The effect of solar zenith angle on MODIS cloud microphysical retrievals

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Cloud optical depth (τ), effective radius (r_e), droplet concentrations (N_d)

Atmospheric Sciences

University of Washington

Why MODIS? Why droplet concentration (Nd)?

- **MODIS provides global coverage and has a long data record :-**
  - **TERRA satellite since 2000, AQUA since mid 2002**

- **Global N_d dataset would be very valuable, e.g. for investigating Aerosol Indirect Effects (AIEs) and their representation in GCMs**
  - **Droplet concentration also a good proxy for aerosol loading in cloudy regions**

- **The representation of AIEs in climate models is complex, involving interactions between:-**
  - **Cloud microphysics.**
  - **Turbulent transport.**
  - **Radiation**
  - **Aerosol production, transport and removal.**
  - **Precipitation**

- **Therefore it provides a strong test for climate models**

- ***Marked differences in N_d exist between different GCMs (Quaas et al., ACP, 2009, Ming et al., JAS, 2006, Gettelman et al., J. Clim, 2008) demonstrating a clear lack of understanding of the key controls***

- **Many climate models fix lower limits for N_d (Hoose et al., GRL, 2009, Quaas et al., ACP, 2009)**
  - **Has been shown to affect the strength of the AIE (Quaas et al., ACP, 2009) across GCMs**
  - **In one model removing this limit changed the global AIE by 80% (Hoose et al., GRL, 2009).**

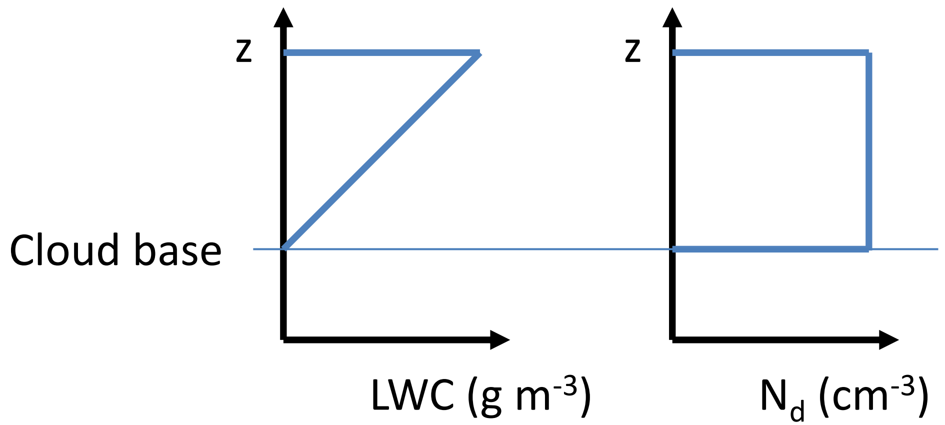
- **But, the robustness of the satellite data also needs to be assessed.**

Obtaining droplet concentrations from MODIS

- **The method follows that of Boers et al. (JGR, 2006) and Bennartz & Harshvardhan (JGR, 2007) and uses Cloud Optical Thickness and effective radius**
  - ***Daytime only***

- **It depends on a few assumptions:-**
  - ***The LWC profile within a cloud is a constant fraction of adiabatic: c = dLWC/dz = constant (for a given cloud top temperature)***
  - ***The droplet concentration within a cloud is vertically constant***
  - ***$k = (r_v/r_e)^3$ = constant = 0.8***
  - ***Scattering efficiency Q = 2***

Given these assumptions we can relate r_e at cloud top, τ and N_d for our model cloud

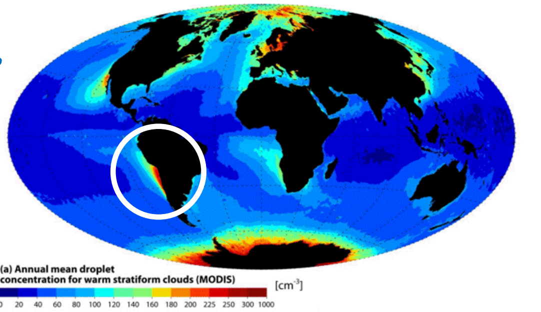


$$N_d = \frac{2\sqrt{10}}{k\pi Q^3}\left(\frac{c(T,P)\tau}{\rho_w r_e^5}\right)^{1/2}$$

τ = Cloud Optical Thickness (Depth)

r_e = Effective radius

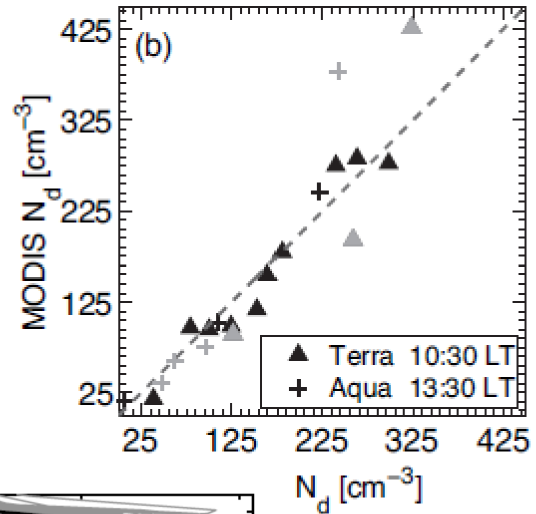
Comparisons with aircraft in SE Pacific



- **Aircraft comparisons suggest very good accuracy for low clouds (e.g. stratocumulus decks, e.g. Painemal & Zuidema, JGR, 2011**

- **But the analysis was performed in horizontally homogeneous clouds (stratocumulus)**

Painemal & Zuidema, JGR, 2011



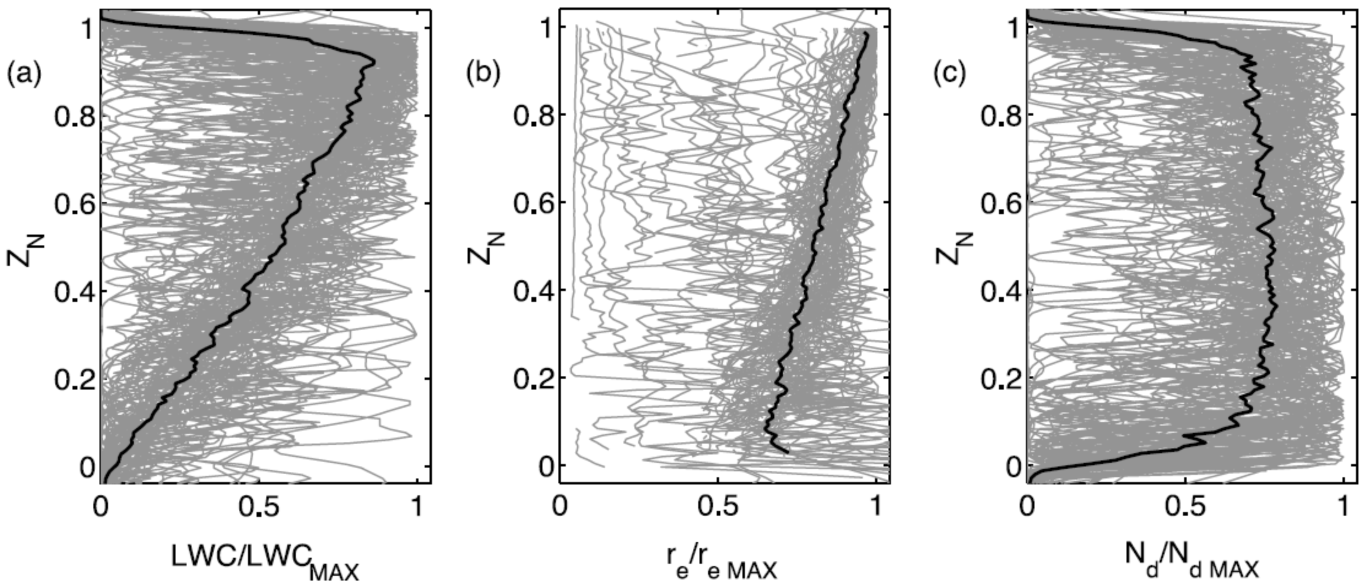
Linear LWC increase with height

However, are sub-adiabatic

Painemal & Zuidema, JGR, 2011

Cloud top

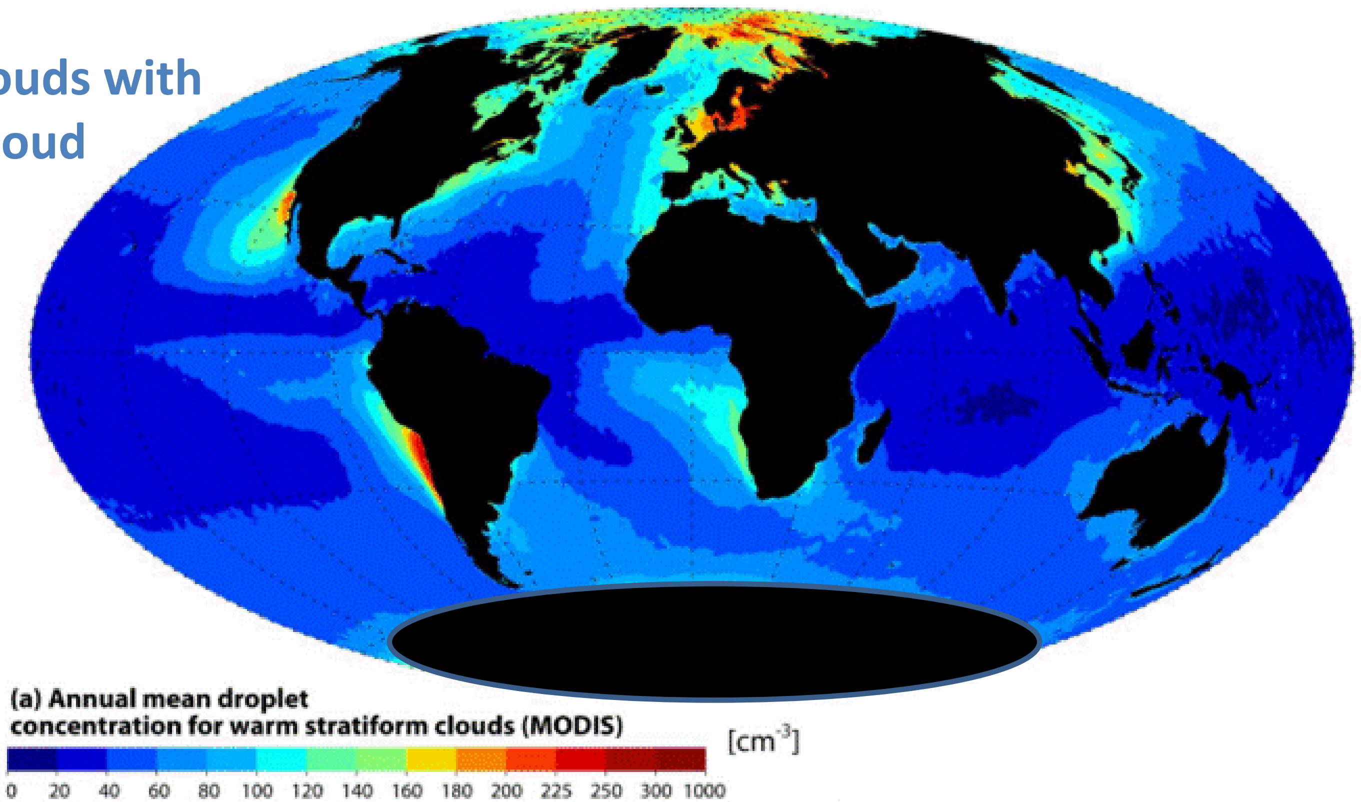
Cloud base



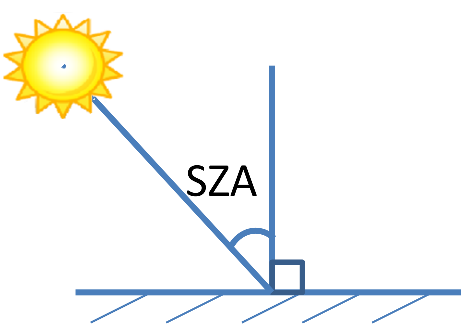
N_d constant with height

Global mean droplet concentration from MODIS using Level-3 product

For liquid clouds with >80% 1x1º cloud fraction

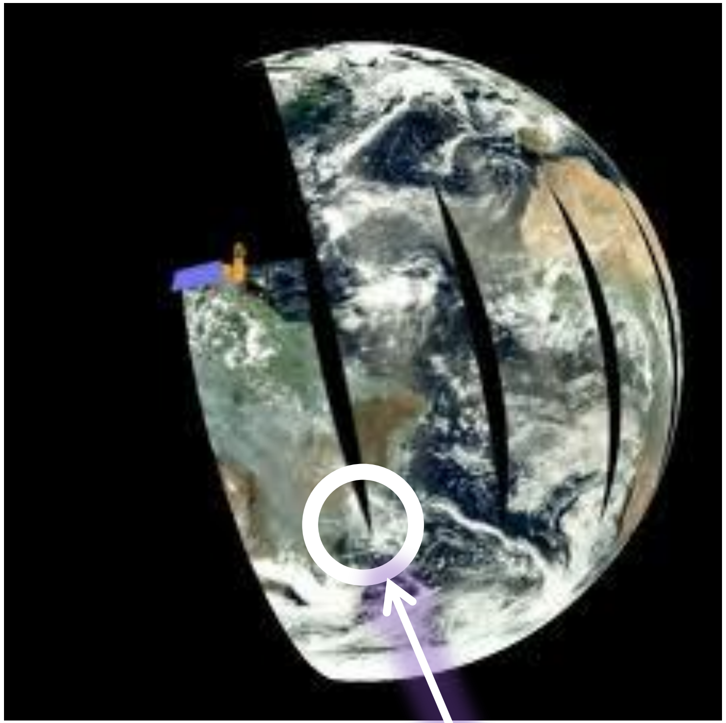


- **Unexpected high N_d values near Antarctica**
  - ***Are the retrievals flawed?***
- ***Possible causes of this result:-***
  - **Ice below clouds?**
  - **Surface characteristics (e.g. sea ice)?**
  - **High *Solar Zenith Angles (SZA)* in winter (Sun is low in the sky)?**

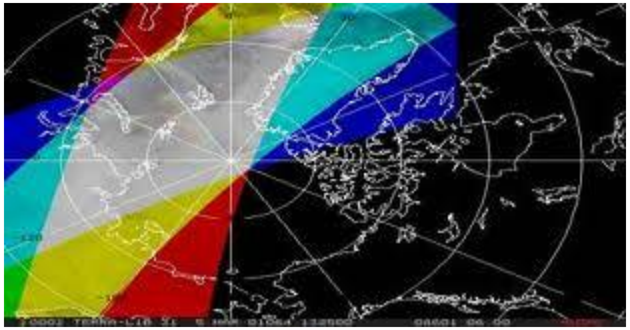


The MODIS Level-3 product

- ***MODIS Level-3 : a 1x1º gridded daily product***
- ***Swaths start to overlap at latitudes higher than 23º***
- ***Polar regions can experience several overpasses per day***
- ***Therefore measurements taken at different local times of day & solar zenith angles***
- ***All daily measurements are averaged together for the gridded Level-3 product***

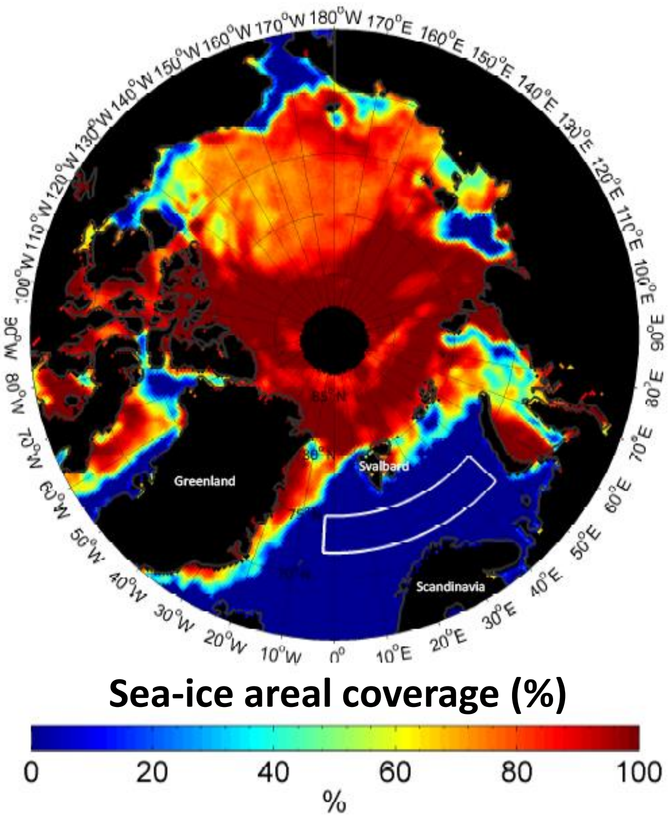


Consecutive orbits start to overlap



Several consecutive orbits overlap near the poles

Estimating the Solar Zenith Angle (SZA) effect on N_d

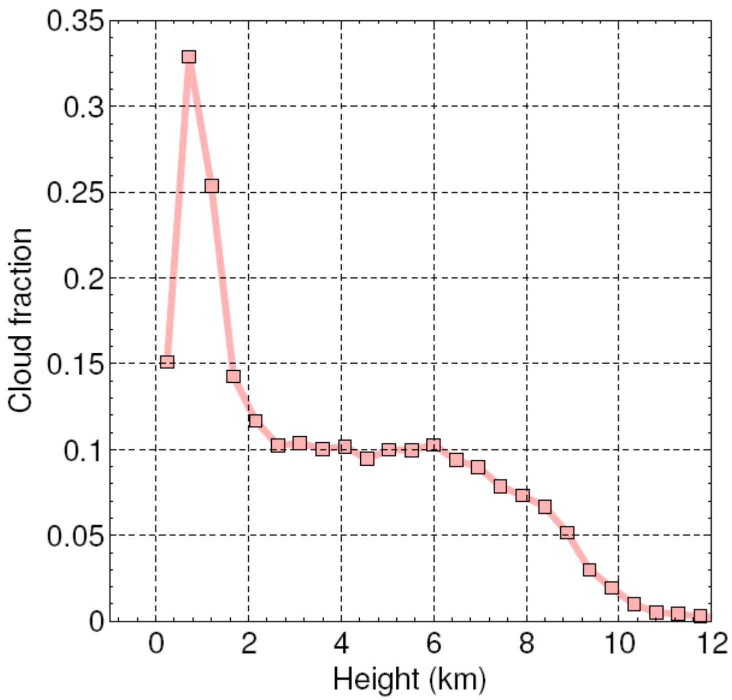


Sea-ice areal coverage (%)

- **Fairly difficult using the MODIS record due to seasonal variations of SZA with time**
- **High latitudes receive multiple overpasses per day**
  - **Therefore a range of SZA (diurnal cycle)**
- **But sea-ice is ubiquitous there**
  - **Except region north of Scandinavia - no sea-ice throughout the year**

- **Have processed Level-2 swaths for this region for the period 13-30th June, 2007-2010 (Aqua and Terra)**

- **Cloud fraction vs height from CALIPSO** →

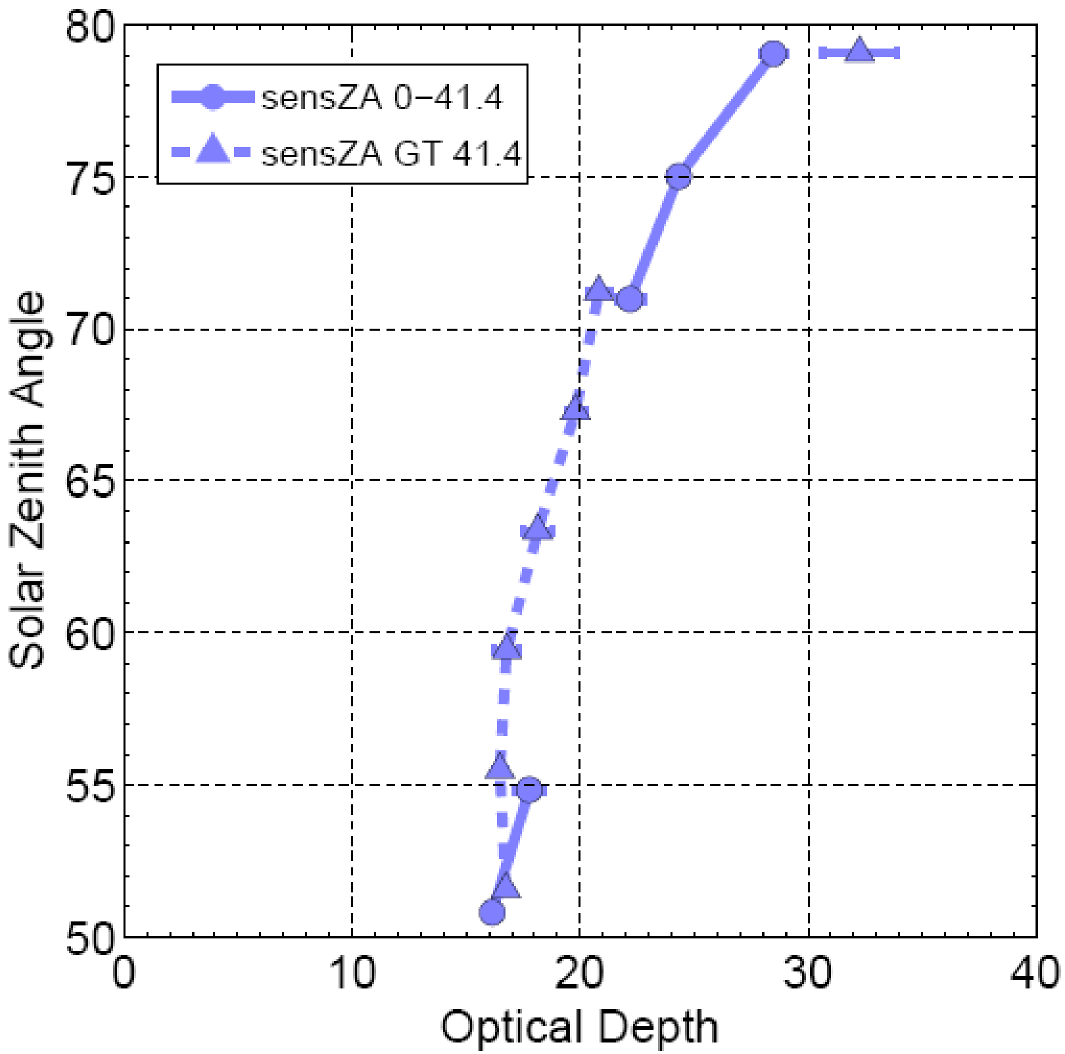


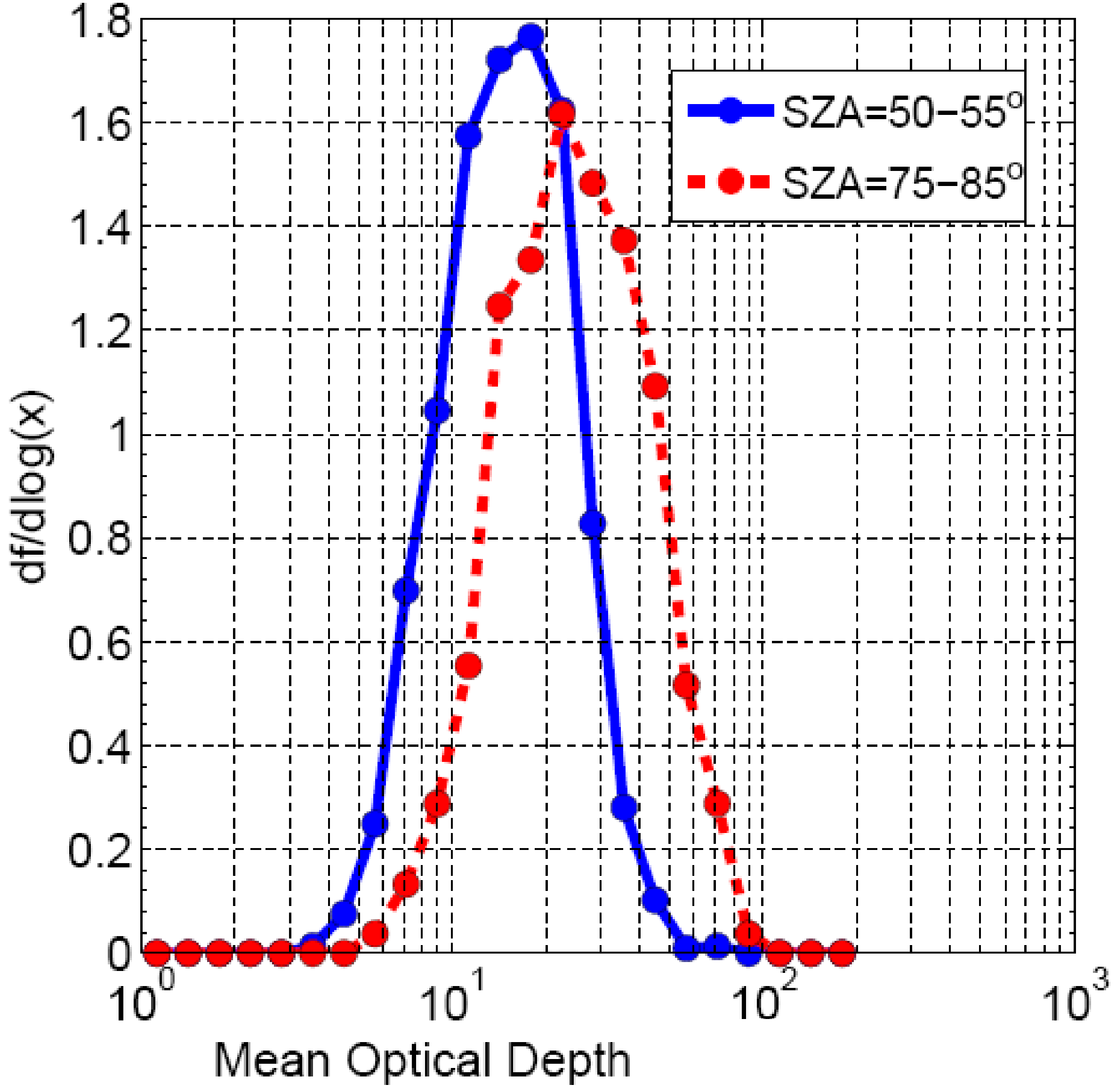
Filtering/retrieval details

- Averaging into 1x1^{o} regions
- Liquid cloud fraction at least 90%
- "Very good" confidence for pixels from MODIS QA
- Only scenes with mean Cloud Top Temperature > -5 ^{o}C
  - *Distributions of CTT and σ_{CTT} very similar for low and high SZA for these temperatures*

Results – optical depth vs SZA

- **Fairly dramatic increase in mean optical depth with SZA**
- **At both low and high viewing angles (sensZA)**
- **High sensZA results suggest constant behavior up to SZA~65º**
- **Main caveat – could this be a real physical change with diurnal cycle?**
- **O'Dell (2008) study using microwave suggests that LWP diurnal cycle is <20 % in this region, which would translate to a similar change in optical depth**

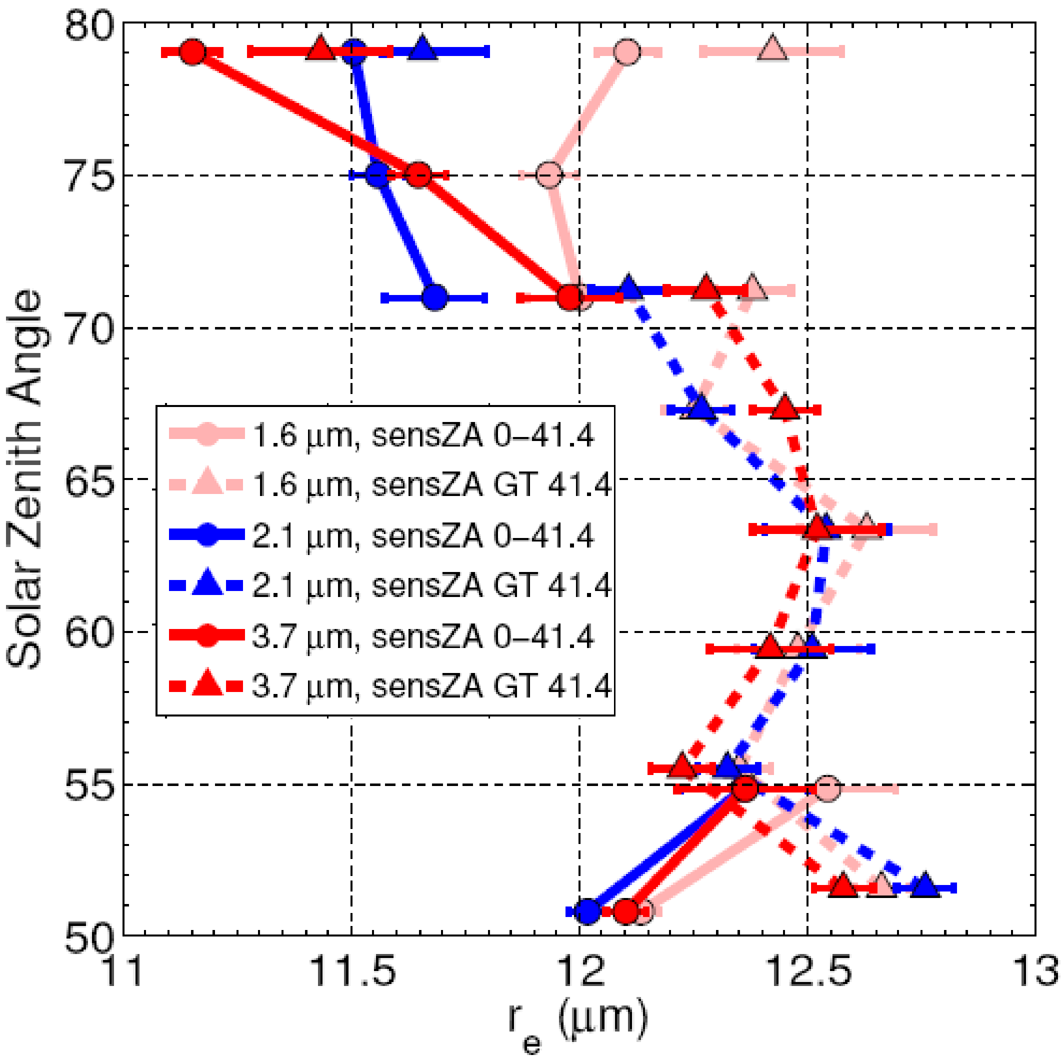


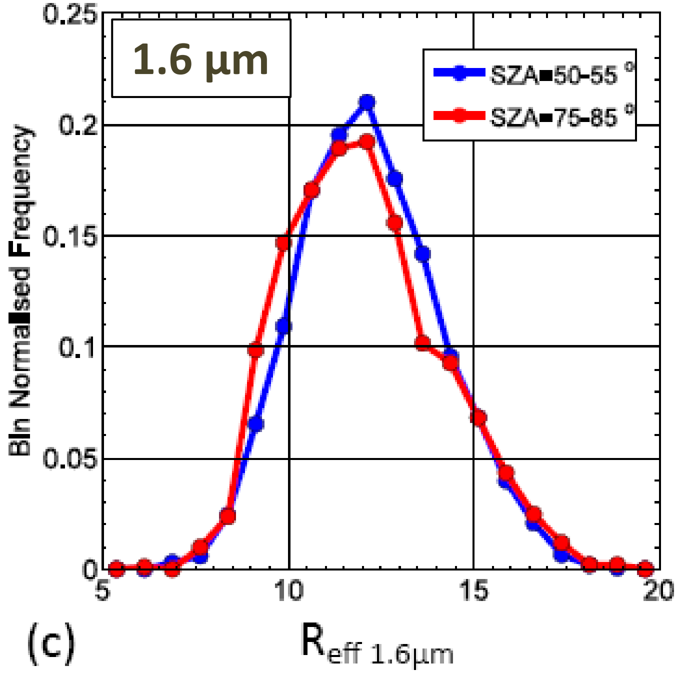


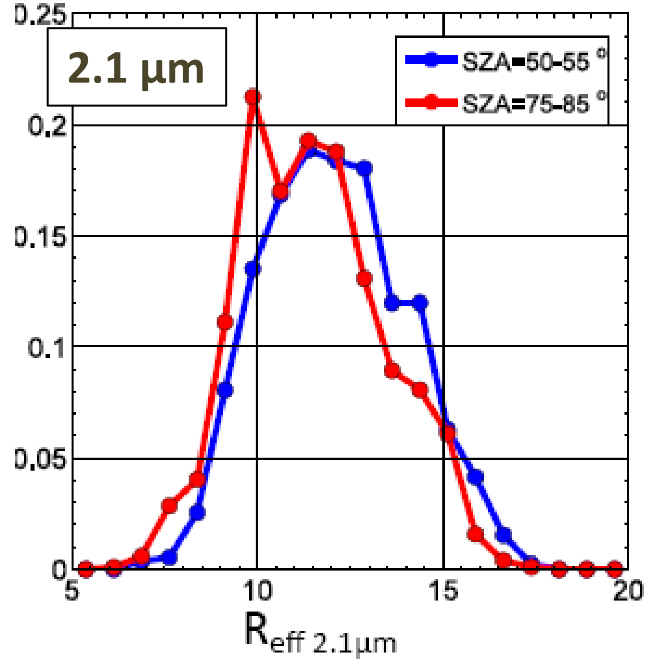
PDF of optical depth (τ) at low (blue) and high (red) SZA

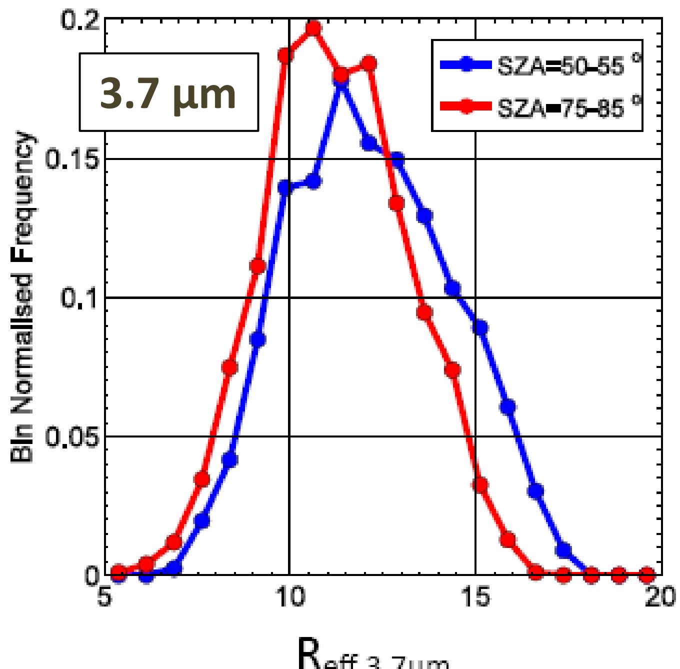
Results – effective radius vs SZA

- **At low SZA and low sensor angle all three wavelengths agree**
- **Large spread at high SZA**
- **Reduction in r_e with SZA for 2.1 and 3.7µm, but not 1.6 µm**
  - **Larger reduction for 3.7 µm**
- **Percentage reductions less than for optical depth**









PDFs of r_e at low (blue) and high (red) SZA

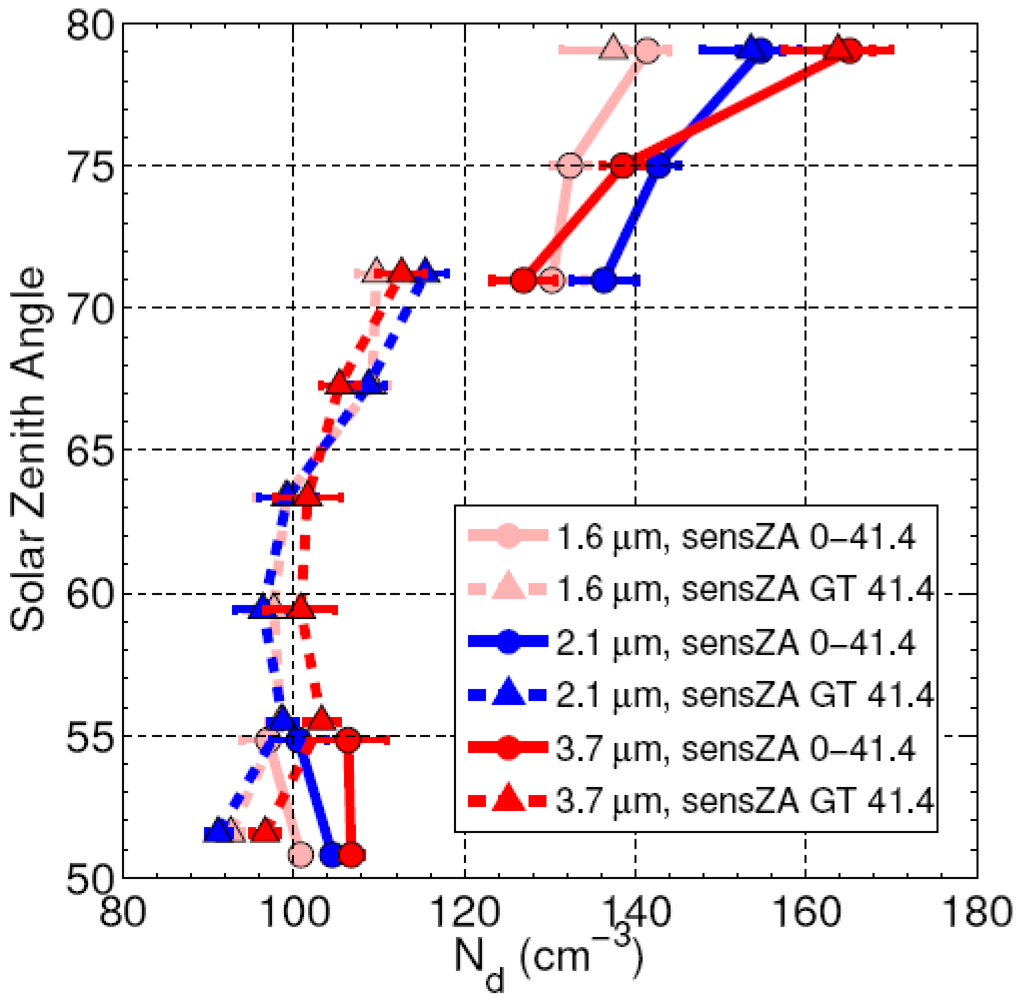
Results – droplet concentration vs SZA

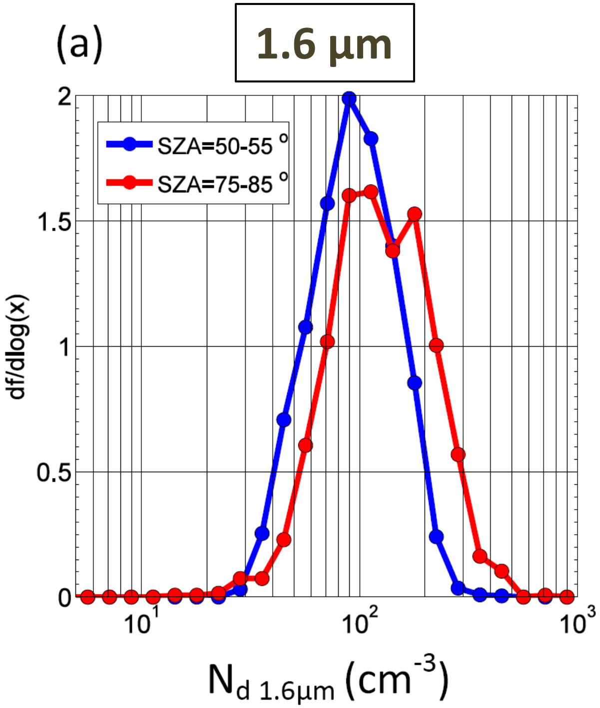
- **Can get a considerable N_d increase (up to 70%)**

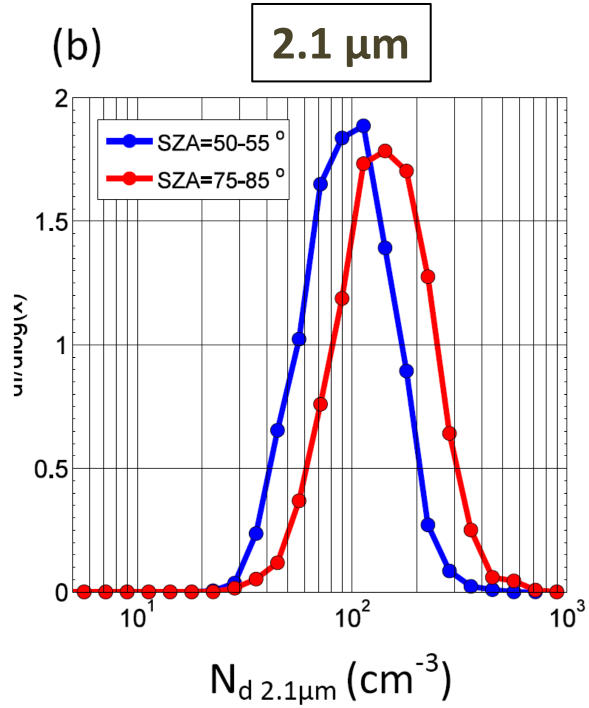
- **Increase is largest for the 3.7μm band**

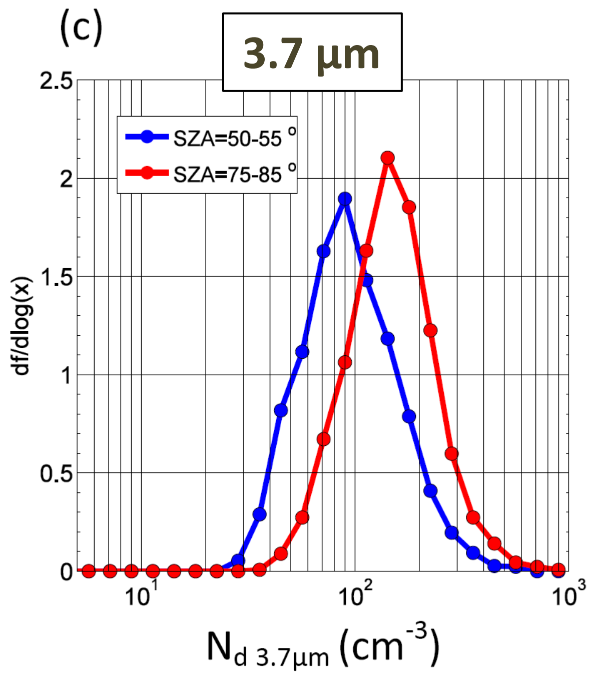
- **Sensitivity analysis shows that majority of this driven by the large optical depth increase, despite the sensitivity of N_d to r_e**

- **Except for 3.7 μm**
  - ***τ and r_e contribution roughly equal***
  - **For the more heterogeneous clouds (as quantified from cloud top temperature variability) r_e contribution is greater**



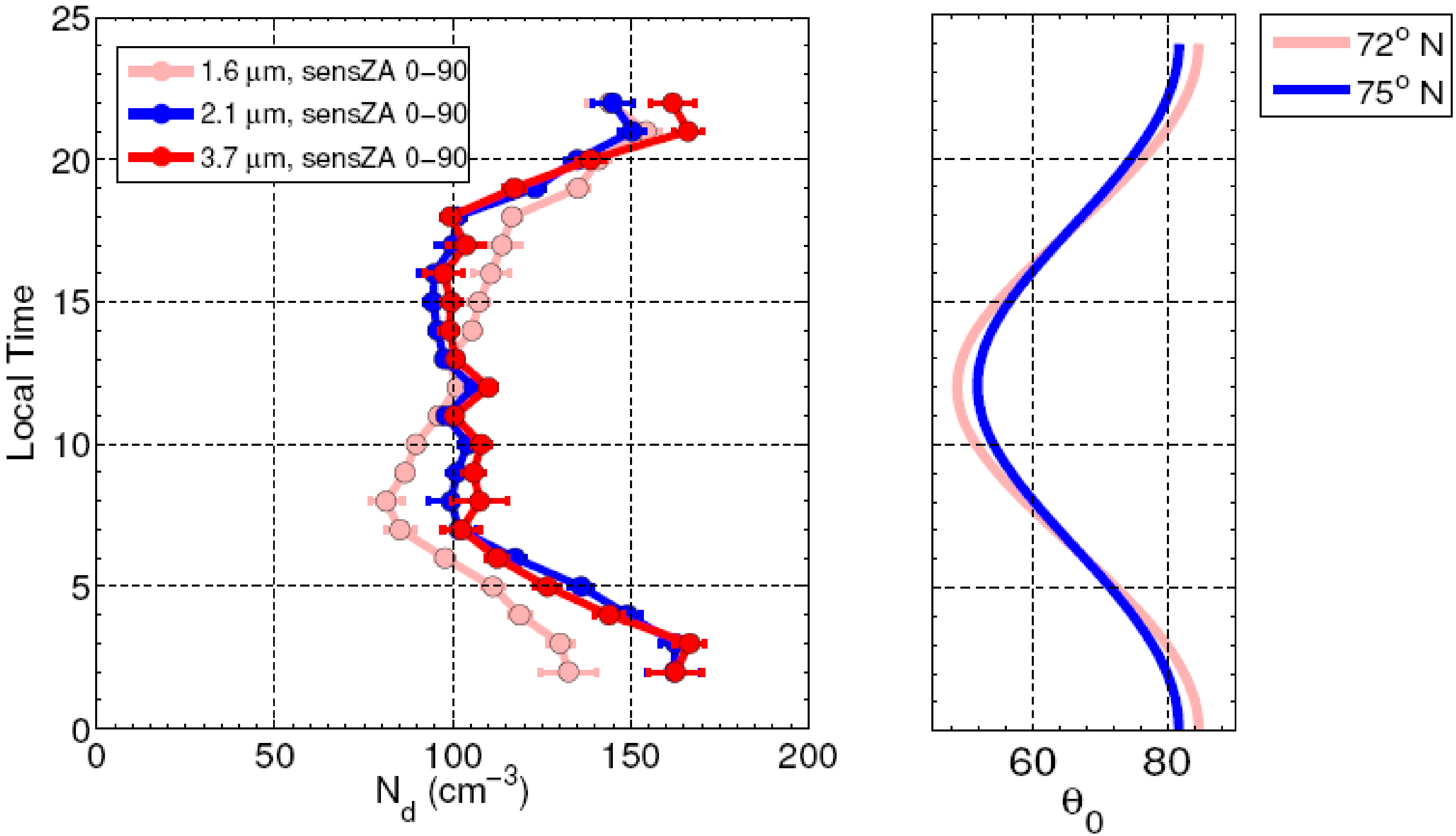






PDFs of N_d at low (blue) and high (red) SZA

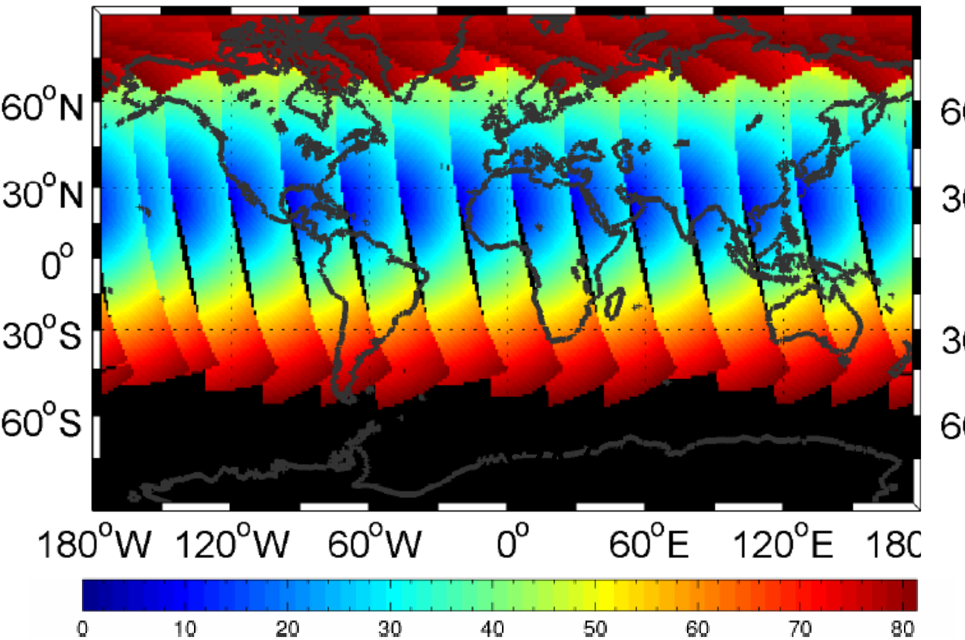
N_d vs local time of day



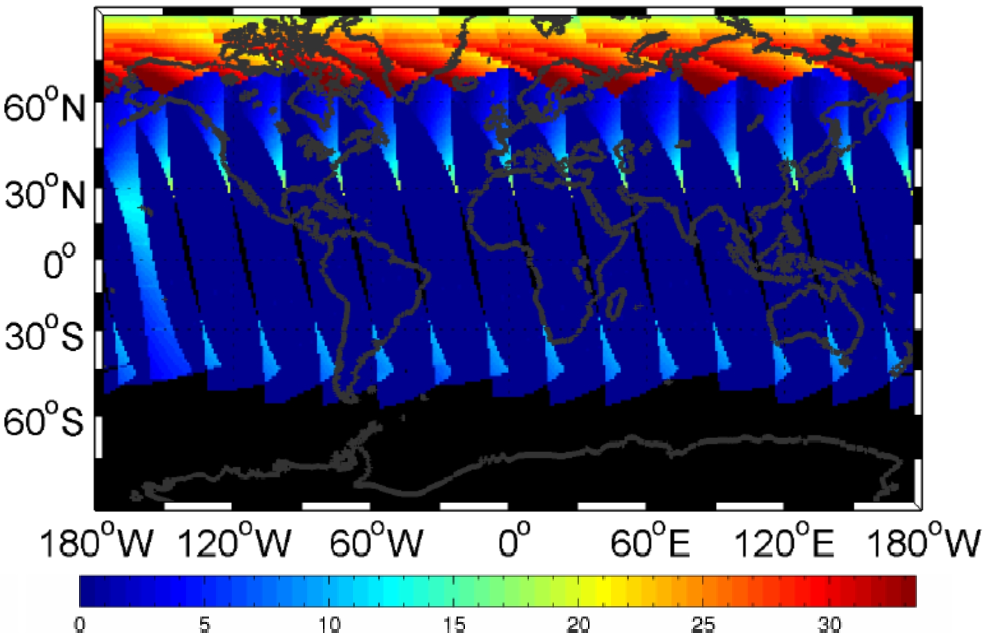
- **Symmetry of N_d diurnal cycle suggests SZA as a cause**
  - **Rather than physical changes, which are usually asymmetric about local noon**
- **Expect a fairly constant N_d throughout the day since the timescales of processes that change CCN & N_d are approx a few days**

20th June, 2007 (single day), Aqua satellite

Max Solar Zenith Angle



Max minus Min Solar Zenith Angle



- *Can see the effect of overlapping orbits*
- *High values obtained over Southern Ocean (winter) and over the Arctic (summer)*
- *But the same latitude will experience a range of max SZA depending on orbit overlap*
- *In the Arctic there is a difference of almost 35° between the min and max SZA on this day*

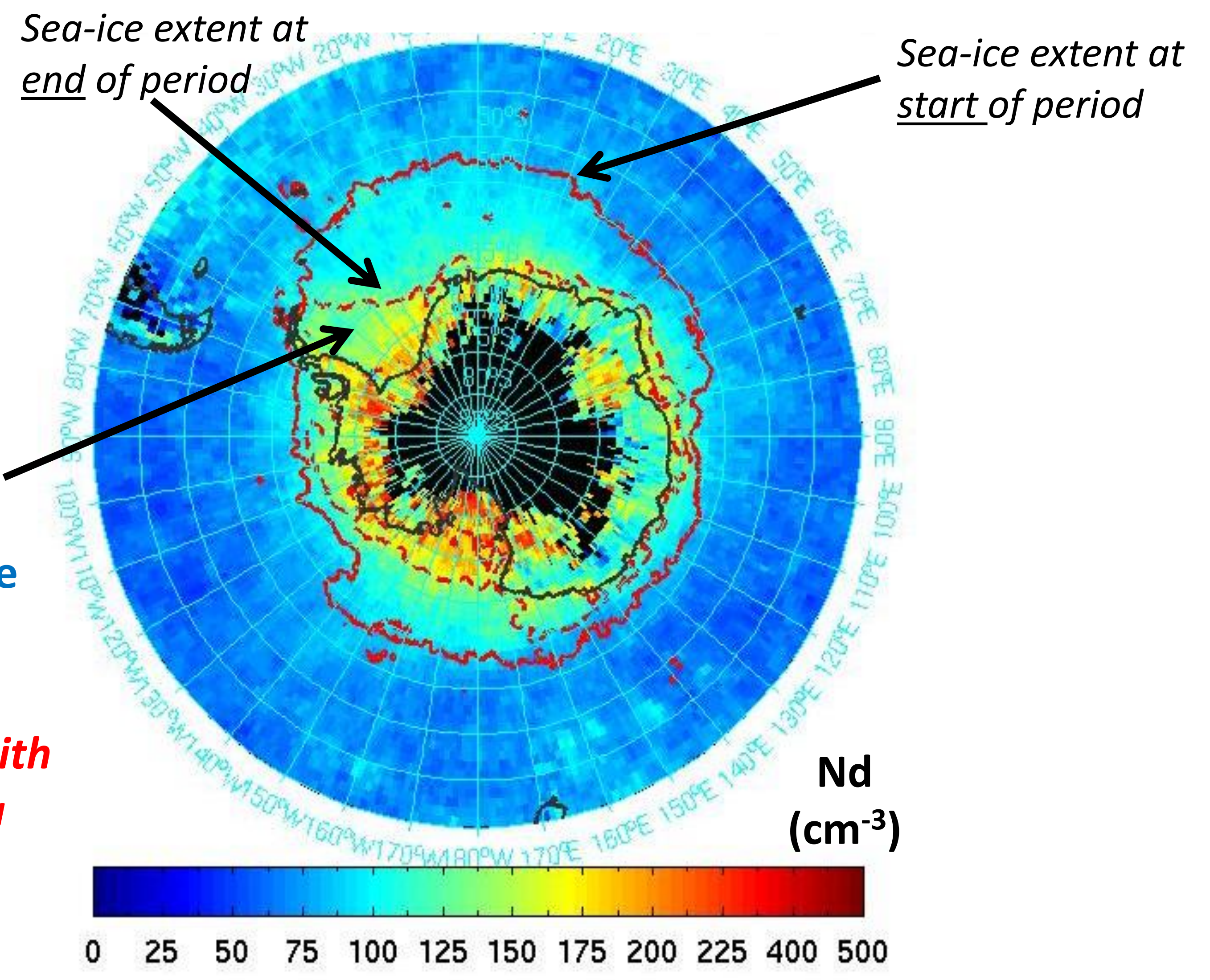
The reprocessing of individual swaths

- **We have re-processed individual Level-2 swaths into a Level-3 like daily 1x1 degree dataset**
  - **Global**
  - **Period Nov 2006 to end of 2007**
  - **Various screenings including for Solar Zenith Angle (<65)**
  - **(No daily averaging until after screening)**

The climatology using the standard Level-3 product - High values near Antarctica

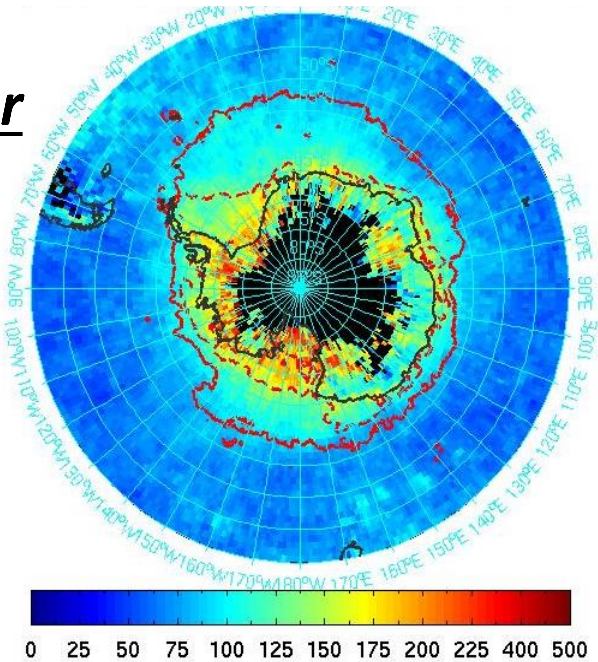
Sea-ice data source:-
Cavalieri, D., C. Parkinson, P. Gloersen, and H. J. Zwally. 1996, updated yearly. *Sea Ice Concentrations from Nimbus-7 SMMR and DMSP SSM/I-SSMIS Passive Microwave Data*, 1st Dec – 1st Mar. Boulder, Colorado USA: National Snow and Ice Data Center. Digital media.

DJF 2006/2007



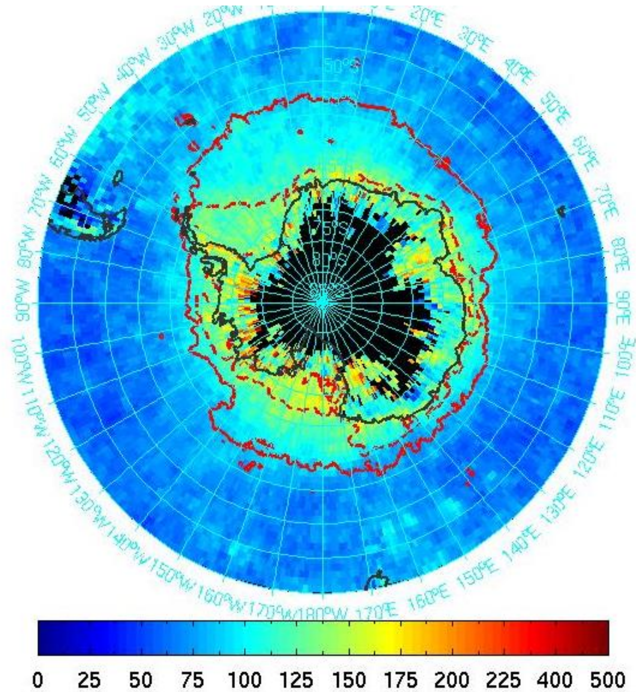
- ***Higher Nd in the regions* where sea-ice remains all summer**
- ***But high Solar Zenith Angle could also be a factor***

All Solar Zenith Angles (SZA)

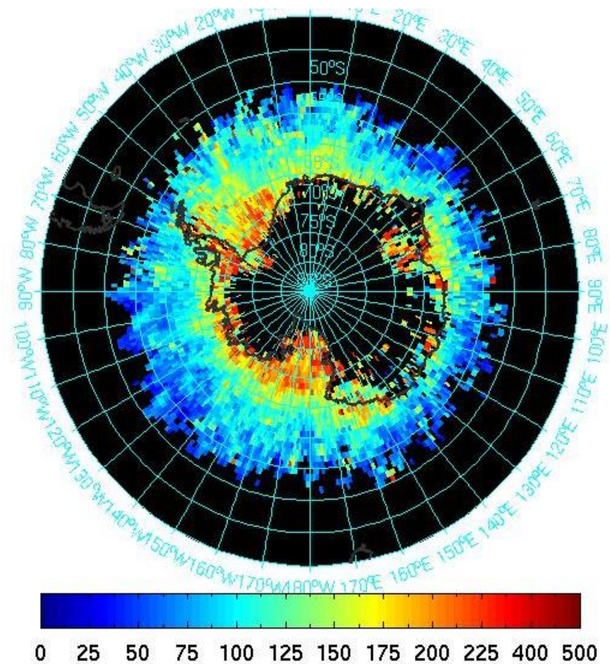


Nd (cm^{-3})

SZA < 65



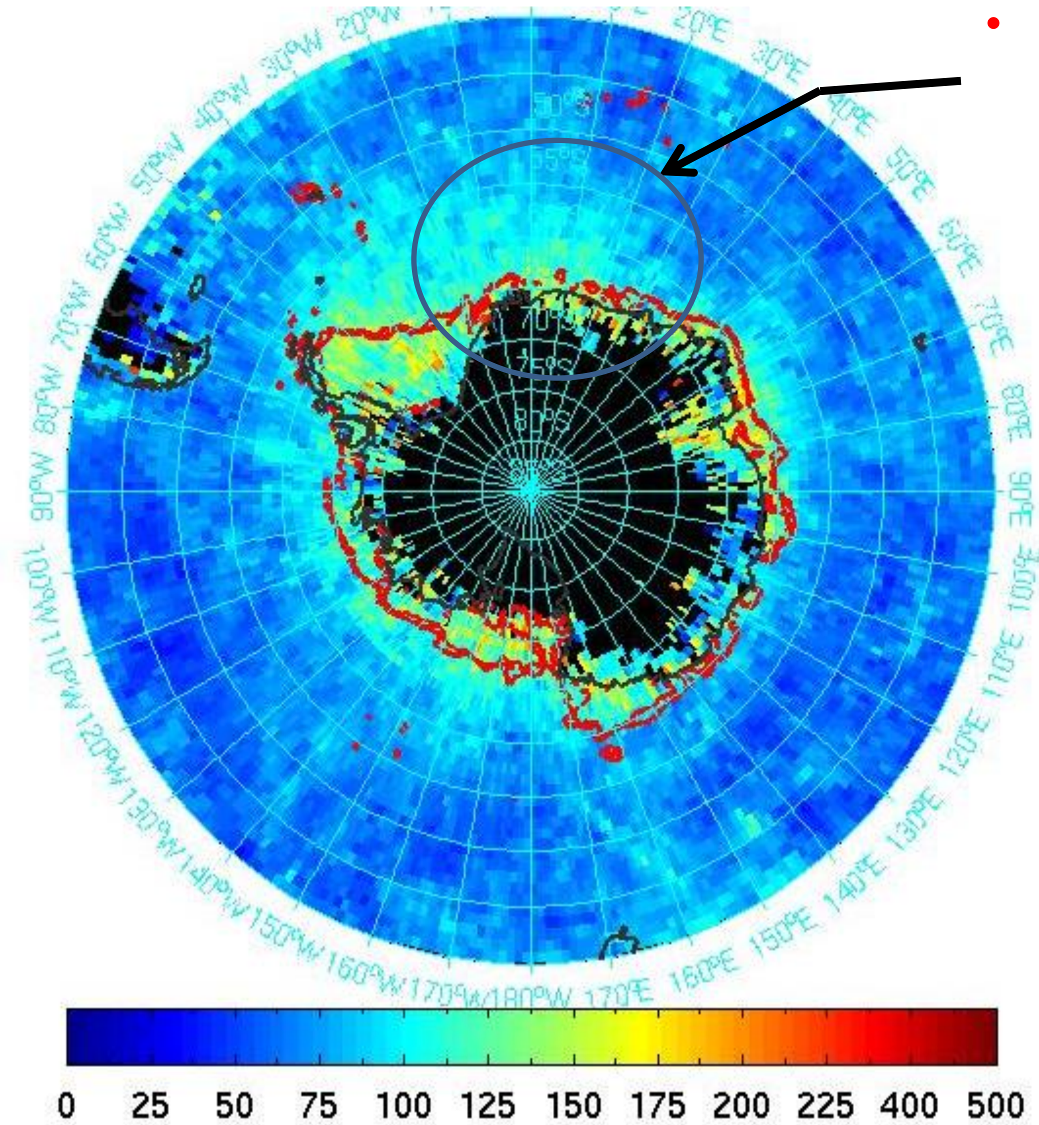
SZA > 65



DJF 2006/2007

Considering single month (for SZA<65 only)

Feb 2007



Nd (cm^{-3})

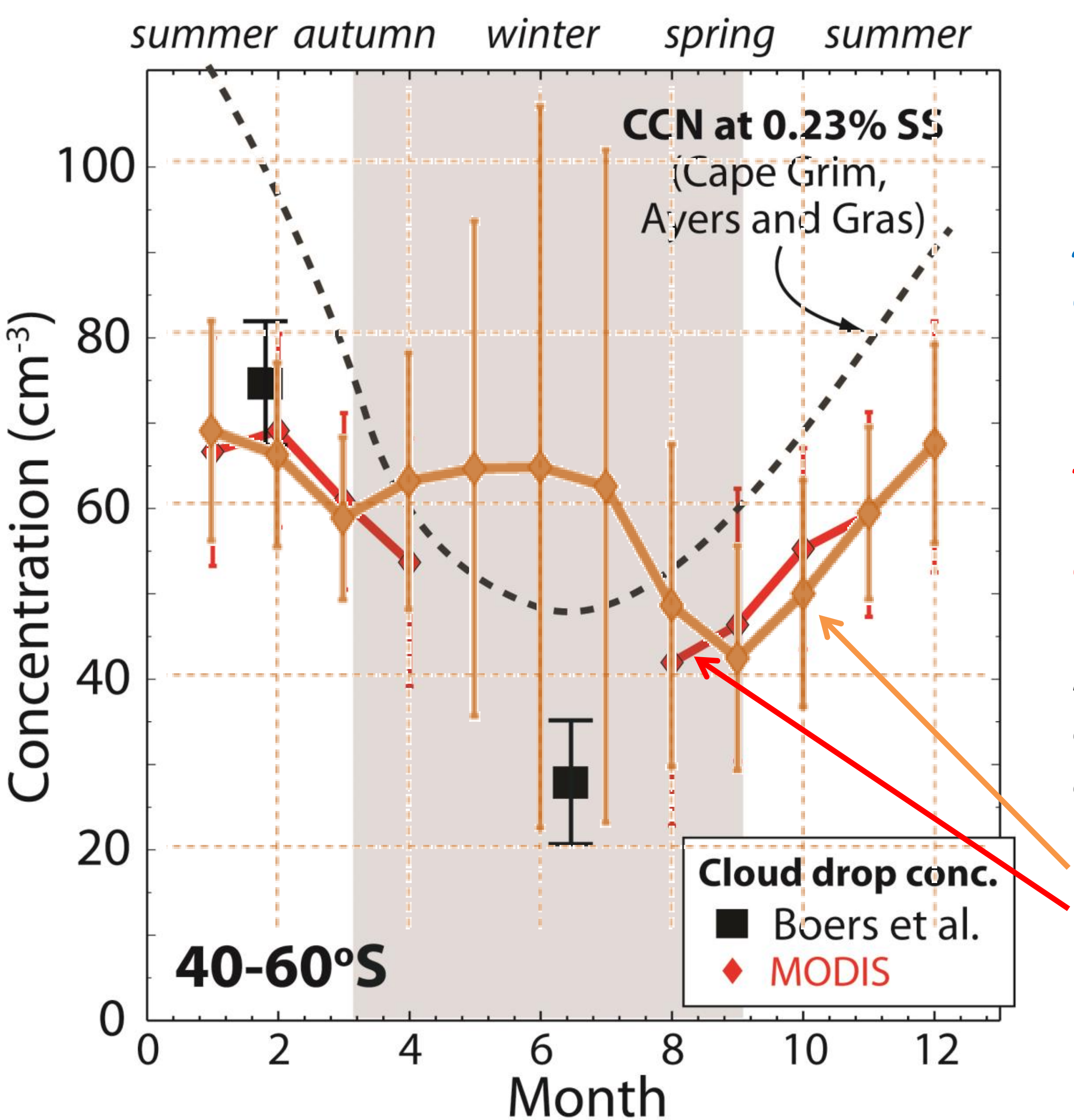
- *High Nd values remain outside of sea-ice regions*
    - *Undetected sea-ice?*
    - *Other retrieval problems?*
    - *Phytoplankton blooms?*

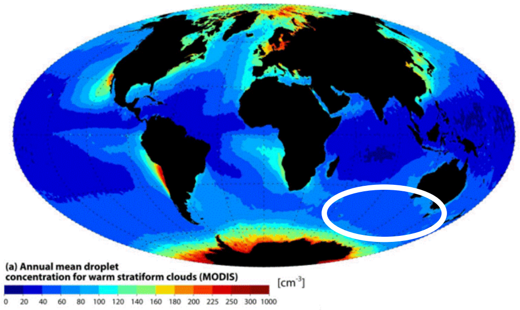
Red lines indicate sea-ice extent:-

Solid: start of period

Dashed: end of period

Southern Ocean seasonal cycle



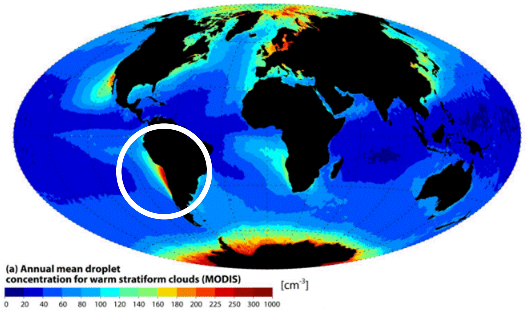


- If include high Solar Zenith Angles then get elevated values in winter
- Removing them leaves us with no data in winter, but seasonal cycle is consistent with the in-situ observations
- Indicative of algae blooms in summer causing elevated CCN concentrations?

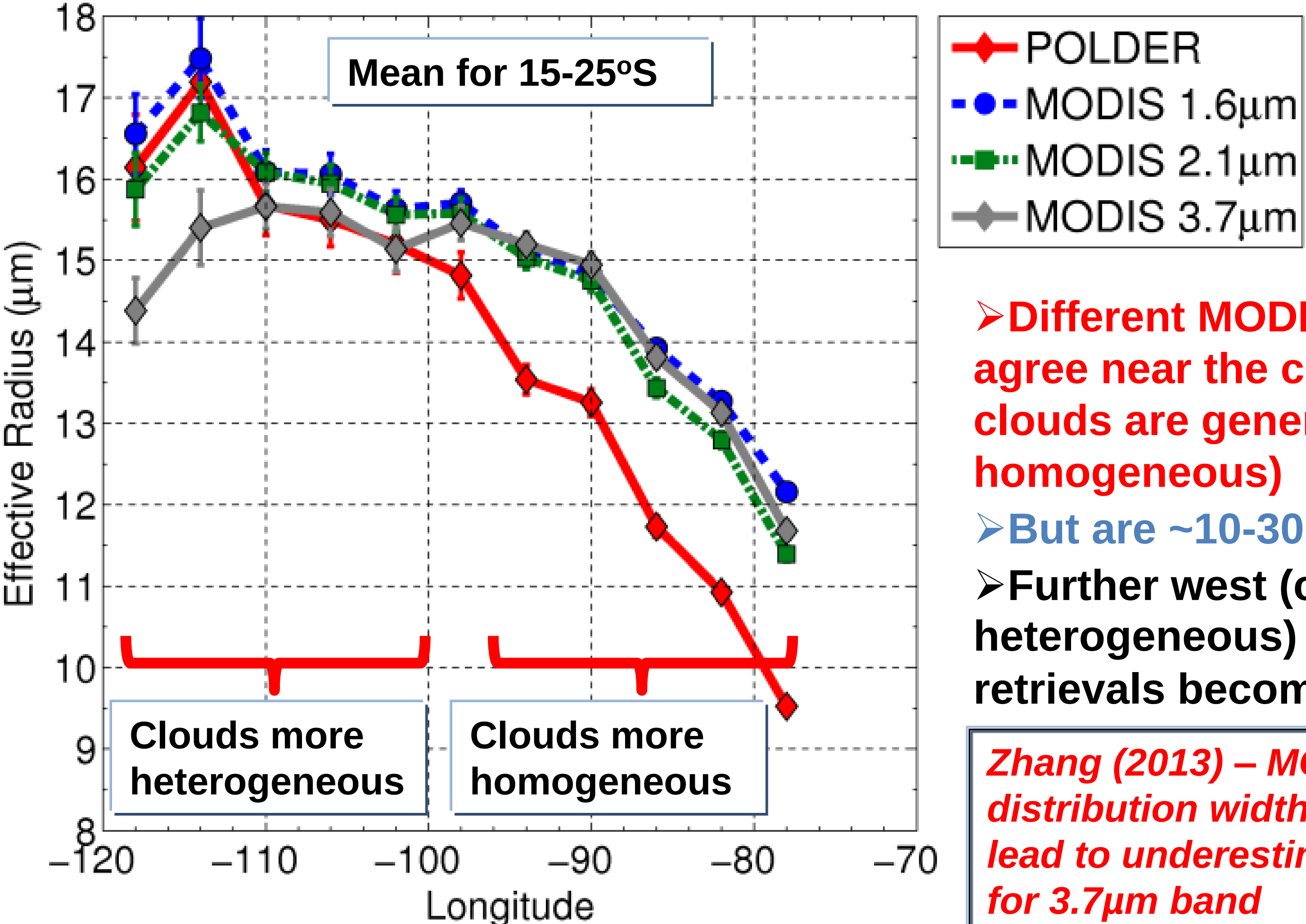
ALL Solar Zenith Angles

Low Solar Zenith Angles only

SE Pacific/VOCALS POLDER comparisons



- ➢Have co-located MODIS L2 1x1° boxes with POLDER measurements (cloud fraction > 80%)
- ➢POLDER uses polarization to measure r_e
  - ➢An independent technique that should not be subject to artifacts



- ➢Different MODIS wavelengths agree near the coast (where clouds are generally more homogeneous)
- ➢But are ~10-30 % too high
- ➢Further west (clouds more heterogeneous) the 3.7μm retrievals become lower

Zhang (2013) – MODIS Drop size distribution width assumption can lead to underestimate – especially for 3.7μm band

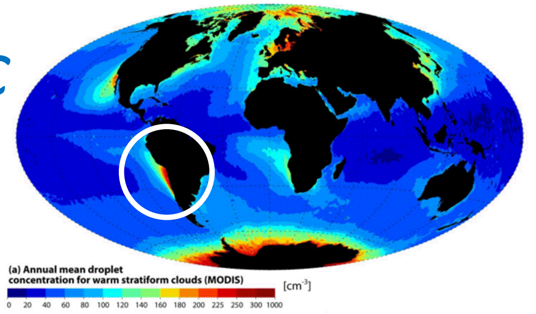
Conclusions (1)

- MODIS can be used to estimate cloud droplet concentrations (N_d) using observed optical depths (τ) and effective radii (r_e)
- The assumptions made to do this seem to hold up – at least in homogeneous clouds with little precipitation
- Utilized the diurnal cycle of Arctic stratocumulus clouds to examine the effect of Solar Zenith Angles (SZA) on retrievals.
- MODIS retrievals of optical depth, effective radius and droplet concentrations are likely dubious at high Solar Zenith Angles (SZAs) > 65^o
- Overestimate of τ and N_d, underestimate of r_e
- Reduction of 3.7μm r_e is greater than that for 2.1μm or 1.6μm
- r_e effect as important as τ effect for N_d changes for this band and for more heterogeneous clouds
- Results unlikely to be due to a real (physical) change in N_d
- Comparisons to POLDER shows interesting changes in MODIS r_e biases when moving between homogeneous and heterogeneous clouds
  - Attempting to characterize and quantify possible MODIS biases – 3D effects, variability, etc.

Conclusions (2)

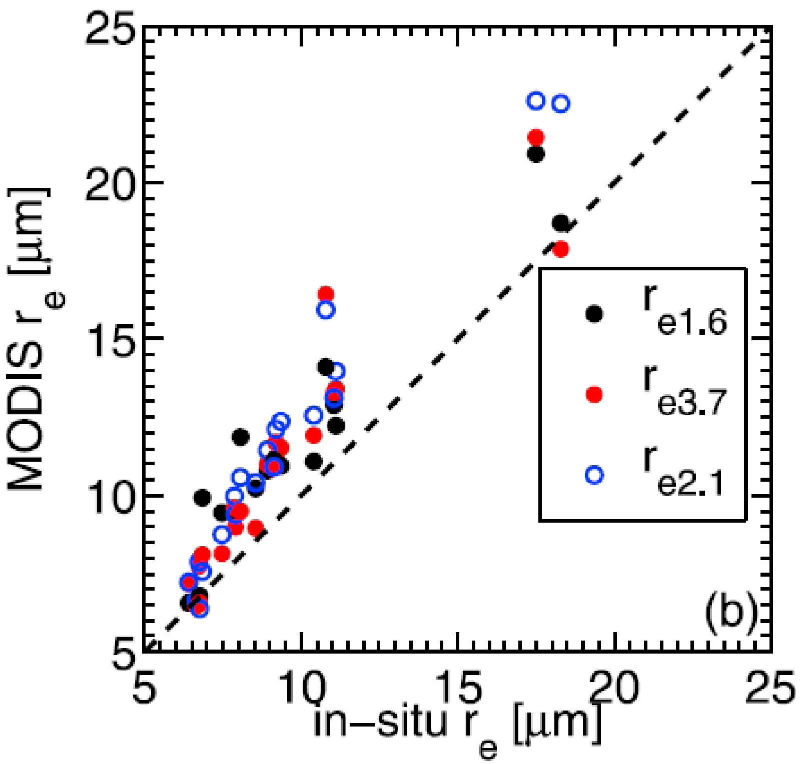
- ***High N_d values around Antarctica not solely due to high SZA – likely sea-ice is the main cause of the increase***
- ***Although some high N_d regions still remain – phytoplankton blooms?***
- ***Removing high SZA retrievals is important, especially when looking at seasonal changes, or particular times of the year***
- ***MODIS N_d retrievals in the Southern Ocean are consistent with a seasonal cycle of CCN that comprises higher concentrations in summer (but only when use exclude higher SZA retrievals)***

Comparisons with aircraft in SE Pacific



- **Aircraft comparisons suggest very good accuracy for low clouds (e.g. stratocumulus decks, e.g. Painemal & Zuidema, JGR, 2011**

- **But the analysis was performed in horizontally homogeneous clouds (stratocumulus)**



- **However, the effective radius was systematically too high by 15-20%**

- **But what about the good match for N_d given the sensitivity of N_d to r_e?**

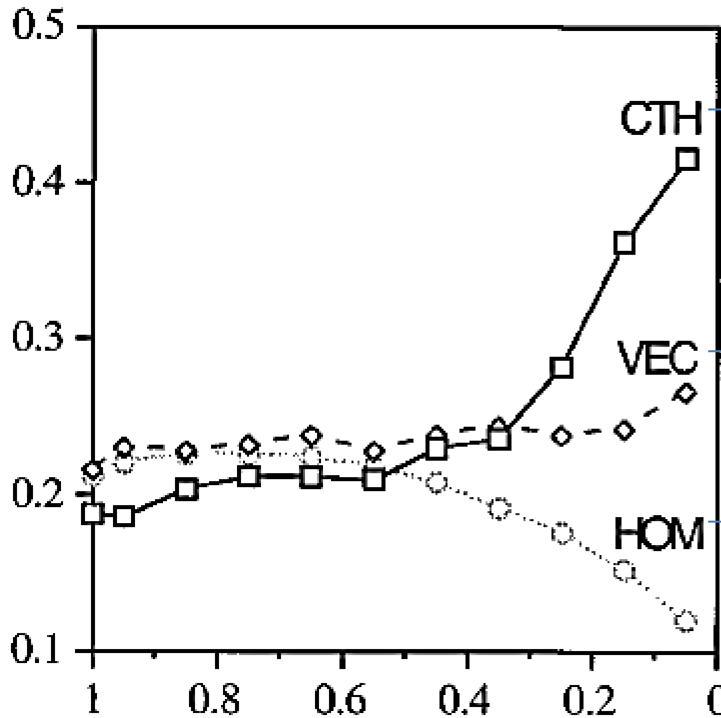
α = 0.7 = sub-adiabaticity

$$N_d = \frac{2\sqrt{10}}{k\pi Q^3}\left(\frac{\alpha c(T,P)\tau}{\rho_w r_e^5}\right)^{1/2}$$

- **The good match between aircraft and satellite was due cancellation of biases in r_e, c and k in the formula above**

Varnai & Davies, JAS, 1999 – artificially generated cloud field

SW (e.g. 0.86μm) zenith reflectance



Cloud Top Height variability

Variable extinction

"Real" clouds

Homogeneous cloud (plane parallel)

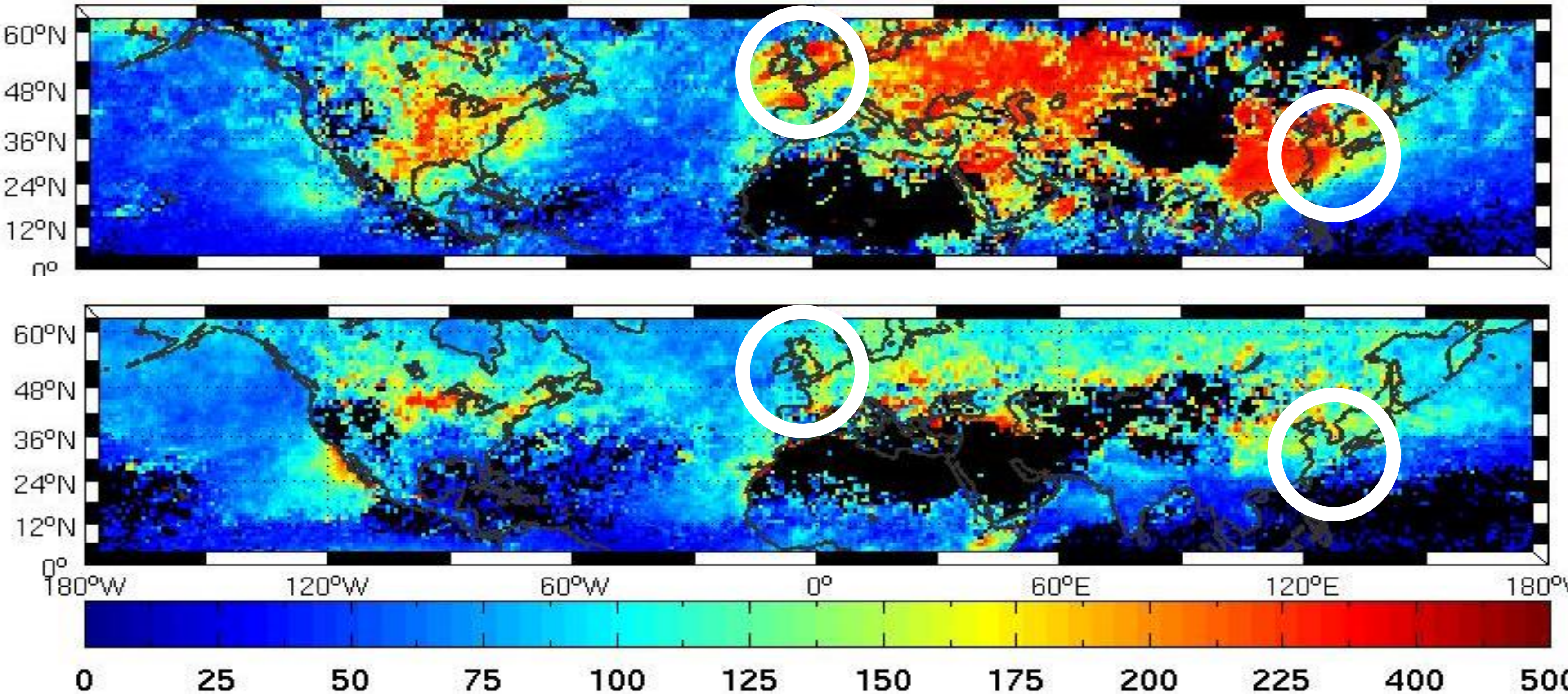
How MODIS assumes clouds behave

Low SZA μ_o High SZA

FIG. 17. Zenith reflectance (BRF) as a function of μ_0 for scenes with cloud-top (solid line) and extinction variations (dashed line) and for a scene that contains a homogeneous cloud (dotted line).

- **Plane parallel model (used for retrievals) predicts that $R_{0.86\mu m}$ decreases with Solar Zenith Angle (SZA) – however, for real clouds it increases**
- **Since $R_{0.86\mu m}\uparrow$ means $\tau \uparrow$ if MODIS measures a high $R_{0.86\mu m}$ at high SZA it will assume that the cloud had a very high τ**
- **A similar effect may occur for absorbing wavelengths, which would lead to r_e underestimation ($R_{2.1\mu m}\uparrow$ means $r_e \downarrow$)**

The N_d climatology using the standard Level-3 product



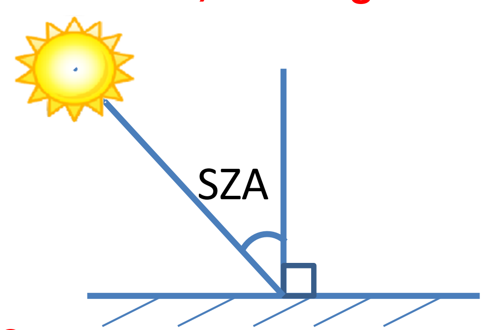
Dec, Jan, Feb

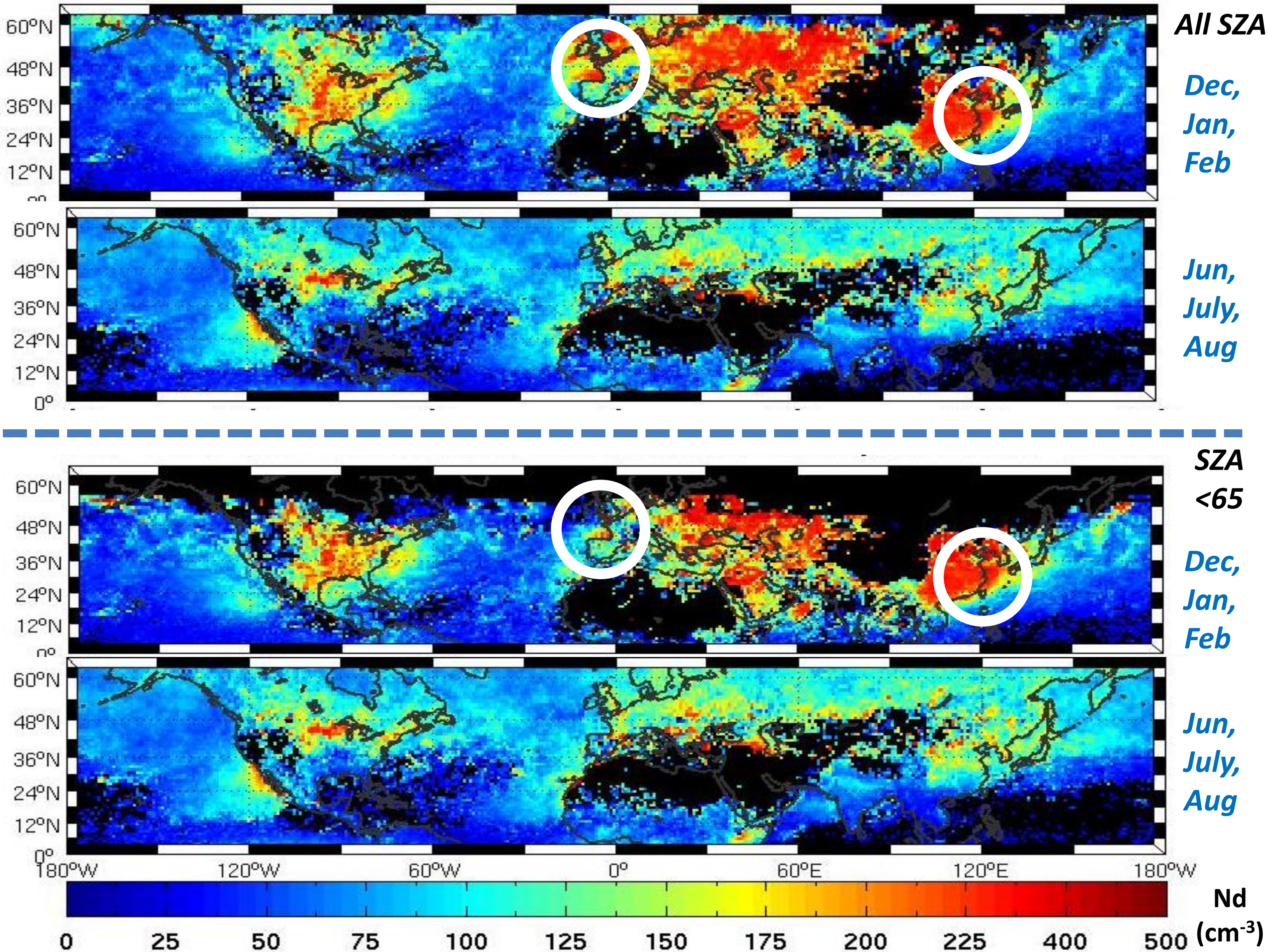
Cloud fraction >80%, y2007

Jun, July, Aug

Nd (cm^{-3})

- **Unexpected seasonal cycle in Nd – much higher in DJF than in JJA**
- **Contrary to what would be expected based on aerosol measurements, although there are few climatologies of CCN**
  - ***Are the retrievals flawed?***
- ***Possible causes of this result:-***
  - **Seasonal cycle of cloud height / type?**
  - **Ice below clouds?**
  - **Surface characteristics (e.g. sea ice)?**
  - **High *Solar Zenith Angles (SZA)* in winter (Sun is low in the sky)?**

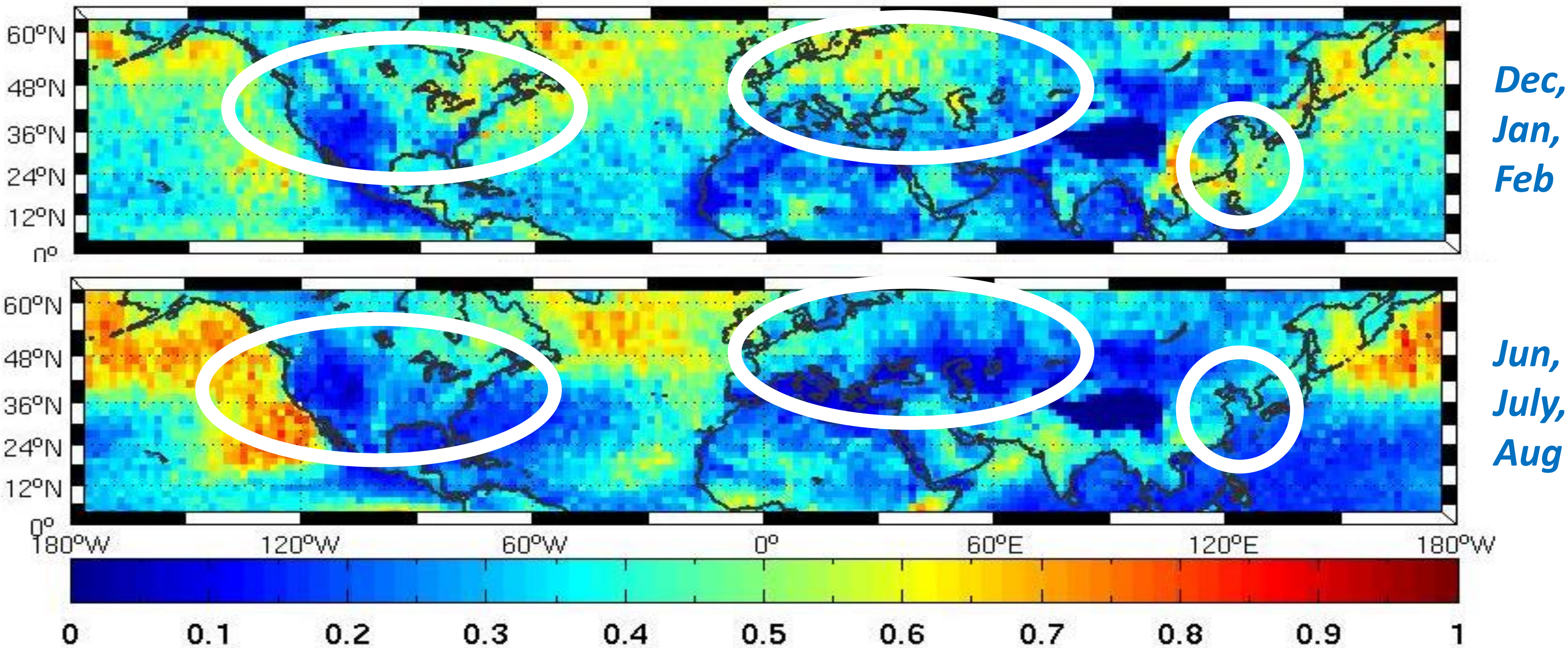




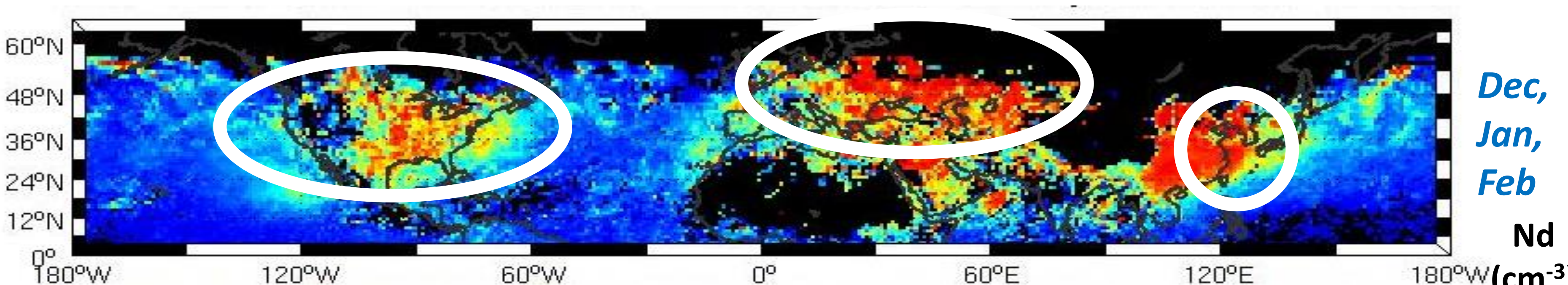
All SZA
Dec, Jan, Feb
Jun, July, Aug
SZA <65
Dec, Jan, Feb
Jun, July, Aug
60°N
48°N
36°N
24°N
12°N
0°
180°W
120°W
60°W
0°
60°E
120°E
180°W
Nd (cm⁻³)
0 25 50 75 100 125 150 175 200 225 400 500

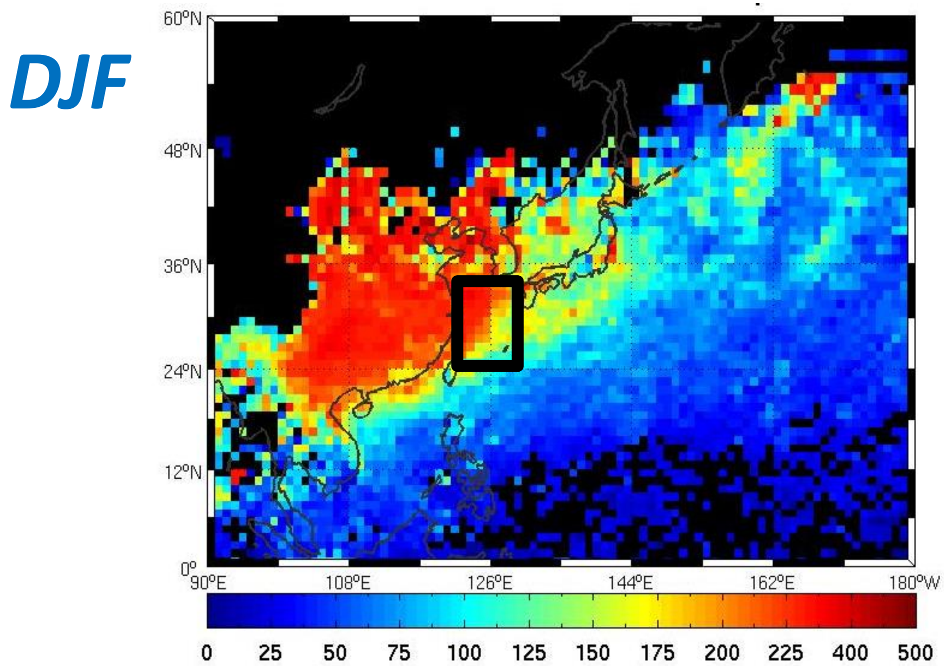
Seasonal cloud variations

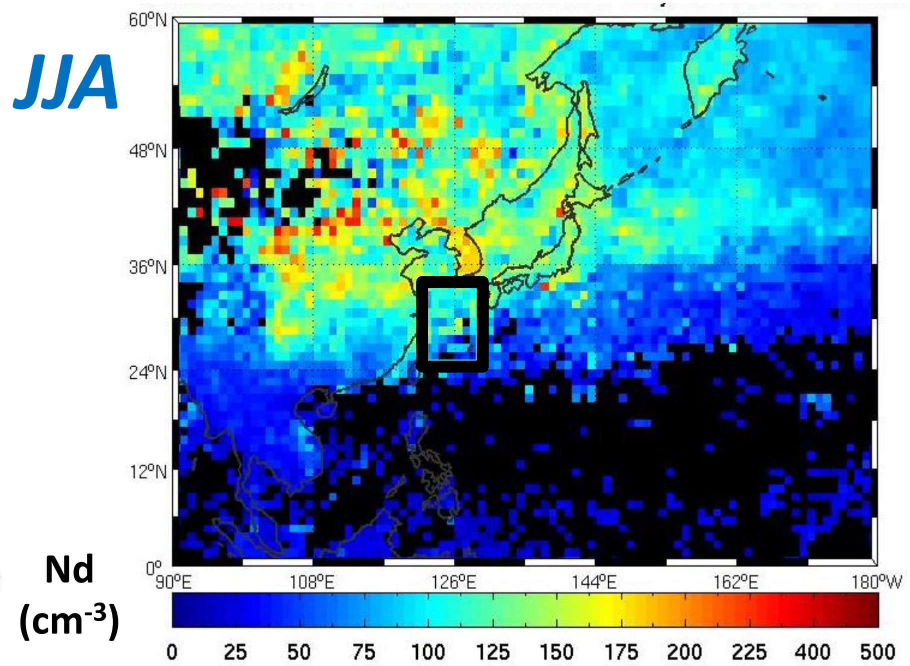
CALIPSO/CloudSat daytime low cloud fraction 2006-2010



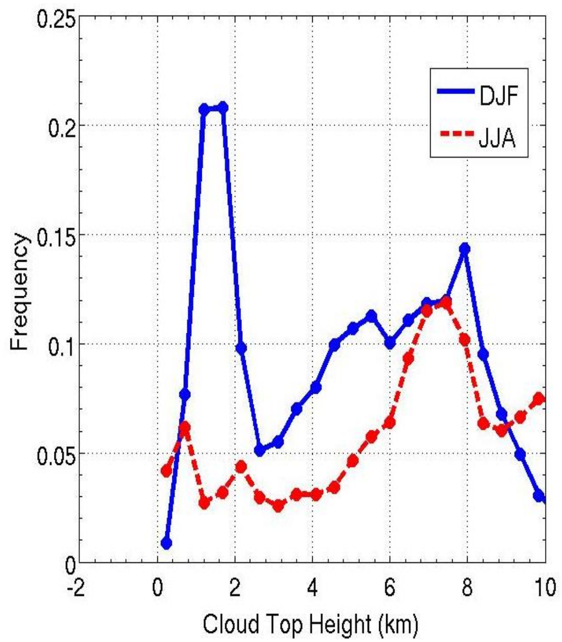
- *Fewer low clouds in JJA relative to DJF – low clouds likely more polluted*







CALIPSO Daytime Cloud Top Height PDF

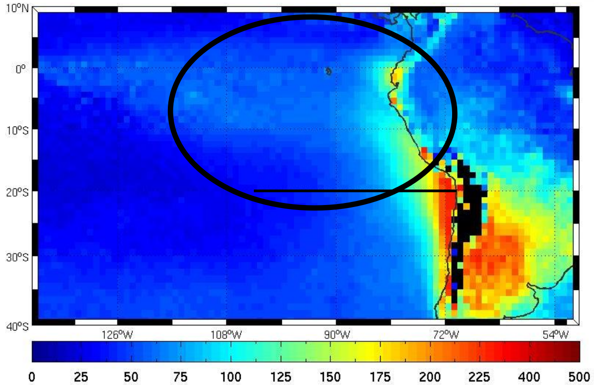


- **Significant change in the mode of cloud top heights between summer and winter**

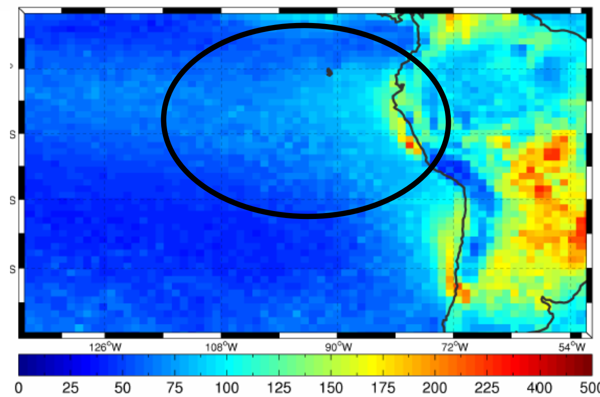
- **More low clouds in winter likely the reason for more polluted clouds**

GCM model evaluation

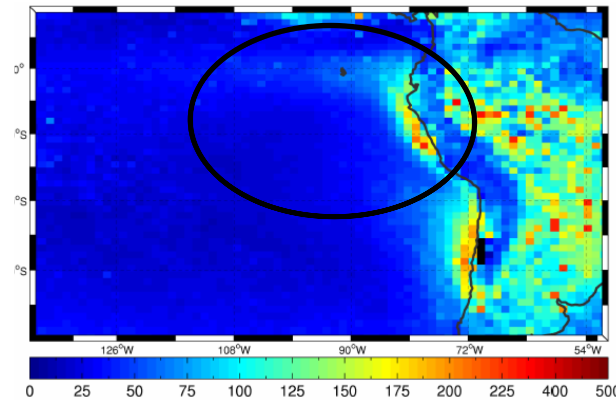
MODIS obs



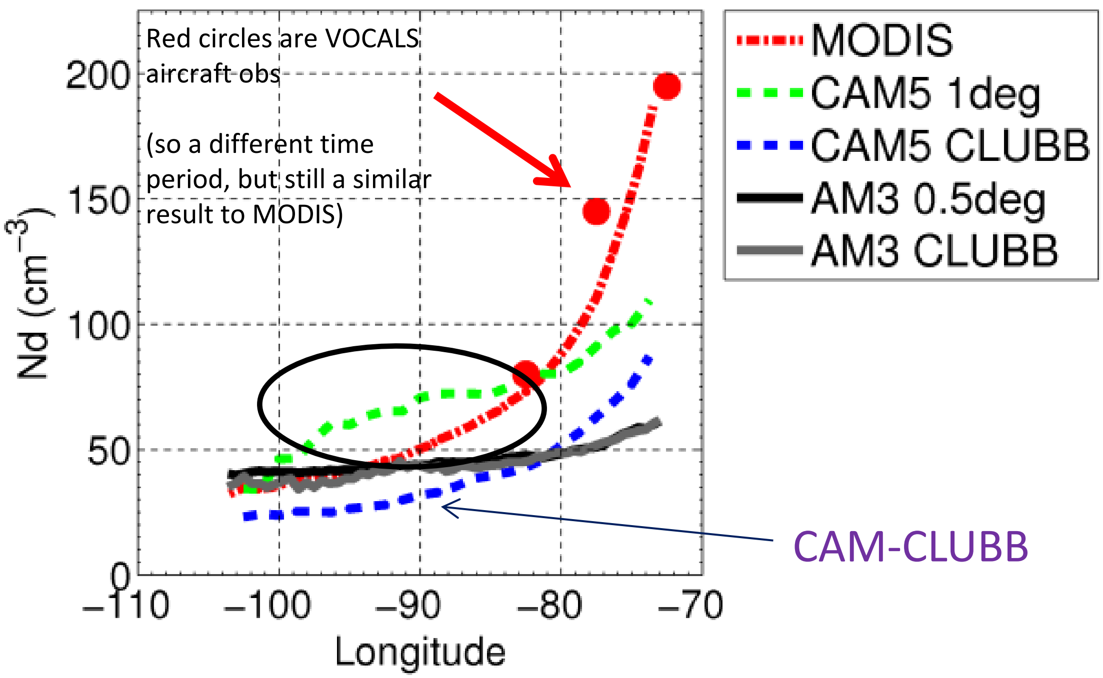
CAM5 1 degree



CAM-CLUBB 1 degree

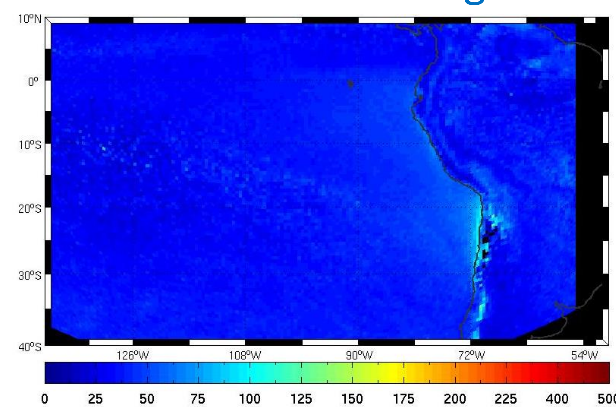


Droplet Concentration (cm^{-3})



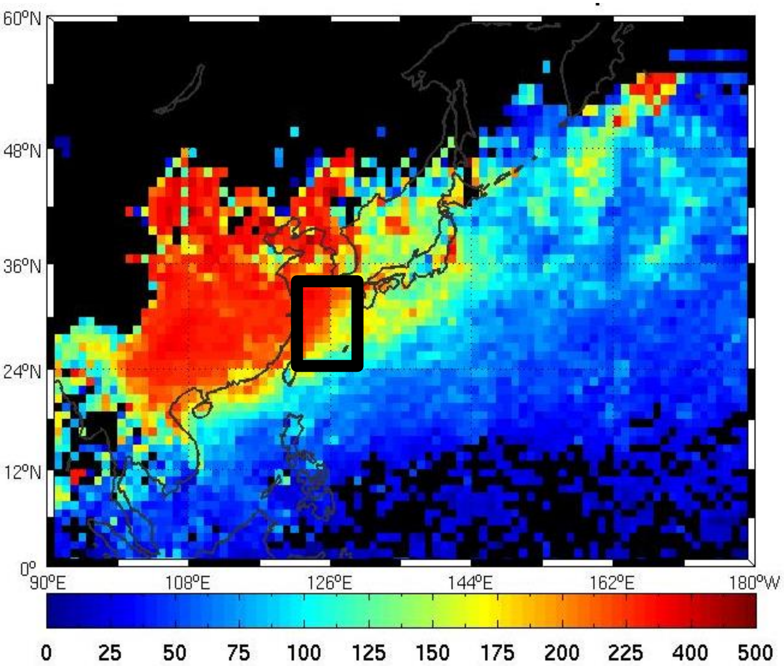
Longitude transects along 20S (VOCALS stratocumulus region)

AM3-CLUBB 0.5 degree



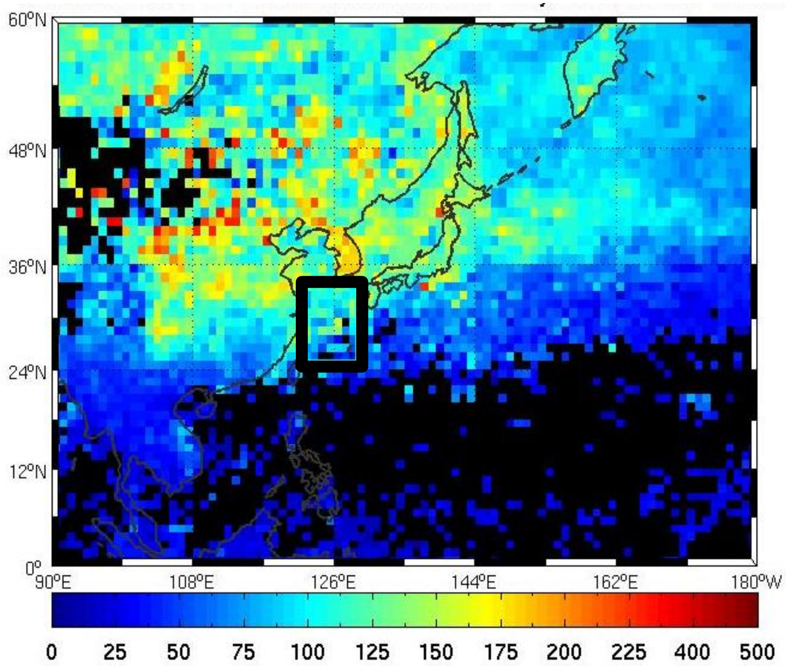
- CAM-CLUBB removes the high Nd values in the stratocumulus to cumulus transition regions
- AM3 values are too low – both base (not shown) and CLUBB
  - CCN are too low despite sulfate loading being too low!

DJF

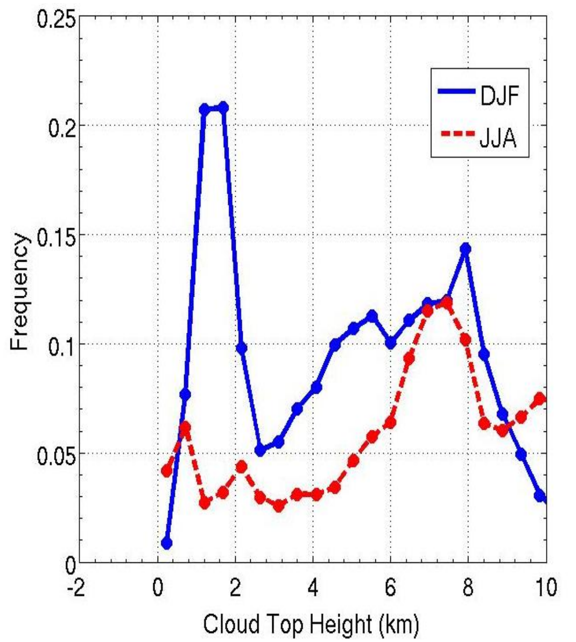


Nd (cm^{-3})

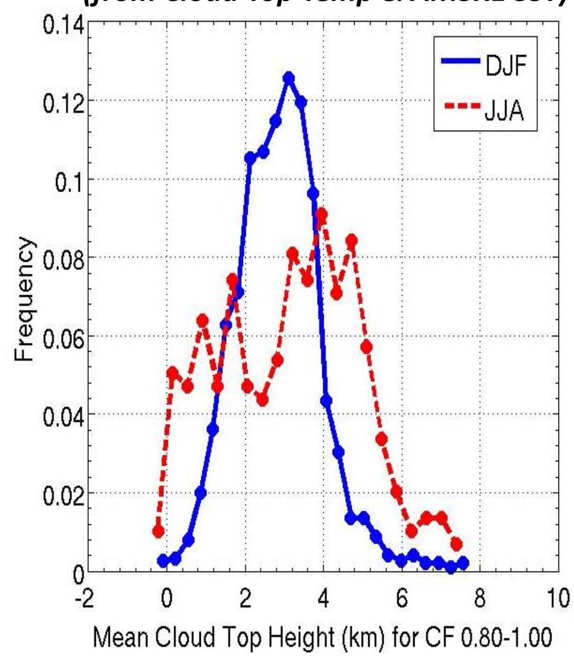
JJA



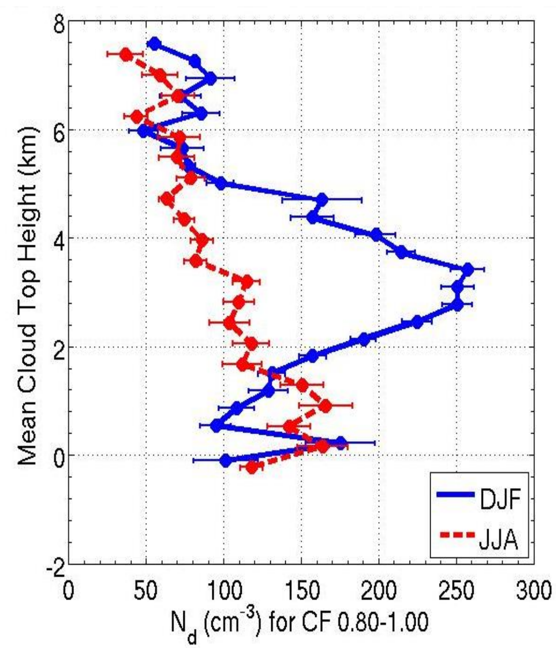
CALIPSO Daytime Cloud Top Height PDF

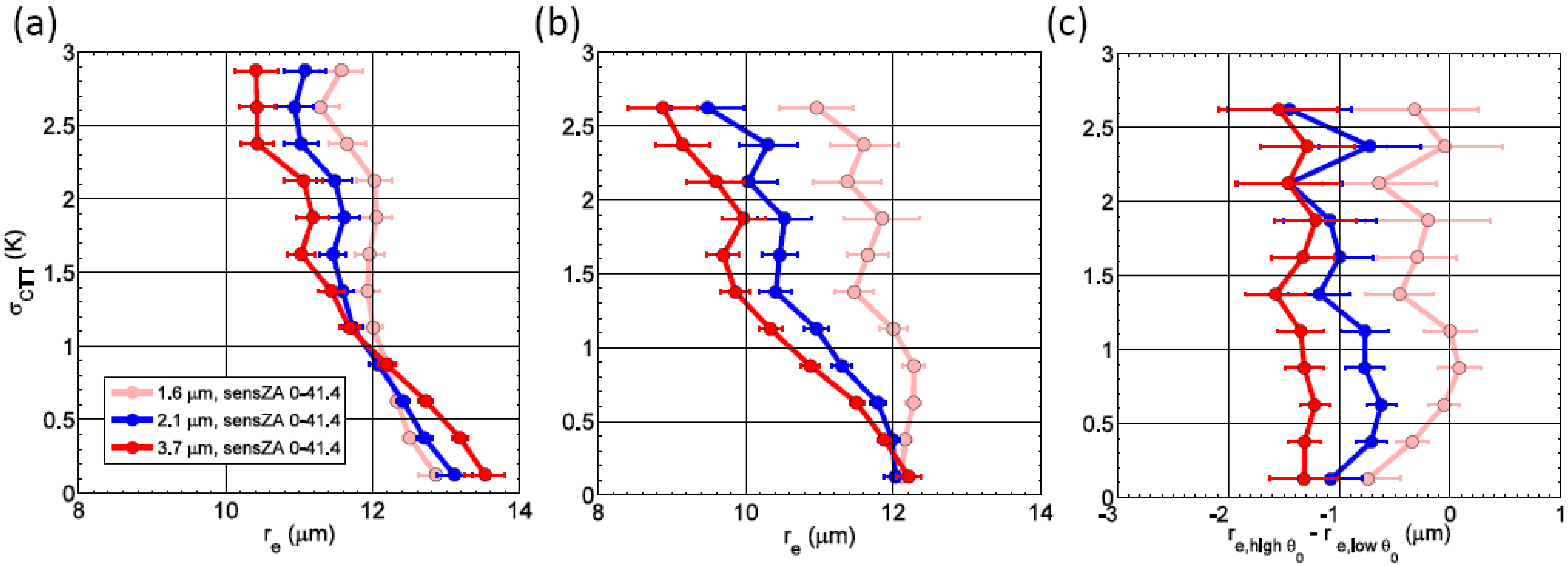


MODIS Cloud Top Height PDF
(from Cloud Top Temp & AMSRE SST)



MODIS Mean Nd vs Cloud Top Height




(a)
(b)
(c)
σCTT (K)
re (μm)
re (μm)
re,high θ0 - re,low θ0 (μm)
1.6 μm, sensZA 0-41.4
2.1 μm, sensZA 0-41.4
3.7 μm, sensZA 0-41.4