Satellite Observations of Ship Tracks using Passive and Active Sensors

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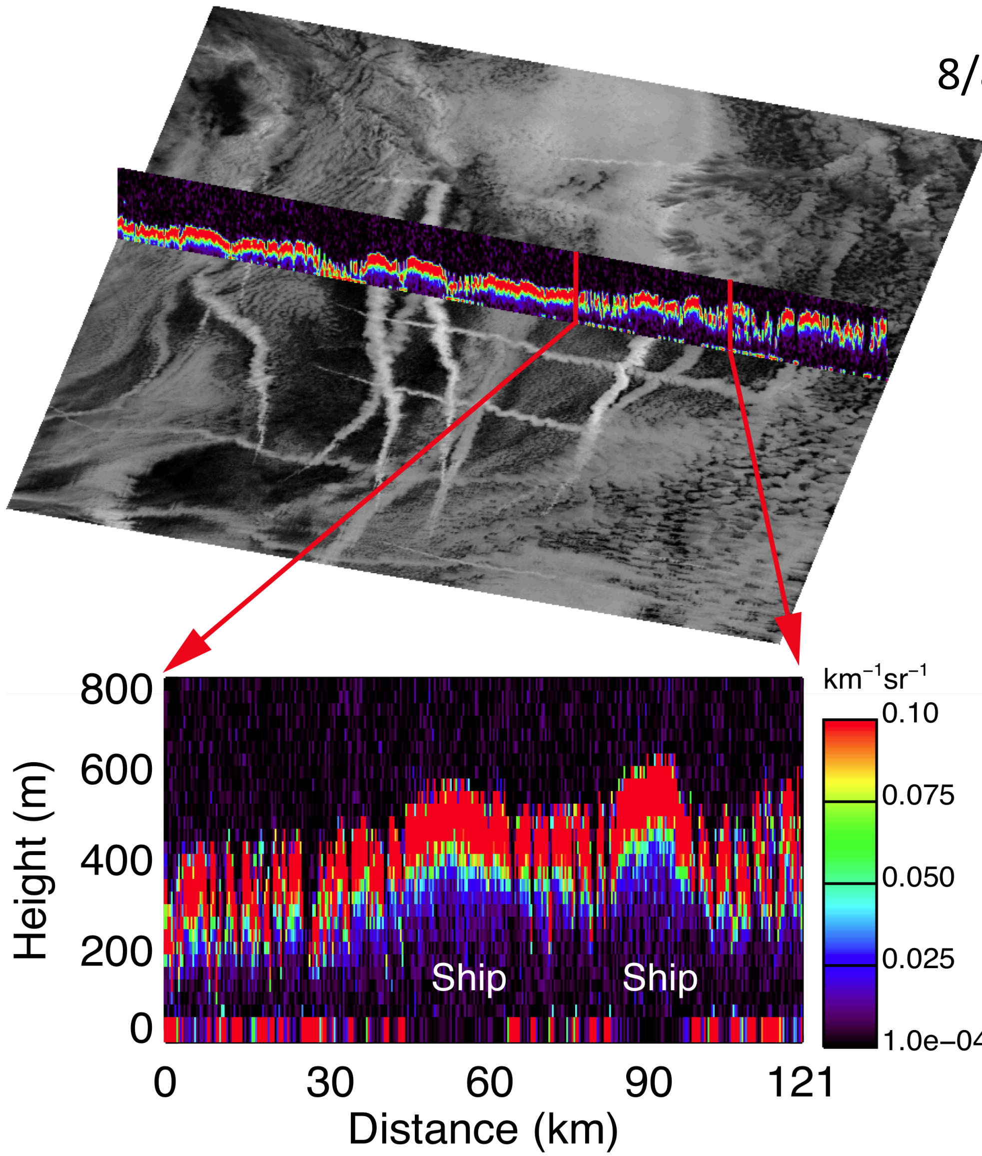
GOAL: *Use ship tracks, that are created by aerosol plumes, to assess the microphysical and dynamical changes to marine stratus. In particular, how does pollution affect cloud top altitude and precipitation?*

Colorado State University

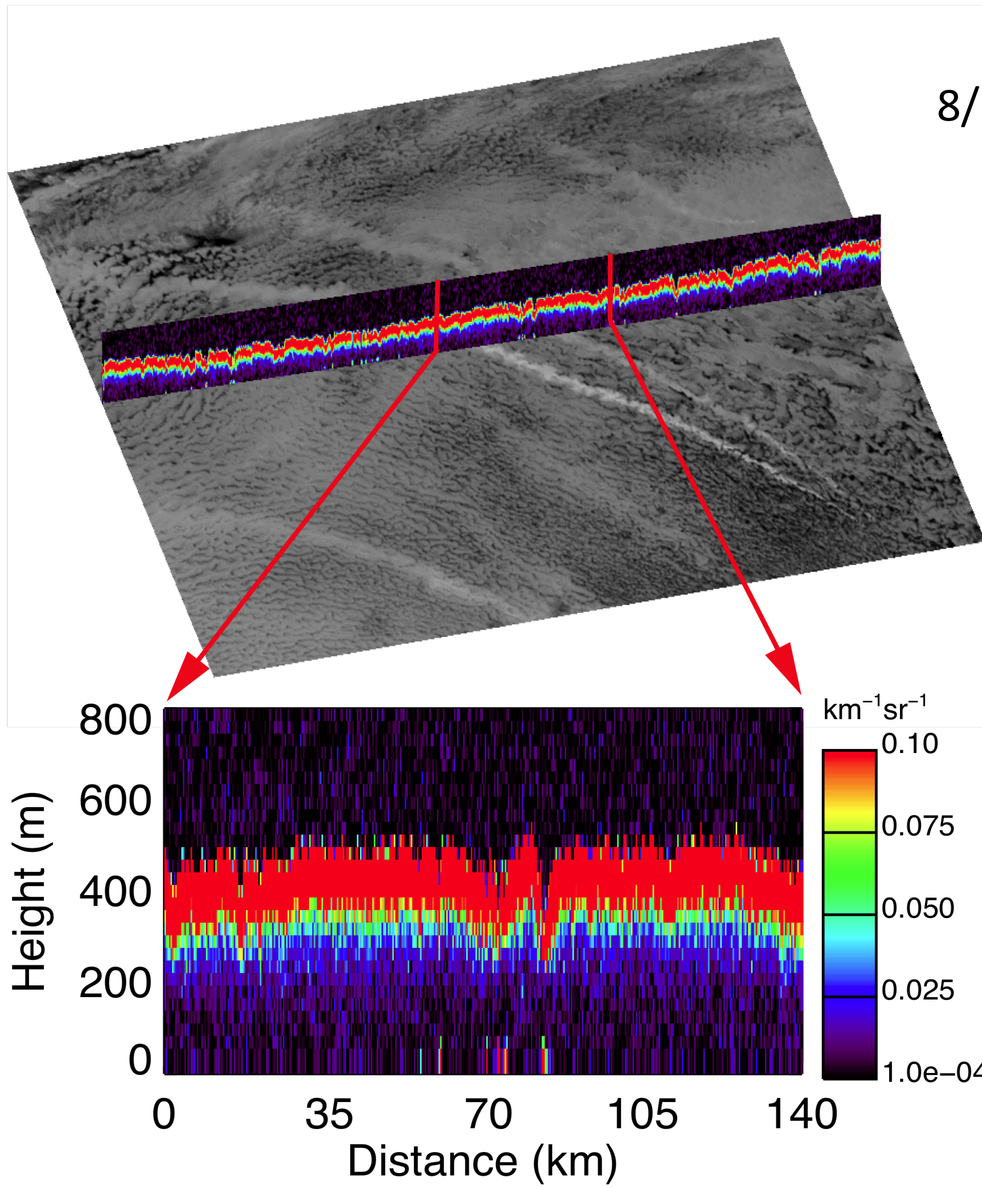
Aerosol Increasing Cloud Top Height

8/8/2007 22:55 UTC



Aerosol Dynamical Effect *Not* Observed

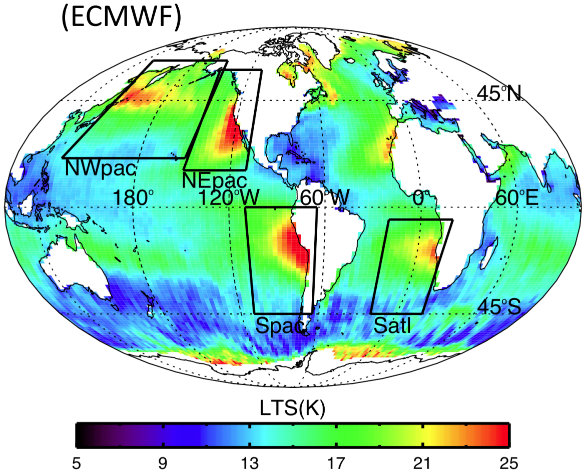
8/23/2007 22:15 UTC



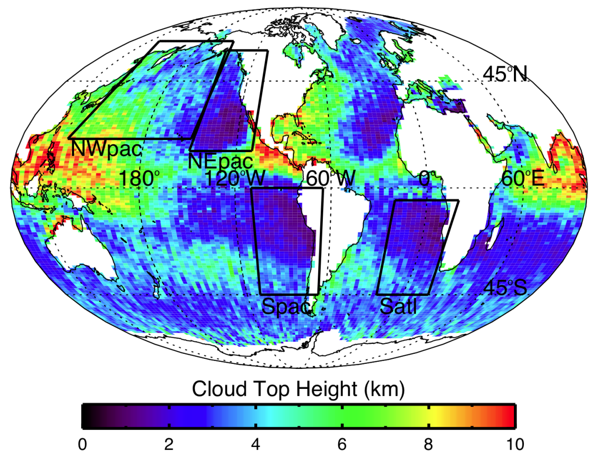
Ship Track Hunting Grounds

JJA Composite (2007, 2008, 2009)

Lower Troposphere Stability
(ECMWF)

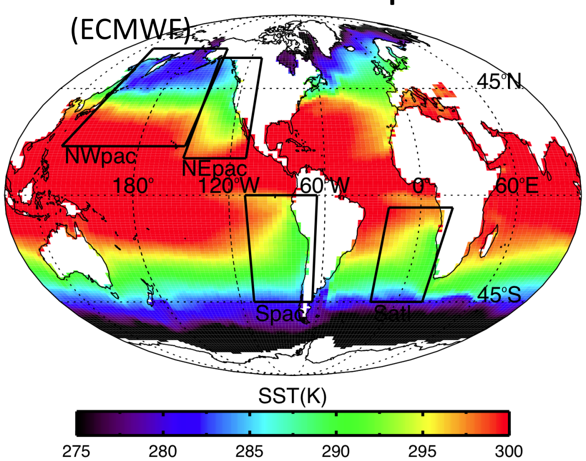


Cloud Top Altitude

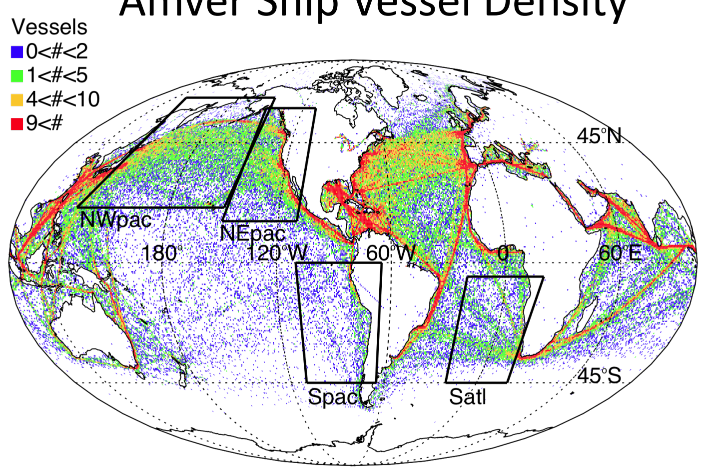


Region	Name
NWpac	Northwest Pacific
NEpac	Northeast Pacific
Spac	South Pacific
Satl	South Atlantic

Sea Surface Temperature
(ECMWF)



Amver Ship Vessel Density



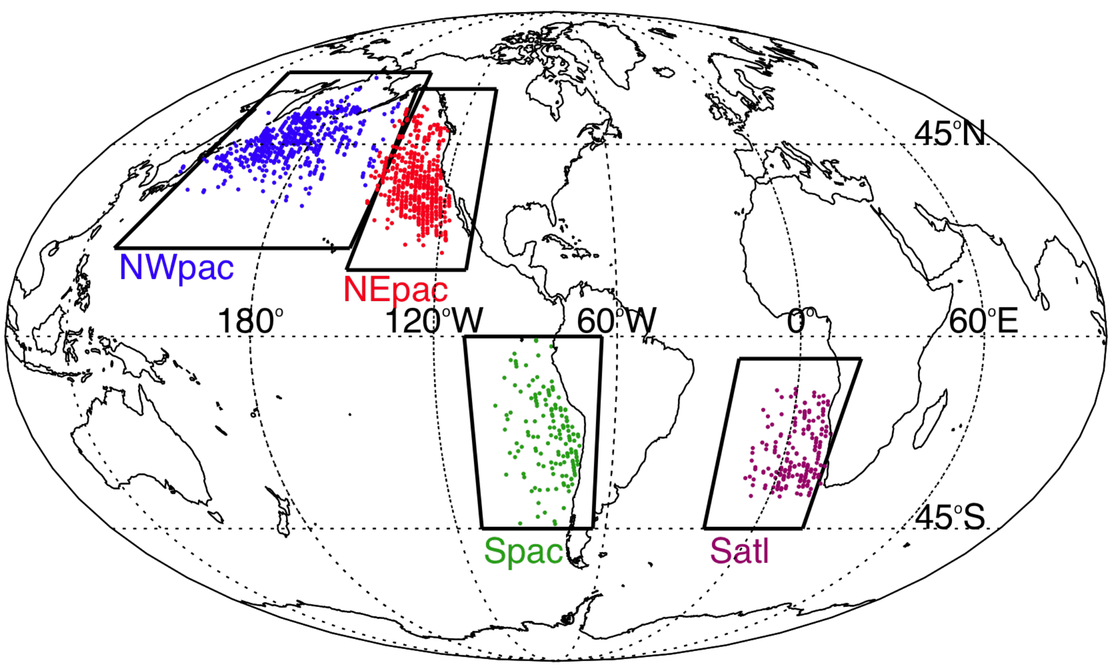
Ship track hunting grounds were selected for regions with high frequencies of:

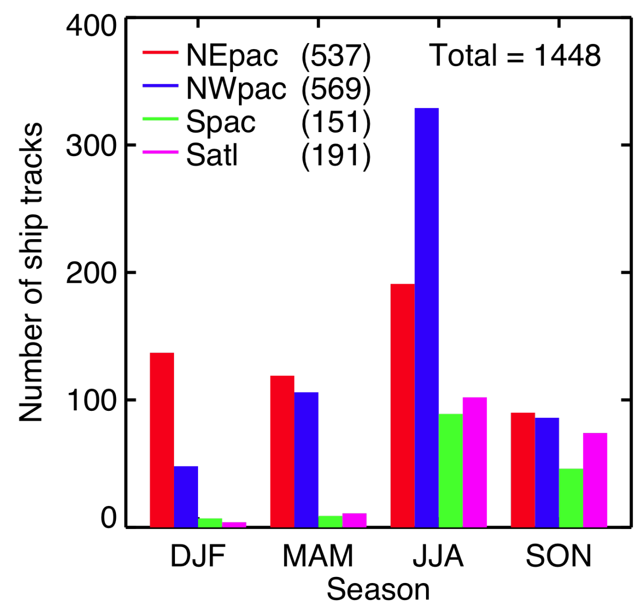
- **High LTS**
- **Low cloud top height**
- **Cold SST**
- **Ship vessel traffic**

Ship Track Database

Ship tracks were 'painstakingly' hand-logged by visually inspecting *thousands* MODIS images. The research described here analyzes the largest database of ship tracks observed synergistically by radar and lidar.

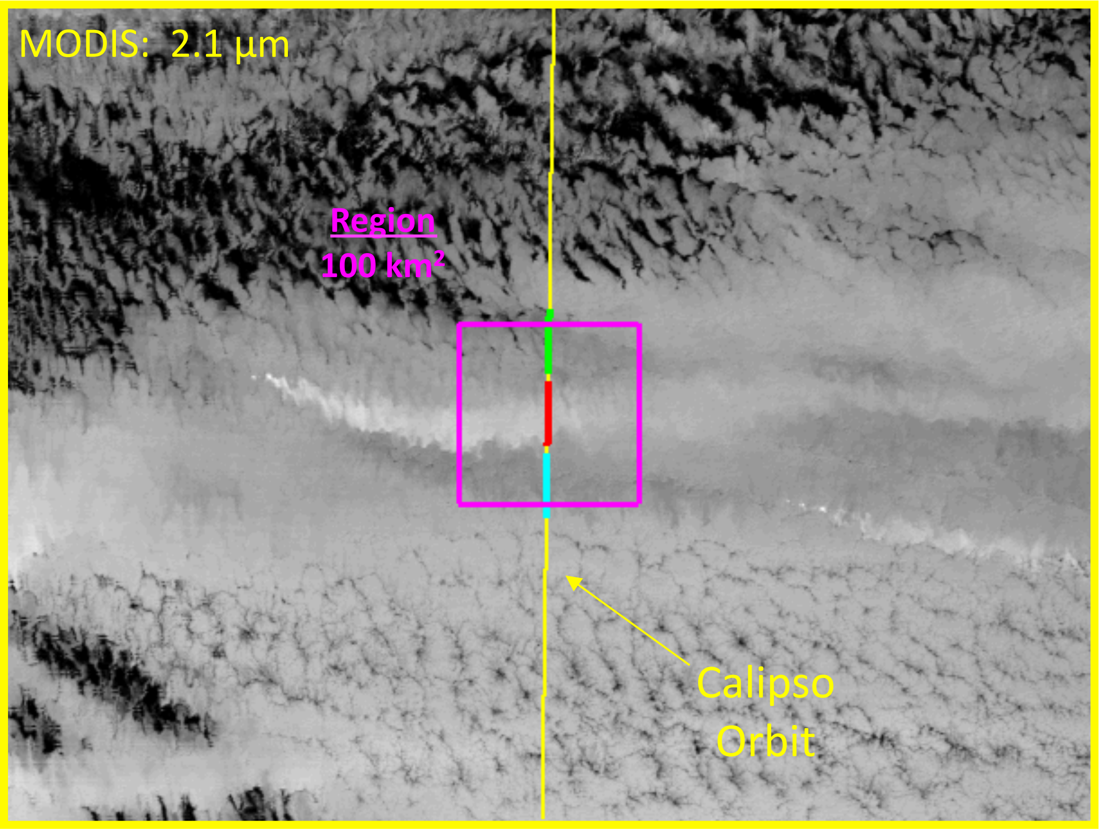
Period: June 2006 – December 2009



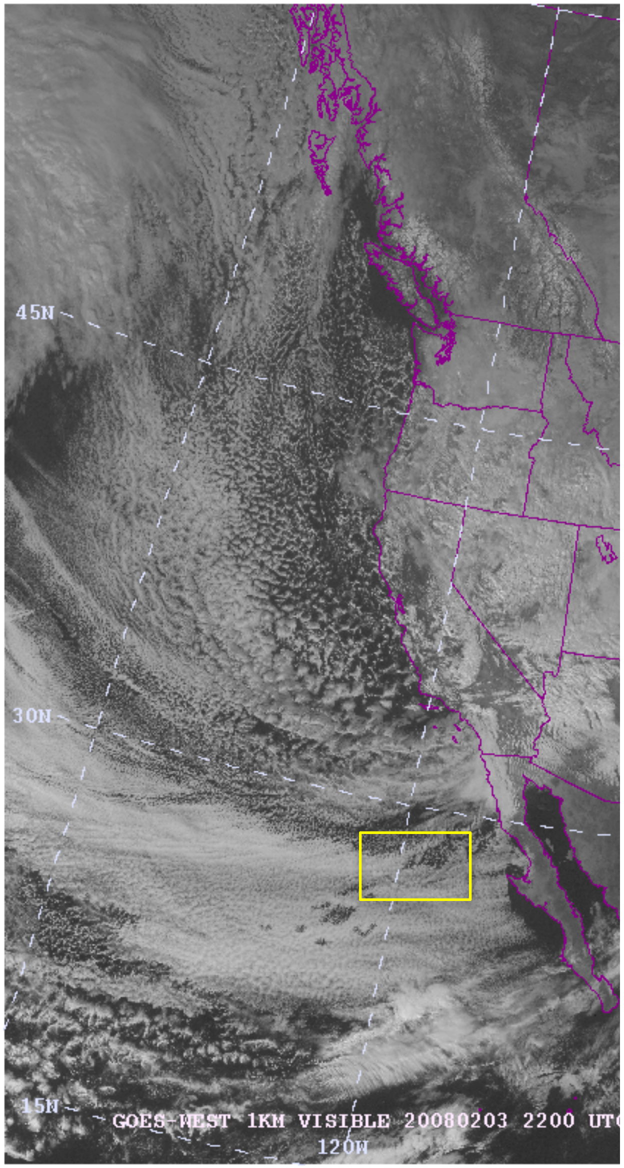


Ship Track Identification

1. Locate Ship Track



February 3rd, 2008 at 2145 UTC



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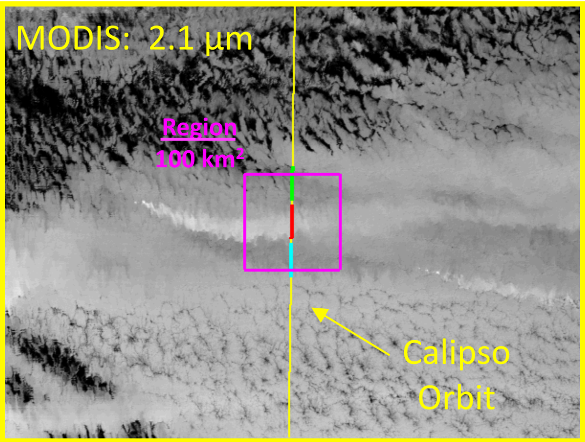
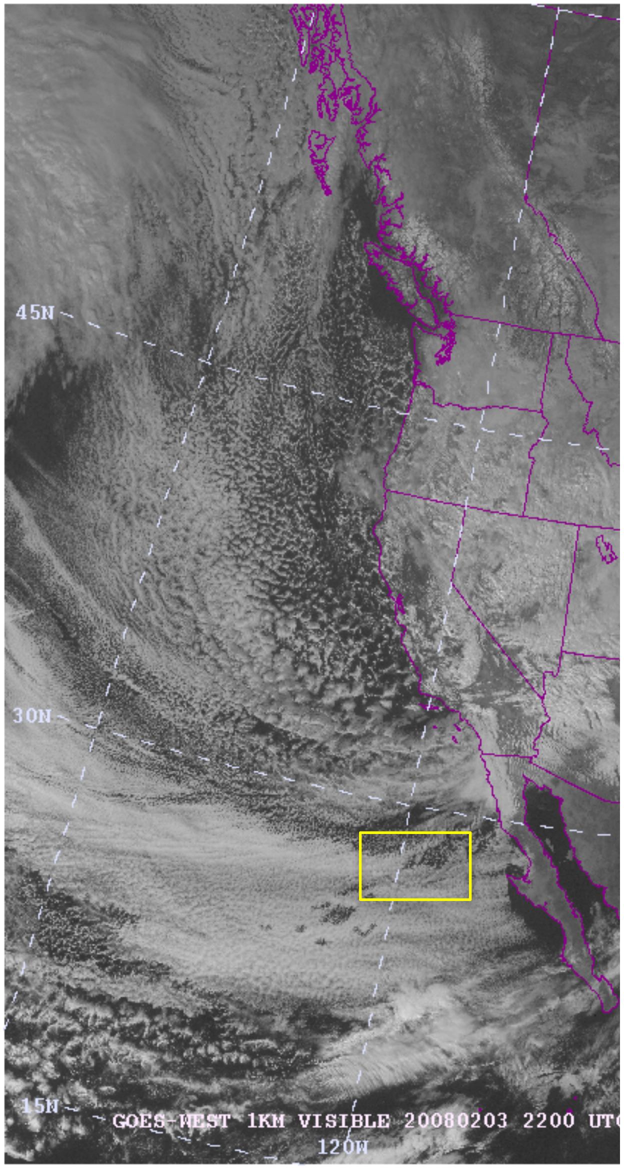


February 3rd, 2008 at 2145 UTC

2. Classify the Cloud Type
(Subjective approach)

250 m MODIS: 0.64 µm



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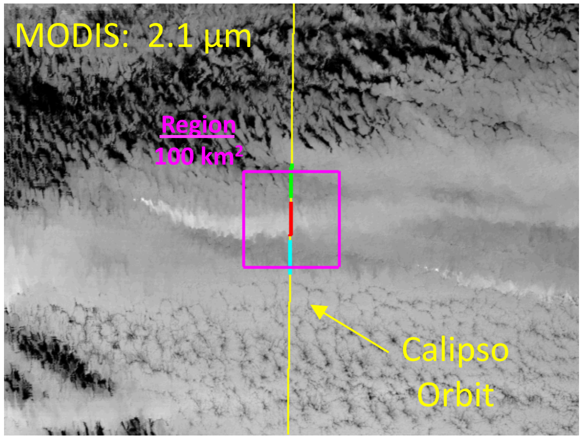


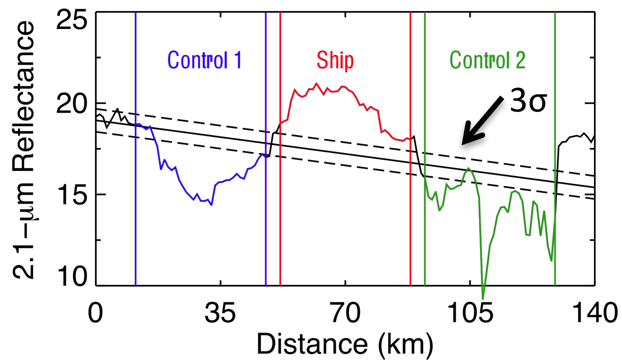
February 3rd, 2008 at 2145 UTC

2. Classify the Cloud Type

(Subjective approach)

250 m MODIS: 0.64 µm

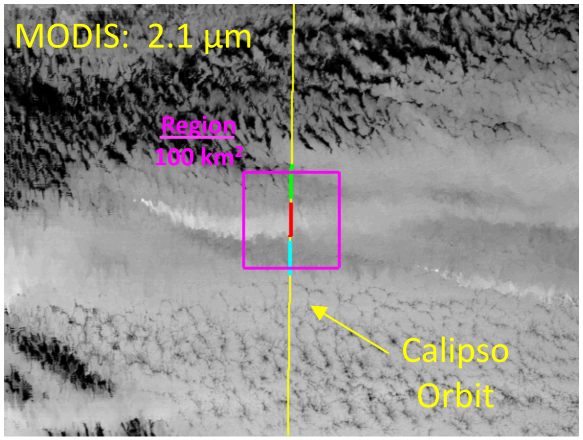
3. Automated Pixel Identification



Method adapted from Segrin et al, (2007).

Ship Track Identification

1. Locate Ship Track



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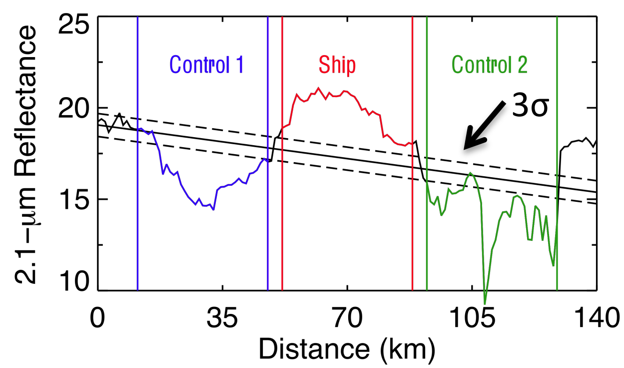


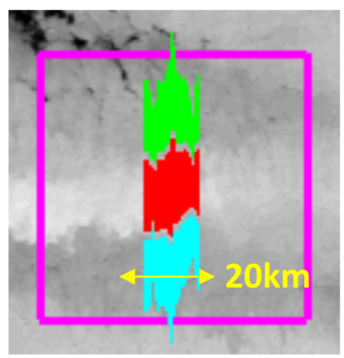
Method adapted from Segrin et al, (2007).

2. Classify the Cloud Type
(Subjective approach)

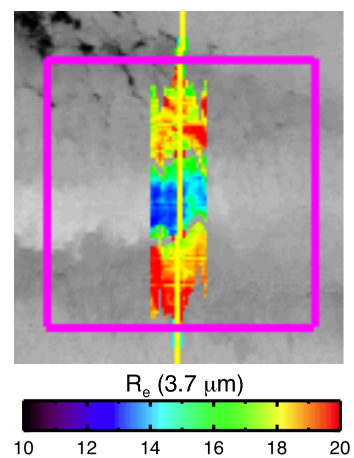
250 m MODIS: 0.64 µm

4. Construct 20 km segment around cross-section

Pixel Identification



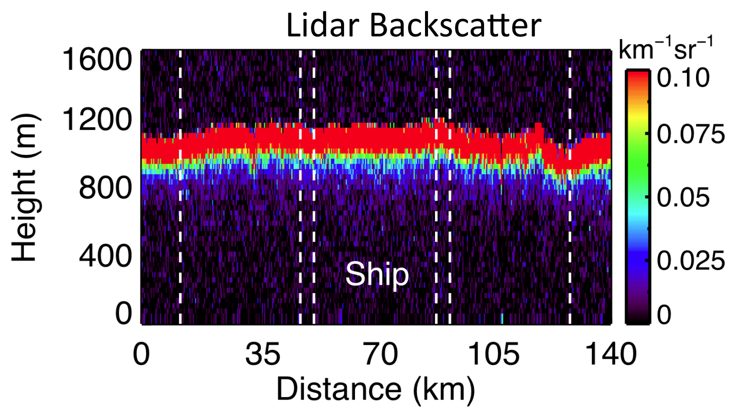
Droplet Radius

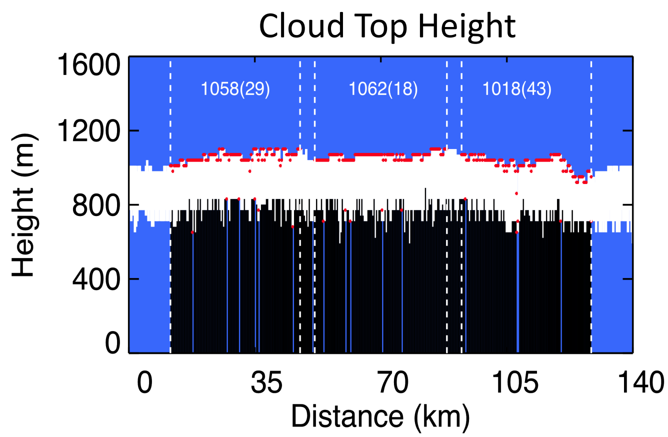


Ship pixels have ***smaller*** cloud droplets than the nearby unpolluted control pixels.

Ship Track Identification

5. Collocate CALIOP to MODIS





Single Layer

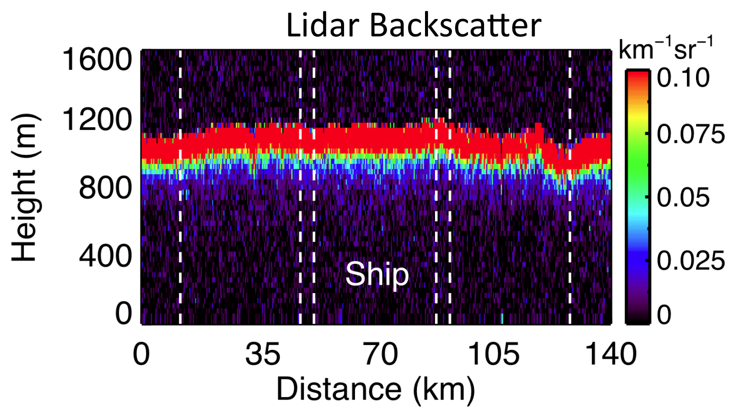
- Clouds above the top of the boundary layer or 3 km are screened.

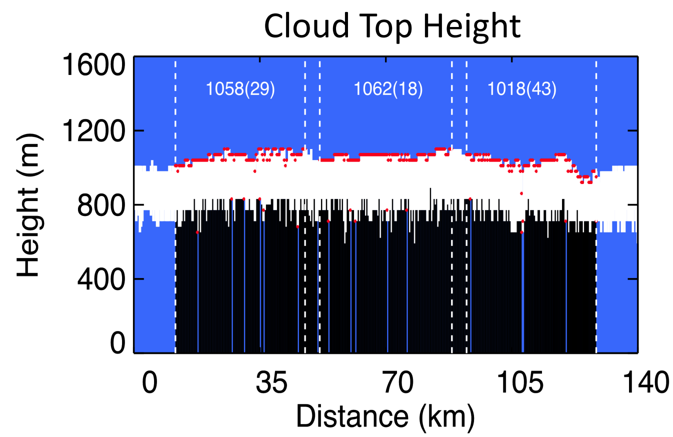
Number:

- At least 2 ship and control pixels (from either side).

Ship Track Identification

5. Collocate CALIOP to MODIS





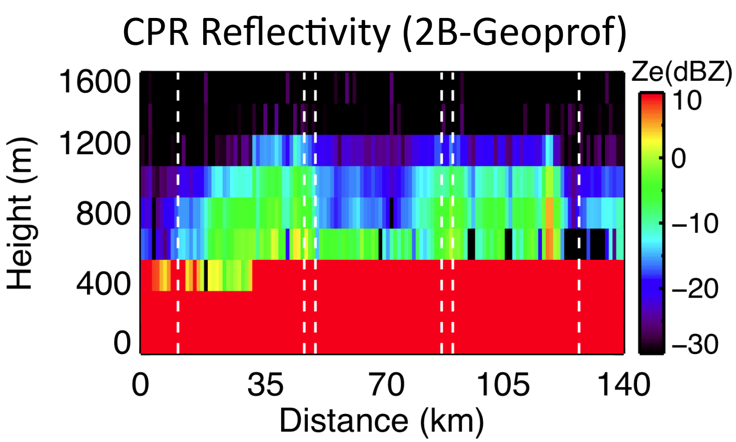
Single Layer

- Clouds above the top of the boundary layer or 3 km are screened.

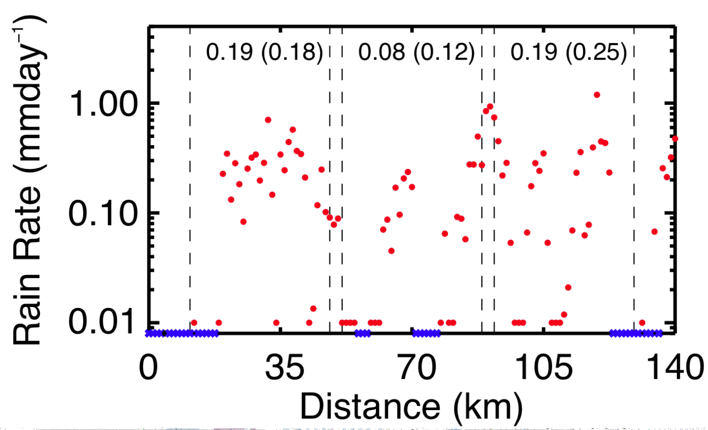
Number:

- At least 2 ship and control pixels (from either side).

6. Collocate to CloudSat



Precipitation Flags and Intensity → 2C-Column-Precip (Haynes et al., 2006)



Clear Sky Profile:

- Cloud mask < 20

Non-raining cloud:

- Cloud mask ≥ 20
- Precip flag = 0

Raining cloud:

- Cloud mask ≥ 20
- Precip flag > 0

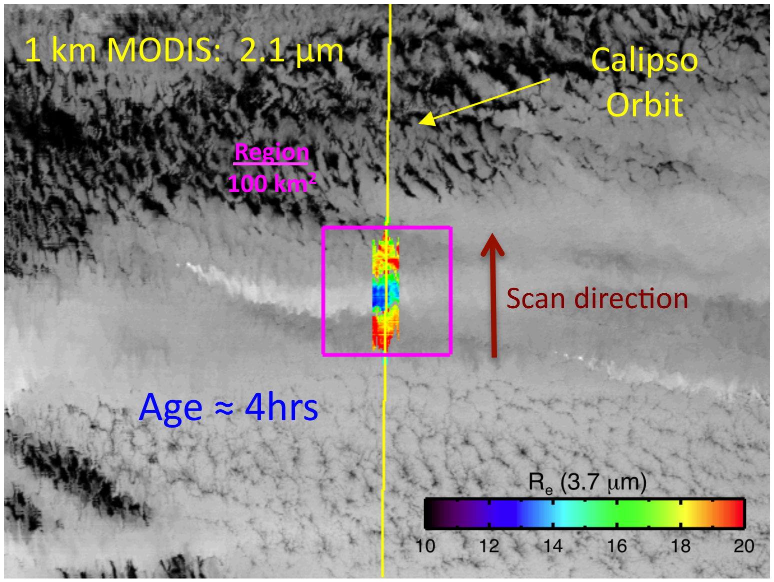
Number:

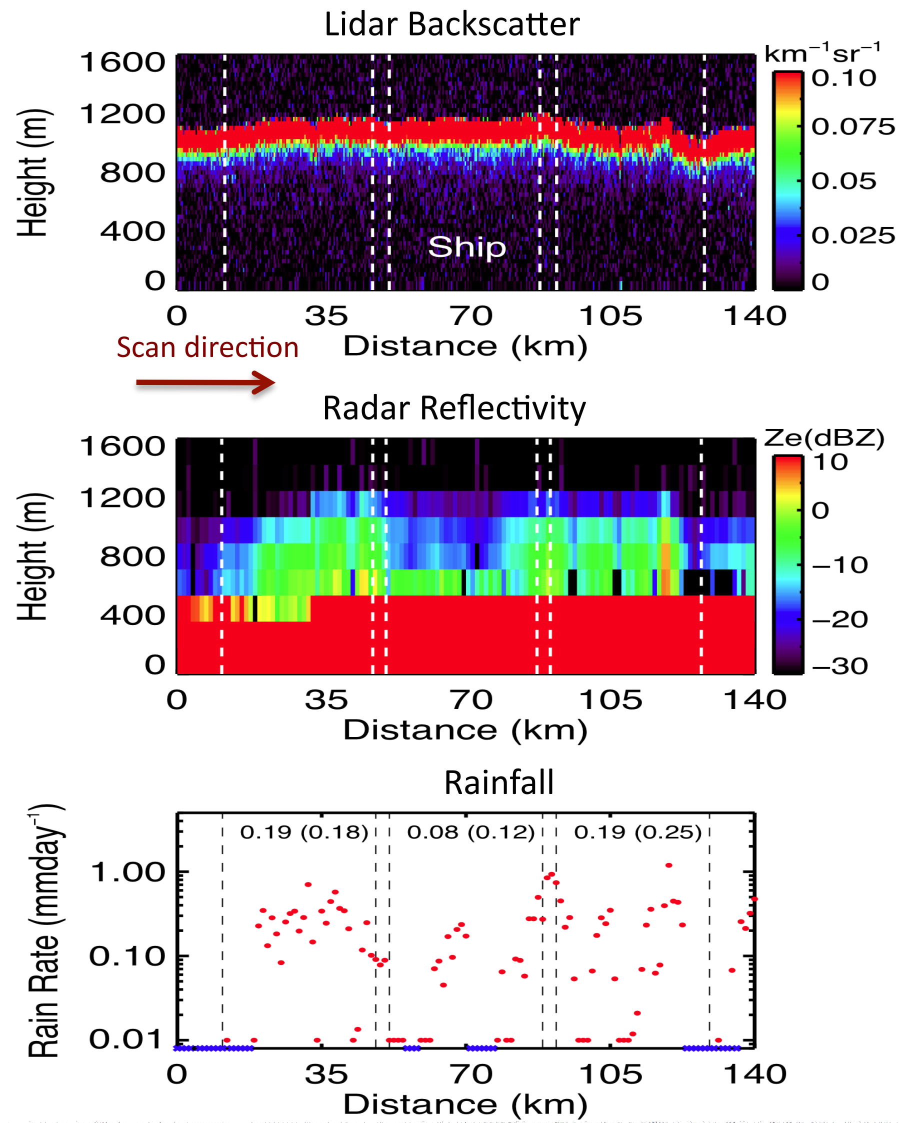
- At least 1 pixel from the ship and 1 from either control.

Rainfall is *reduced* in polluted clouds
"For this particular case"

Case Study 1: Suppressed Precipitation in Ship Track

February 3rd, 2008 at 2145 UTC





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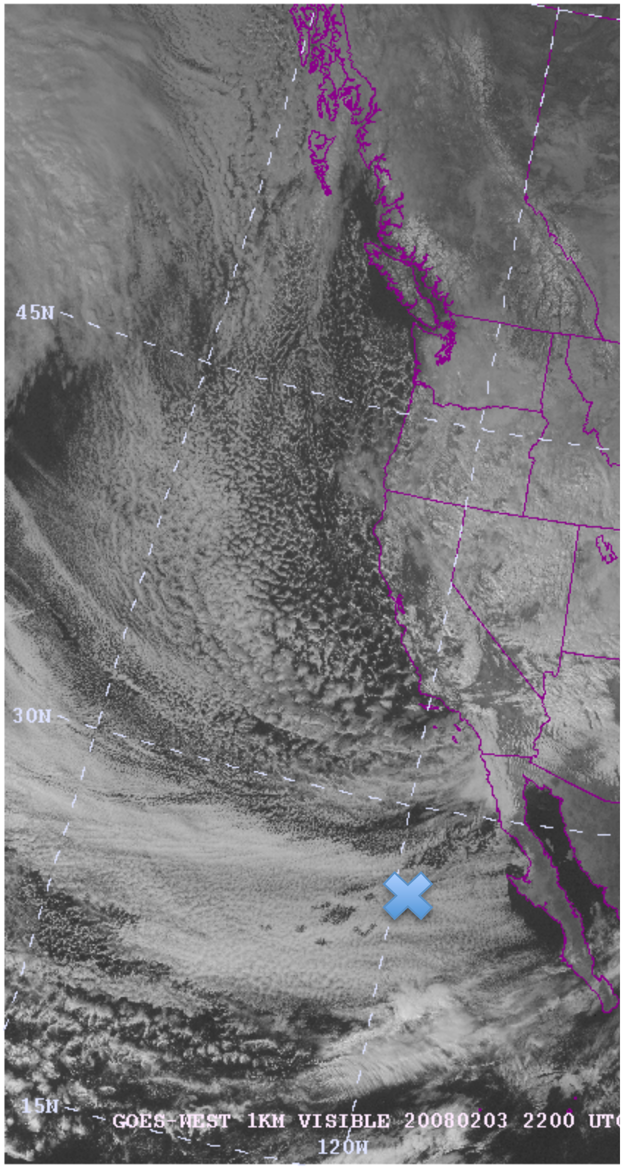
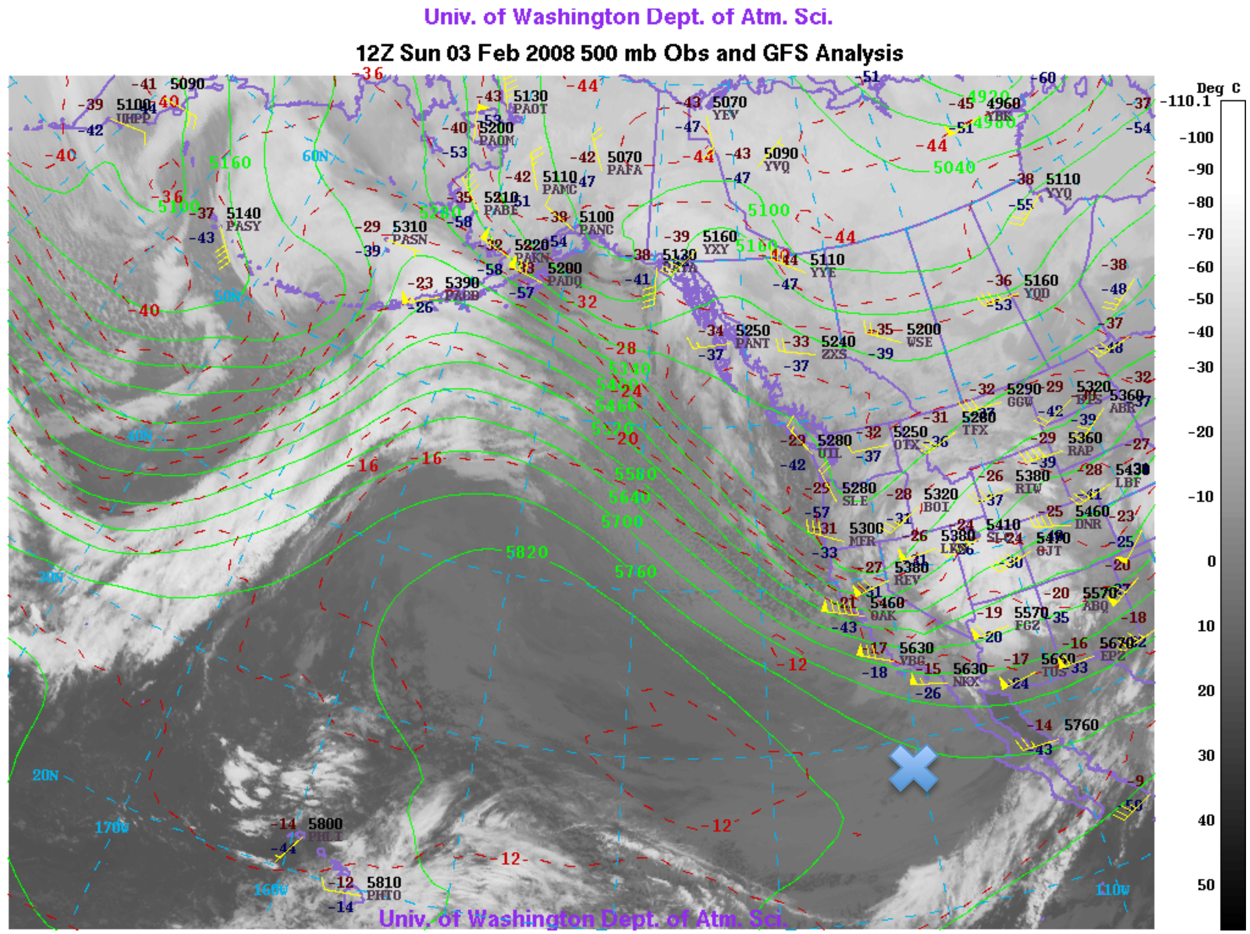
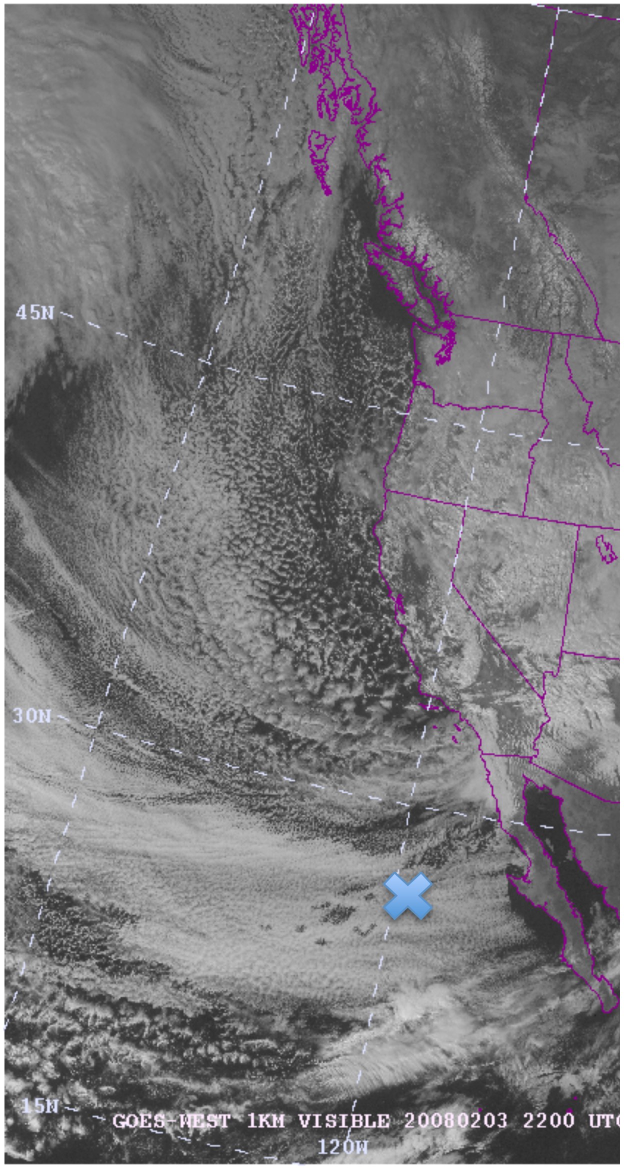


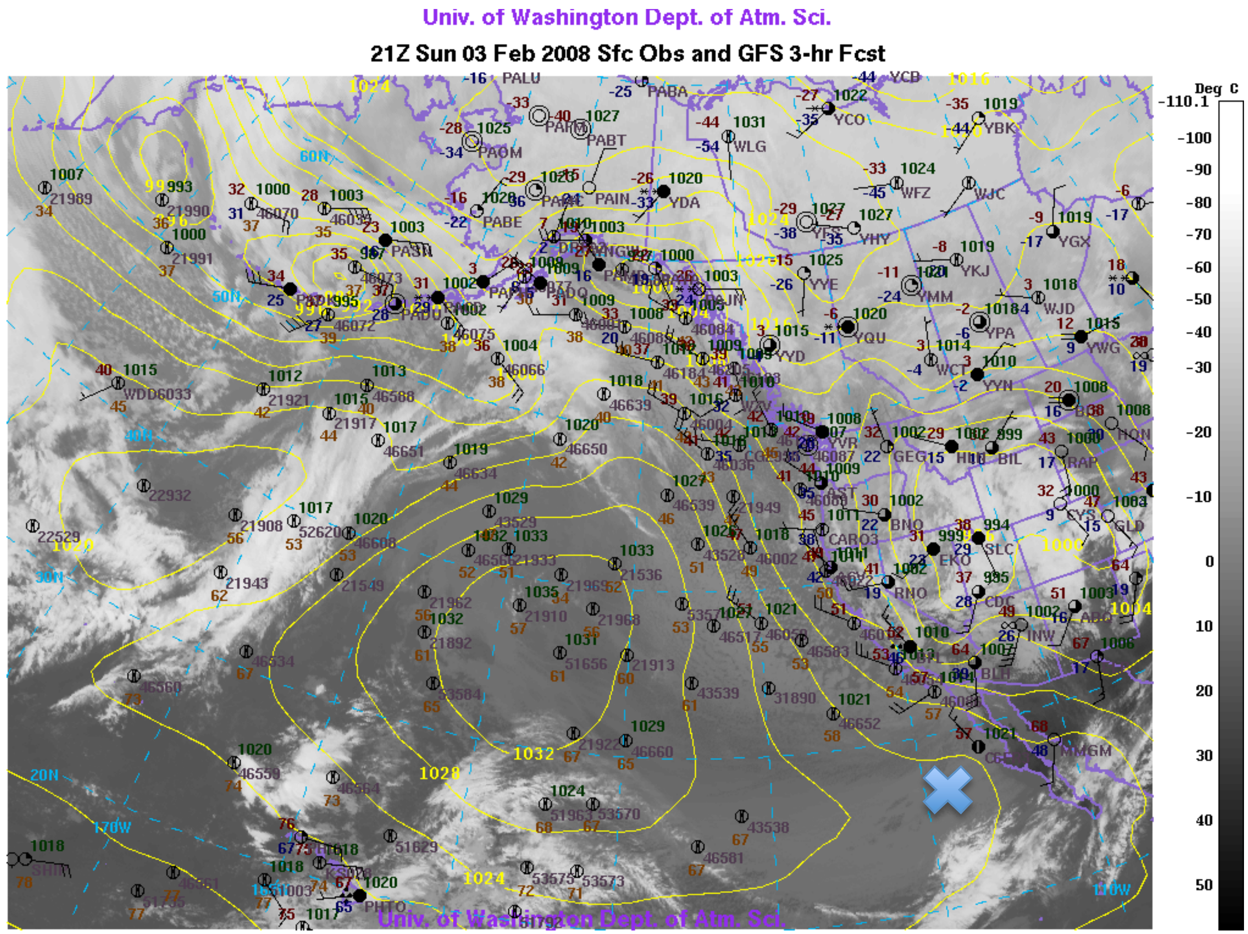


Ship track is located in an expansive sheet of closed cells bordering several pockets of open cells (POCS) near the bottom of a 500 mb trough.

Case Study 1: Suppressed Precipitation in Ship Track

February 3rd, 2008 at 2145 UTC





Surface Conditions:

Air temperature = 290 K

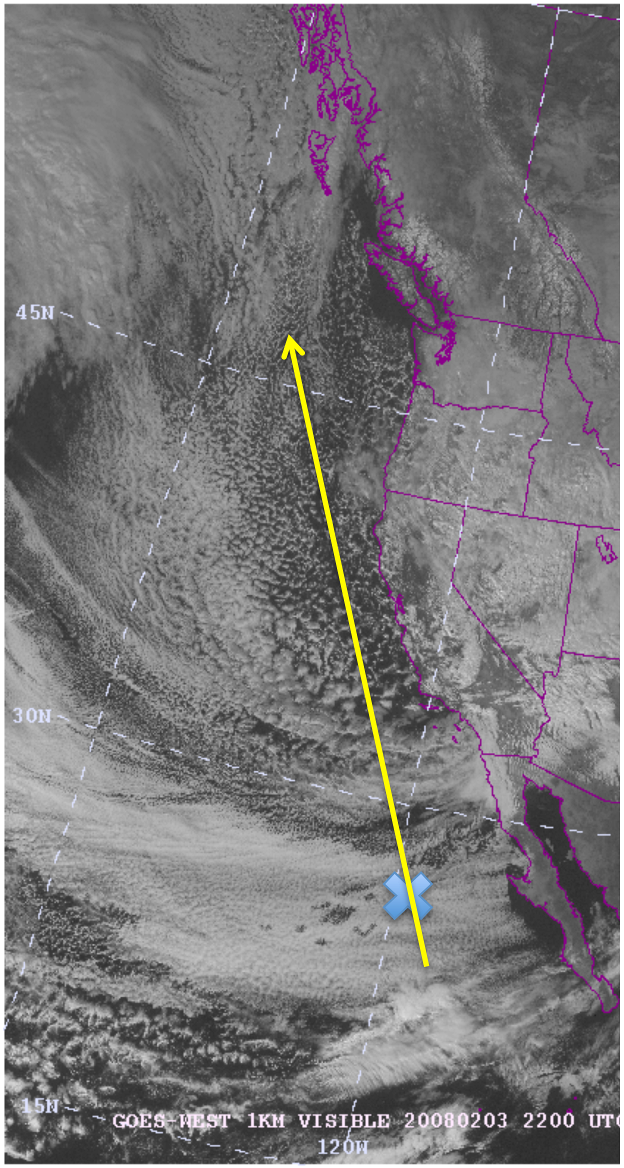
Sea level pressure = 1020 mb

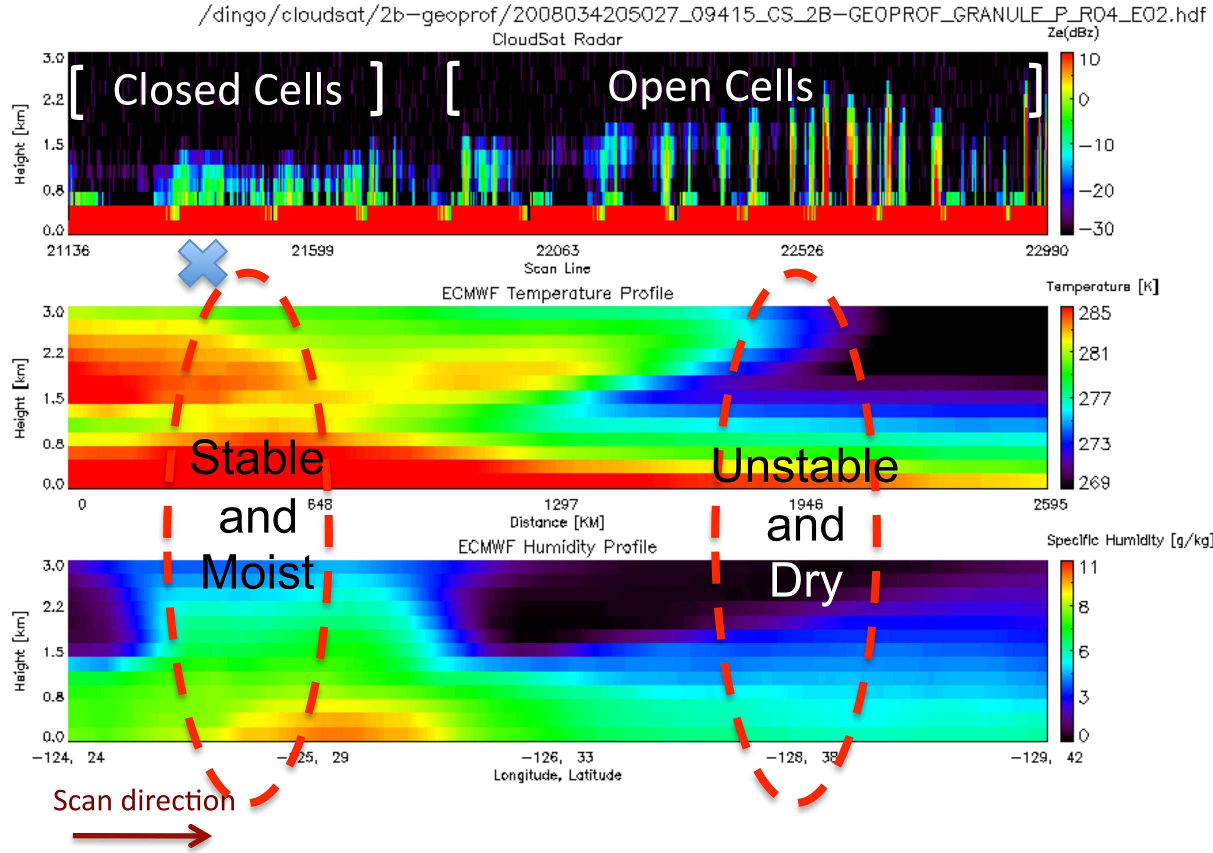
Weak northwesterly flow = 7 m/s

LTS = 20 K

Case Study 1: Suppressed Precipitation in Ship Track

February 3rd, 2008 at 2145 UTC





Thermodynamics:

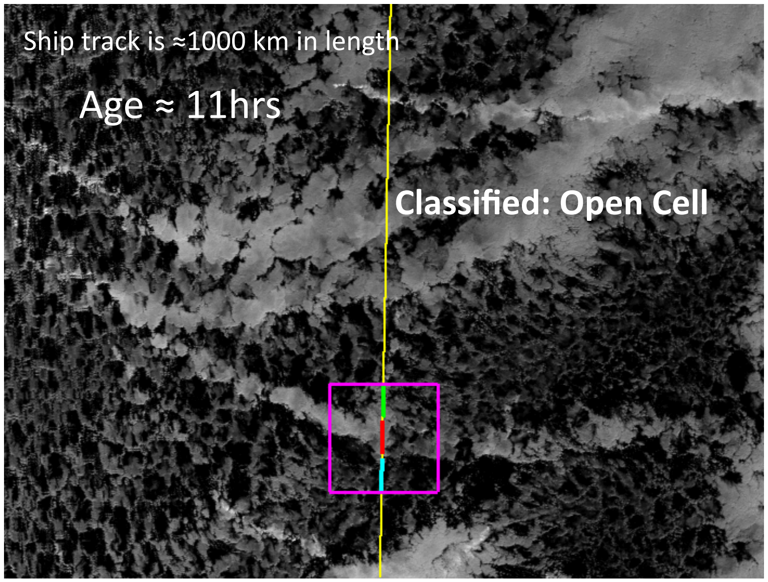
High static stability over region of closed cells.

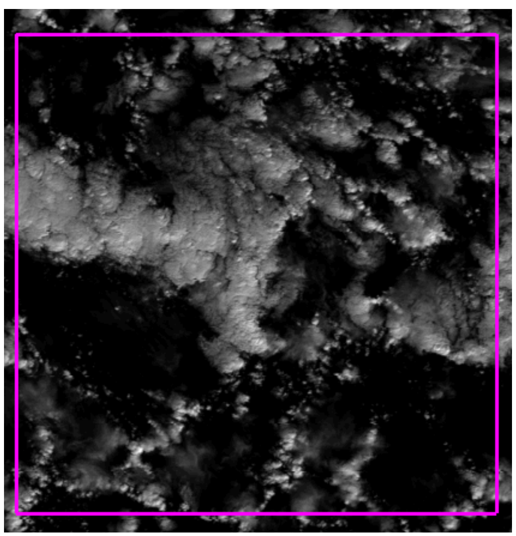
High amount of moisture above the boundary layer.

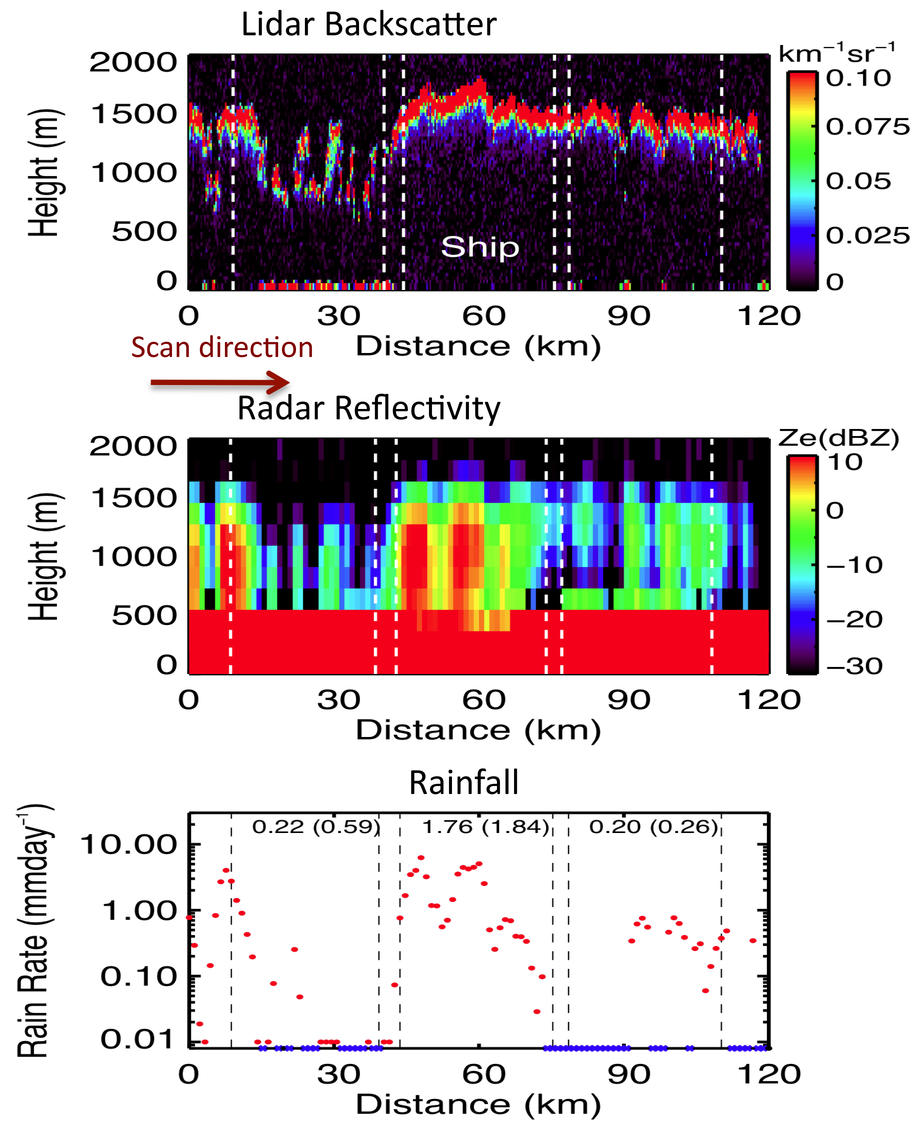
Cloud depth and reflectivity increases towards the North where the instability increases.

Case Study 2: Enhanced Precipitation in Ship Track

January 11th, 2007 at 2210 UTC

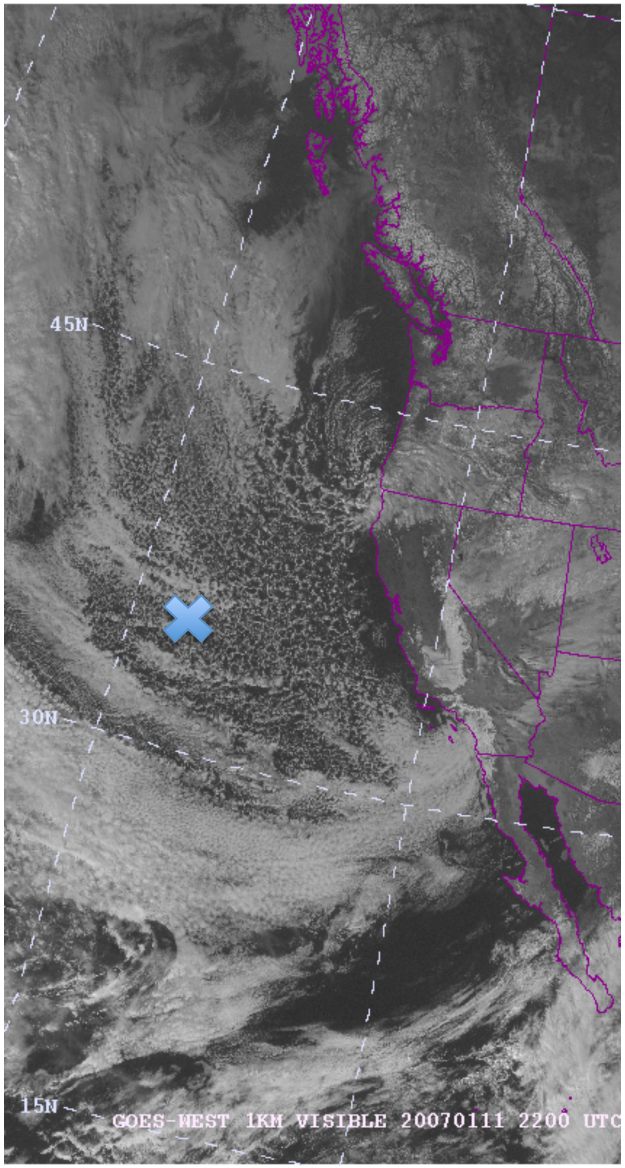


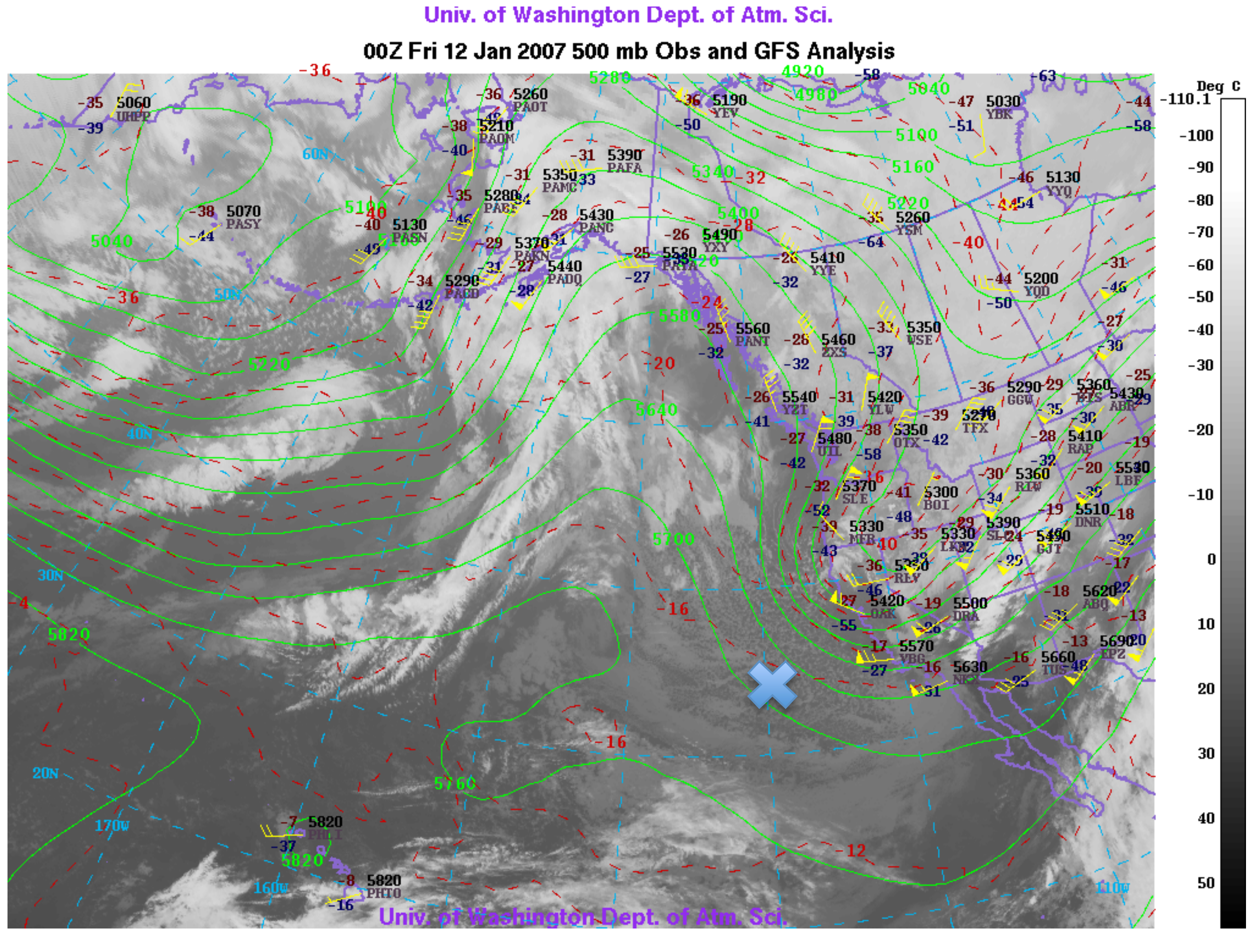




Case Study 2: Enhanced Precipitation in Ship Track

January 11th, 2007 at 2210 UTC

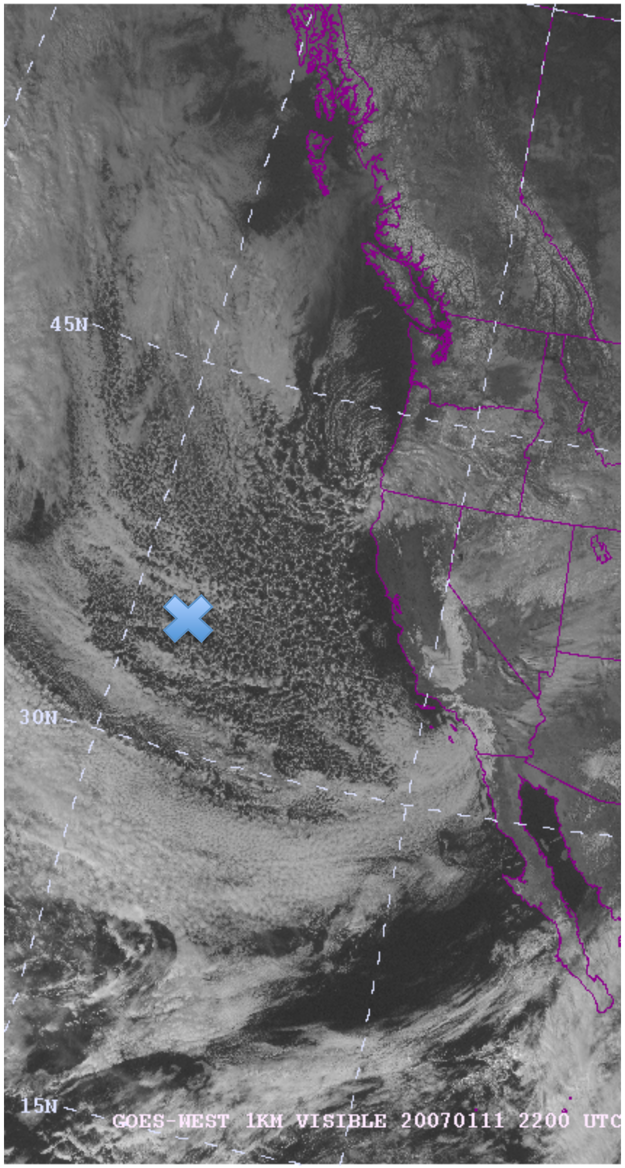


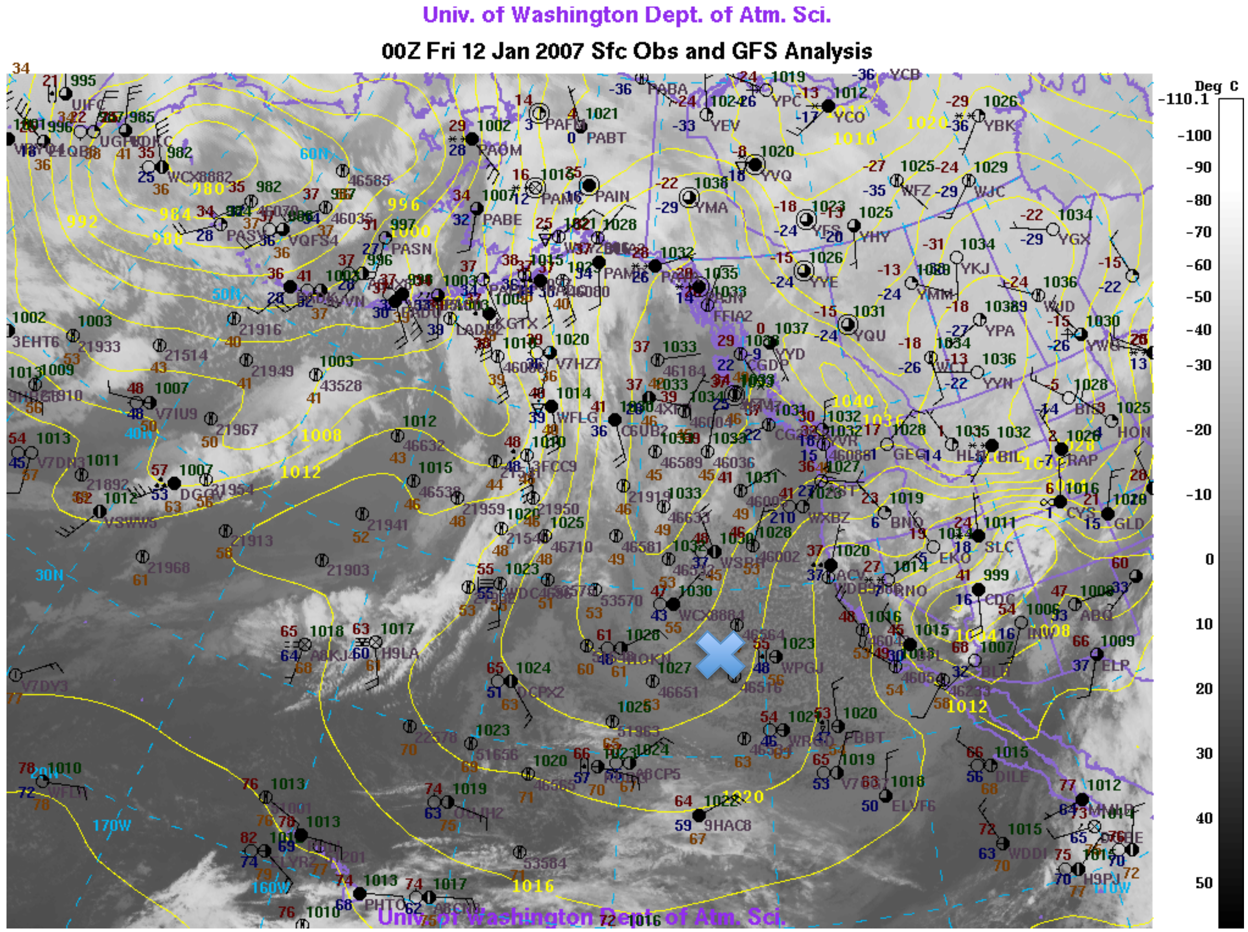


Ship track is located in an expansive sheet of *open cells* near the bottom a tilted 500 mb trough.

Case Study 2: Enhanced Precipitation in Ship Track

January 11th, 2007 at 2210 UTC





Surface Conditions:

Air temperature ~ 285 K

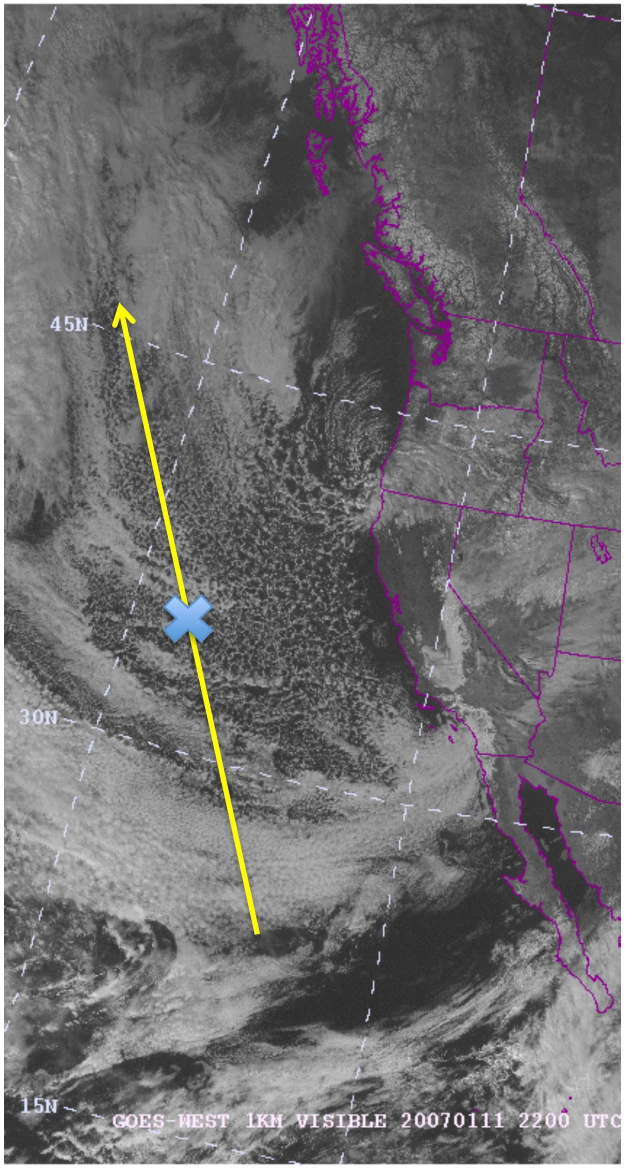
Sea level pressure ~1025 mb

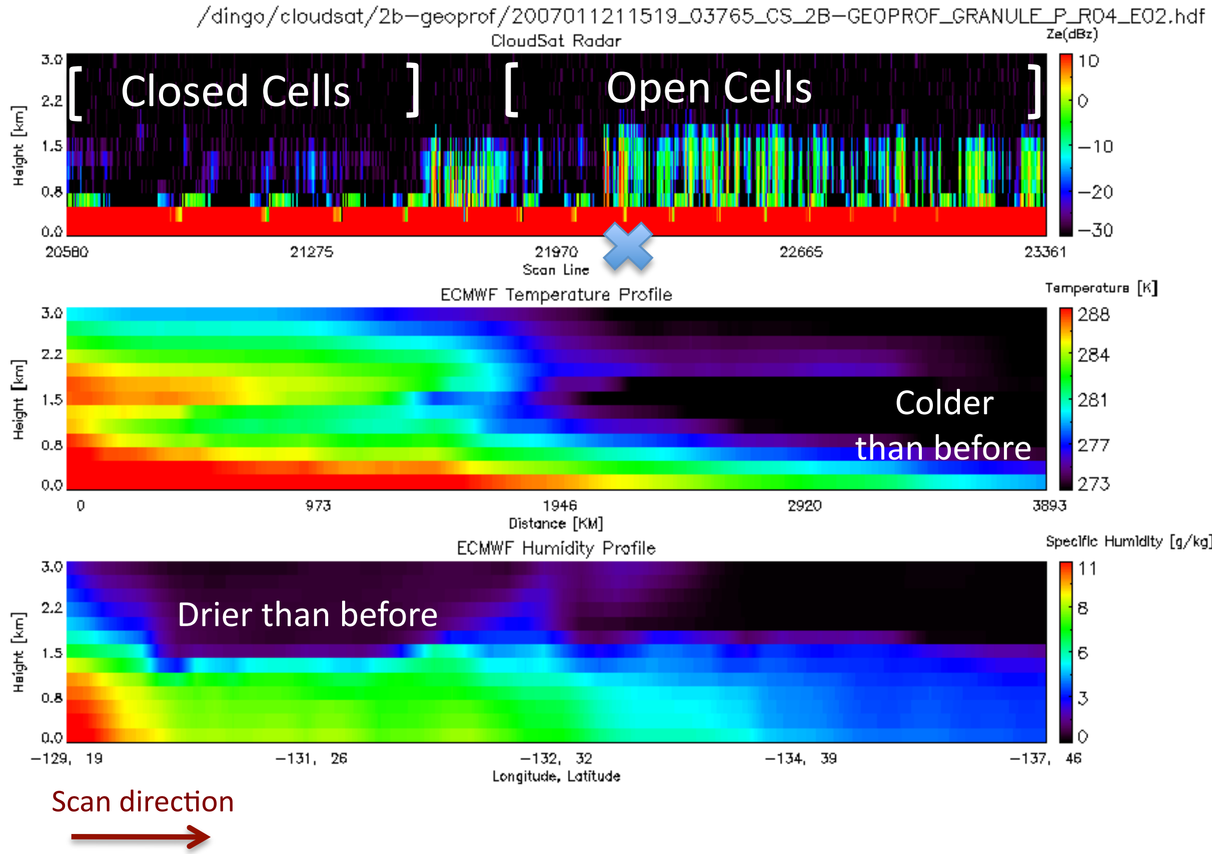
Weak Northeasterly flow ~7 m/s

LTS ~ 18 K

Case Study 2: Enhanced Precipitation in Ship Track

January 11th, 2007 at 2210 UTC





Thermodynamics:

Large lower tropospheric static stability over region of closed cells.
Low amount of moisture above the boundary layer this time.
Cloud depth and reflectivity remains roughly constant towards the North.

Rainfall Departures (Ship – Controls)

How often is rainfall suppressed?

Short answer: **70% of the time**

	Confidence level (%) (two tailed T-test)			
Response	**No Threshold**	**90th %**	**95th %**	**99th %**
Reduction	161	48	28	16
Increase	70	35	29	17

Longer answer: **At higher significant levels enhanced precipitation is just as likely to occur as rainfall suppression.**

→ Most of the reduction cases are removed at large T values because there are a Large number of small negative rainfall departures.

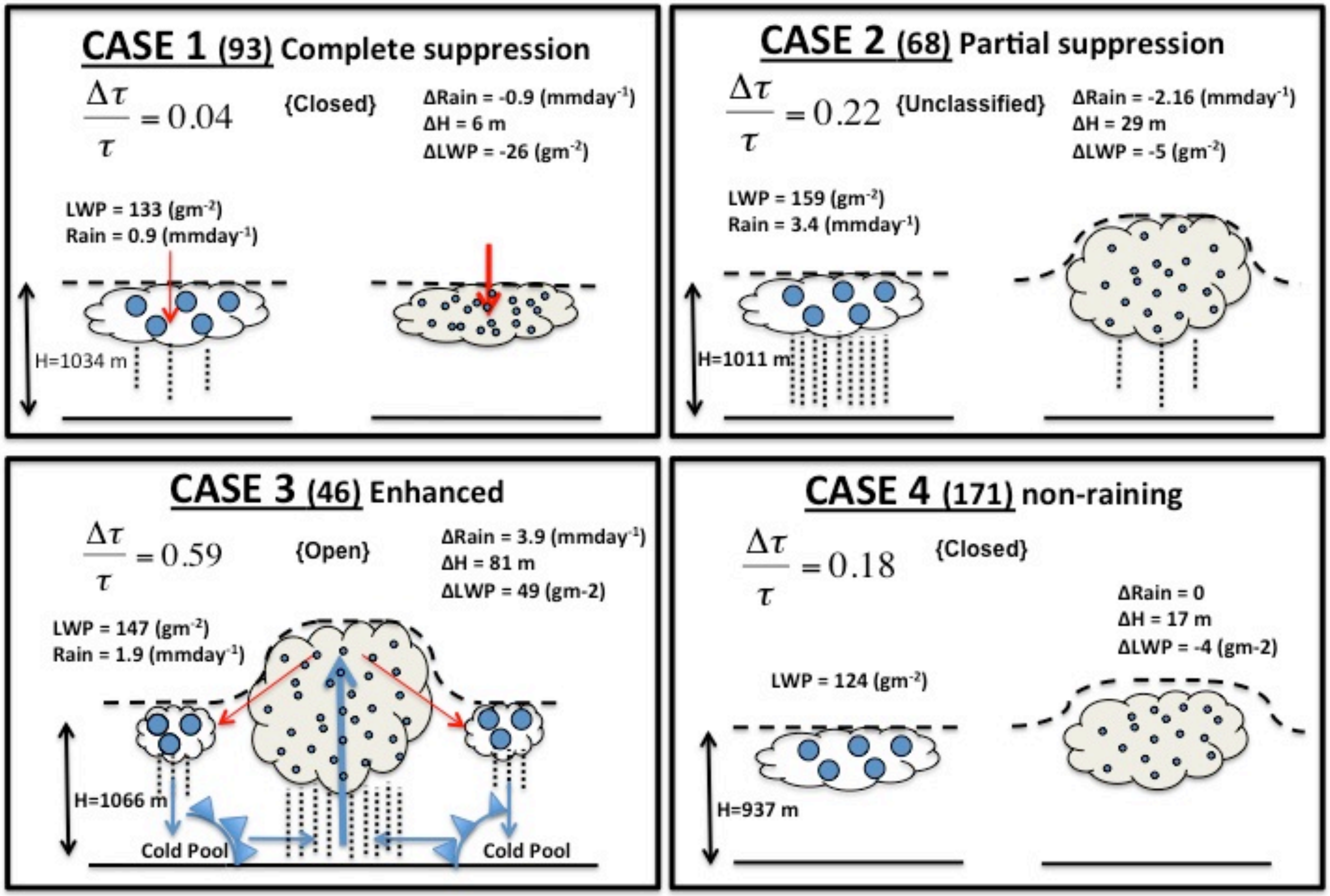
	Number
Observed by the CPR	401
Observed to have Rainfall	231
Non-raining	170

$$T = \frac{\overline{x_{ship}} - \overline{x_{cons}}}{s/\sqrt{n}}$$

<u>For the T statistic to be large:</u>
Difference between ship and controls → large
Pooled standard deviation (s) → small
Number of samples (n) → large

Implications for aerosol indirect forcing

40%
30%
20%

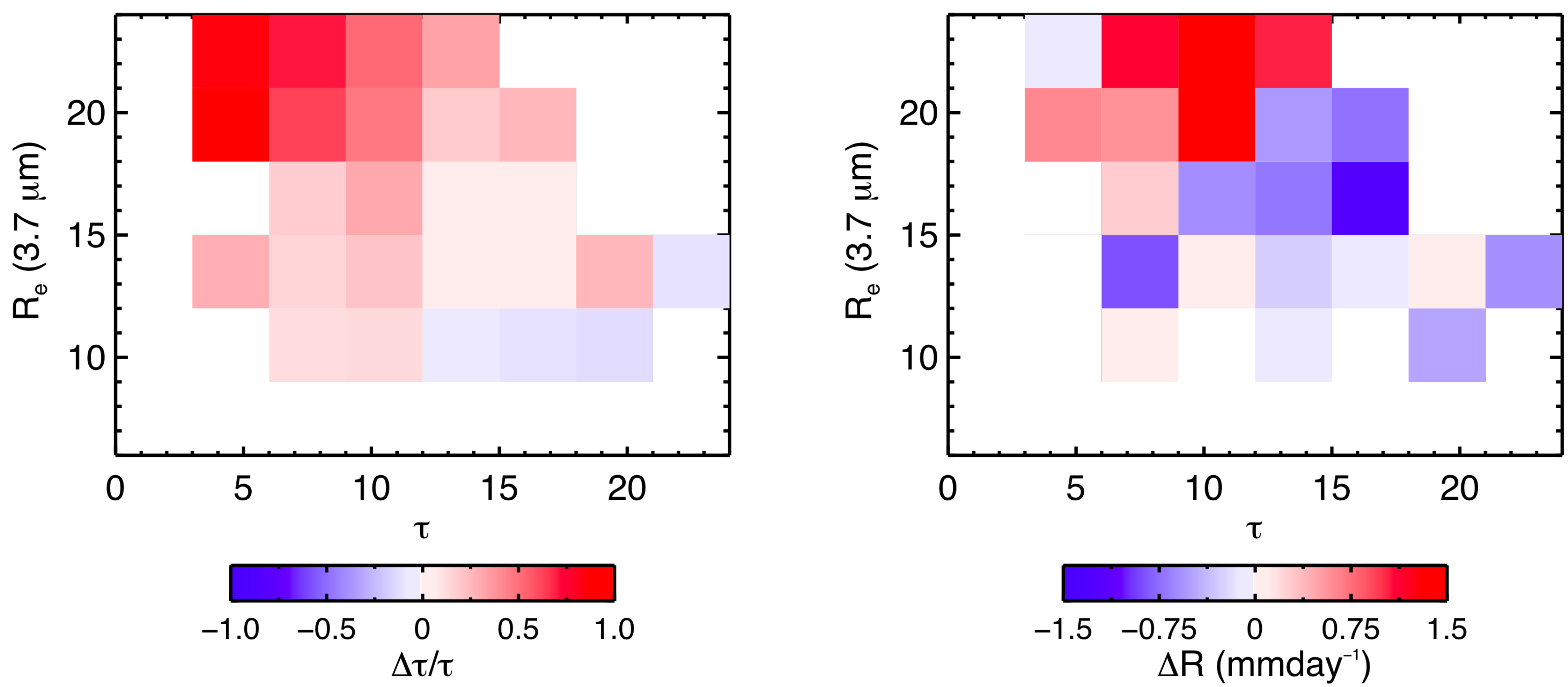


$$A \approx \tau \approx N_d^{1/3} LWP^{5/6}$$

No guarantee that suppression of precipitation will lead to enhanced cloud albedo

Cloud albedo is always enhanced when increased aerosol burden leads to enhanced precipitation, cases which are generally found in open cellular clouds.

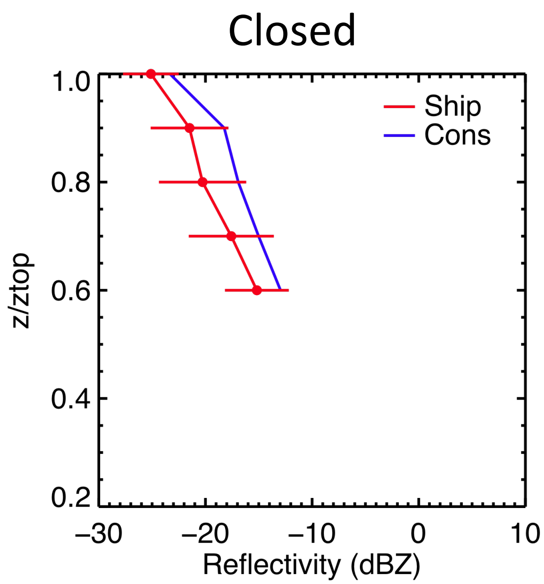
Implications for aerosol indirect forcing

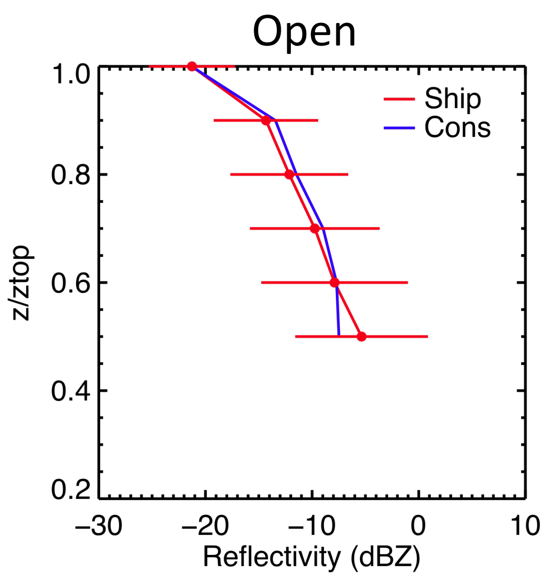


Clouds with small optical depths and large effective radius are most susceptible enhanced cloud albedo and precipitation responses to aerosol (these cases are primarily associated with open cells).

Clouds with larger optical depths and small effective radius have a negligible or even negative cloud albedo response.

Radar Reflectivity





- Radar reflectivity binned vertically into normalized height coordinates given by the cloud top height estimated from CloudSat. A running mean filter was applied to both the polluted (ship) and unpolluted (con) pixels.

- Larger reflectivities are observed in open cell clouds compared to the closed cells.

- Reflectivity is reduced in the polluted clouds throughout the profile by ~3dBZ in the *closed cell regime* compared to the controls. This results in a 50% reduction in the received power!

- Reductions in reflectivity are modest in the *open cell regime*.

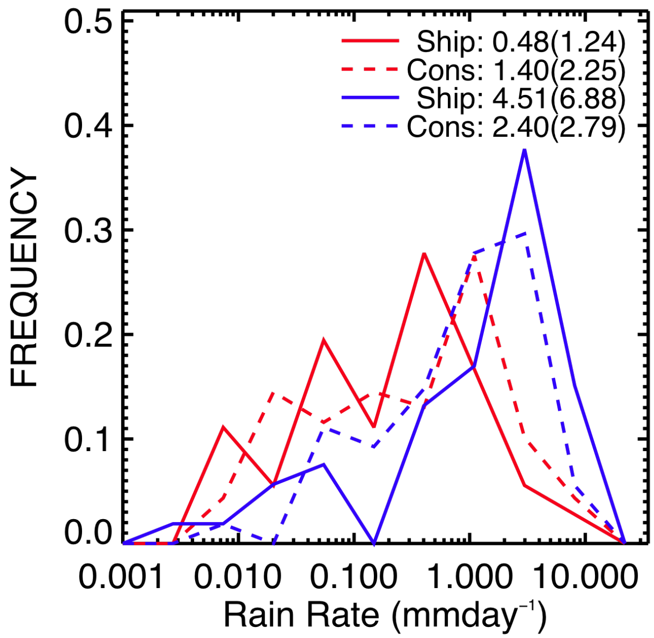
Segment Averaged Rainfall Intensity

<u># of Tracks with rainfall occurring "somewhere" in the ship track domain</u>

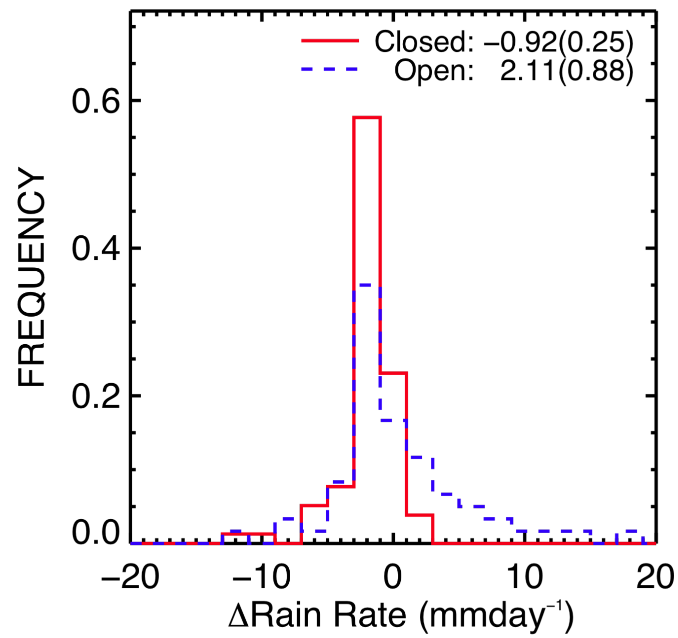
78 Closed Cell

61 Open Cell

Segment Average



(Ship-Controls)



Averages are smaller because non-raining clouds are averaged into each segment. Rainfall departures arise due to changes in the **intensity** and the spatial coverage of the rainfall (**rain cover fraction**).

<u>Main result:</u>

Rainfall is *reduced* in closed cellular clouds (**-63%**)

Rainfall is *enhanced* in open cellular clouds (**+88%**)

Rain Cover Fraction

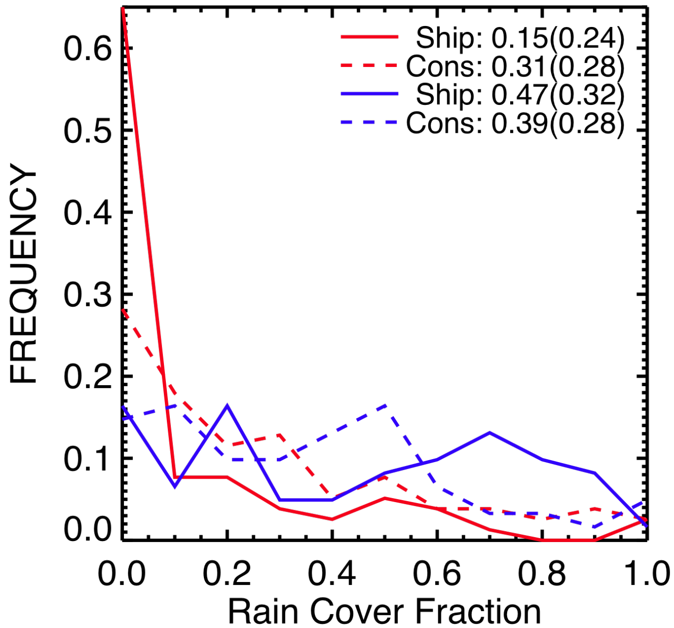
$$\left(\#Rain^{pixels} \big/ \#Cloud^{pixels} \right)$$

<u># of Tracks</u>

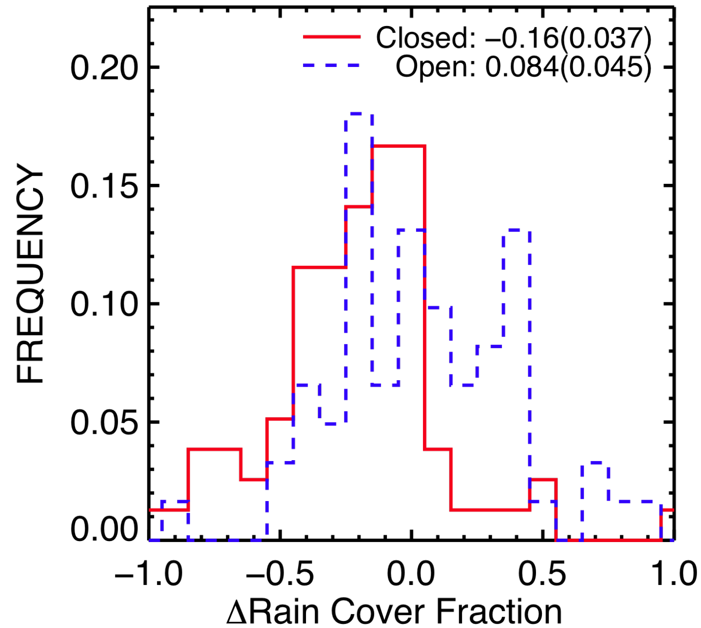
78 Closed Cell

61 Open Cell

Segment Average



(Ship-Controls)



- Open cellular clouds have more frequent precipitation than closed cell clouds.
- Polluted pixels in the *closed cell regime* rain *less* frequently than do those in nearby unpolluted clouds.
- In the *open cell regime* polluted clouds have a higher spatial coverage of precipitation than the unpolluted clouds.
  → *cloud cover fraction is larger over the region of polluted clouds*

<u>Main result:</u>

Rain Cover Fraction is *reduced* in closed cellular clouds (**-55%**)

Rainfall is *enhanced* in open cellular clouds (**+22%**)

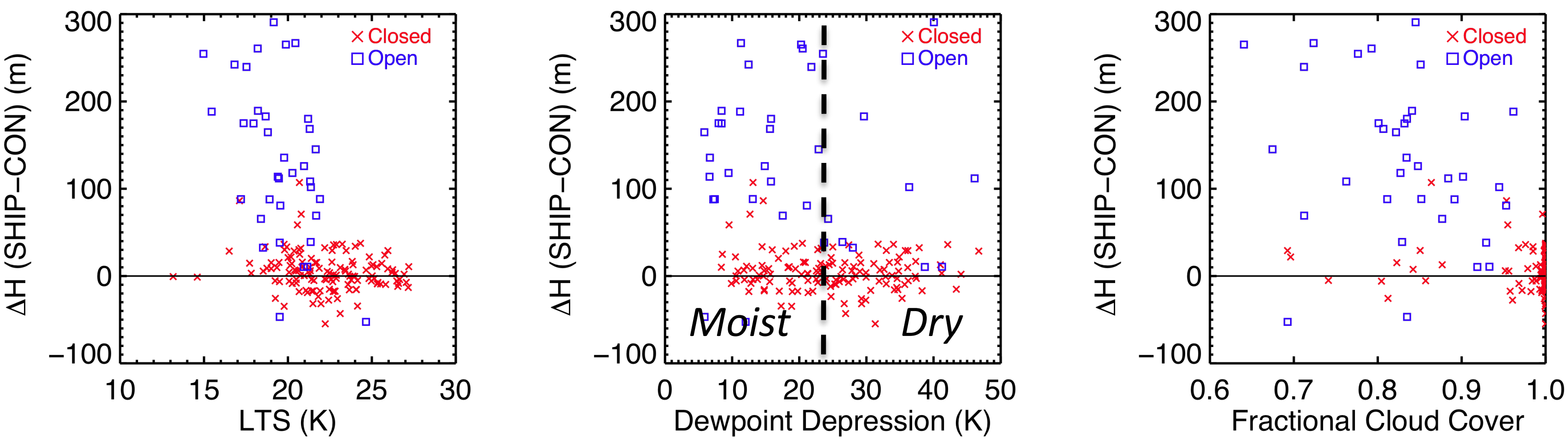
Differences in Cloud Depth (Ship – Controls)

<u># of Tracks for NEpac</u>

136 Closed Cell

36 Open Cell

Christensen and Stephens, (2011)



Height differences are *most* pronounced for ship tracks inhabiting regions of open cells, observed generally with low static stability, high moisture content above the boundary layer, and low cloud cover fraction.

Polluted clouds in *open cell* convection are ~15% deeper than the unpolluted clouds.

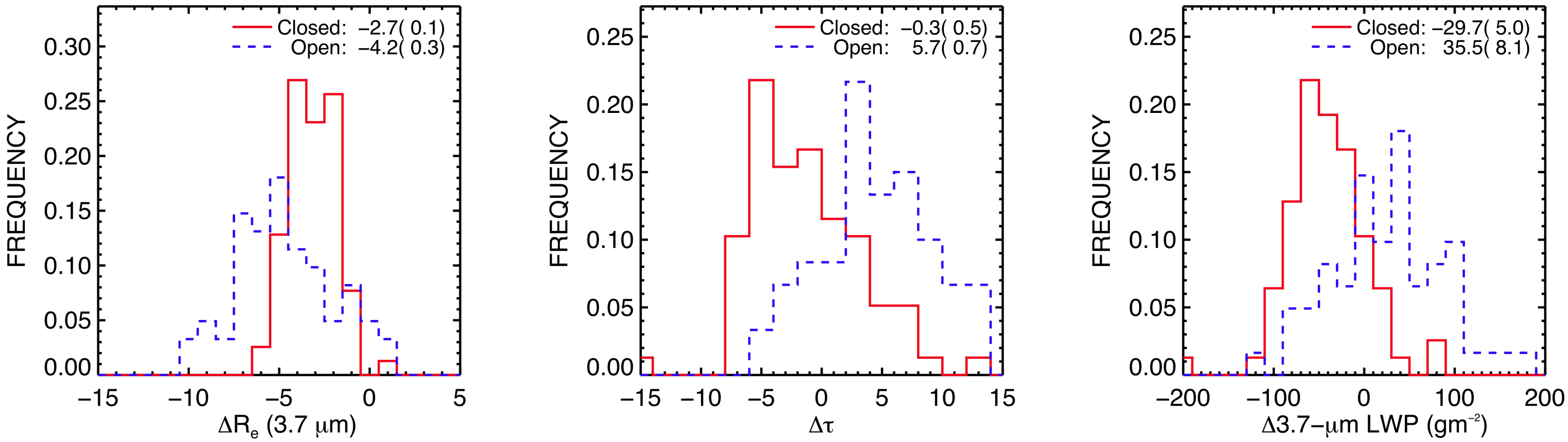
- **➔ Increased static stability squelches vertical cloud development.**
- **➔ Weak inversion strength may promote cloud dynamical aerosol indirect effects.**
- **➔ A relatively moist overlying free troposphere can support vertical cloud development.**
- **➔ Closed cell convection inhibits vertical cloud development for polluted clouds.**

Differences in Cloud Optical Properties (Ship – Controls)

<u># of Tracks</u>

78 Closed Cell

61 Open Cell



Droplet radius is reduced in polluted clouds (fractional changes are approximately the same between closed and open cell regimes).

→ Higher concentrations of CCN increase droplet numbers and decrease droplet size (Twomey, 1974)

- In the *closed cell regime*: polluted clouds lose liquid water.

  → *overlying free troposphere sufficiently dry that the increased entrainment in clouds with smaller droplets leads to the drying of polluted clouds as suggested by the results of a large eddy simulation (LES) model (Ackerman et al., Nature,**432**,1014,2004).*

- In the *open cell regime*: polluted clouds thicken and gain liquid water.

  → *drizzle from the nearby clouds adjacent to the ship track provide a source of moisture convergence below the ship track which leads to the moistening the polluted clouds as suggested by the results of a LES model (Wang and Feingold., J. Atmos Sci,**66**,3257,2009).*

Rain rate and Cloud Top Height Variability

	Closed Cell		Open Cell	
	Rain rate (mmday^{-1})	Height (m)	Rain rate (mmday^{-1})	Height (m)
CON1-CON2	0.06 (0.29)	5 (3)	-0.39 (0.59)	40 (30)
SHIP-CONS	-0.75 (0.20)	5 (2)	2.23 (1.03)	131 (15)
σ_{SHIP}	0.56	17	5.75	51
σ_{CONS}	1.65	25	4.06	128

- Means and standard errors of the means for the differences in rain rate and cloud top height between each control (CON1-CON2) and between the ship and combined controls (SHIP-CONS). Also listed is the ensemble average standard deviation for the polluted (σ_{SHIP}) and unpolluted cloud (σ_{CONS}).
- Both precipitation and cloud top height have larger variability in open cells compared to closed cells.
- Cloud top height was unchanged by the ship plume in closed cells but significantly increased in regions of open cells.
- Departures in rainfall between the polluted and unpolluted clouds are significantly larger than that given by the natural variability alone.

Summary

- Data from Calipso and CloudSat provide evidence that aerosol plumes from ships modify the microphysical and dynamical properties of clouds.

- The extent of the dynamical response depends primarily on the type stratocumulus and the direction of the macrophysical response (changes in **liquid water path** and **cloud depth**).

- Open cell convective clouds exhibit large cloud top height differences between polluted and nearby unpolluted clouds, while closed cell clouds do not.

- For regions of closed cells, polluted clouds have decreased liquid water amounts and rainfall presumably due to the enhanced entrainment of dry air above the boundary layer for the clouds with smaller droplets.

- Ship plumes ingested into broken cloudy conditions (open cells) result in deeper, wetter, rainier, and brighter clouds where presumably heavier rainfall in the nearby clouds leads to enhanced moisture convergence below the ship track.