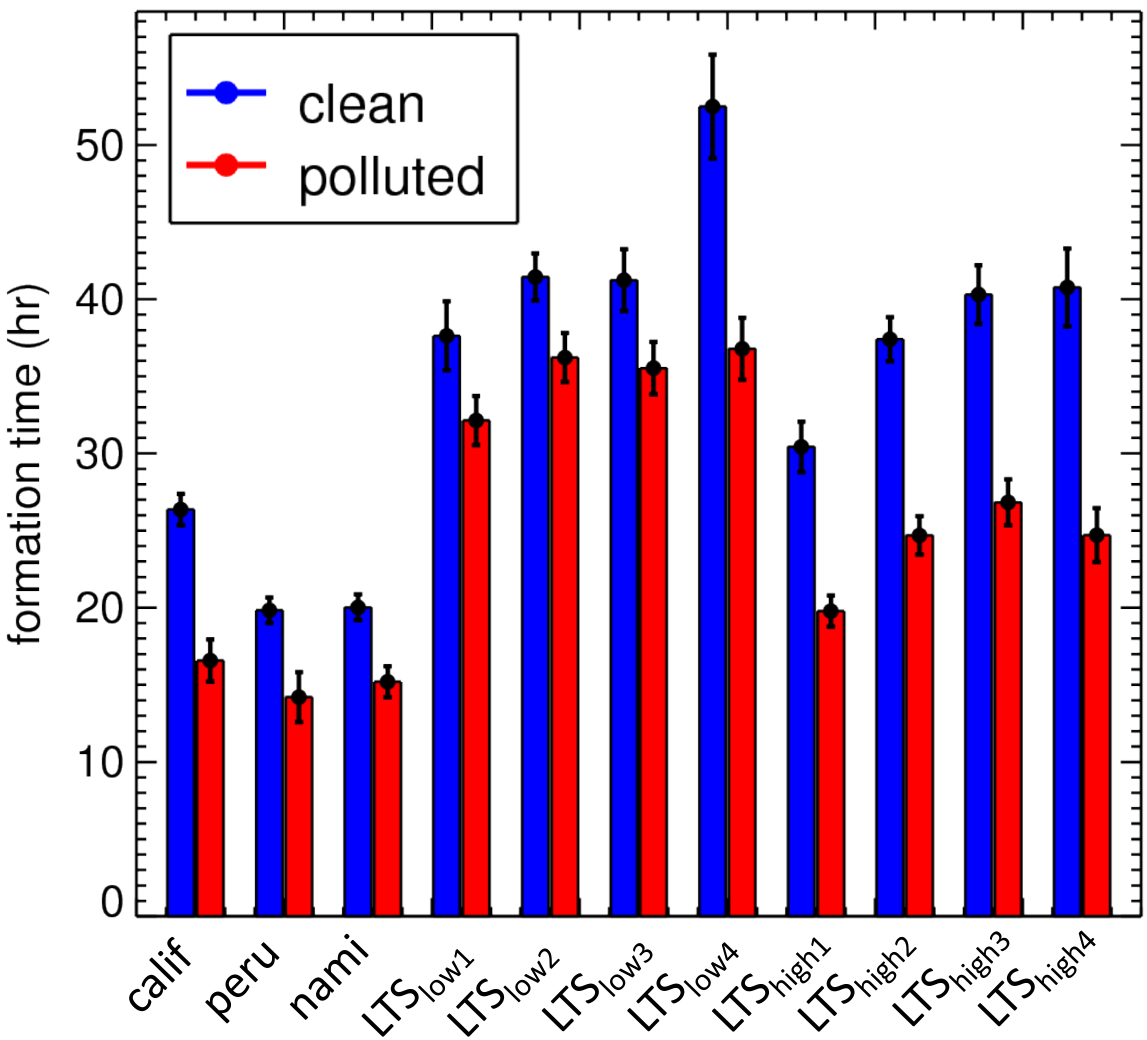
- Clouds persist ~2 hours longer when AOD levels are high.
- ***Meteorology*** affect on cloud lifetime.
  - Mauger and Norris (2007) show that scenes with large AOD and large cloud fraction have origins closer to Europe and experience greater lower tropospheric static stability (LTS) during the past 2 – 3 days than did scenes with small AOD and small cloud fraction.
  - Adebiyi and Zuidema, 2018 show that meteorological co-variation with aerosol loading is small in this region using daily MODIS data.

Global-Scale Assessment



- Stable conditions:
  - Aerosol prolongs cloud lifetime by ~2 hours
- Unstable conditions:
  - Aerosol may lead to less longevity.

Global-Scale Assessment

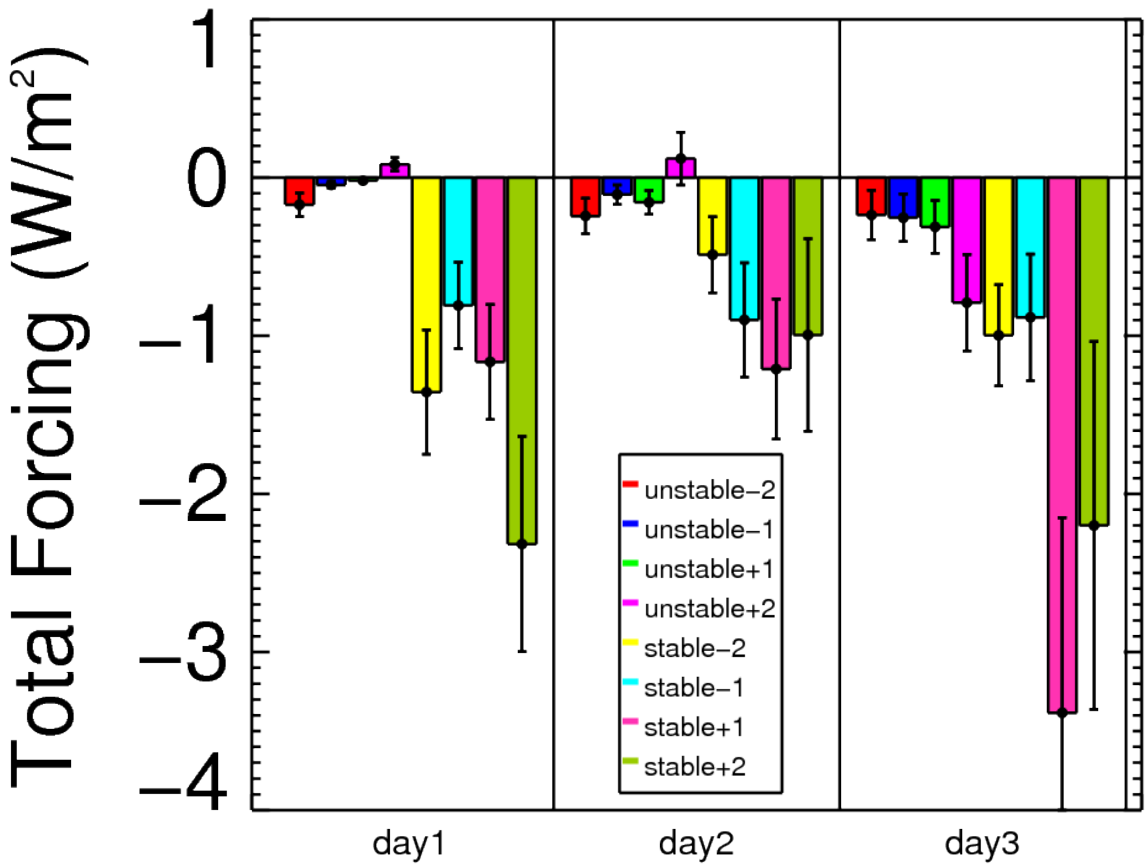


- Cloud forms significantly earlier under polluted conditions (10 hours)
  - Water vapor release from biomass combustion may contribute to higher moisture content (Parmar et al. 2008, ACP).
  - Higher propensity for artefacts in the satellite cloud mask retrieval at high AOD (Remer et al. 2005, AMT).

Radiative Forcing

$$\Delta F_{TOA} = -F^{\downarrow} C\alpha_c(1-\alpha_c)\frac{d\ln N_d}{d\ln AOD}\left(\frac{1}{3}+\frac{5}{6}\frac{\Delta\ln\mathcal{L}}{\Delta\ln N_d}+\frac{\Delta\ln C}{\Delta\ln N_d}\right)\Delta\ln AOD_{anth}$$

*see Quaas et al. (2008), JGR for derivation



Radiative forcing largest under stable atmospheric conditions.

LWP and CF adjustments add to about 40% of the total response.

Radiative forcing remains roughly constant as a function of time along trajectories. .

Summary

- Lagrangian trajectory modeling was combined with satellite data to study the time-dependent properties of the aerosol-cloud system.
  - Geostationary satellite observations can be used to fill in the gaps from polar orbit satellite data.
- An ensemble of lagrangian trajectories show that aerosols enhance the longevity of low-level clouds by about 2 hours.
  - Co-variation of meteorology influences cloud fraction and cloud lifetime particularly in stable atmospheric conditions.
- Forcing calculations indicate that the cloud fraction and Twomey effects are large compared to the liquid water path response.

Radiative Forcing

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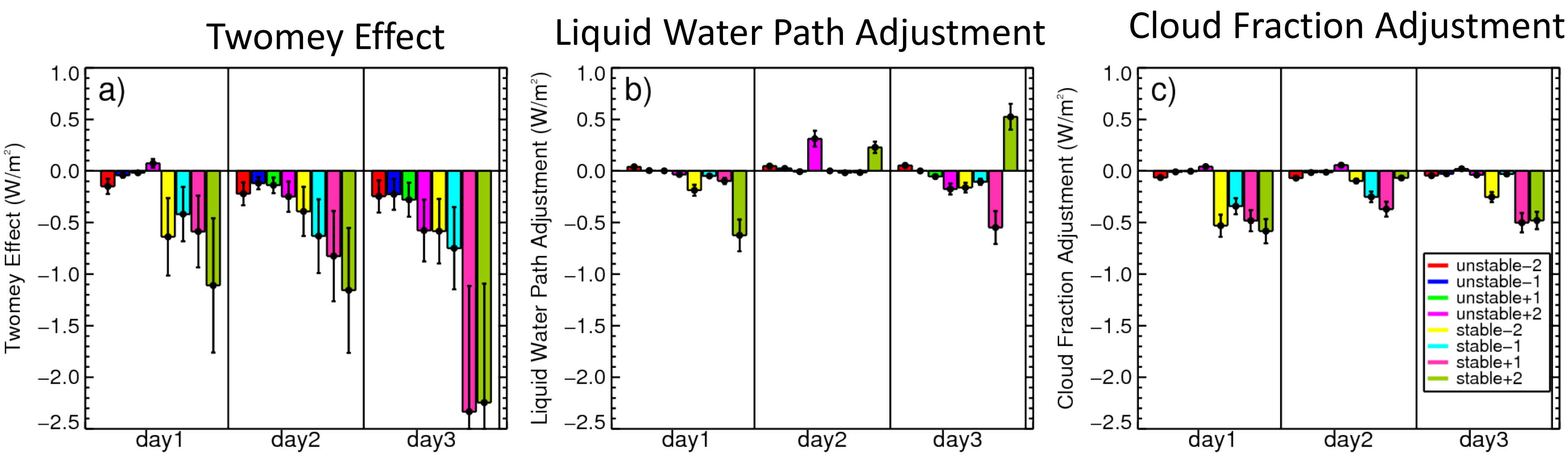
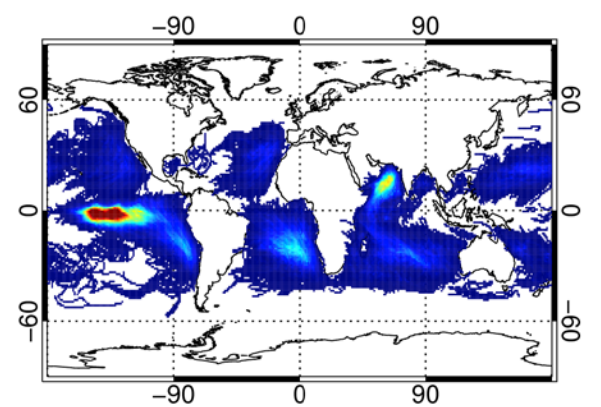


Cloud fraction and liquid water path responses have significant contributions to the total forcing.

- Seifert et al. (2015) deepening leads to a decrease in RH and reduction in cloud lifetime.



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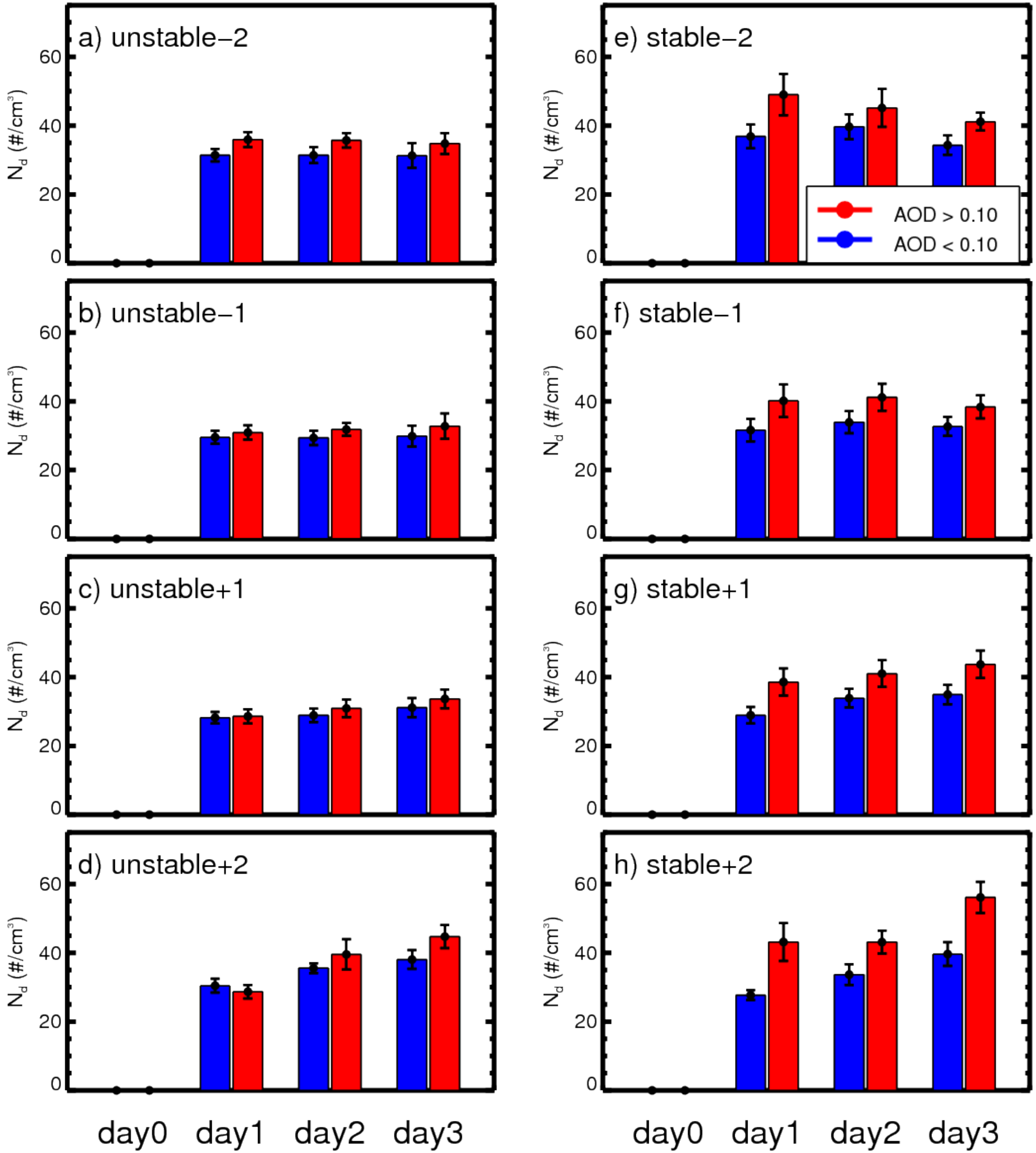
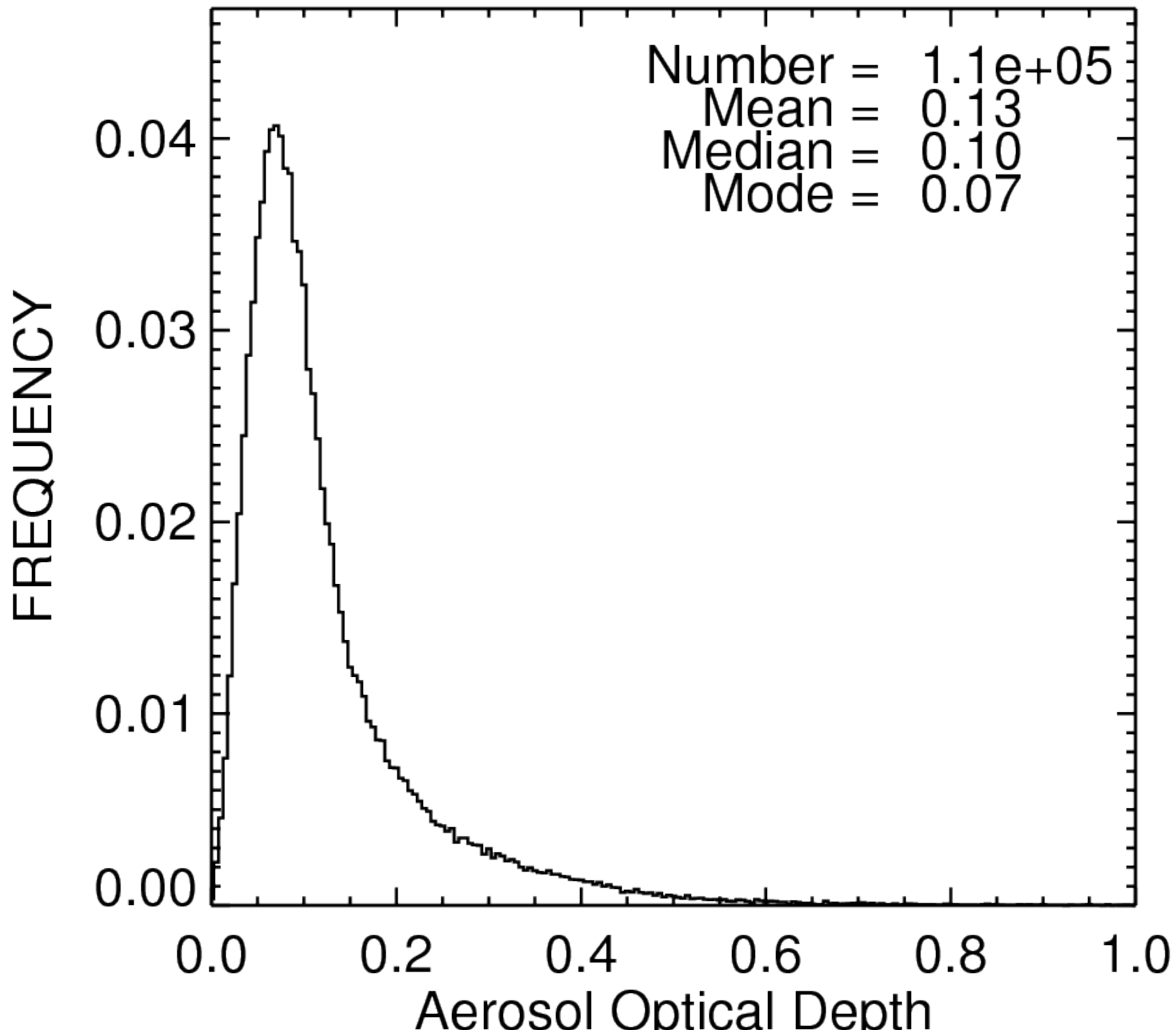


a) unstable−2
b) unstable−1
c) unstable+1
d) unstable+2
e) stable−2
f) stable−1
g) stable+1
h) stable+2
N_d (#/cm³)
0
20
40
60
AOD > 0.10
AOD < 0.10
day0
day1
day2
day3



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0.6
0.8
1.0
Aerosol Optical Depth