Factors leading to the breakup of marine Sc, a Lagrangian perspective using the A-Train

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The role of Sc decks in the climate

- Continent-sized cloud decks in the subtropics
- Reflect an enormous amount of sunlight
- Radiate LW similar to the surface
- Form in stable environments on large and small scales

MODIS image courtesy Jeff Schmaltz
Sc climatology from surface obs

- Study Sc in eastern sub-tropical ocean basins, in regions of subsidence, offshore flow, and cool SST
- Looking for maxima near continents and declining Sc gradient offshore

Hahn & Warren Cloud Atlas: www.atmos.washington.edu/CloudMap
Marine Sc boundary layer

- Clouds form at the base of the marine inversion
- Cloud tops radiatively cool, especially at night, driving convective overturning
- Strong diurnal cycle
- Boundary layer deepens as Sc advects offshore
  - Greater SST
  - Decline in lower tropospheric stability (700mb - surface)
- Clouds eventually break up, 'trade Cu' prevails
Shallow vs Deep Boundary Layers

(a) Radiative cooling → Entrainment → VERY DRY

Sea surface

Drizzle below thickest cloud

800 m

Weak surface forcing

5 km

(b) Locally enhanced entrainment → Radiative cooling → VERY DRY

QUIESCENT → TURBULENT

MOIST

Stronger surface forcing

1.5 km

Trade inversion

20-30 km

Wood 2012
Well-mixed STBL

(a) $q_1$

(b) $\theta_v$

(c) $z_i$, $z_{bd}$, $z_{bu}$, buoyancy flux

Cumulus-coupled STBL

(d) $q_t$ ($q_v$ dotted)

(e) $\theta_v$

(f) $z_i$, $z_{bd}$, $z_{bu}$, buoyancy flux

Bretherton 1997
Uncertainties concerning Sc breakup

- Many factors may contribute to Sc breakup over the remote ocean
  - Precipitation stabilizing the boundary layer
    - Condensation at cloud level, evaporation below
    - Removing CCN, encouraging precip, positive feedback
  - Weakening divergence offshore
  - Warming SSTs weakening the inversion
    - Boundary layer deepens, Sc layer decouples from surface
- Most of these things are correlated with one-another
24-hour Lagrangian Study

- Sample a large (100 km radius) piece of a Sc deck
- Compute a 24-hour trajectory for that piece
- Sample cloud properties at 0, 12, and 24 hours, following the flow
24-hour Lagrangian Study

- 24-hour trajectories from reanalysis data
  - ERA-Interim reanalysis U and V fields, 0.75°
  - 925 mb

- For years 2007 & 2008 only for now
24-hour Lagrangian Study

- Start at randomly chosen points along A-Train swath, at least 200 km apart, Day and Night,
  - Over 60,000 individual trajectories
  - Only study trajectories moving east-to-west
24-hour Lagrangian Study

- Example: Night → Day → Night, MODIS swaths
- Sample the trajectory if it falls within MODIS and AMSR swaths.
24-hour Lagrangian Study

• Look at A-Train sounding for a 200 km chunk of swath at trajectory beginning
  – CloudSat precipitation
  – CALIPSO vertical feature mask for boundary layer depth
  – MODIS cloud mask for 100 km radius
  – AMSR LWP also for 100 km radius

• Look at MODIS and AMSR at 12 and 24 hours also
A-Train Afternoon Constellation

- Numerous satellites flying together, crossing the equator at ~1:30 am/pm
CloudSat Precipitation

- CloudSat carries a 94 Ghz cloud-profiling radar
- Rain-Profile product (not precip_column)
  - Rain-Profile only returns a positive precipitation value when rain is observed at the surface
  - For this work: A 200 km CloudSat sample is considered to contain precipitation if the Rain-Profile product finds any precipitation along the sample
CALIPSO Cloud Top Height

- Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation
  - Vertical Feature Mask (VFM) uses LIDAR to detect particles in the atmosphere
  - We use this to find cloud tops in the lowest 3km (red line shows the estimated cloud top)
• Cloud top is not always obvious
  – Use histogram to find peaks in the frequency distribution of cloud tops below 3km
  – Peaks in the distribution are considered relevant if they are at least 40% as high as the highest peak
  – Choose the highest altitude relevant peak
MODIS

- **Moderate Resolution Imaging Spectroradiometer**
- Uses 36 spectral bands:
  - Study ocean/land surfaces, clouds & cloud optical properties
  - Wide footprint: 2330 km (zenith angle > 65°)
- We use 'Cloud Mask' product and several optical properties products
  - Day and night mean cloud cover from cloud mask
  - Day ice / liquid / unknown cloud amounts
  - Liquid Water Path
  - Cloud Droplet Effective Radius
MODIS Level 3 Mean Cloud Cover
Droplet concentration $N_d$ from MODIS

- $N_d$ can be derived from daytime LWP and effective radius
  - Both available from MODIS optical properties data

$$N_{\text{eff}} = \sqrt{2} B^3 \Gamma_{\text{eff}}^{1/2} \frac{LWP^{1/2}}{r_e (h)^3}$$
AMSR-E

- **Advanced Microwave Scanning Radiometer for Earth-Observing-System (EOS)**
- Passive microwave radiometer
  - 12-channels, dual polarization
  - Swath width: 1445 km
- Use this for day & night liquid water path
- Blue – low, White - high
Precipitation and Sc breakup

- Original Motivation
- First figure (ever):
  - Mean cloud cover for dry and precipitating trajectories at 0 and 24 hours
  - Appears to show a strong signal indicating precipitation contributes to Sc breakup
- Is misleading
Biases in a Lagrangian study

- Dry and precipitating trajectories should not be directly compared
  - Mean locations of dry and precipitating trajectories are different
  - Distance travelled is also different
  - Precip trajectories tend to go farther, and cover more CC gradient offshore
Biases in a Lagrangian study

- Geographical differences between precipitating and dry trajectories make them unsuitable for direct comparison
- Instead create anomalies relative to the long-term climatology
  - Use seasonal anomalies
  - For day and night separately
  - On a 1x1 lat/lon grid
  - For a MODIS climatology using all available data between 2007 and 2008
- Subtract the mean cloud cover from individual amounts to create anomalies
Biases in a Lagrangian study

- Day and night can be studied together
- Trajectories with precip at the beginning tend to start cloudier, and cloud cover declines over time, on average
- Dry trajectories appear to start less-cloudy and cloud cover increases
Biases in a Lagrangian study

• MODIS's wide swath observes much of the Earth in a day, but the swath width comes at a cost

• Sensor zenith angle bias
  - Cloud cover observed at high angles (towards horizon) reported as cloudier
  - Due to MODIS seeing the sides of vertically developed clouds
  - Also due to thin clouds appearing more opaque at high sensor zenith angles

• Must be quantified and removed from data
Biases in a Lagrangian study

- MODIS only provides daytime sensor zenith data
- Night zenith angle must be estimated based on distance between observation and satellite track
- Polynomial fit to estimates
- Bias is different for day & night
Biases in a Lagrangian study

- Precip trajectories travel farther than dry
  - Mean zenith angle of 24-hour observations are different
  - Precip: 47°
  - Dry 54°
- Biases differences in \( \Delta \) Cloud Cover for dry vs. precip
  - ~1% at night
  - ~2% during the day
Biases in a Lagrangian study

- Using the curve from the previous figure, the zenith angle bias is subtracted from each cloud amount observation.
- 24-hour trajectory values look more reasonable, precipitation still appears to have an effect.
Zenith Angle Bias: MODIS LWP, Effective Radius

- All other MODIS data (that we use) has zenith angle biases
- We remove these biases again using polynomial fits
- Used these unbiased values to calculate $N_d$
- No bias observed in AMSR data
Biases in a Lagrangian study

• Most significant: A bias due to the differing initial cloud-cover anomaly distributions between precipitating and non-precipitating environments

• Clouds are necessary for precipitation to occur, therefore:
  - Precipitating trajectories must start off with some cloud cover (usually lots of clouds)
  - Dry trajectories can start cloud-free
  - Dry trajectories can show larger cloud cover increases than precipitating
Biases in a Lagrangian study

- Directly comparing Delta Cloud Cover Anomaly ($\Delta$CCA) is misleading.
- Not comparing samples that evolve in the same way, regardless of precip.
  - Dry trajectories can show a larger $\Delta$CCA, due to 0% Cloud Cover values are only possible for dry.
Biases in a Lagrangian study

- More **positive** precipitating initial cloud cover anomalies (CCA)
- More **negative** dry initial CCA
- $\Delta$CCA must (in part) be a function of initial CCA

![Graph showing the relative frequency of initial cloud cover anomalies](image)
Limits to $\Delta$CCA

- An anomaly of -100% can only increase
- An anomaly of 100% can only decrease
- Blue line – If $\Delta$CCA were perfect
- Black line - If $\Delta$CCA were random
Random vs. Actual ΔCCA

- Test the random assumption:
  - Determine if this assumption works for this distribution
  - Assign a random trajectory end-point to each of the 60k trajectory starting points
  - Calculate ΔCCA as though each were a real trajectory
Random vs. Actual ΔCCA

- ΔCCA for actual 12 and 24-hour trajectories
- Linear relationships, with the slope steepening over time
- ΔCCA can be represented as a function of initial CCA and time
- We can predict ΔCCA
Random vs. Actual ΔCCA

- We now can use this linear relationship to compare the evolution of two samples with differing starting distributions of CCA.
- Compare the observed change with the predicted change for each trajectory.
Random vs. Actual ΔCCA

- eg: A trajectory begins with a cloud anomaly of +10%.
  - Using the previous figure, we predict a ΔCCA of -5% in 12 hours and -8% in 24 hours
  - Compare the actual ΔCCA to the predicted ΔCCA
    - Subtract the predicted ΔCCA from the actual ΔCCA to get DPΔCCA, the difference from predicted ΔCCA
    - Actual ΔCCA is -20%, for 12 hours, -25% for 24 hours
    - DPΔCCA(12) = -15%, DPΔCCA(24) = -17%
  - Look for variables that significantly alter the DPΔCCA, with no initial distribution bias
DPΔCCA and Precipitation

- Precipitation still appears to have an effect, though smaller
  - Difference of only 0.7 or 1.2%
  - Significant at 12 and 24 hours
- Both are positive
  - Due to residual zenith angle bias
  - Selection Bias (westward trajectories only)
Factors aside from precipitation

- Precipitation is correlated with other variables, which, in turn, are correlated with each other eg...
  - Precipitation tends to occur in deeper boundary layers \( (r = 0.35) \), and is slightly correlated with lower-tropospheric stability \( (\theta_{700} - \theta_{1000}, r = -0.12) \)
    - Derived from CloudSat Auxiliary reanalysis from ECMWF
  - Lower tropospheric stability values correlate negatively with boundary layer depth \( (r = -0.45) \)

- What is actually producing this result? Is precipitation the driving variable, or is it something correlated with precipitation?
Binning DPΔCCA for constant boundary layer depths

- Hold boundary layer depth constant in separate bins for precipitating and dry trajectories
  - Bins with equal N
- See if precipitation still has a significant effect
- Appears not to
Binning DPΔCCA for constant precipitation frequency (inverse)

- Hold precipitation frequency constant, see if shallow and deep boundary layers evolve differently
- They do
  - Shallow boundary layers persist
  - Deep boundary layers tend to break up
Binning $\text{DP} \Delta \text{CCA}$ for constant LTS ($\theta_{700} - \theta_{1000}$) Anomalies

- Boundary layer depth is well correlated with LTS
- Deep boundary layers break up more readily for bins of constant LTS
- Slopes suggest that LTS may also have an influence
Binning DPΔCCA for constant boundary layer depths (inverse)

- Invert the previous figure to see if LTS has an effect for bins of constant boundary depth
  - Appears to have a significant effect
    - High LTS (strong inversion) allows clouds to persist
    - Low LTS associated with breakup
Results for binning DPΔCCA

- Precipitation does not appear to be a driver of cloud breakup
- Instead LTS and boundary layer depth both seem to matter more
- Strong inversions tend to maintain cloud cover independent of boundary layer depth
- Deep boundary layers tend to break up more readily independent of inversion strength
MODIS $N_d$ and AMSR LWP

- Even if precipitation does not affect the actual cloud amount, it likely affects other cloud properties
  - Precipitation should act to scavenge CCN, which would reduce $N_d$ (Wood 2006, JGR and Wood et al. 2012)
  - Changes in $N_d$ may alter Liquid Water Path (Albrecht, 1989)

- We will re-do this same analysis for $N_d$ and LWP
  - Determine $\Delta (N_d \& LWP)$ as a function of their starting anomalies (based on climatology)
  - Study differences relative to predicted changes for bins of the same variables as before
Δ(\(N_d\), LWP) anomalies as a function of their starting anomalies

\[ \Delta(N_d, \text{LWP}) \]

\[ \times 10^7 \]

\[ \begin{align*}
\text{Delta } N_d \text{ Anomaly} \\
\text{Beginning } N_d \text{ Anomaly} \\
\end{align*} \]

\[ \begin{align*}
\text{Delta LWP Anomaly (kg/m}\^2) \\
\text{Beginning LWP Anomaly (kg/m}\^2) \\
\end{align*} \]
DPΔ(LWP, Nd) for constant boundary layer depth

- Precipitation appears to negatively impact LWP
  - Thinner clouds
- Nd declines more in shallow boundary layers when precipitation is present, less so in deep layers
Binning $\text{DP} \Delta (\text{LWP}, N_d)$ for constant precipitation frequency (inverse)

- $\text{DP} \Delta \text{LWP}$ is less affected by boundary layer depth
- $\text{DP} \Delta N_d$ is affected by boundary layer depth
  - Shallow boundary layers see less decline in $N_d$
  - Precipitation appears to matter only for shallow boundary layers
Binning $\text{DP} \Delta (LWP, N_d)$ for constant LTS ($\theta_{700} - \theta_{1000}$) Anomalies

- $\text{DP} \Delta LWP$ shows a complex pattern...
  appears to be a mess here

- $\text{DP} \Delta N_d$ is more positive in shallow boundary layers
Binning $\text{DP} \Delta (\text{LWP}, \text{Nd})$ for constant boundary layer depths (inverse)

- $\text{DP} \Delta \text{LWP}$ slightly more clear than previous
  - Strong inversions may matter for shallow or deep boundary layers, reducing LWP
- $\text{DP} \Delta \text{Nd}$ is affected by inversion strength in shallow layers
  - Is consistently (-) in deep boundary layers
Conclusions 1

- Numerous biases must be dealt with in a Lagrangian study
  - Geographic biases
  - Zenith angle biases
  - Initial distributions of cloud anomalies will not agree, and could warp the results

- It is important to create a quantity that minimizes these biases
  - In this case a 'difference from predicted value', which allows us to directly compare these different samples
Conclusions 2

- Boundary layer depth and LTS appear to be much better predictors of Sc break up, rather than precipitation.
- Precipitation does appear to affect LWP, while LWP shows a less significant, more complex association with LTS and boundary layer depth.
- Nd is affected by precipitation and LTS in shallow boundary layers, while it evolves very steadily (negatively) in deeper boundary layers.
Future Work

• Improve our DPΔ functions:
  – Better trajectories (using cloud fields and short Δt)
  – Quantify how long anomalies persist in Sc decks

• Use new cloud cover & precip products, esp. Merged IR (as shown by Burleyson), and new drizzle detection

• Back trajectories
  – If boundary layer depth matters so much, what factors control that? SST? 700mb T?
  – What predicts precipitation?
  – POC detection & evolution