Influence of aerosol on deep convection through its life cycle over tropical continents

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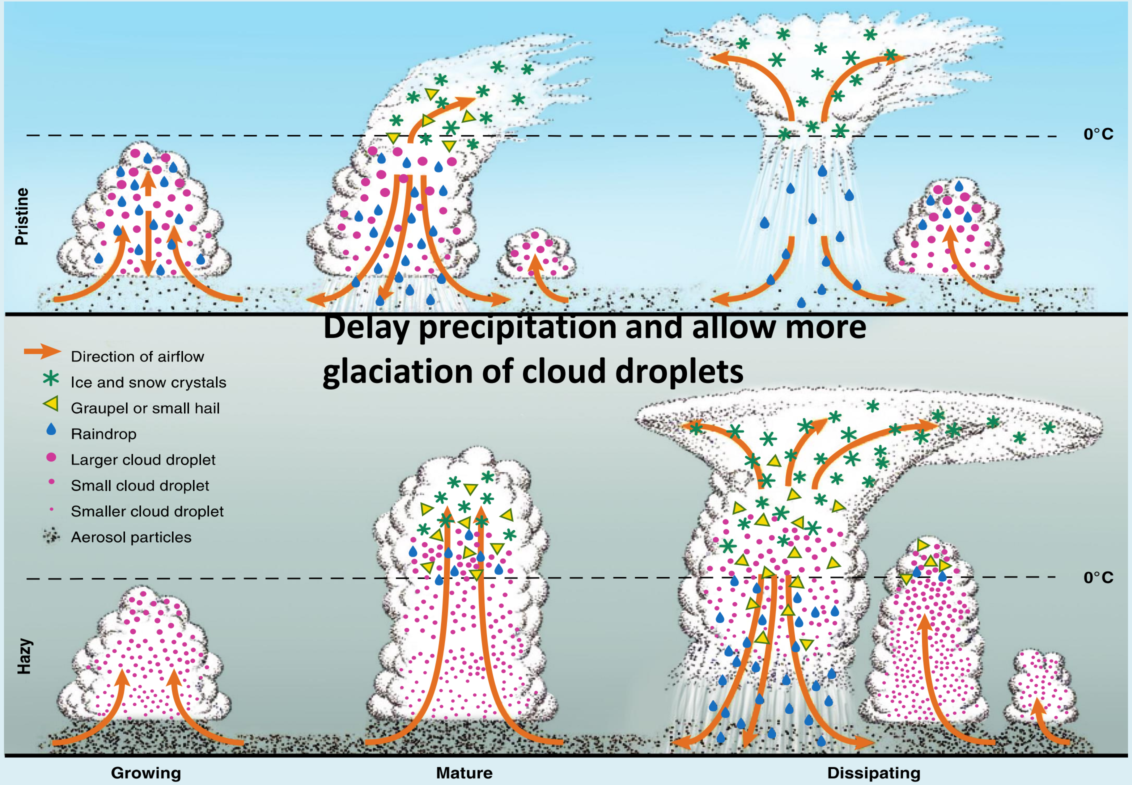
Hypothesis of aerosols influence on cloud and precipitation:

- Albrecht 1989: By suppressing precipitation, the aerosols can <u>increase cloud lifetime</u> and thus enhance radiative forcing
- Rosenfeld et al. 2008: Through delaying precipitation during growing and mature stages, aerosol enhances ice water content, <u>and invigorate precipitation and increase convective life time, especially during its decay phase</u>.

Clean

Polluted



Delay precipitation and allow more glaciation of cloud droplets

Longer convective lifetime

A main source of uncertainty:

- ***Lack of direct observational evidence showing aerosol increase cloud lifetime on large scale.***
- ***Influence of aerosol varies with meteorological and aerosol conditions, and convective types. Thus, the aerosol influences on convection at regional to large spatial and climate scales is unclear (e.g., Tao et al, 2012, Altarze et al. 2014; Rosenfeld et al. 2014).***

Challenges:

- ***Lack of large-scale, long-term observations of the convective life cycle as functions of aerosols and meteorological conditions to allow us isolating the aerosol influence from those of the meteorological conditions.***

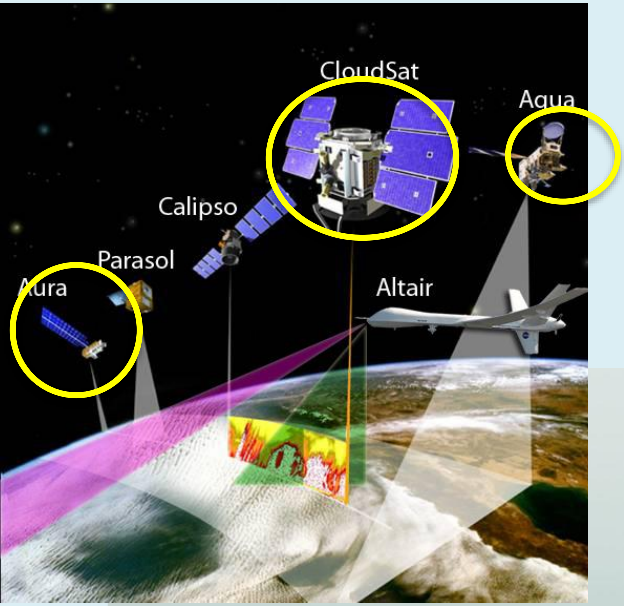
Approach:

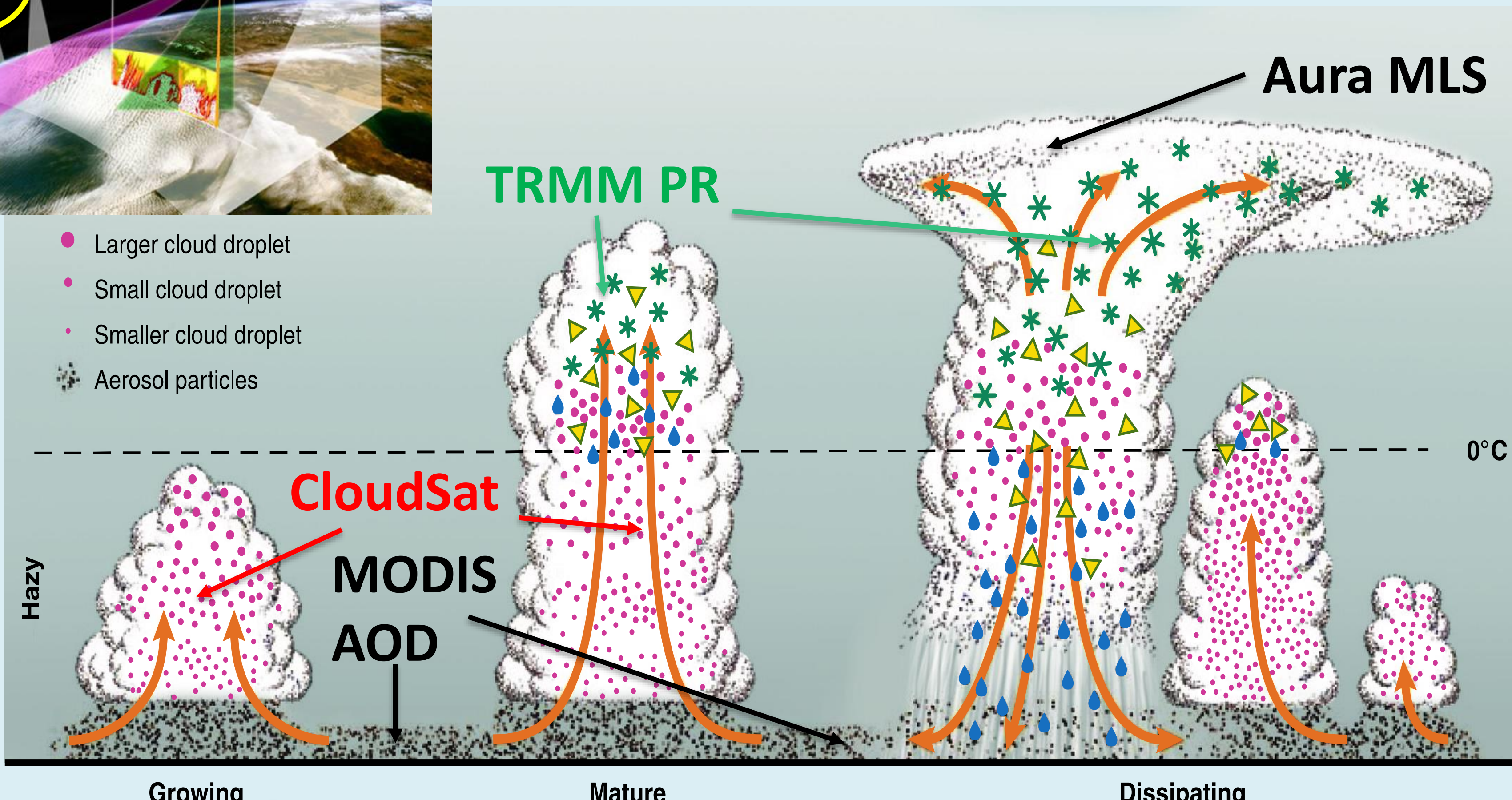
- ***Use multiple co-located instantaneous geostationary and polar orbital satellites datasets.***

Focus of this study:

- ***Very large mesoscale convective complexes (MCCs' diameter >100 Km) that dominate tropical rainfall, especially drought and floods (e.g., Houze et al. 2015).***
  - ***Can we detect influence of aerosol on convective lifetime on global and regional scale in the tropics?***
  - ***If so, what is the relative importance of such influence vs. those of the meteorological conditions?***
  - ***What processes might be responsible?***

Using multi-satellite sensors to detect changes of convective and anvil cloud droplets, precipitation-sized hydrometeors through convective life cycle.

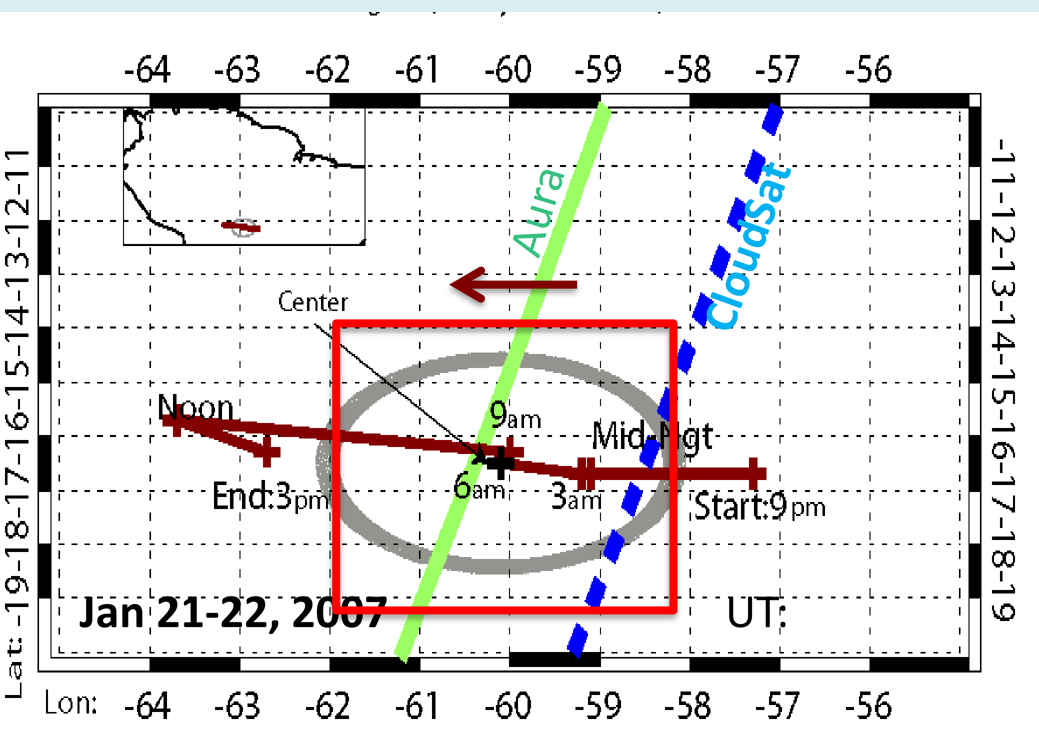




ISCCP Convective Cluster Tracking Data, MERRA, ERA-I

Satellites	Parameters
ISCCP Convective tracking Infrared (~11µm); Visible (~0.6 µm) **(Machado et al. 1998)**	Lifecycle of the convection. Position of the center, Convective radius, Convective Fraction number of convective core, and cloud top temperature.
CloudSat RO/Cldclass Radar (94 GHz) reflectivity (large cloud droplets, drizzle side rain droplets)	Cloud Water Content (CWC) and Cloud Water Path (CWP). To locate deep convection along with CALIPSO and ISCCP.
TRMM (2a25) (Radar), large precipitation hydrometoors)	Rainrate, latent heating profiles
Aura MLS CO/IWC Data (thermal microwave emission from the edge of the atmosphere; 240/190GHz) (most sensitive to convective anvil ice cloud particles)	Ice water content in the anvils and CO
MERRA (Reanalysis; Assimilation)	Vertical wind shear, Omega
MODIS **(**Spectroradiometer**)**	Ambient AOD and cloud top R_eff

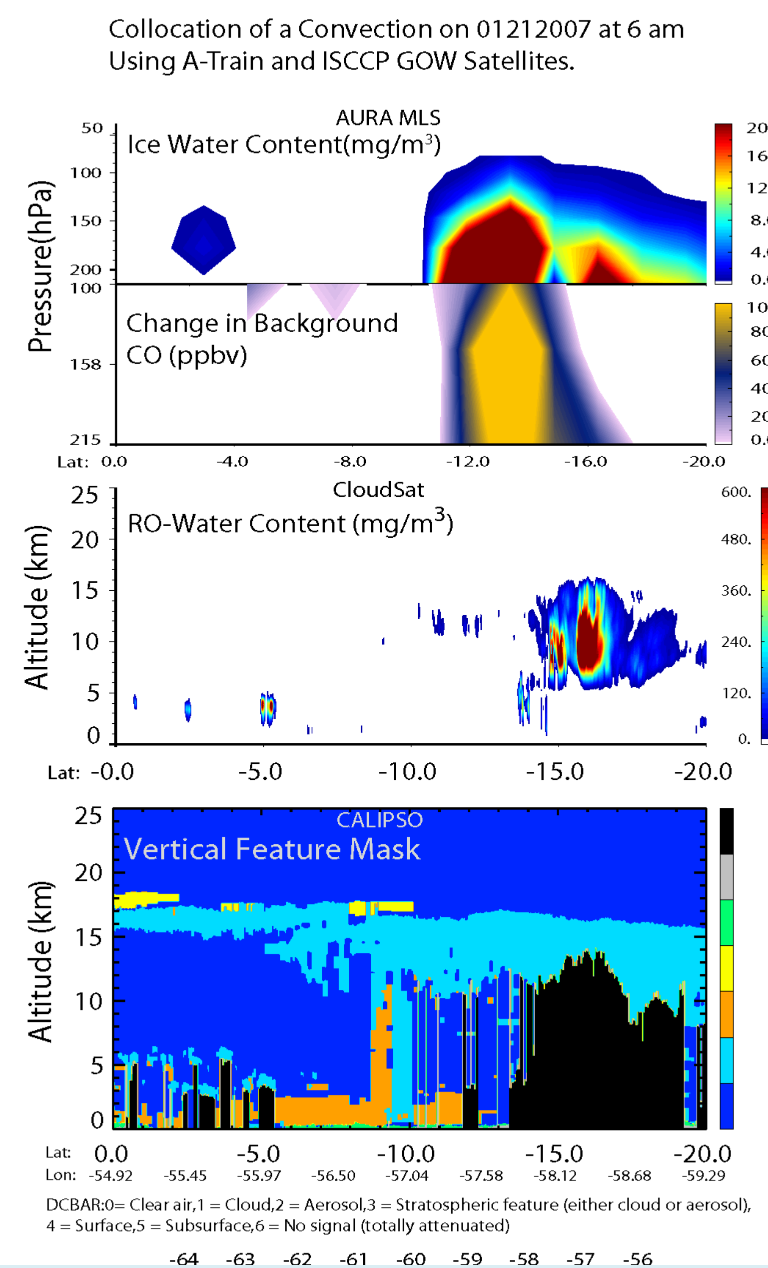
Linking A-Train measurements to the life cycle of convection as indicated by the ISCCP



Gray Cirle is the Cloud Position at Closest Time Match with All the Satellites. Center during collocation is Black plus Sign.

Tracks: AURA(5:35 am; Green); CALIPSO(5:27 am; Dash Blue); ISCCP (6 am; Red)

Inset: Location of the Same Convection over S.America



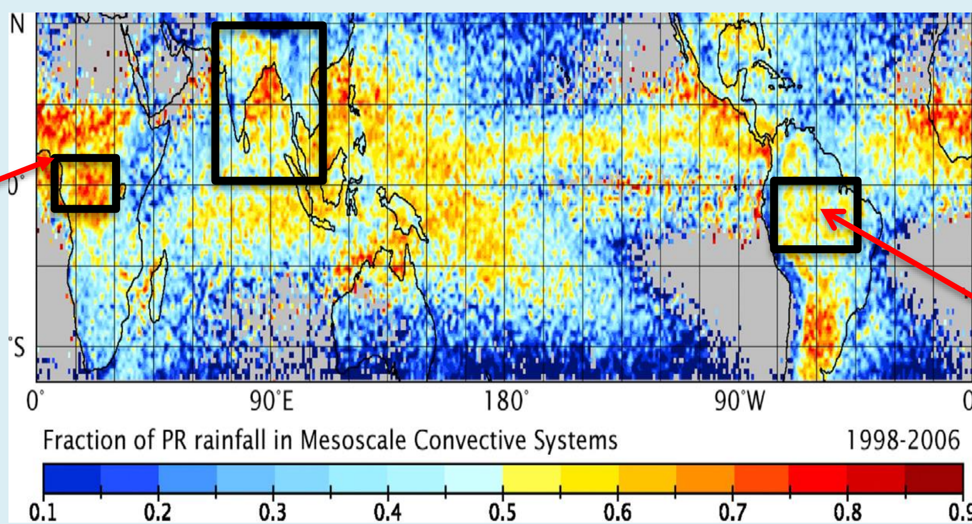
Satellite data: South America: 5N-15S, 40-80W, Congo: 10N-10S, 10E-40E, SE Asia: 0-40N, 70-100E, for the period of June 2006-May 2008

- *966 cases MCSs, with life-time > 6 hours & d >100Km, were colocated with A-train measurements, 355 cases in growing phase, 401 in mature phase and 210 during decay phase.*
- *1-2 pm local time*

DOE ARM data:

- *GoAmazon, Manacapuru site (3S, 60E): Jan 2014-Feb 2015*
- *AMMA, Niamey, Niger (13N, 2E): April-December 2006.*
  - *Averaged into hourly resolution for all convection > 6 km on diurnal time scale*
  - *Afternoon (1 -2pm)*

DOE-AMMA

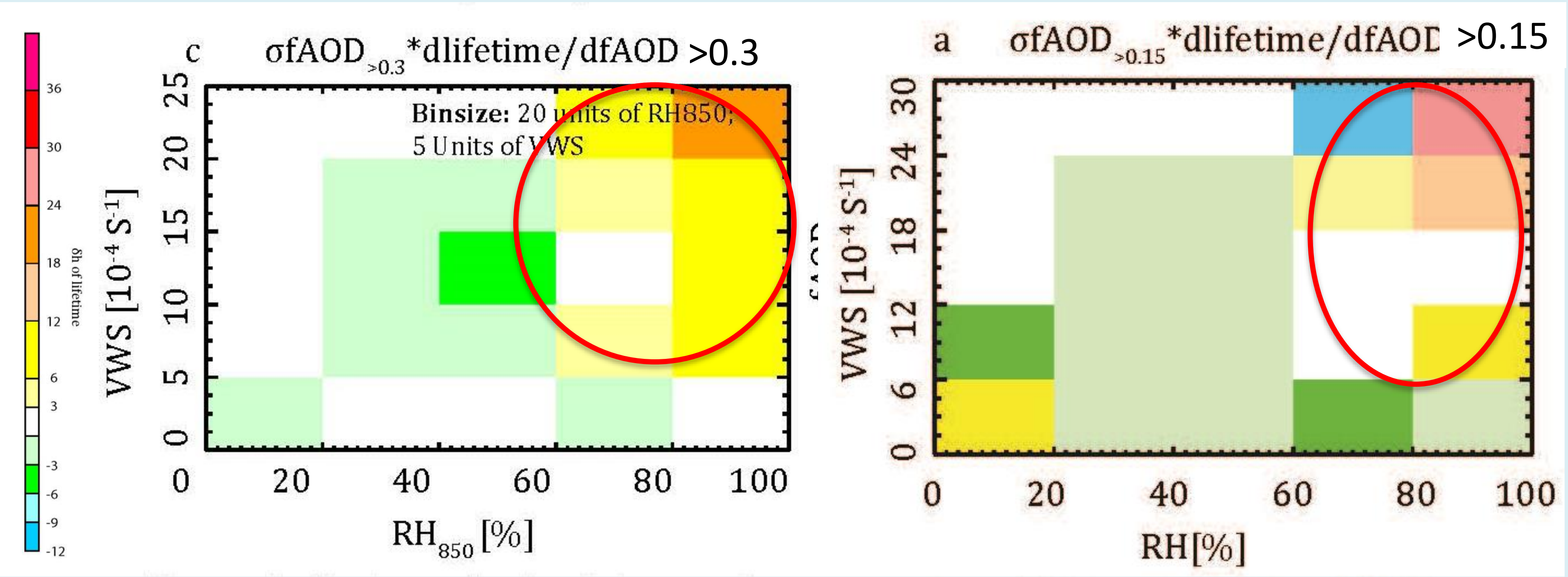


DOE-GoAmazon

- ***Changes of the MCCs lifetime and lifecycle with aerosol optical depth (AOD), and meteorological conditions (CAPE, RH, VWS) at global tropical continental scale***

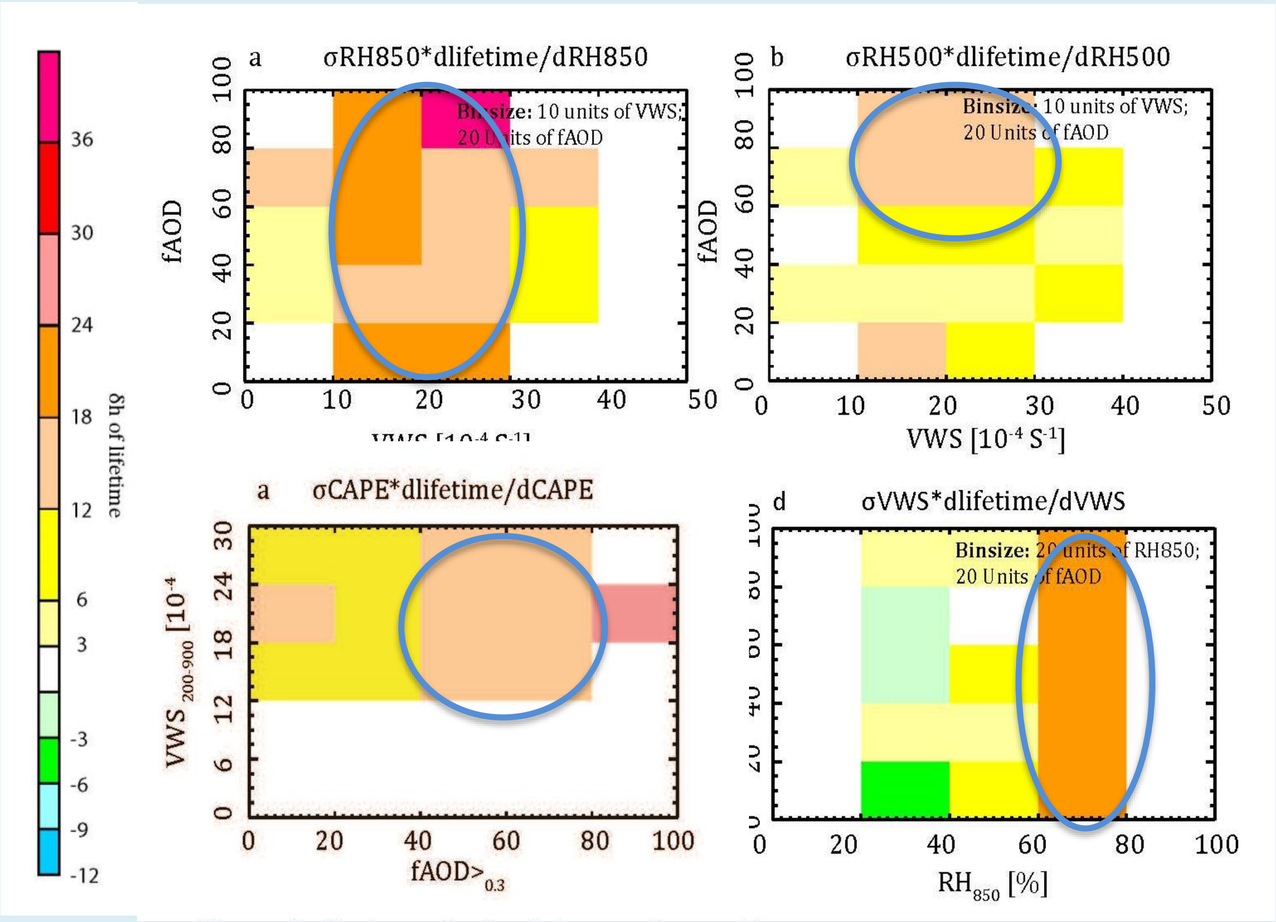
Variation of MCCs Lifetime with AOD under various meteorological conditions

- ***The rate of MCCs' lifetime increases associated with 1σ increase of the fractional area of heavy pollution (AOD>0.3) under high RH850 (>60%) and moderate VWS (5-25 10^{-4} S^{-1}), but decreases with AOD under lower RH850 (<60%).***
- ***This general pattern holds for both AOD>0.3, and AOD>0.15.***



Variation of MCCs Lifetime with meteorological condition:

- ***MCCs' lifetime increases the most with RH850 under low VWS ($<20X10^{-4}$ S^{-1}). It also increases with VWS under high RH850 (>40%), increase with RH500 and CAPE under high AOD and moderate VWS.***



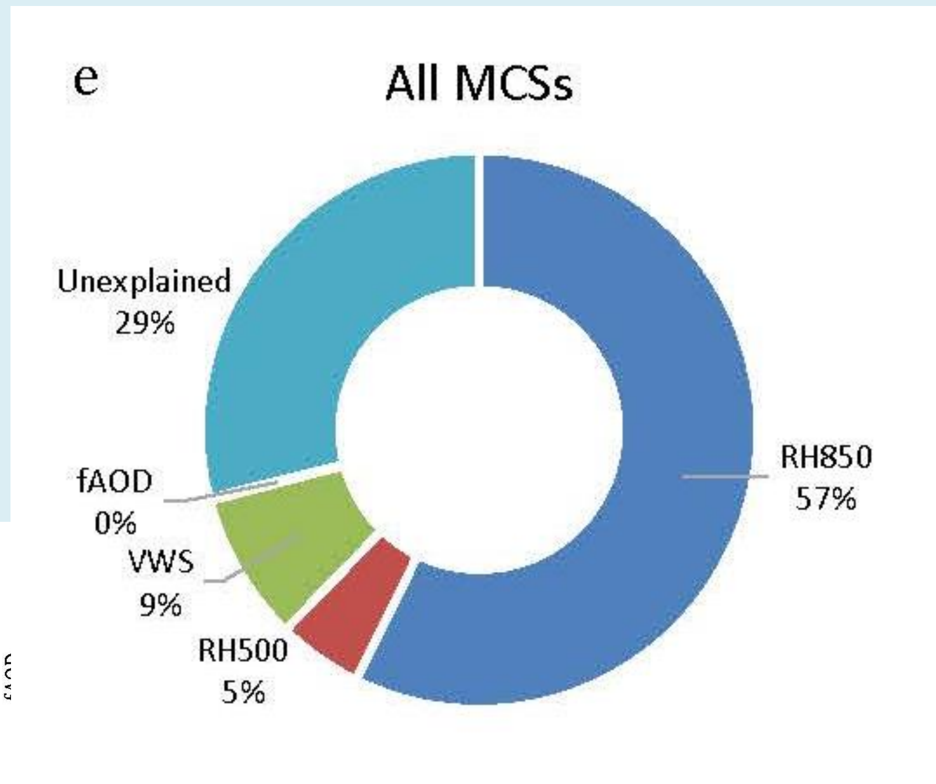
Rate of MCCs lifetime change with 1s of meteorological variable

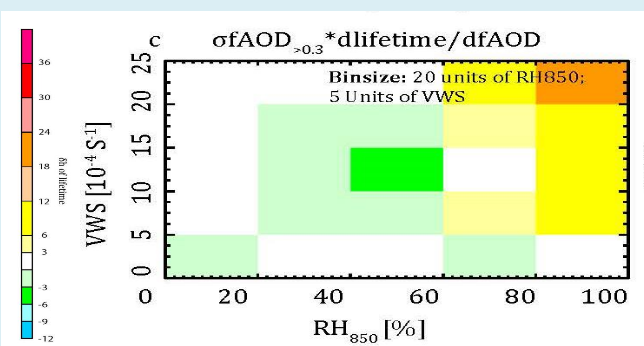
Inferred influences of aerosol vs. meteorological conditions on the variance of the MCCs Lifetime:

- ***RH850 explains about 57% of total variance of the MCCs lifetime, VWS explains about 9%, and AOD explains ~0% on global tropical continental scale.***

- ***Aerosol effect is either canceled out or overwhelmed by meteorological conditions, or not detectable by satellites.***

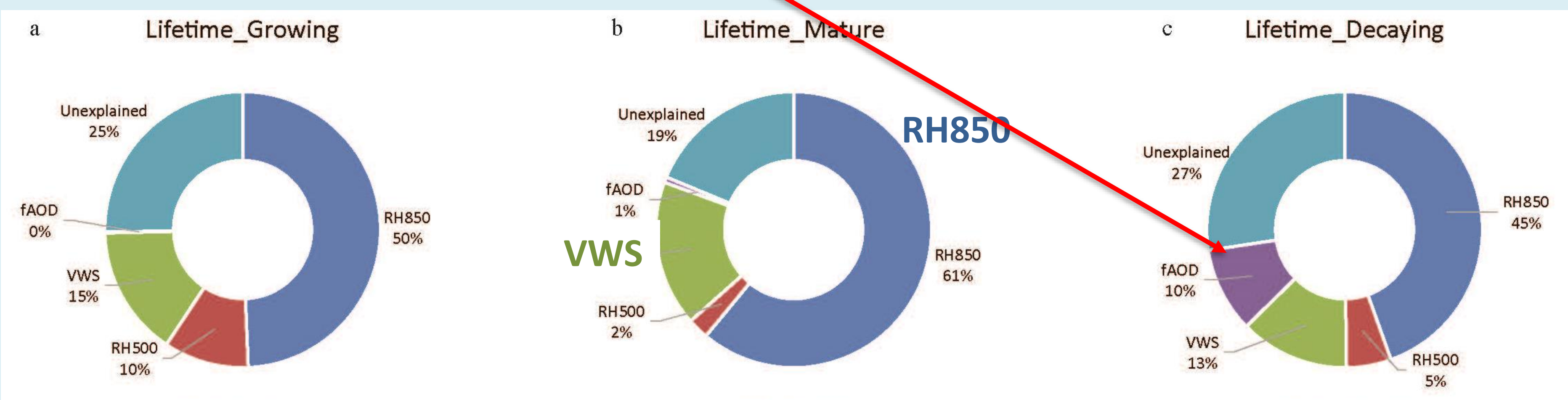
% of total variance explained (CAPE Is not included)





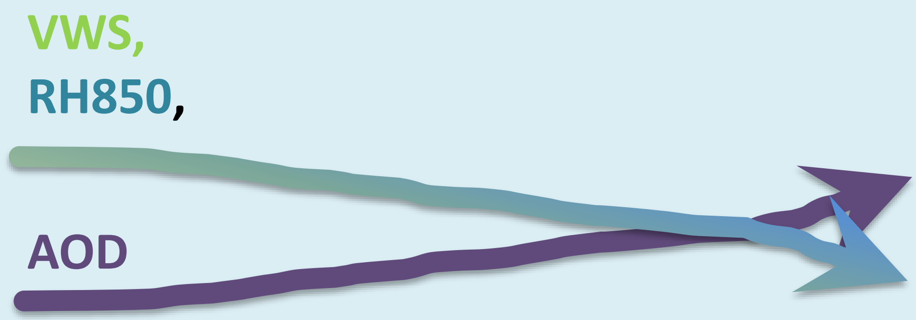
Inferred influences of AOD vs. meteorological conditions on the evolution of the MCCs:

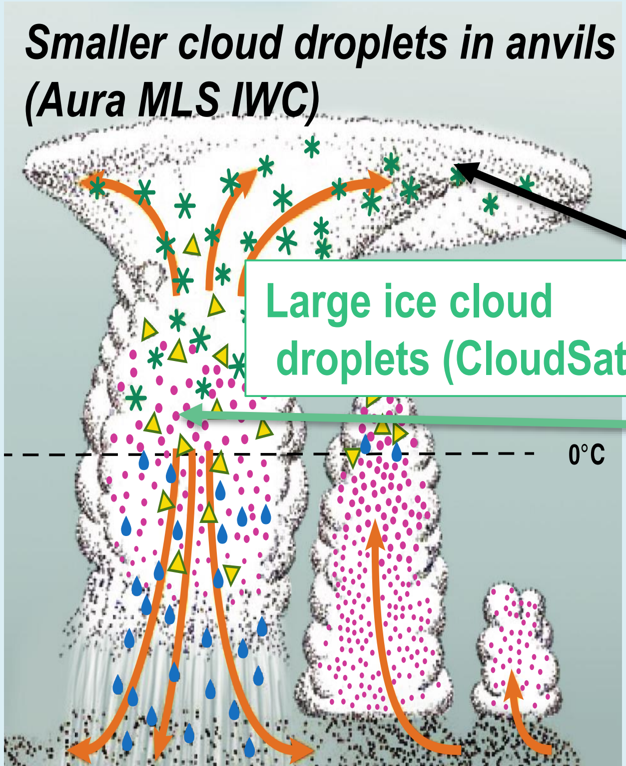
- AOD appears to have strongest influence on the length of decay phase of the MCCs, explains ~10% of its total variance, comparable to that of the VWS (13%).
- RH850 dominates the variances of the MCCs lifetime (45%-61%), and VWS also has significant influence on MCCs' lifetime through all phases of the MCCs lifecycle (13%-17%).



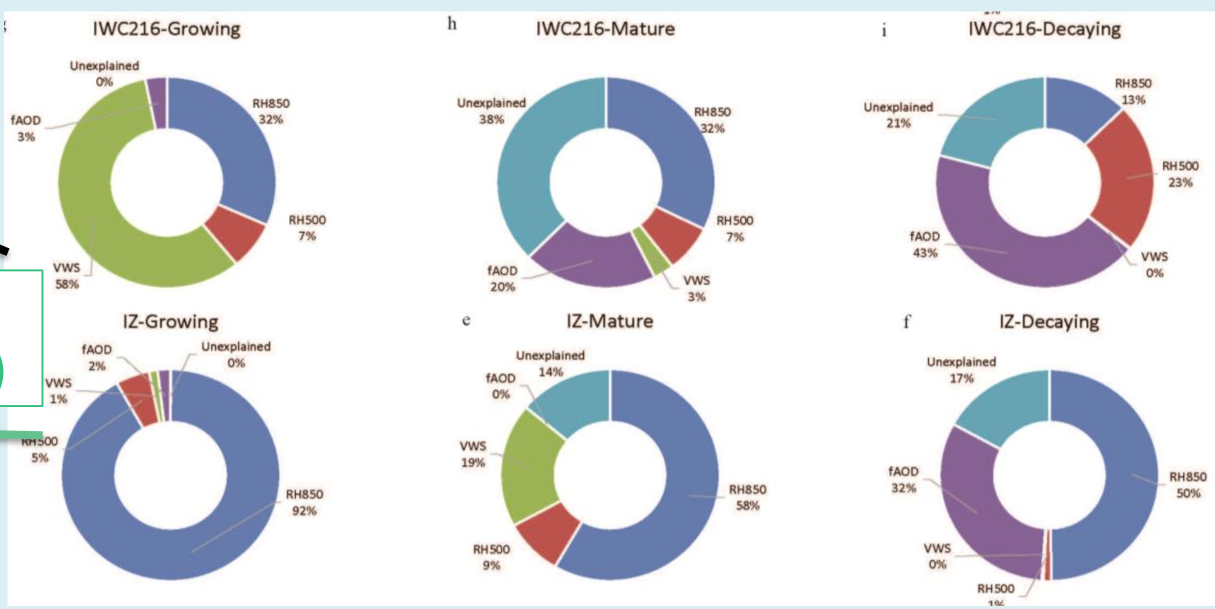
- ***What processes might contribute to a stronger influence of AOD on the decay phase of the MCCs' life cycle?***

- ***Aerosol effect on convective and anvil cloud ice detectible by satellite is the strongest during the decay phase.***



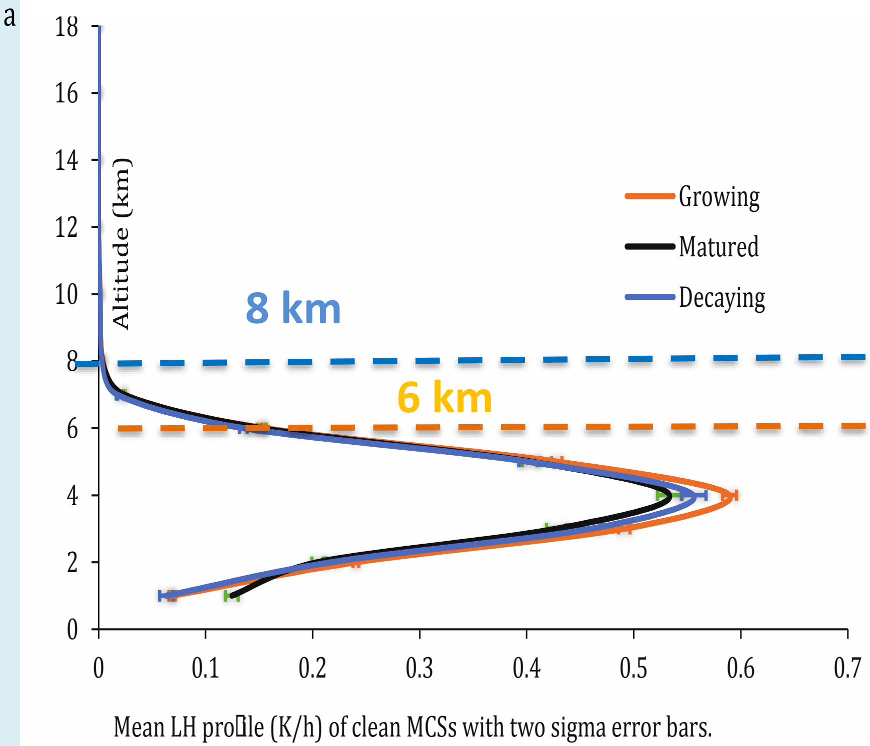


Growing **Mature** **Decay**

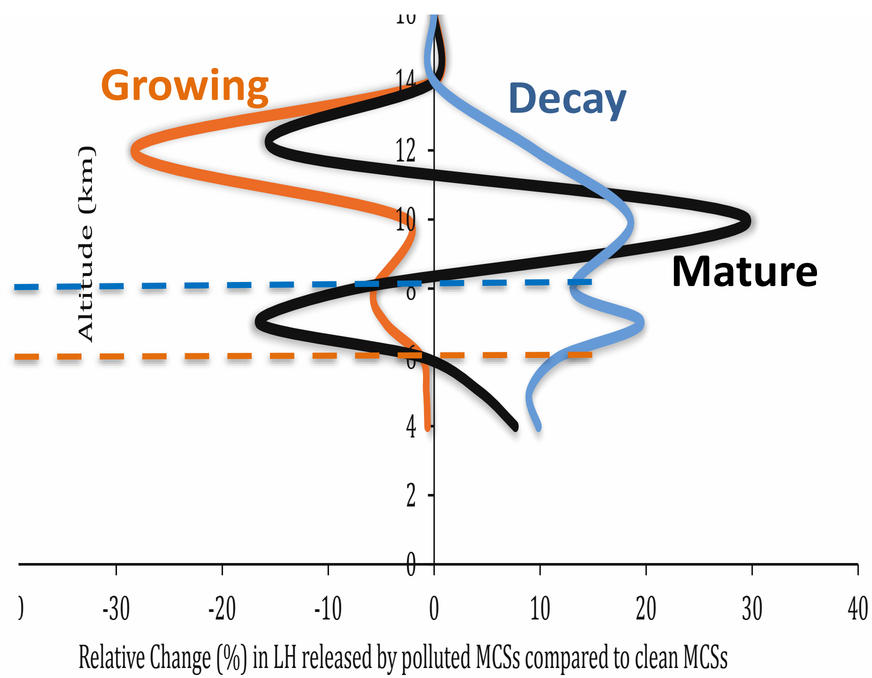


- ***Latent heating increases in the middle and upper troposphere in polluted environment during the decay phase of the MCCs.***

Mean latent heating profiles (determined by the co-located TRMM & ISCCP)



Difference of the latent heating profiles between the polluted (AOD≥0.3) and clean (AOD<0.3) environment.

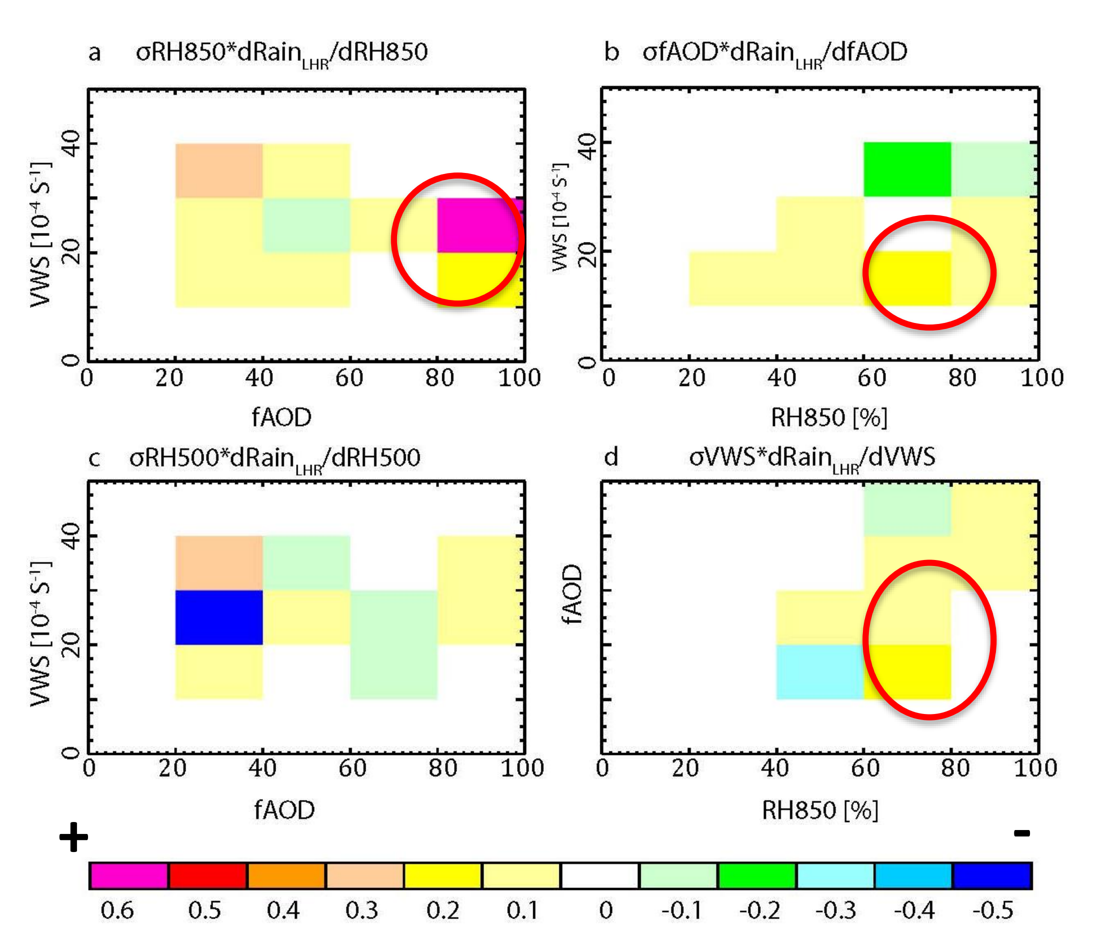


Inferred influences of ADO vs. meteorological conditions on MCCs rainrate:

- ***The MCCs' rainrate increases with AOD at the comparable rate as that with VWS.***
- ***MCCs rainrate increases with AOD under low VWS, with RH850 under high AOD and low VWS; and with VWS for high RH850 and moderate AOD.***

Variation with RH850hPa

Variation with AOD

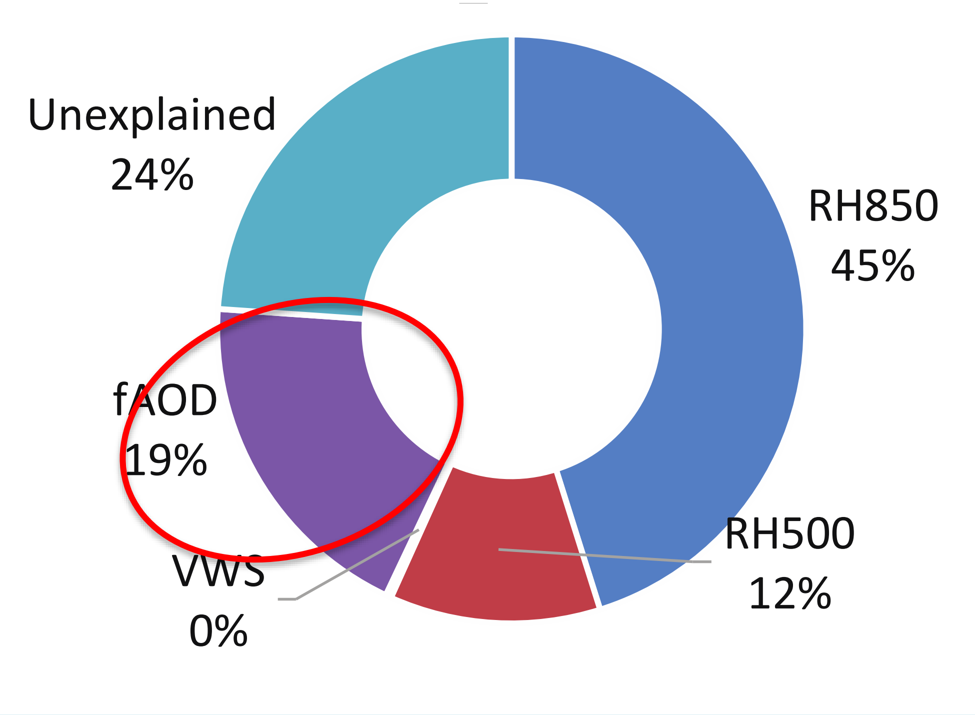


Variation with RH500hPa

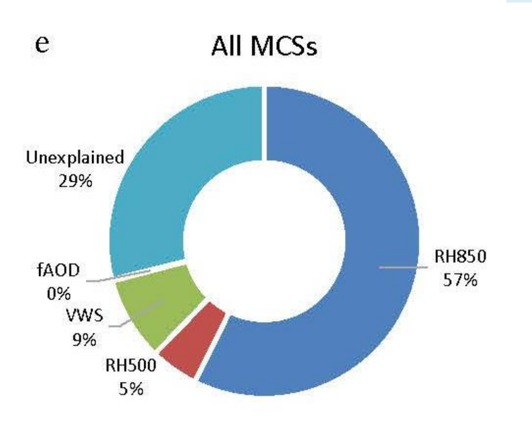
Variation with VWS

- ***AOD explains 15% of the total variances of rainrate through MCCs' lifetime.***
- ***AOD may have stronger influence on the MCCs' rainrate than lifetime.***

Variance of MCCs rainrate explained:



Variance of MCCs lifetime explained:



Summary:

Combined geostationary and polar orbital satellite observations over the global tropical continents suggest that

- ***MCCs lifetime increase with AOD under high RH in the lower troposphere (RH850>60%) and moderate VWS, but it decreases under lower RH.***
- ***Aerosol has significant effect (comparable to VWS) during the decay phase of the MCCs lifecycle, probably by increasing ice water in the anvils and latent heating in the middle and upper troposphere.***
- ***Aerosol appears to have more detectible influence on the rainrate than on lifetime of the MCCs.***
- ***Variations of MCCs lifetime, convective and anvil cloud ice and rainrate are dominated by RH850, and also significantly influenced by VWS, especially during the growing and mature phases.***

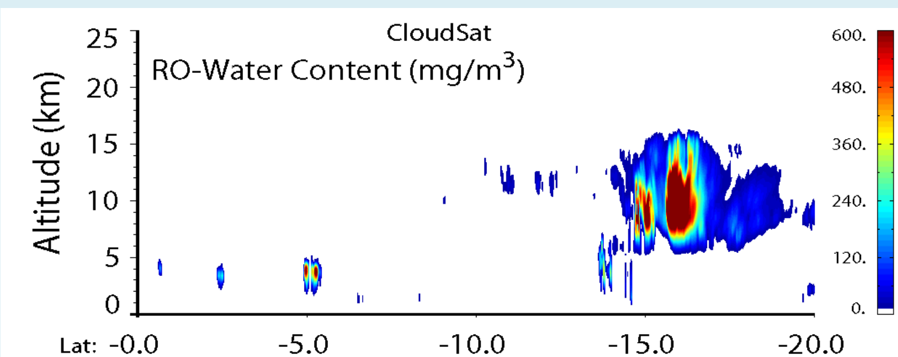
GoAmazon and AMMA ground based data:

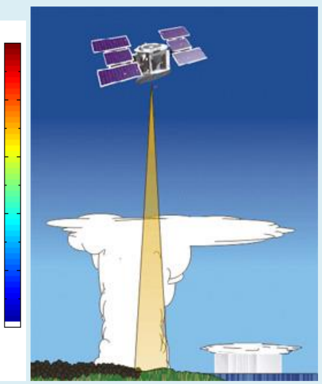
Instrument	
W- Band 95 Ghz Arm Cloud Radar (similar to CloudSat)	Convective cloud ice water content
Radionsonde profiles	RH, VWS, CAPE
Multifilter rotating shadowband radiometer	CCN number concentration

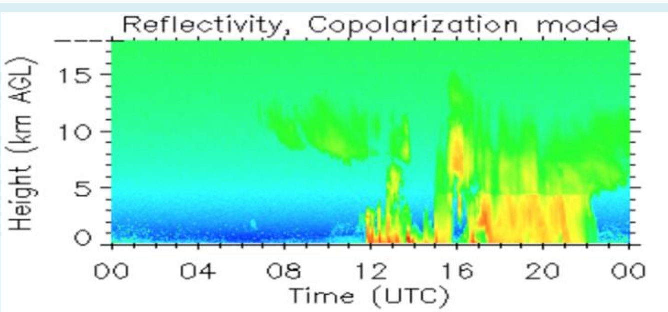
Validation against ground based measurements

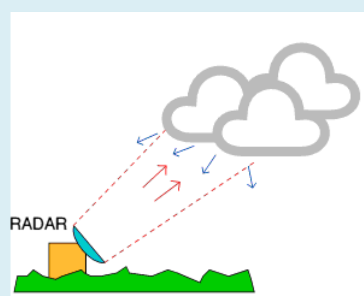
Challenges:

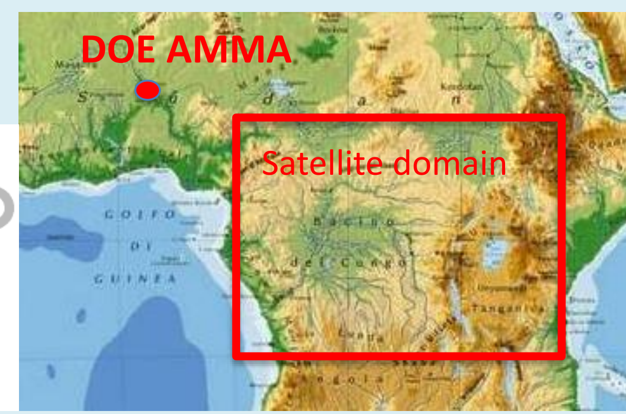
- ***Measure different part of the MCCs (CloudSat is most sensitive to cloud water above 5 km, ground-based cloud radar is most sensitive to cloud water below 5 km***
- ***Different climate regimes and period.***
- ***Different convective types.***









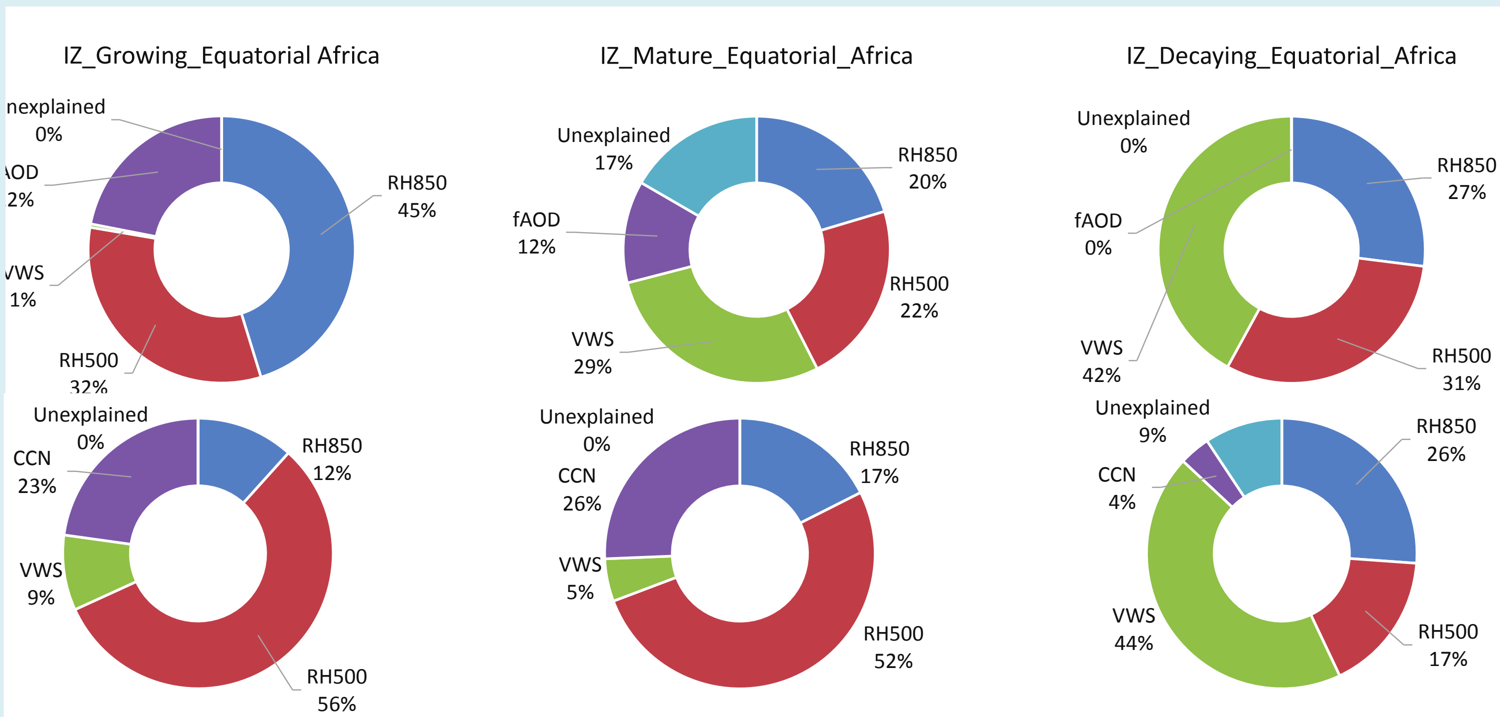


Inferred aerosol influence on MCCs over tropical Africa

- ***Both satellite and ground-based data suggest significant aerosol influence on convective cloud ice during the growing and mature phases,***
- ***Noticeable discrepancies in the relative influences of the meteorological conditions on total cloud ice water content (IZ) between satellite and ground based cloud radar.***

CloudSat W-band Radar IZ Congo

W-band Radar IZ AMMA

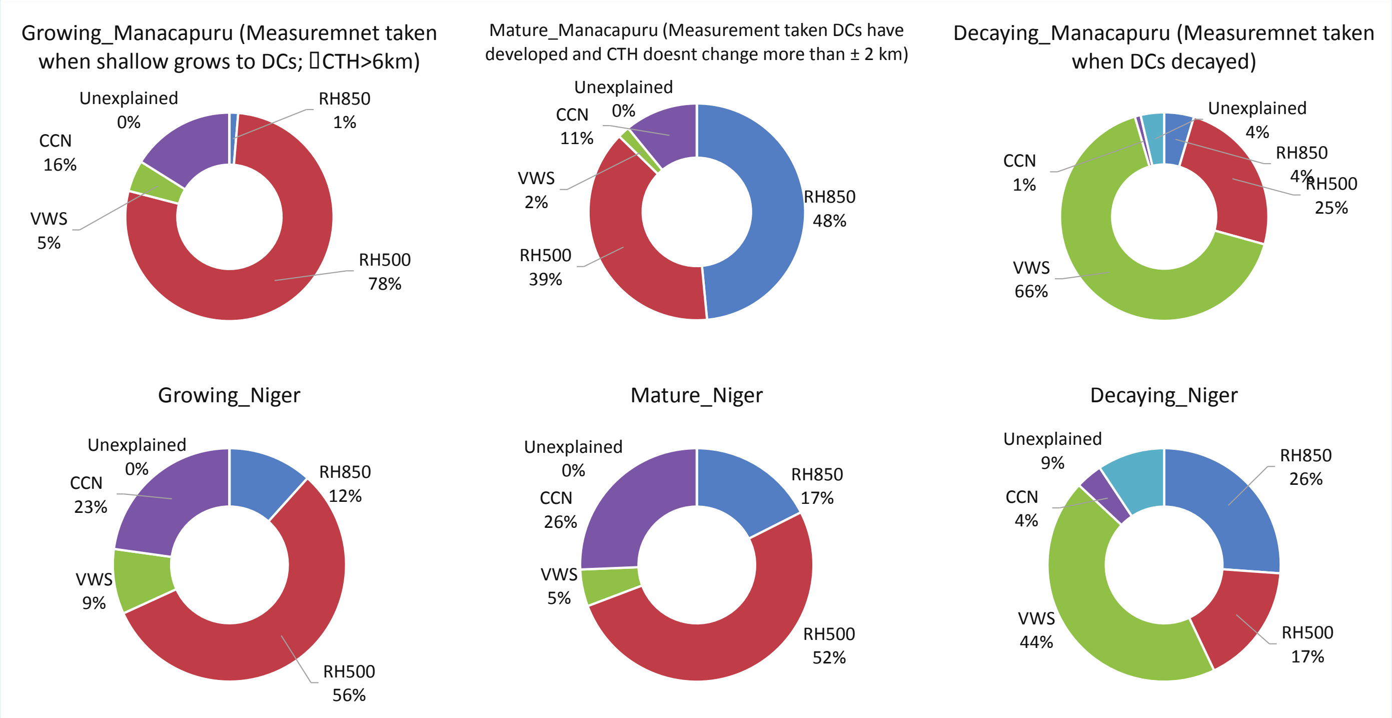


Comparison between GoAmazon and AMMA field Campaign data

- ***GoAmazon cloud radar shows a similar, but somewhat weaker, aerosols influence on convective cloud ice during the growing and mature phases compared to that of AMMA field campaign.***
- ***In both regions, RH500 explains the largest fraction of the cloud ice variance, and the cloud ice is dominated by meteorological conditions, especially VWS during the decay phase.***

W-band Radar IZ GoAmazon

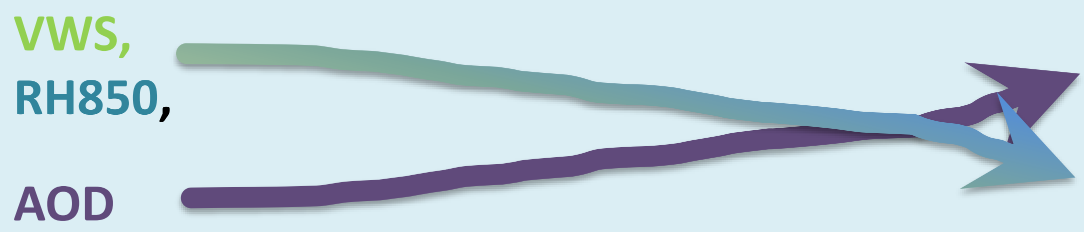
W-band Radar IZ AMMA

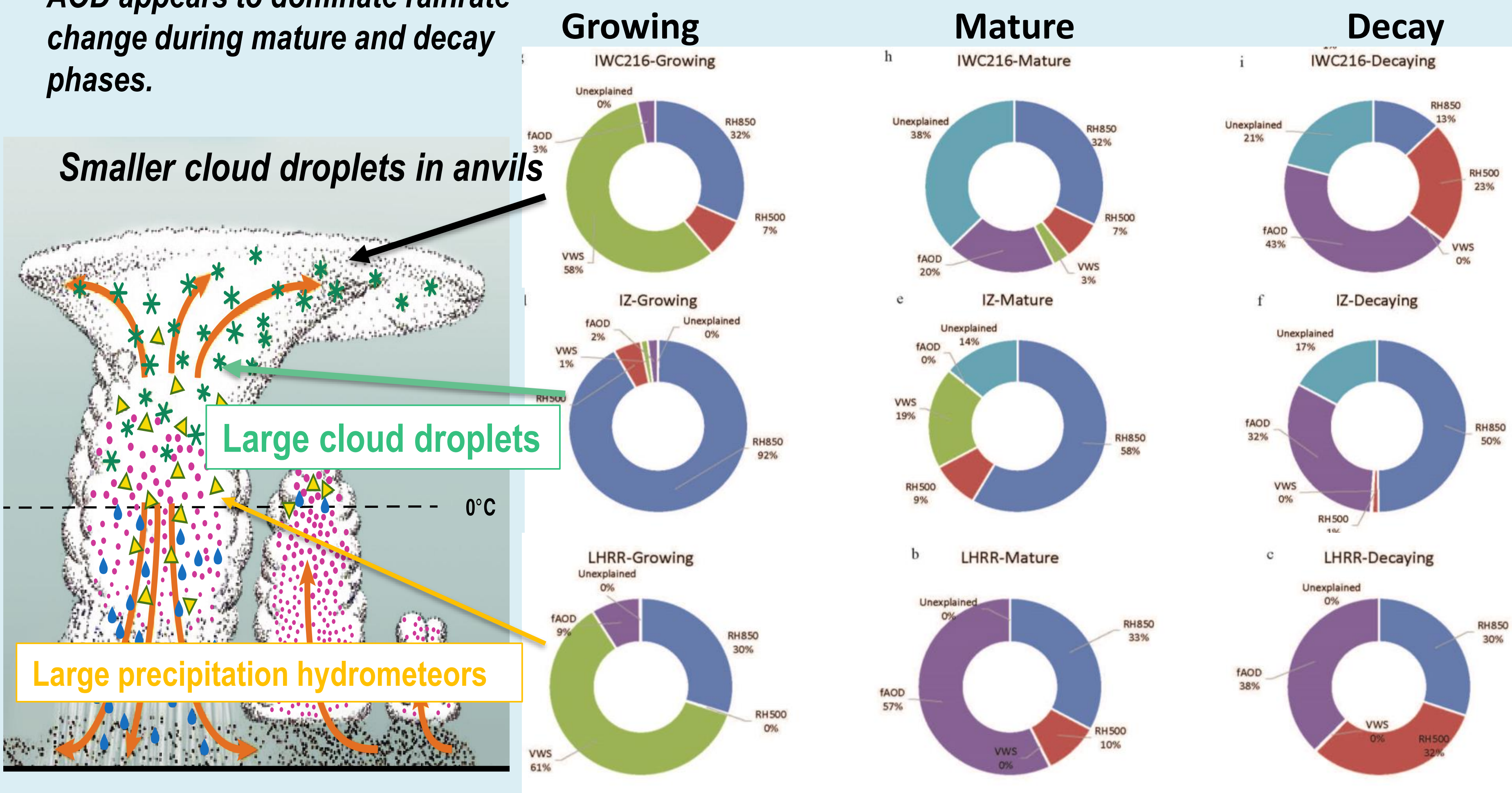


Final Remark:

- Joint use of available geostationary and polar orbital satellite measurements have shown great potential for clarifying the relative influences of aerosol and meteorological conditions on MCCs on global scale, and their regional and temporal variations.
- Available satellite measurements are more appropriate in detecting MCCs morphology variations in the middle and upper troposphere, probably less reliable for detecting aerosol influence in the lower troposphere within clouds.
- Ground based observations tend to be more sensitive to changes in the lower troposphere and representing mainly temporal variations. Optimal interpretation of these complement observations is needed to further clarify the influences of aerosol and meteorological conditions on MCCs.

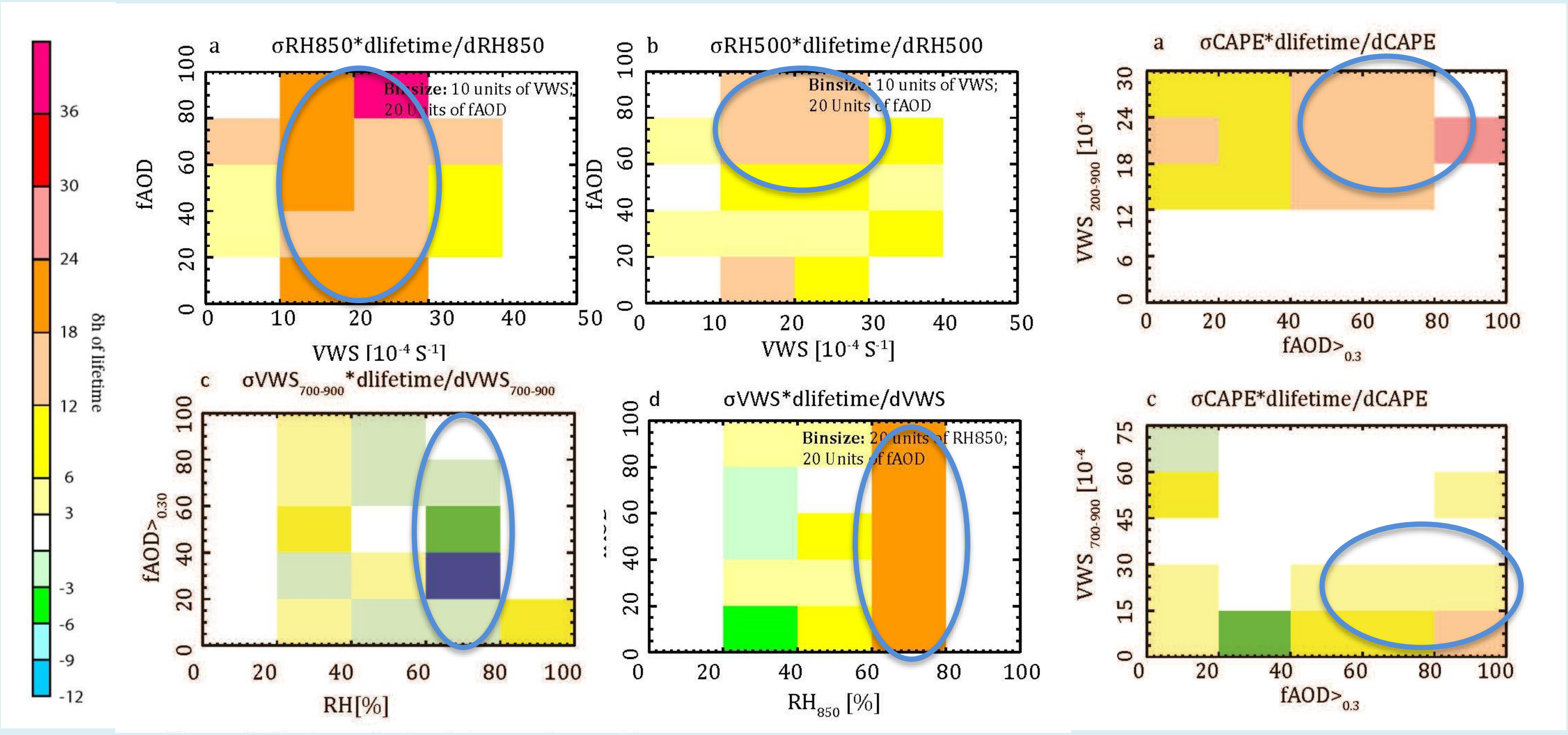
- *Aerosol effect on convective anvil, ice cloud water during mature and decay phases are generally consistent with model results (e.g., Rosenfeld et al. 2008; Fan et al. 2013);*
- *AOD appears to dominate rainrate change during mature and decay phases.*



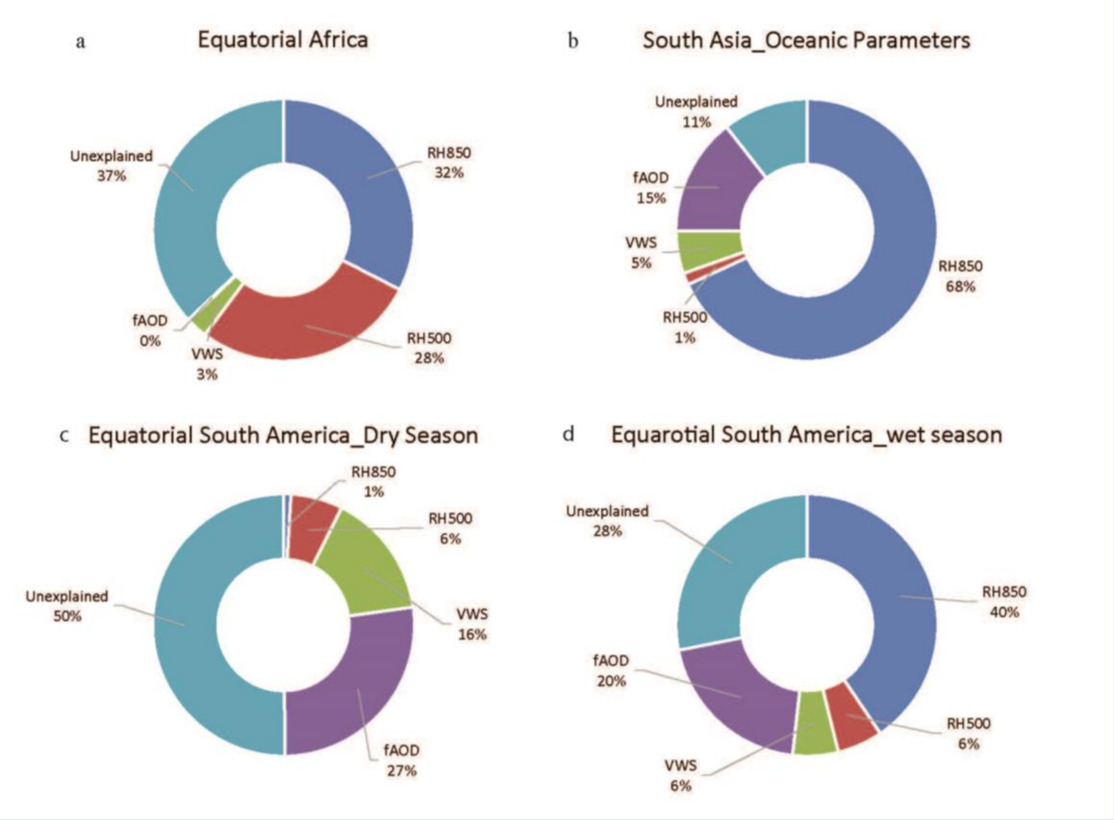


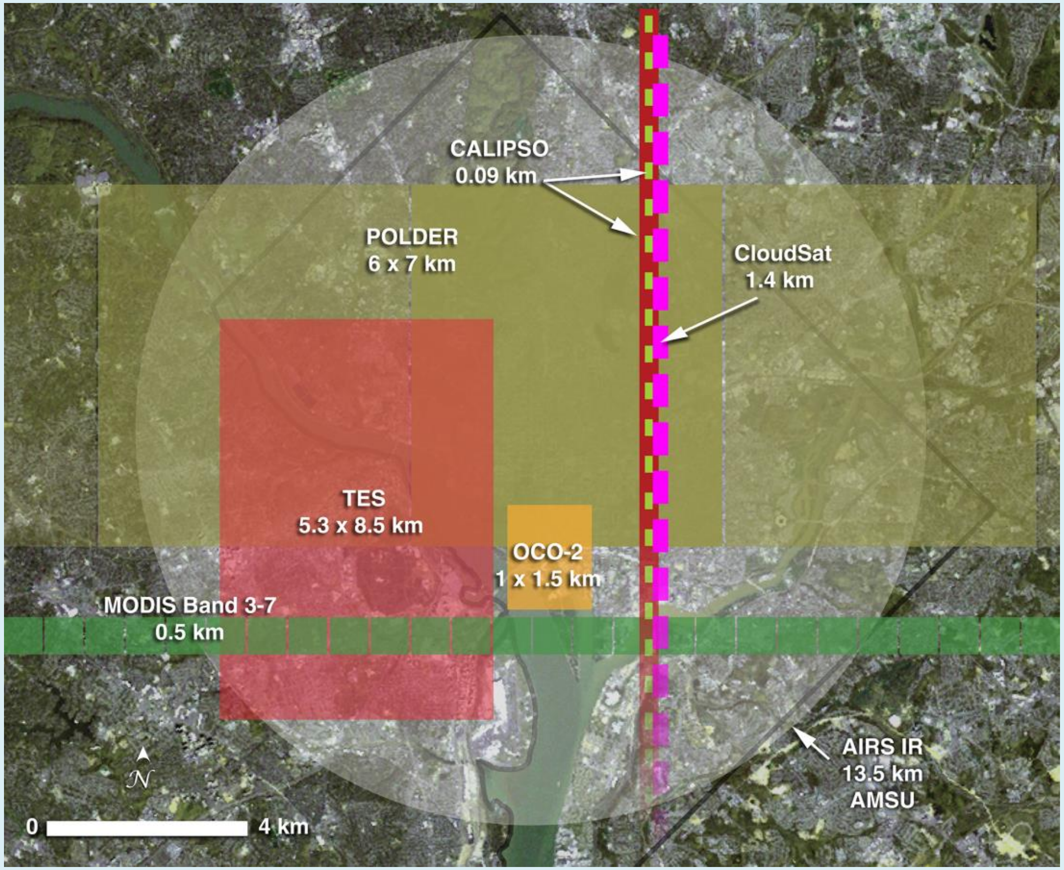
Variation of MCCs Lifetime with meteorological condition:

- ***MCCs' lifetime increases the most with RH850 under low VWS (<20X10^{-4} S^{-1}). It also increases with VWS under high RH850 (>40%), increase with RH500 under high AOD and moderate VWS.***



Regional Variation




CALIPSO
0.09 km
POLDER
6 x 7 km
CloudSat
1.4 km
TES
5.3 x 8.5 km
OCO-2
1 x 1.5 km
MODIS Band 3-7
0.5 km
AIRS IR
13.5 km
AMSU
N
0
4 km

GoAmazon data from the Manacapuru site:

Filename	Parameters	Instruments
Maowacrm1	IZ, DZ (convective cloud ice, drizzle size rainfall	W- Band 95 Ghz Arm Cloud Radar (similar to CloudSat)
Maomwrlosm1	LWC (liquid water content)	Microwave water radiometer
Maoaosmets1	Rainrate	Meteorological measurements associated with AOS observations
maomplpolfsM1/Mao 30smpl	Cloud top height	MPL
maosonde	Vertical wind share	Balloon Sounder
maoaosneph	Aerosols	Multifilter Rotating Shadowband Radiometer
maosodar	Vertical velocity	SODAR (Mini SOund Detector And Ranging)
maoceilpblhtM1	ABL	Ceileometer
maosonde	RH	Balloon Sounder

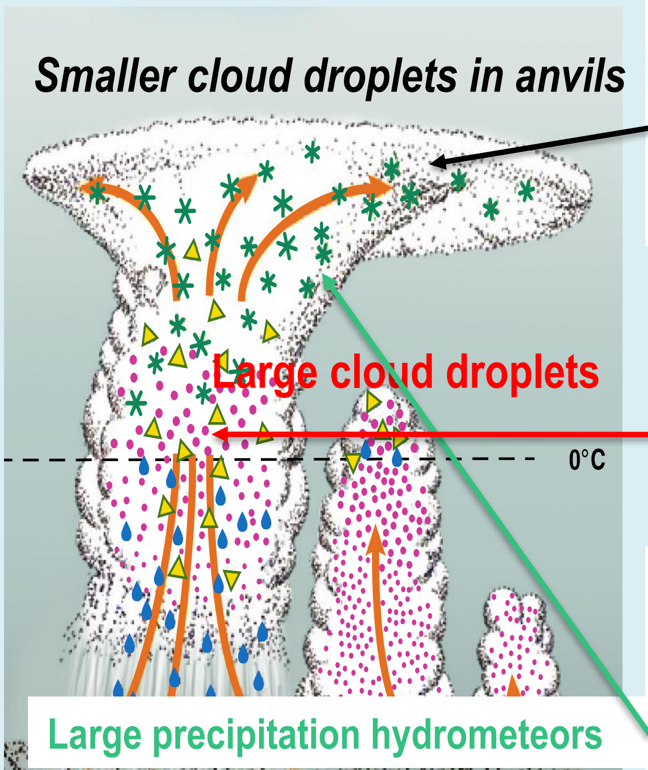
A main source of uncertainty:

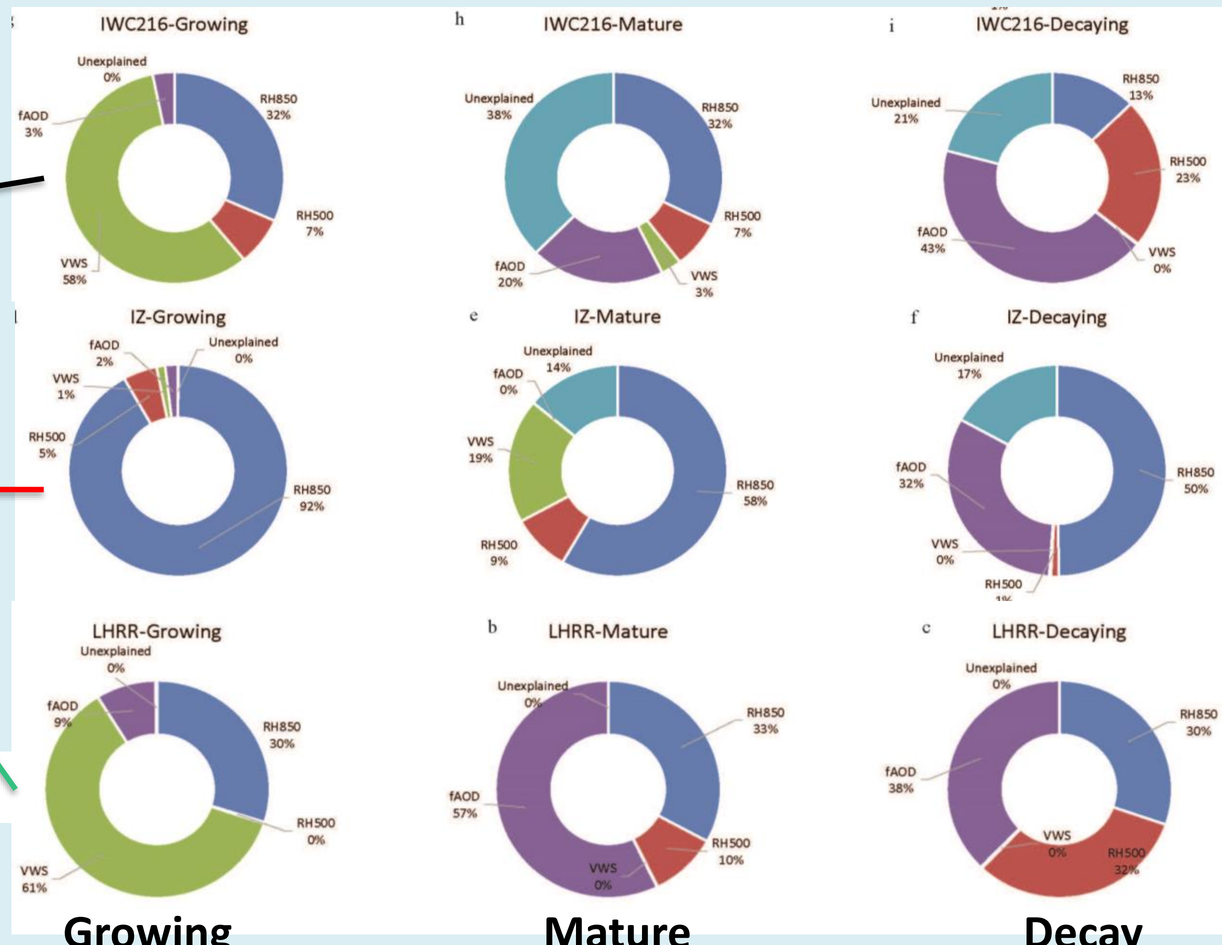
- ***Lack of direct observation of aerosol impact on cloud lifetime on large scale.***
- ***Influence of aerosol varies with meteorological and aerosol conditions, and convective types. Thus, the aerosol influences on convection at regional to large spatial and climate scales is unclear (e.g., Tao et al, 2012, Altarze et al. 2014; Rosenfeld et al. 2014).***
  - ***Tao et al. 2012: ??***
  - ***Altarze et al. 2014: Aerosol appears to have stronger influence on strong convection with less diluted cores.***
  - ***Rosenfeld et al. 2014: aerosol influence on clouds varies with meteorological condition, thus it is less clear (smoothed out) on large scale.***

- We have averaged all data (Jan2014 to Feb2015) into hourly resolution.
  - Afternoon (12noon -1pm) and evening (4-5 pm)
- We have calculated IZ if the cloud height is more than 6 km.
  - Growing clouds: CTH increases more than 6 km from afternoon to evening
  - Demising clouds: CTH decreases more than 4 km from afternoon-evening
  - Steady-state clouds: CTH changes between -4 to 6 km from afternon to evening
- For this analysis, we have used
  - Mean IZ of the day if cloud is more then 6 km high.
  - 4-5 pm Omega, BL Height, AOD.
  - 7 pm radiosonde RH (700, 500, 300 hPa) and wind data for VWS.
- VWS = $meanU_{925\text{-}850} - meanU_{250\text{-}200} / meanZ_{925\text{-}850} - meanZ_{250\text{-}200}$

Inferred influence on cloud microphysical process through MCCs' life cycle:

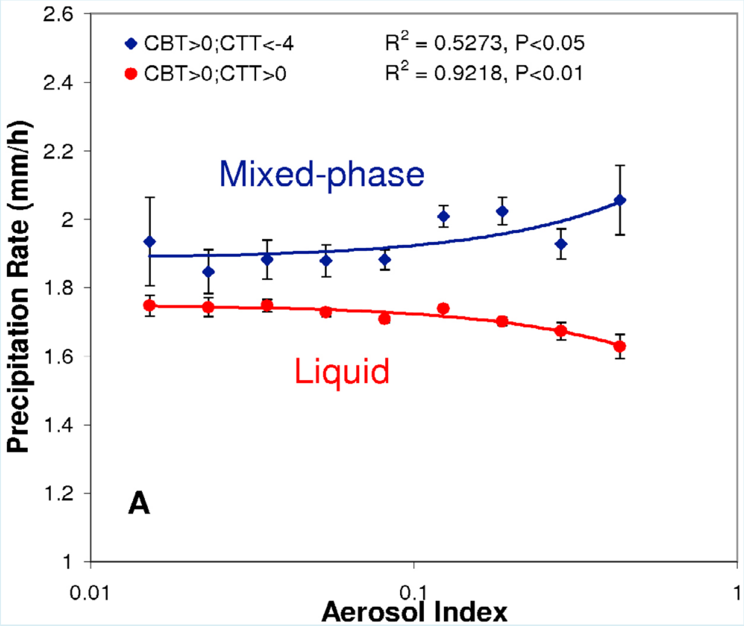
- ***Growing phase:** VWS dominate the variances of anvil cloud ice amount and rainrate; RH850 dominates convective cloud ice. Aerosol does not have detectible infuence by satellites;*
- ***Mature phase:** RH850 dominates cloud ice, aerosol dominates rainrate;*
- ***Decay phase:** aerosol dominates anvil cloud ice and rainrate, has significant influence on convective ice cloud droplets, has overall comparable infuence to those of RH850 and RH500.*





Key uncertainties in determining aerosols influence on cloud and precipitation on climate scale:

- **Aerosol effect on convection depends on large scale meteorological conditions, e.g., CAPE, RH, wind shear (e.g, Williams et al. 2003; Tao et al 2011, Stevens and Feingold 2009).**
- **No direct observational evidence on the Influence of aerosols on cloud life cycle on climate scale (e.g., Stevens and Feingold 2009).**



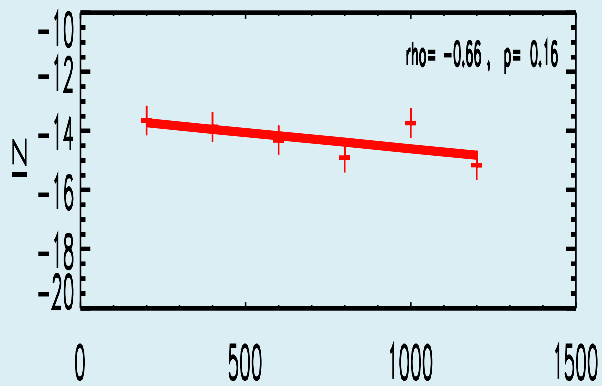
Niu and Li 2011, Source: Tao et al. 2011

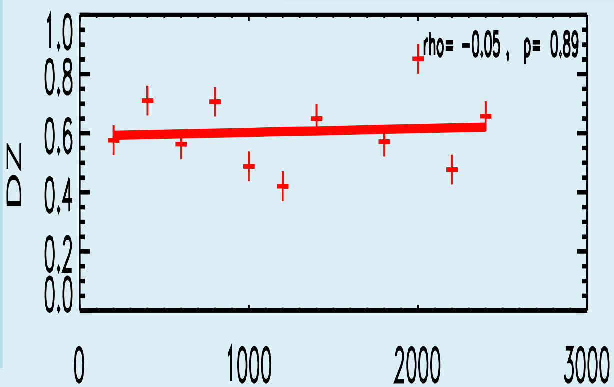
"The absence of observations of cloud life cycles that show aerosol influence cloud life cycle and precipitation underscores how loosely the term 'lifetime' has come to be applied."

- Stevens and Feingold 2009

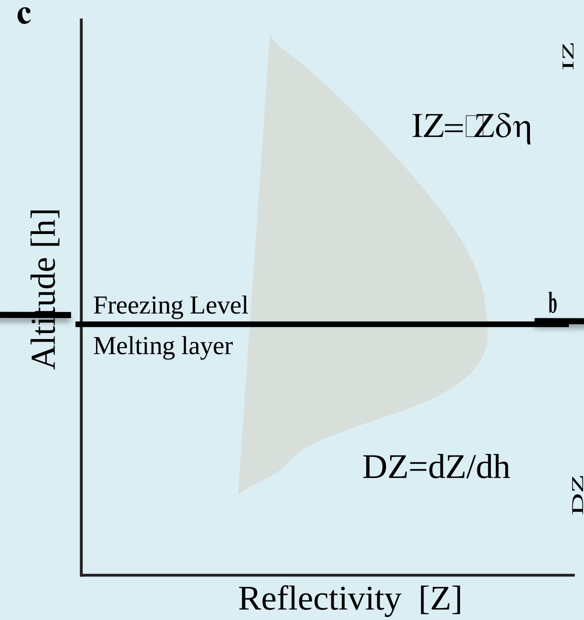
• Changes of cloud ice and liquid water with aerosols vary with convective life cycle.

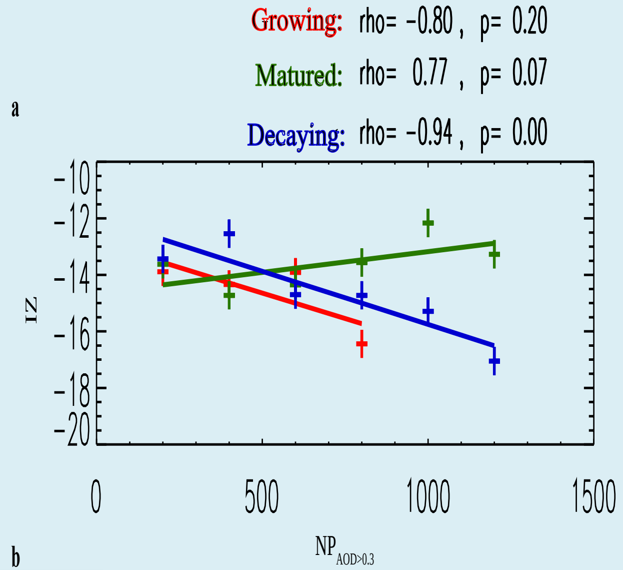
Pixel numbers with AOD>0.3 (MODIS)

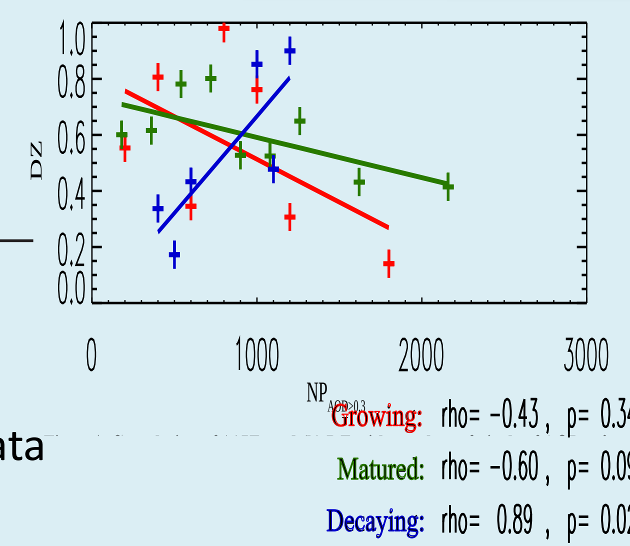




CloudSat reflectivity:







Pixel numbers with AOD>0.3 (MODIS)

Use ISCCP cloud tracking data (Machado et al. 1998)..

Changes of the MCCs lifetime with AOD, RH and vertical wind shear at global tropical continental scale

- ***MCCs' lifetime increases with AOD under high RH850 (>60%) and moderate VWS (5-25 10^{-4} S^{-1}) at the rate of 3-12 hrs/1σ increase of the AOD values, but decreases with AOD under lower RH850.***
- ***MCCs' lifetime increases the most with RH850 under low VWS (<20X10^{-4} S^{-1}) at the rate of 12-24 hrs/1σ of RH increase, increase with VWS under high RH850 (>40%) at the rate of 3-24 hrs/1σ of VWS, increase with RH500 under high AOD and moderate VWS at the rate of 6-18 hrs/1σ variation of RH500.***
- ***Overall, RH850 explains about 57% of total variance of the MCCs lifetime, VWS explains about 9%, and AOD explains ~0%.***