Could wildfires amplify drought and heatwave through the coupling between aerosols, clouds, precipitation?

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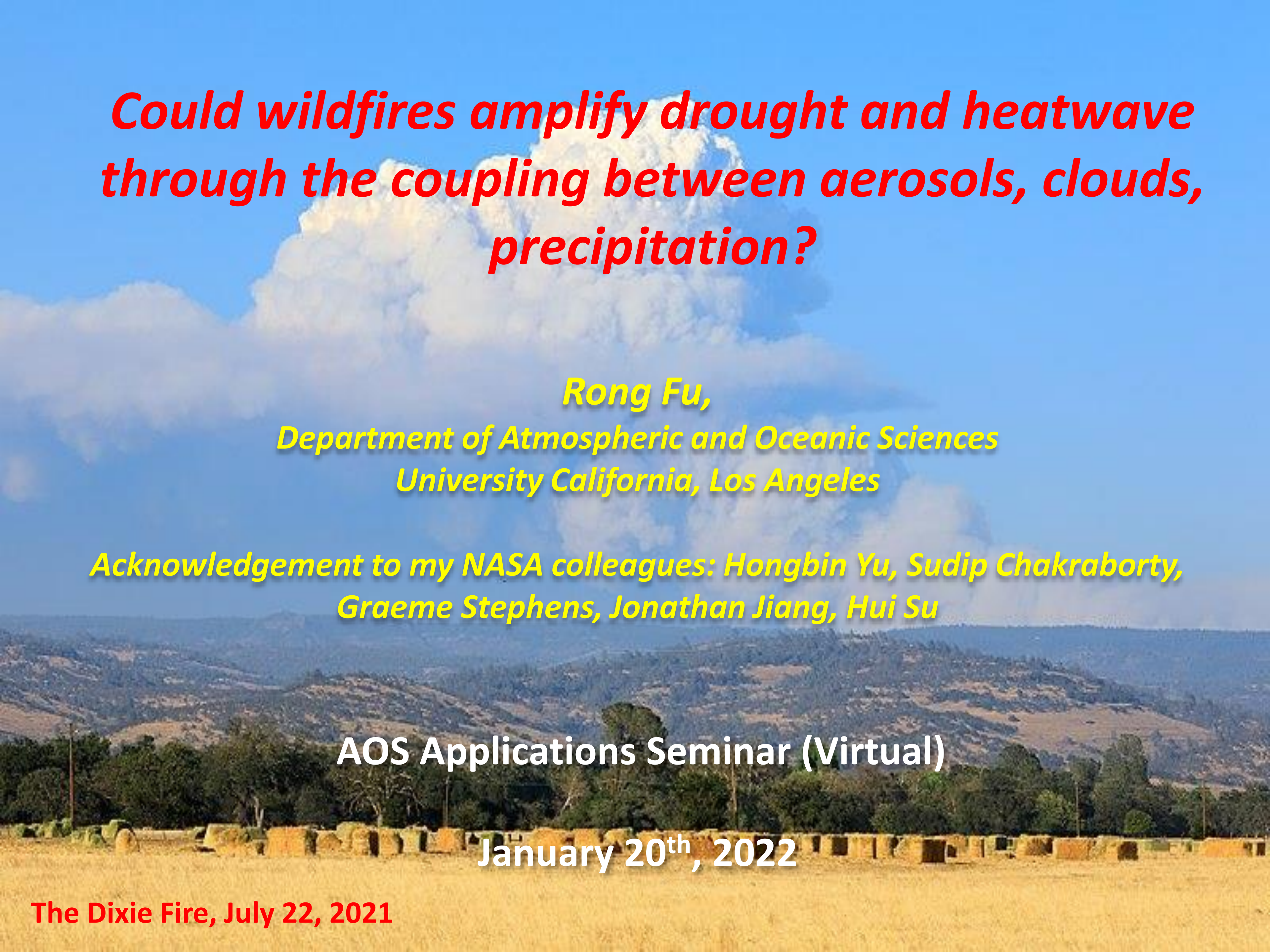
Acknowledgement to my NASA colleagues: Hongbin Yu, Sudip Chakraborty, Graeme Stephens, Jonathan Jiang, Hui Su

AOS Applications Seminar (Virtual)

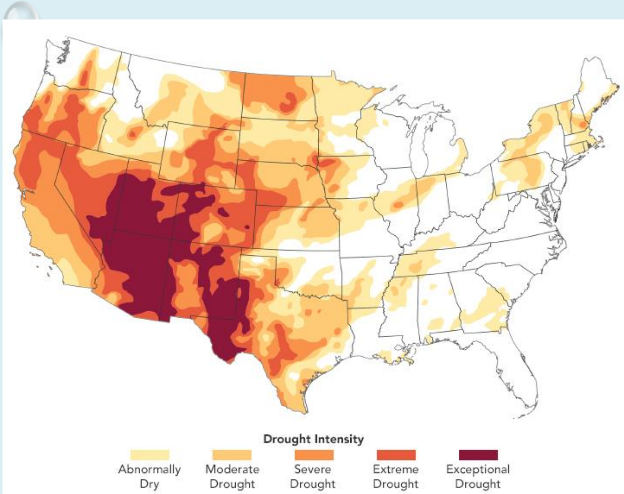
January 20th, 2022

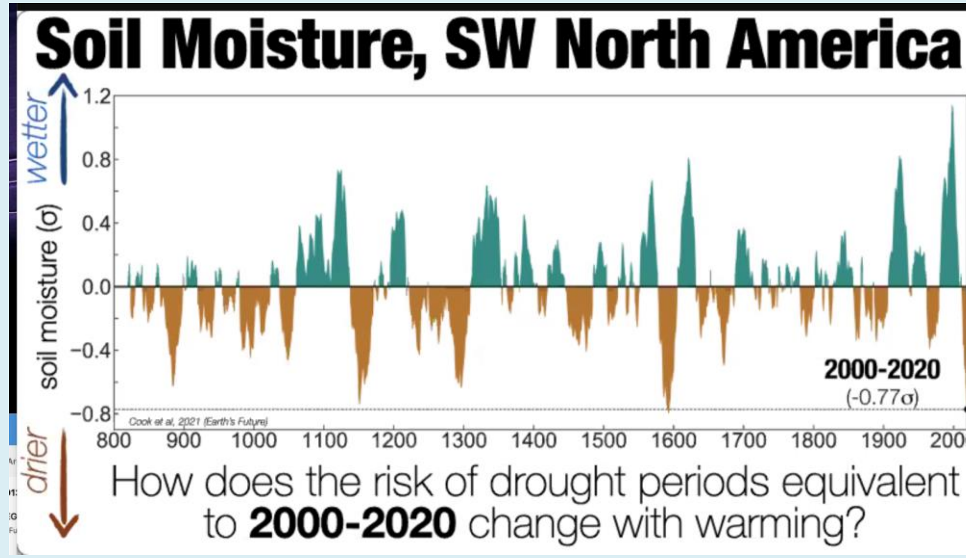


The Dixie Fire, July 22, 2021

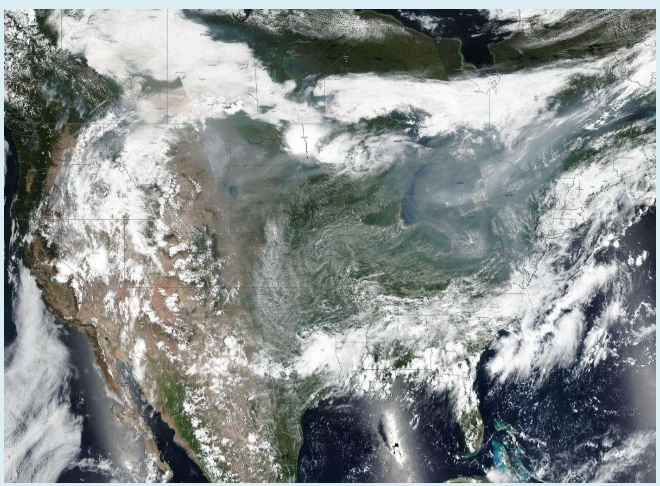
Rapid increases of wildfires and droughts and their impacts over Western US

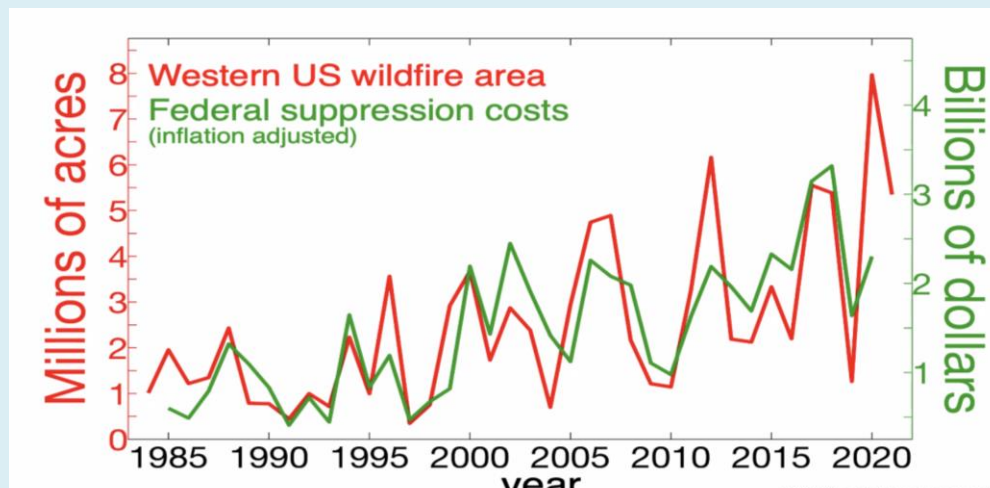
US Drought Monitor, Dec 8th, 2020



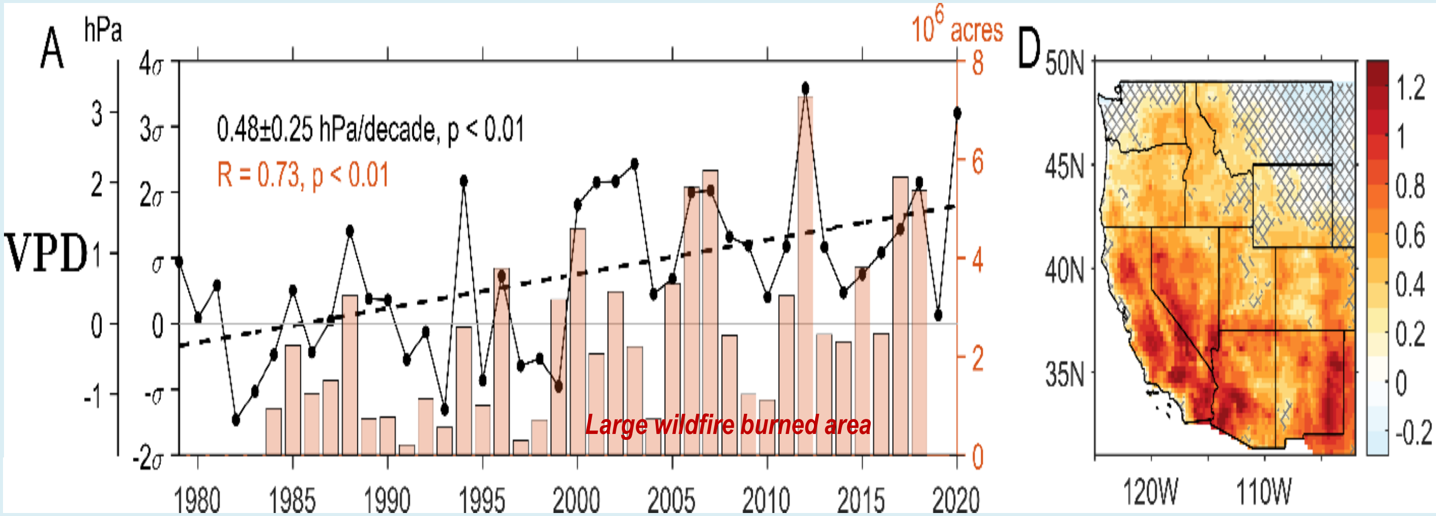


Smoke generated by wildfires, July 20, 2021



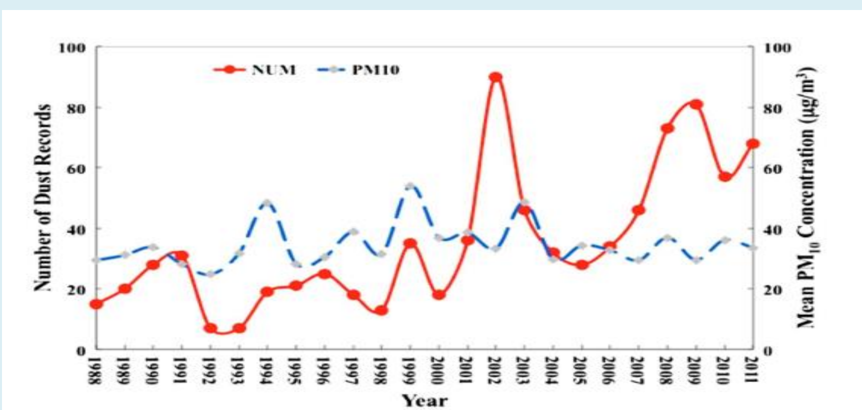


- ***Increase wildfire and dust due to climate change and agriculture expansion over western US.***



Zhuang et al. 2021, PNAS

Dust storms over Western US, 1988-2011, IMPROVE network



Tong et al. 2017, GRL

MODIS AOD_{dust} 2000-2018

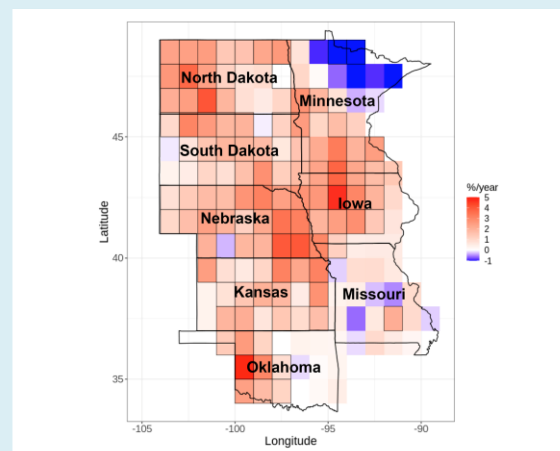
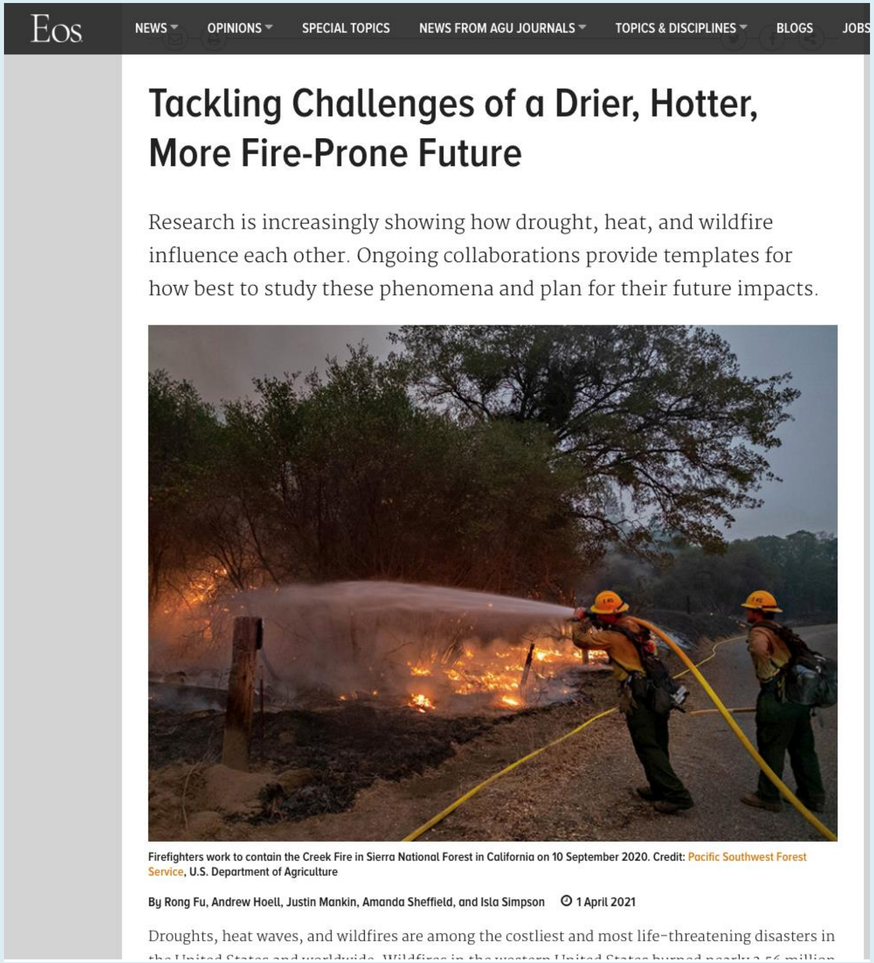


Figure 1. Trends in all MODIS AOD_{dust} observations at 550 nm for 2000–2018 in the U.S. Great Plains. Percent change is based on the median AOD_{dust} for each tile. Outlined tiles indicate statistical significance ($p < 0.05$).

Lambert et al. 2020, GRL

Could aerosol – drought interaction further amplify droughts, wildfires and dust?



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Tackling Challenges of a Drier, Hotter, More Fire-Prone Future

Research is increasingly showing how drought, heat, and wildfire influence each other. Ongoing collaborations provide templates for how best to study these phenomena and plan for their future impacts.

Firefighters work to contain the Creek Fire in Sierra National Forest in California on 10 September 2020. Credit: Pacific Southwest Forest Service, U.S. Department of Agriculture

By Rong Fu, Andrew Hoell, Justin Mankin, Amanda Sheffield, and Isla Simpson 1 April 2021

Droughts, heat waves, and wildfires are among the costliest and most life-threatening disasters in

Fu et al. 2021, EOS, NOAA Drought Task Force, Phase 4

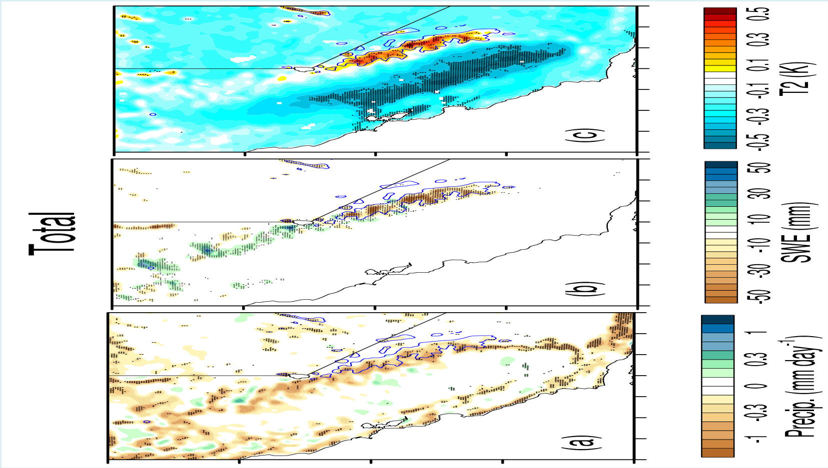
Aerosol impacts on surface weather condition and water resources over western US is not clearly understood

Invigorate clouds and rainfall:

- ***Clavner et al. 2018, Logan et al. 2018: Aerosol enhance MCSs and lightning over US Great Plains.***
- ***Saide et al. 2015: Biomass burning aerosol enhances tornado severity in US.***
- ***Li et al. 2012: invigorate mixed phase clouds with warm and low cloud base, but not clouds with liquid-only droplets or cold/high cloud bases.***

Suppress rainfall:

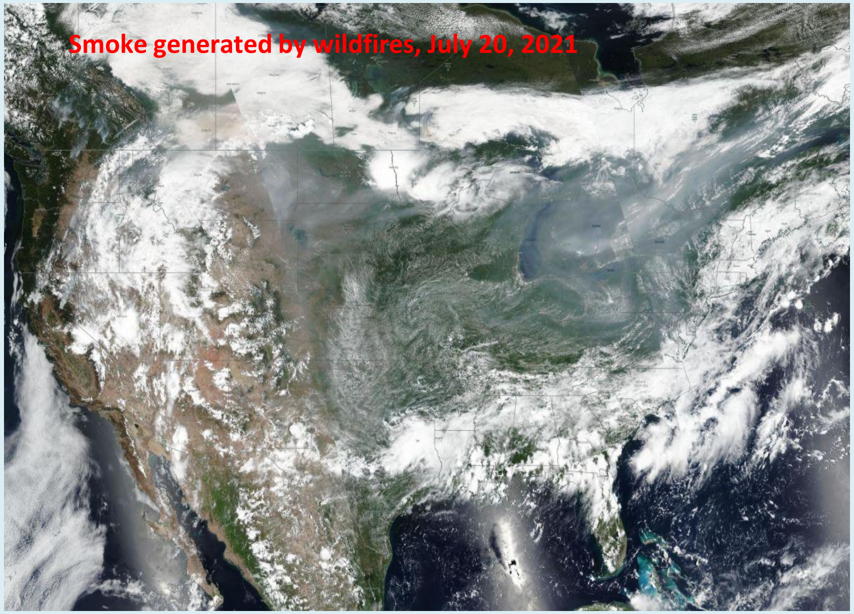
Black carbon influence on water resources



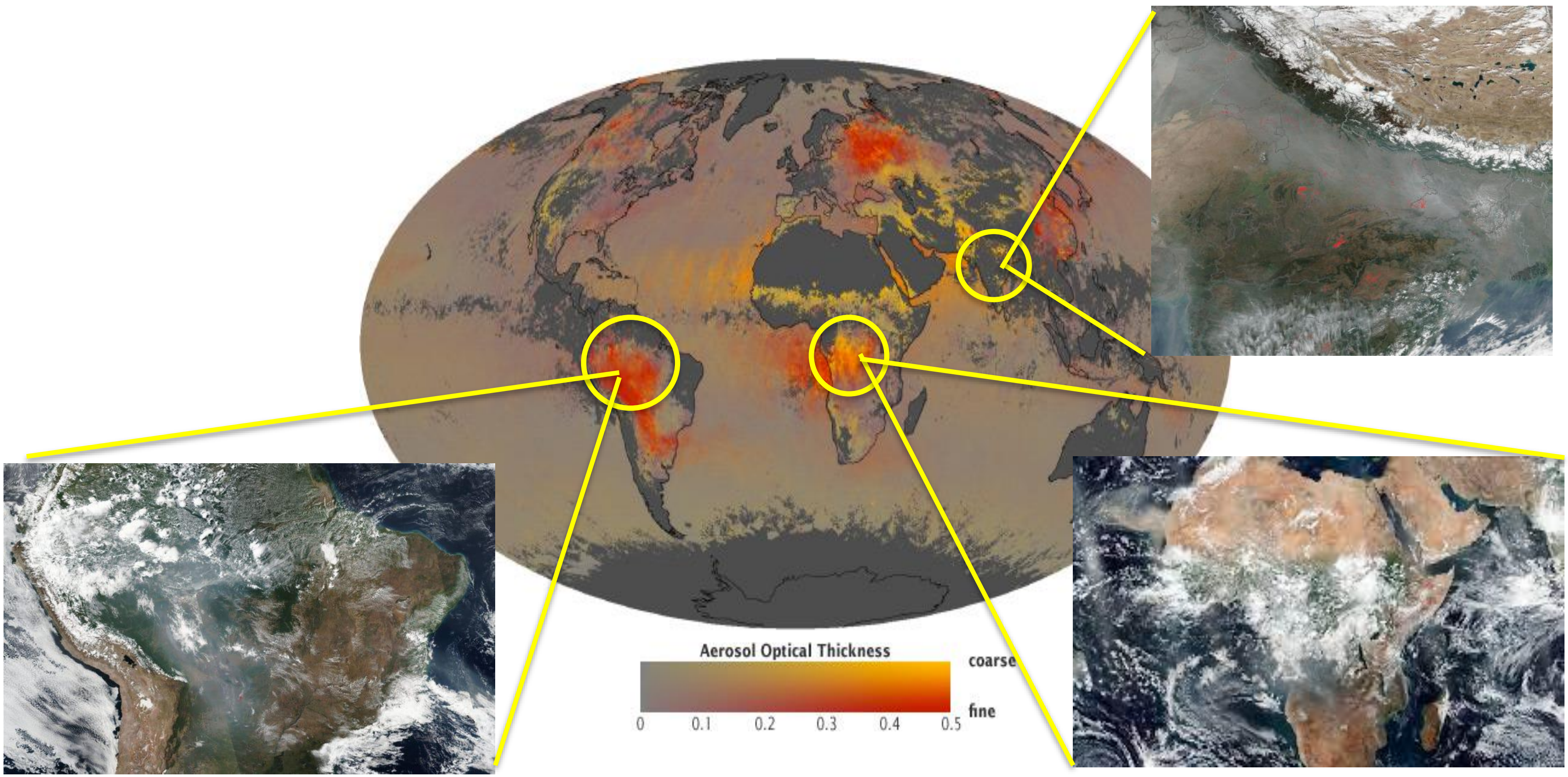
Wu et al. 2018, ACP

Outstanding Science questions:

- ***Do biomass burning and dust aerosols increase or decrease of clouds and rainfall over semi-arid regions such as western US?***
- ***How does convection affect distribution of aerosols?***
- ***How can ACCP clarify these societally important outstanding science questions?***



What can we learn from extensive research of aerosol impacts on cloud, precipitation over tropical continents?



e.g., Andreae et al. 1988, ABLE 2A

(NASA map by Robert Simmon, based on MODIS data from NASA Earth Observations.)

Hypotheses:

- ***Hypothesis-1: Aerosols can weaken mesoscale convective systems (MCSs) under low humidity and weak CAPE and vertical wind shear, potentially intensify droughts/aridification.***

- ***Hypothesis-2: MCSs detrainment can significantly increase aerosols in the upper troposphere during the growing and mature phases, likely due to greater number and height of the convective cores in MCSs. This effect could broaden the spatial impacts of wildfires and dusts, possible further suppress rainfall.***

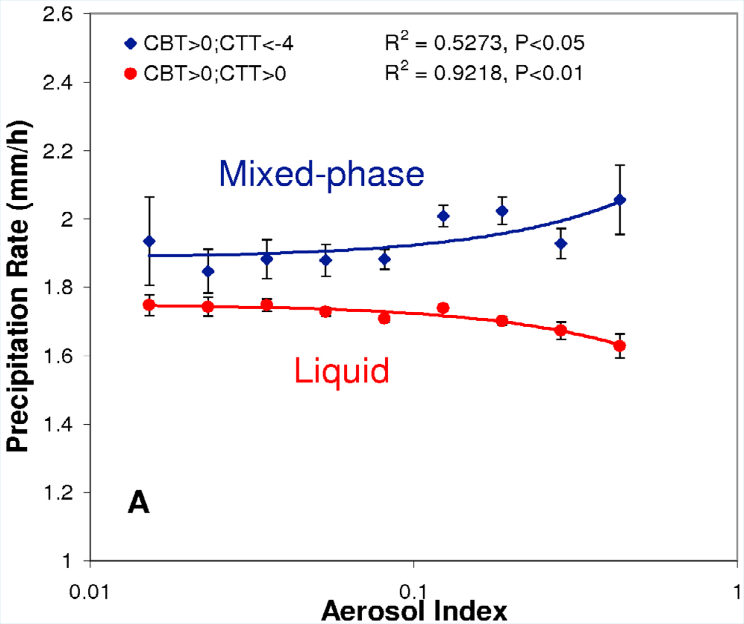
Aerosols influence on cloud and rainfall:

- ***Albrecht 1989: By suppressing precipitation, aerosols might increase cloud lifetime and thus enhance radiative forcing***

- ***Rosenfeld et al. 2008: Through delaying precipitation during growing and mature stage, aerosols intensify precipitation, enhance ice water content during decaying state and increase convective lifetime.***

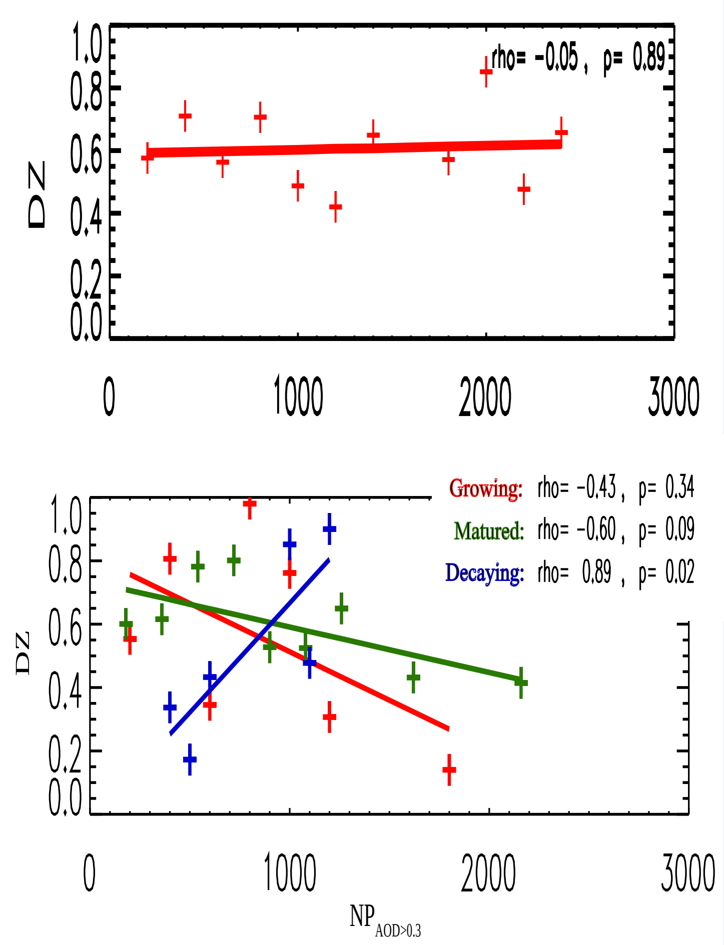
Influence of aerosols on rainfall varies within convective life cycle

Tao et al. (2011): Lack of robust variation of rainrate with aerosols



Variation of precipitation rate with aerosol index over the tropical oceans from CloudSat and MODIS satellite products for warm liquid clouds (Adapted from Niu and Li [2011]).

Chakraborty, unpublished analysis



CloudSat liquid cloud radar reflectivity

Challenges:

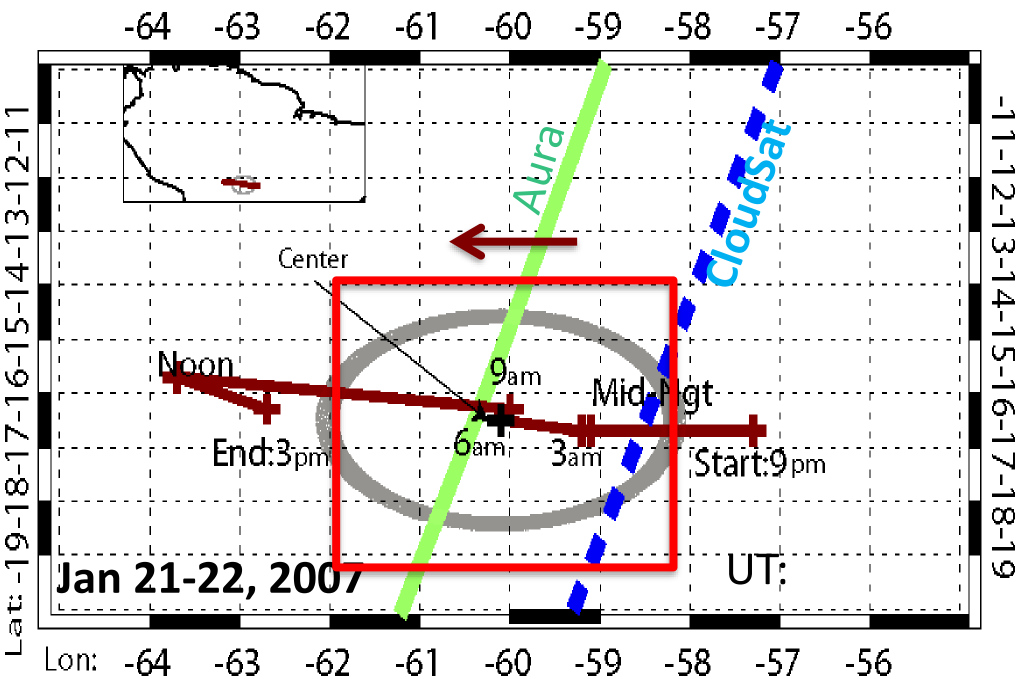
- ***Lack of direct observational evidence showing that aerosols influence cloud lifecycle and lifetime on large scale.***

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

  - Stevens and Feingold 2009

- ***Influence of aerosol varies with meteorological and aerosol conditions, and convective types, and are likely non-linear. 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).***

Linking A-Train satellite measurements to the life cycle of mesoscale convective systems (MCSs):

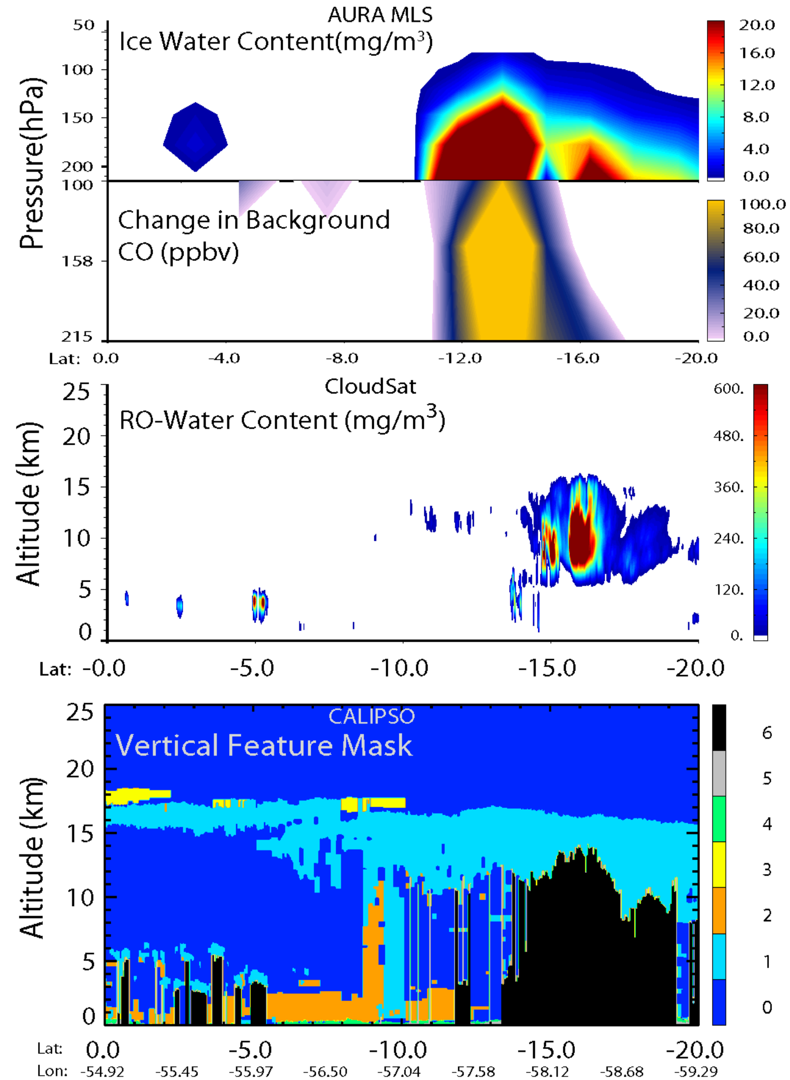


Gray Cirle is the Cloud Position at Closest Time Match with All the Satellites. Center during collocation is Black plus Sign.

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

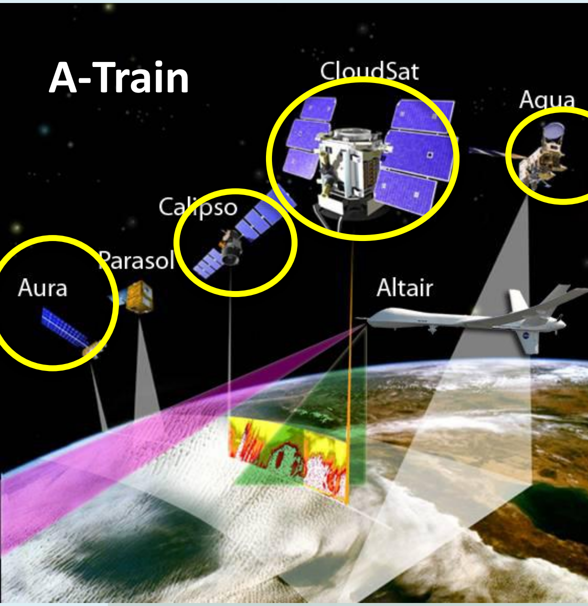
Inset: Location of the Same Convection over S.America

Collocation of a Convection on 01212007 at 6 am Using A-Train and ISCCP GOW Satellites.

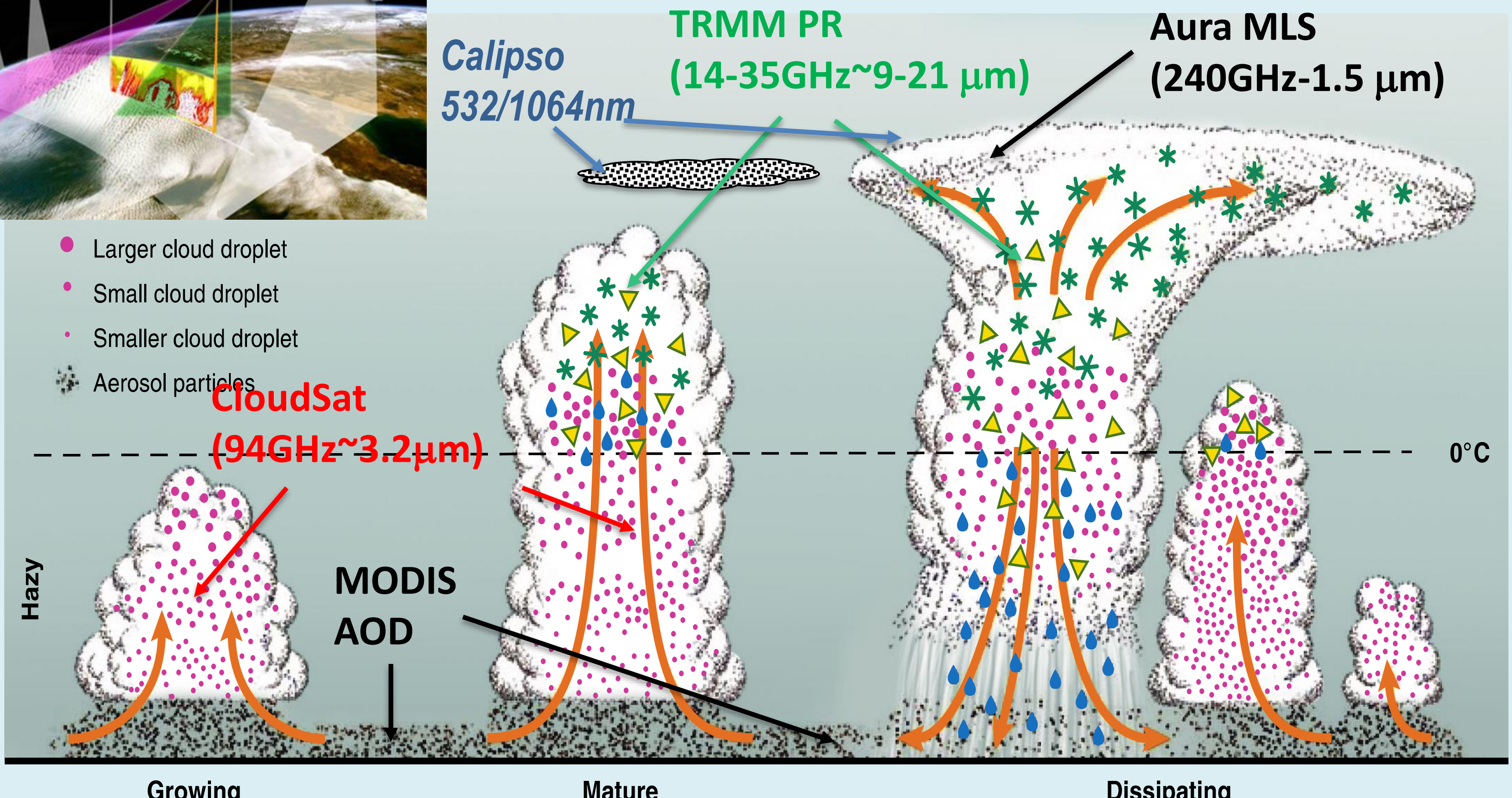


DCBAR:0= Clear air,1 = Cloud,2 = Aerosol,3 = Stratospheric feature (either cloud or aerosol), 4 = Surface,5 = Subsurface,6 = No signal (totally attenuated)

-64 -63 -62 -61 -60 -59 -58 -57 -56



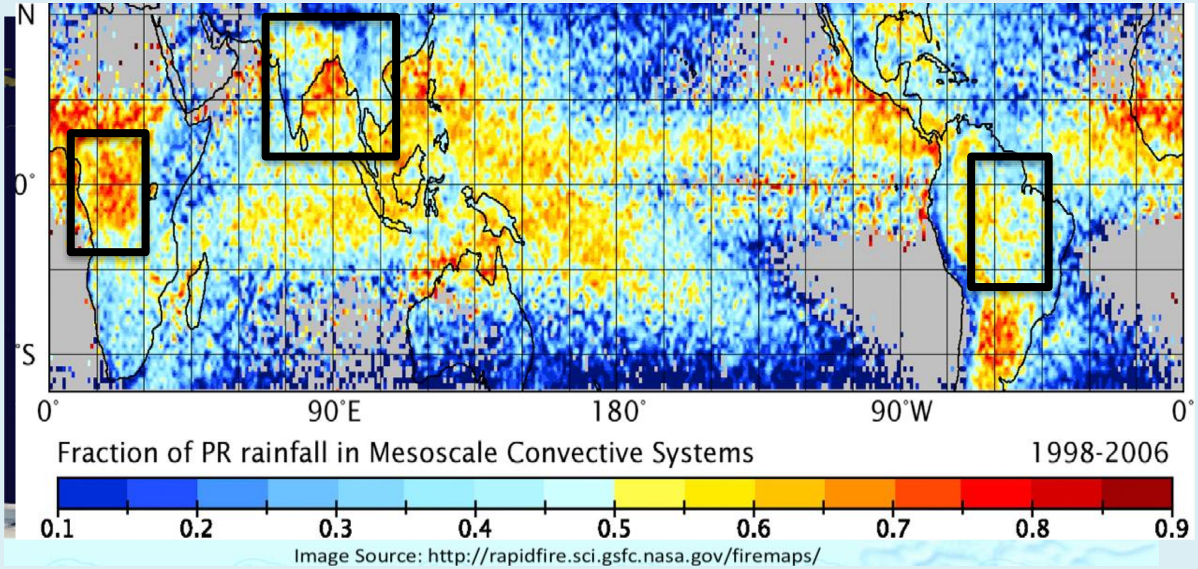
Using multi-satellite sensors to detect changes of convective and anvil cloud droplets, precipitation-sized hydrometeors through convective life cycle.



ISCCP Convective Cluster Tracking Data, MERRA, ERA-I

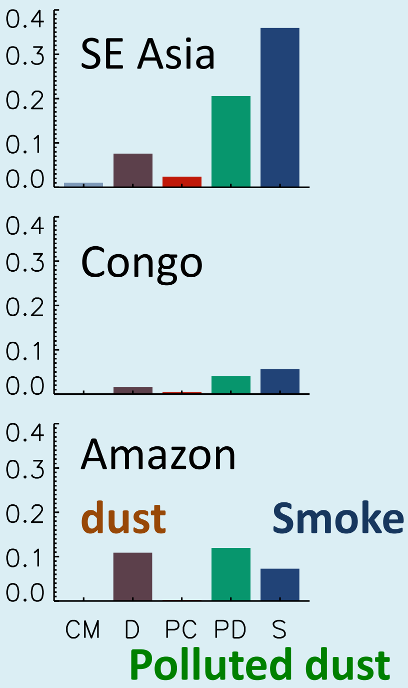
Domains and periods of our analysis:

- South America: 5N-15S, 40-80W, all seasons, June 2006-May 2008
- Congo: 10N-10S, 10W-40E, all seasons, June 2006-May 2008,
- SE Asia: 0-40N, 70-100E, for the periods of June - August, 2006, 2007, June 2008
- 966 cases mesoscale convective systems with life-time > 6 hours & diameter > 100Km were co-located with A-train measurements, 355 cases in growing phase, 401 in mature phase and 210 during decay phase.



Chakraborty et al. 2015, 2016, 2018

Aerosols types:



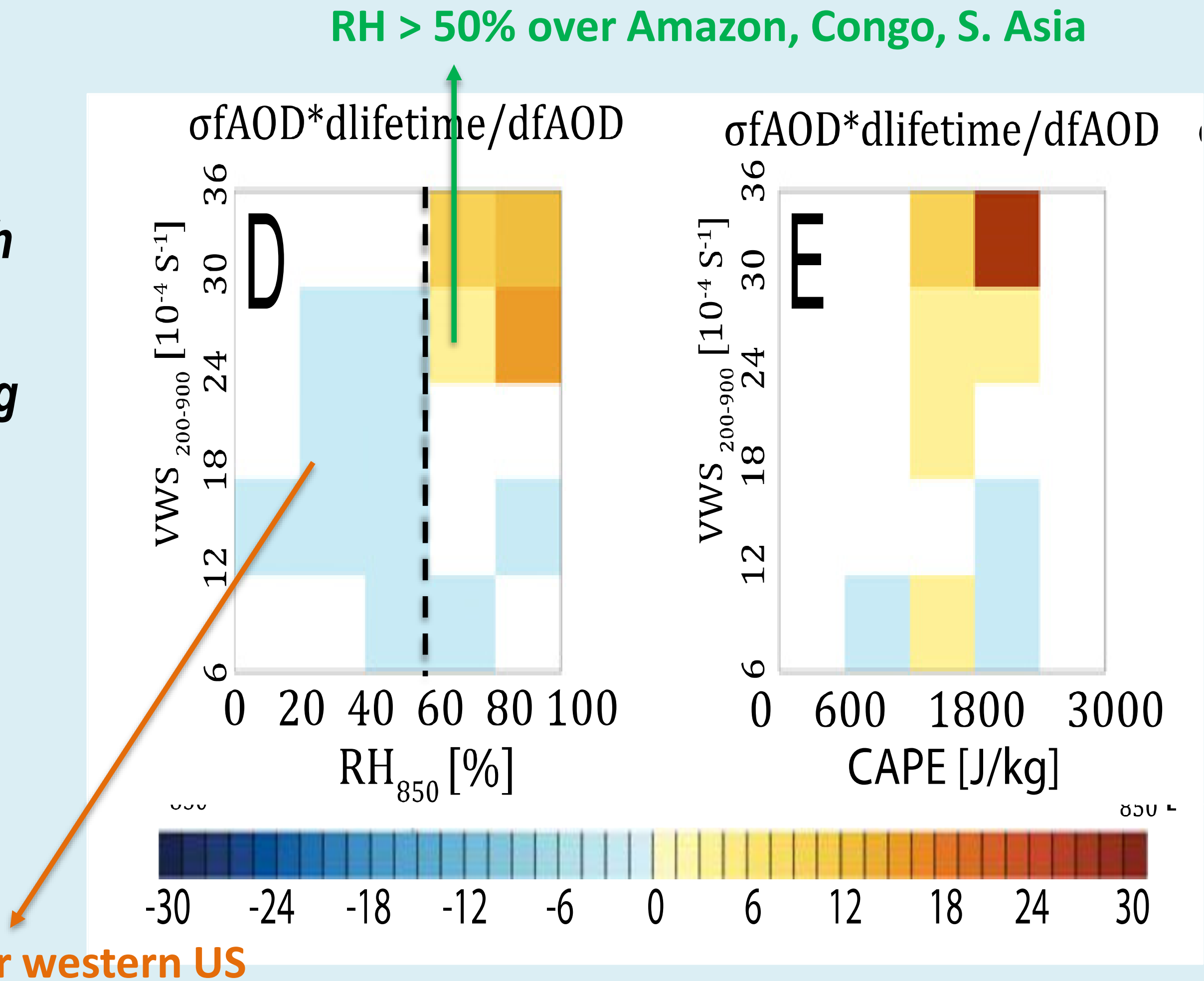
How do aerosols influence MCSs lifetime?

- *How does aerosol influence on MCSs vary with meteorological condition?*
- *What is the relative importance between the influence of aerosols and meteorological conditions?*

Non-linear change of MCS' lifetime with AOD

- ***Increases with $f_{AOD>0.15}$ (~ 3 – 24 hrs/1σ of AOD) under high RH_{850} (≥60%), high CAPE(≥1200J/kg), and strong deep VWS (≥18X10^{-4} s^{-1});***

- ***Decreases with $f_{AOD>0.15}$ (~3-6 hrs /1σ of AOD) under lower RH850 (<60%) and weaker deep VWS (< 18X10^{-4} s^{-1}).***



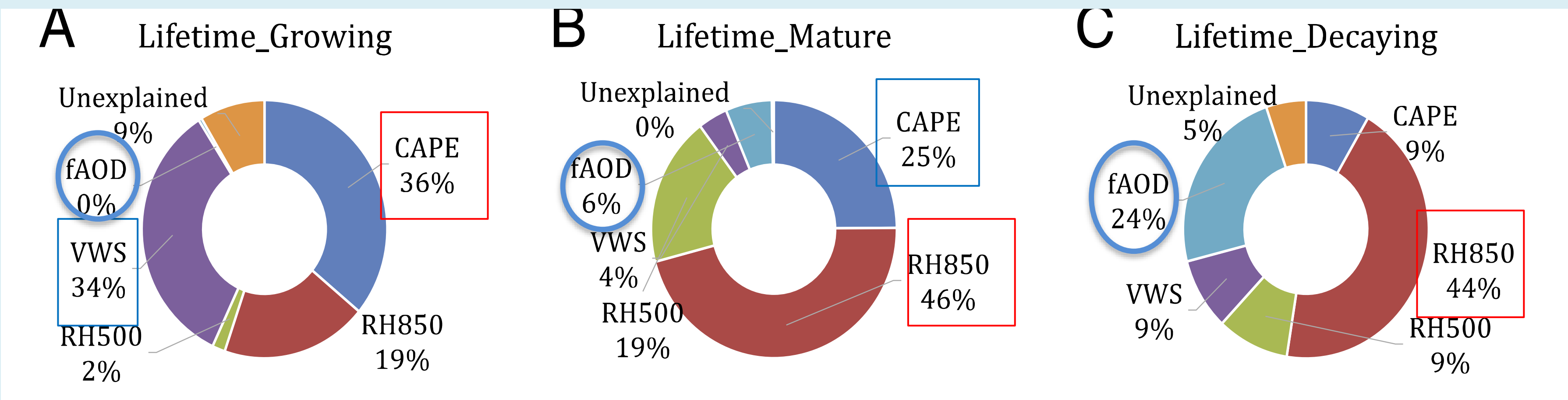
Hours/1σ increase of the fractional area of heavy pollution (AOD>0.15), similar patterns for AOD>0.3

Chakraborty et al 2016, PNAS

The influence of aerosol vs. meteorological conditions on the MCSs lifecycle

- ***CAPE and VWS dominate the variance of the MCSs' lifetime during the growing phase (36% and 34%, respectively)***
- ***Lower tropospheric humidity (RH_{850hPa}) dominates the variance of the MCSs lifetime during the mature and decay phases (46%, 44%, respectively).***
- ***f_{AOD} appears to have significant influence on the decay phase, explains ~24% of its total variance.***

Lifetime (ISCCP)

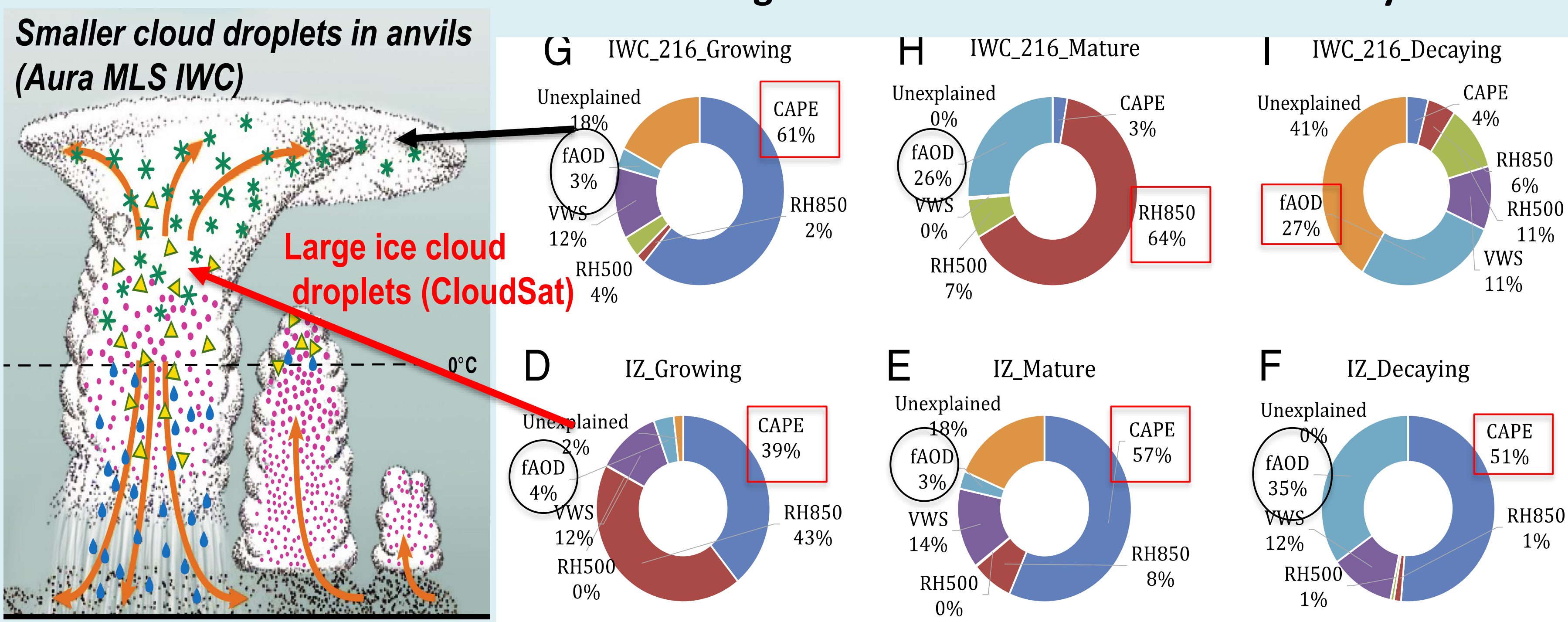


Chakraborty et al 2016, PNAS

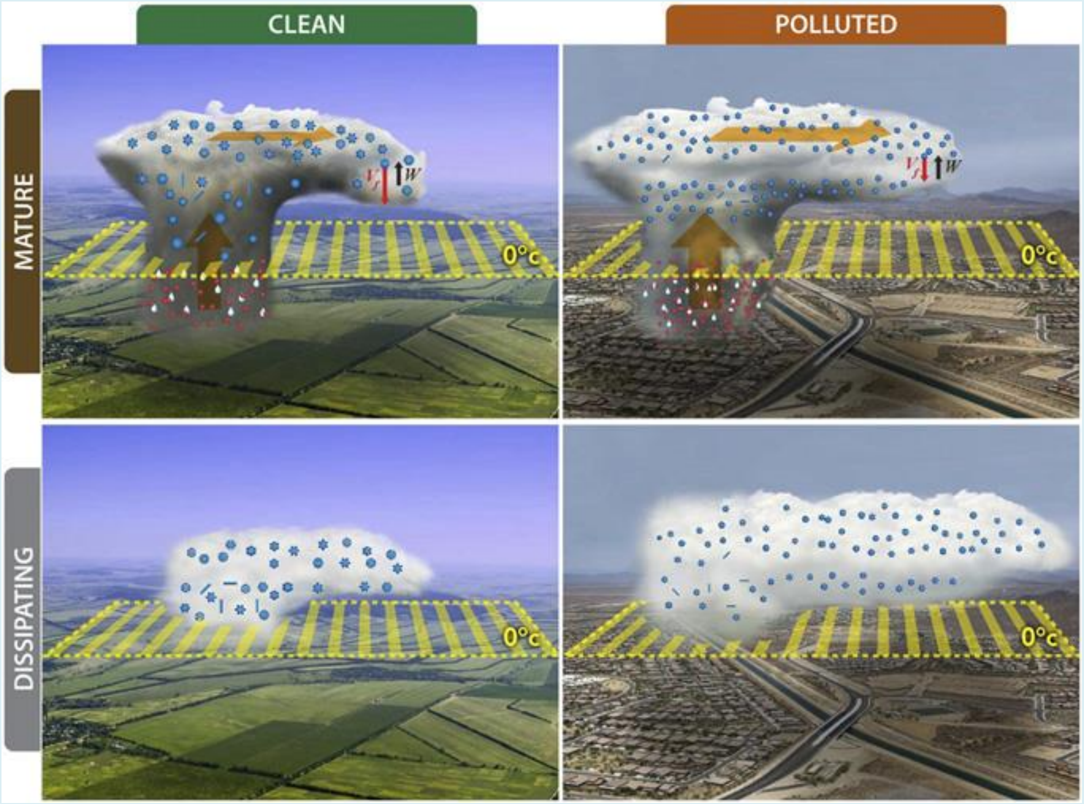
Influence of aerosol vs. meteorological conditions on cloud ice in convective cores and anvils during MCS lifecycle

- ***Aerosol effect on convective and anvil cloud ice becomes increasingly detectible by satellite during the mature and decay phases.***

Growing **Mature** **Decay**



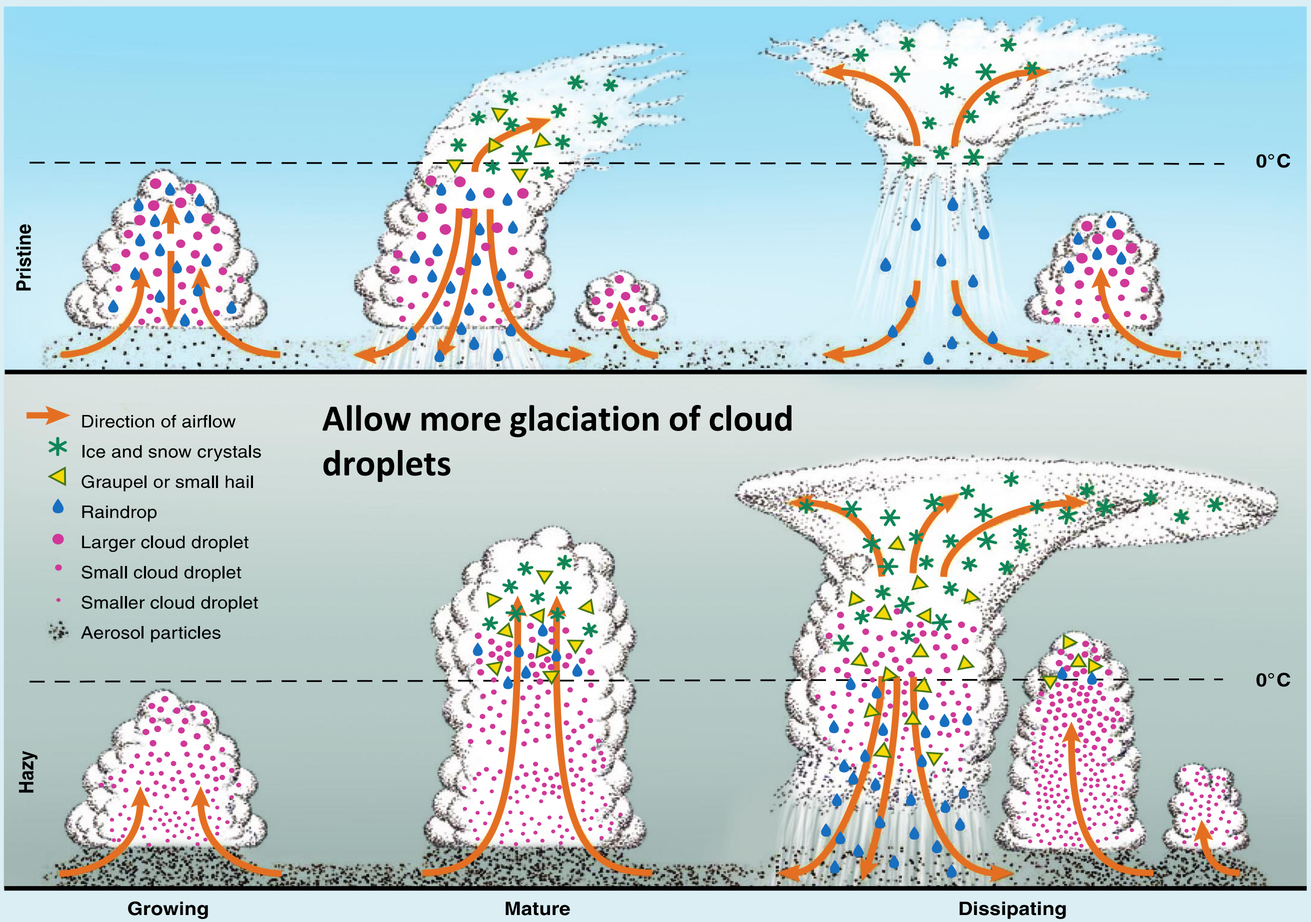
Why?



Fan et al. 2012, PNAS

- *Growing phase: Increasing latent heating invigorates convection (hard to detect from satellite)*
- *Mature and decay phases: Aerosols microphysical effect, which induces larger amount of smaller but longer-lasting ice particles, is responsible for larger and thicker convective anvils.*

How do aerosols influence total (cumulative) rainfall during MCS's' lifetime?

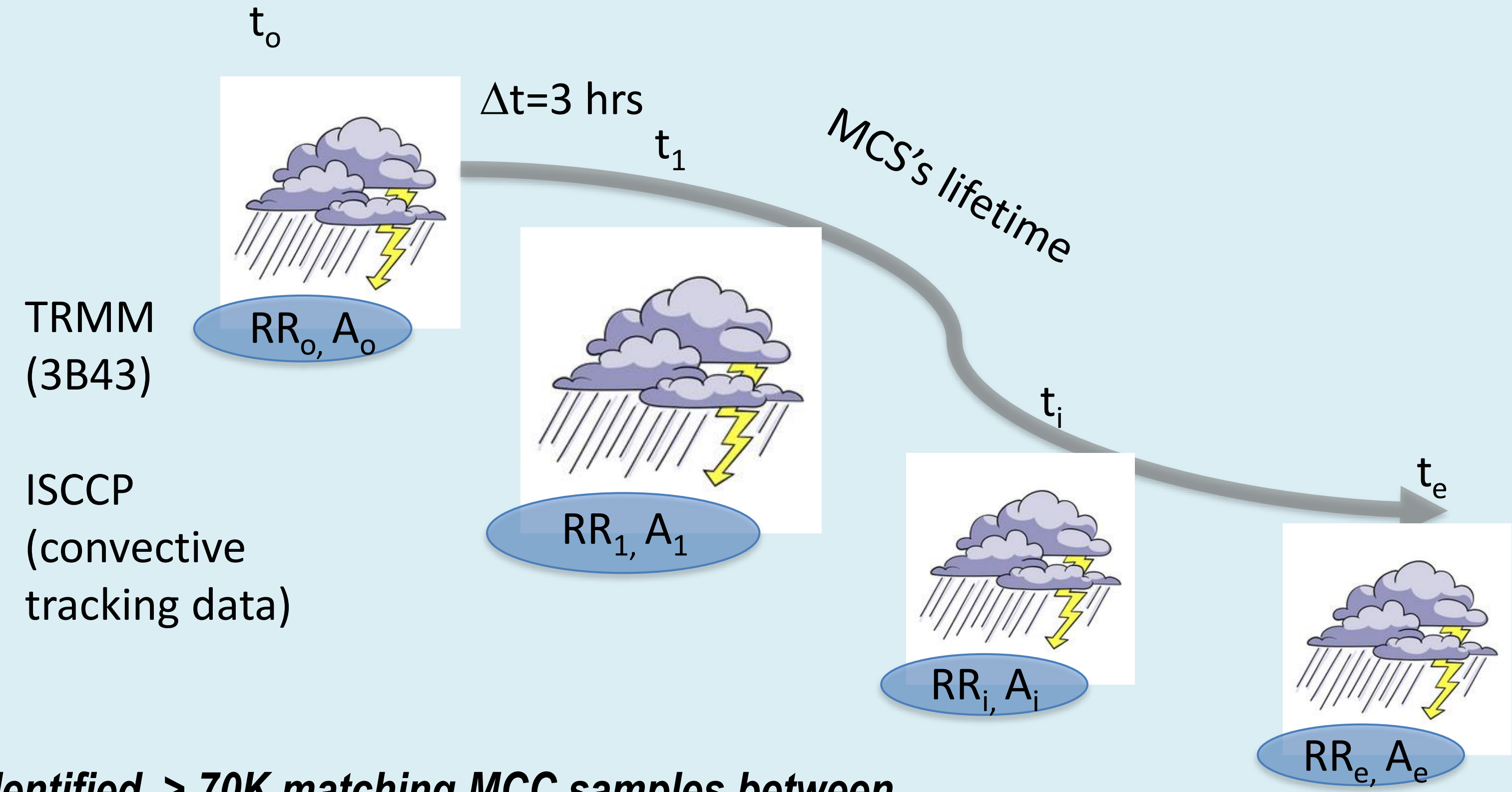


Allow more glaciation of cloud droplets

Delay and reduce precipitation **Increase precipitation and convective lifetime**

Compute total rainfall produced during MCSs' lifetime:

$$\mathrm{TRV} = \sum_{t_o}^{t_e} RR_{t_i} \cdot A_{t_i}$$



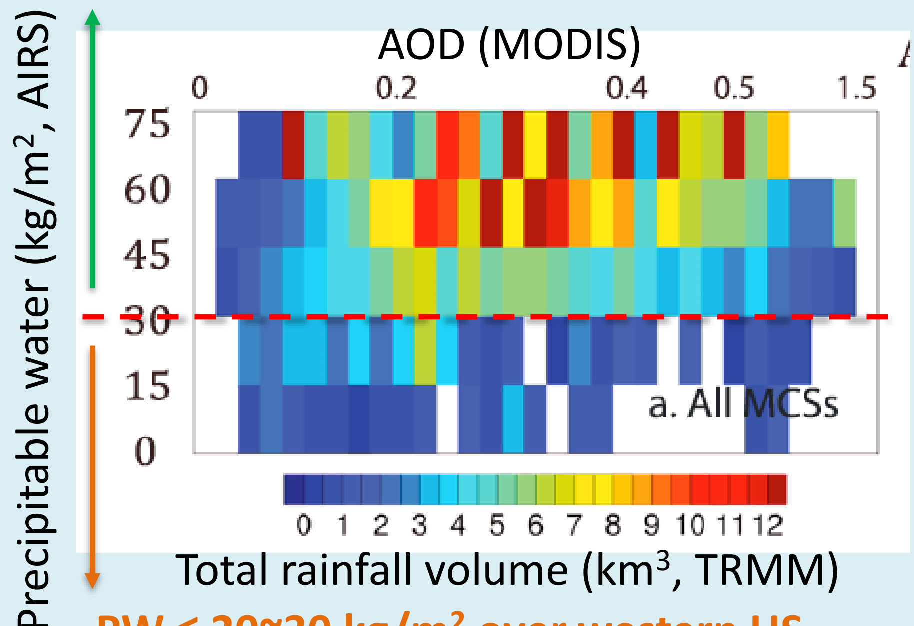
Identified > 70K matching MCC samples between TRMM and ISCCP.

Chakraborty et al. 2018, GRL

Non-linear influence of aerosols on total rainfall produced during MCSs' lifetime

- ***Under high precipitable water value (> ~ 45 kg/m², mm), total rainfall increases strongly with AOD (0.2<AOD <0.5).***
- ***Under low precipitable water values (≤ ~30 kg/m², mm), total rainfall of MCSs decreases with AOD.***
- ***The influence is mainly due to change of MCSs lifetime, strong during mature and decay phase***

PW > 40 kg/m² over Amazon, Congo, S. Asia



PW ≤ 20~30 kg/m² over western US

Chakraborty et al. 2018, GRL

Summary - 1

Hypothesis -1 : Aerosols can weaken MCSs under low humidity and weak CAPE and vertical wind shear, potentially intensify droughts/aridification.

Results:

- *Aerosols tend to invigorate strong MCSs (increase lifetime and total rainfall) under humid (RH≥60%, PW≥30mm), unstable condition (CAPE ≥1200 J/kg) that are typically found in humid tropical continents*
- *Aerosols tend to weaken MCSs under relatively dry (RH<60%, PW<30mm), and stable conditions (CAPE<1200 J/kg) that are typically found in semi-arid subtropical-like regions, such as western US.*
- *Aerosols influence on MCSs lifetime and total rainfall is ~ 1/2 of those of meteorological conditions (CAPE, VWS and RH_{850hPa}), stronger during mature and decay phases.*

The influence of deep convection on aerosols in the upper troposphere

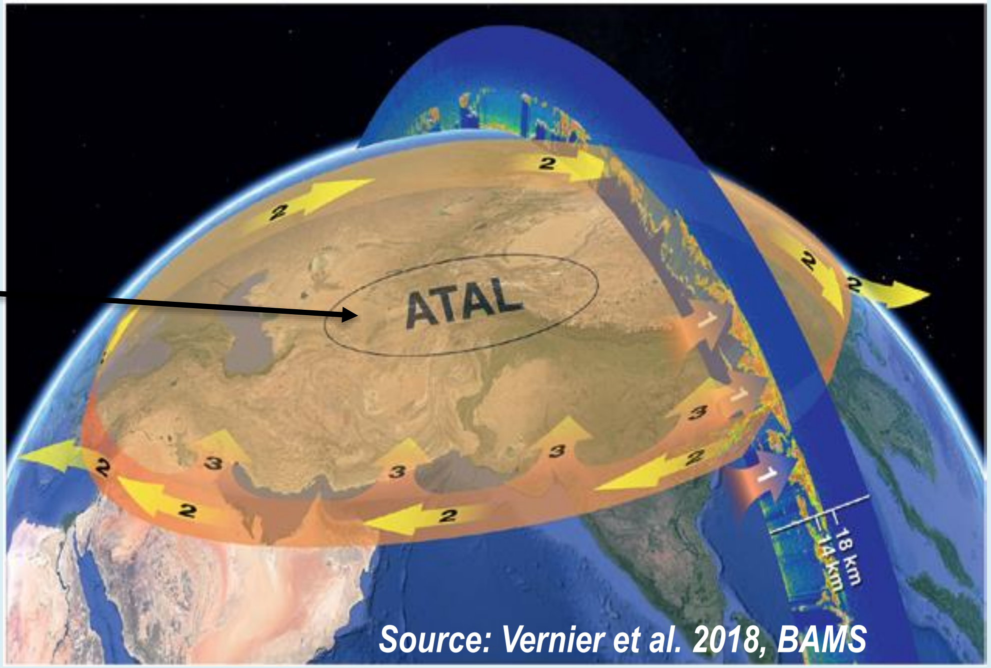
Sources of aerosols in the upper troposphere:

- ***<u>Convective transport of aerosols (e.g., Andreae et al. 2001; Chakraborty et al. 2015, Lau et al. 2018)</u>***
- ***Generation of secondary aerosols through ice cloud microphysical and chemical processes (e.g., Andreae et al. 2018)***
- ***Volcanic eruptions,***

Effect:

- ***Fadnavis et al. 2019: ATAL worsens the Indian Drought***

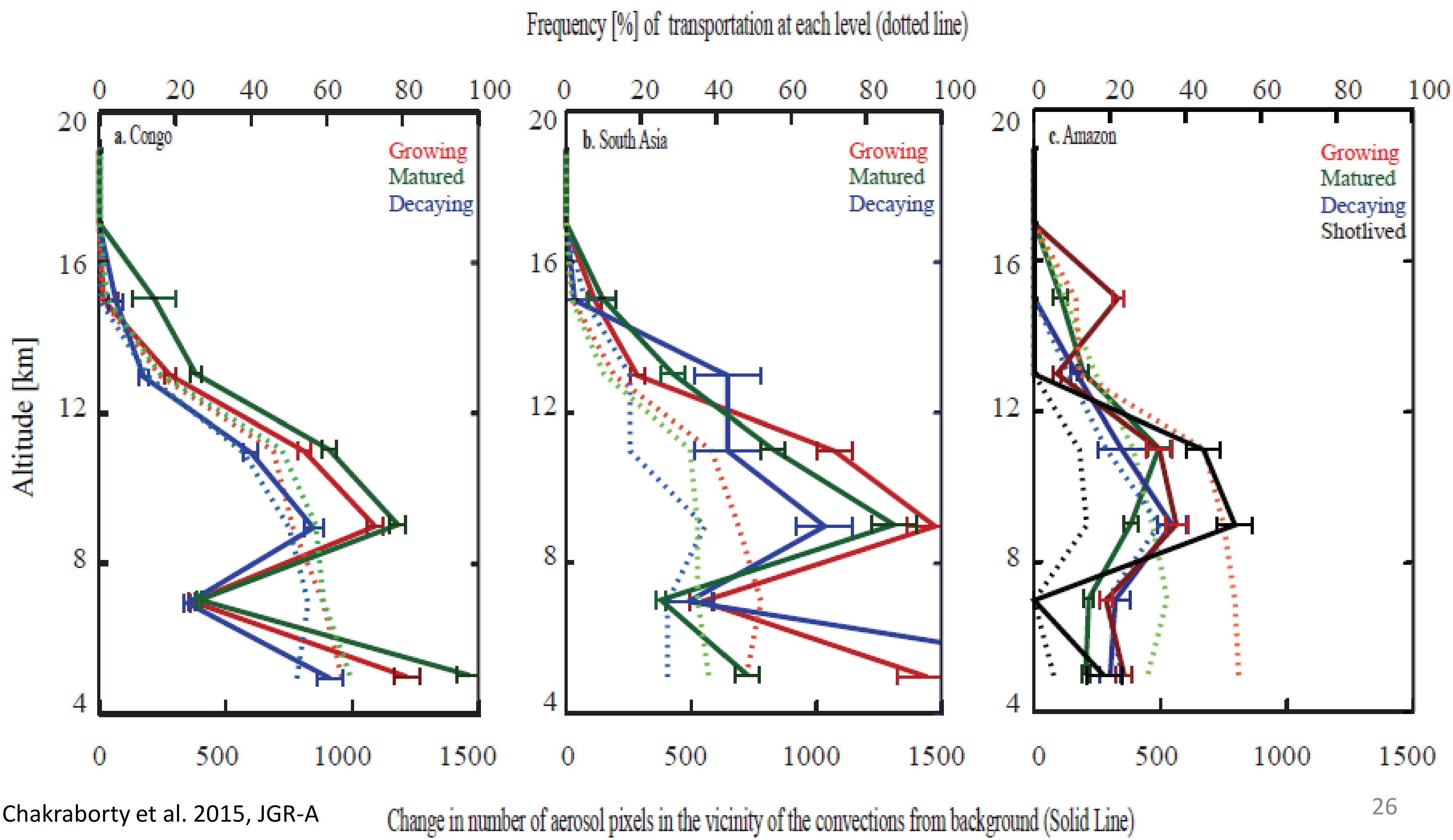
Asian tropopause aerosol layer (ATAL)



Source: Vernier et al. 2018, BAMS

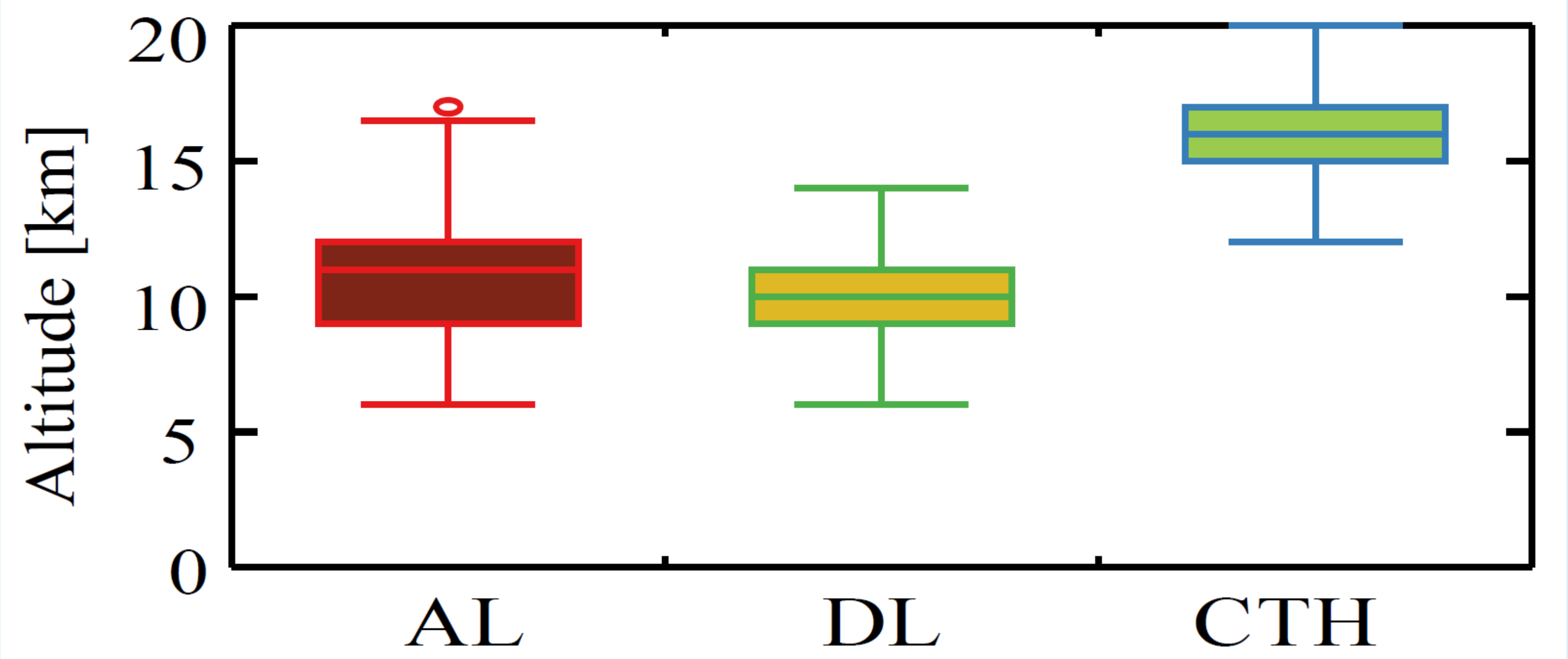
Increase of aerosols in the mid-upper troposphere by detrainment of MCSs

Growing and Mature stages are associated with stronger increase in aerosols in the vicinity of MCSs.



Chakraborty et al. 2015, JGR-A

- ***The vertical distribution of the aerosol layers match that of the convective detrainment layers.***



Aerosol Layer Height (CALIPSO)

Height of detrainment layer (CloudSat)

Cloud top height (CALIPSO)

Chakraborty et al. 2015, JGR-A

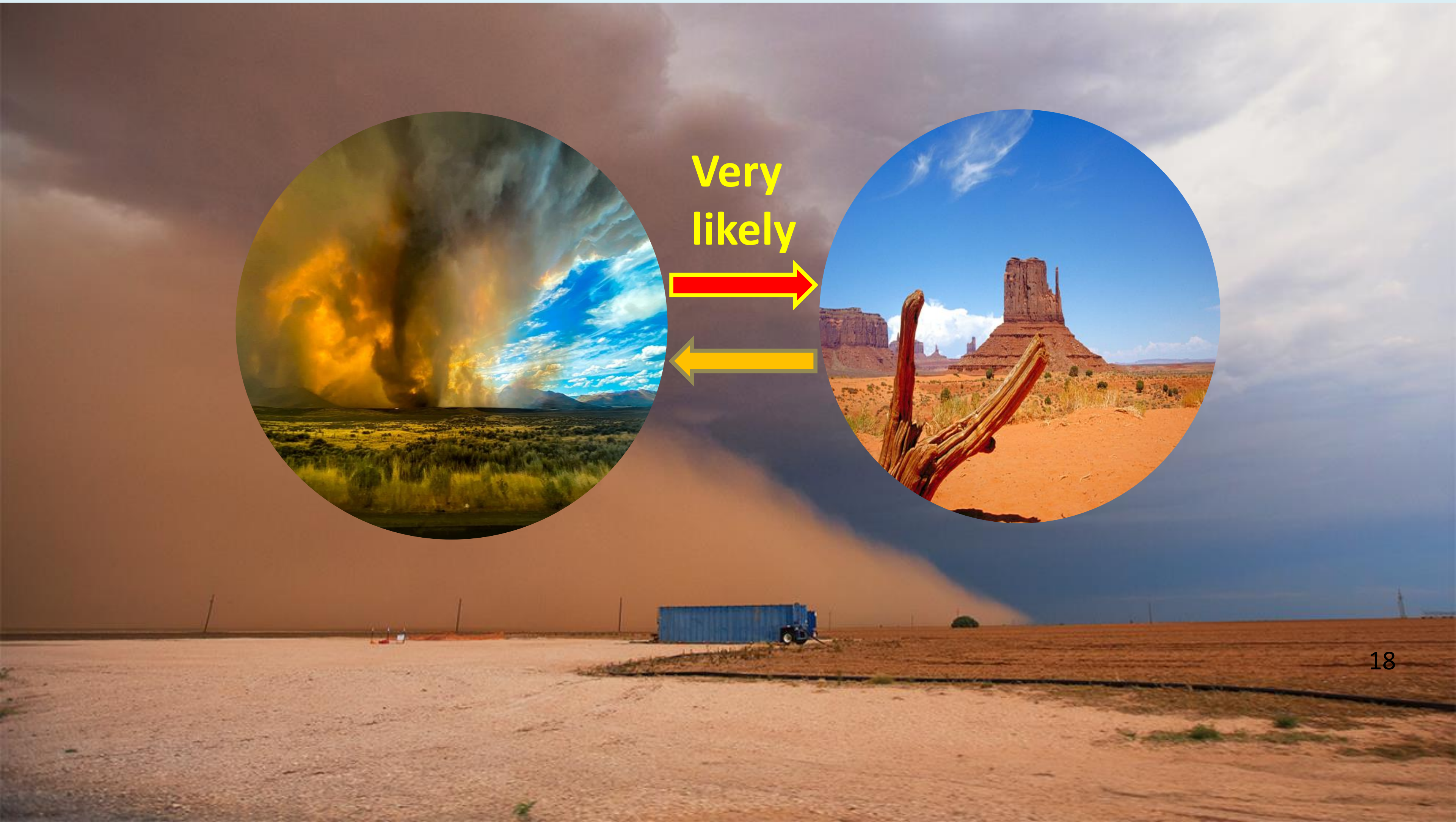
Summary -2

Hypothesis-2: MCSs detrainment can significantly increase aerosols in the upper troposphere during the growing and mature phases, likely due to greater number and height of the convective cores in MCSs. This effect could broaden the spatial impacts of wildfires and dusts, possibly further suppress rainfall.

Results:

- ***MCSs can significantly increase aerosols in the upper troposphere.***
- ***The detrainment of aerosol is stronger during the growing and mature stages, presumable due to larger number of deeper convective cores and stronger wind shear than decaying stages.***

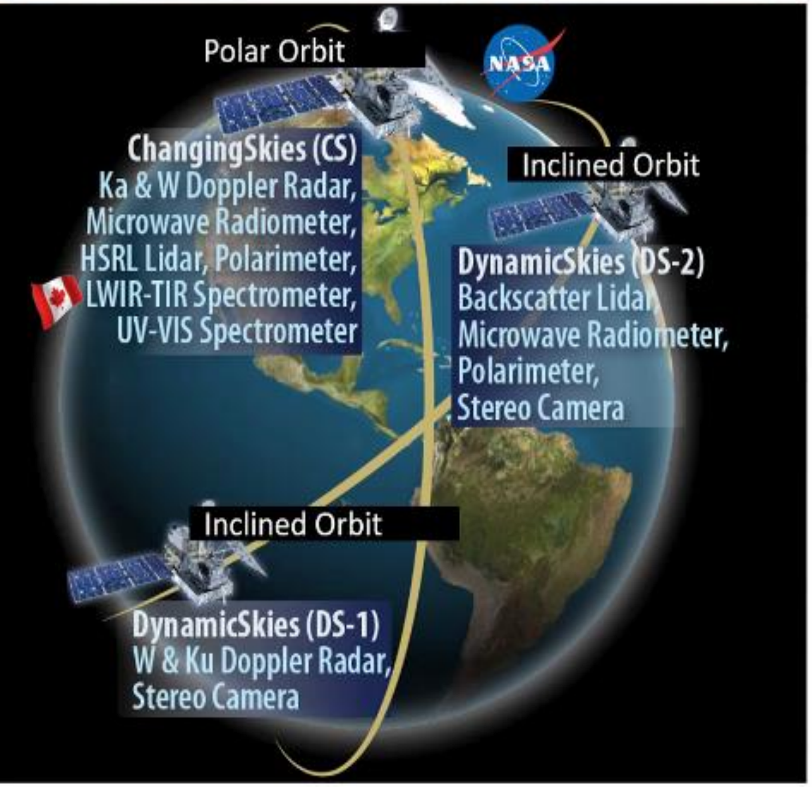
Could aerosols further amplify droughts and aridification of western US?



Limitations of our approach:

- ***Limited samples under relatively dry and stable conditions, in part due to few MCSs and limited co-located TRMM/GPM and A-train measurements.***
- ***Large distance between co-located TRMM/GPM and A-train measurements***
- ***Available satellite measurements are more appropriate for detecting the variations of MCSs morphology in the middle and upper troposphere, not reliable for detecting aerosol influence in the lower troposphere within clouds.***
- ***Unable to resolve diurnal variations of the cloud ice water, aerosol vertical distribution: A-train measurements are limited to early afternoon and morning***
- ***Lack of information on relative vertical locations of clouds and aerosols***

Summary 2)Architecture Recommendation—Dual Orbit Constellation



1st launch of inclined orbit ~2028

2nd launch of polar orbit ~2029

Inclined Orbit

- W-, Ku-band* Doppler radar
- Microwave radiometer (118-880 GHz)
- 532 and 1064 nm backscatter lidar
- Polarimeter (1130 km swath, 1 km resolution)
- Time-differenced stereo camera measurements

Polar Orbit

- W-, Ka-band Doppler radar
- Microwave radiometer (118-880 GHz)*
- 532 nm HSRL*, 1064 nm backscatter lidar
- Polarimeter (550 km swath, 0.5 km resolution)
- Spectrometers (LWUV-VIS-SWIR, LWIR-FIR*)

* Contributions from international partners under discussion

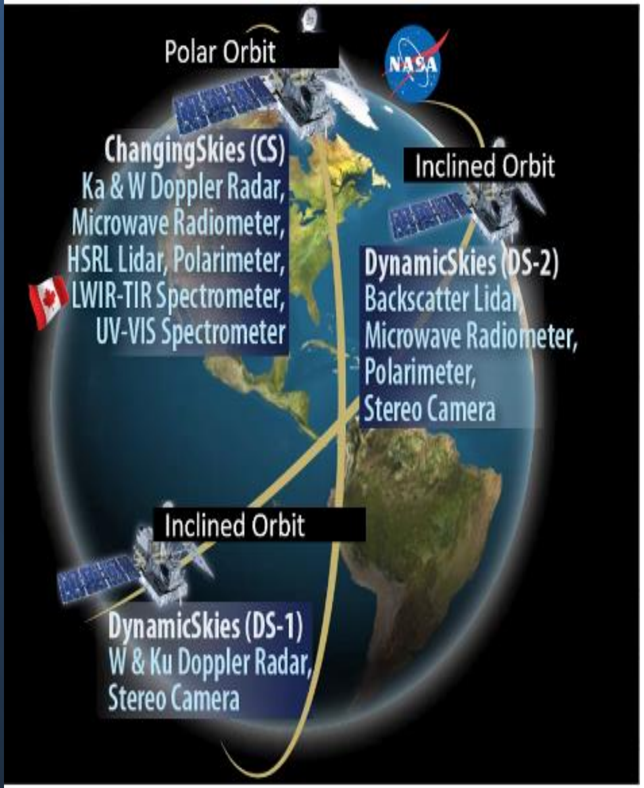
Source: Graeme Stephens

Two important science game changing firsts expected from ACCP (AtmOS)

- Unambiguous aerosol profiles of extinction
- Vertical motion profiles in clouds and convective storms

Source: Graeme Stephens

Limitations of our approach:



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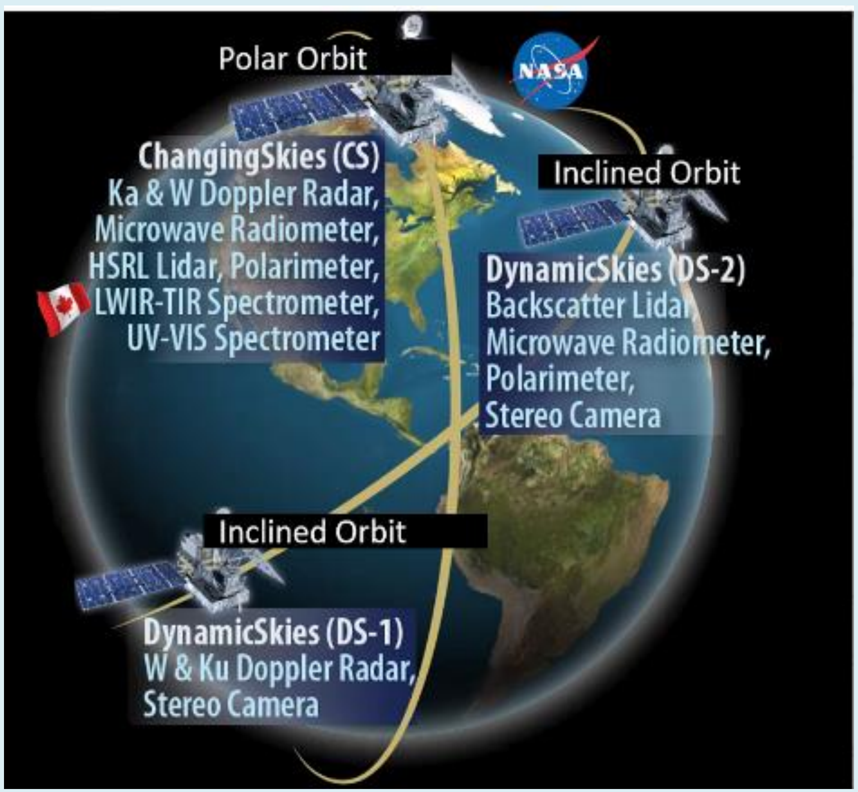
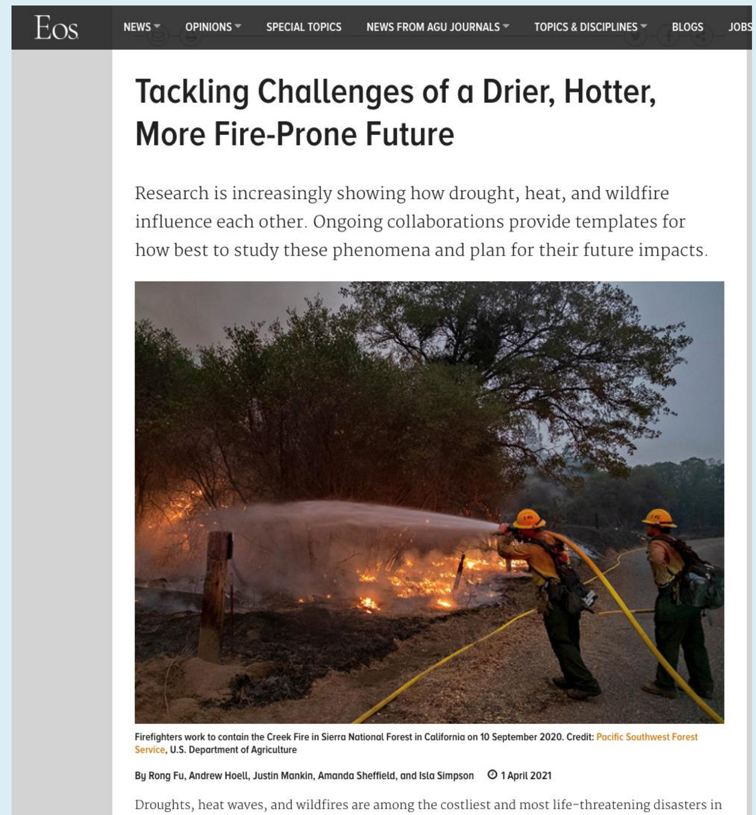
- ~~*Unable to resolve diurnal variations of the cloud ice water, aerosol vertical distribution: A-train measurements are limited to early afternoon and morning*~~
- ~~*Lack of information on relative vertical locations of clouds and aerosols*~~

- ***Measurements proposed for ACCP could be a game changer for understanding the role of aerosol-cloud-precipitation interaction in a drier, hotter and more fire-prone future in western US and semi-arid regions worldwide***





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Tackling Challenges of a Drier, Hotter, More Fire-Prone Future

Research is increasingly showing how drought, heat, and wildfire influence each other. Ongoing collaborations provide templates for how best to study these phenomena and plan for their future impacts.

Firefighters work to contain the Creek Fire in Sierra National Forest in California on 10 September 2020. Credit: Pacific Southwest Forest Service, U.S. Department of Agriculture

By Rong Fu, Andrew Hoell, Justin Mankin, Amanda Sheffield, and Isla Simpson 1 April 2021

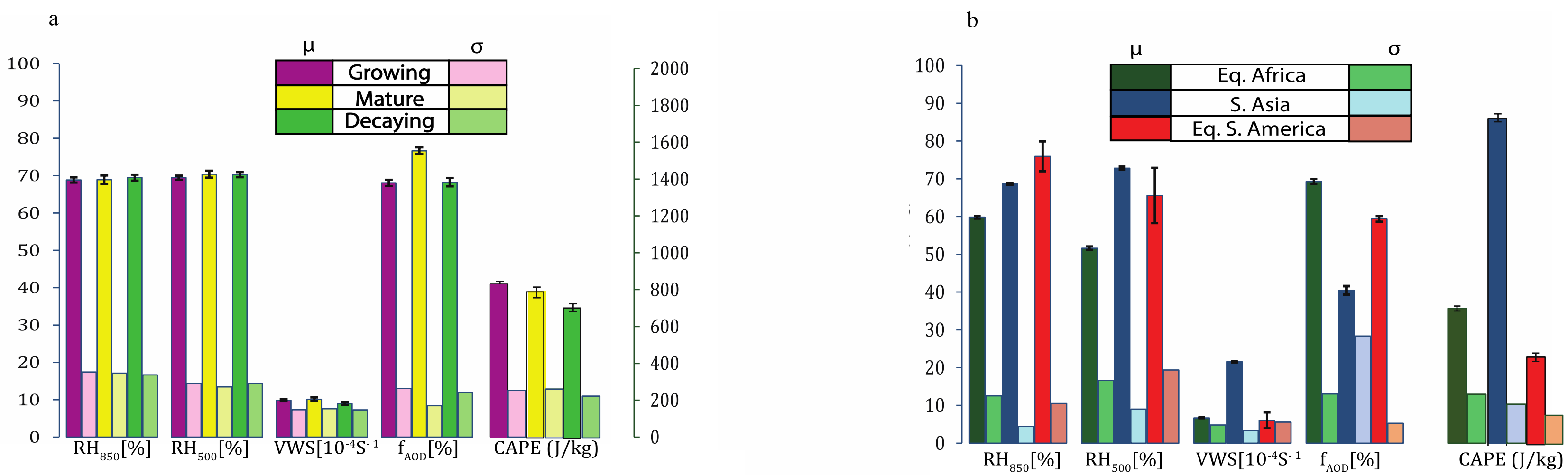
Droughts, heat waves, and wildfires are among the costliest and most life-threatening disasters in

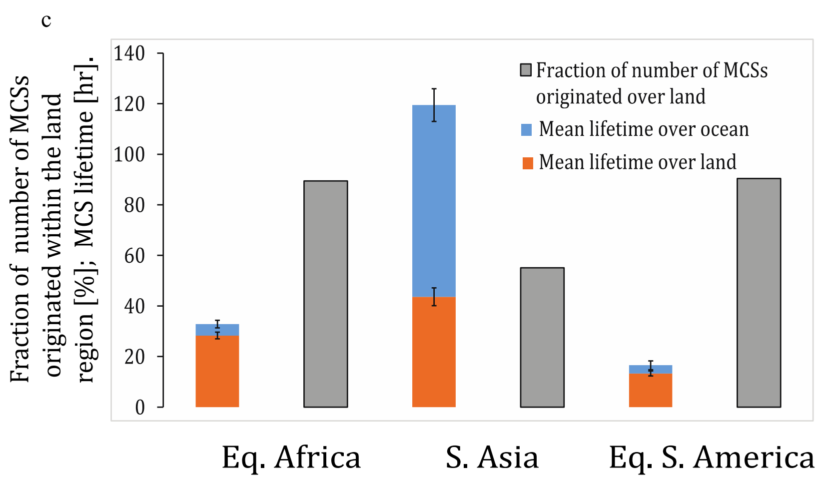
Fu et al. 2021, EOS, NOAA DTF4

Thank you!

Concord, California, Sept. 9, 2020. (Brittany Hosea-Small/AFP via Getty Images)

Could our results be an artifact of spatial and temporal variations of the MCCs, aerosols and meteorological conditions?





- ***Samples of high CAPE, VWS and MCCs with the longest lifetime tends to come from S. Asia.***
- ***But overall relationships of aerosols, meteorological conditions and MCCs are unlikely due to spatial variations.***