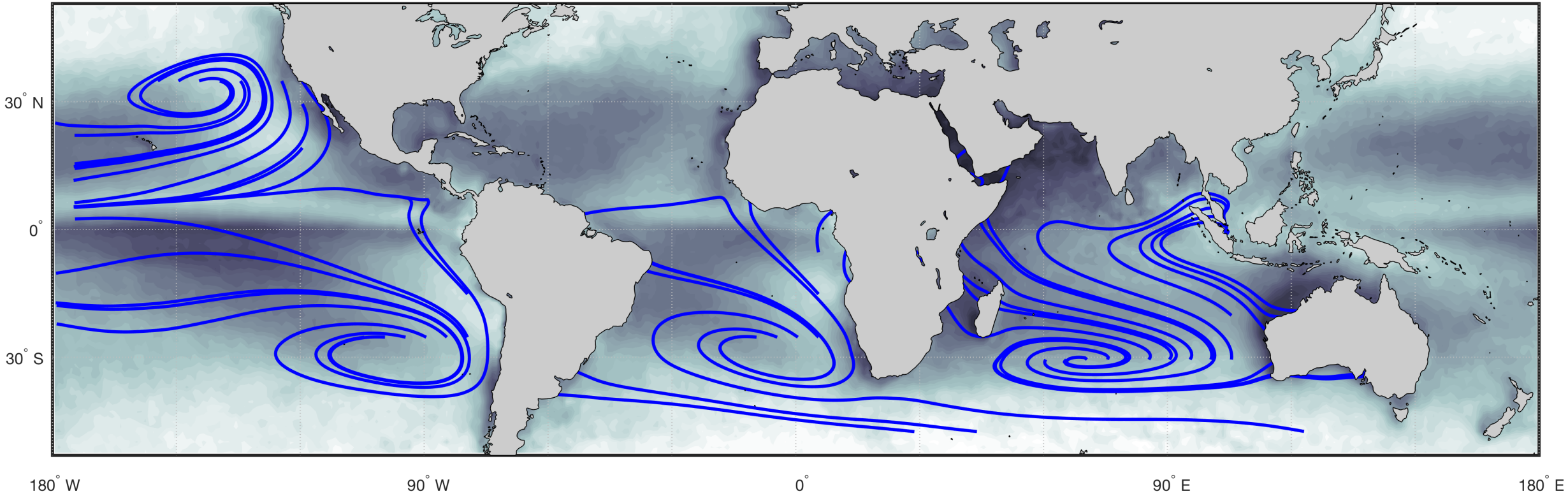
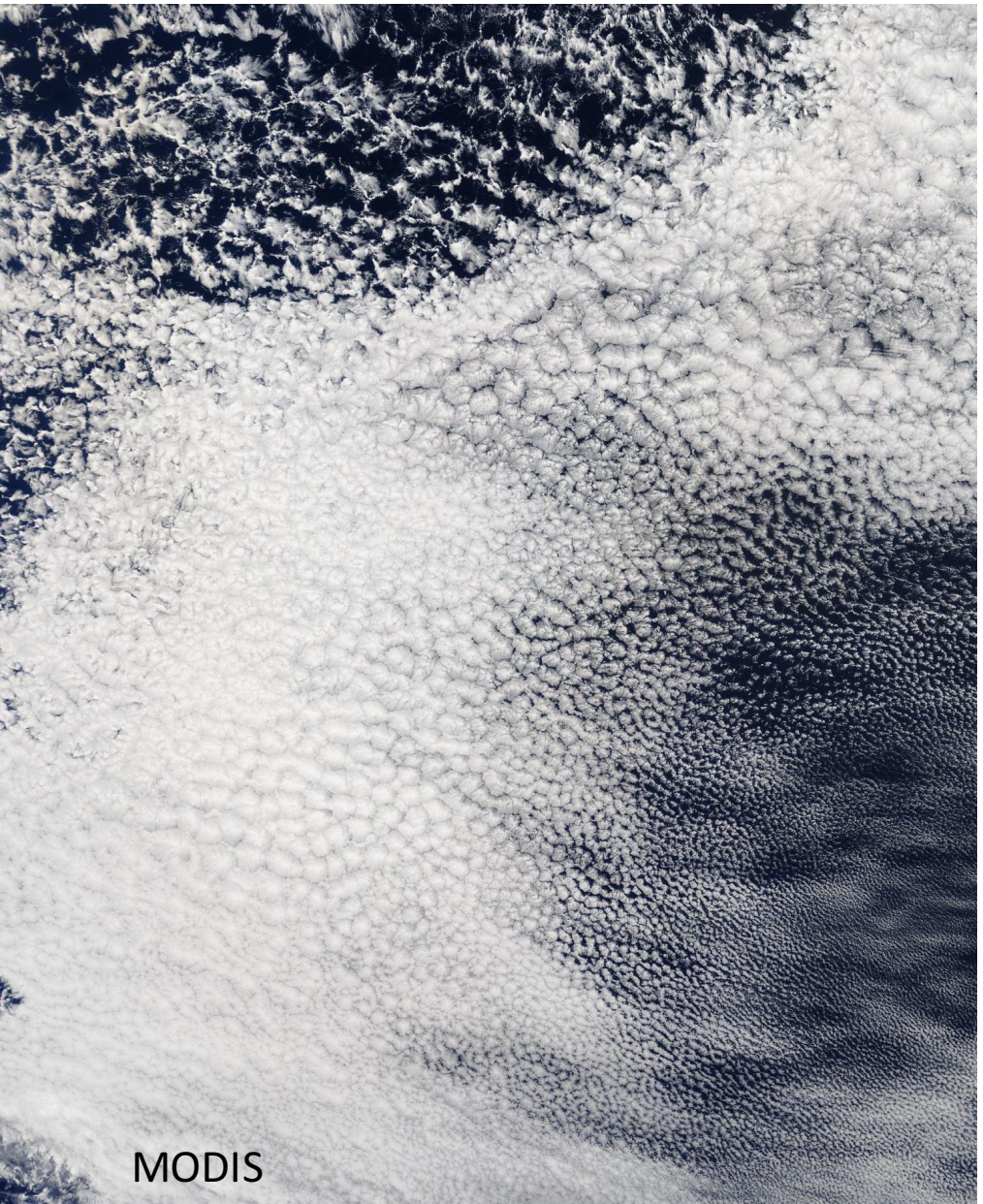
Using a Lagrangian Framework to Study the Temporal Evolution of Subtropical Stratocumulus PBL



Ryan Eastman, Robert Wood, Kuan Ting O

University of Washington Dept. of Atmospheric Sciences, June 2019

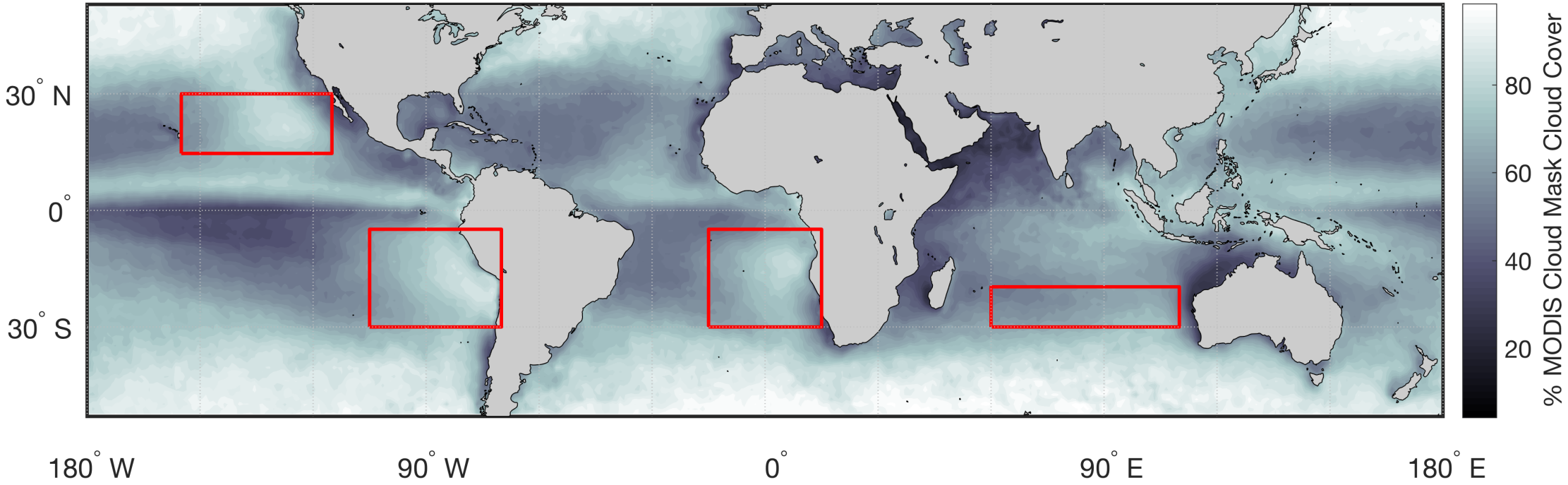
Subtropical Stratocumulus (Sc) over the Ocean



- Extensive cloud decks 100's of km across.
- Clouds reflect a great deal of visible solar radiation that would otherwise be absorbed by a dark ocean.
- Clouds are low enough to emit IR at a relatively warm temperature.
- SW cooling and strong IR emission combine to create a strong cooling effect in the climate system.
- Processes driving the evolution of these clouds are poorly resolved by climate models.

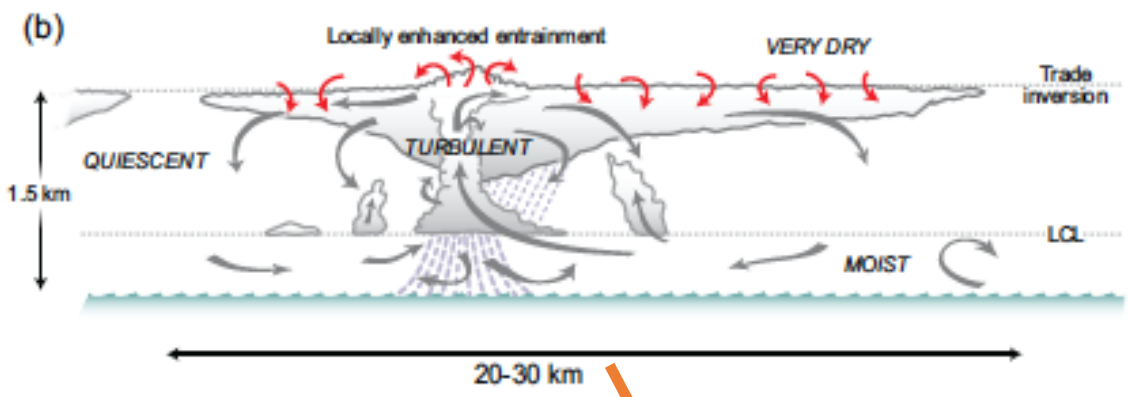
Subtropical Stratocumulus (Sc) over the Ocean

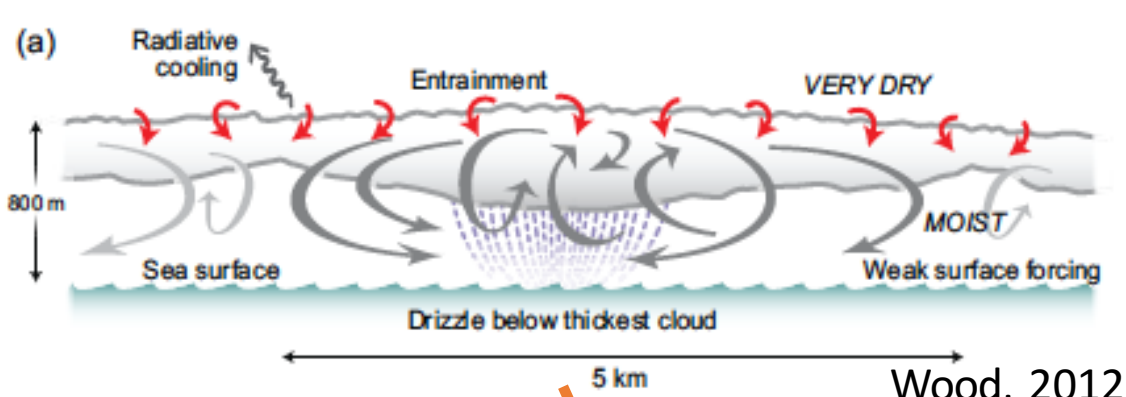
- Sc Cloud decks persist in eastern ocean basins.
  - Warm air flows offshore over cold, upwelling ocean water, creating a strong inversion over a shallow planetary boundary layer (PBL).
  - Mean, large-scale subsidence maintains a warm, clear atmosphere overhead.
- Clouds decline as offshore winds blow the boundary layer to the west and toward the equator over warmer sea surface temperatures (SSTs).



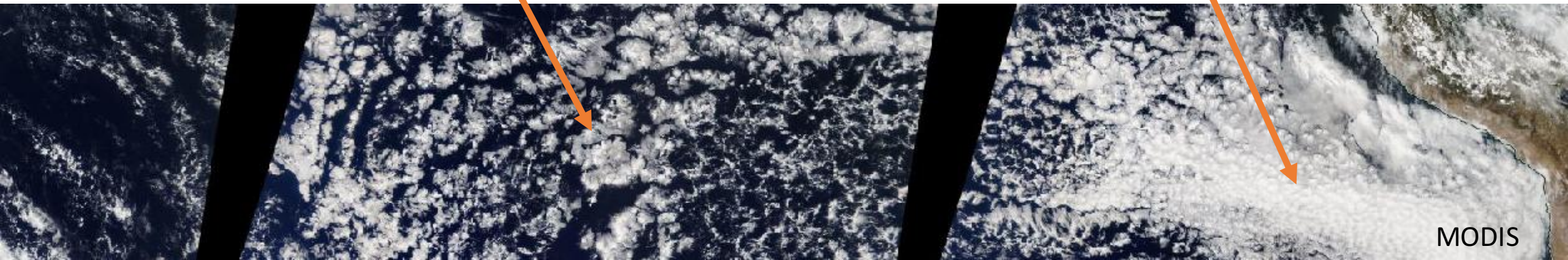
Mean Evolution of the Subtropical Boundary Layer

- Near the coast (a, right), clouds are organized in shallow, unbroken decks, with cloud top cooling driving a circulation from cloud top to sea surface.
- Farther offshore (b), the cloud deck becomes broken, the boundary layer deepens, and the circulation from cloud top 'decouples' from the surface.



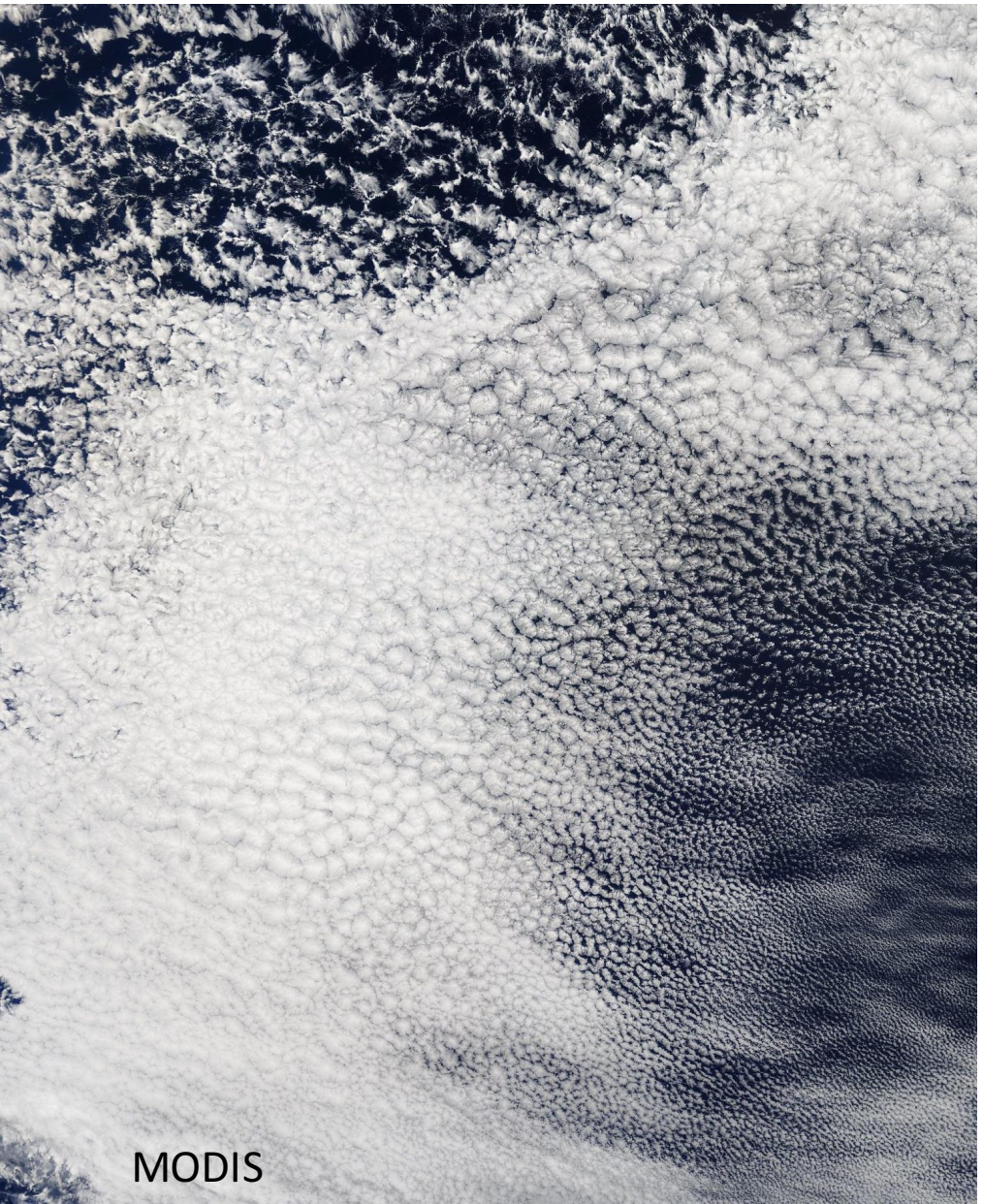


Wood, 2012



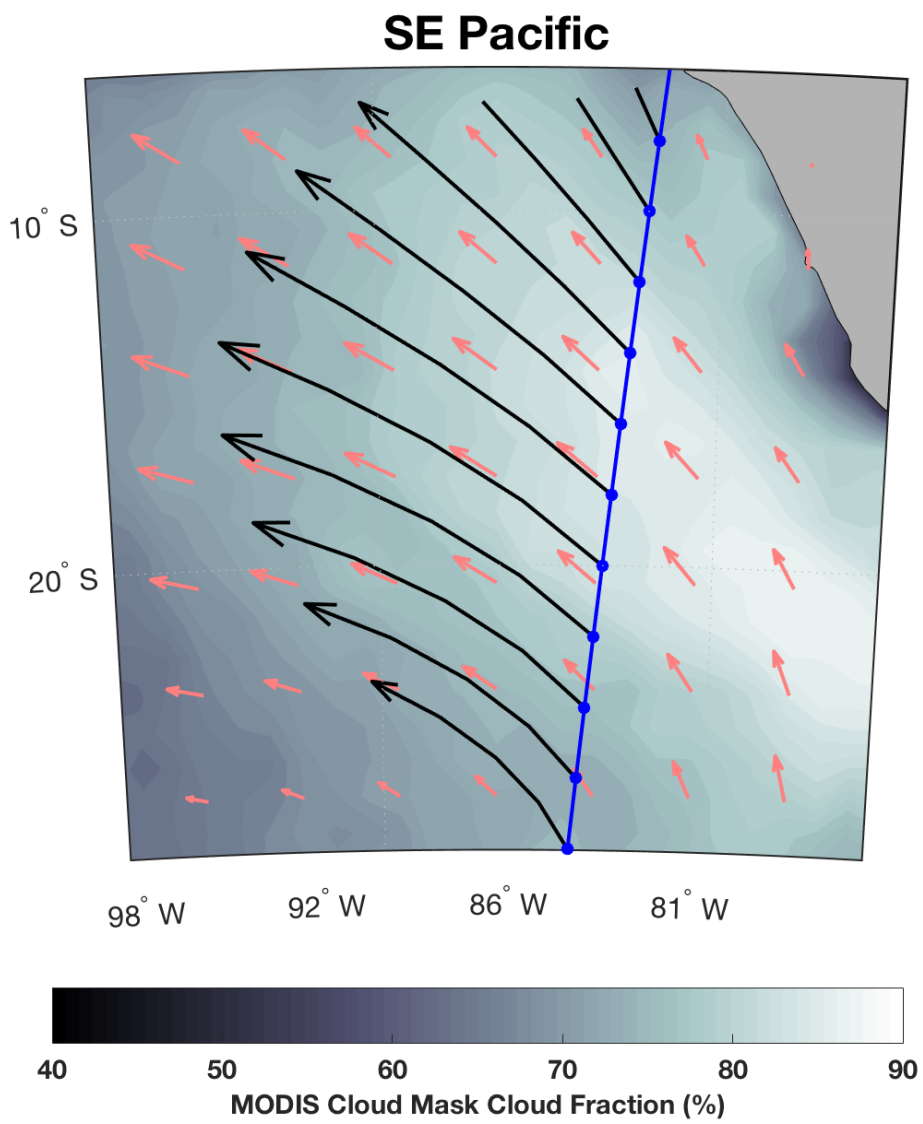
MODIS

Subtropical Stratocumulus (Sc) over the Ocean



- We want to know: How do these cloud decks evolve? What factors control their variability in space and time?
- Project Outline:
  - Review a prior study, which motivates study of PBL depth, as it was shown to significantly modify cloud evolution.
  - New data product using the A-Train satellites that are made to study time evolution of the boundary layer.
  - Climatologies and correlational studies using this PBL product.
  - A more comprehensive Lagrangian study showing PBL depth sensitivity to several predictor variables.

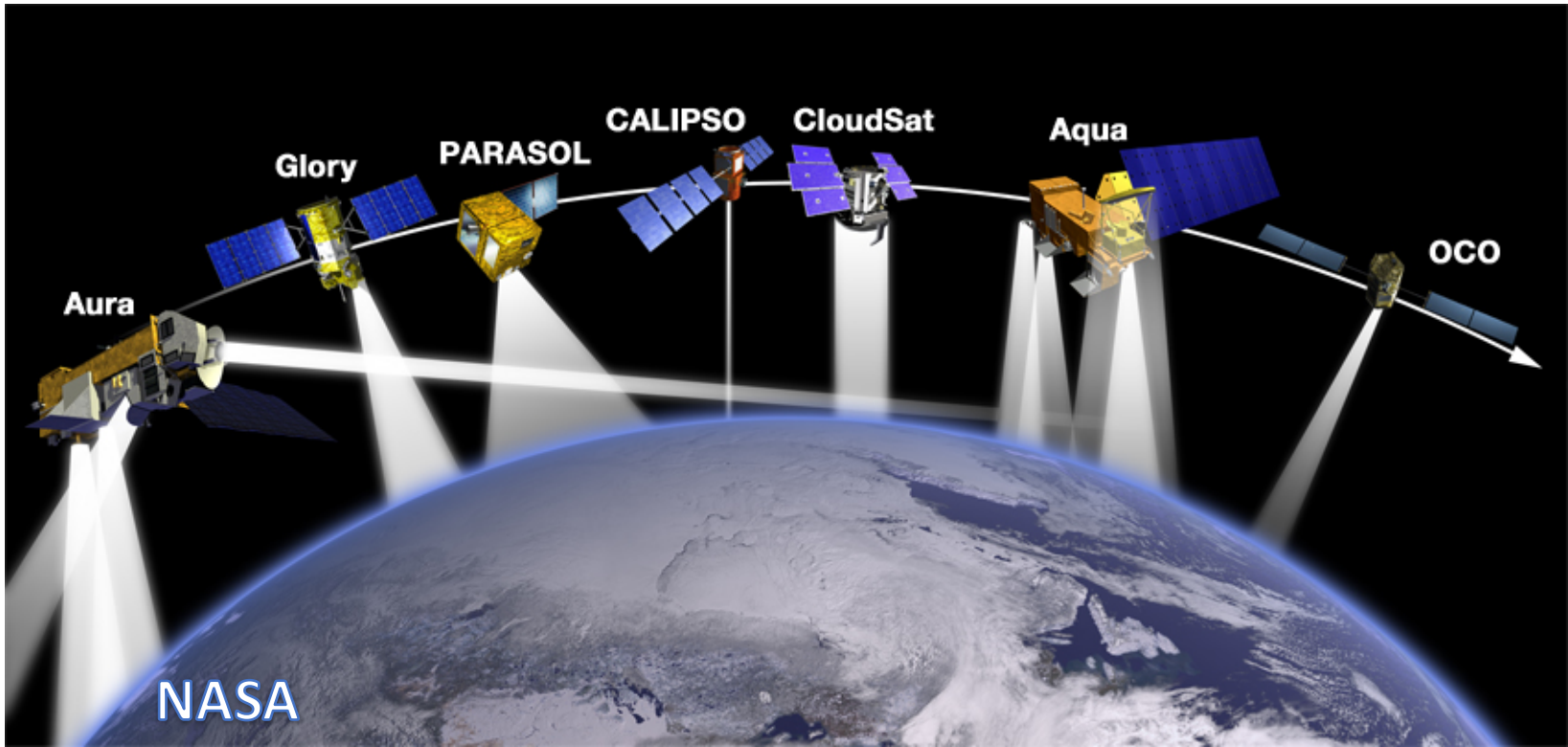
Structure of and Motivation for a Lagrangian PBL Study



- Prior work (Eastman and Wood, 2016) sought to test whether raining Sc was more prone to breakup.
- Structure:
  - Identify raining and non-raining Sc samples along the CloudSat/CALIPSO satellite track.
  - Use reanalysis winds to generate 2-D trajectories at 925 hPa to track those samples over time.
  - Use the A-Train satellites and sensors (MODIS, AMSR/E, CloudSat, and CALIPSO) to quantify cloud and PBL properties.

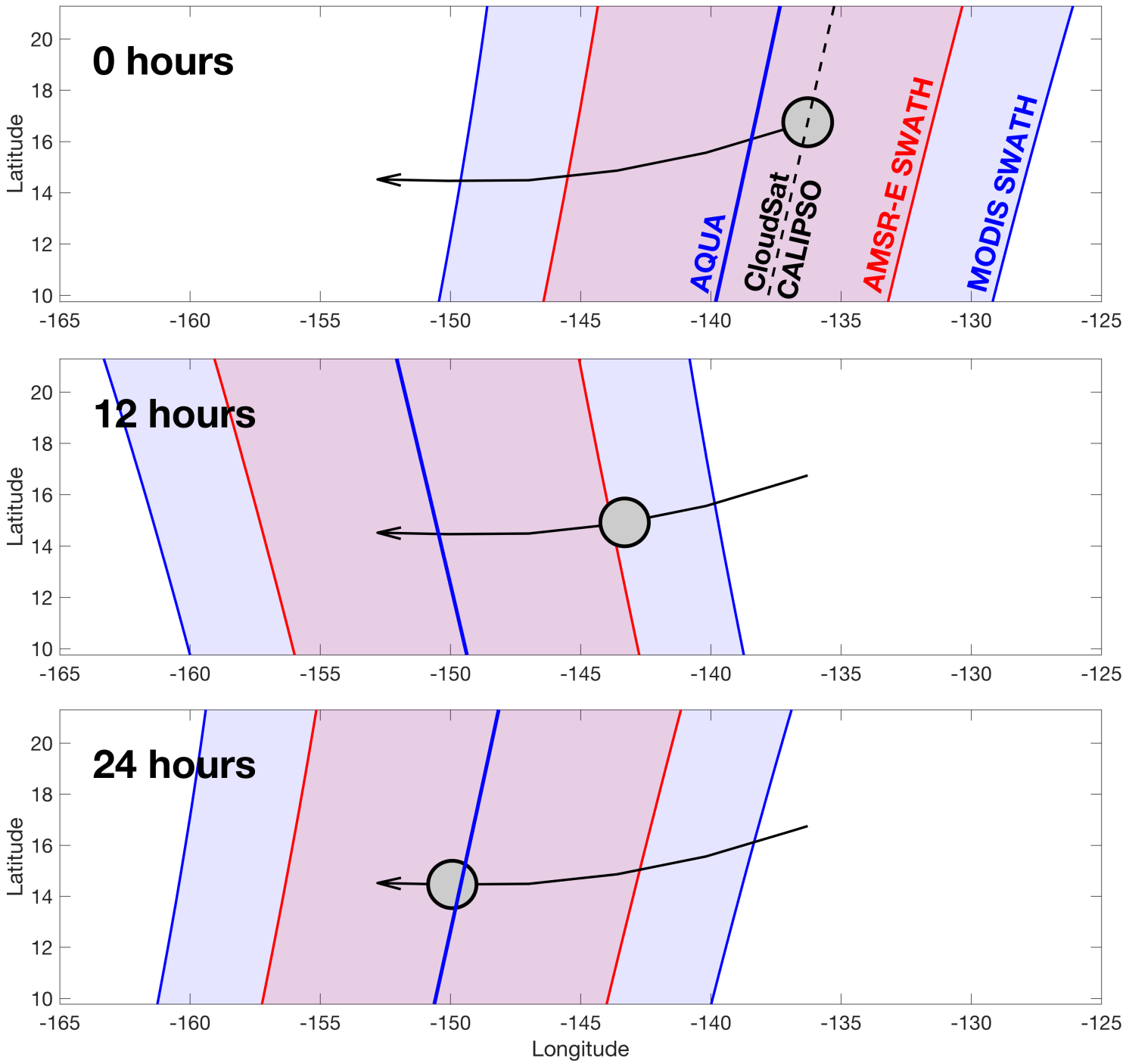
NASA A-Train Satellites

- Afternoon-Train satellites fly together as a constellation, sampling the same scenes with a variety of sensors along a sun-synchronous polar orbit, crossing the equator at 1:30 and 13:30.
- Sensors & Satellites:
  - CloudSat: Cloud profiling radar capable of detecting clouds and drizzle.
  - CALIPSO: Cloud Aerosol Lidar, observing cloud & aerosol profiles.
  - MODIS: Spectroradiometer observing outgoing visible and IR, observing clouds and cloud properties.
  - AMSR/E: Passive microwave sensor observing moisture profiles and cloud liquid water.



Structure of and Motivation for a Lagrangian PBL Study

- All A-Train sensors observe the 0-hour clouds within a 100km radius.
- Instruments with a wide swath (MODIS and AMSR/E) observe the clouds as they evolve downwind.

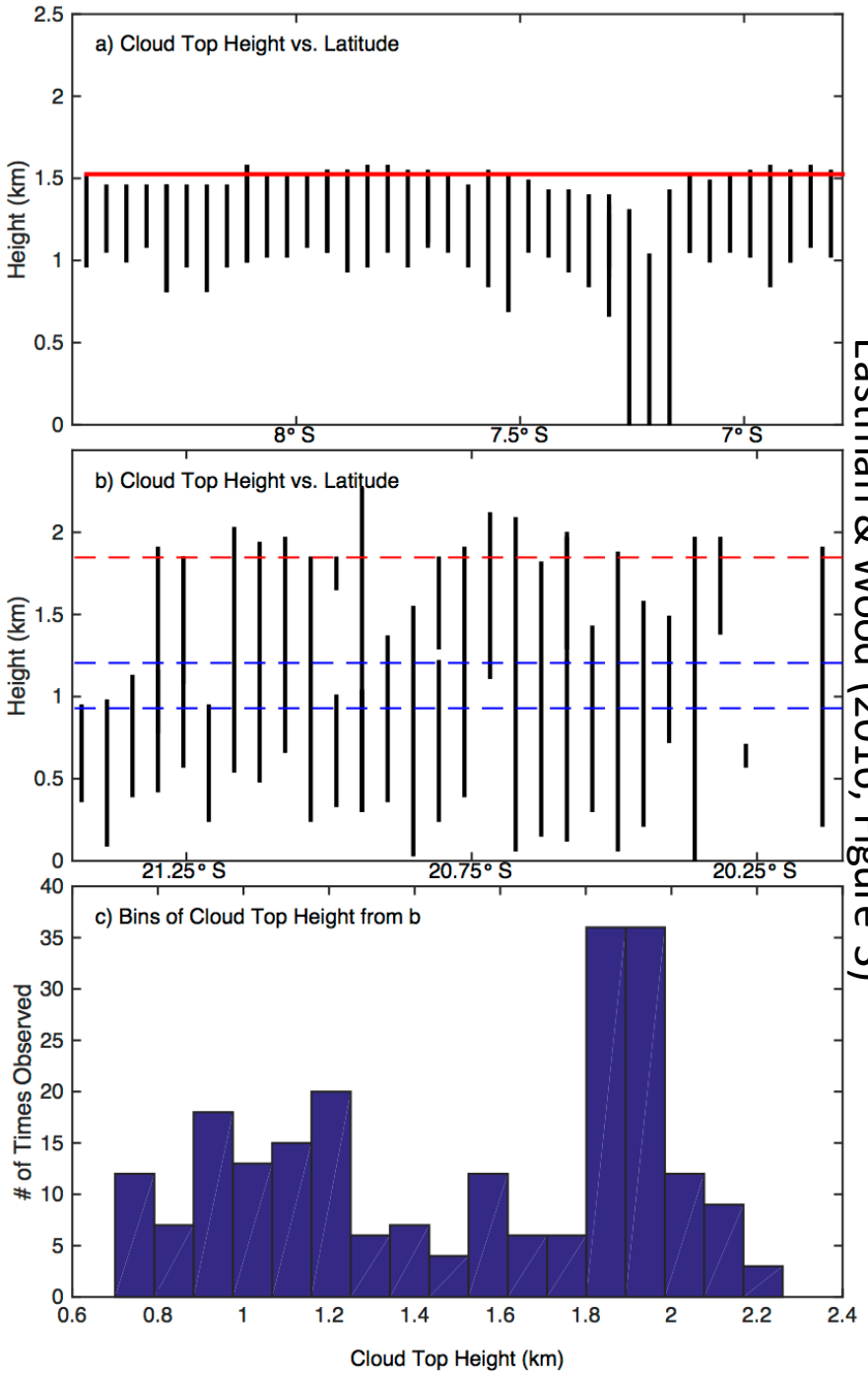


Early Lagrangian Results Suggested that Rain Leads to Sc Breakup

- Results from Eastman and Wood (2016).
- 40,000 Trajectories were run in our four subtropical regions for years 2007 & 2008.
- Trajectories were grouped by whether or not they were precipitating, as seen by CloudSat at 0-hours.
- Precipitating clouds were initially shown to break up more readily than non-precipitating.
- This design failed to account for other variables covarying with precipitation, most notably the depth of the boundary layer, which is often deeper when there is precipitation.

Creating a PBL depth product

- CALIPSO PBL product relies on the assumption that boundary layer cloud tops rest just below the inversion, using 'Vertical Feature Mask'.
- For a shallow, unbroken Sc deck, this is a straighforward assumption (a) for a 200 km sample.
- For a deeper, more complicated PBL (b), we develop an algorithm based on the frequency distribution of LIDAR-retrieved cloud tops (c), looking for the highest-altitude peak in the distribution.
- Limited to just the LIDAR curtain, though, not to a 2-D swath needed for sampling at later times.



Eastman & Wood (2016, Figure 3)

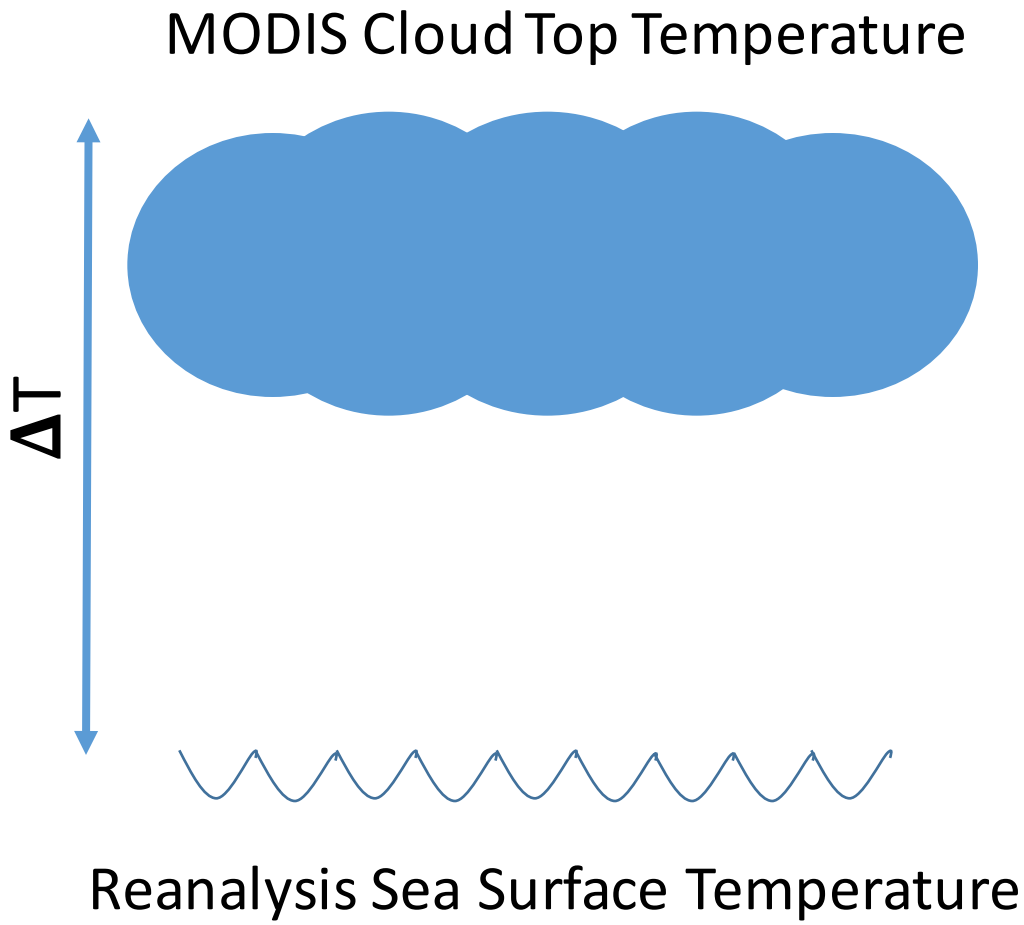
Better Results Suggested that Rain May Not Lead to Sc Breakup

- After some time and constructive feedback, we designed an analysis that compared the evolution of precipitating and non-precipitating trajectories within bins of constant PBL depth.
  - Deeper boundary layers (as seen by CALIPSO) were shown to precipitate (as seen by CloudSat) significantly more than shallower boundary layers.
  - So was the precipitation to blame for cloud declines, or was the depth of the PBL?
- After accounting for PBL depth, the effects of precipitation appeared less significant, while the effects of PBL depth appeared stronger, with deep boundary layers more prone to anomalous cloud decline compared to shallow boundary layers.

Better Results Suggested that Rain May Not Lead to Sc Breakup

- Motivates the question: What controls PBL depth, if it's such an important driver of cloud evolution? And how to study the time evolution of the PBL?
- Requires the creation of a new data product capable of studying the time-evolution of the PBL:

Creating a PBL Depth Product for a Lagrangian Analysis

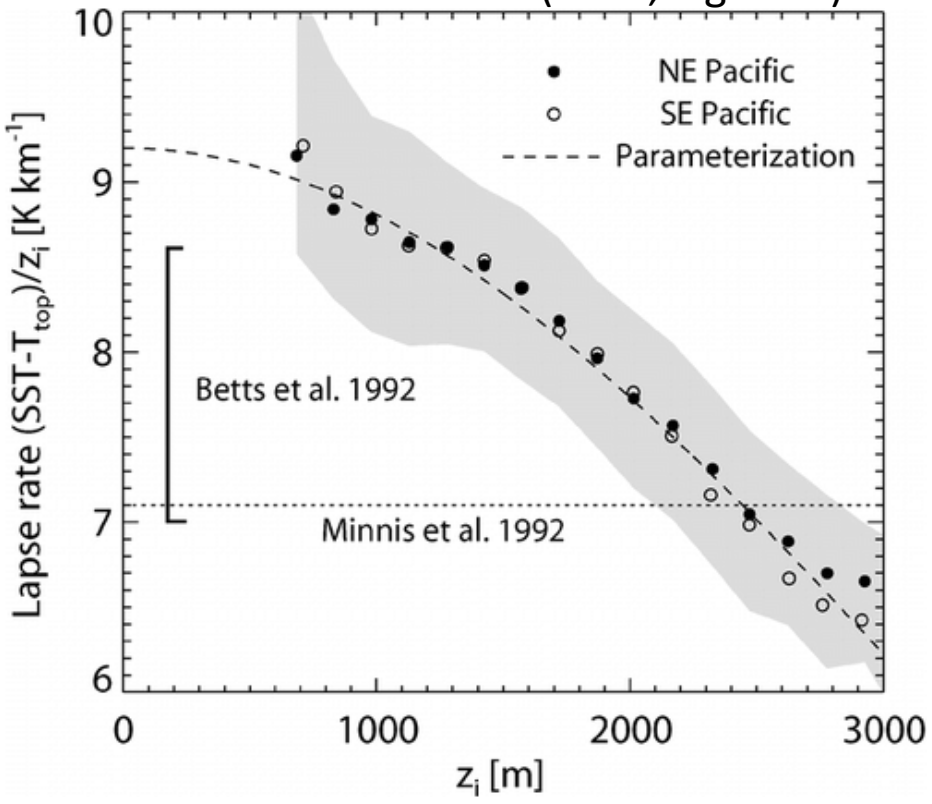


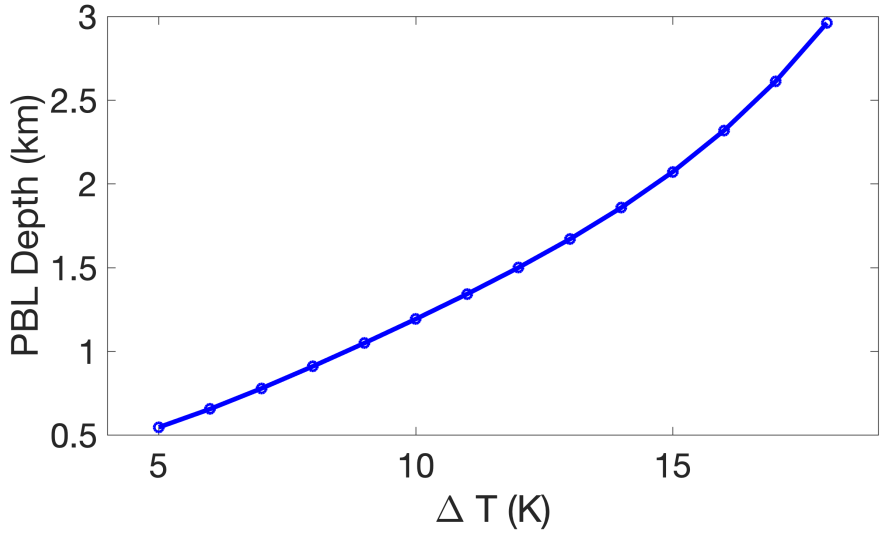
- PBL depth can be estimated using the temperature difference (**Δ**T) between the sea surface and cloud tops.
  - Sea surface temperatures (SSTs) are sourced from the ERA-Interim.
  - Cloud top temperatures (CTTs) come from MODIS L3 (1x1 lat/lon grid) histograms, showing the frequency distribution of CTT for all sub-grid pixels within an L3 grid box.
- Two issues:
  - 1) Lapse rates (**Δ**T/**Δ**Z) must be calculated.
  - 2) In broken cloud scenes, only a fraction of CTT pixels sit at the inversion base.

Parameterized Lapse Rate is Assumed

- The lapse rate is assumed to be dependent on PBL depth, with a steeper lapse rate (more cooling with height) for shallower PBLs.
- Lapse rate is derived from Wood & Bretherton (2004) as shown by the curve on the top figure.
- PBL depth is then calculated as a function of **Δ**T, as shown by the blue curve.

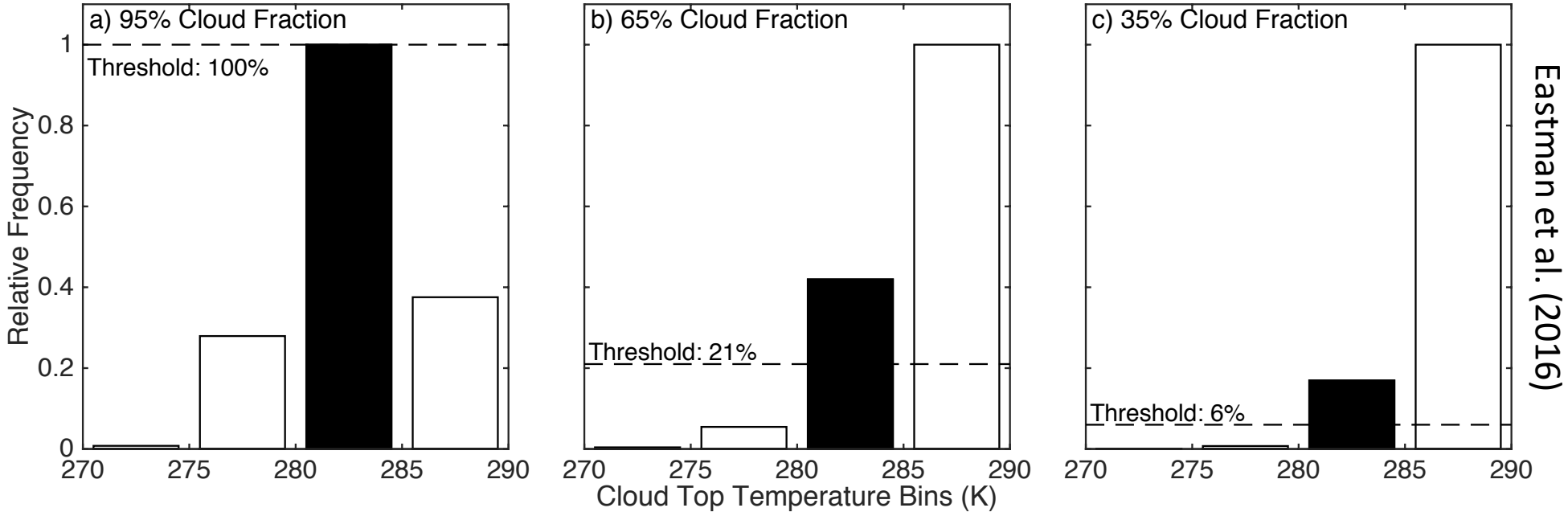
Wood & Bretherton (2004, Figure 4)



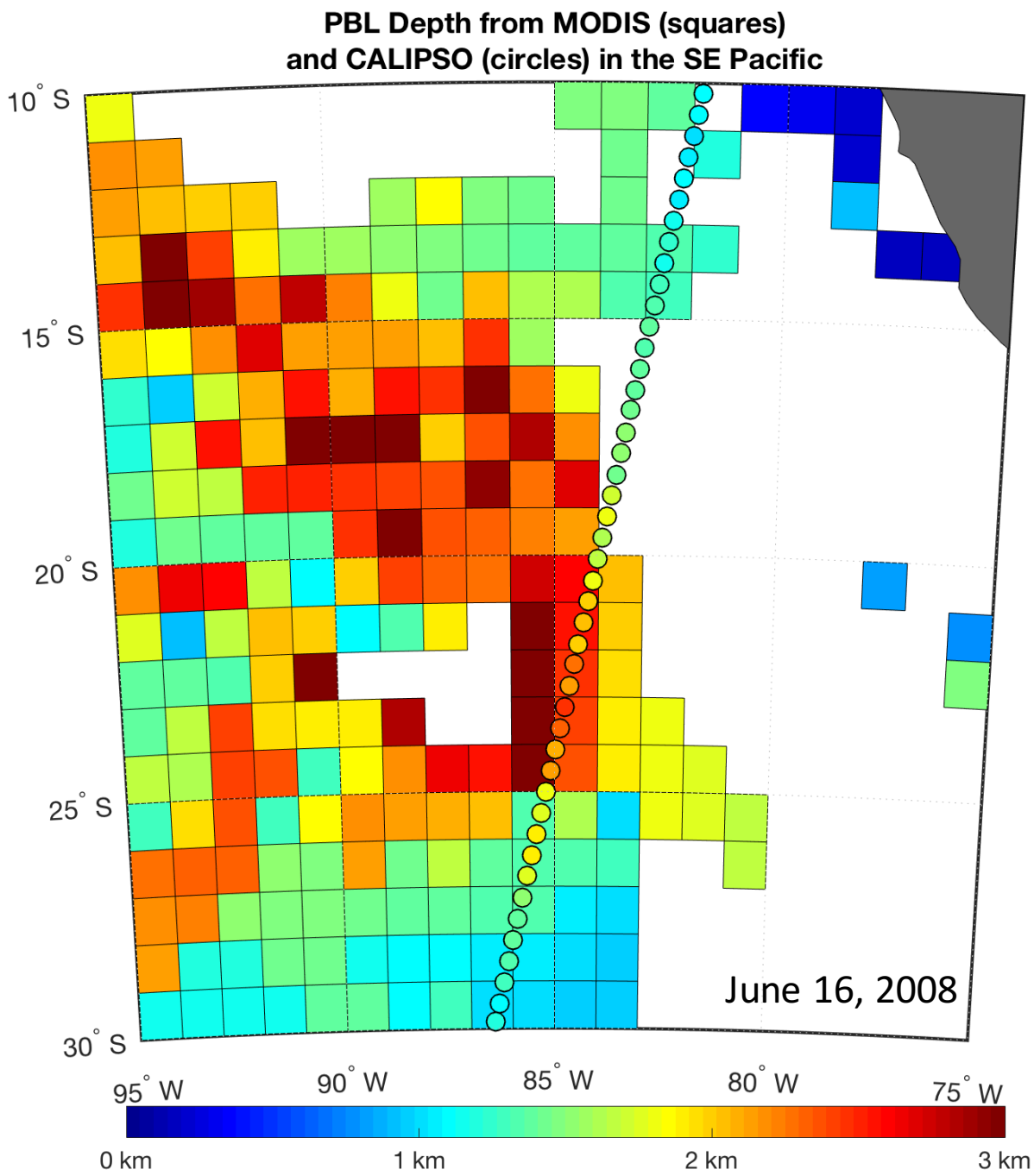


Fraction of Clouds at the Inversion Base

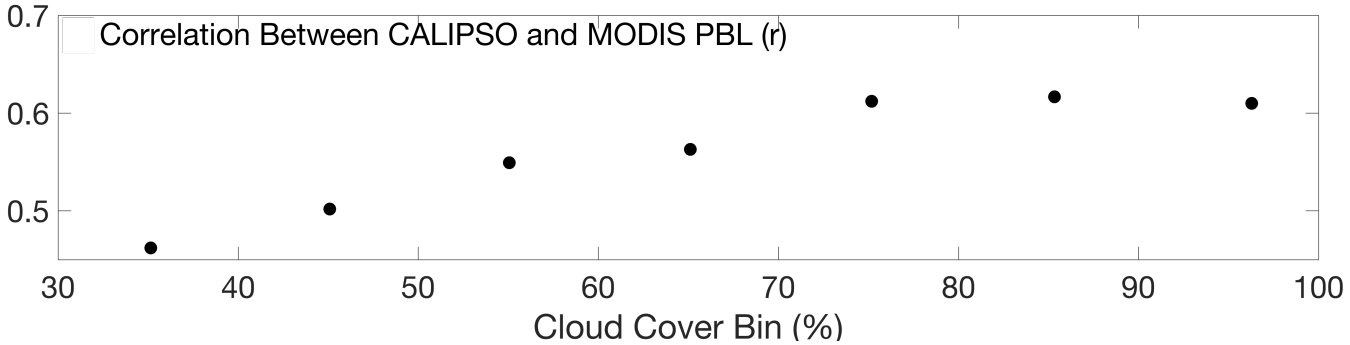
- In broken cloud scenes, many cloud tops are not at the top of the PBL.
- An iterative routine is developed to estimate the % of CTT pixels that sit at the inversion base for bins of % cloud cover:
  - Done for a subset of L3 grid boxes that are sampled by MODIS and CALIPSO.
  - Compare CALIPSO and MODIS-derived PBL depths for the same scene.
  - If the MODIS PBL is too high or low, modify the assumption about the number of CTT pixels at the PBL top, then iterate until MODIS and CALIPSO agree.



CALIPSO vs. MODIS PBL

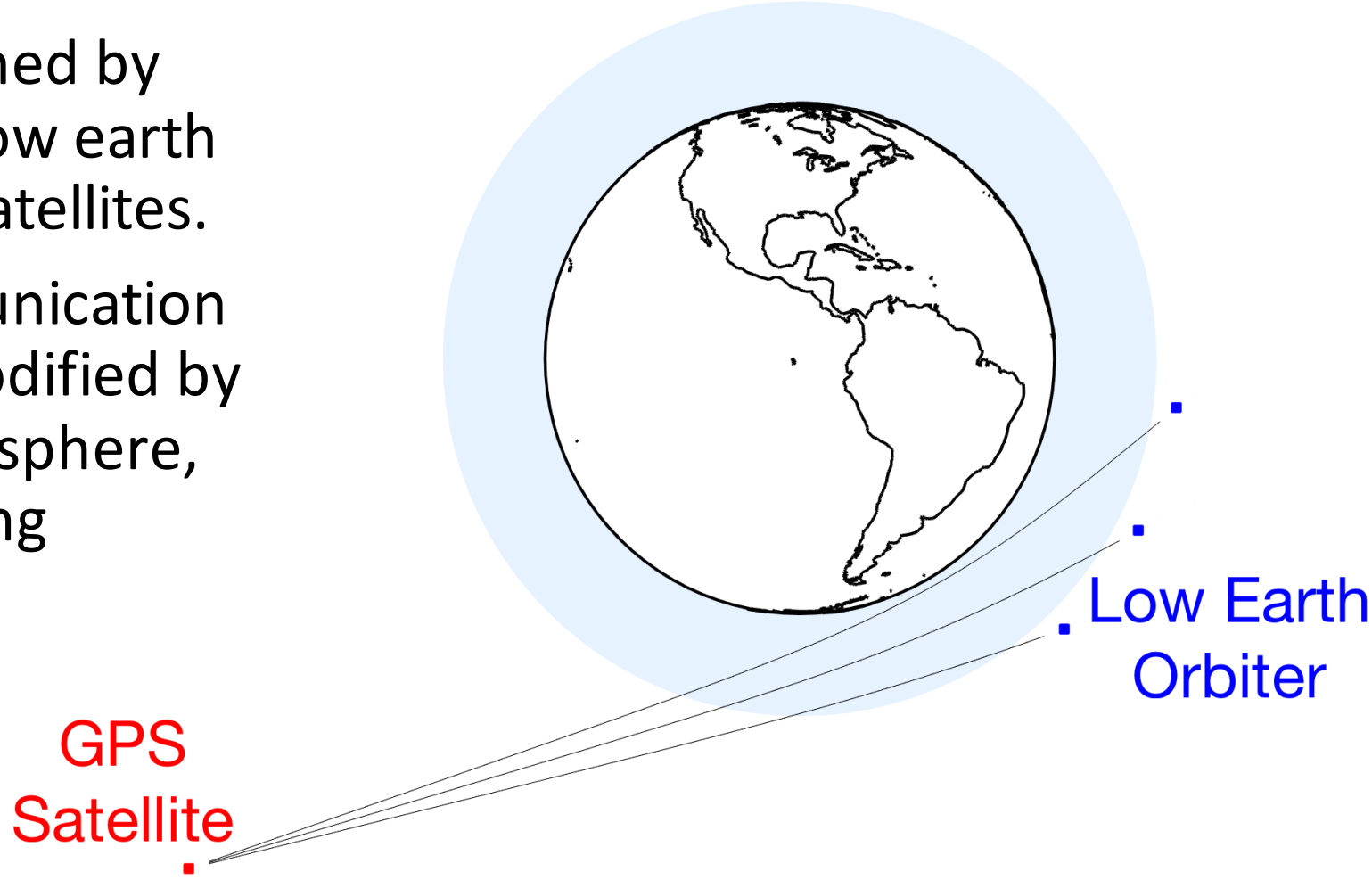


- Our MODIS PBL estimate compares reasonably well with the CALIPSO training dataset.
- Regions with high clouds are excluded from MODIS PBL.
- Correlations are significant and positive, and best with more cloud cover.



Comparison with COSMIC GPS PBL

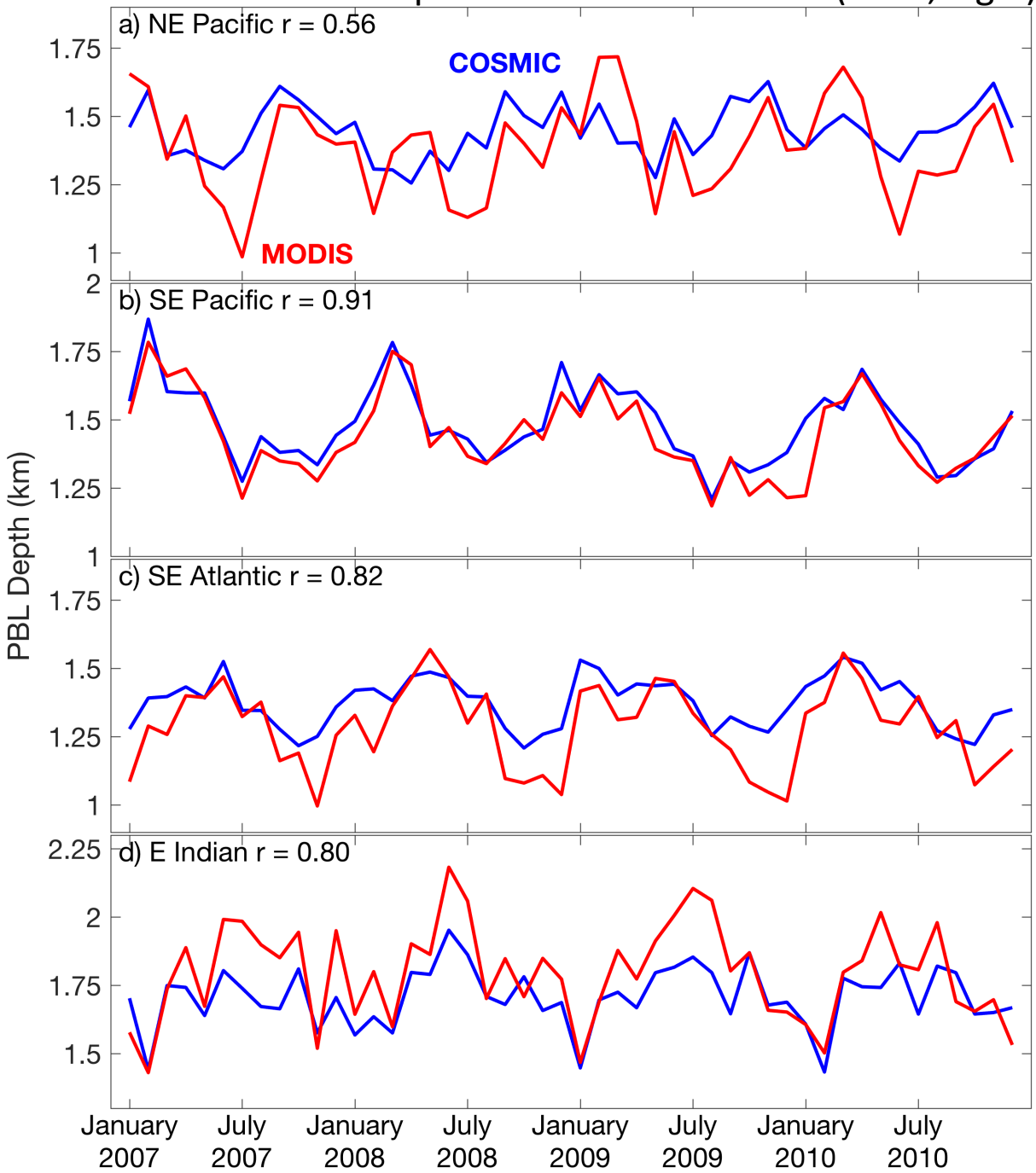
- Comparison with an independent PBL product, by Kuan Ting (Andy) O.
- COSMIC GPS PBL is determined by radio occultation between low earth orbiting satellites and GPS satellites.
- The line-of site radio communication between two satellites is modified by density changes in the atmosphere, usually in the form of a strong hydrolapse or inversion.



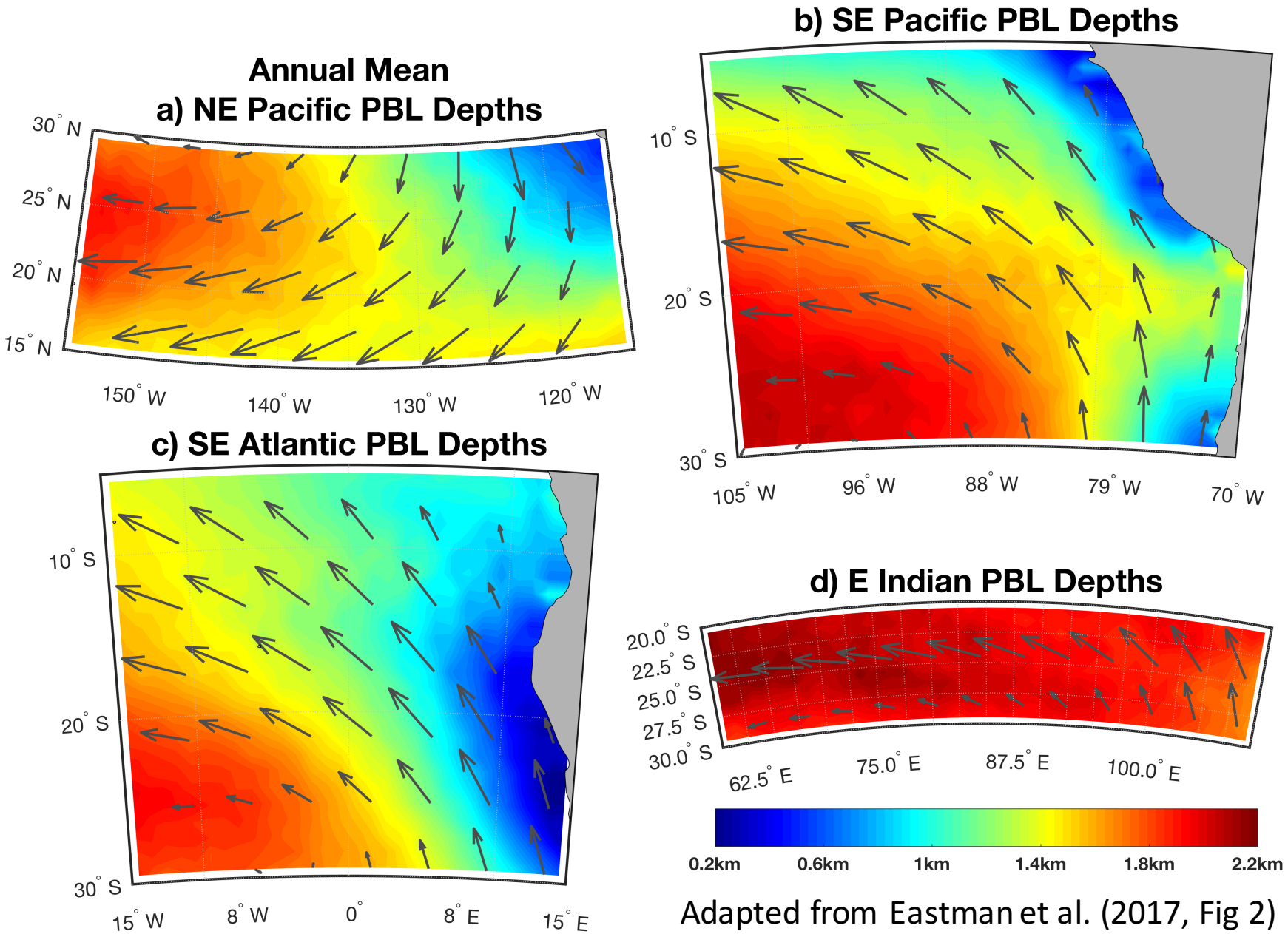
Comparison with COSMIC GPS PBL

- Monthly mean PBL depth values are shown as time series from 2007-2010.
- Correlation is strong between COSMIC and MODIS PBL depths.
- Temporal and spatial variation appear reasonable for our MODIS PBL product, and are independently verified, thanks Andy!

Adapted from Eastman et al. (2017, Fig 1)



Climatology of the Subtropical PBL, 2007-2010



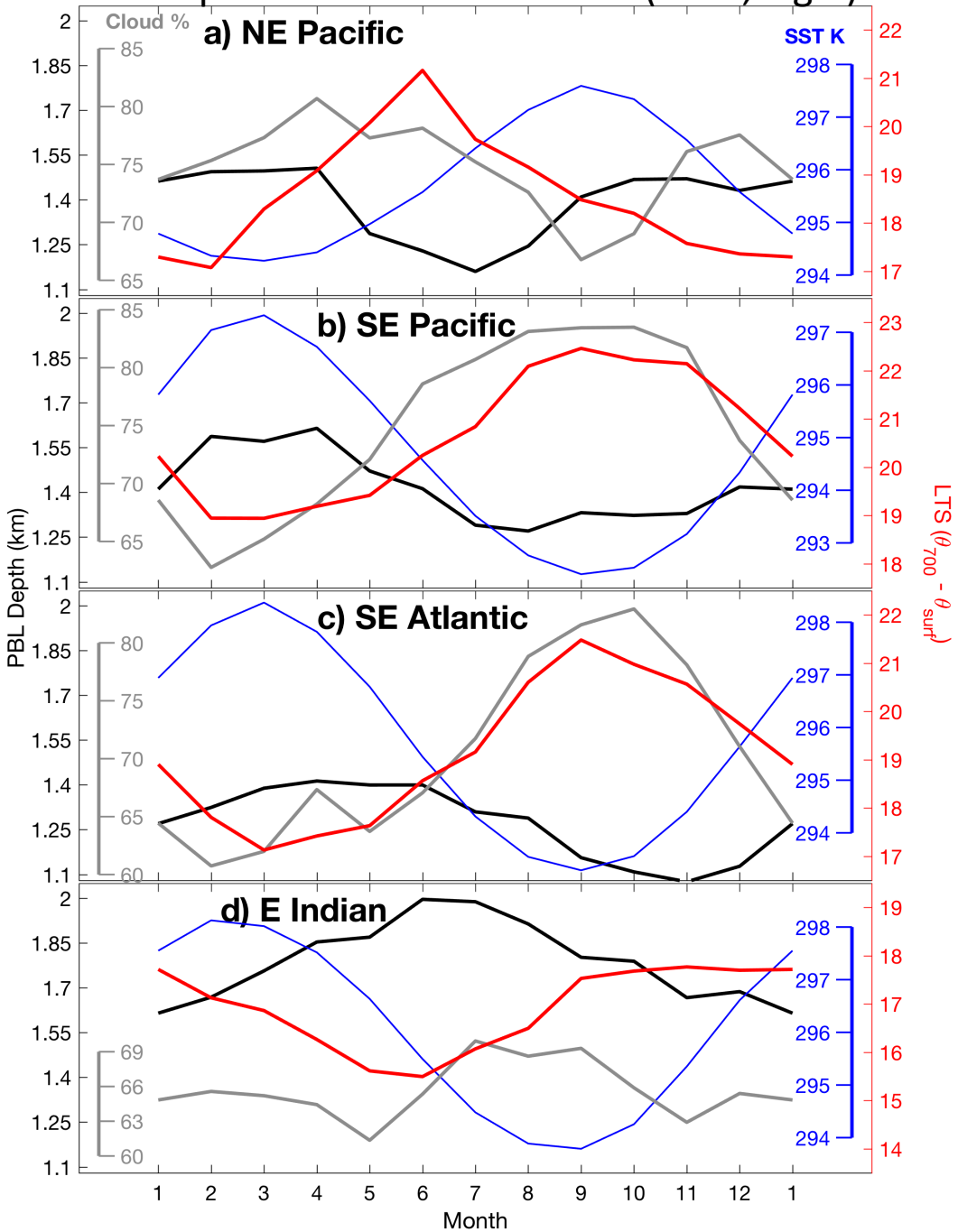
Adapted from Eastman et al. (2017, Fig 2)

- The annual mean climatologies of PBL depth match prior assumptions and models somewhat well.
- The PBL tends to be very shallow near the continents and deepens offshore.
- The mean wind fields (arrows) show the flow going across the PBL gradient (b & c).

Seasonal Cycle of the Eastern Subtropical PBL

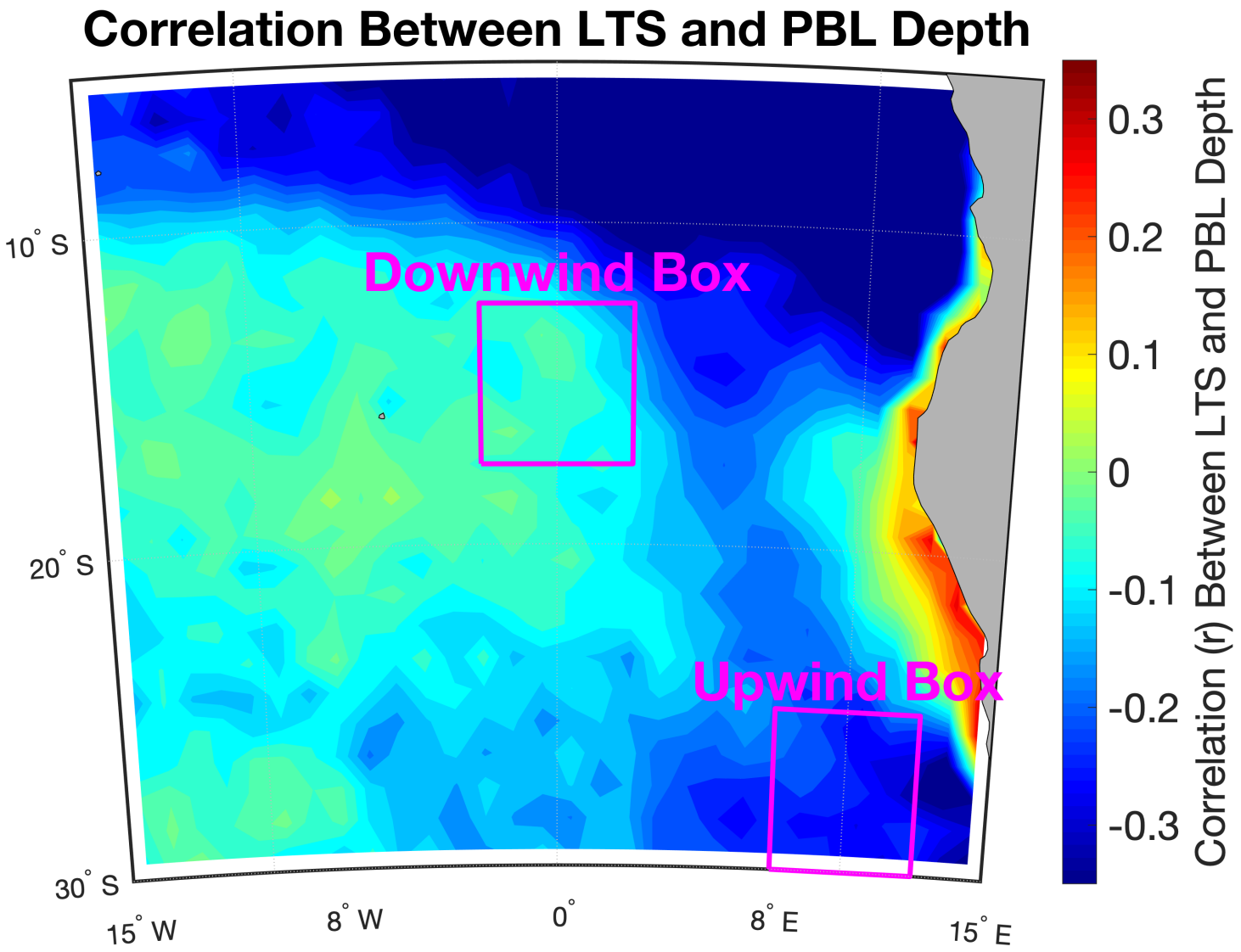
- The PBL tends to vary in depth throughout the year (black line), by about 300-400 meters on average.
  - The cycle in PBL depth matches the annual cycle in lower tropospheric stability (LTS), defined as the difference in θ between 700 and 1000 hPa.
  - High stability is associated with a shallow PBL.
- Cloud cover tends to vary in opposition to SST, with greater cloud cover associated with a cool sea surface.

Adapted from Eastman et al. (2017, Fig 5)



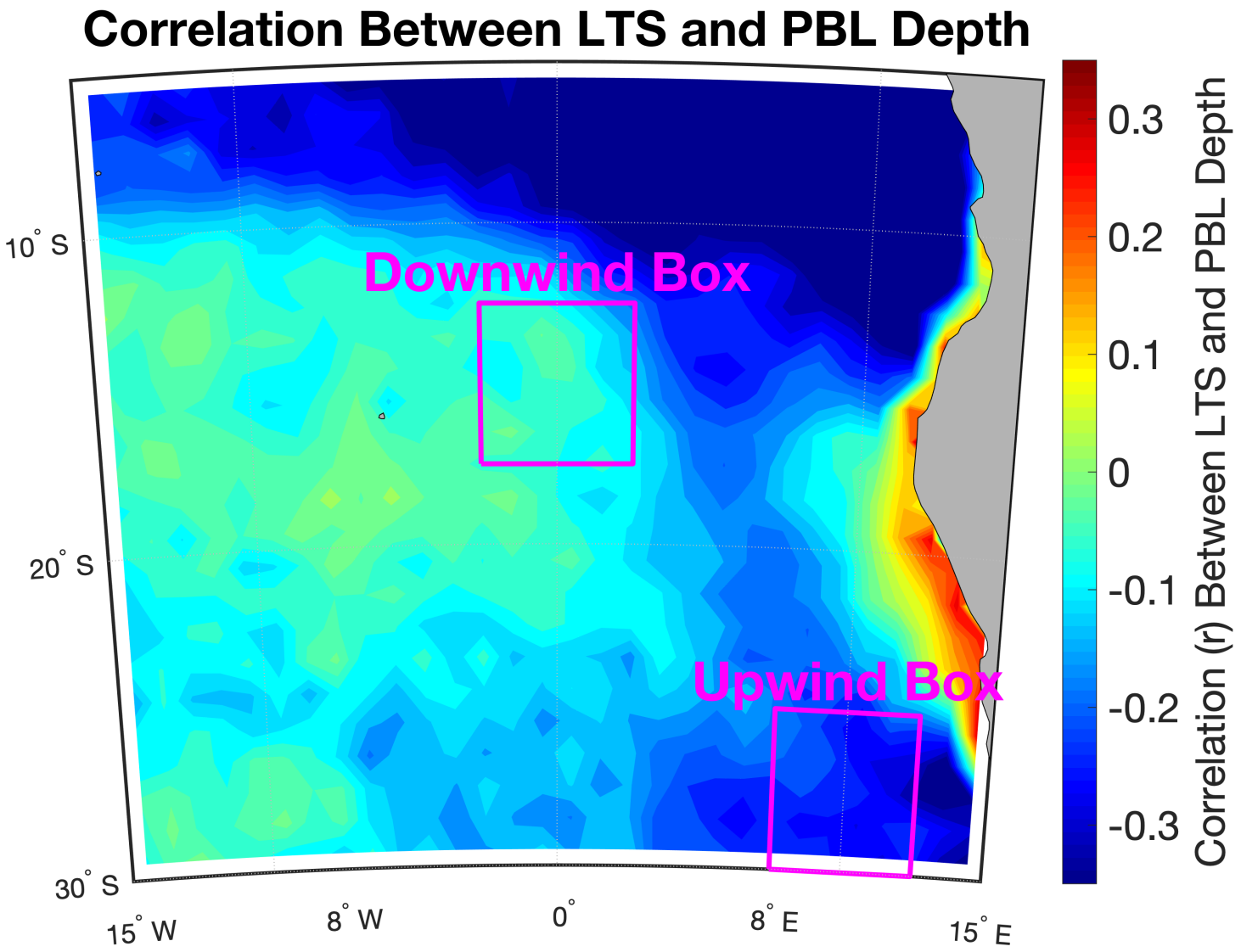
The PBL and LTS, Southeast Atlantic

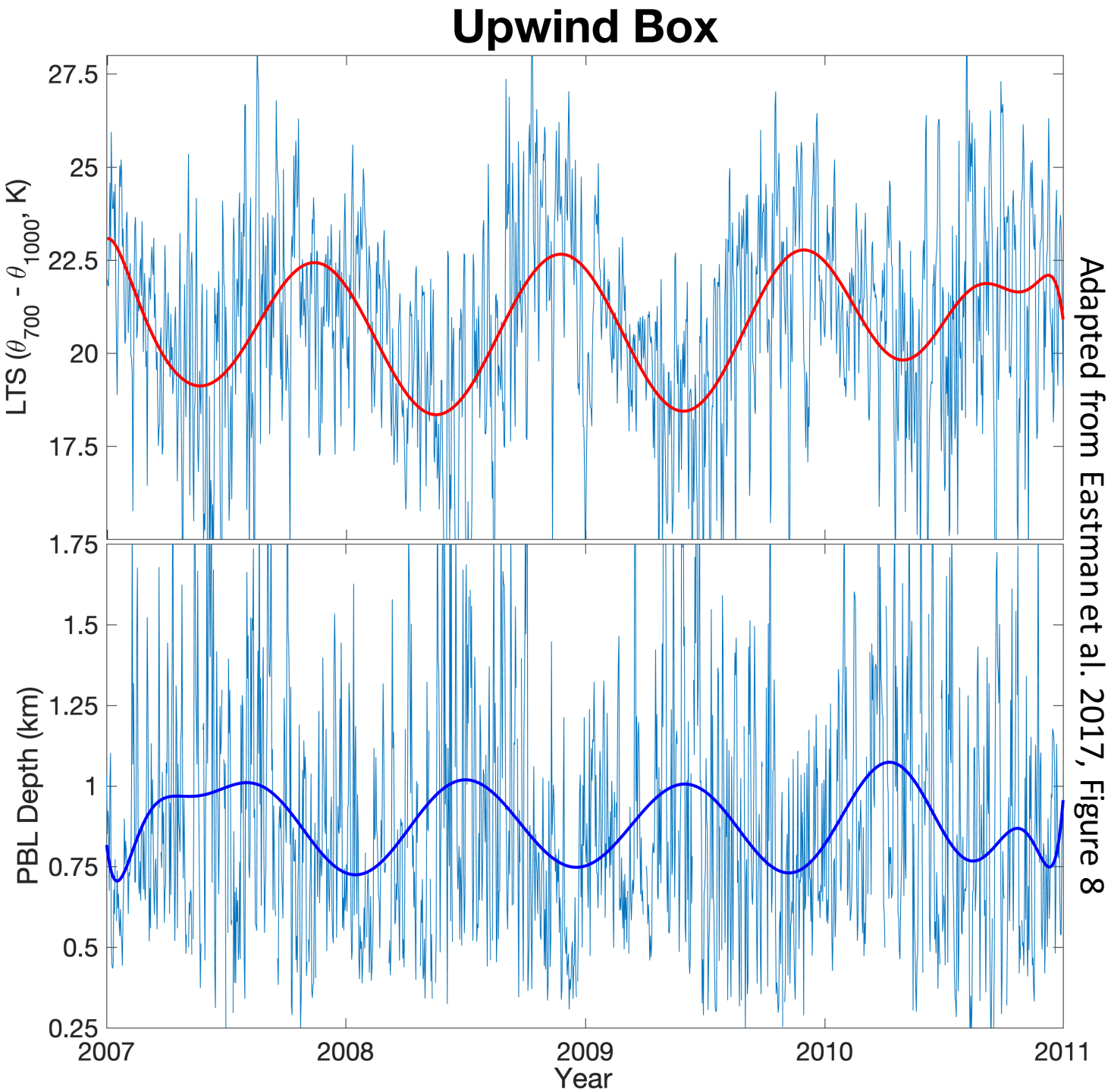
- The *regional average* annual cycle of PBL depth varies in opposition to LTS.
- If LTS is the primary driver of PBL depth, then this should be apparent on all time and spatial scales.
- Correlations between daily values of LTS and PBL depth are shown for each 1x1 L3 box in the SE Atlantic.



The PBL and LTS, Southeast Atlantic

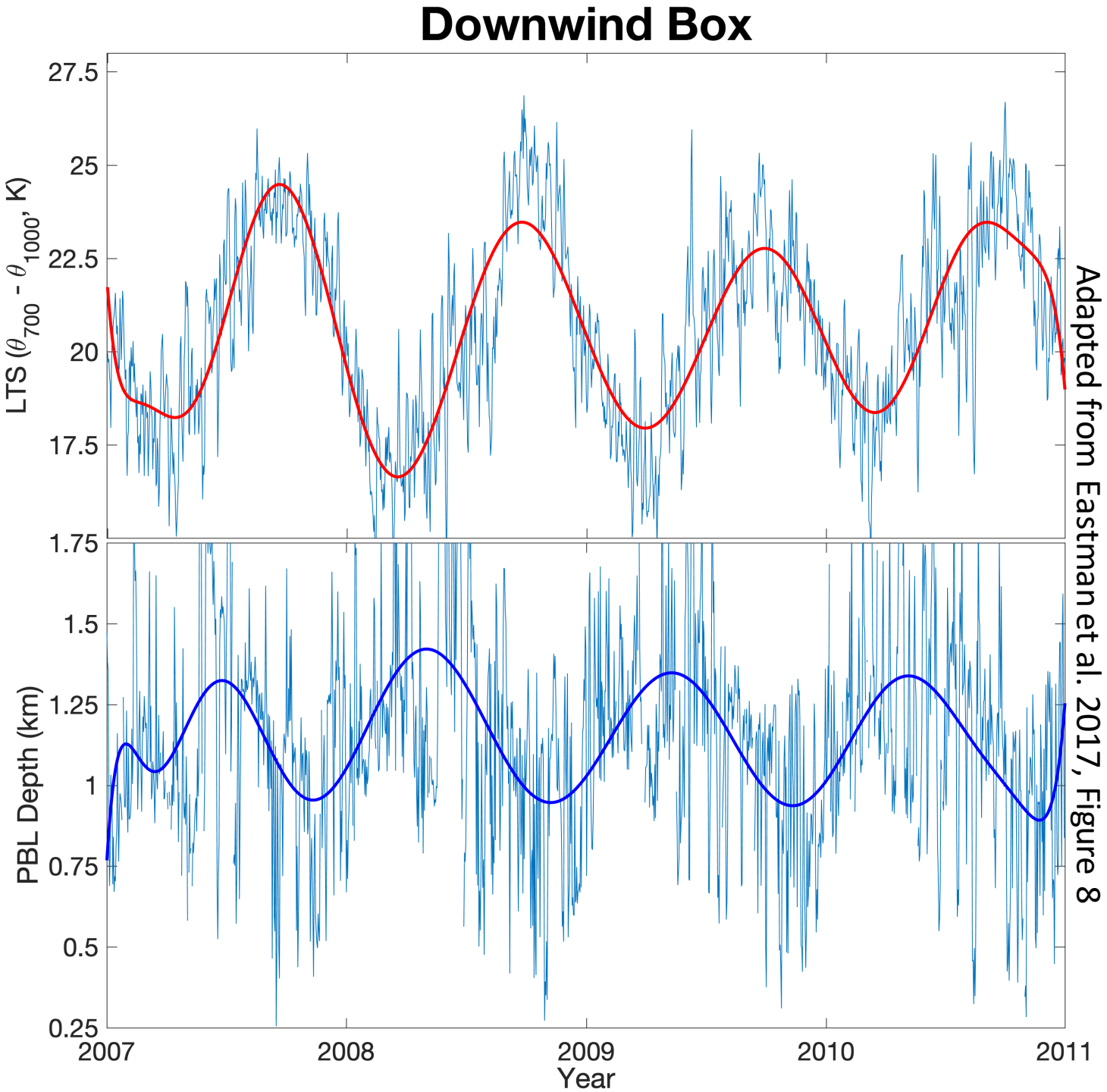
- The map of r values shows an inconsistent pattern, with negative correlations near the coast and upwind, but weak correlations downwind.
- We will compare the relationship between LTS and PBL depth in these two regions.





LTS and PBL Depth Upwind

- Time series of PBL depth and LTS are broken into two types:
  - Seasonal scale, long-term variability is shown by the blue and red curves fit to the time series (polynomial).
  - Daily, deseasonalized 'residuals' are calculated by subtracting the seasonal scale variability from the time series.
- Seasonal scale variations compare as expected upwind.

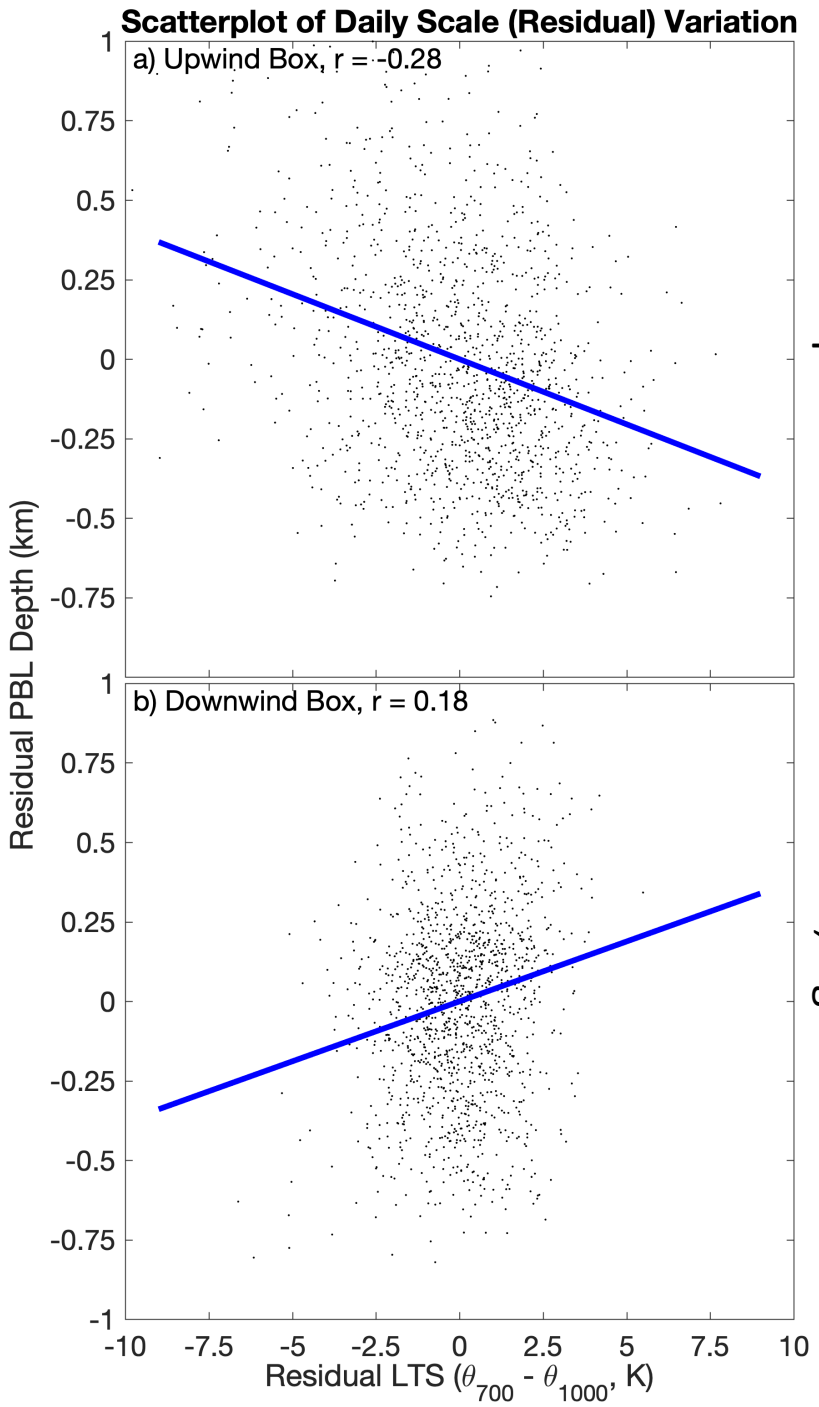


LTS and PBL Depth Downwind

- Seasonal scale variations again compare as expected downwind.
- In both upwind and downwind boxes, the seasonal-scale variations of PBL depth and LTS are anticorrelated.
- What about the residual, daily-scale variability

LTS and PBL Depth on Daily Timescales

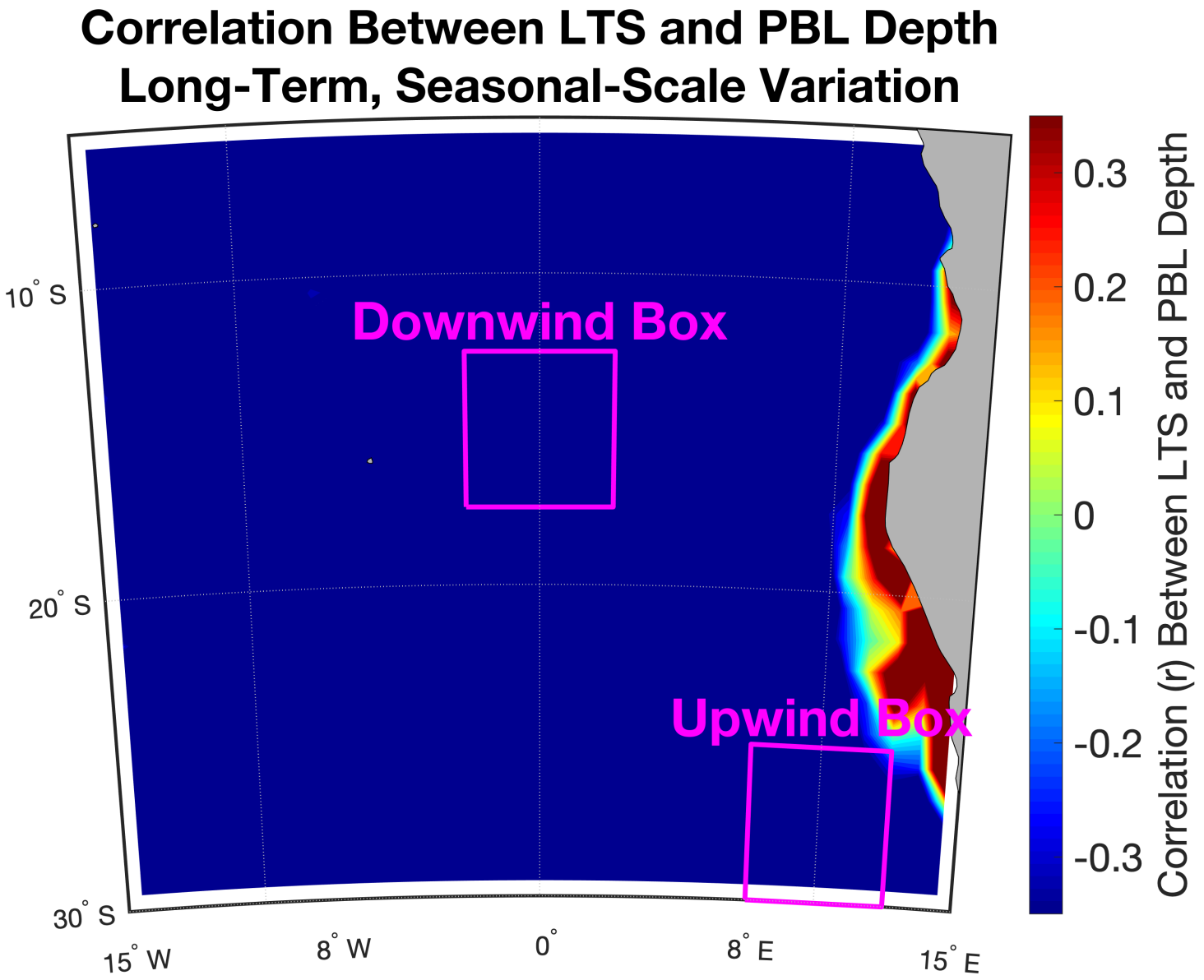
- Scatterplots between residual (deseasonalized) time series of PBL depth and LTS.
- Correlations remain negative upwind.
- Correlation flips downwind, now showing short-term variability to be positively correlated.
- On daily timescales, the variability of PBL depth is not consistently explained by the strength of the inversion.



Adapted from Eastman et al. 2017, Figure 8

Daily Versus Seasonal Timescales

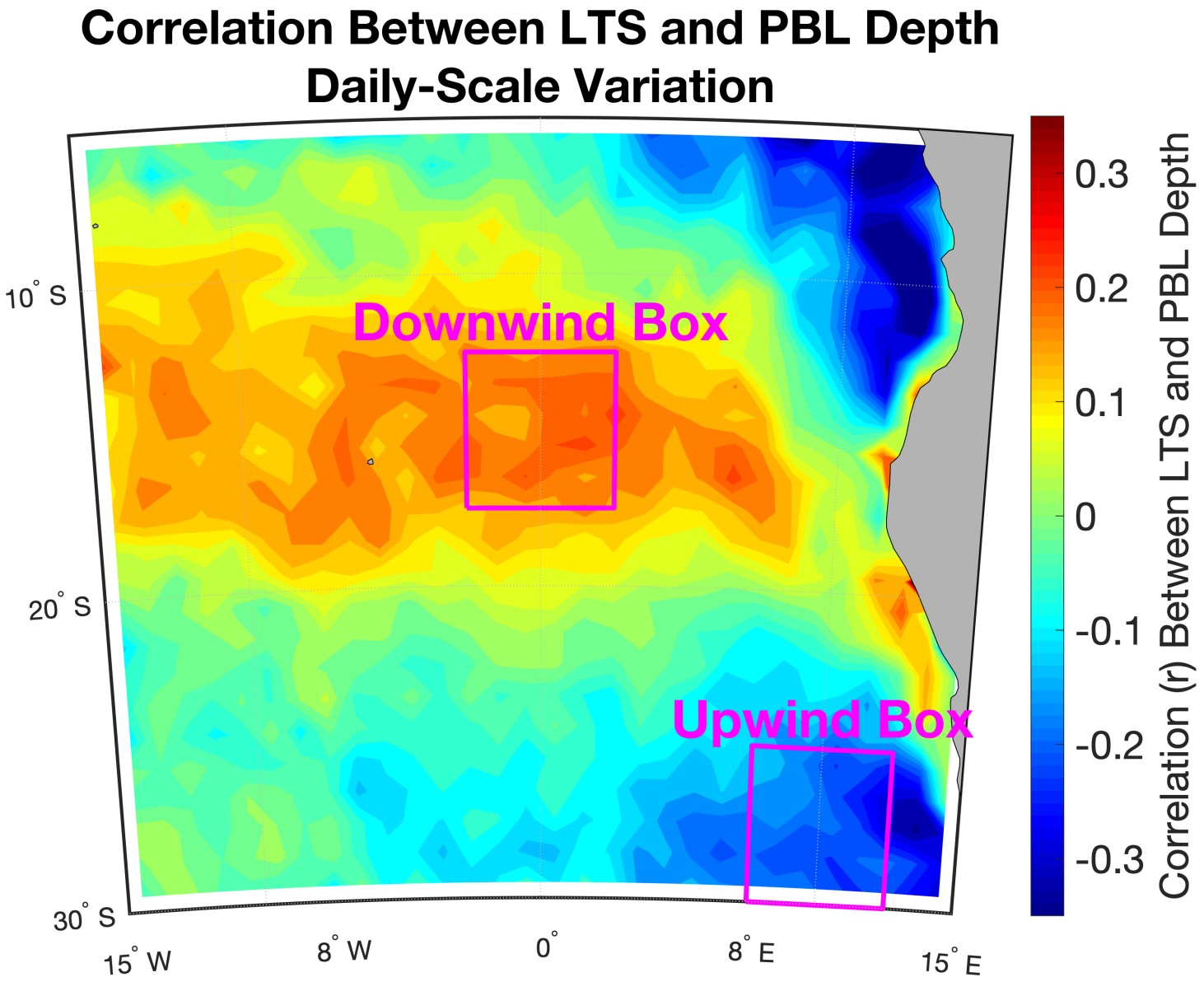
- A similar analysis is carried out for all 1x1 L3 boxes.
- Here we show that the seasonal scale time series of LTS and PBL depth are uniformly anticorrelated, except very near the coast.



Adapted from Eastman et al. 2017, Figure 9c

Daily Versus Seasonal Timescales

- Daily-scale time series of LTS and PBL depth are not uniformly correlated.
  - LTS and PBL depth remain anticorrelated upwind.
  - Downwind, the relationship flips.
- If LTS is not consistently driving day-to-day variability of PBL depth, what is, and how do we show it?



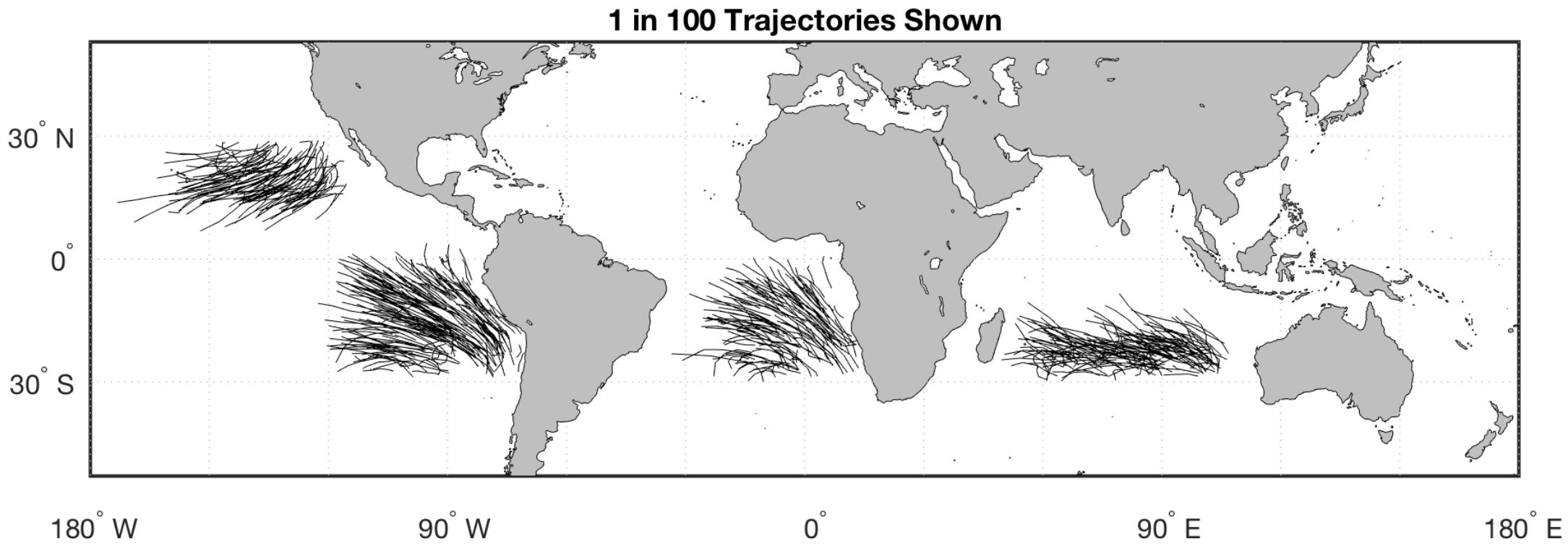
Adapted from Eastman et al. 2017, Figure 10c

Motivation for a Comprehensive Lagrangian Study

- Correlation studies are limited by a few factors:
  - Causality, geographic disparities when using lag correlations.
  - Covariance between predictor variables.
  - Differences in time scales, effect follows cause at different lag times for different predictors.
- A parcel-tracking Lagrangian study can resolve much of this.
  - Trajectories can be grouped by differences in predictor variables, then their cloud and PBL evolutions can be compared.
  - The response to a predictor variable can be seen at several lag times as parcels advect to different regions.
  - We can control for covariance between predictors by looking at subsets of trajectories where a chosen predictor remains constant.

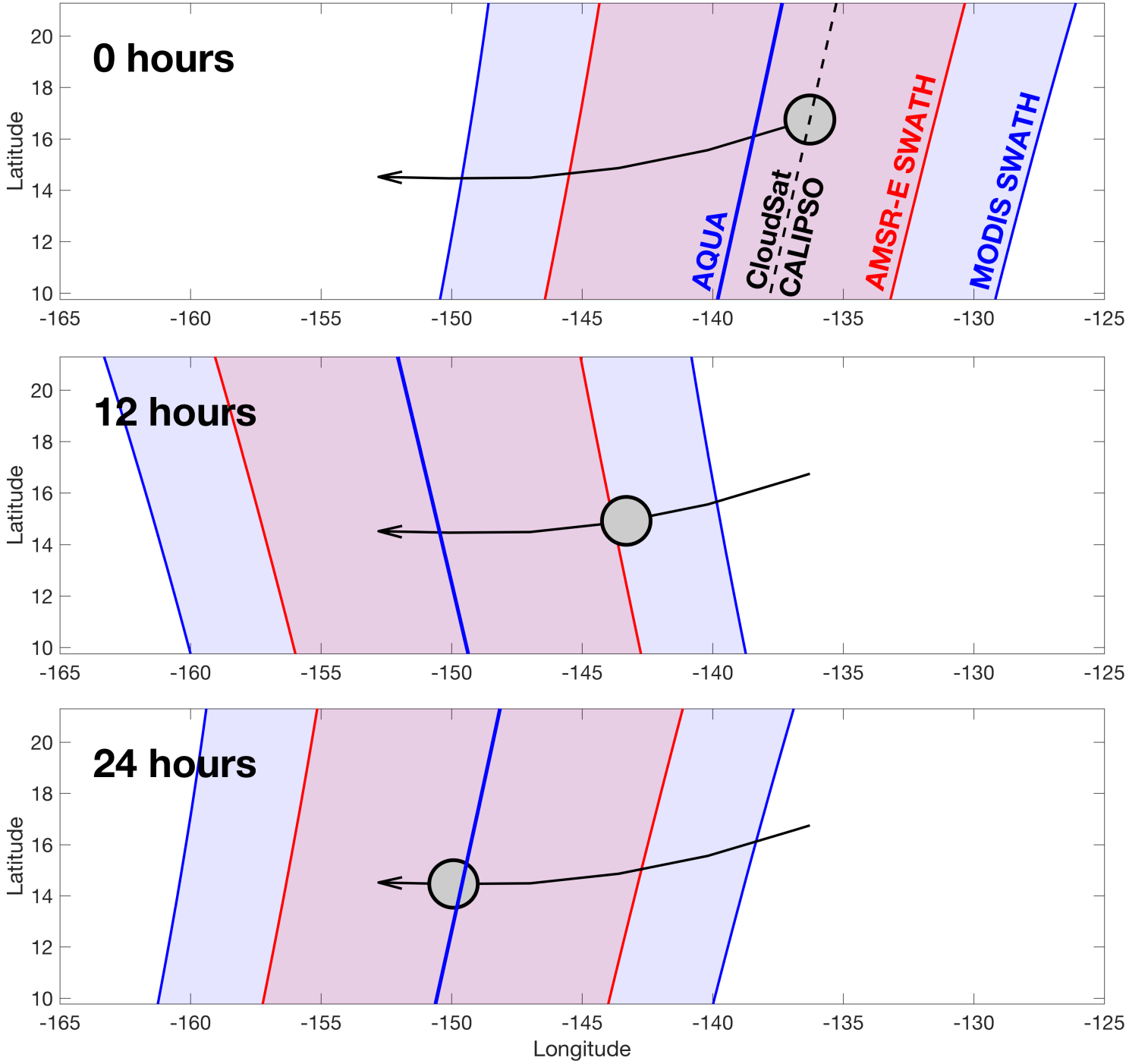
A 4-Year Lagrangian Study of PBL Evolution

- ~160,000 trajectories are run in the subtropics for years 2007-2010.
- Driven forward by ERA-Interim isobaric winds at 925 hPa for 48 hours.
- Trajectories begin along the CloudSat/CALIPSO track to quantify precipitation at 0 hours.



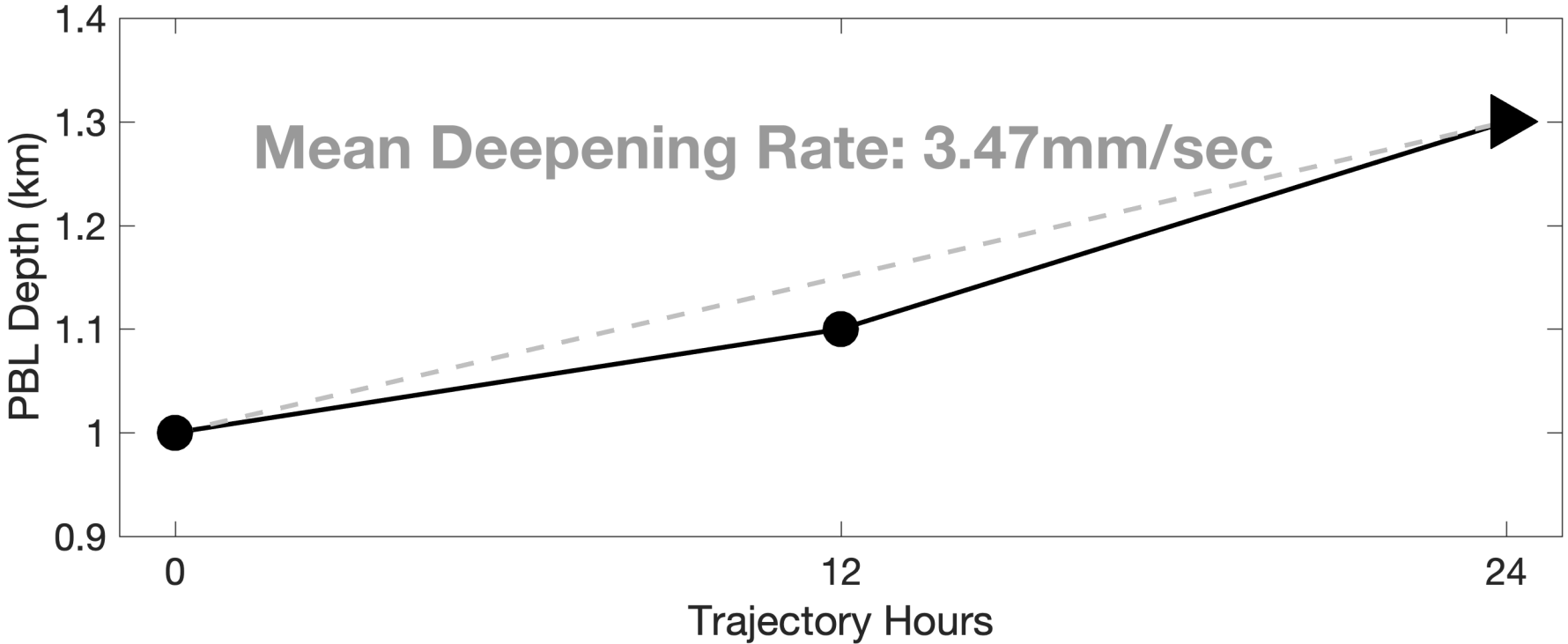
Structure of a Lagrangian PBL Study

- Same as our earlier 2016 paper, just bigger.
- CloudSat, CALIPSO, MODIS and AMSR/E observe our trajectory at 0 hours.
- Instruments with a wide swath (MODIS and AMSR/E) observe the clouds as they evolve downwind at 0-48 hours.



Lagrangian Deepening Rates

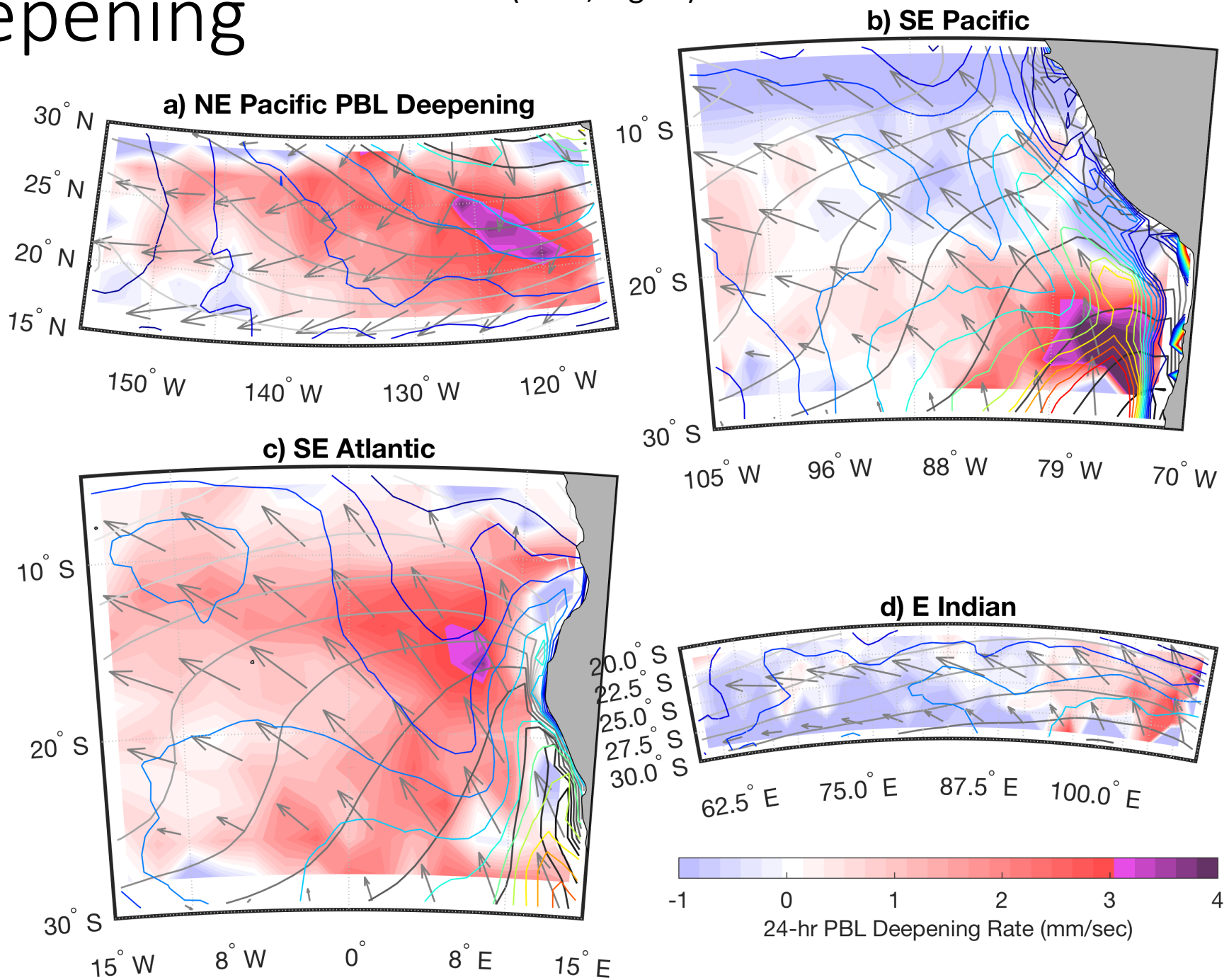
- With ~160,000 trajectories, we can look at the mean deepening rate along all trajectories.
- Mean deepening is defined here as the mean change in PBL depth over a complete diurnal cycle in mm/second.



Lagrangian Deepening Rates

Eastman et al. (2017, Fig 11)

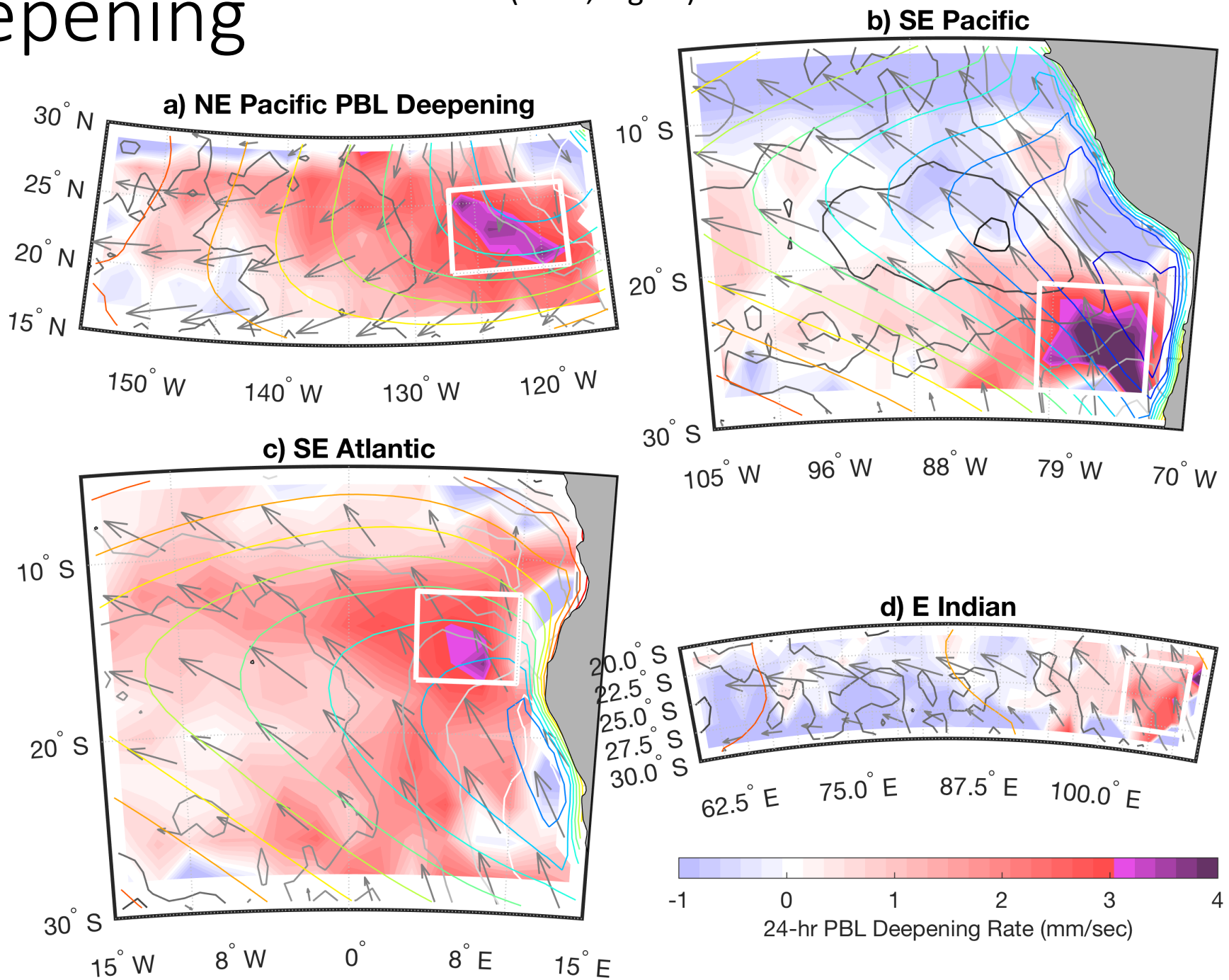
- The mean deepening rate for each trajectory is assigned to its midpoint then all rates are gridded and contoured.
- Also shown are SST (gray) and 700 hPa subsidence (colored).
- Regions of intense deepening stand out.
- Often coincide with decline in subsidence.



Lagrangian Deepening Rates

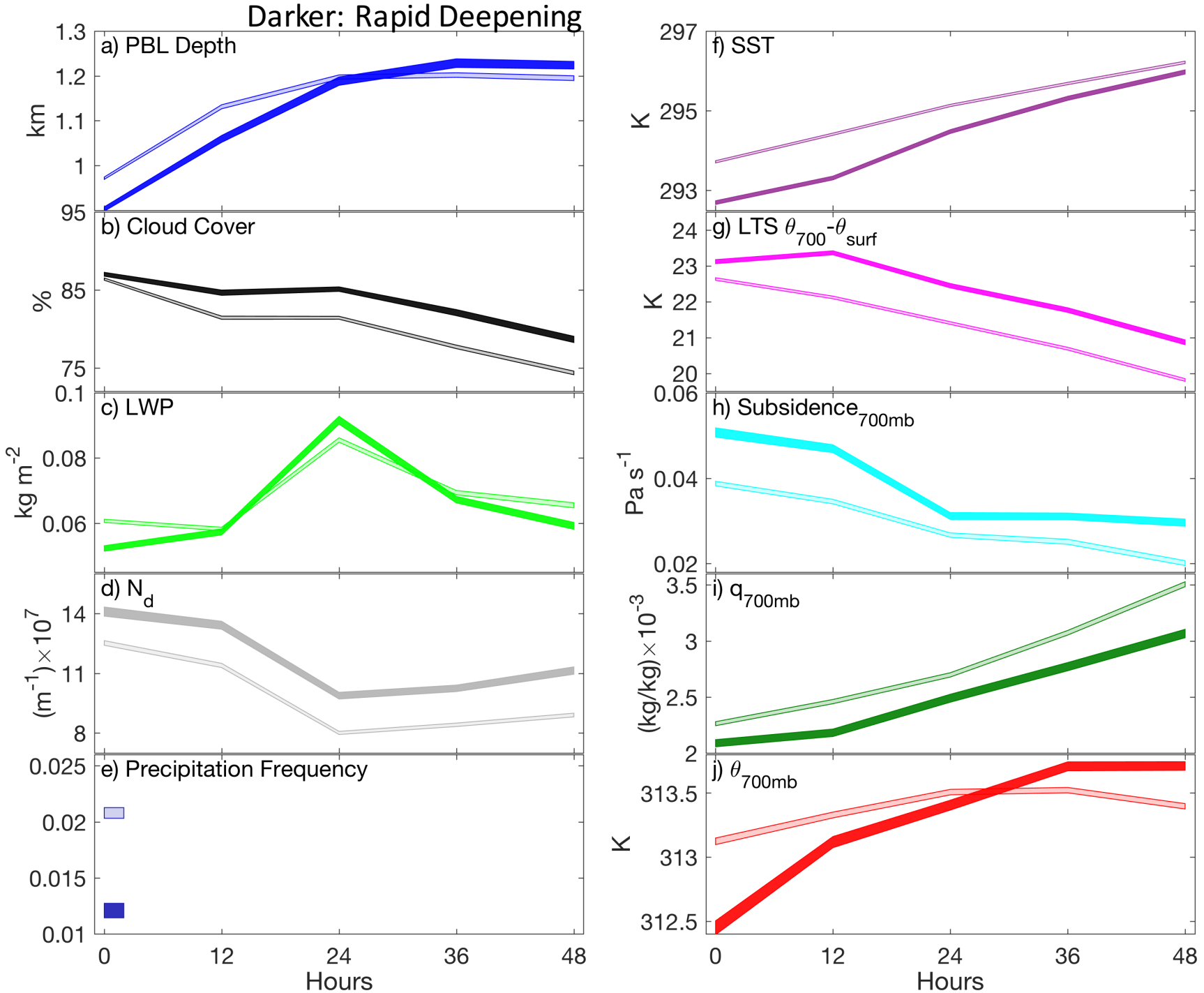
Eastman et al. (2017, Fig 12)

- Regions of intense or rapid deepening shown in white boxes.
- Also shown are LWP (gray) and LTS (colored).
- In SE Pacific, LWP peak is situated just downwind of regions of intense deepening.
- What is happening in these regions?



Regions of Rapid Deepening

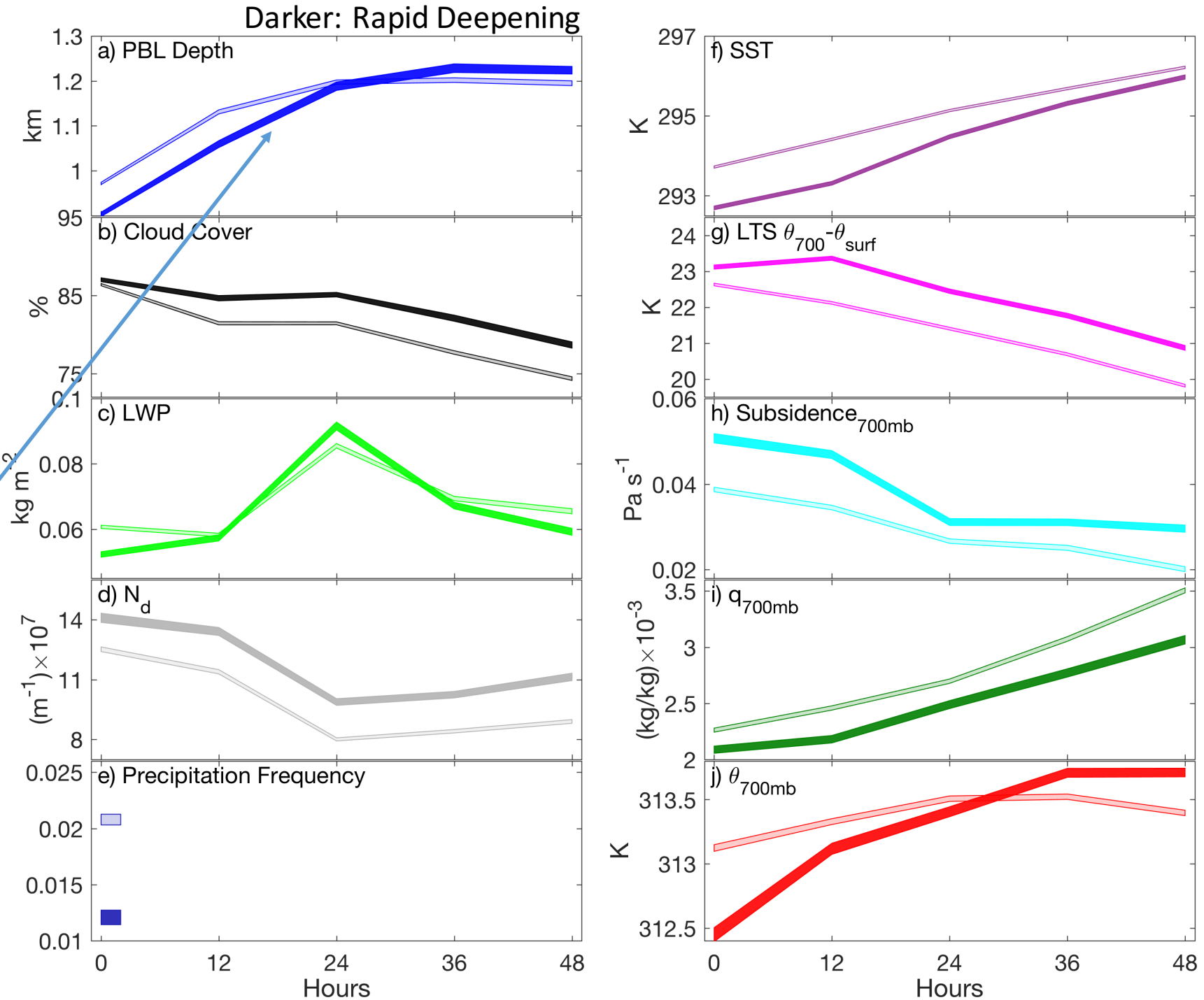
- We compare the mean evolution of cloud & PBL variables for two composite trajectories.
  - **Darker lines:** trajectories pass through **rapid deepening** regions.
  - Lighter lines: Start on eastern half, but do not pass through rapid deepening regions.



Eastman et al. (2017, Figure 13)

Regions of Rapid Deepening

- Variables internal to the clouds and PBL show significant differences in regions of rapid deepening.
  - **PBL starts shallower, ends deeper**.
  - Cloud cover remains higher
  - LWP spikes before declining
  - Nd is greater
  - Less rain at 0-hours



Eastman et al. (2017, Figure 13)

Regions of Rapid Deepening

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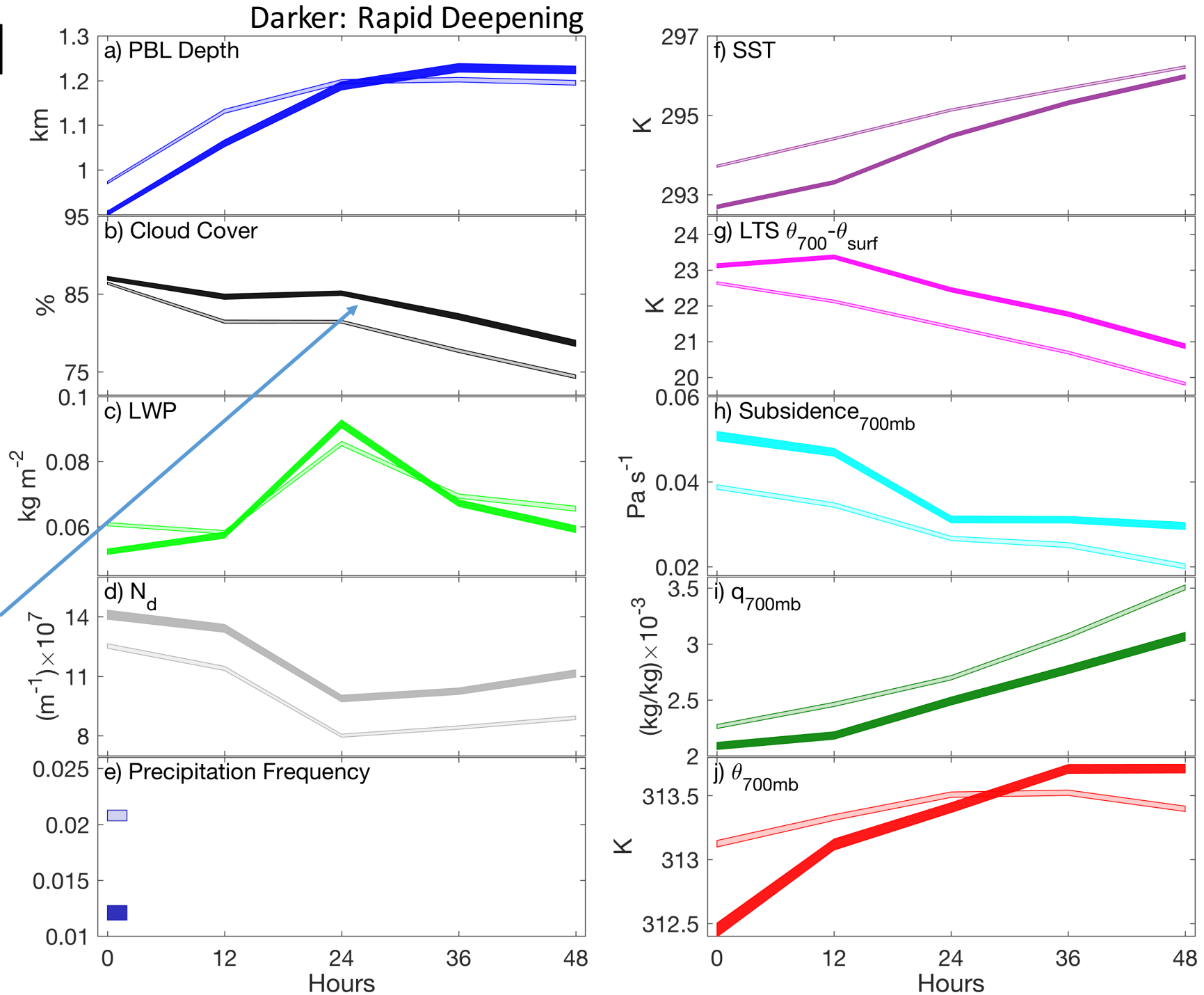

Eastman et al. (2017, Figure 13)

Regions of Rapid Deepening

- Variables internal to the clouds and PBL show significant differences in regions of rapid deepening.
  - PBL starts shallower, ends deeper.
  - Cloud cover remains higher
  - **LWP spikes before declining**
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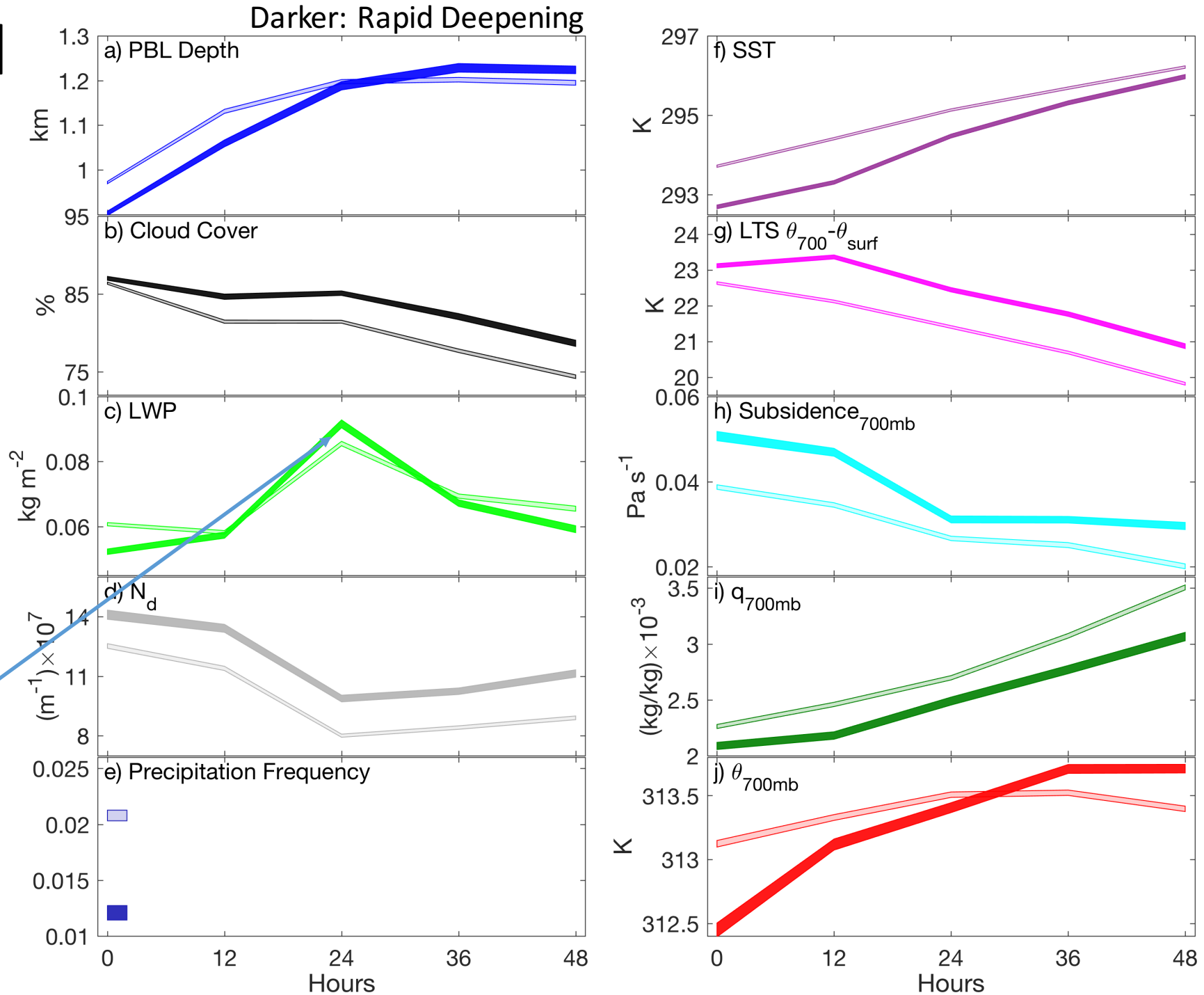

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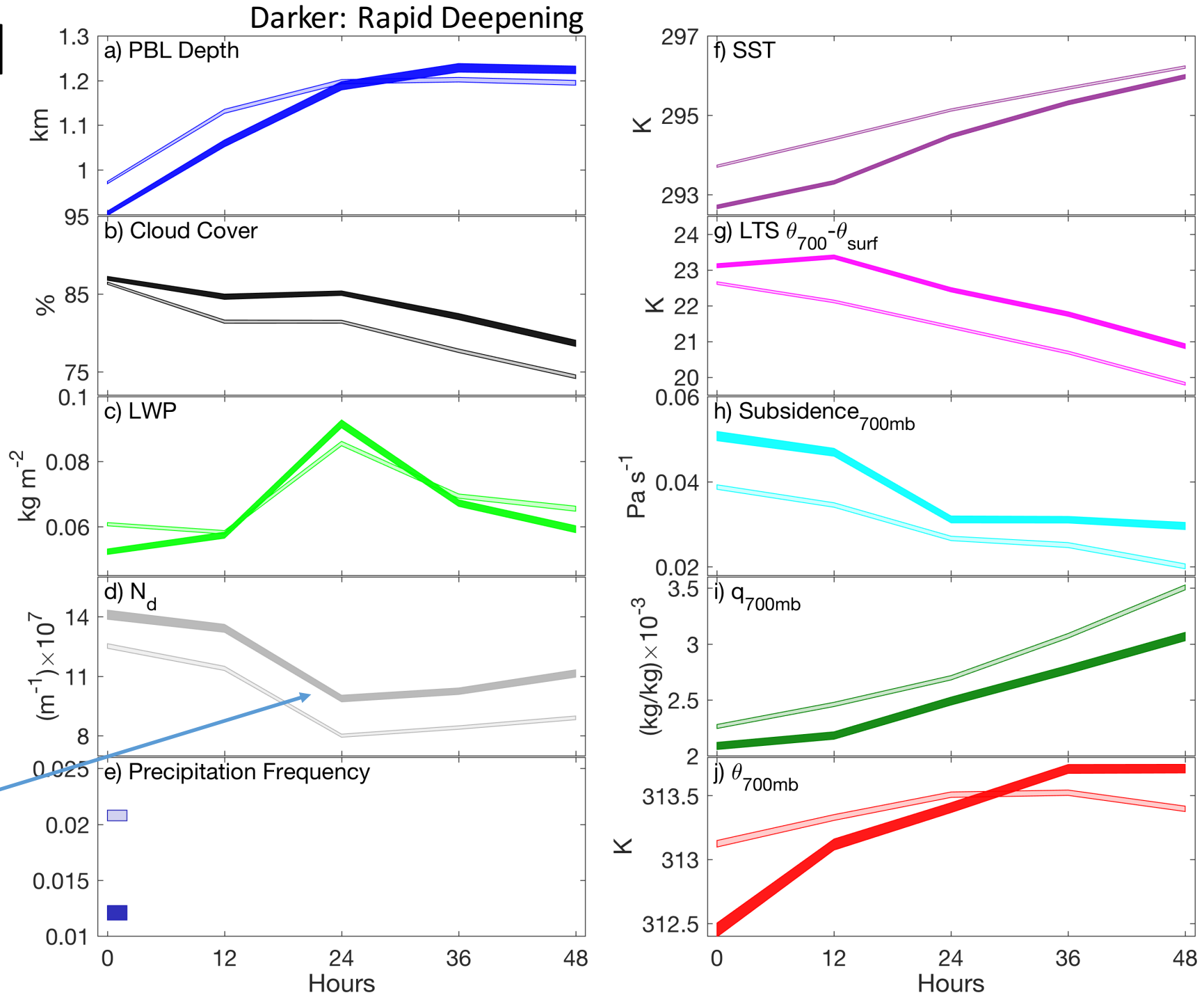

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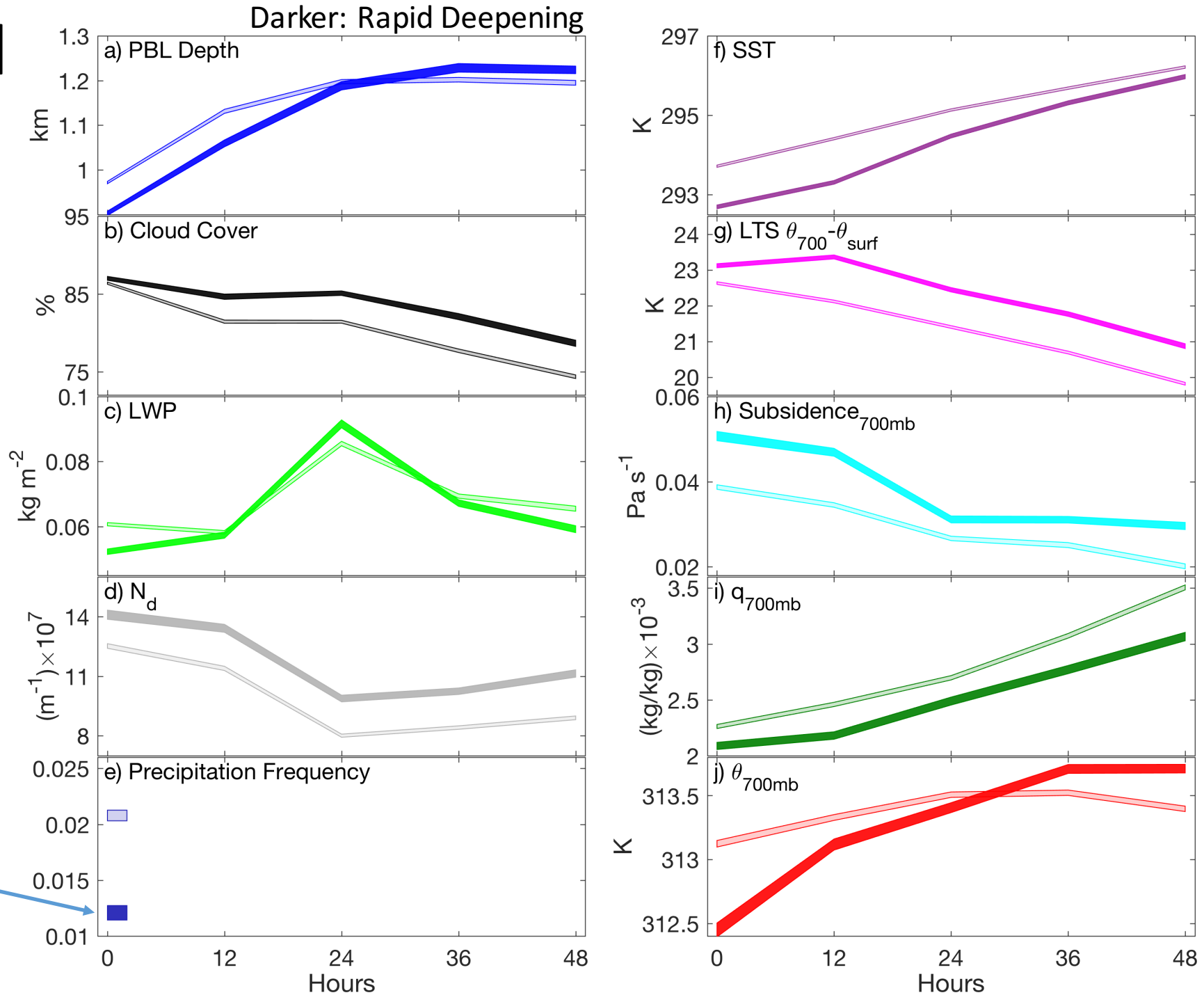

Eastman et al. (2017, Figure 13)

Regions of Rapid Deepening

- Variables external to the PBL also show significant differences in regions of rapid deepening.
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  - Subsidence declines more initially.
  - 700 hPa specific humidity is lower.
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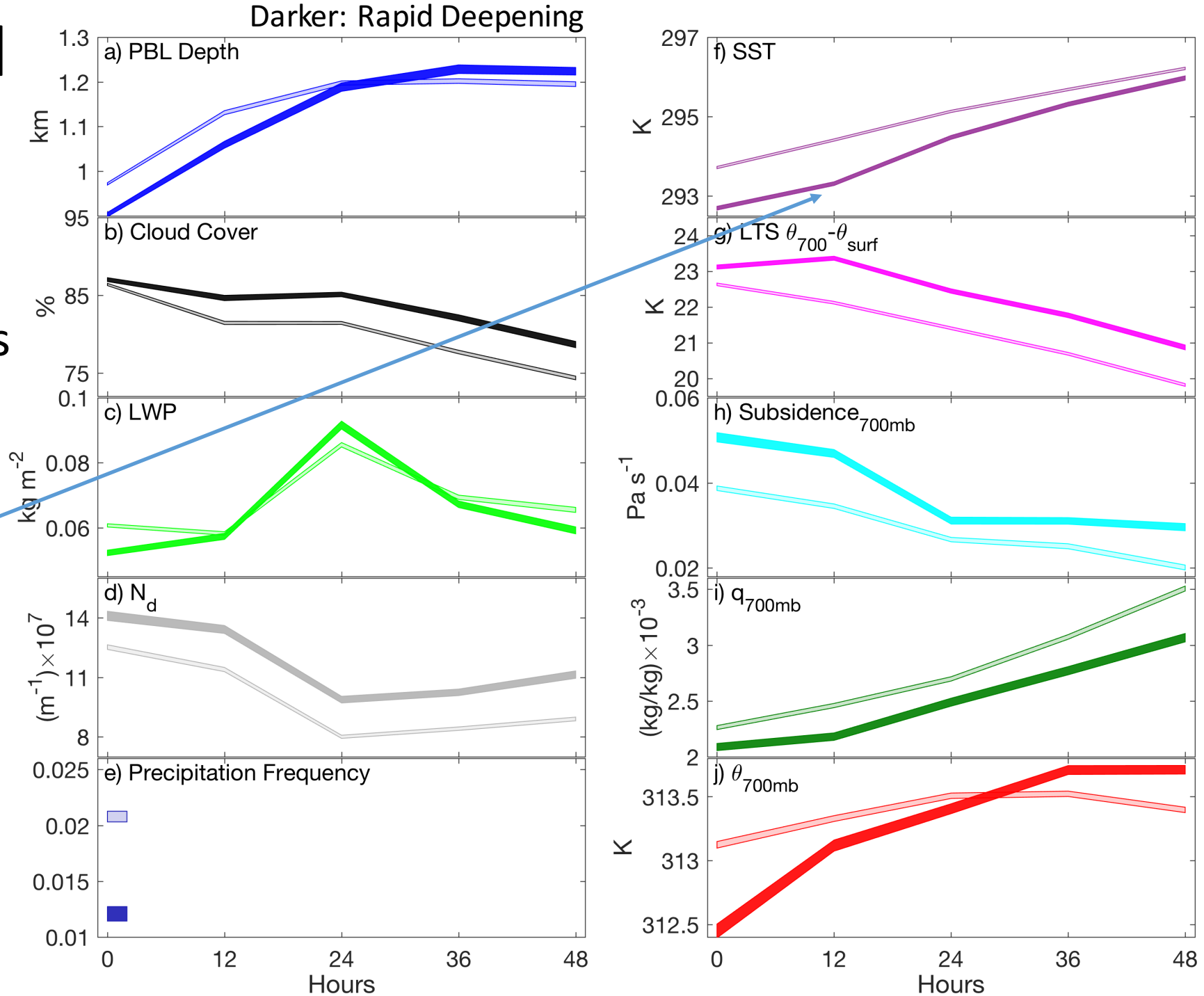

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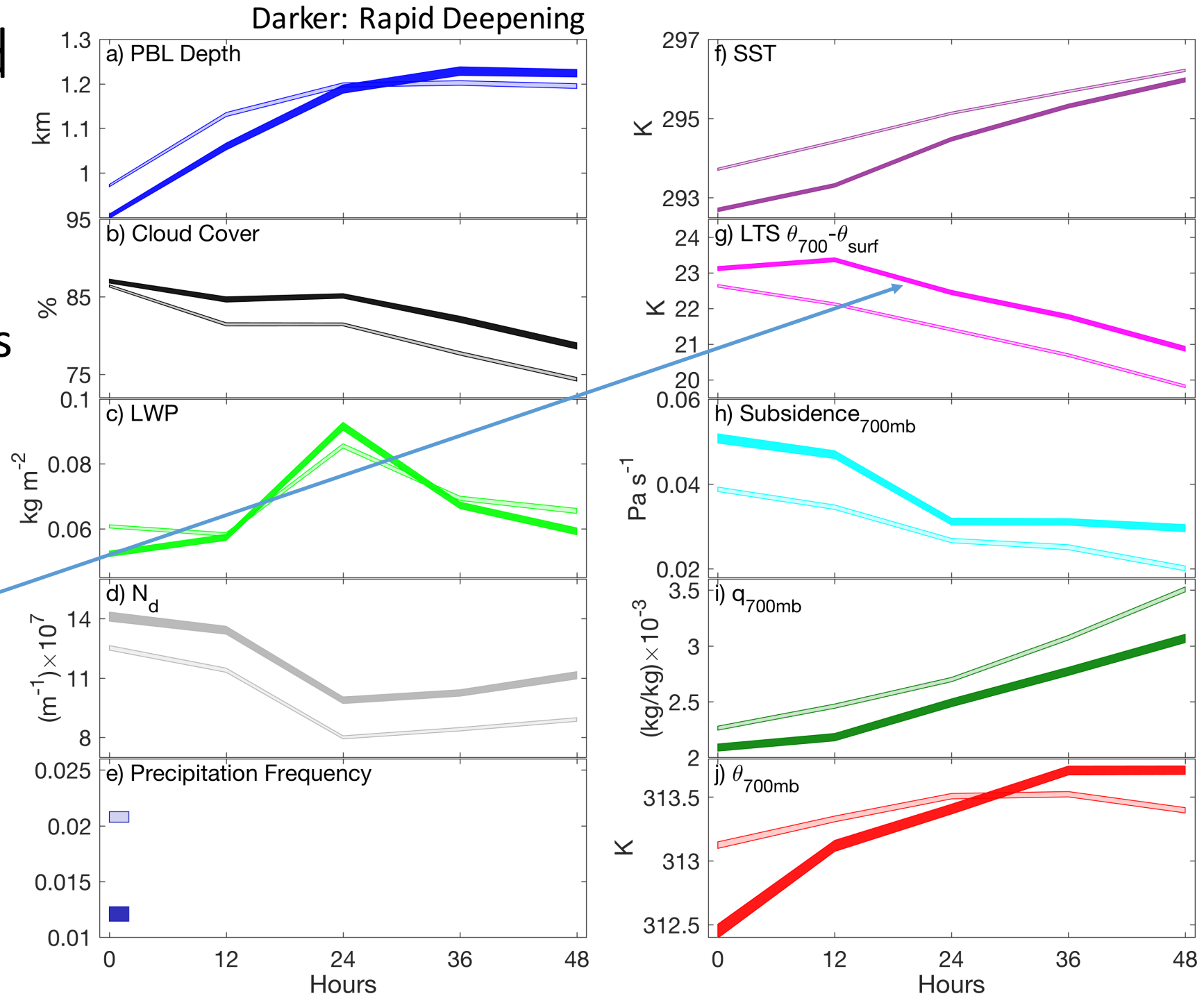

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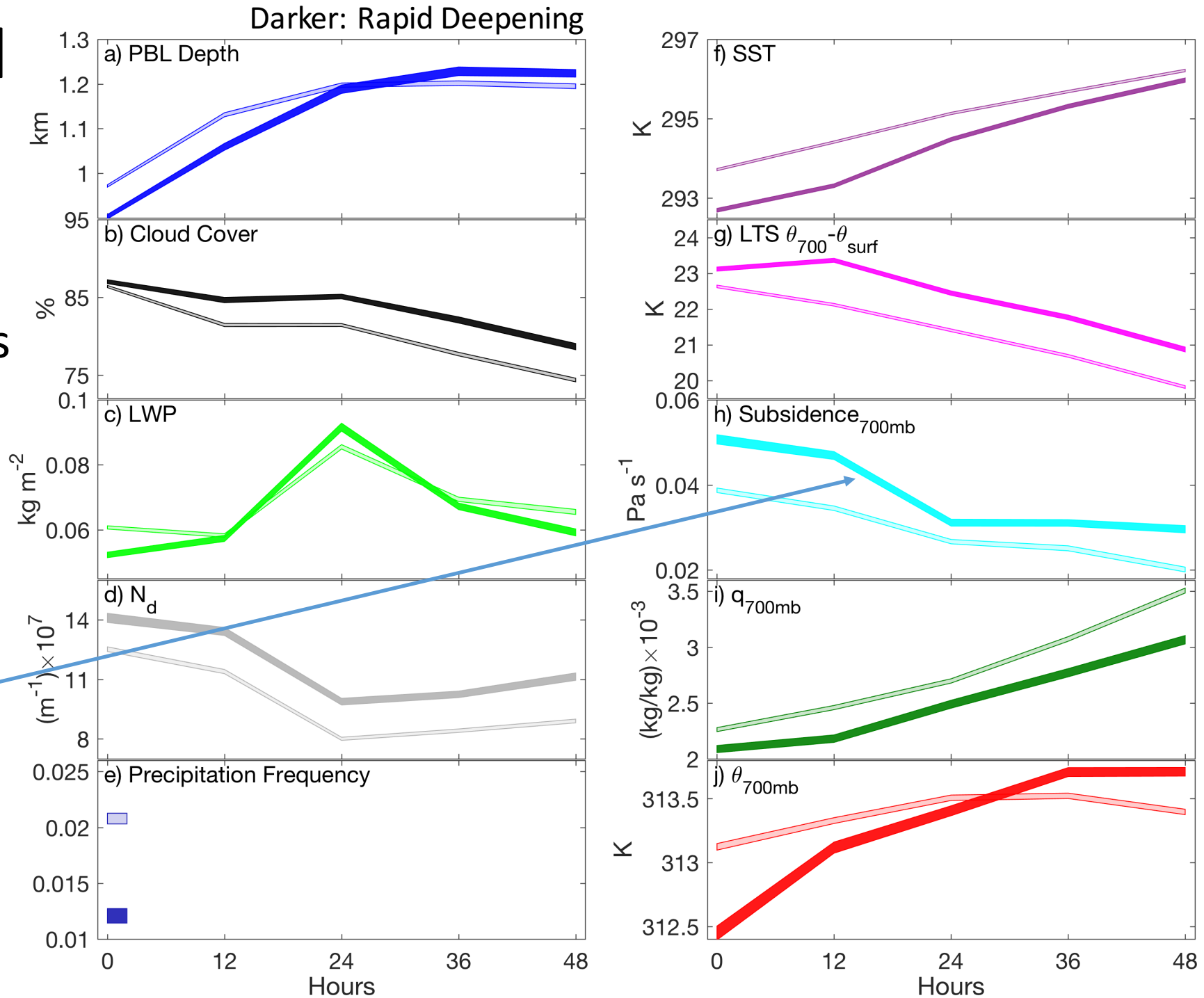

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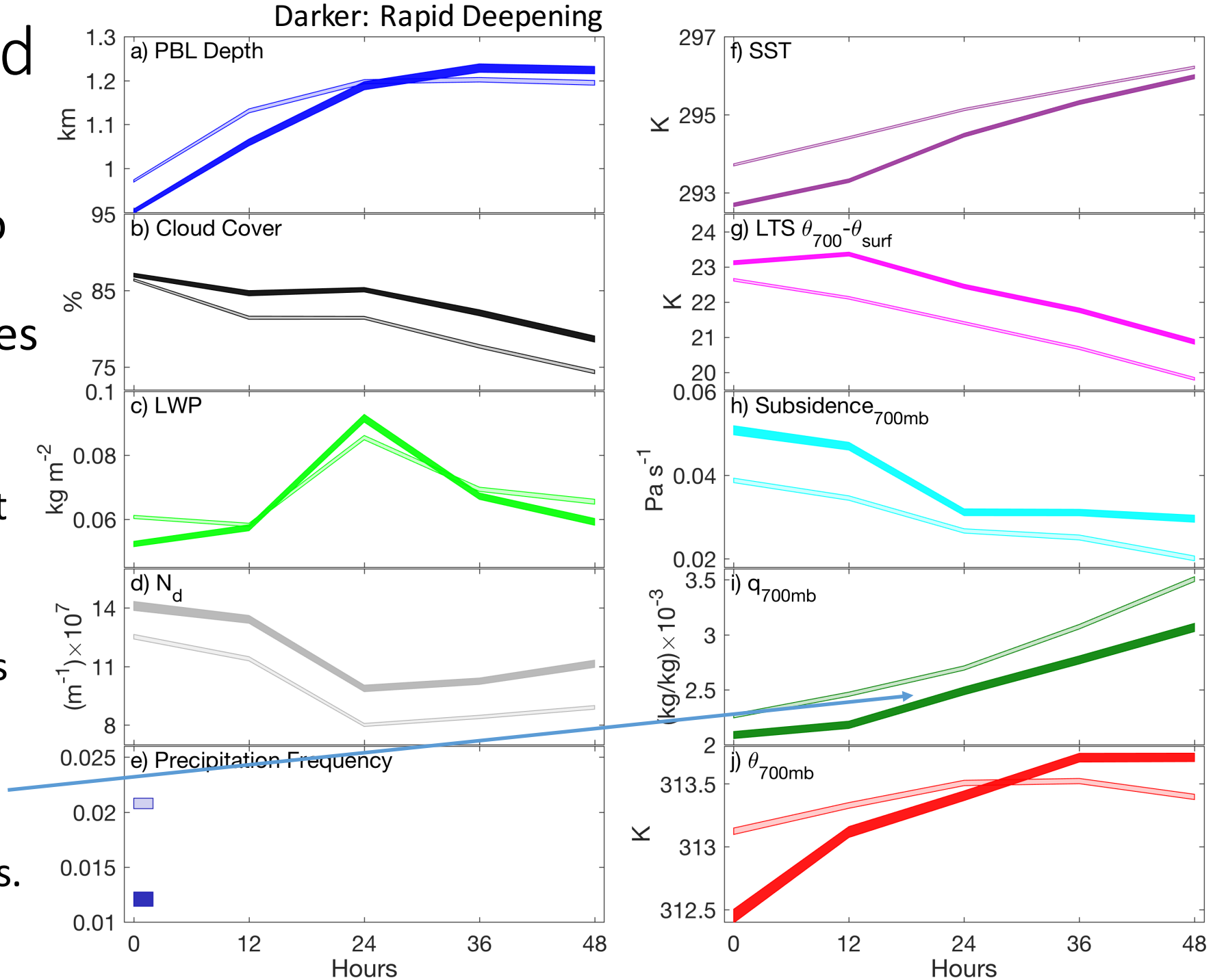

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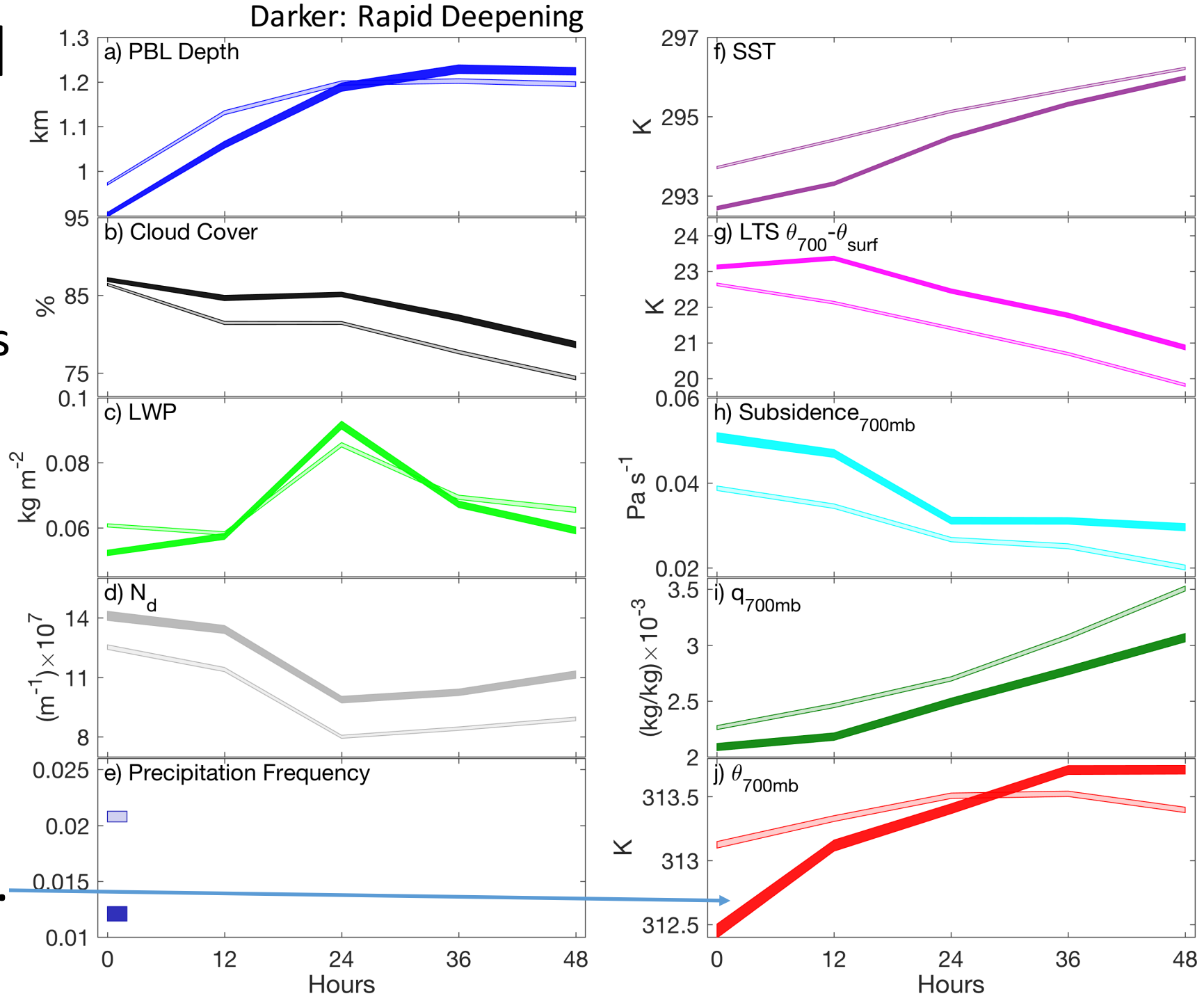


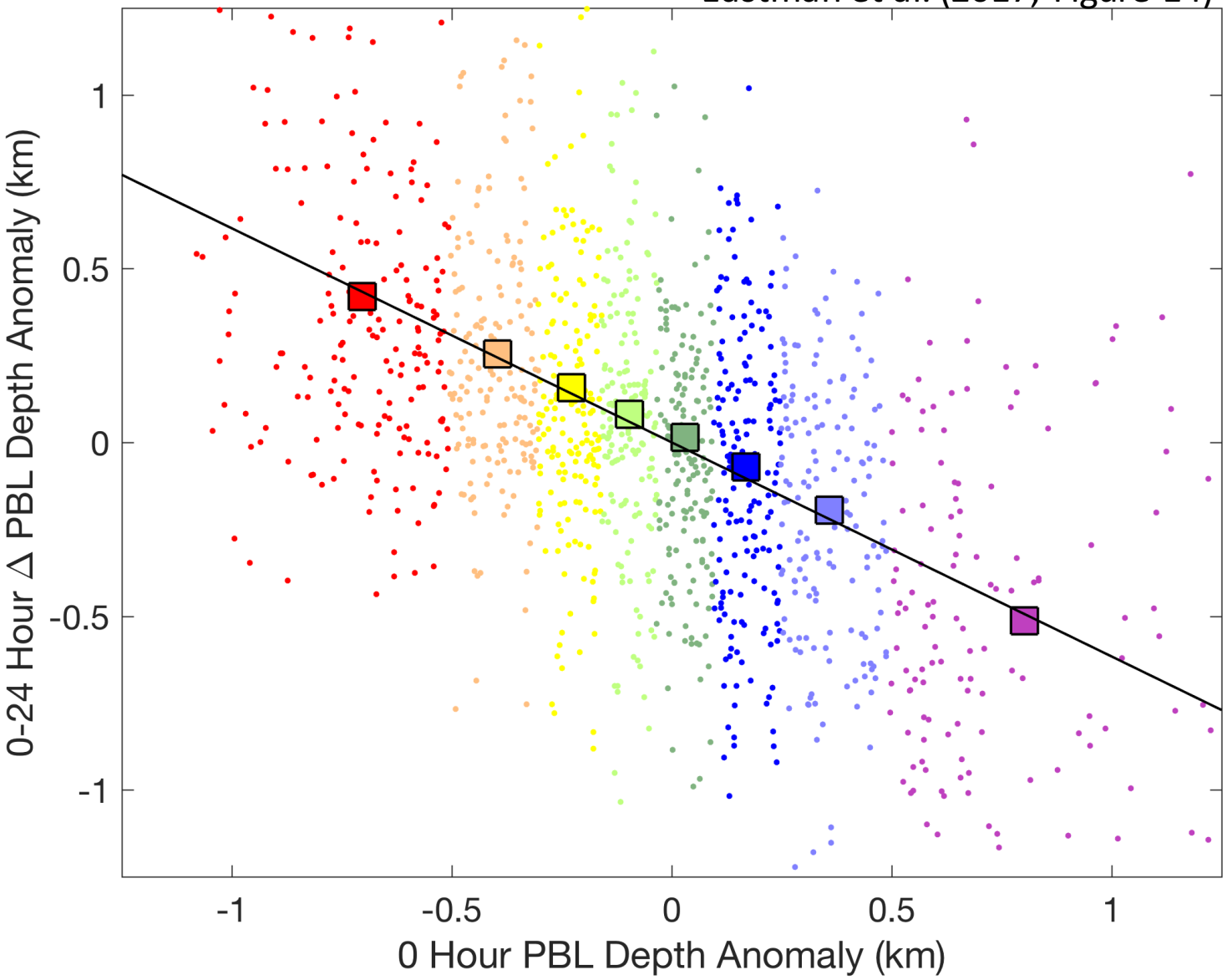
Eastman et al. (2017, Figure 13)

Challenges when Comparing Predictors

- All predictors show significant differences in rapidly deepening regions compared to surroundings, how to determine what's important?
- How to objectively compare sets of trajectories separated by their initial conditions.
  - No two trajectories are identical, so how can they be compared when there are geographical differences? (ie. Different start, end points, different length).
  - Converting to an anomaly framework allows us for a more objective comparison.
  - Anomalies are taken based on a 100-day running mean centered on each day, for day and night separately.
- How to define a null hypothesis when comparing time evolution of trajectories?
  - If we subset trajectories by a predictor variable, their initial values of cloud cover and PBL depth will differ between the sets.

Comparing Lagrangian Change

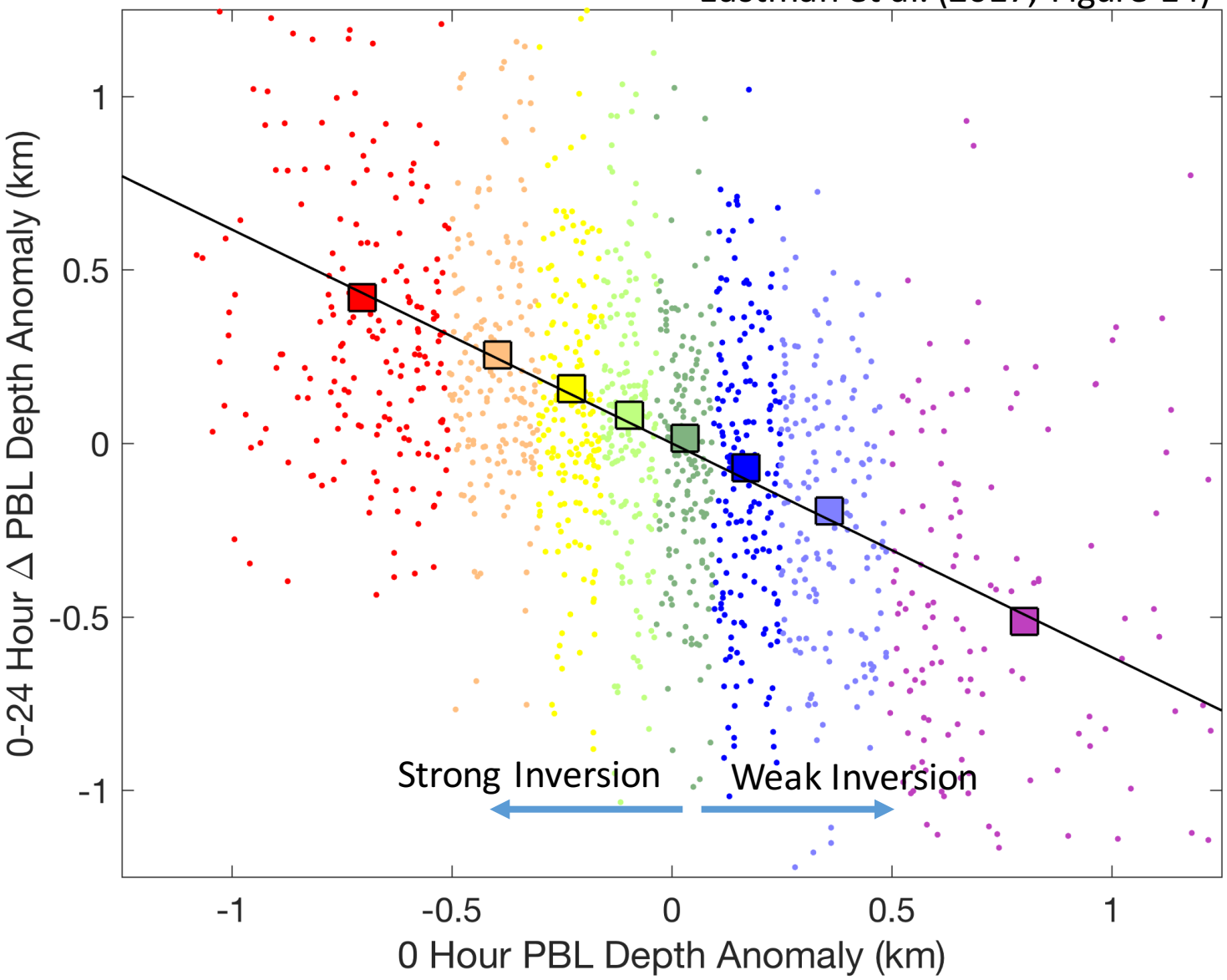
Eastman et al. (2017, Figure 14)



- On average, anomalous PBL depth values tend to regress to zero.
  - This 'Regression to the mean' is well modeled by a red noise assumption. (Eastman et al. 2016)
  - Larger anomalies regress more.
- When comparing sets of trajectories with different mean PBL depths, this red noise behavior must be accounted for.
- **Δ**PBL = **Δ**PBL(red)+ **Δ**PBL(env)

Comparing Lagrangian Change

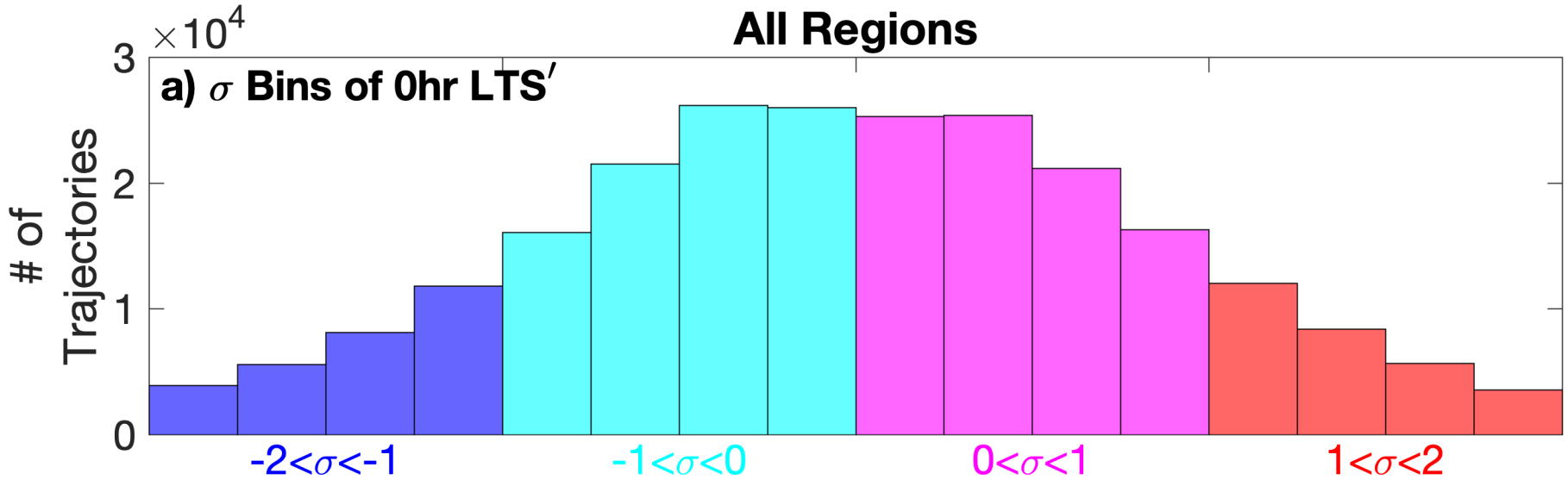
Eastman et al. (2017, Figure 14)



- To compare anomalous environmental forcing caused by predictor variables, we must calculate residual changes in PBL depth.
- **Δ**PBL(residual) = **Δ**PBL(obs) - **Δ**PBL(red)
- Residual **Δ**PBL values can now be compared between two sets of trajectories with the effects of red noise removed.

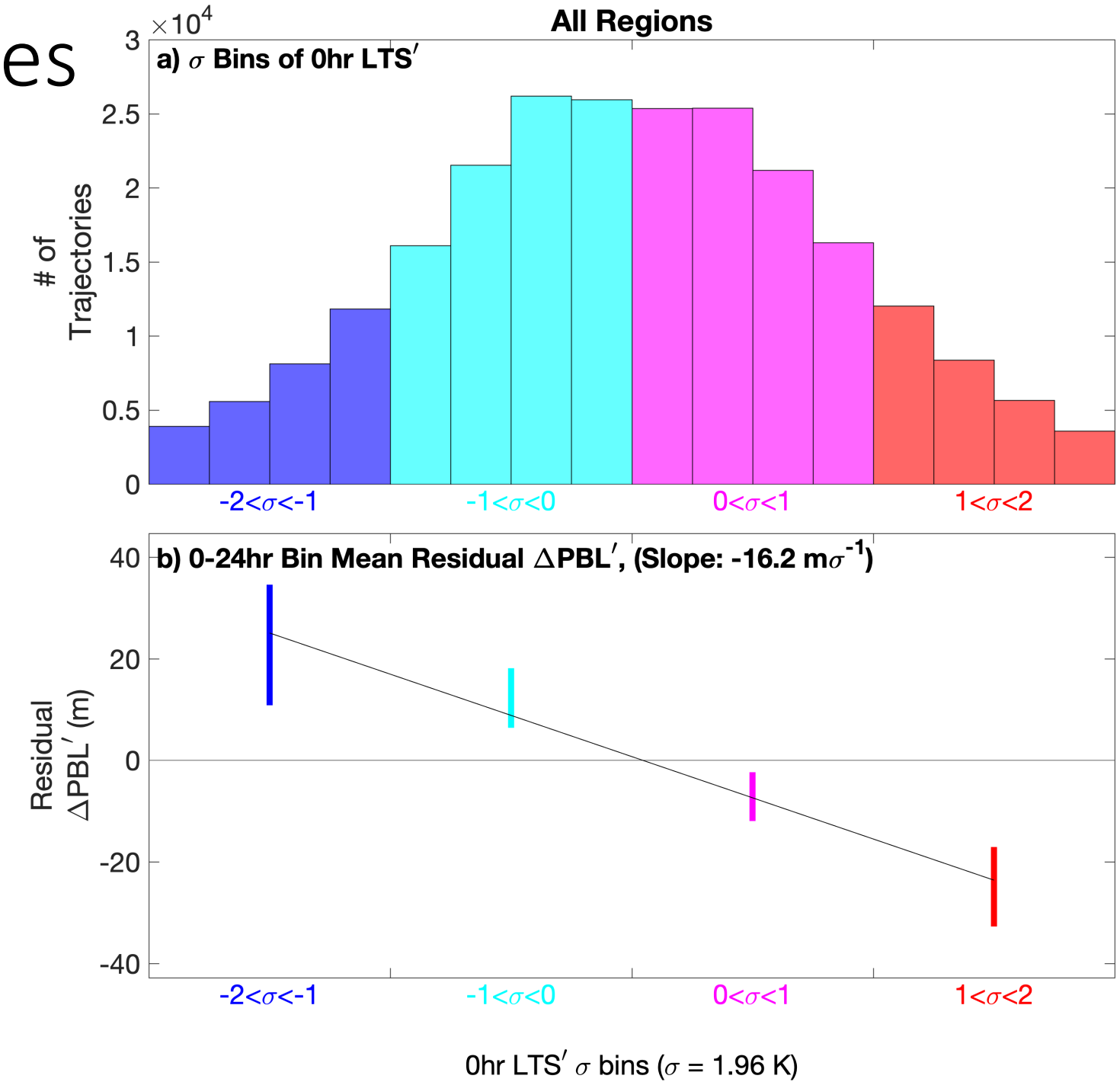
Comparing Variables

- In order to compare the power of different predictors, we must first standardize the predictor variables by dividing by the standard deviation (σ).
  - Now the effects of a 1σ anomaly in one predictor can be compared to a 1σ anomaly in another.
  - To do this, we create sets of trajectories binned by the standard deviation of each predictor.



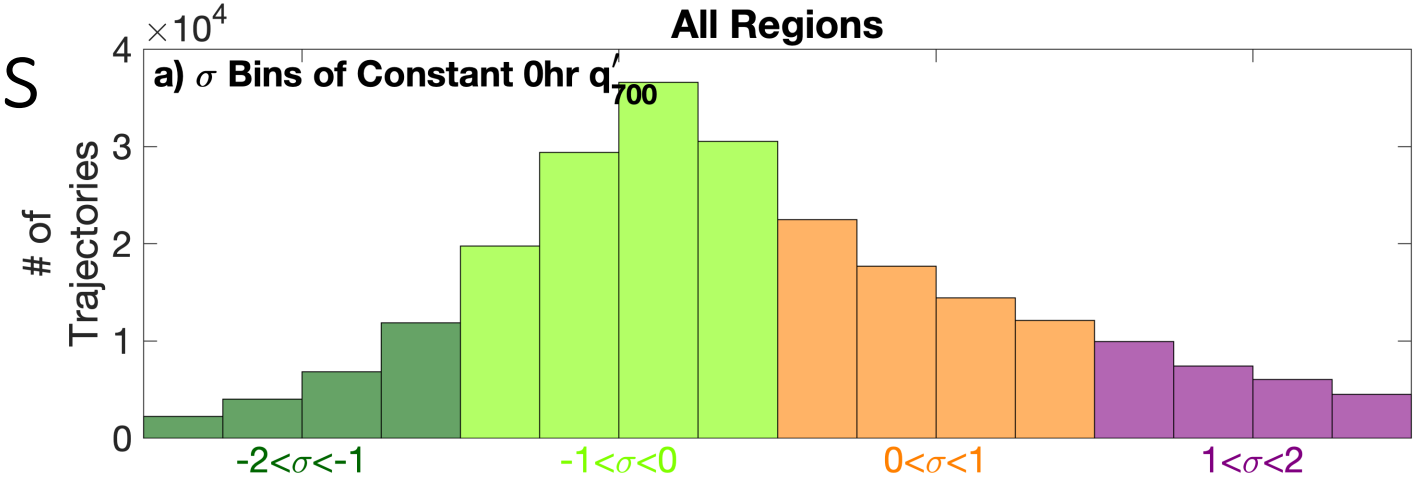
Comparing Variables

- Residual changes in PBL depth anomalies are then calculated for each σ bin of our predictor variable
- Anomalously high LTS is associated with anomalous Lagrangian shallowing of the PBL
- What about confounding variables?



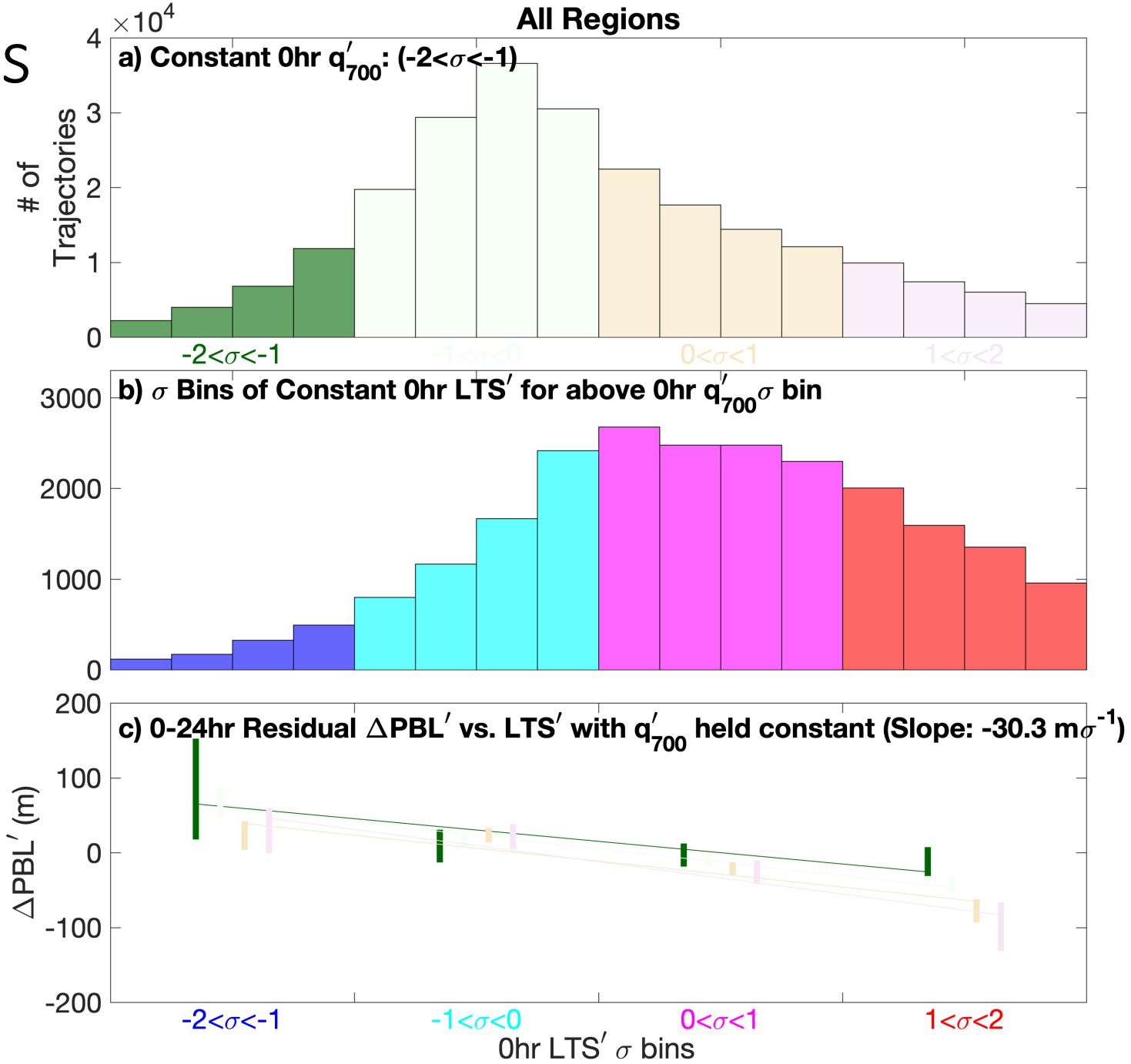
Confounding Variables

- The LTS-PBL relationship could be skewed by other variables.
  - LTS and q700 anomalies are anticorrelated.
  - The free lower troposphere is more humid when LTS is low (r = -0.26)
- We can further subset our trajectories into bins of constant q700’



Confounding Variables

- After subsetting by 0-hour q700', we can repeat the prior analysis for bins of LTS'
  - The value of the slope in frame c changes significantly.
  - After controlling for q700', the effects of LTS' appear nearly twice as strong.



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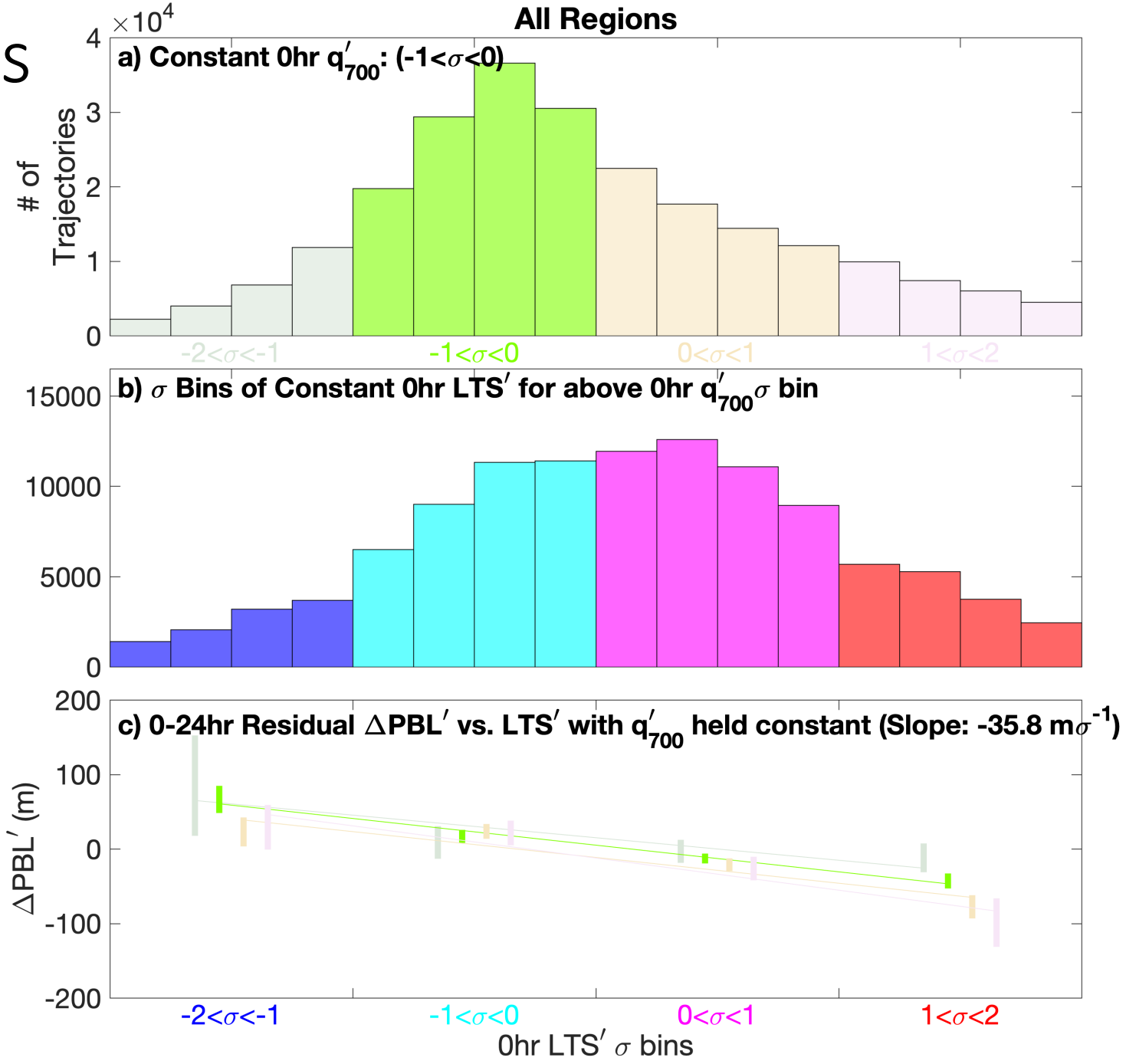

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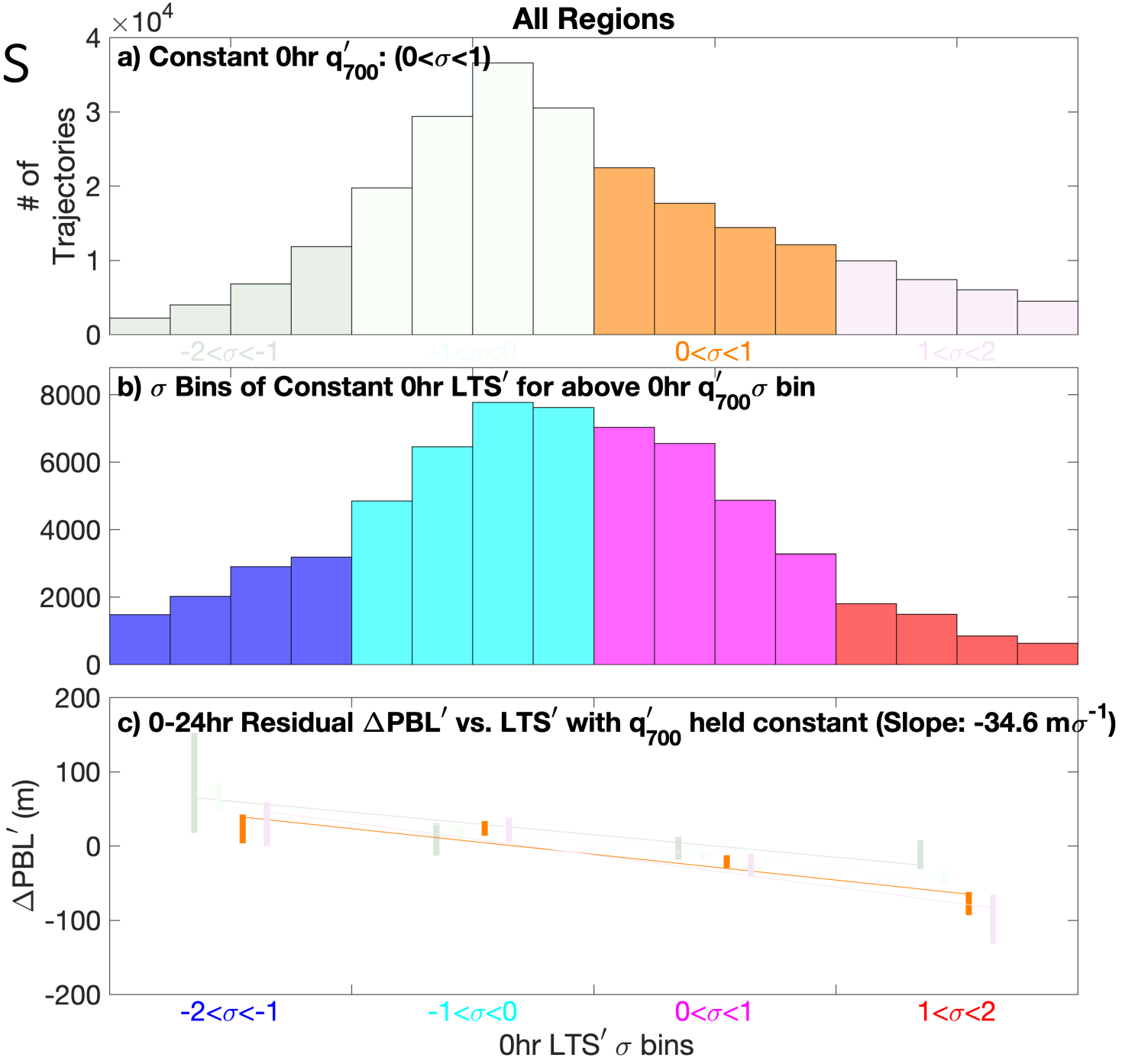

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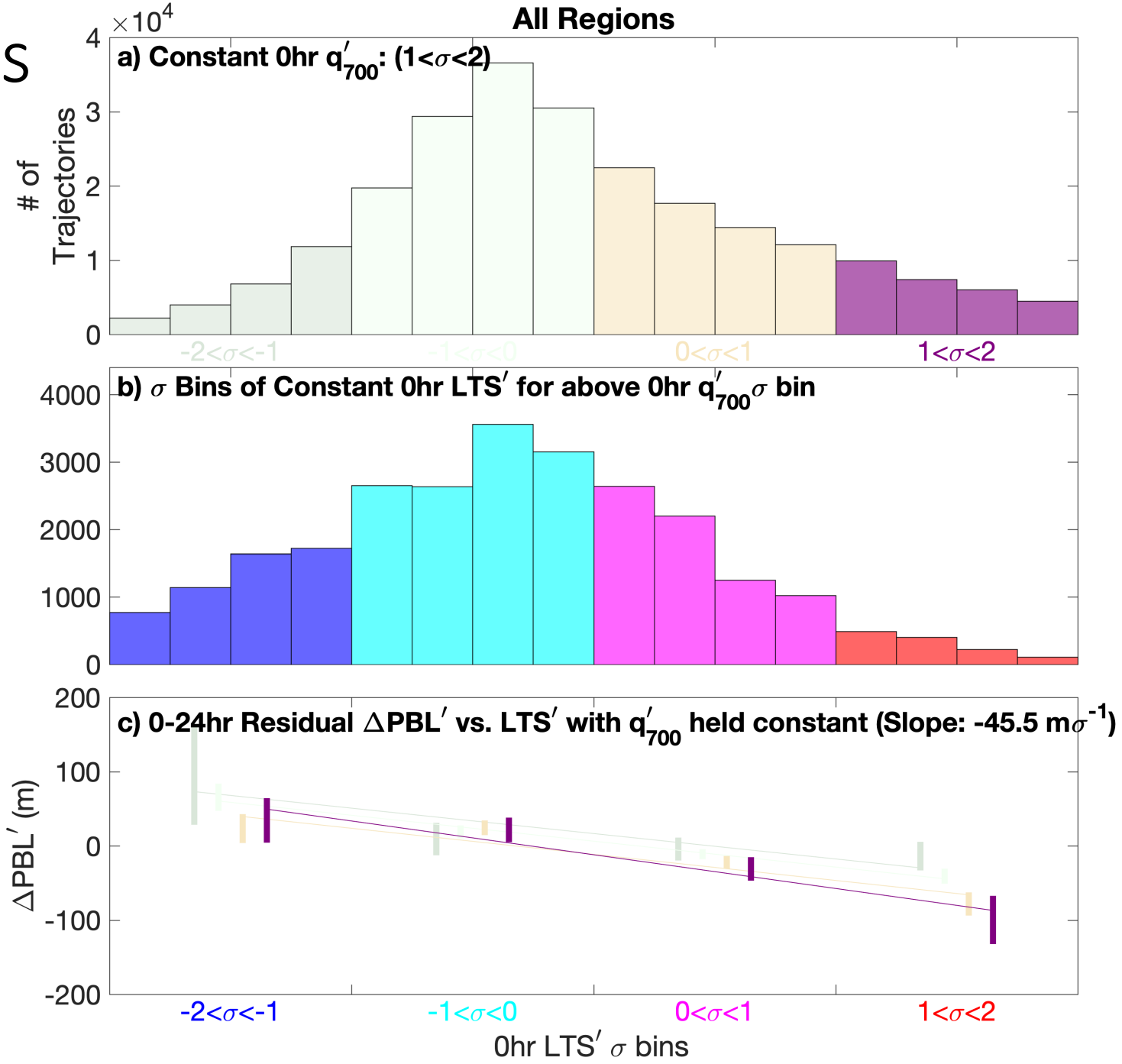
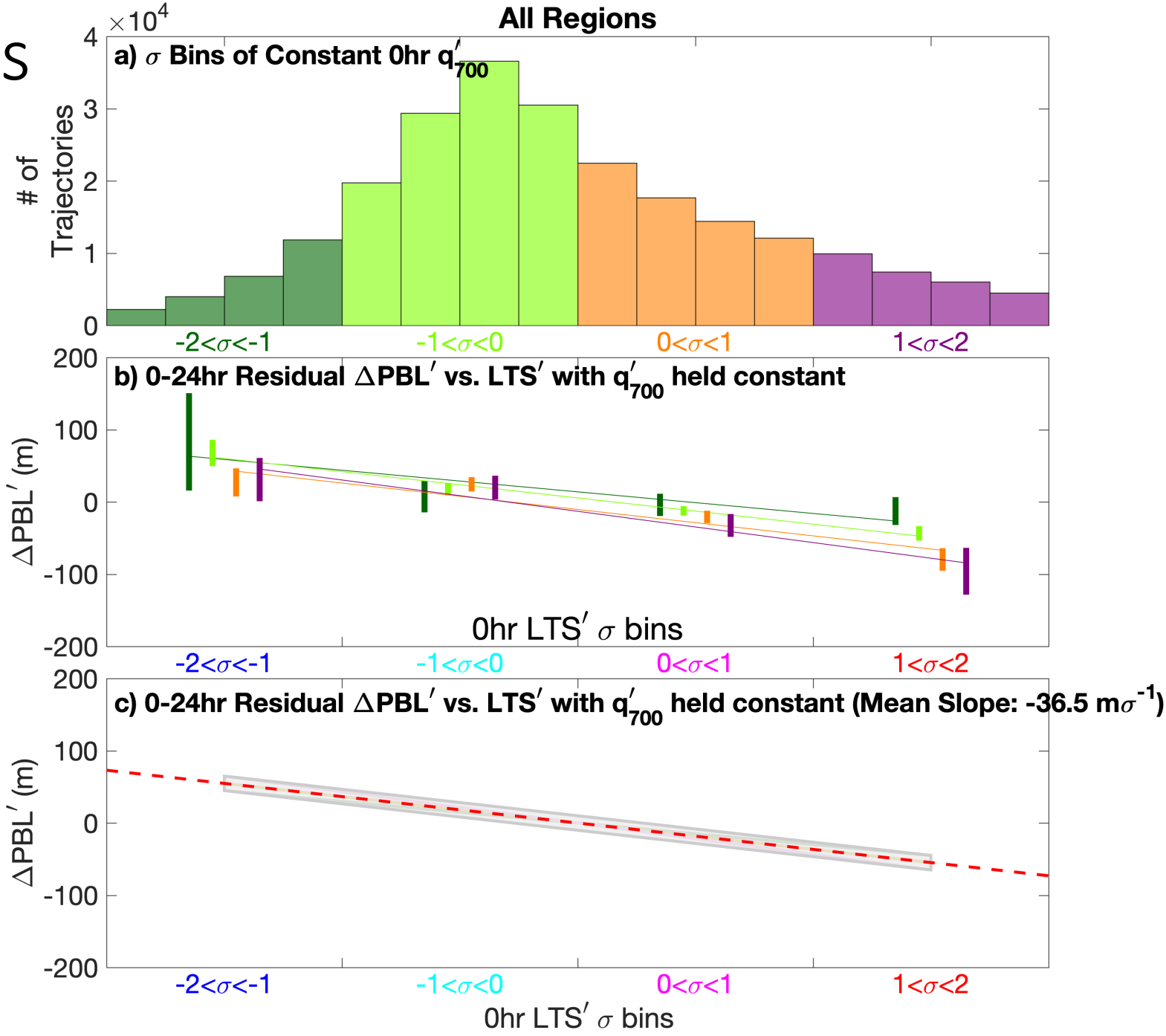


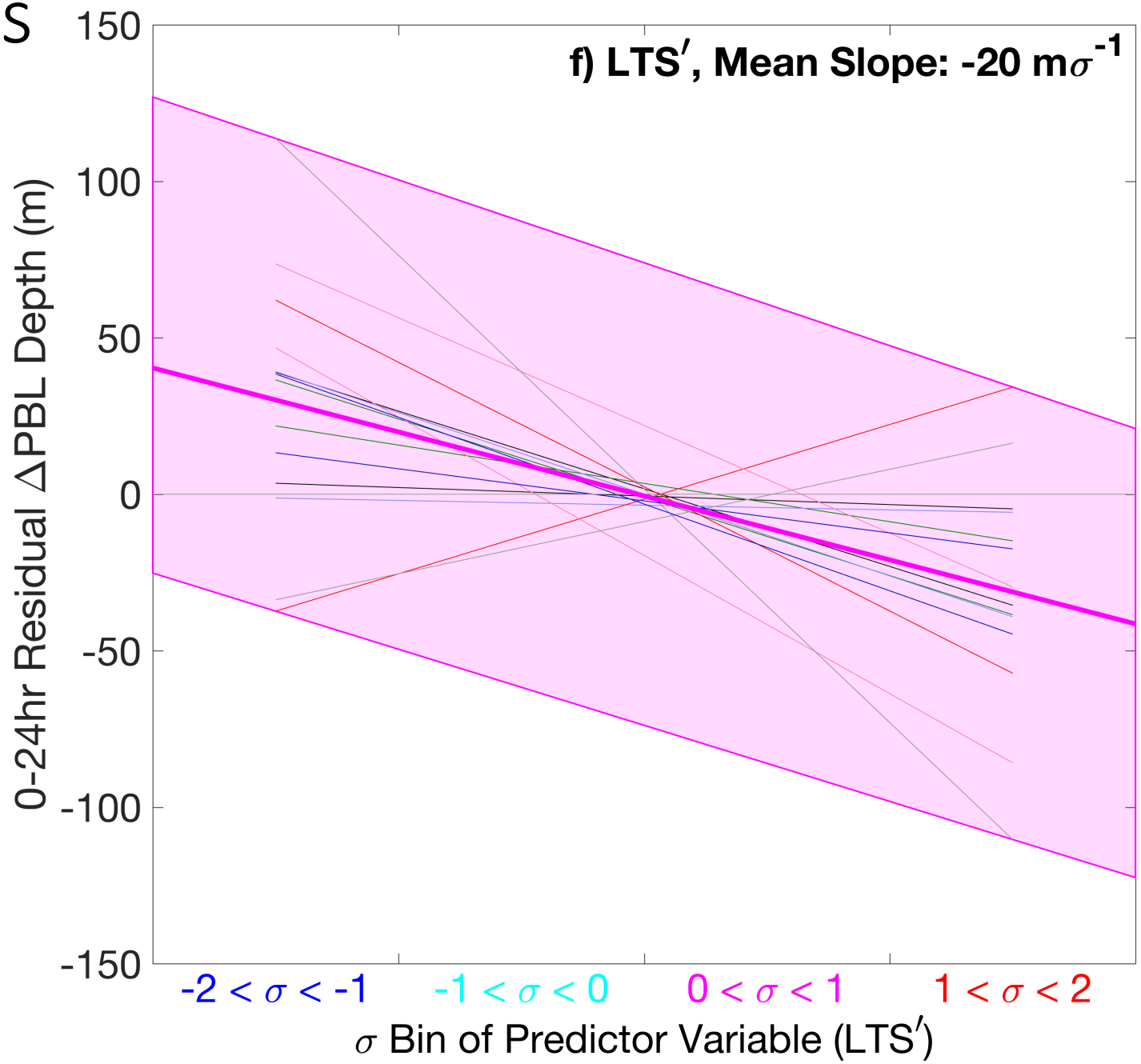
Confounding Variables

- The mean slope of Residual **Δ**PBL' versus LTS' for the four bins of constant q700' is nearly twice as steep as the slope without controlling for q700'.
- Error bounds are created based on the spread of the slopes.
- This analysis is repeated for all predictor variables.

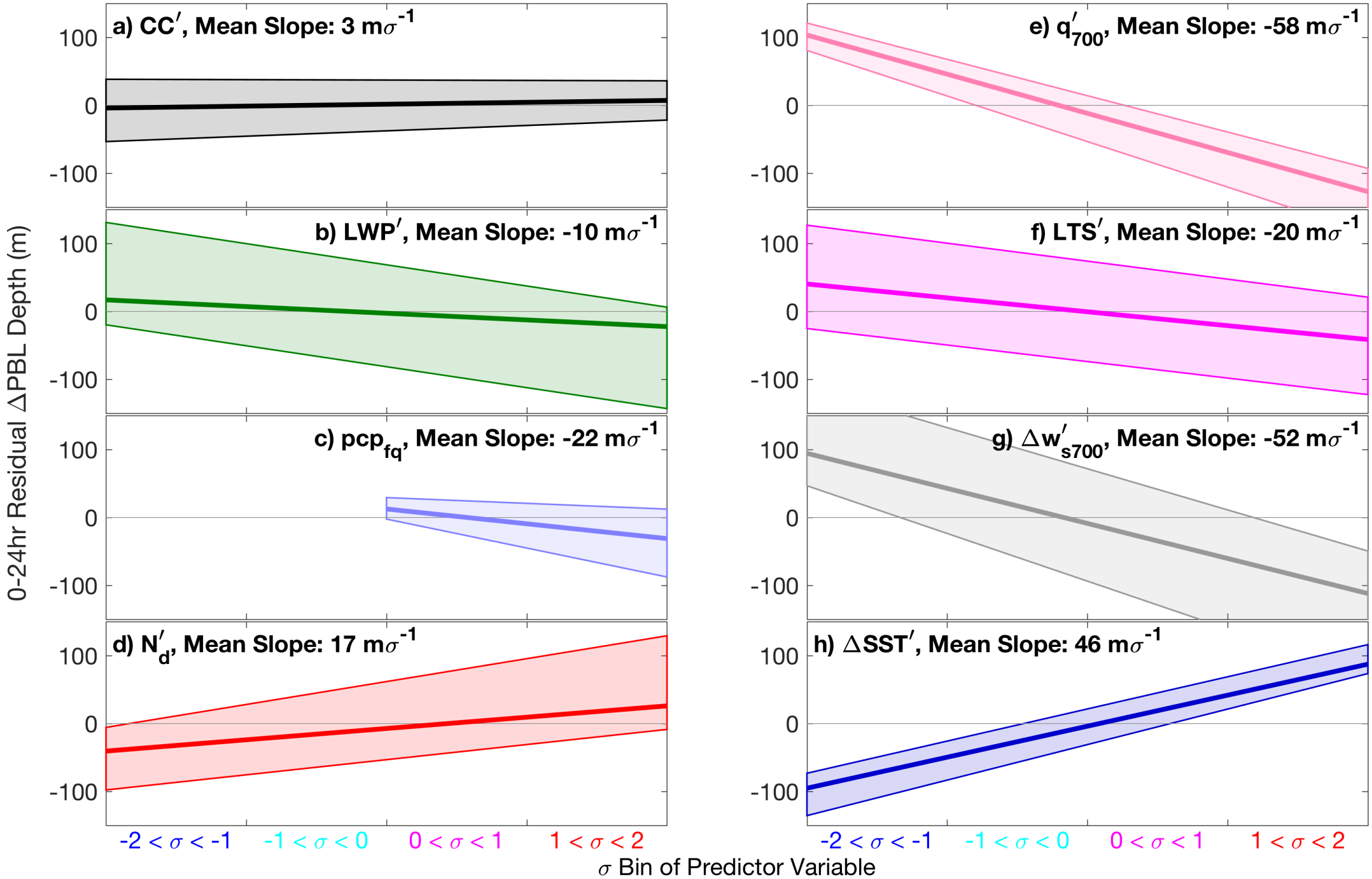


Confounding Variables

- Perform the prior analysis for an entire list of predictor variables.
- Create bounds based on the range of slopes generated by holding each predictor constant while testing the power of LTS'.
- This example shows very wide bounds, indicating a messy relationship between LTS and PBL deepening with many confounding variables.

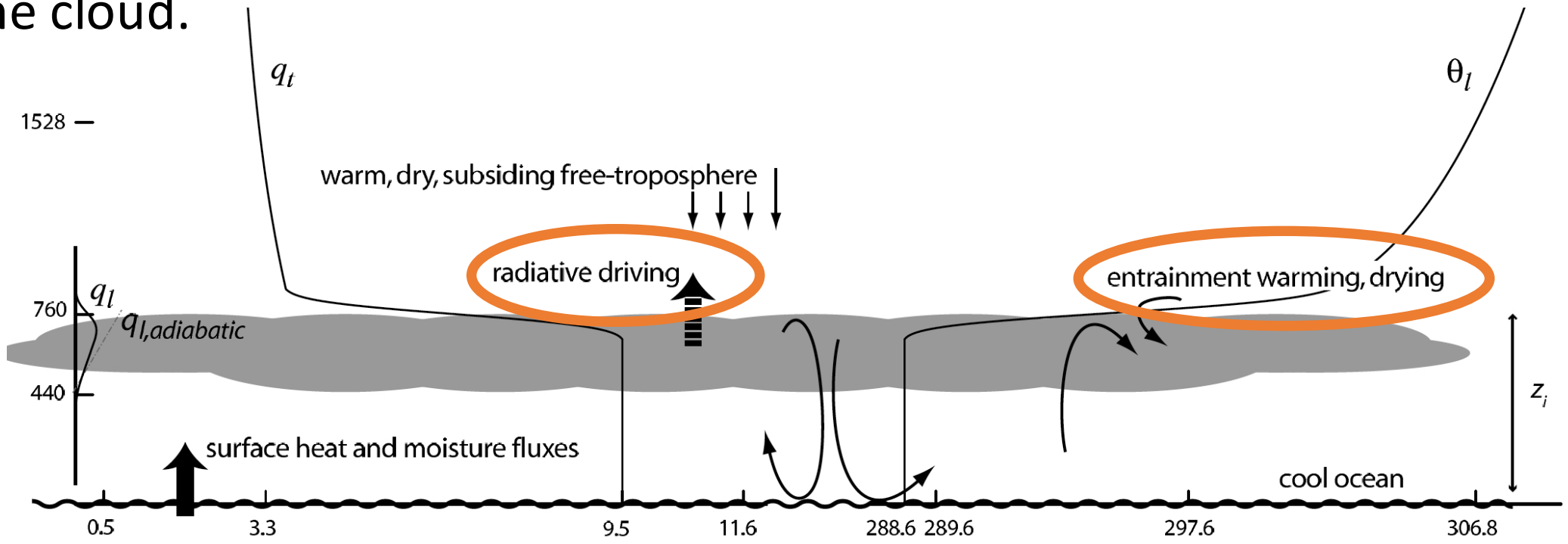


Results


a) CC′, Mean Slope: 3 mσ-1
b) LWP′, Mean Slope: -10 mσ-1
c) pcpfq, Mean Slope: -22 mσ-1
d) N′d, Mean Slope: 17 mσ-1
e) q′700, Mean Slope: -58 mσ-1
f) LTS′, Mean Slope: -20 mσ-1
g) Δw′s700, Mean Slope: -52 mσ-1
h) ΔSST′, Mean Slope: 46 mσ-1
0-24hr Residual ΔPBL Depth (m)
100
0
-100
-2 < σ < -1
-1 < σ < 0
0 < σ < 1
1 < σ < 2
σ Bin of Predictor Variable

How is free-tropospheric humidity acting on the PBL?

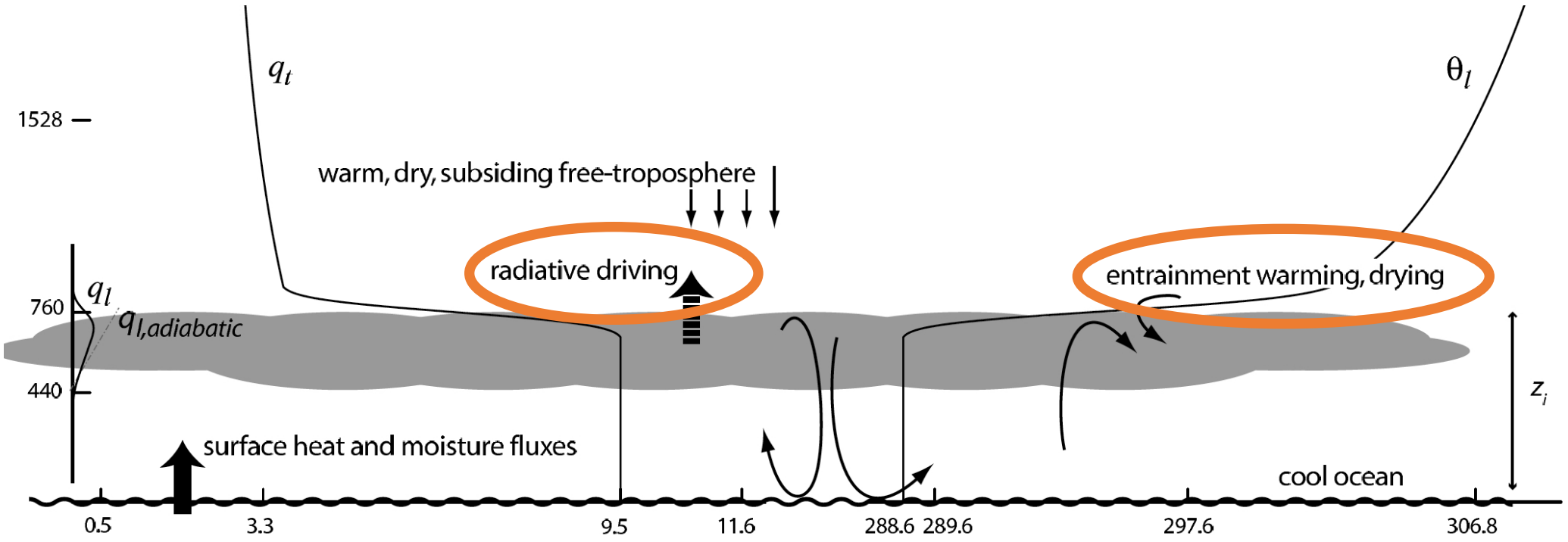
- Humid layers above the PBL can modify the radiative balance at cloud top, limiting cloud top cooling if too much IR is directed downward.
- Increased water vapor entraining into the cloud can also modify cloud top cooling by reducing evaporation at cloud top, weakening the lapse rate within the cloud.



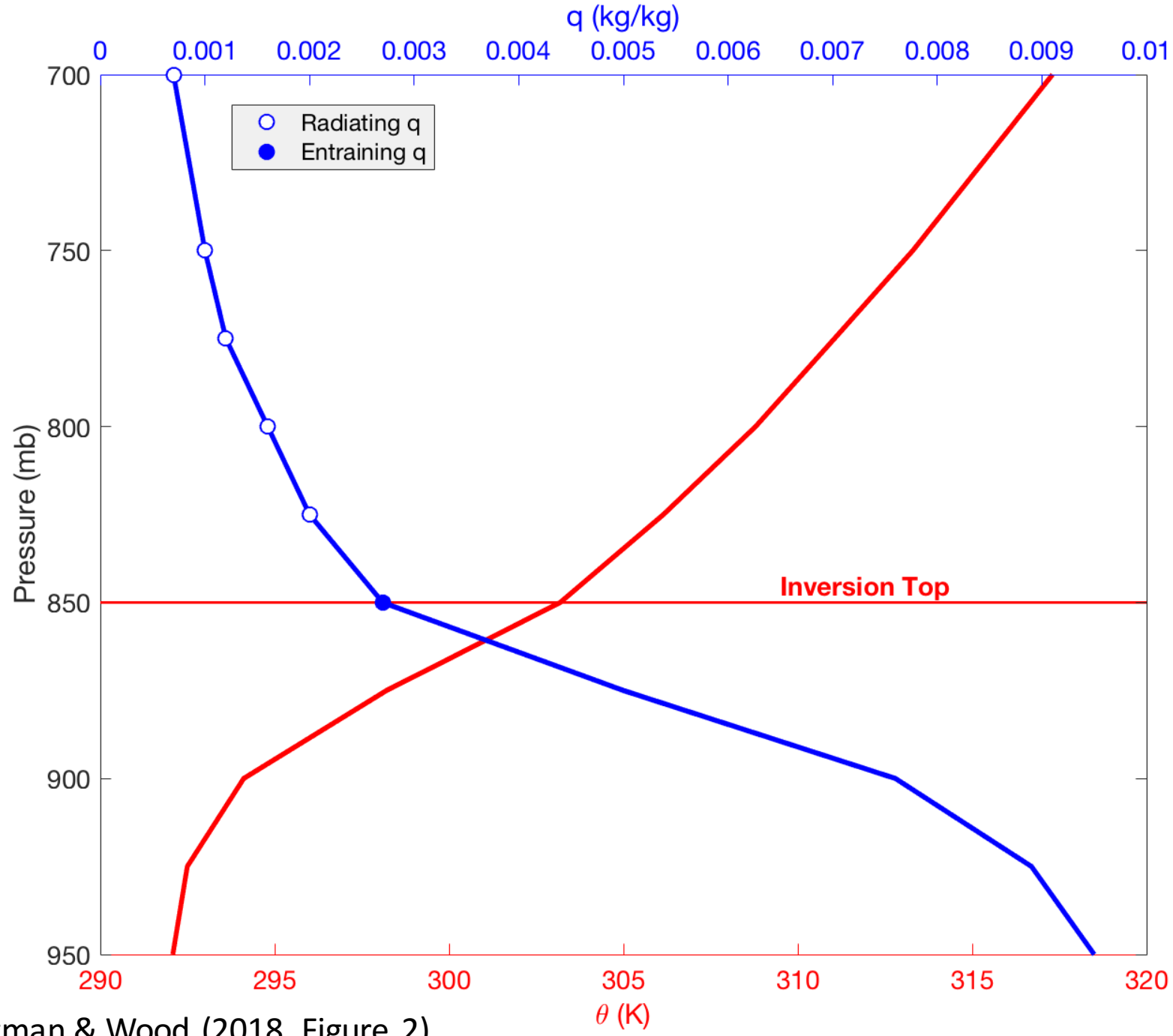
Wood, 2012

How is free-tropospheric humidity acting on the PBL?

- We can use this Lagrangian analysis along with the reanalysis profiles of free tropospheric specific humidity to test which of these mechanisms is driving the deepening of the PBL.



Wood, 2012



Eastman & Wood (2018, Figure 2)

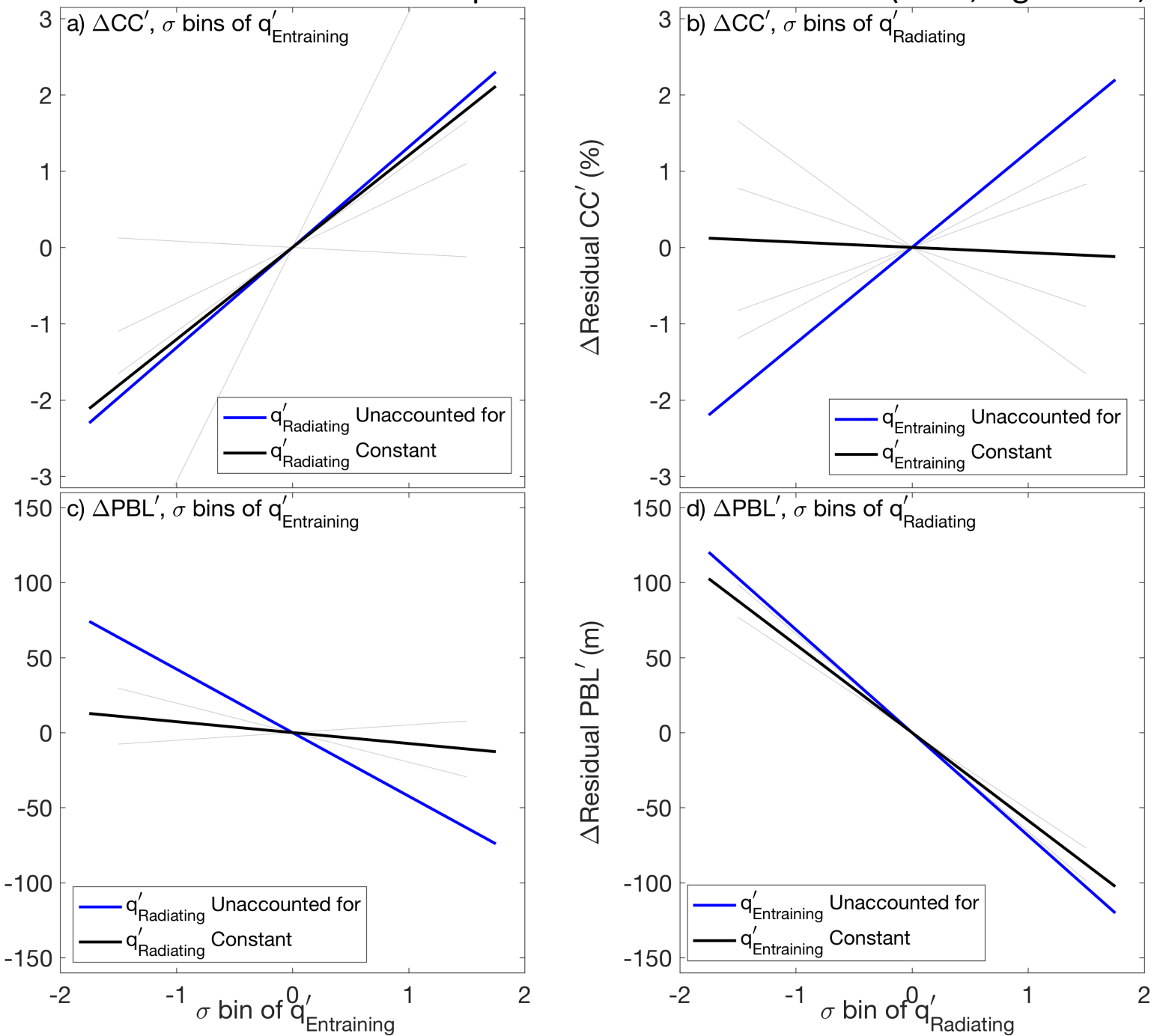
Measures of Humidity

- In order to test these mechanisms we can create two quantities of humidity using ERA-I:
  - Entraining humidity, which is in contact with the PBL top.
  - Radiating humidity, consisting of the model layers above the entraining layer, but below 700 hPa.
- Compare their effects with and without holding the other constant.

Lagrangian Effects of Humidity

- We test the effects of our two measures of humidity, which are positively correlated, on 24-hour Lagrangian cloud cover and PBL evolution.
- In each frame the power of one humidity measure is tested as a predictor without (blue) and with (black) the other humidity measure held constant.

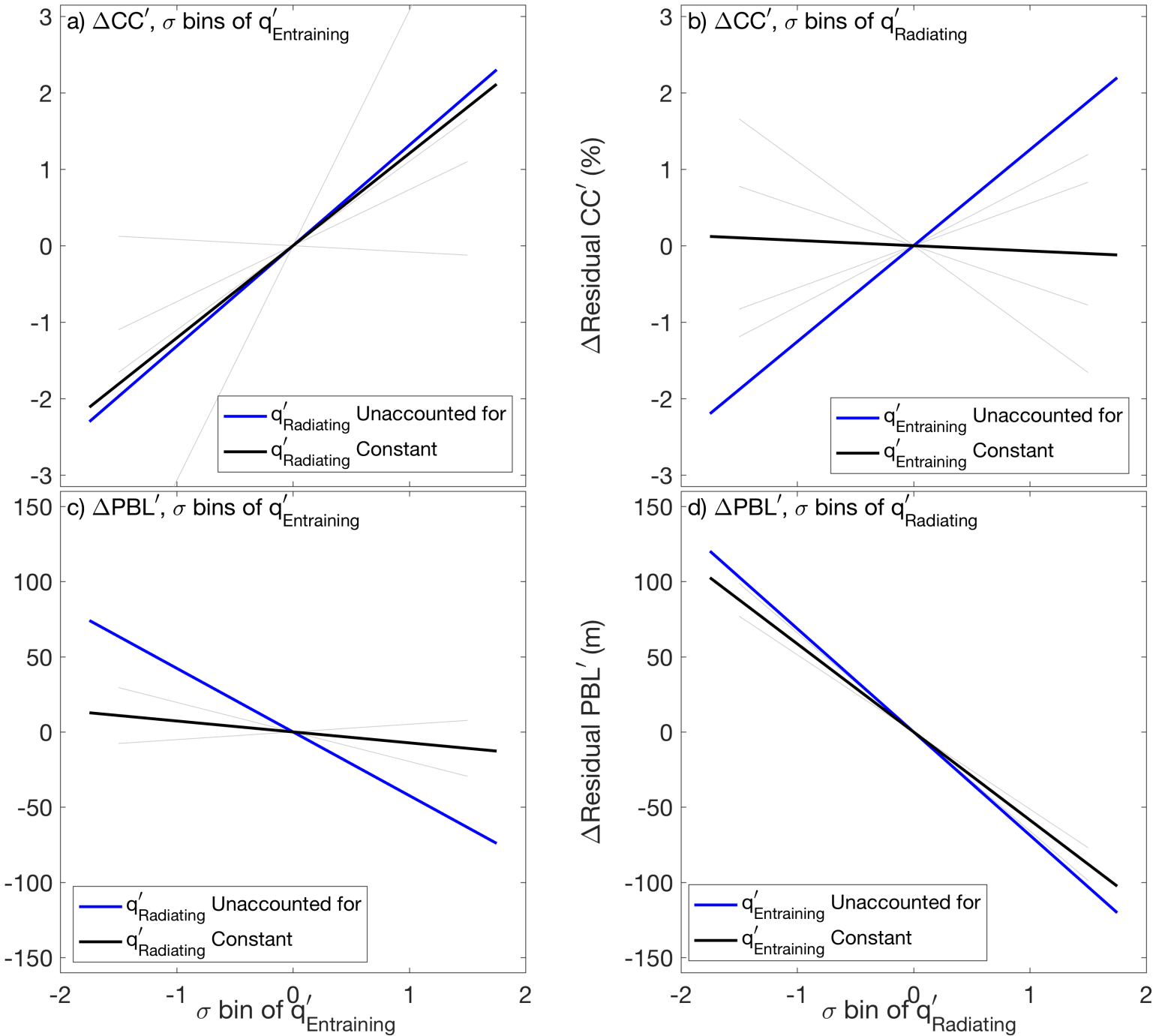
Adapted from Eastman & Wood (2018, Figures 10, 11)



Lagrangian Effects of Humidity

- Lagrangian Cloud Cover evolution is more affected by entraining water vapor.
- Lagrangian PBL evolution is much more affected by the radiating effects of overlying humidity.

Adapted from Eastman & Wood (2018, Figures 10, 11)



Conclusions

- Lagrangian PBL deepening is geographically irregular, not a smooth process as is often simplified in current models
- Although the seasonal cycle of PBL depth correlates strongly with inversion strength, a closer look shows that inversion strength is a dubious predictor with irregularities at different time scales and with many confounding variables affecting the relationship.
- Many other variables drive Lagrangian changes in PBL depth:
  - Humidity above the PBL (strongest), Δsubsidence, ΔSST, precipitation, and Nd.
  - Humidity can modify the PBL through radiative and evaporative effects.
- The radiative effects dominate PBL deepening while evaporative effects dominate cloud evolution.

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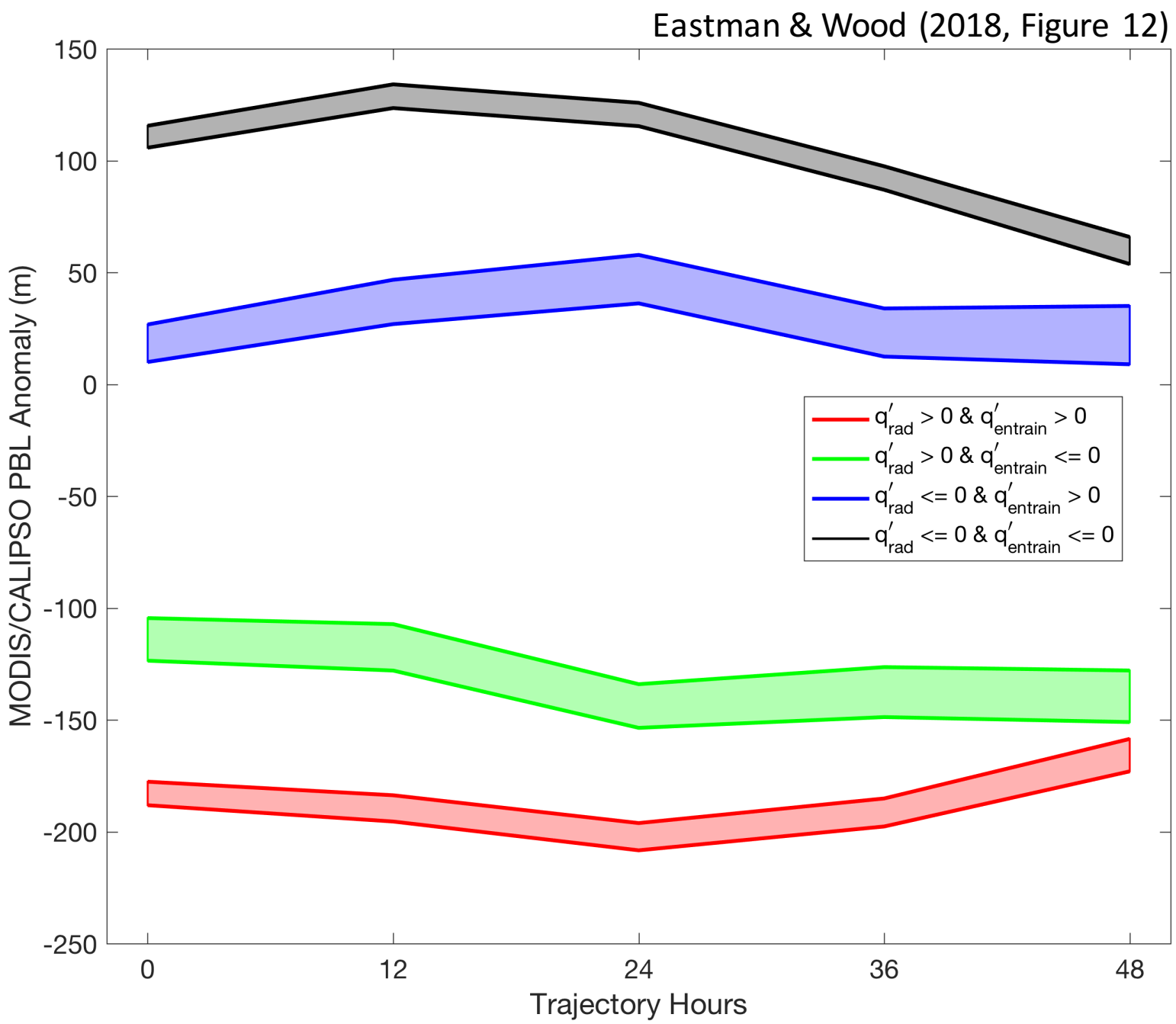
Thanks to…

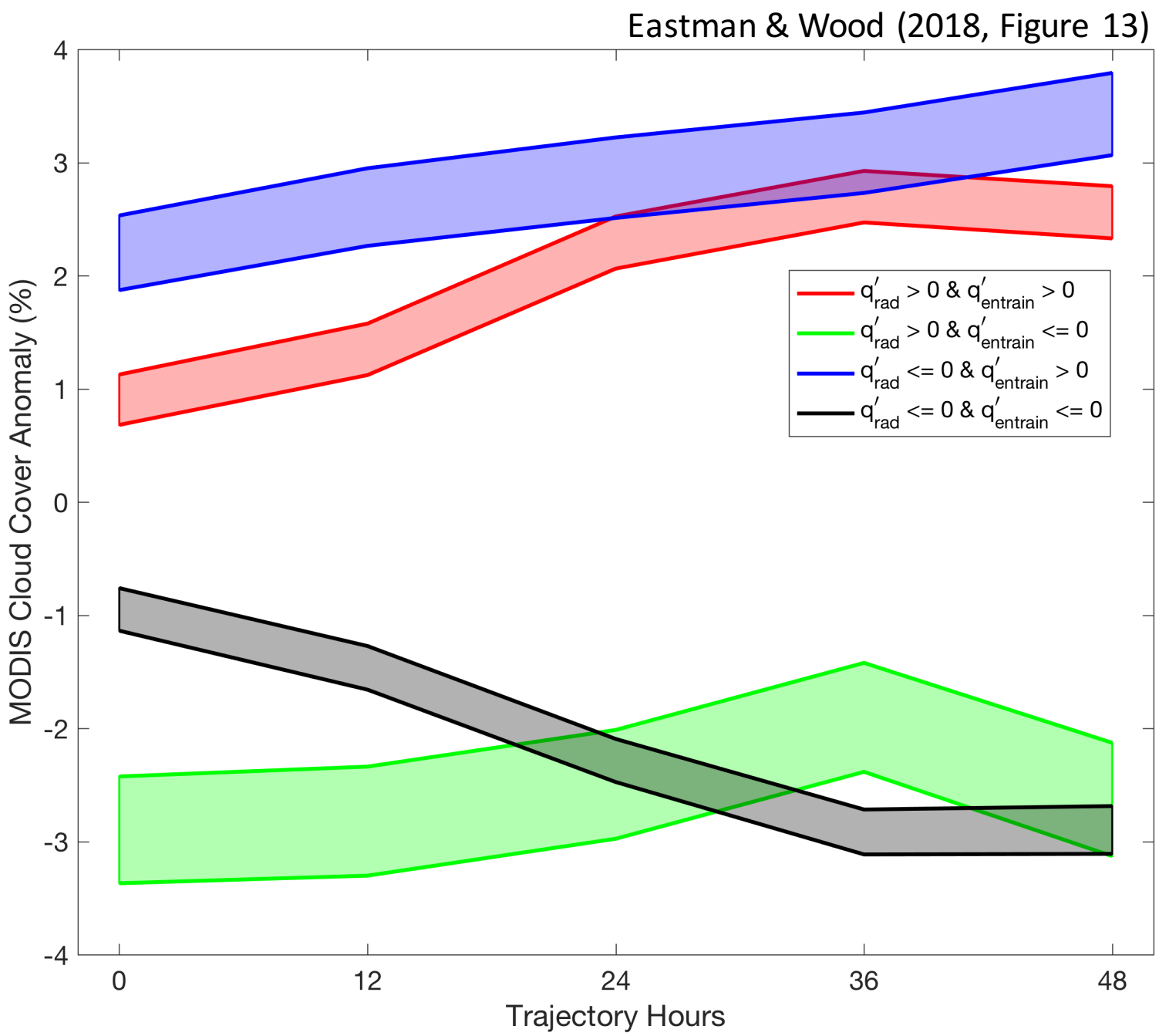
- Rob Wood
- Wood Group: Andy, Hans, Isabel, Michael, Sam, Matt W.
- Chris Bretherton
- Steve Warren
- Dennis Hartmann

Lagrangian Effects of Humidity, a Simpler Perspective



- Trajectories are composited into four groups, based on mean 48-hr humidity anomalies.
- The Lagrangian evolution of PBL' is compared between the four.
- The PBL is deeper and stays deep when radiating humidity is low, especially when entraining humidity is also low.

Lagrangian Effects of Humidity, a Simpler Perspective



- The Lagrangian evolution of CC' is also compared between the four groups.
- Cloud cover is greater and tends to increase when entraining humidity is high, vice-versa when humidity is low.