A Lagrangian Analysis of the Subtropical Stratocumulus PBL

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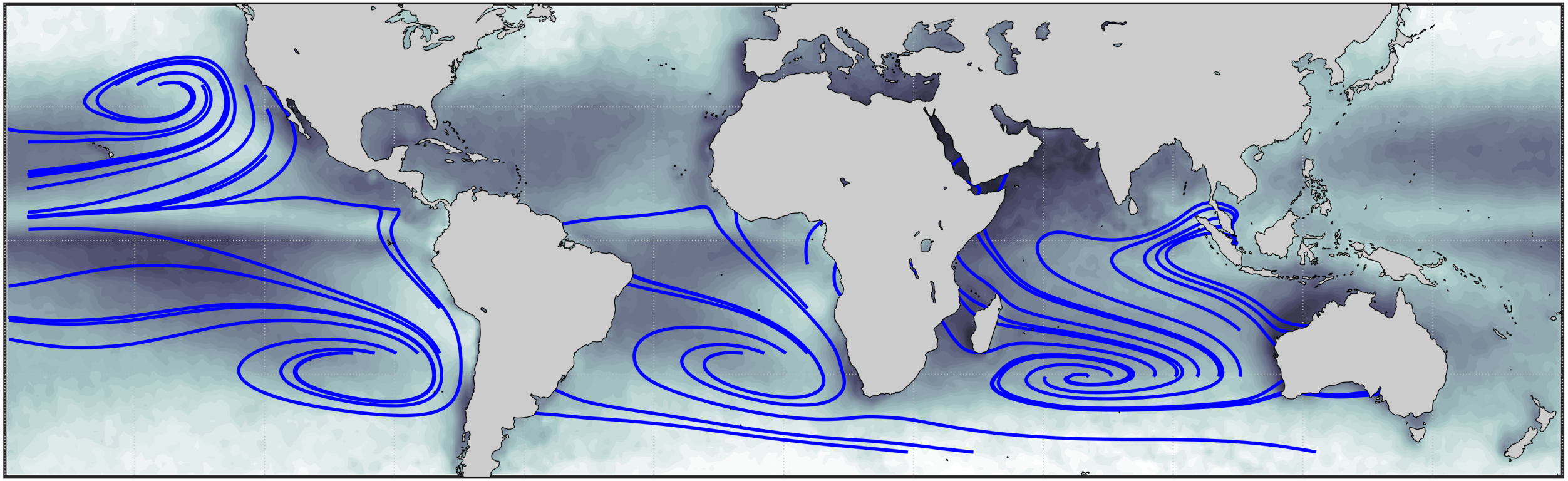
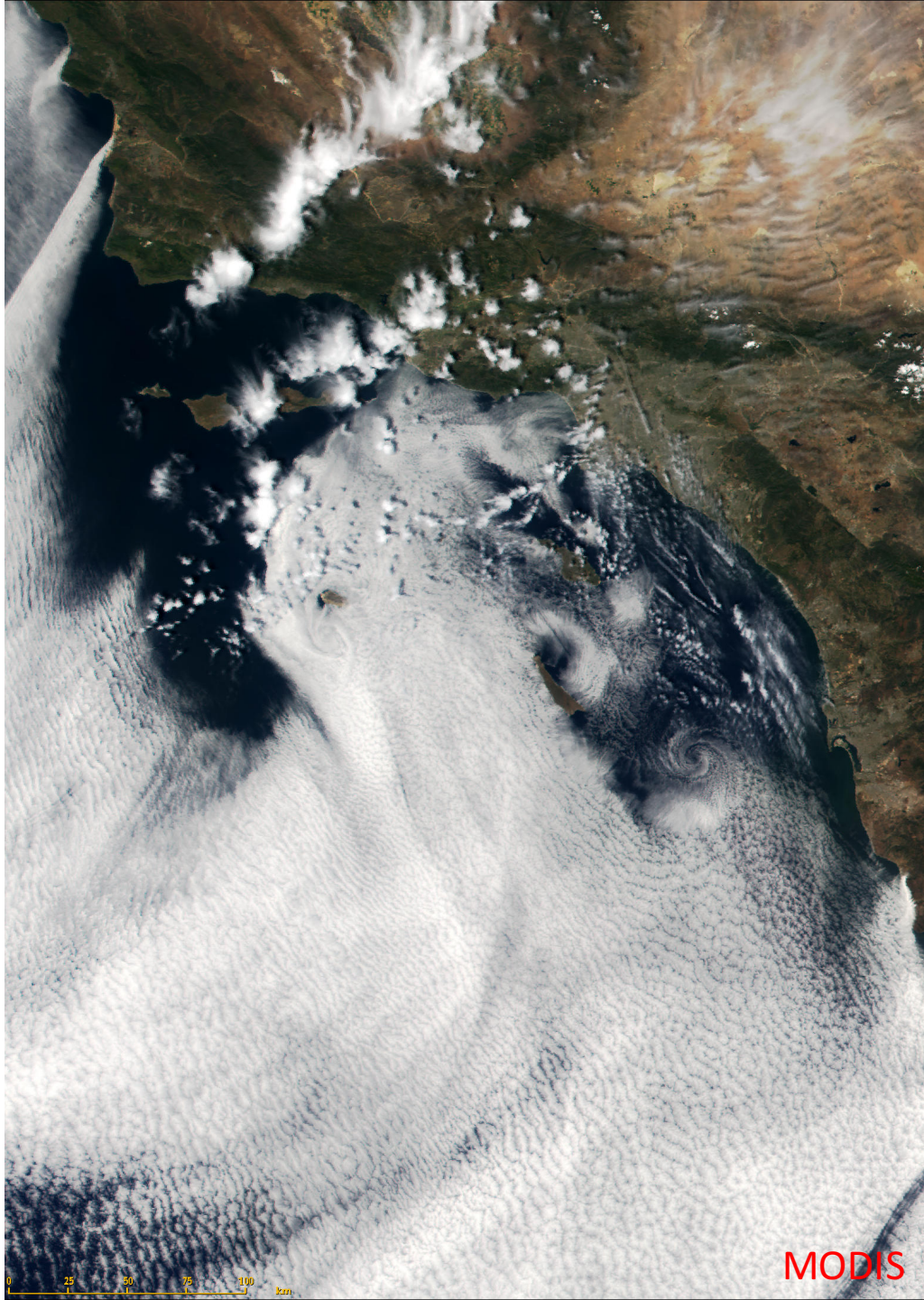
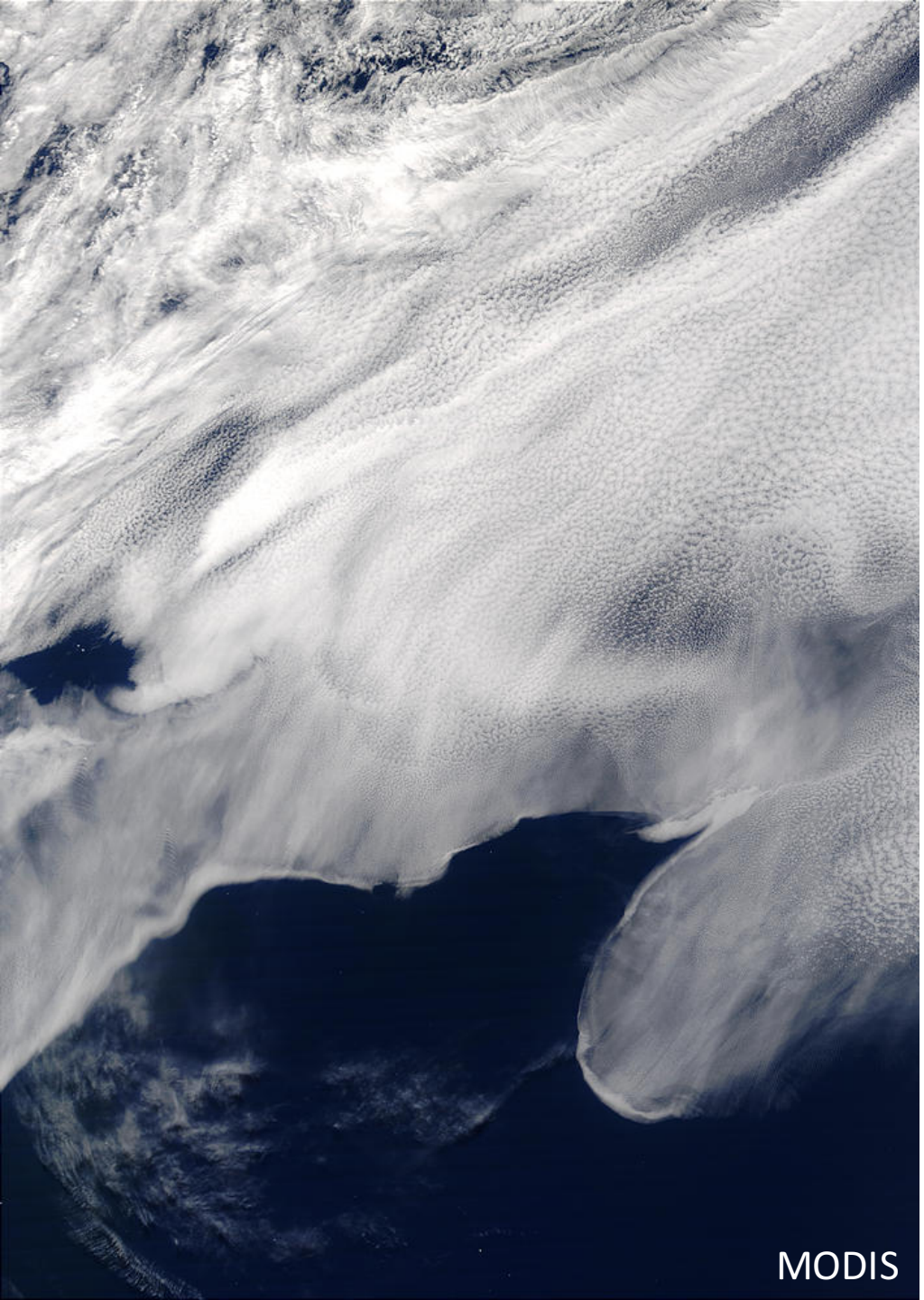
University of Washington, Atmospheric Sciences, NASA A-Train Symposium 2017



Subtropical Stratocumulus (Sc)

- Have a significant cooling effect on Earth's climate:
  - Optically thick, reflecting much of the incoming sunlight
  - Covering a large expanse of an otherwise dark, cool ocean surface
  - Persistent near the equator where sunlight is powerful
  - Emit longwave radiation upward at a high temperature
- Essential that we understand the drivers of their variability



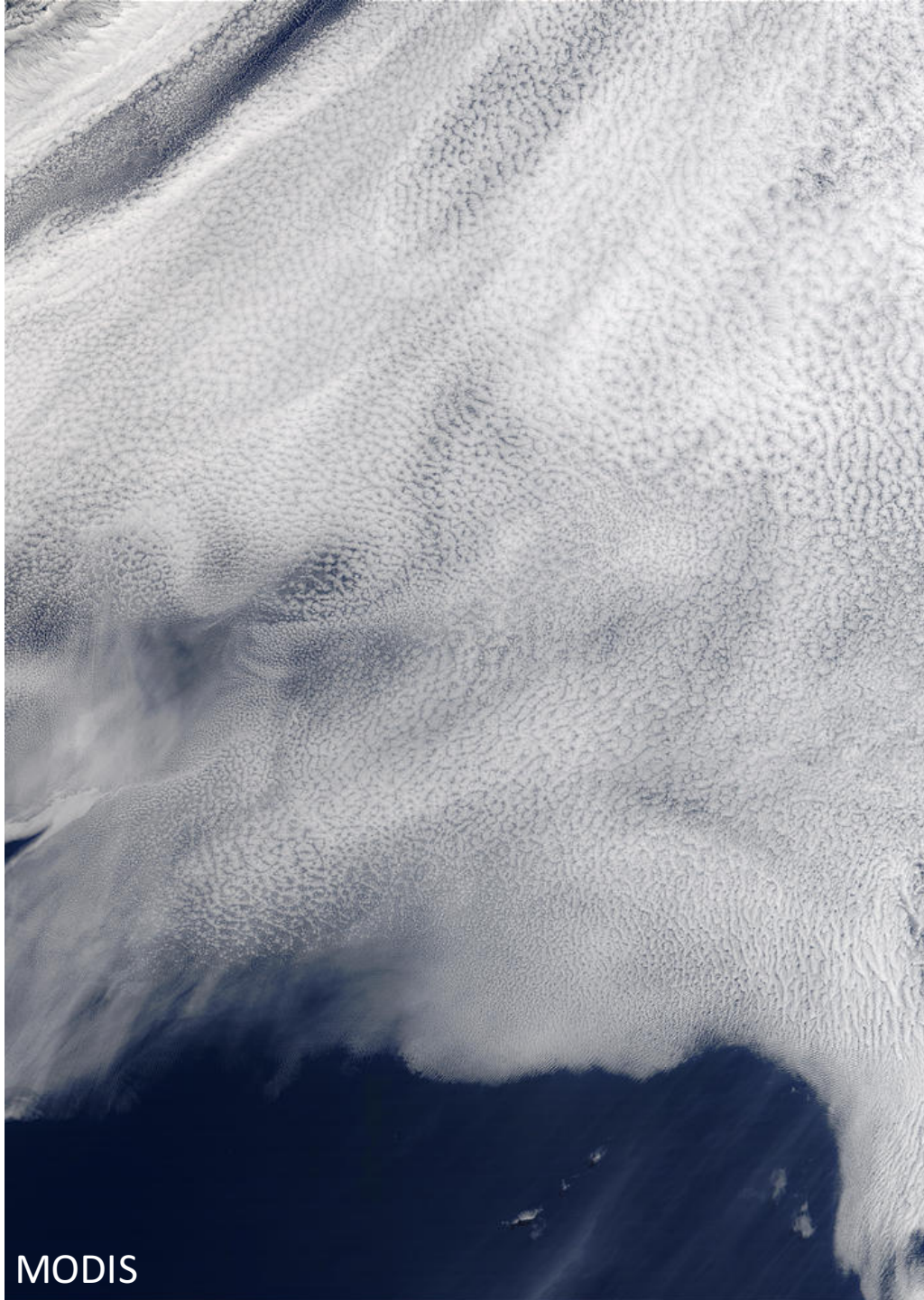


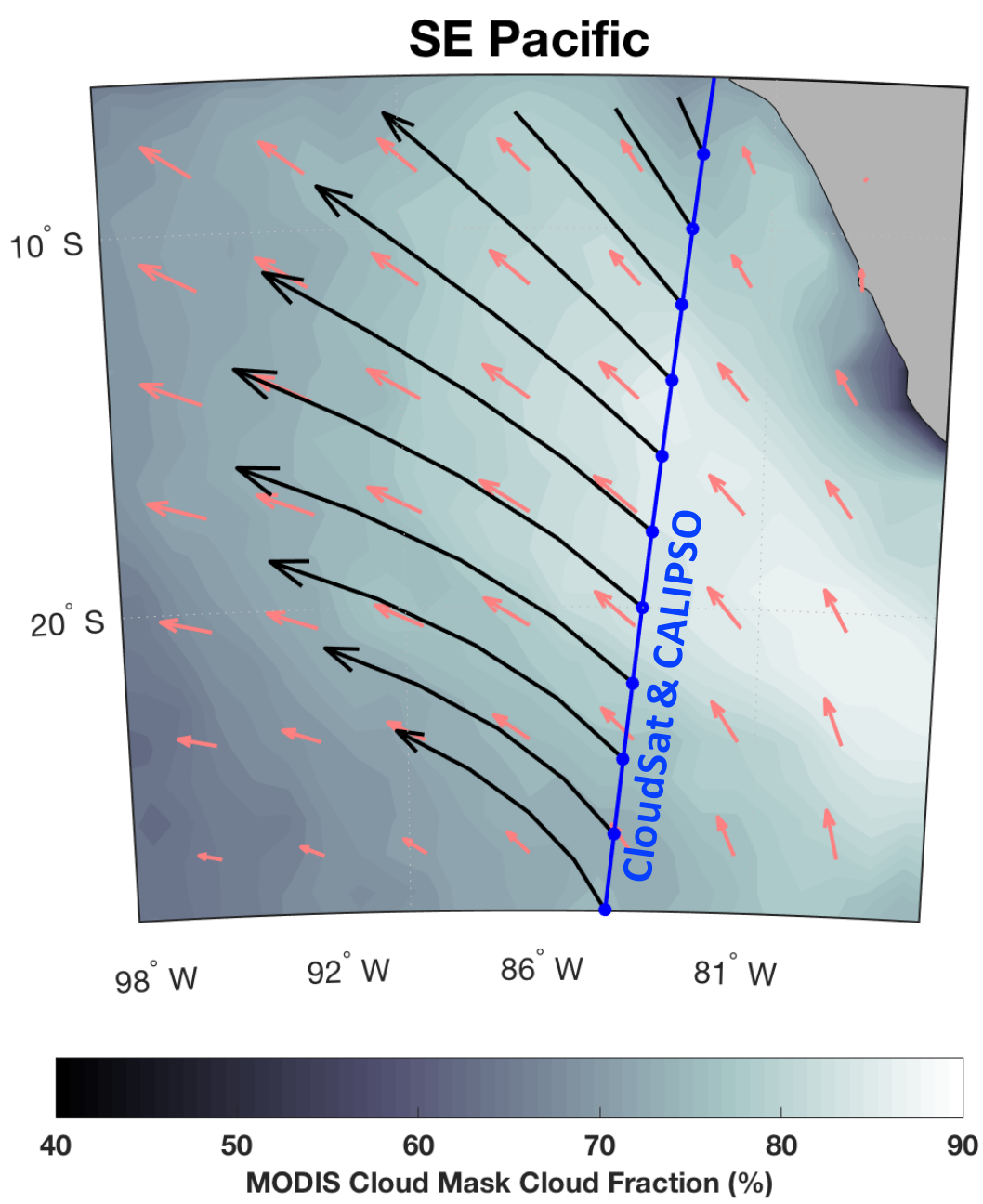
Stratocumulus Climatology

- Clouds persist under a strong inversion beneath the warm middle troposphere and over the cool sea surface in offshore, equatorward flow in eastern ocean basins
  - Initially form shallow, unbroken sheets
  - Deepen & thicken in offshore flow
  - Break up, leaving only shallow cumulus (Cu)
- Persistent cloud circulation sustained by radiative cooling at cloud top
  - Drives a diurnal cycle with more, deeper clouds during nighttime

Stratocumulus Variability

- Subtropical Sc Experience many simultaneous external changes as they advect offshore and equatorward
  - Increased SST, decreased inversion strength, decreased subsidence, increased upper-level humidity
- Corresponding Internal changes also take place
  - Deepening planetary boundary layer (PBL) & thermodynamic decoupling, spikes in precipitation and liquid water path (LWP), declining droplet concentration (Nd)

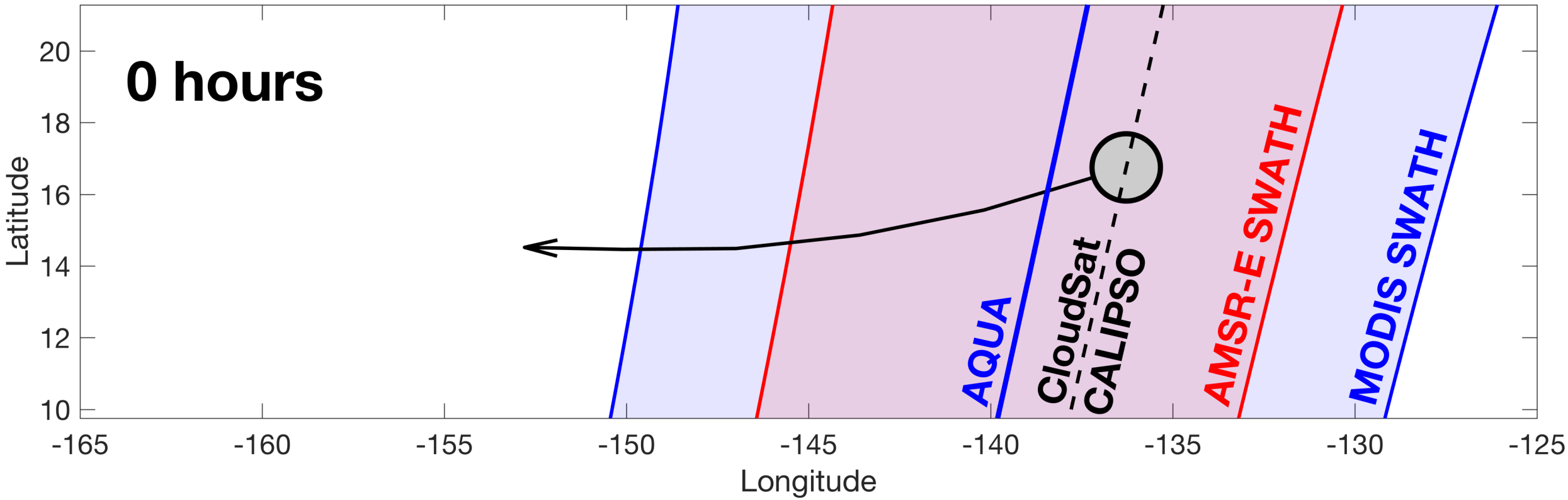




A Lagrangian Approach

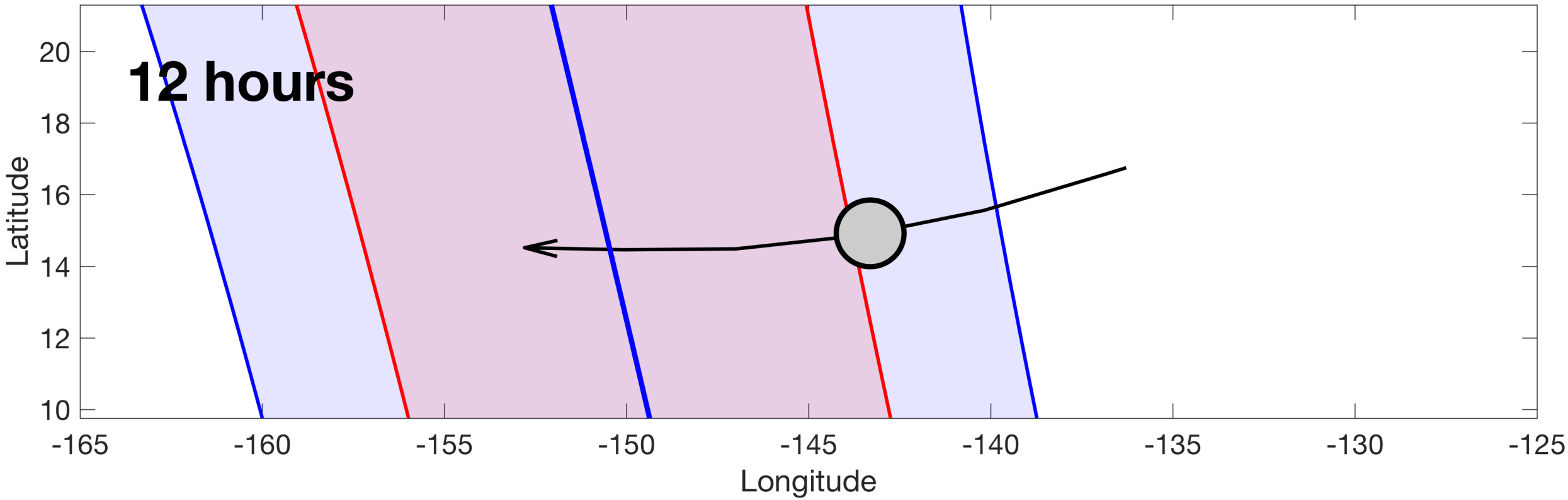
- Clouds decks are in motion flowing offshore
- Clouds are constantly adjusting to perturbations from above and below the boundary layer
  - ie. Temperature, Humidity, Subsidence, which are not following the flow
  - Internal PBL processes may take several hours or even days to fully adjust
  - A static "Eulerian" approach will fail to observe the effects of perturbations, which may manifest 10's or 100's of km downwind
- Better to track individual parcels and observe them throughout their evolution

Lagrangian Design



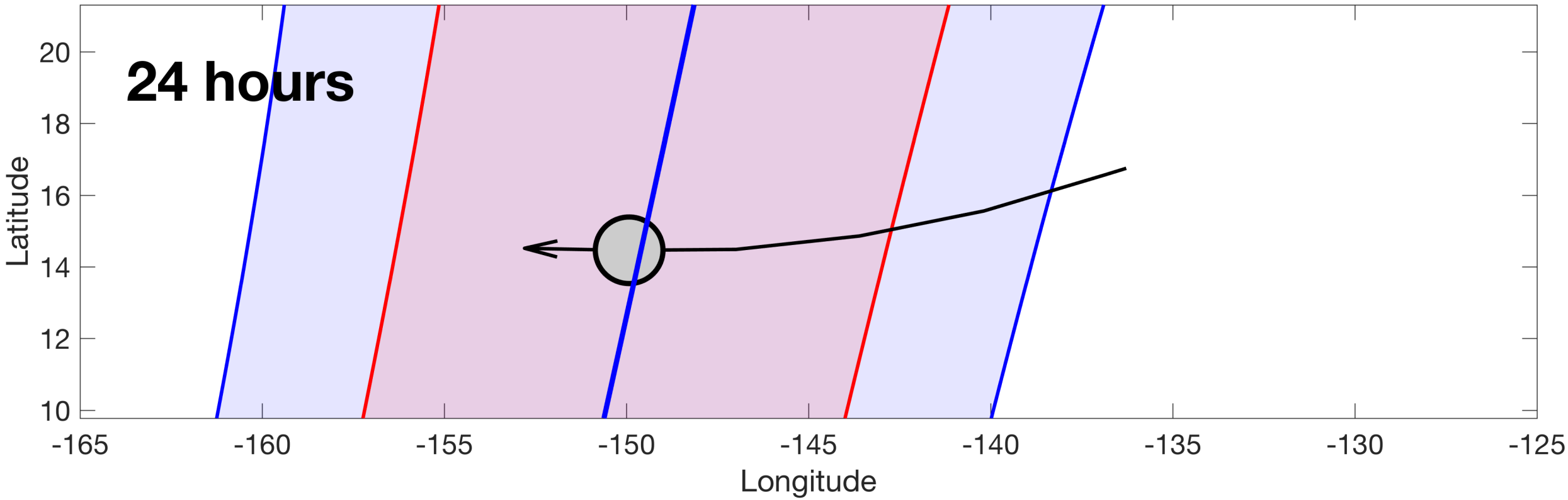
- Trajectories are initiated every 200km along the CloudSat/CALIPSO track.
  - 0-hour precipitation is measured by CloudSat within a <u>100km observing radius</u>
  - PBL Depth is measured by CALIPSO & MODIS
  - Cloud properties are measured by MODIS and AMSR-E

Lagrangian Design



- A second observation is made with the next A-Train flyover after following the 2-D winds at 925mb for 12 hours
  - Winds from ERA-Interim
  - Cloud properties are measured again by MODIS and AMSR-E (if the observation falls within the instrument swaths)

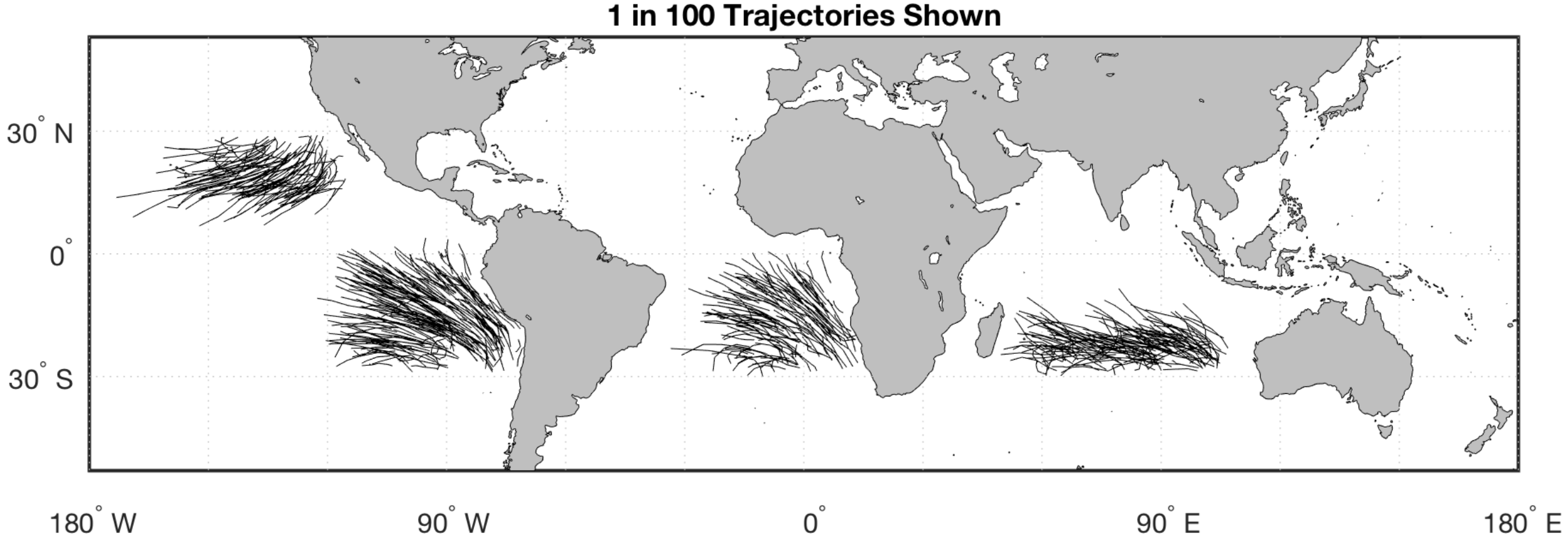
Lagrangian Design



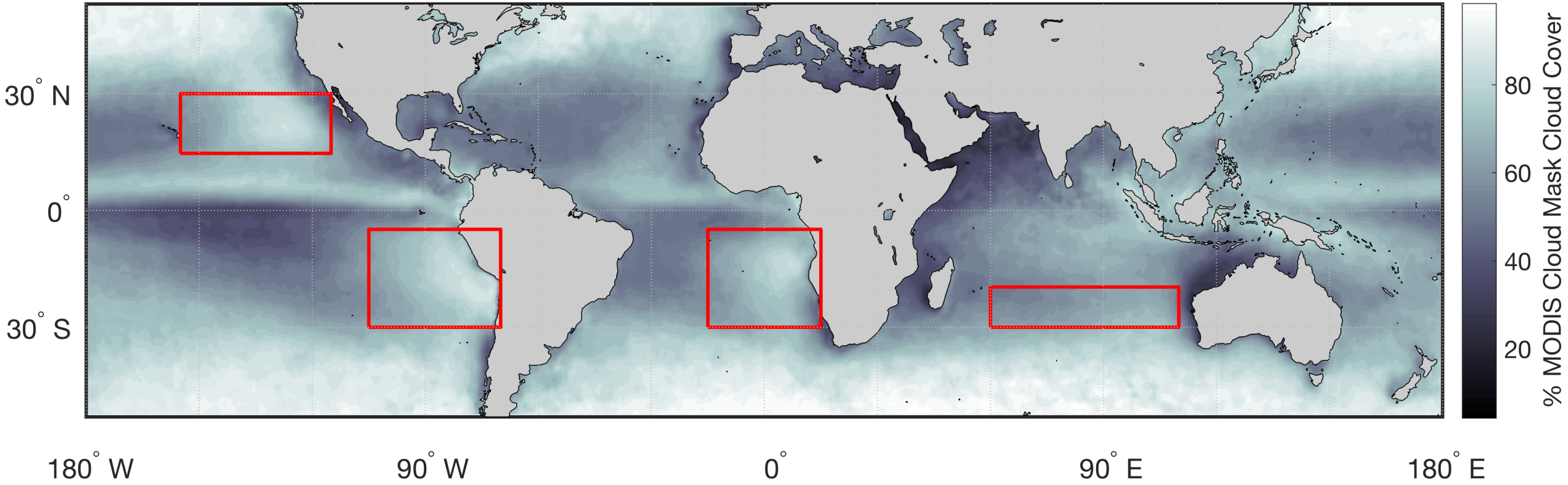
- A third observation is then made at 24 hours with the next A-Train flyover
- Observations are available out to 48 hours, but we focus on 24 hours for improved accuracy and to remove diurnal sampling issues

Lagrangian Design

- 169,824 Trajectories have been computed in four subtropical ocean basins
- The project uses all available data from 2007-2010.

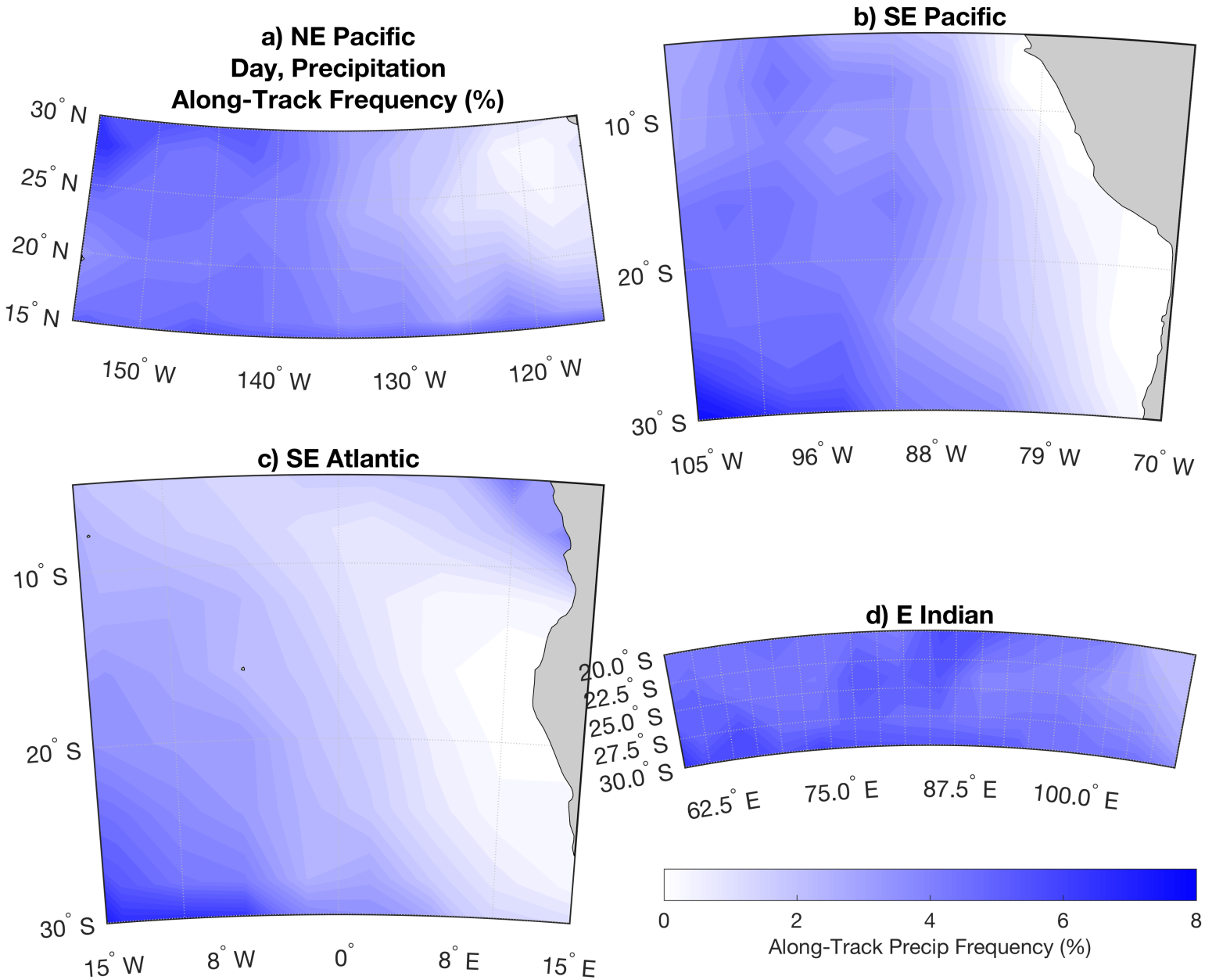


Regions of Study & Satellite Data Products



- Study regions chosen to capture the Sc maximum and the declining gradient further offshore. Ocean areas only.
- Cloud cover comes from MODIS cloud mask for day & night
- All cloud & PBL products are on the MODIS 1°×1° L3 grid, ~1:30 & 13:30 LT

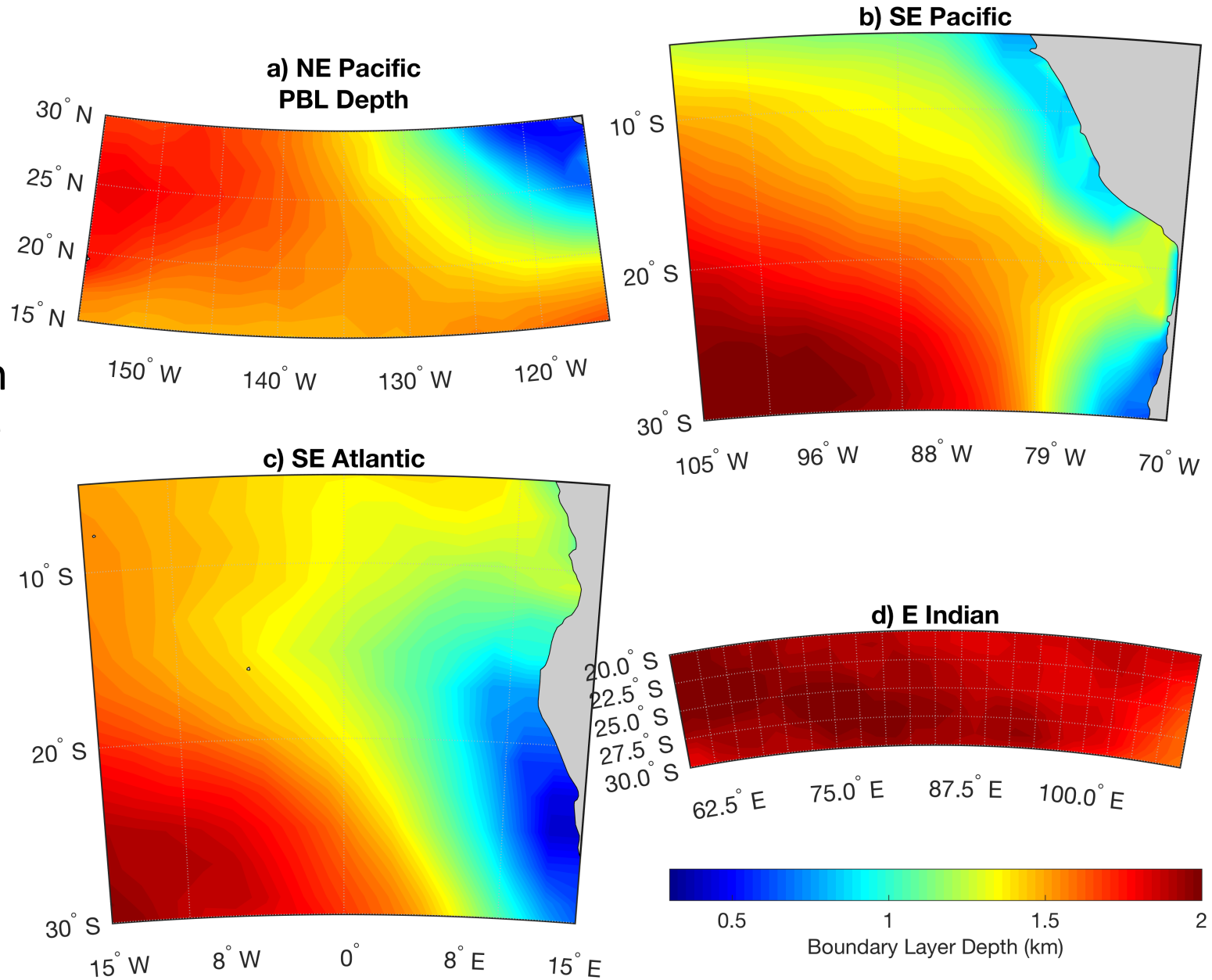
Satellite Data Products: CloudSat Precipitation



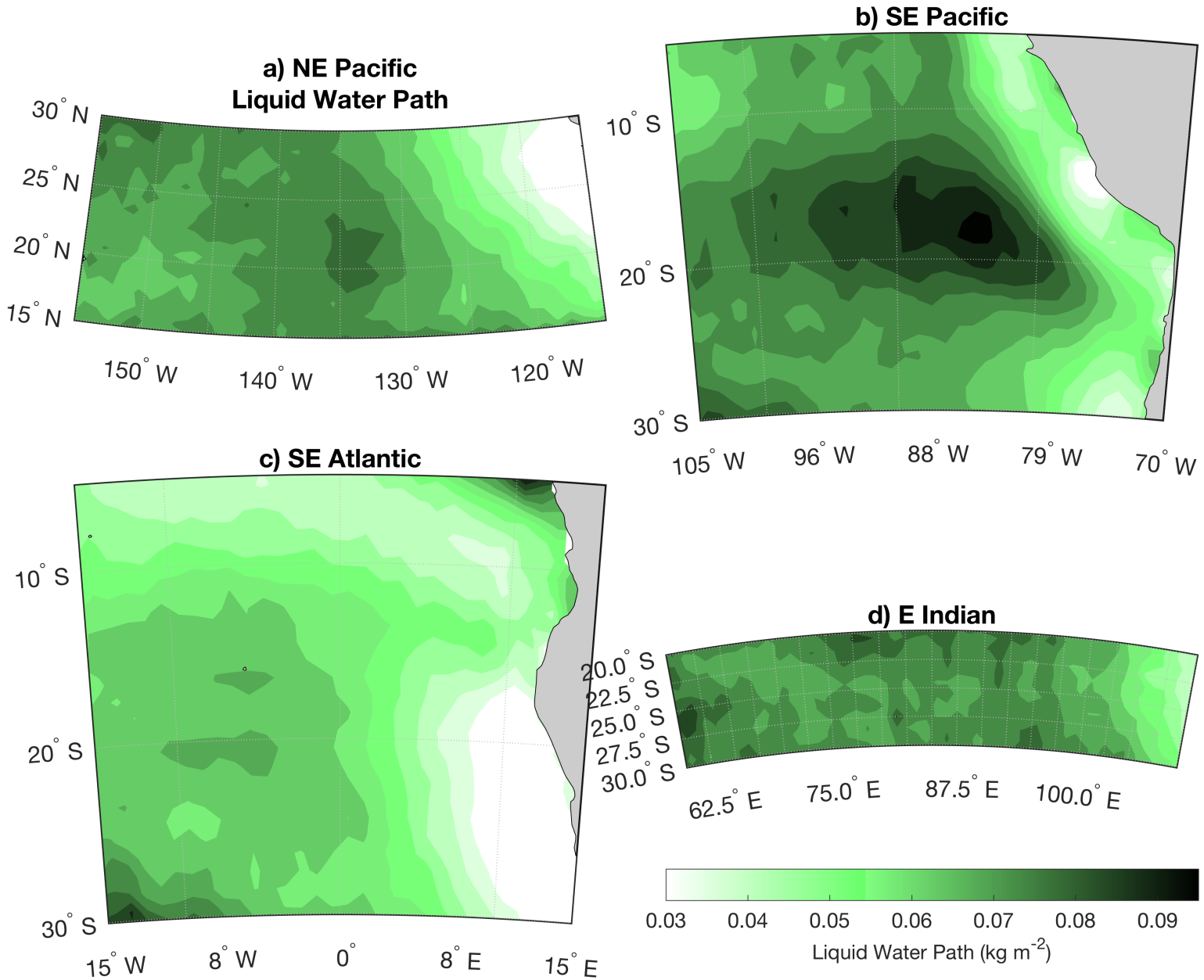
- Rain is measured using the CloudSat Rain_Profile product, detecting rain at the sea surface.
- Showing along-track frequency of precipitation, though rates are also being incorporated into the analysis
- Importance of rain in the evolution/breakup of Sc is still an open question

Satellite Data Products: CALIPSO & MODIS PBL Depth

- Using a routine based on CALIPSO Vertical Feature Mask retrievals co-located with MODIS Aqua Cloud top temperature retrievals.
  - Using the difference between the cloud top and sea surface temperatures and a parameterized lapse rate
  - **Eastman et al. 2017, in review**
- Deeper PBL's have a less 'coupled' circulation from cloud top to sea surface, breaking up more readily



Satellite Data Products: AMSR-E Liquid Water Path

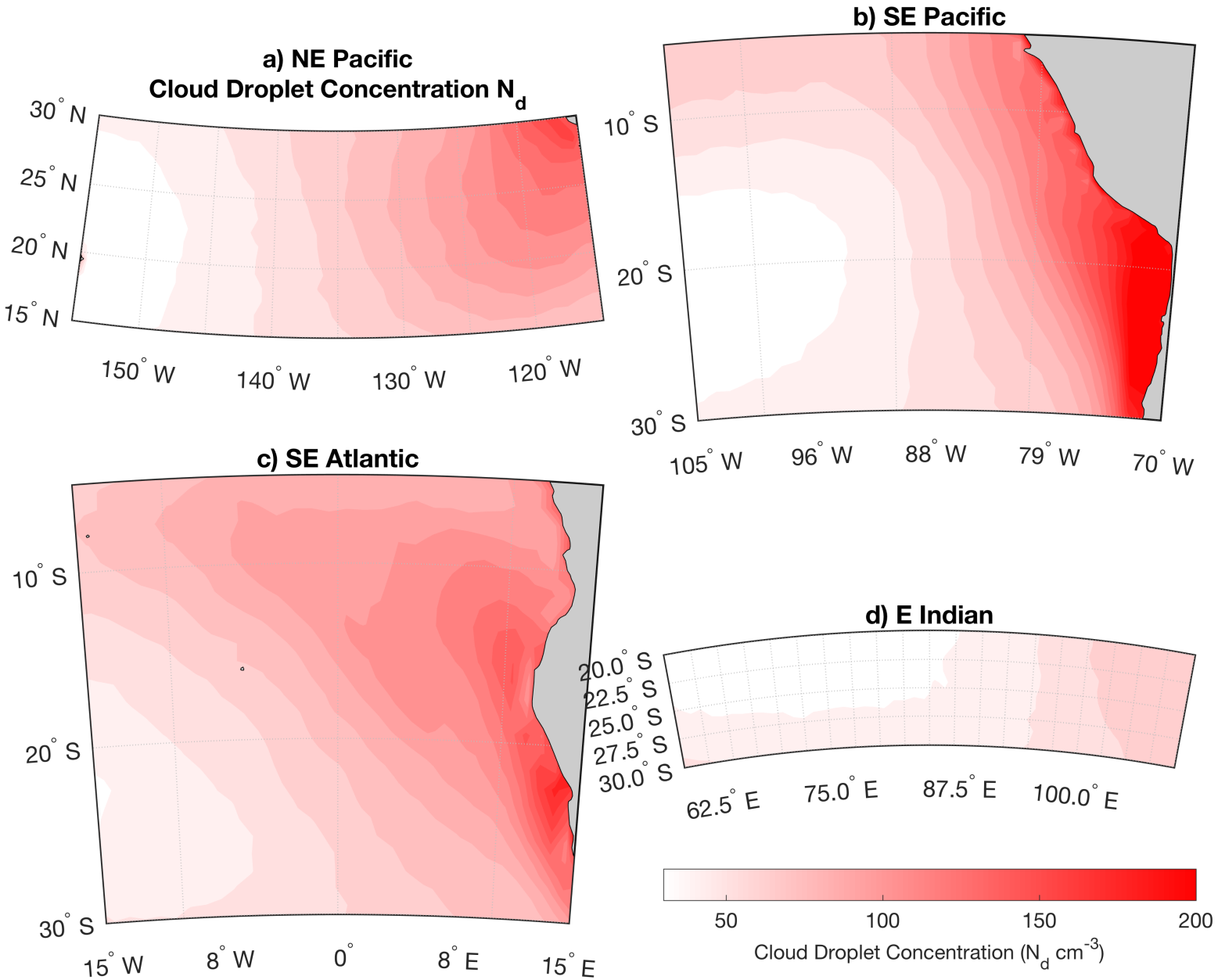


- A liquid water path (LWP) observation co-located with the Aqua MODIS cloud cover product
- Observations averaged from 1/4°×1/4° to the MODIS L3 grid
- Thicker clouds with more liquid water likely have a greater albedo

Satellite Data Products: MODIS Droplet Concentration

$$N_{eff} = \sqrt{2}\,\frac{3}{4}\pi\rho_{\omega}\Gamma_{eff}^{1/2}\,\frac{LWP^{1/2}}{r_e(h)^3}$$

- Derived from two Daytime MODIS Optical Properties (3.7 μm) products: Liquid Water Path (*LWP*) and Effective Radius (r_e)
- Droplet number (N_d) may affect cloud lifetime, precipitation, PBL deepening, and albedo



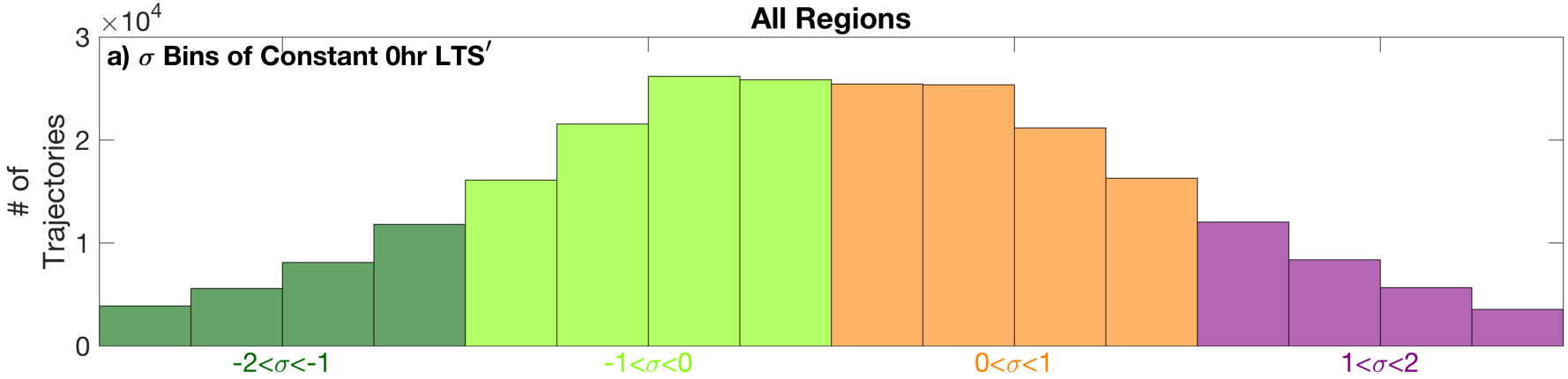
Reanalysis Products External to the Boundary Layer

- Reanalysis data are used for quantities ‘external’ to the boundary layer clouds
- All reanalysis data are from the ERA-Interim
  - Trajectories driven by 2-D winds at 925mb
  - Sea surface temperature (SST) is inferred from surface skin temperature
  - Subsidence (w) is calculated at 700mb by subtracting the surface pressure tendency from the pressure velocity
  - Lower tropospheric stability (LTS) is the difference between the potential temperature at 700mb and the surface temperature
  - Upper level humidity (q) is the specific humidity at 700mb

Overcoming Issues

- Many MODIS products have a sensor zenith angle bias, which is accounted for in our analysis
  - Eastman, R, and R. Wood, 2016: Factors controlling low-cloud evolution over the eastern subtropical oceans: A Lagrangian perspective using the A-Train Satellites. *J. Atmos. Sci.,* **73**, 331-351.
- All variables except precipitation are converted to anomalies to avoid biases caused by geographical differences between trajectories
- 'Residual' cloud cover changes are calculated, which reduce the effects of red noise behavior seen along the trajectories
  - Eastman, R., R. Wood, and C. S. Bretherton, 2016: Time scales of clouds and cloud-controlling variables in subtropical stratocumulus from a Lagrangian perspective. *J. Atmos. Sci*., **73**, 3079-3091.

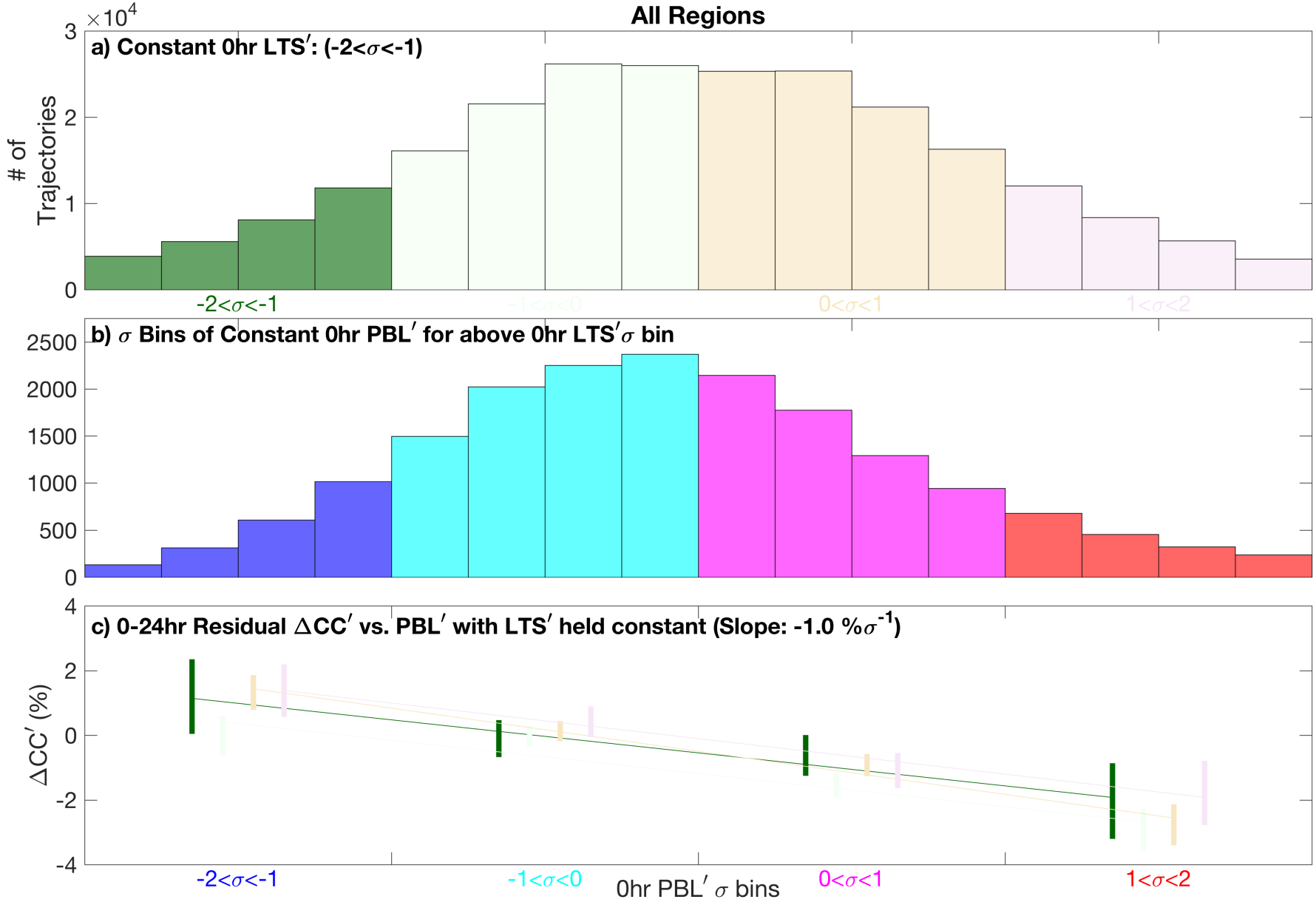
Binning by σ, Controlling for Other Variables



- Cross correlation between variables can lead to false results
  - Two variables may vary in concert with one-another, as in LTS and PBL depth
  - One, or the other, or both may be driving variability
- We can control for cross-correlation by holding a potentially confounding variable constant (LTS), then doing our analysis on the other (PBL depth)
- In order to *compare* the effects of cloud controlling variables, we group our trajectories into bins bounded by the standard deviation (σ) of our controlling variables.

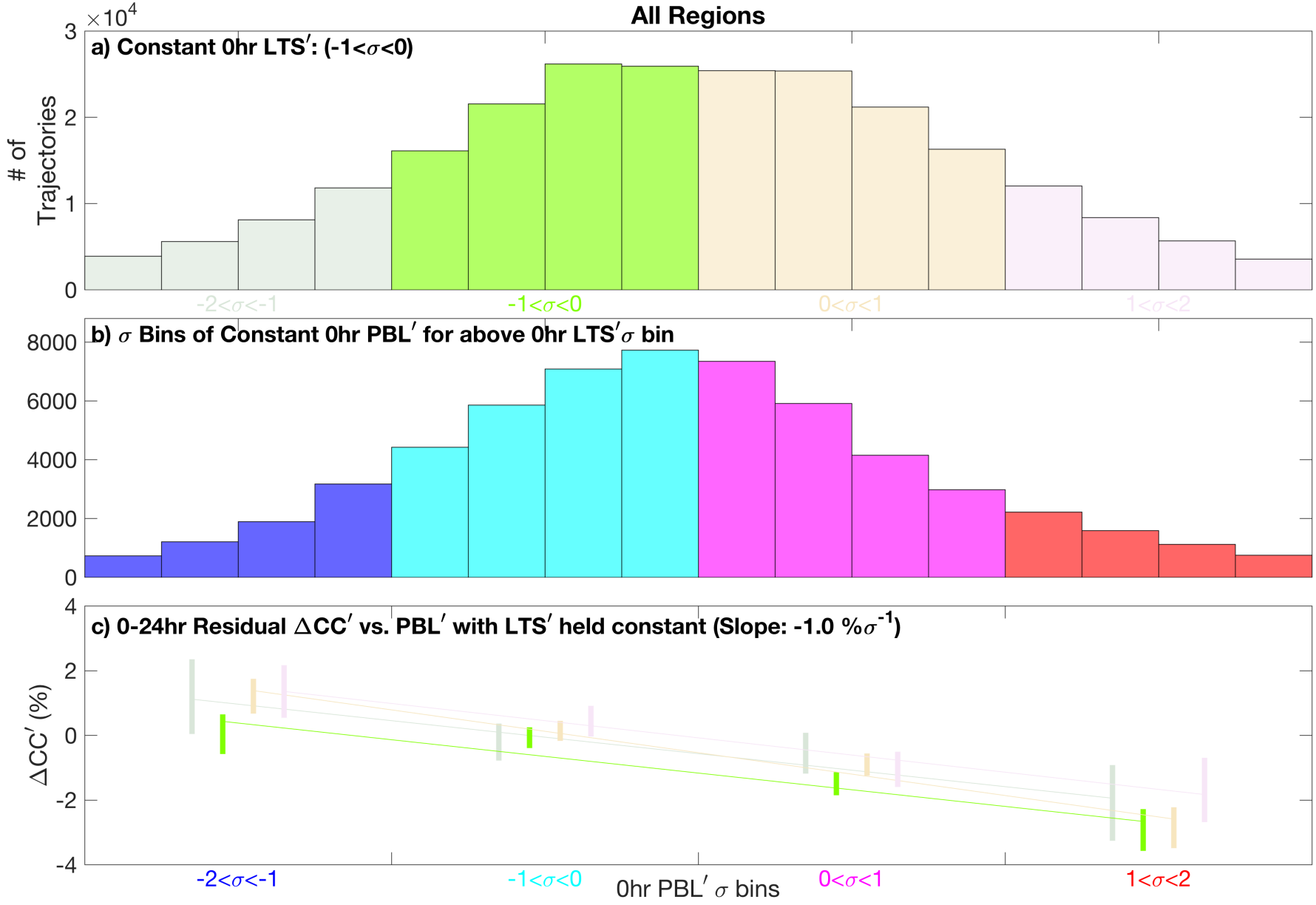
Binning by σ, Controlling for Other Variables

- Holding LTS constant, low stability
- Looking at σ bins of PBL depth anomalies with LTS constant
- Residual change in CC vs. PBL depth for constant low LTS



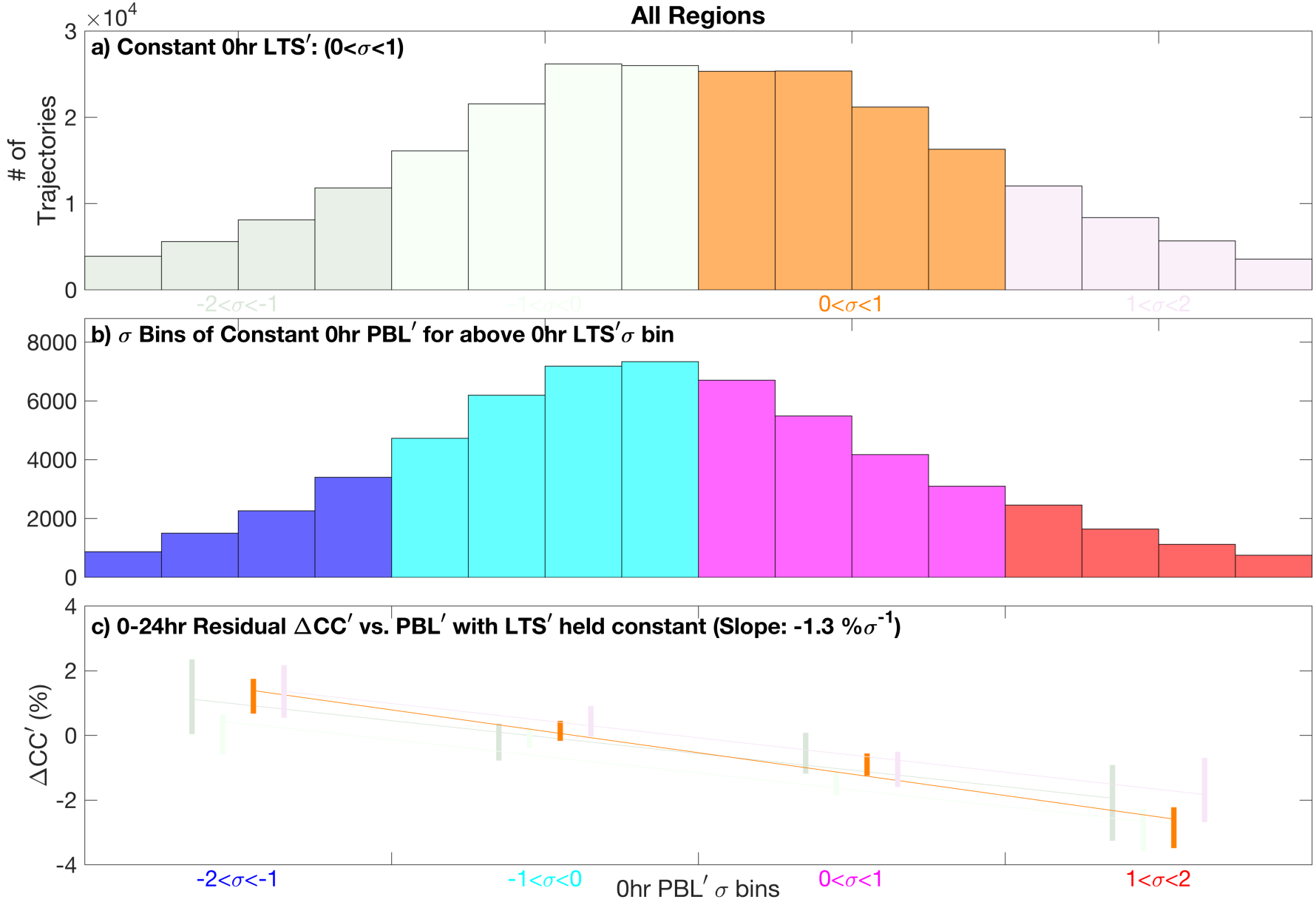
Binning by σ, Controlling for Other Variables

- Middle-low stability



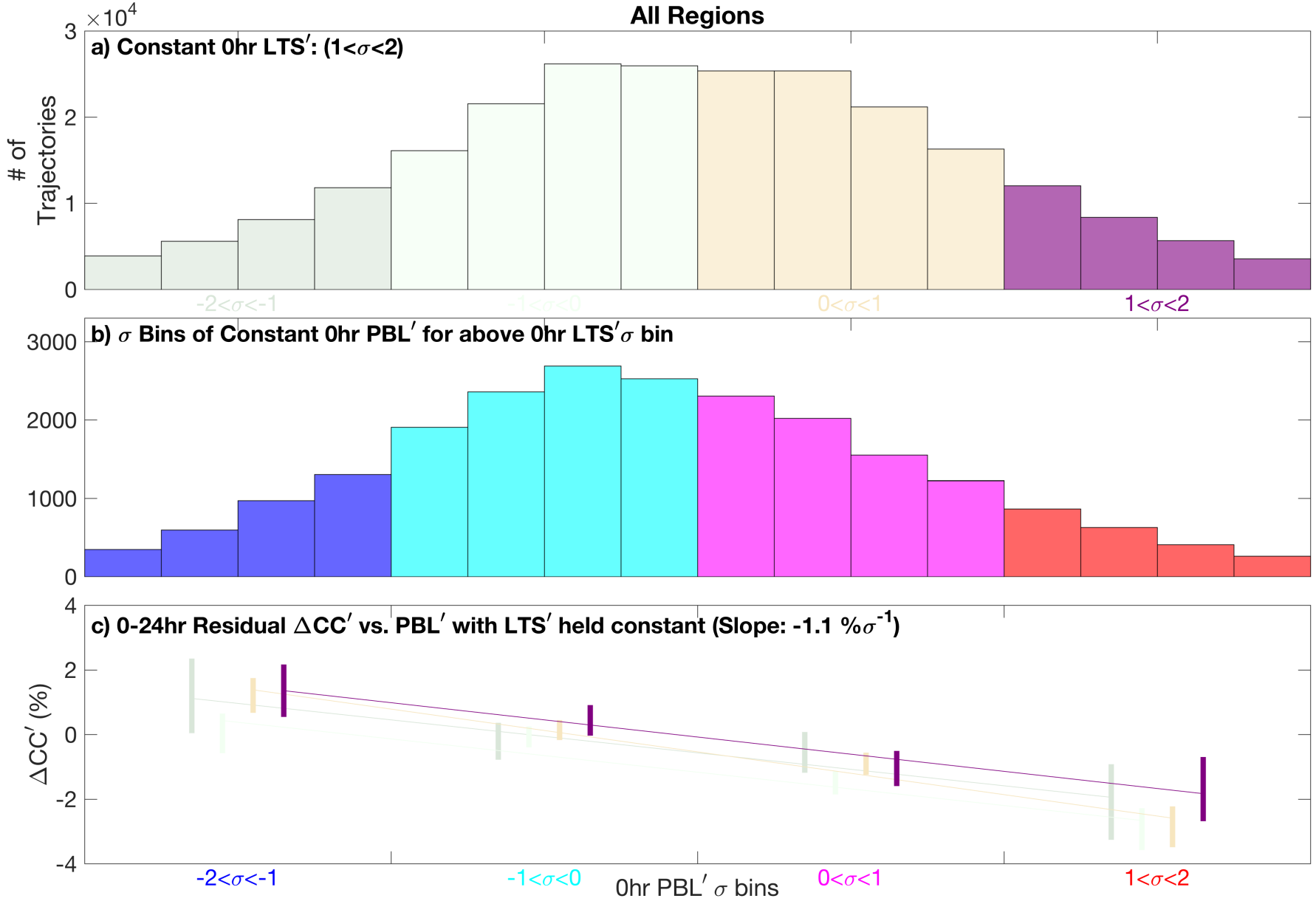
Binning by σ, Controlling for Other Variables

- Middle-high stability



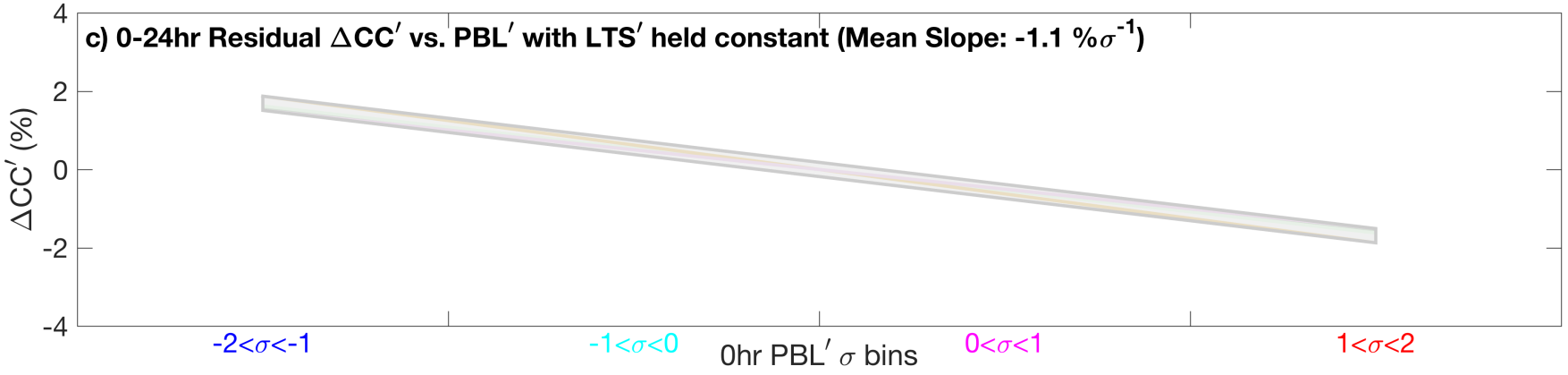
Binning by σ, Controlling for Other Variables

- High Stability



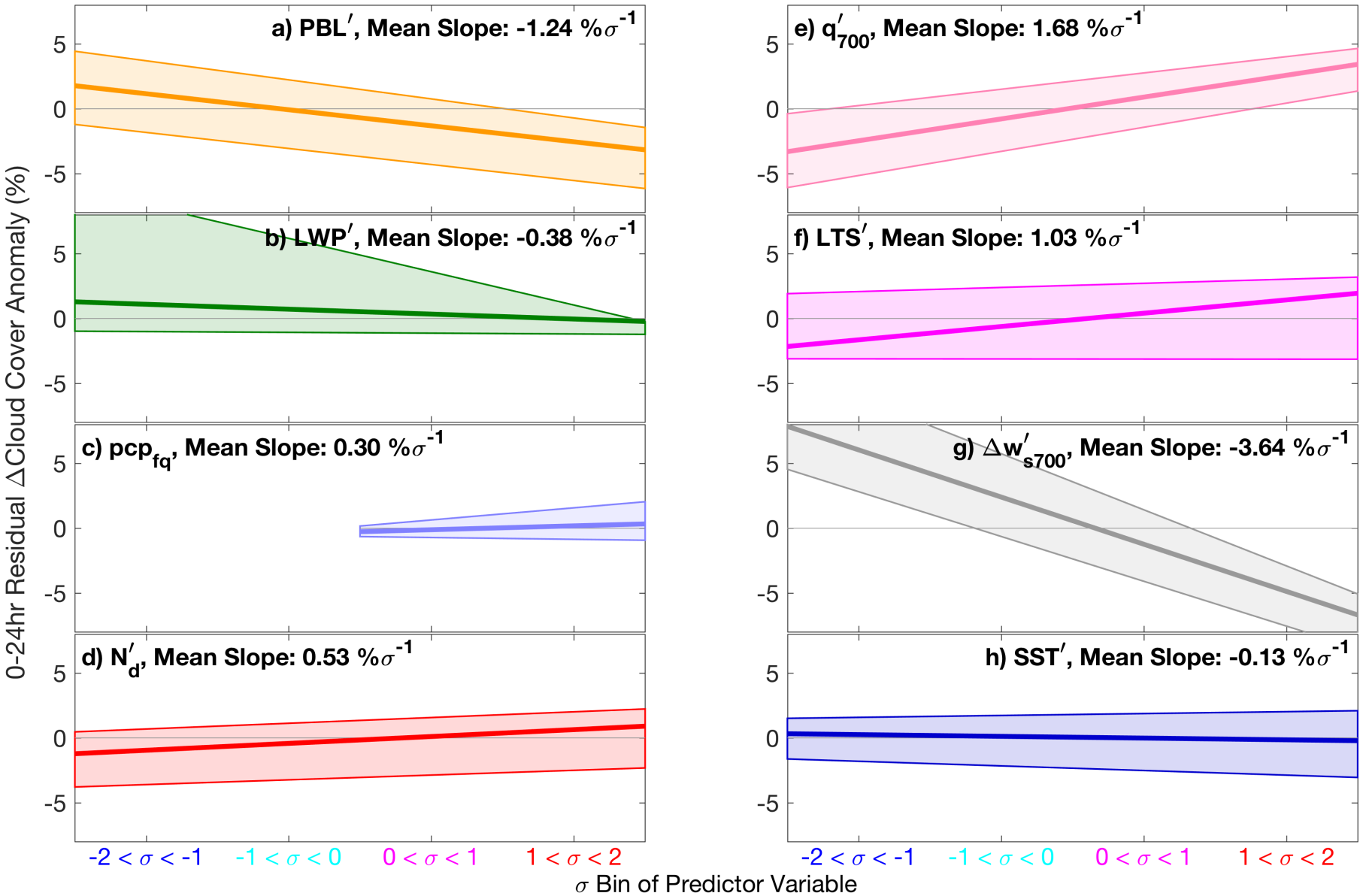
Binning by σ, Controlling for Other Variables

- We assemble a range of slopes for different values of 0-hour LTS
- Deeper PBLs show anomalous Lagrangian declines even after taking coinciding stability anomalies into account
- We can apply this method to all variables to produce ranges of slopes for each after holding all other constant

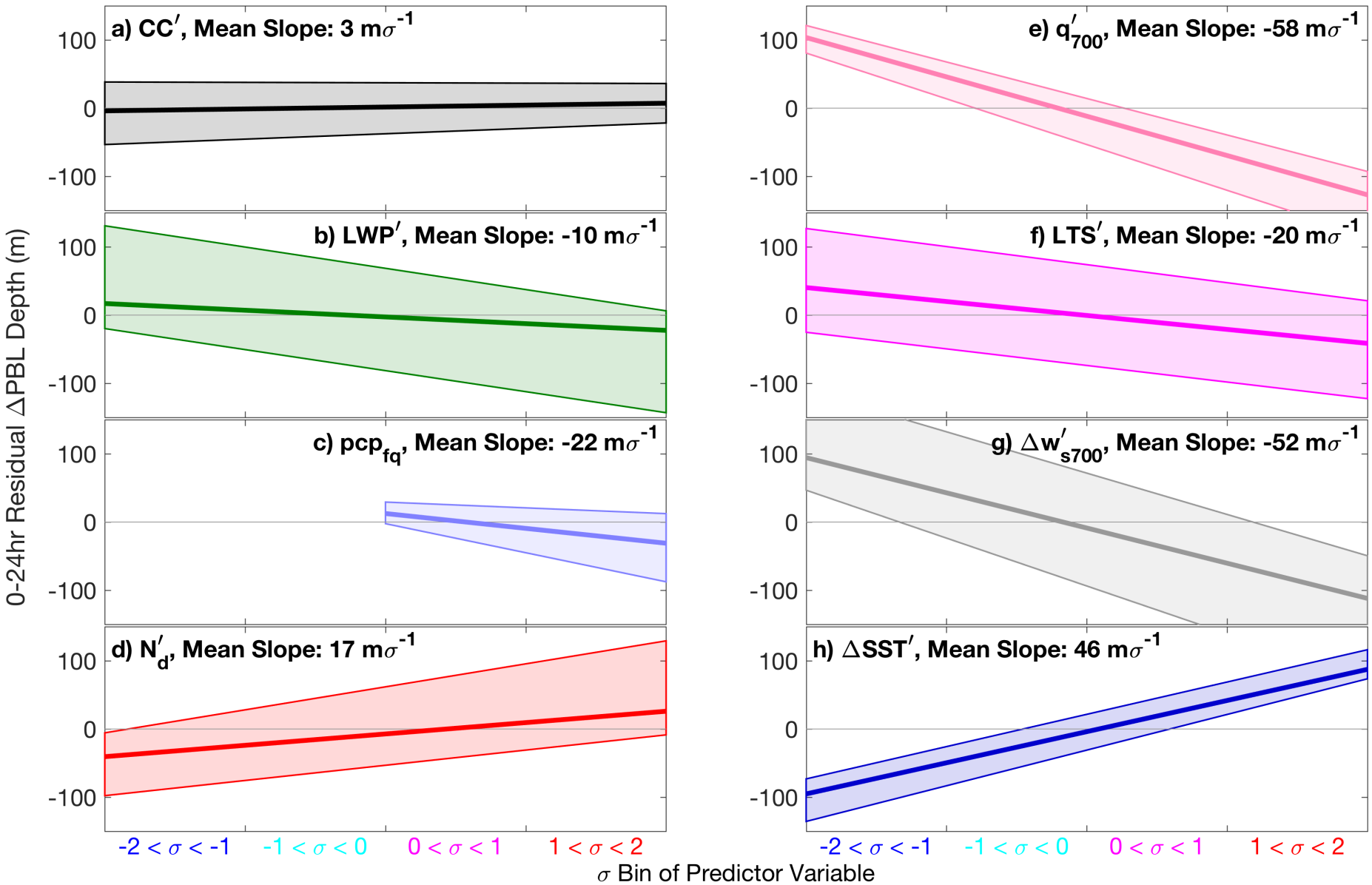


Results: Lagrangian Cloud Cover Variability

- Cloud cover is most sensitive to:
  - Subsidence
  - q700
  - PBL depth
  - LTS
  - Droplet concentration
- SST changes sign based on lag time, indicating complexity



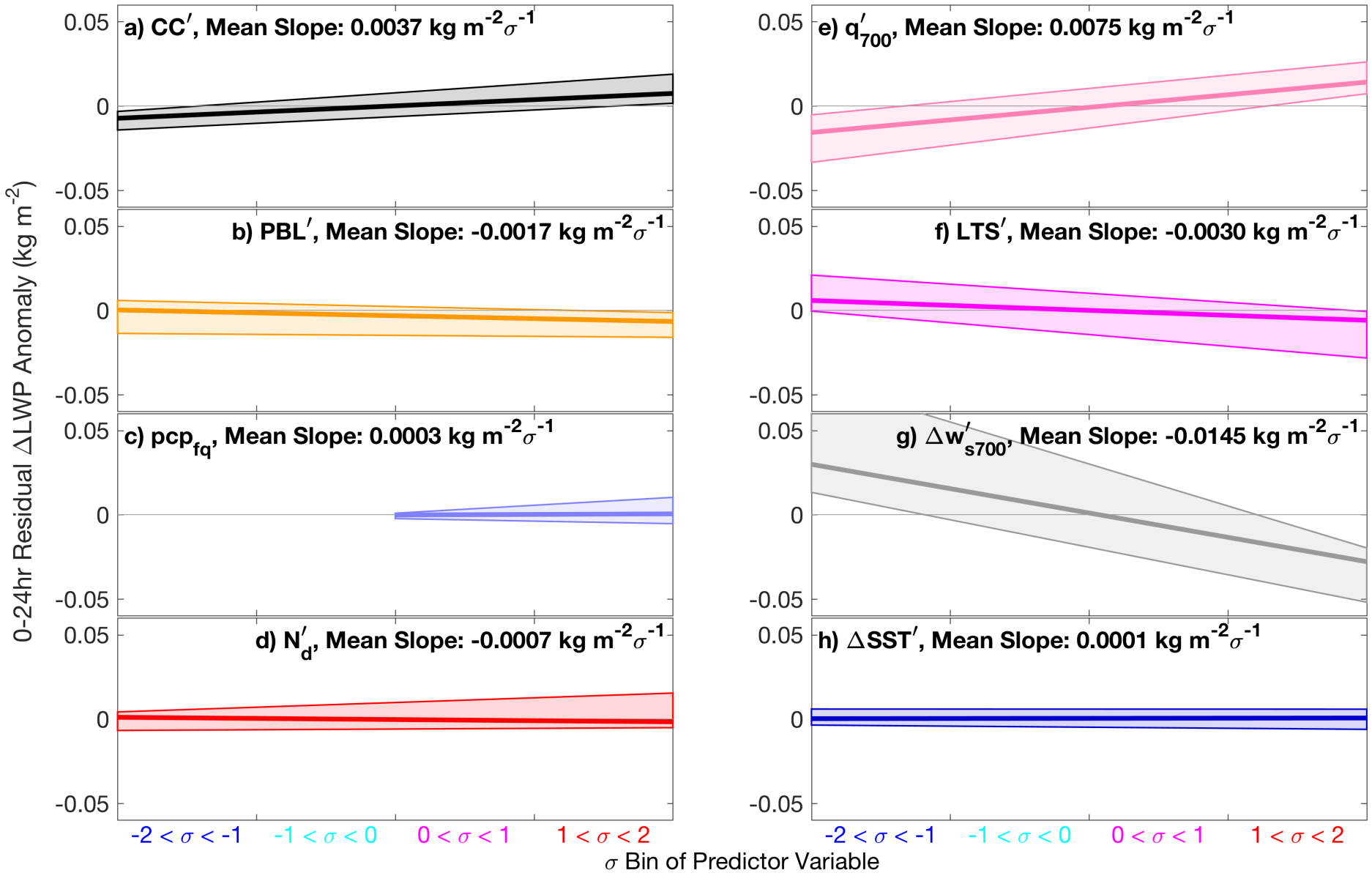
Results: Lagrangian PBL Depth Variability



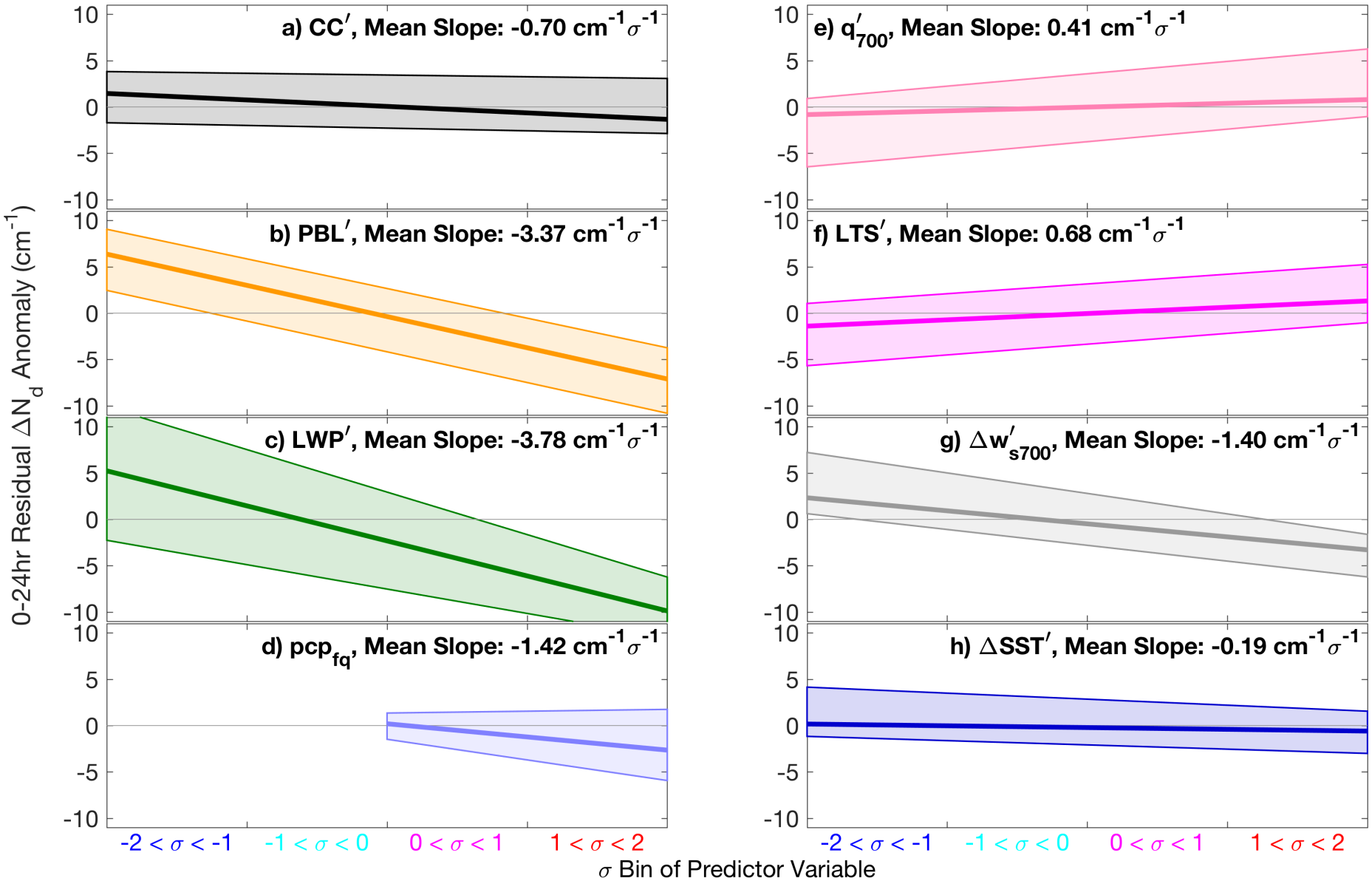
- PBL depth is most sensitive to:
  - q700
  - Subsidence
  - SST
  - Precipitation
  - LTS
  - Droplet concentration

Results: Lagrangian LWP Variability

- LWP is most sensitive to:
  - Subsidence
  - q700
  - Cloud Cover
  - LTS



Results: Lagrangian N_d Variability



- N_d is most sensitive to:
  - LWP
  - PBL Depth
  - Precipitation
  - Subsidence

Conclusions

- The Lagrangian format allows us to follow cloud scenes as they evolve following the flow
  - Seeing behavior that actually exists in nature, rather than in idealized models that may miss some nuances and details of the actual variability
  - Find solutions to manage difficulties with: zenith angle bias, trajectory irregularities, differences in initial conditions
- Grouping trajectories by standard deviation bins of predictor variables allows us to directly compare their influence
- PBL depth (measured by CALIPSO and MODIS) is shown to effect the evolution of cloud cover and droplet concentration
  - Deep PBLs lead to anomalous cloud breakup
  - Deep PBLs appear to lead to cloud drop decline

Conclusions

- Precipitation as observed by CloudSat influences PBL depth and droplet concentration
  - Precipitation is followed by PBL shallowing
  - Precipitation leads to declining droplet concentration
  - The effect of rain on cloud breakup appears less significant and may be complex
- External variables have significant impacts
  - Stability leads to increasing clouds & Nd, PBL shallowing, and LWP declines
  - q700 has a very powerful effect driving cloud & LWP persistence, and PBL shallowing
  - Subsidence is also very powerful, driving cloud, Nd & LWP declines, and PBL shallowing
  - SST appears to drive PBL deepening, but effects on other variables do not appear as important, though time scales are likely to blame for this

Conclusions

- Wide error bounds suggest that much more detail is present than can be shown here. Future work must investigate:
  - Non-linearities and state-dependencies where relationships change based on the states of other variables
  - Example: rain rates and thermodynamic decoupling may change the way many variables evolve
- This project will be applied to subtropical Sc to study:
  - External forcings on all available cloud variables
  - Internal feedbacks and their interplay with one-another as the cloud decks evolve
  - Controls on rapid breakup and cellular changes that remain elusive

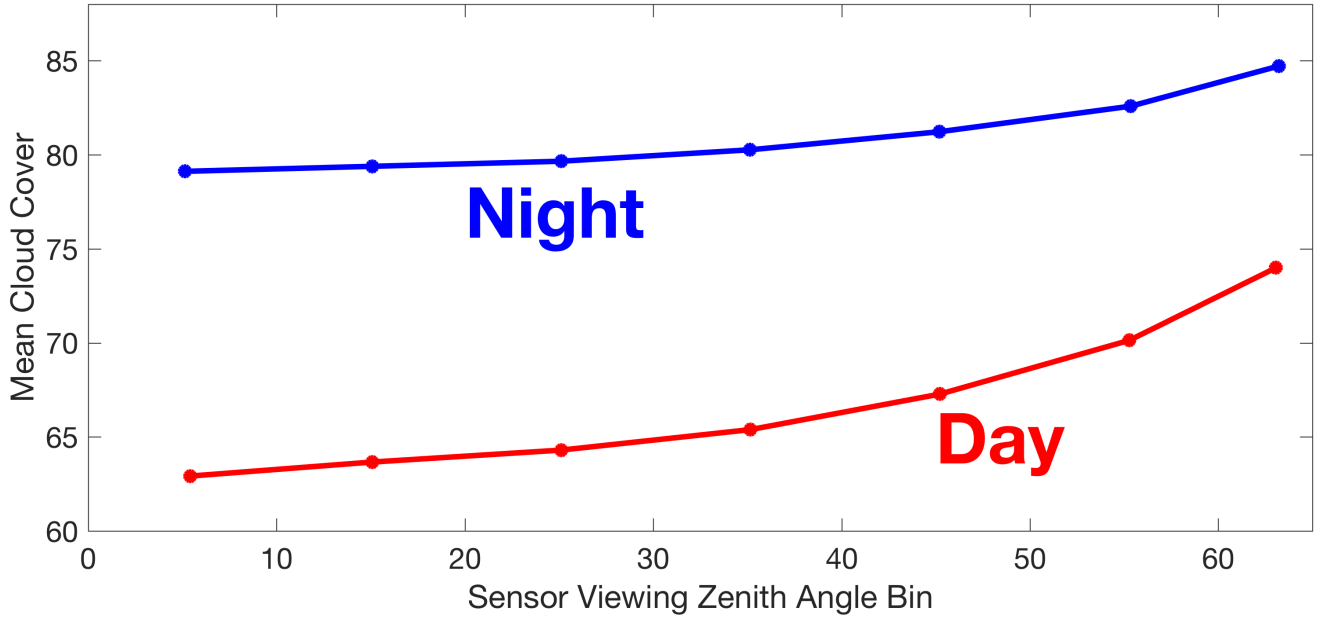
Acknowledgements

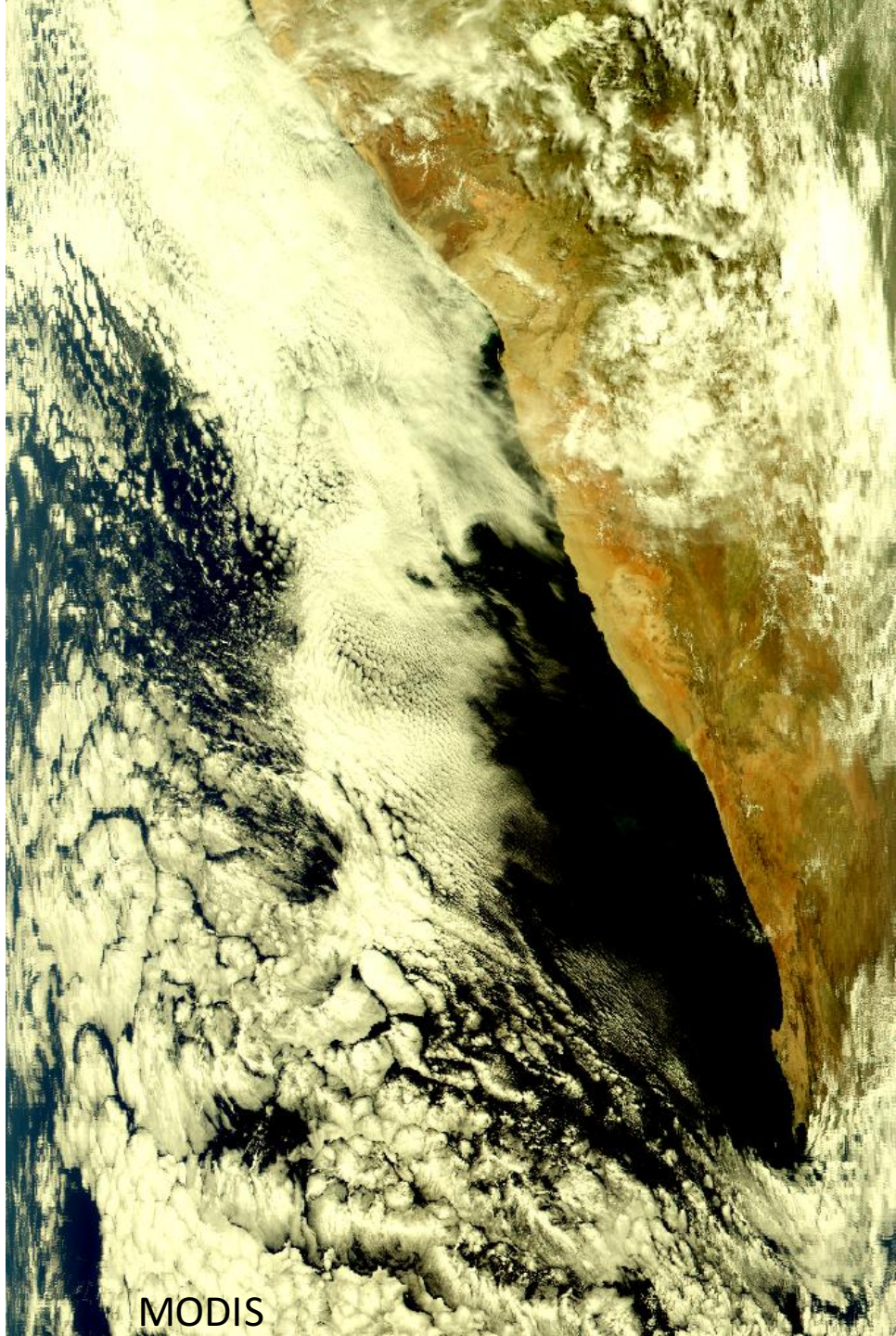
- Chris Bretherton, Sandra Yuter, Casey Burleyson, Stephen Warren, Kuan-Ting (Andy) O, Hans Mohrmann, Isabel McCoy
- NASA grant NNXBAQ35G
- CloudSat / CALIPSO science team

Extra Slides

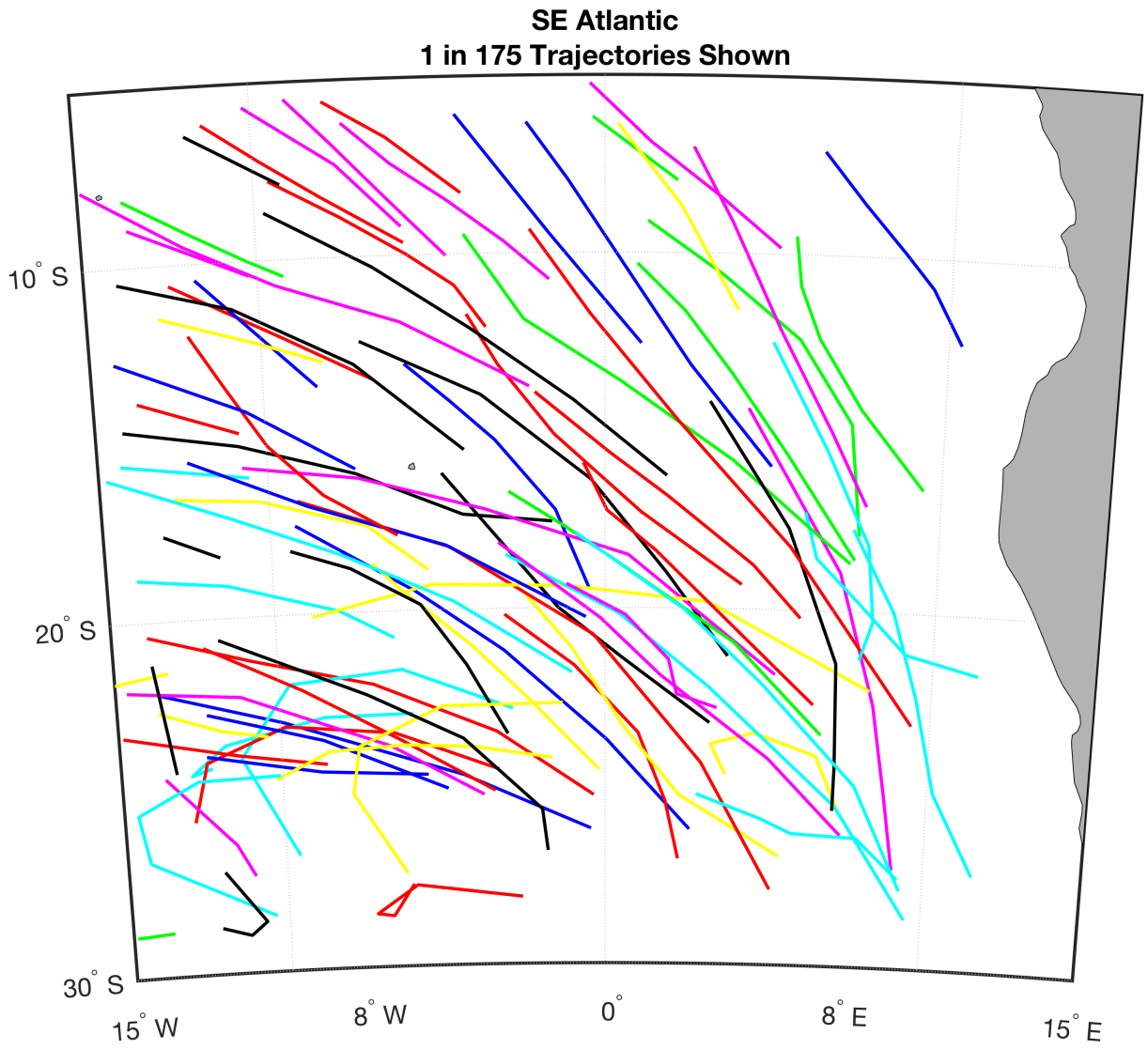
Zenith Angle Bias

- At high viewing (zenith) angles, satellite sensors see clouds at an angle rather than straight down
  - Leads to an overestimation of cloud amount, and optical thickness
  - We remove this bias using a polynomial





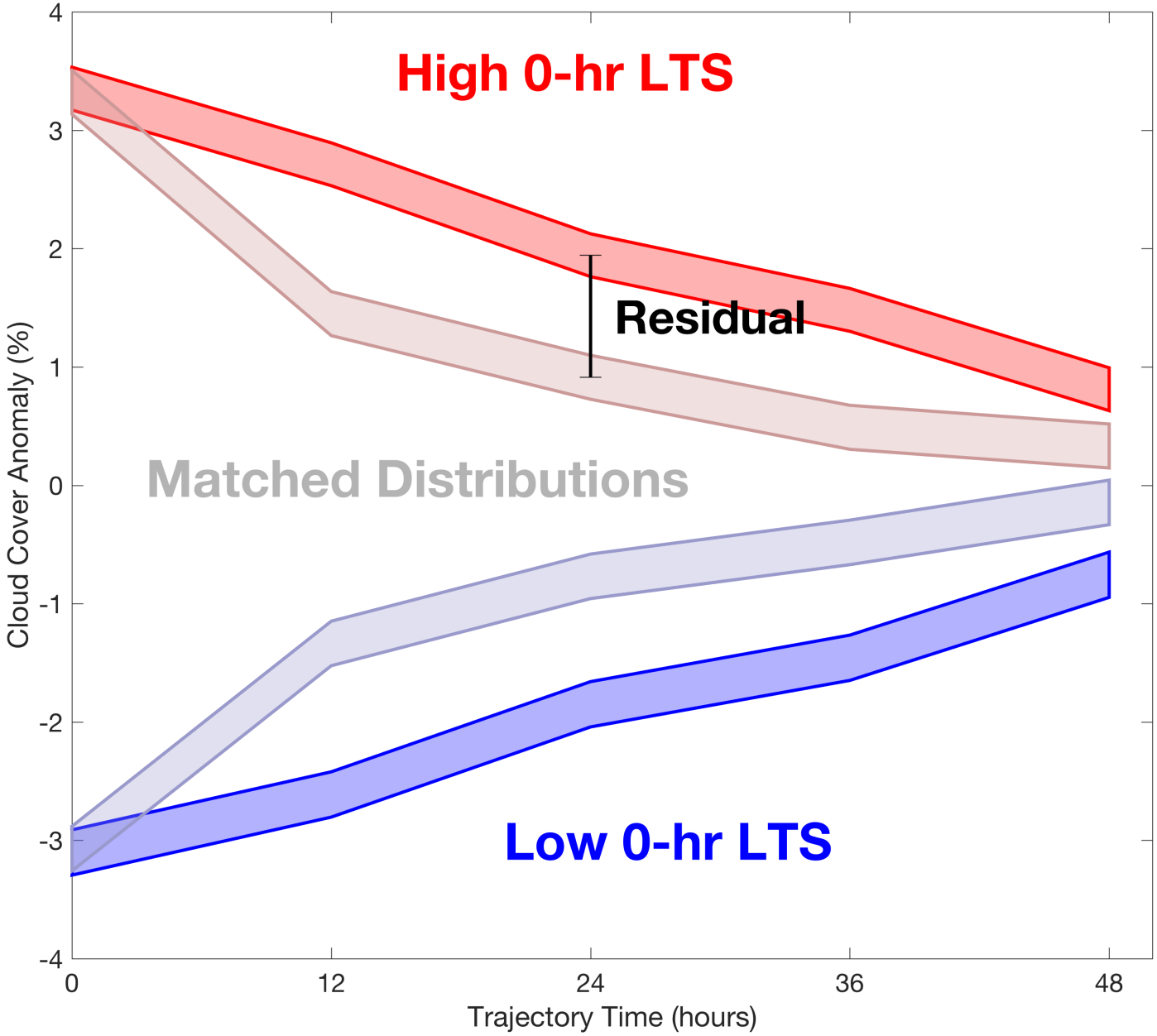
Anomaly Framework



- Our goal is to compare changes in trajectories when grouped by different initial conditions
- Trajectories are irregular in distance and direction
- Comparisons of trajectories must take this diversity into account, otherwise systematic bias could arise
- All values are converted to “seasonal” anomalies to account for this
  - By subtracting 100-day running mean

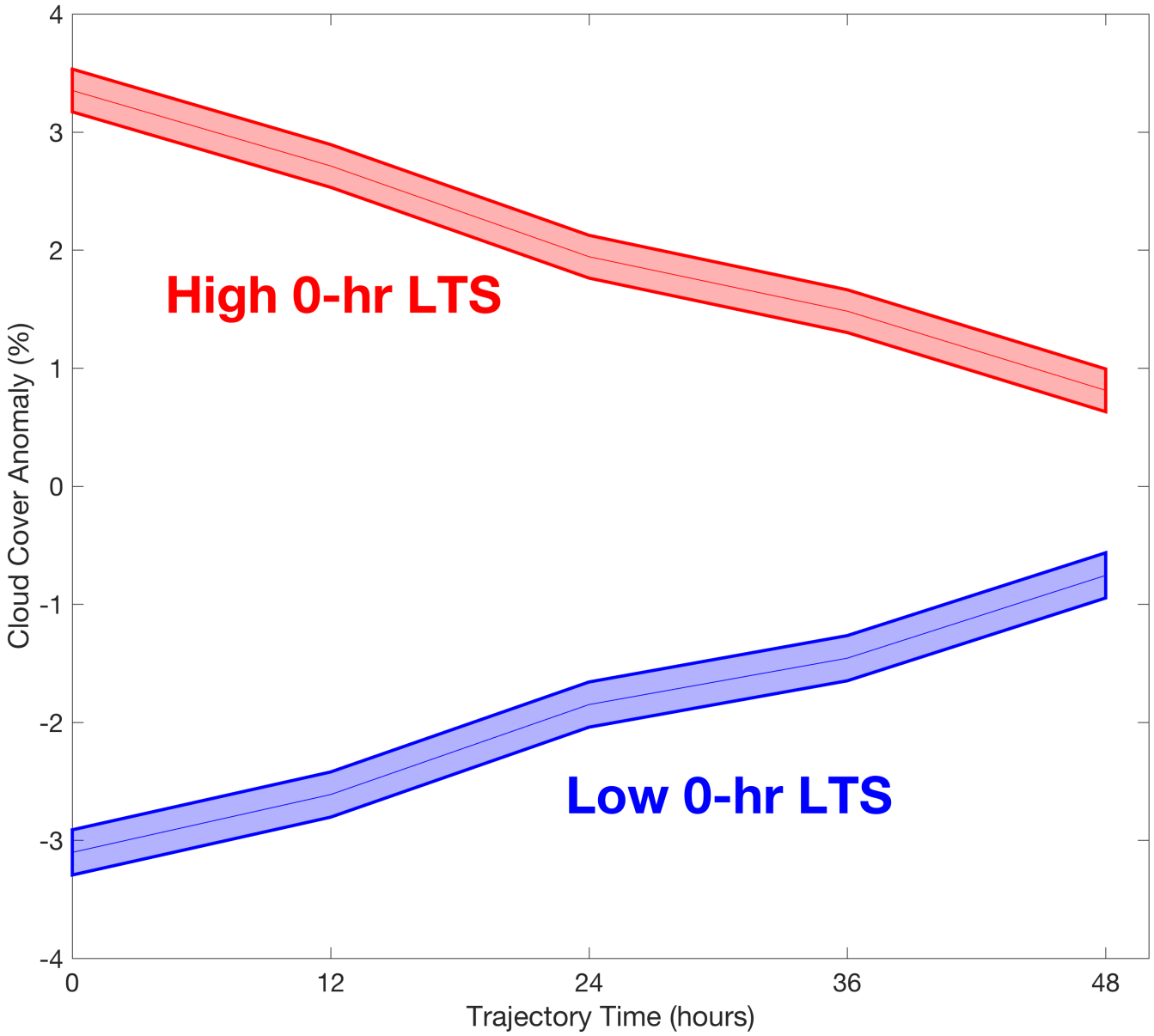
Initial Distributions Driving Variability

- Separating trajectories by LTS creates two populations
  - High LTS trajectories are cloudier, low LTS less cloudy
  - **Δ**CC is dependent on CC_0 AND LTS, so we must separate these effects.
- We compare our trajectories grouped by LTS to a set with identical 0-hour CC frequency distributions (matched), but randomly chosen.
- The difference between the LTS group and randomly chosen, 'matched' group is called the residual

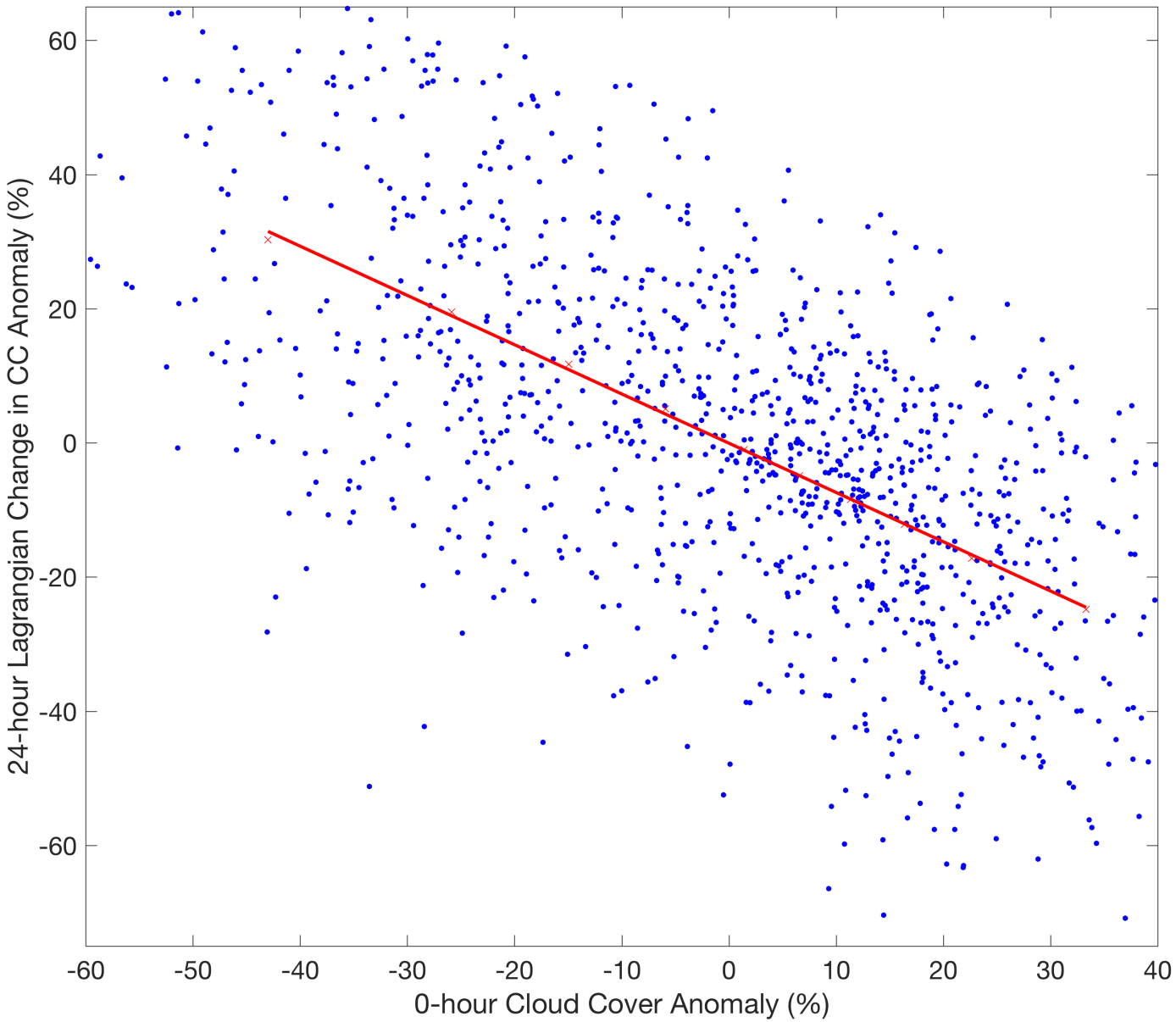


Red Noise Causing Variability

- Example: Trajectories are grouped by stability at 0-hours
  - To see how anomalous Lower Tropospheric Stability (LTS) changes cloud evolution
  - Above/below median LTS anomaly
  - High LTS is associated with anomalously cloudy environments and persistent clouds, but this plot clearly shows declining cloud cover.
  - A comparison of **Δ**Cloud Cover (CC) would conclude that high stability leads to declining cloud cover anomalies



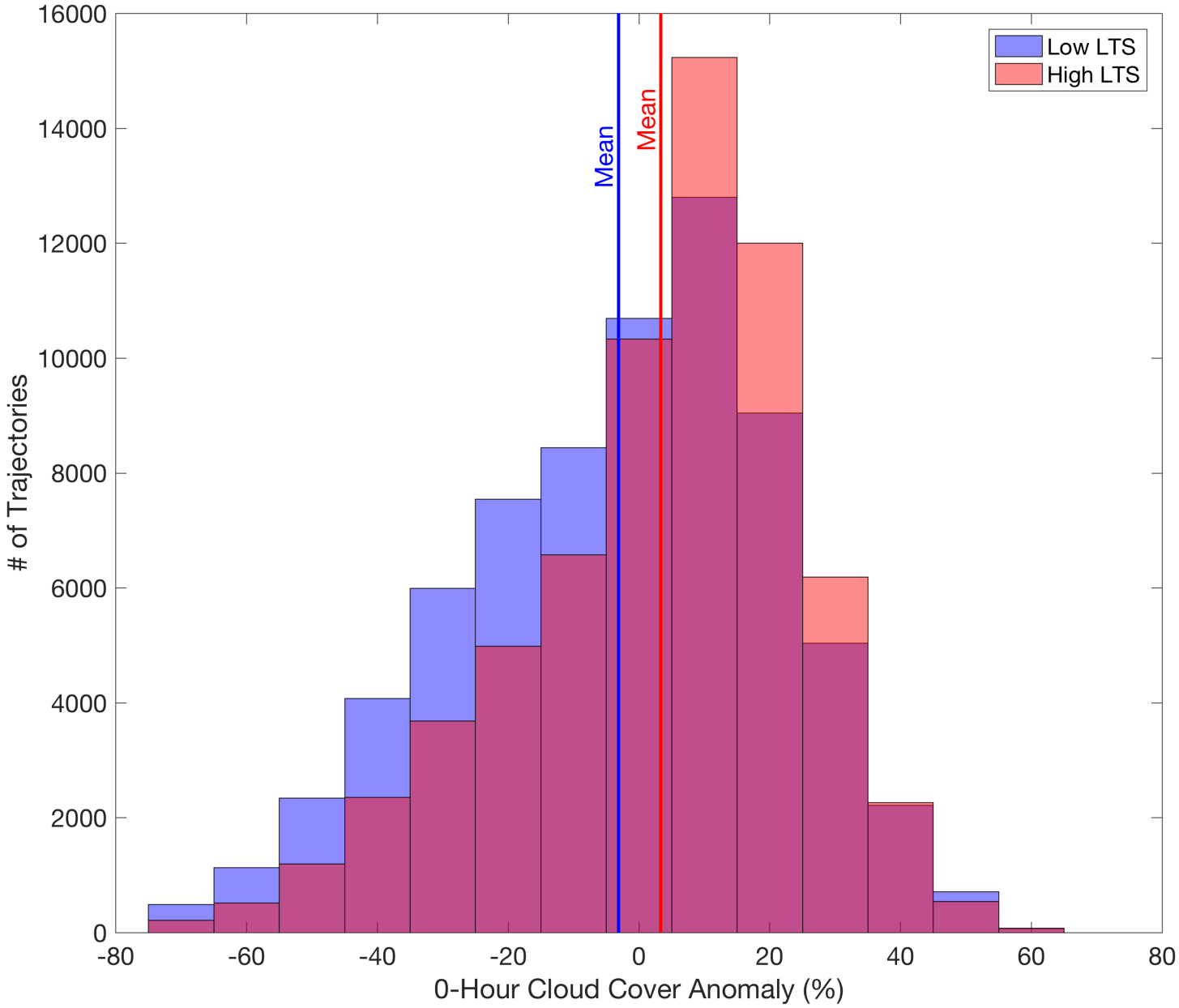
Red Noise Causing Variability



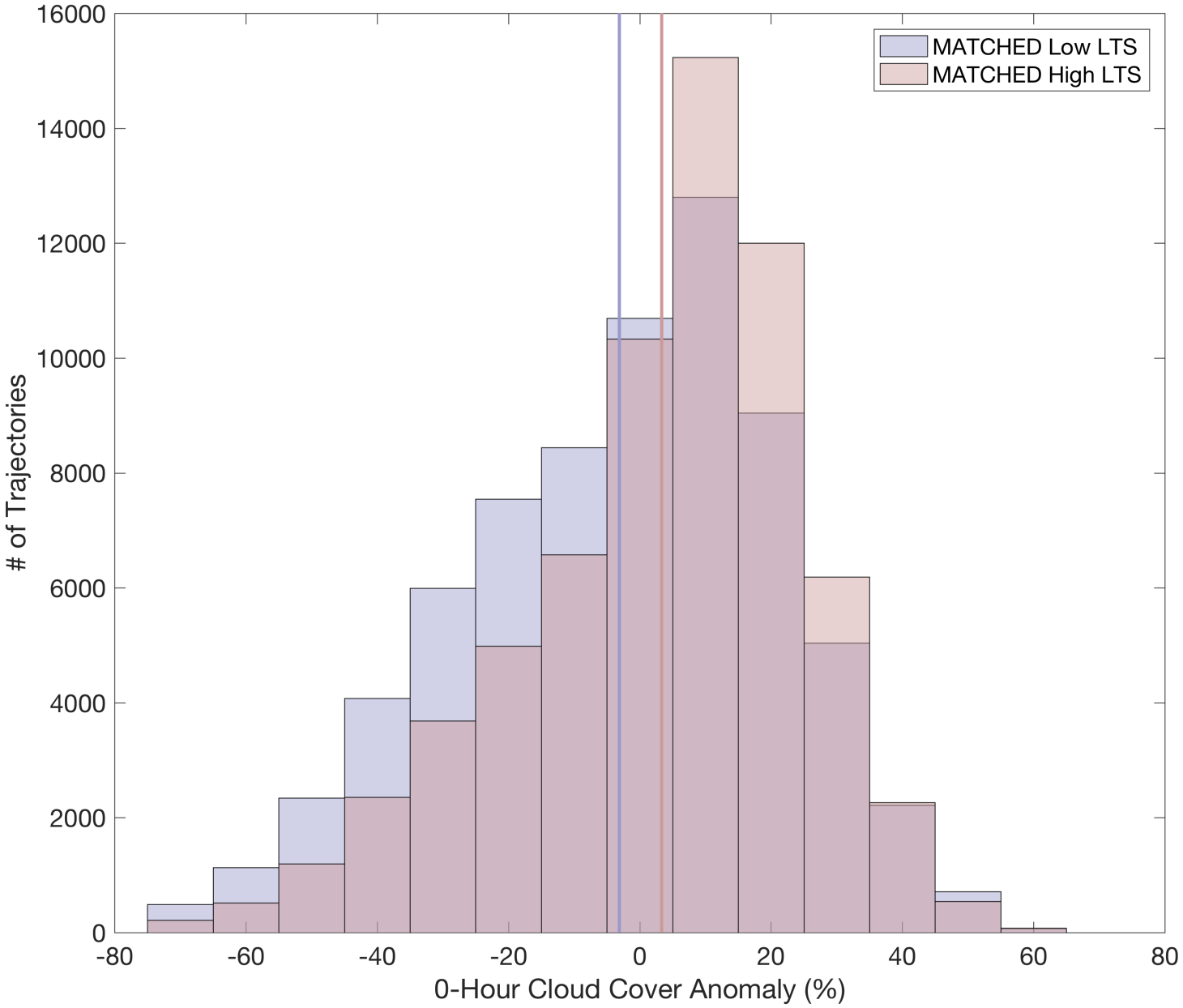
- 24-hour **Δ**cloud cover anomalies are in-part a function of their 0-hour anomalies
  - High 0-hour CC anomalies tend to be followed by CC declines, low 0-hour anomalies are likely followed by CC increases
  - The slope of this relationship is dependent on lag-time, and is on-average well-described as a red noise function with a defined timescale $\boldsymbol{\tau}$: $r(T) = e^{-T/\tau}$
- Lagrangian red noise behavior is shown for CC, PBL depth, LWP, and Nd

Red Noise Causing Variability

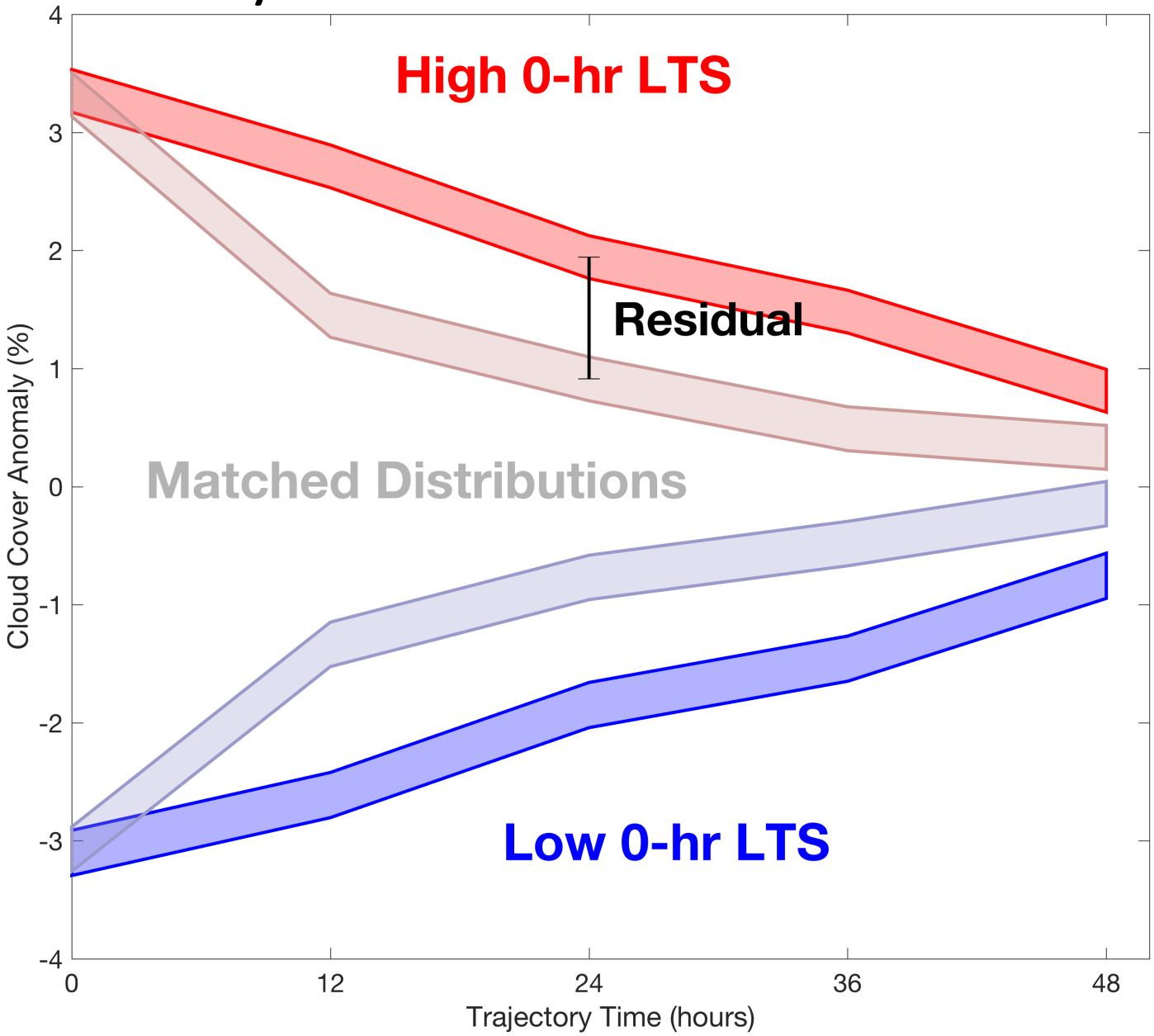
- Binning trajectories based on 0-hour LTS creates two populations of trajectories with substantially different mean 0-hour CC anomalies
- The mean **Δ**CC seen by the two populations will be strongly influenced by the different 0-hour CC anomalies
- For a meaningful comparison we must separate the effects of the different 0-hour CC anomalies from the 0-hour LTS anomalies



Red Noise Causing Variability



- Choose a second set of trajectories with identical 0-hour CC frequency distributions, but with no dependence on stability
- Randomly sample the entire set of trajectories in order to make 'matching' distributions
- Now we compare changes for identical frequency distributions, removing the effects of the differing 0-hour CC anomalies

Red Noise Causing Variability

- Comparing the LTS-separated trajectories to the randomly sampled ones
- High stability is shown to prolong cloud life relative to the mean behavior that would otherwise be observed with that frequency distribution
- We must compare 'residuals', where the effects of red noise are now accounted for