Near-global Aerosol-Cloud-Precipitation relationships from a Cloud Regime perspective

Lazaros Oreopoulos (NASA-GSFC)

Nayeong Cho (USRA/NASA-GSFC)
Dongmin Lee (Morgan State/NASA-GSFC)

According to Yoram

- "Future research will need to unravel the magnitude of the aerosol effect on clouds and precipitation, on regional and global scales, and its sensitivity to aerosol chemistry and cloud dynamics."
  - *A satellite view of aerosols in the climate system, Kaufman et al., Nature 2002*
- "The contradictory pathways by which aerosols can affect clouds, and the large natural variability of cloud properties, represent the largest uncertainty in understanding climate change forcing. A better understanding of the effect requires large-scale systematic measurements to resolve the effect of aerosol on the hydrological cycle and distinguish it from natural variability."
  - *The effect of smoke, dust, and pollution aerosol on shallow cloud development over the Atlantic Ocean, Kaufman et al., PNAS 2005*

Our approach

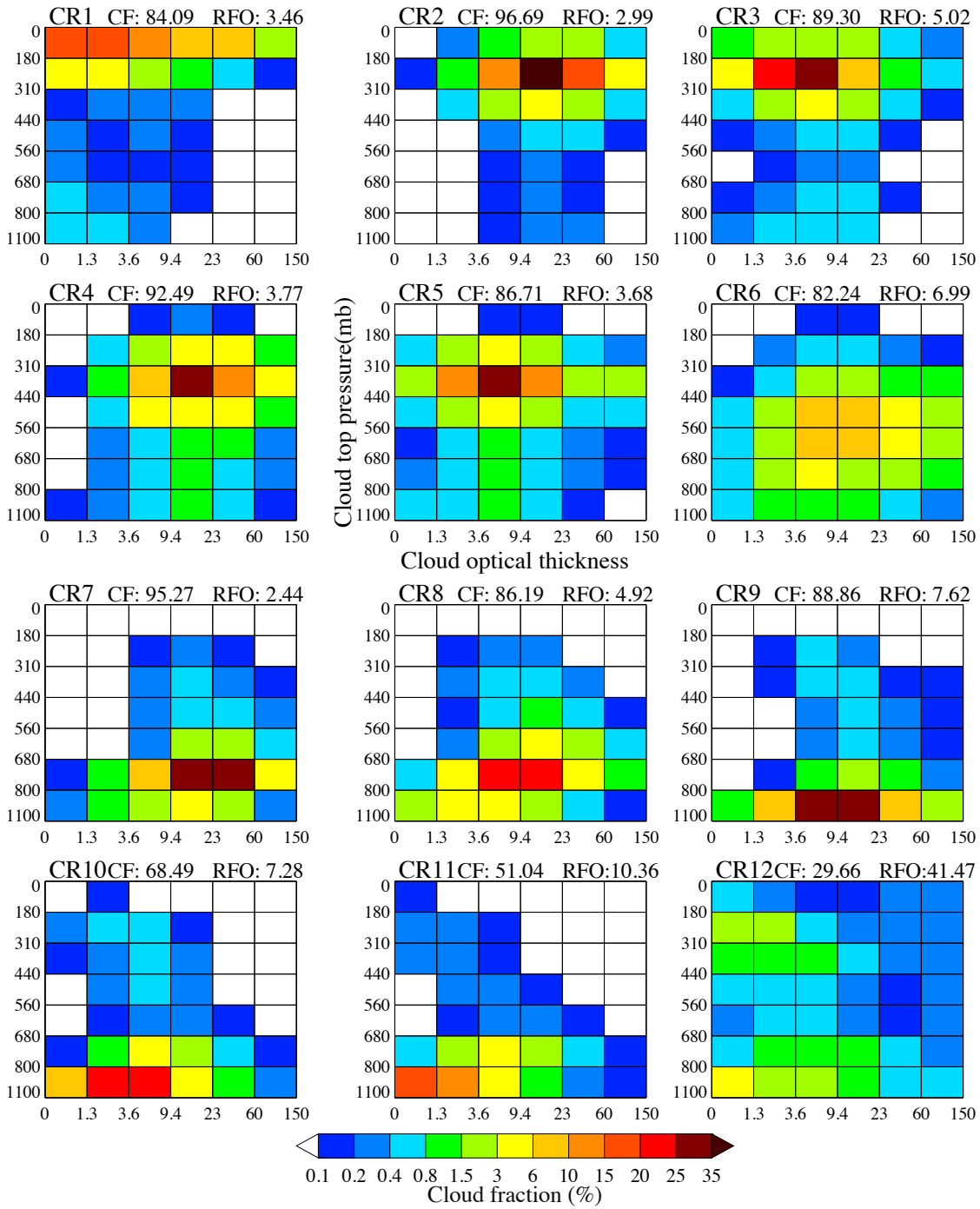
- Diagnostics of aerosol-cloud-precipitation interactions from space at near-global scales
- How to separate aerosol from all other effects?
- Breaking down the analysis by "regime" (groups of similar cloud conditions) may help
- But how do we define regimes?
  - Exploiting cloud appearance (from passive obs) is a good starting point
  - This poses <u>some</u> constraint on environmental conditions
  - Additional constraints can be imposed
- We adopt a "cloud regime" (CR) type based on CTP-TAU joint histograms
  - Our CRs are based on MODIS
  - You may also know ISCCP "Weather States"

Datasets

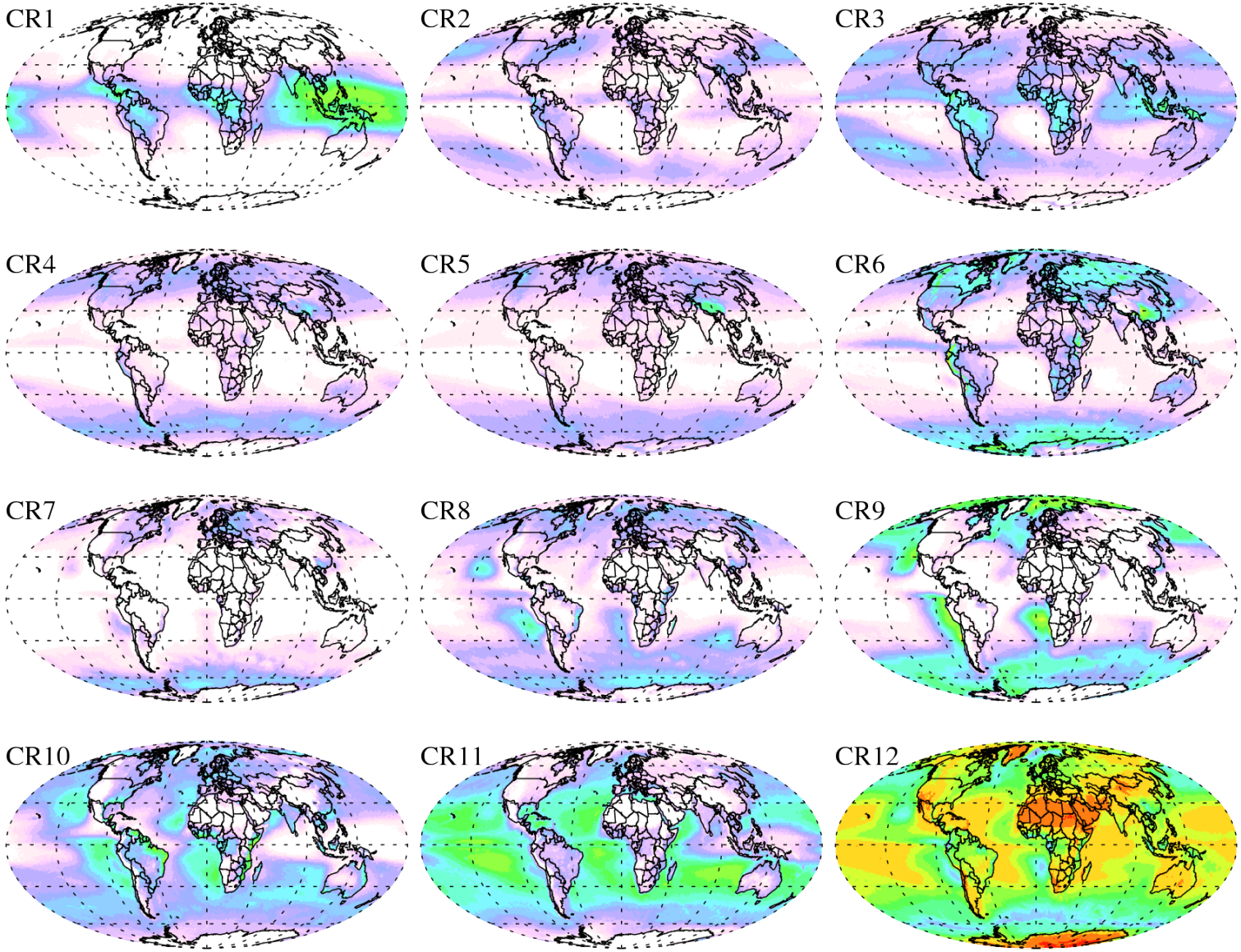
- ***12 years*** of Aqua-Terra L-3 daily (D3) 1° data
  - Collection 6
- Joint histograms of CTP-TAU
  - MODIS CRs from *k-means* clustering
- Other cloud variables: CF, CTP, TAU, REFF
- Dark Target AOD
- MERRA-2 AOD, 3-hr
- TMPA-3B42 surface precipitation (3-hr, 0.25°)
  - 50°S-50°N
- Some CloudSat-CALIPSO data as ancillary

MODIS CRs

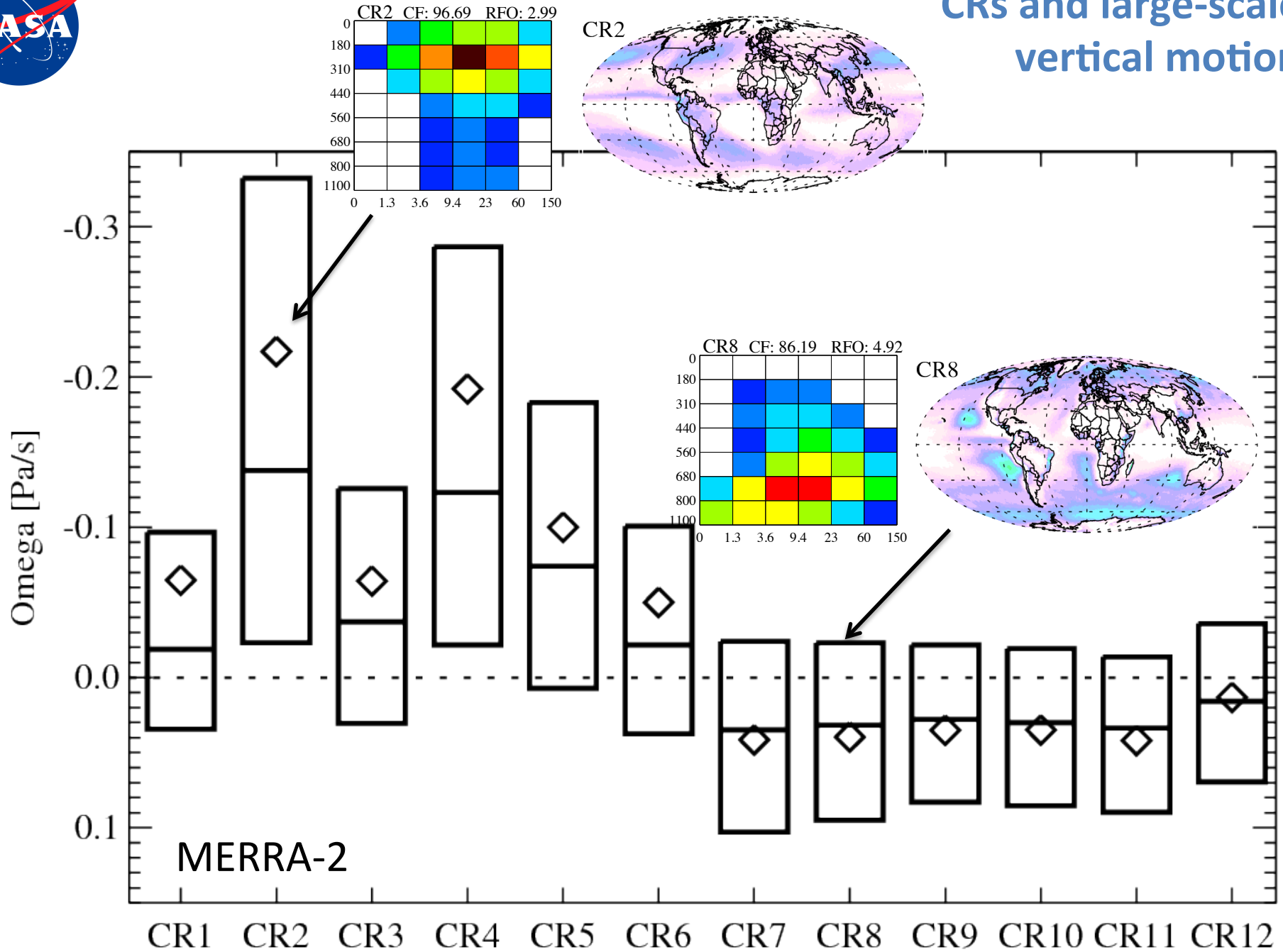
The 12 MODIS Collection 6 CRs



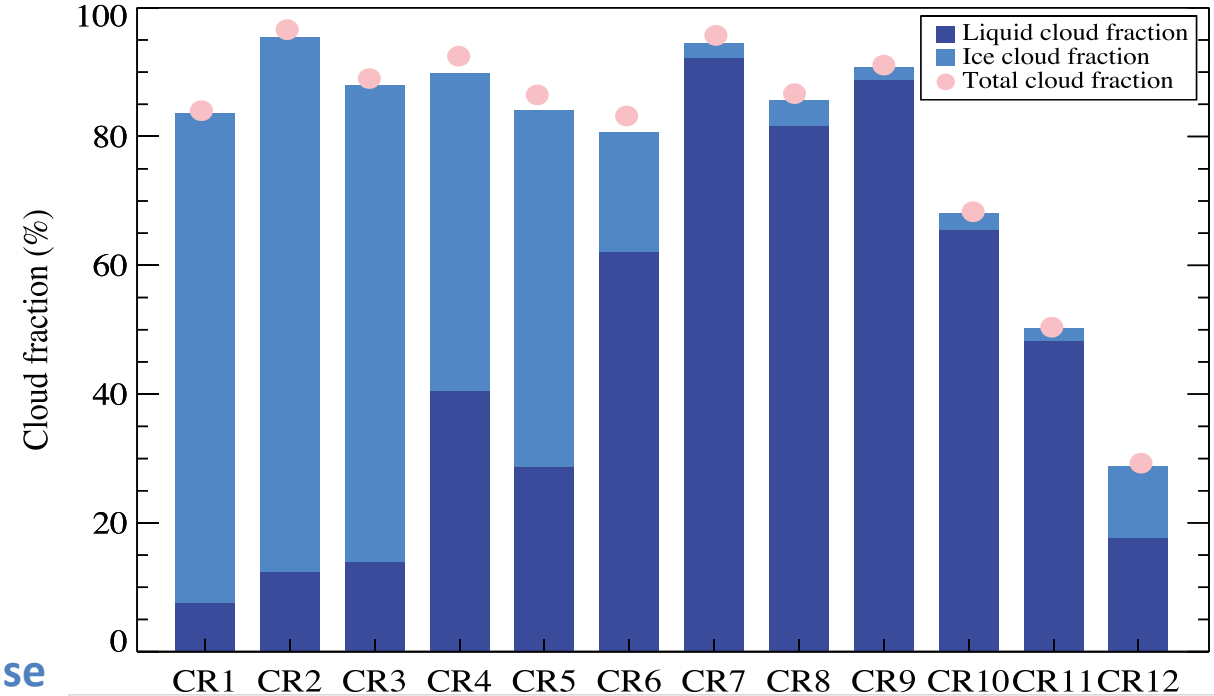
Where the CRs occur



CRs and large-scale vertical motion

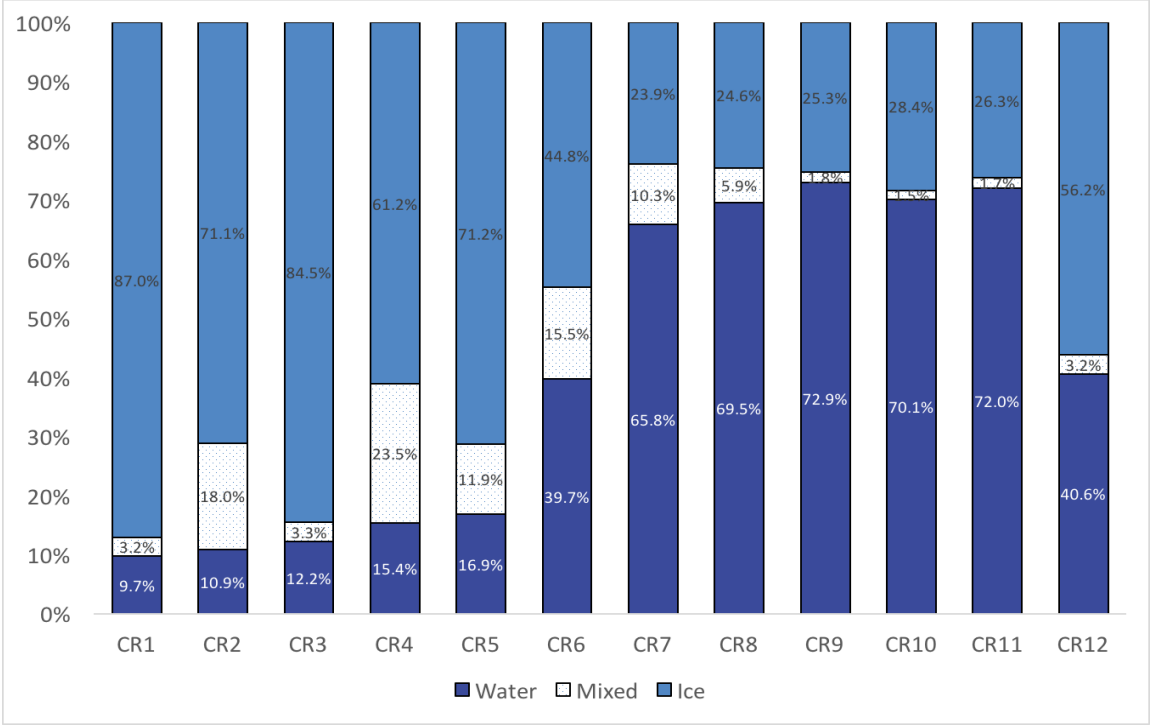


MODIS CF



CR thermodynamic phase

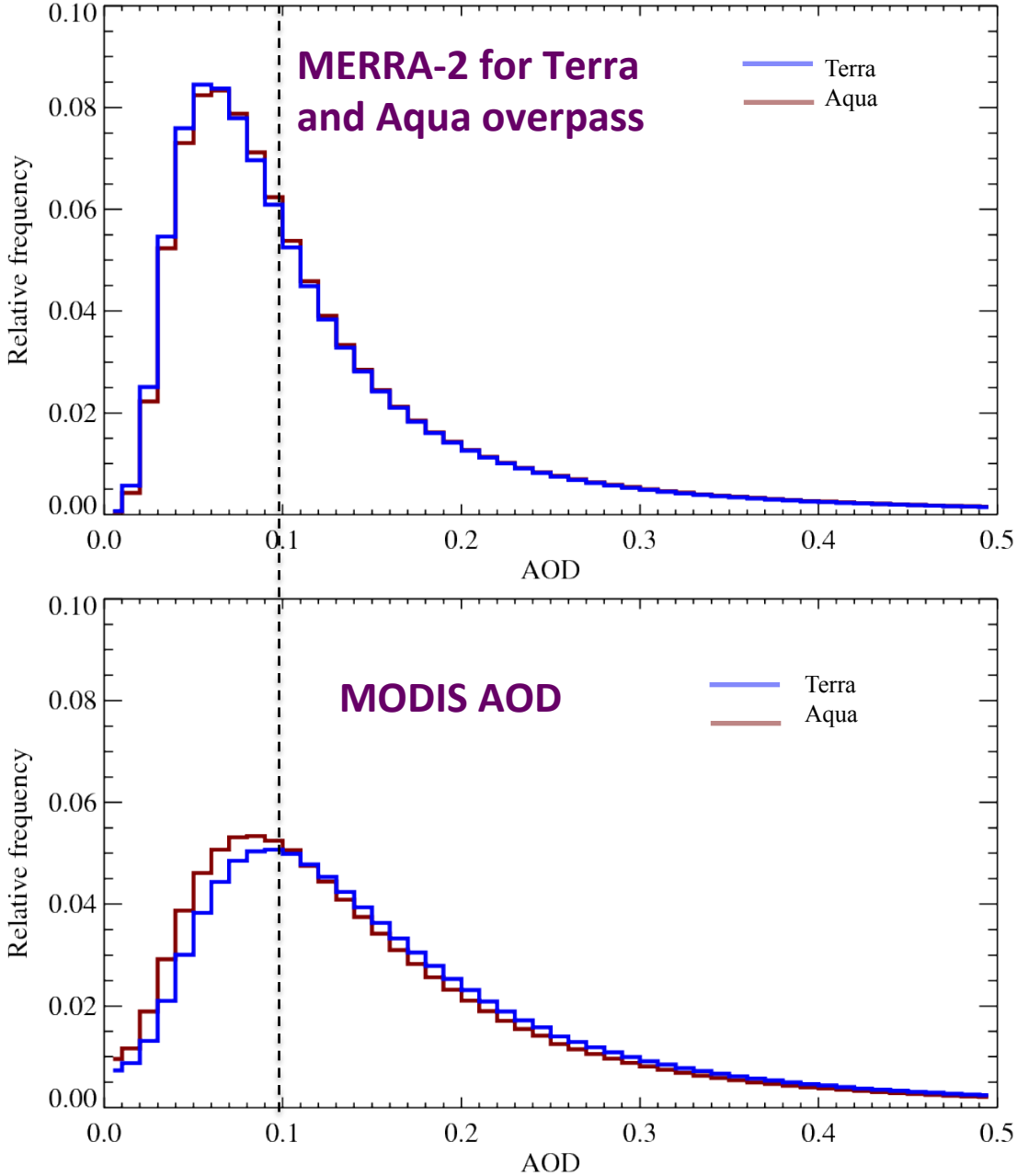
2B-CLDCLASS-LIDAR
* Cloud phase



Aerosols

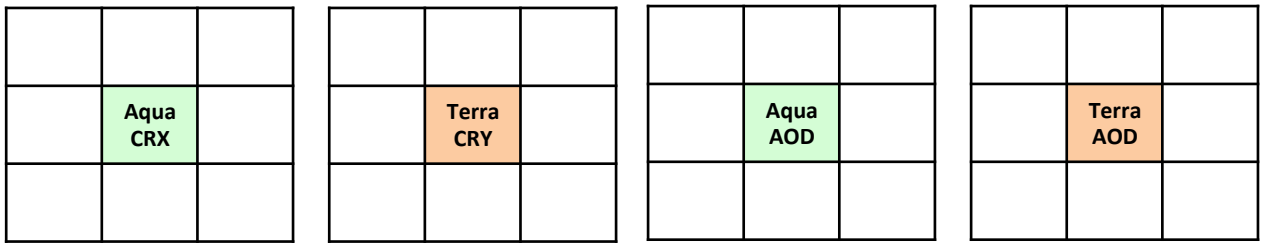
MODIS-MERRA-2 aerosol comparison

50S-50N



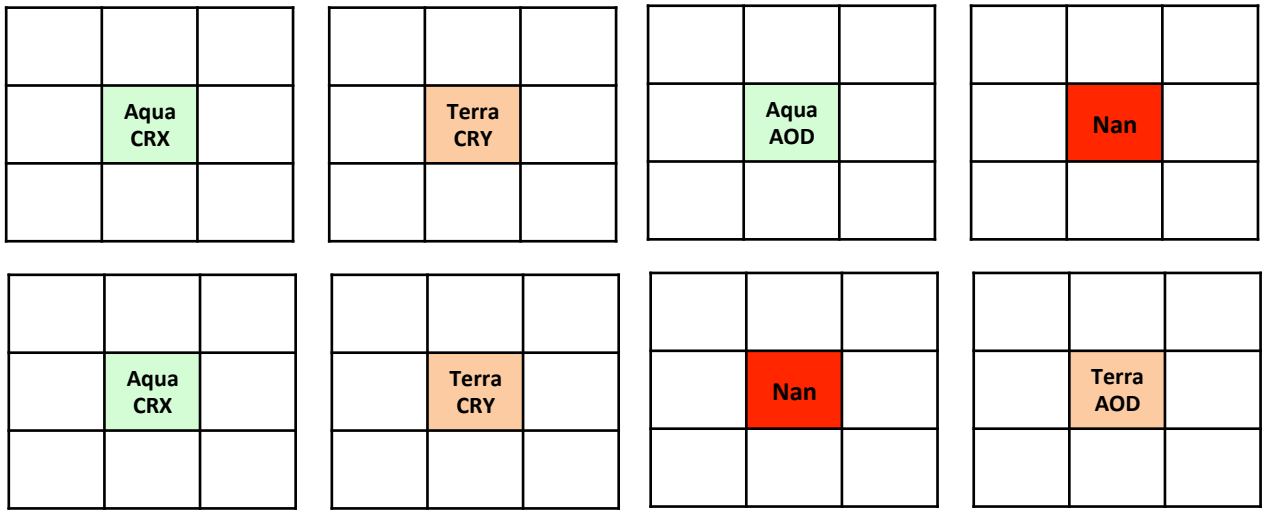
AOD Determination

1)



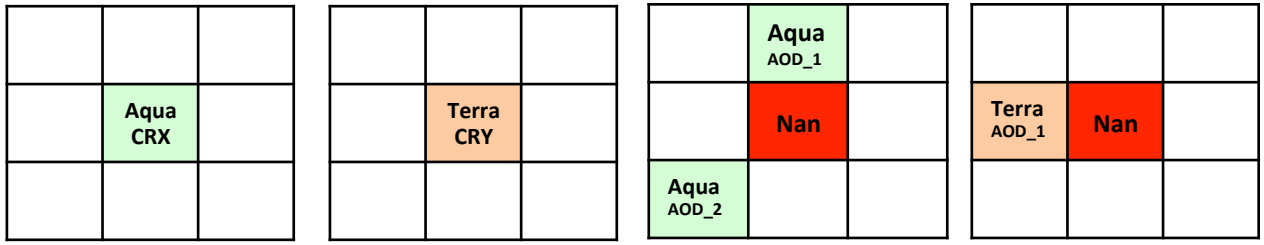
AOD = (Aqua AOD + Terra AOD) / 2.

2)



AOD = Aqua AOD OR AOD = Terra AOD

3)



AOD = (Aqua_AOD_1+Aqua_AOD_2+Terra_AOD_1) / 3.

Methodology

- Daily MODIS aerosol AOD defined for each gridcell from Terra and Aqua (previous slide)
- Follow same procedure for MERRA-2 (pick 3-hr containing the Terra-Aqua overpass)
  - Far fewer missing values for MERRA-2
- Examine Precip, CF, CTP, TAU, REFF vs collocated aerosol
  - Relative AOD value (position within distribution for *that location and season*)
- Composite by CR (generally one Terra and one Aqua CR occurrence per day per gridcell)
  - Pick the appropriate 3-hr TMPA value

What are we searching for?

- Invigoration for (mostly) ice and mixed phase CRs
  - Precipitation increase with AOD (what about scavenging?)
  - CTP decrease with AOD
  - TAU increase with AOD (?)
- First indirect effect for (mostly) liquid CRs
  - TAU increase with AOD
  - REFF decrease with AOD
- Second indirect effect for (mostly) liquid CRs
  - Precipitation suppression with AOD
  - CF increase with AOD

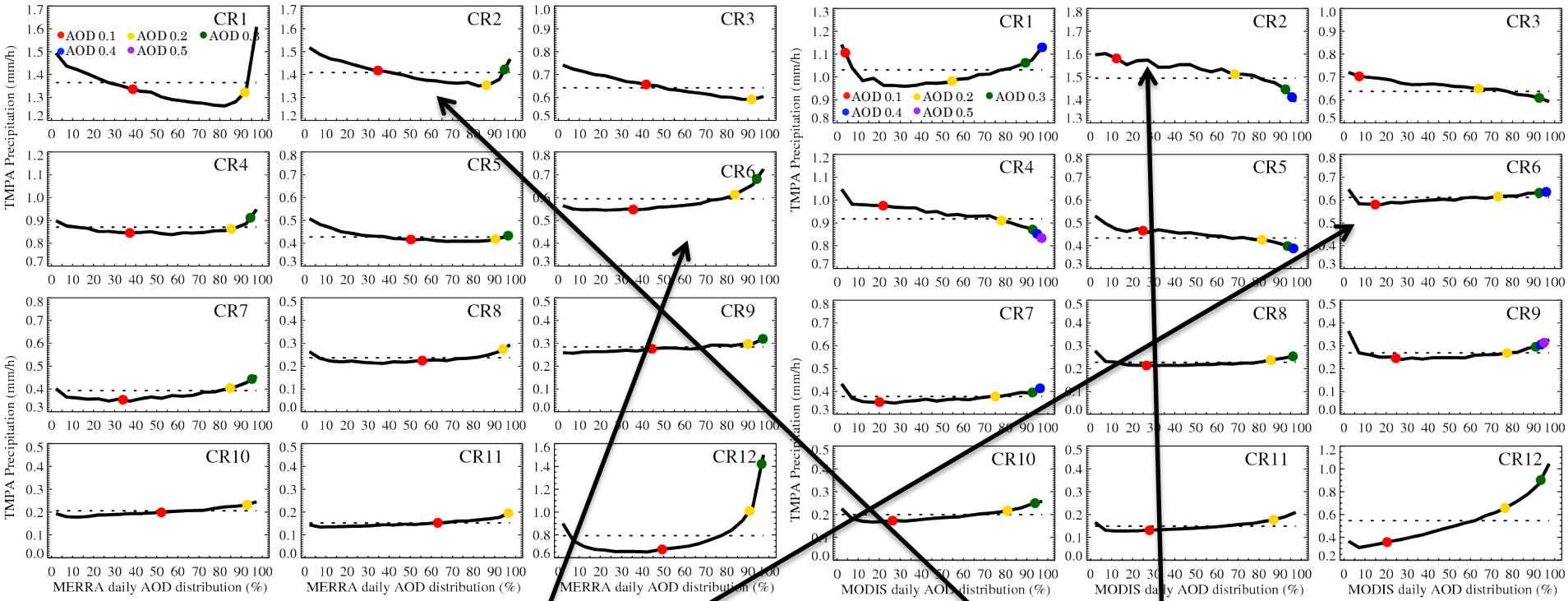
Precipitation

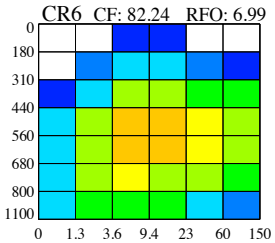
Does the AOD dataset matter?

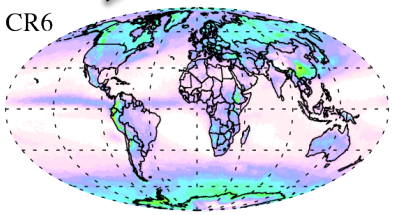
TMPA (P > 0)

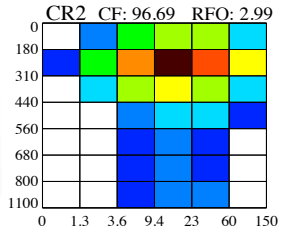
AOD data from Merra-2

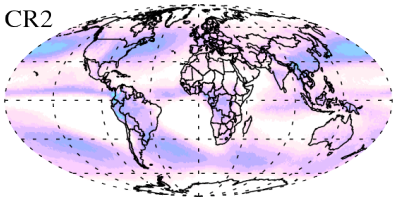
AOD data from MODIS









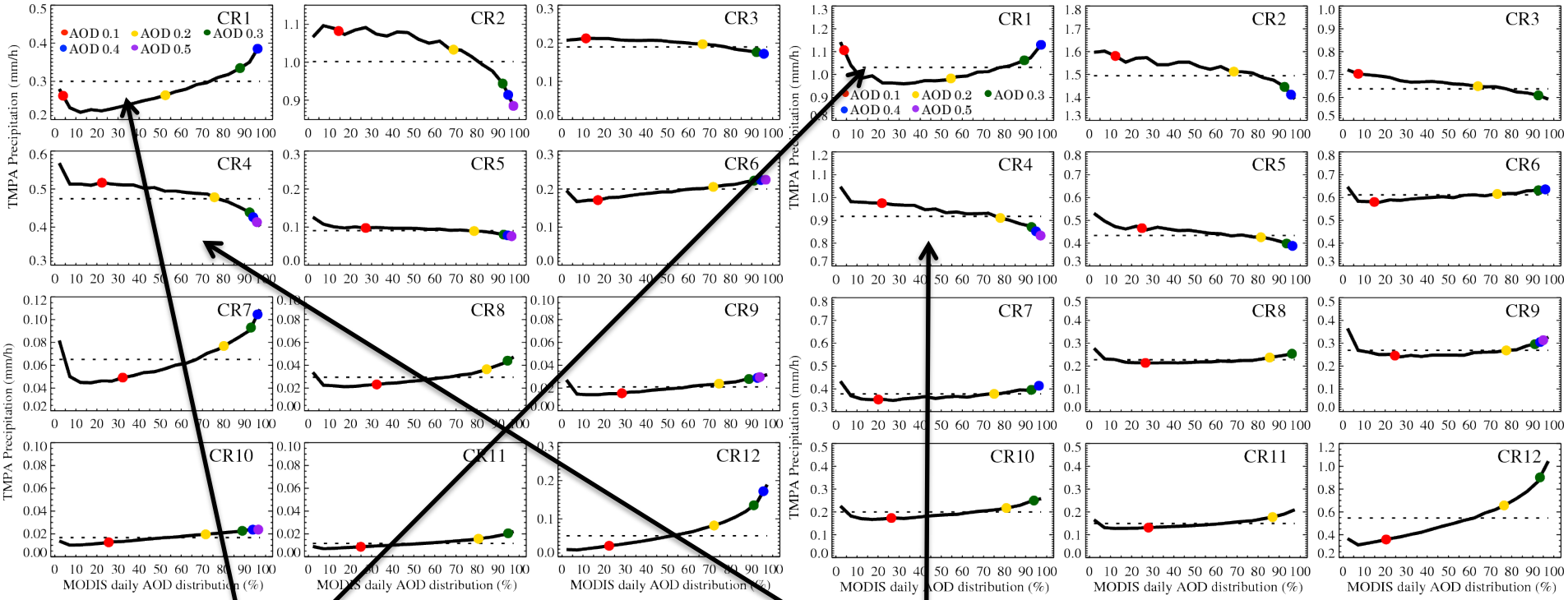


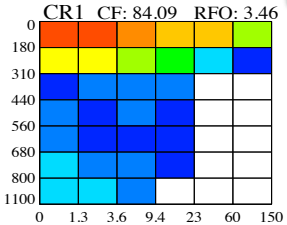
Does inclusion of non-precipitating matter?

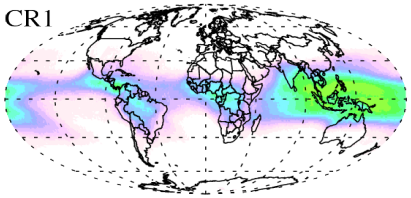
TMPA (P ≥ 0)

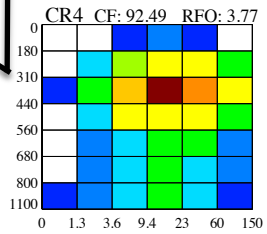
AOD data from MODIS

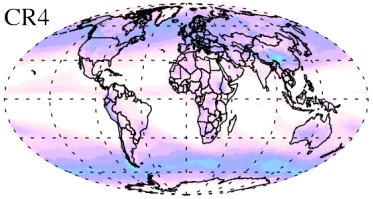
TMPA (P > 0)







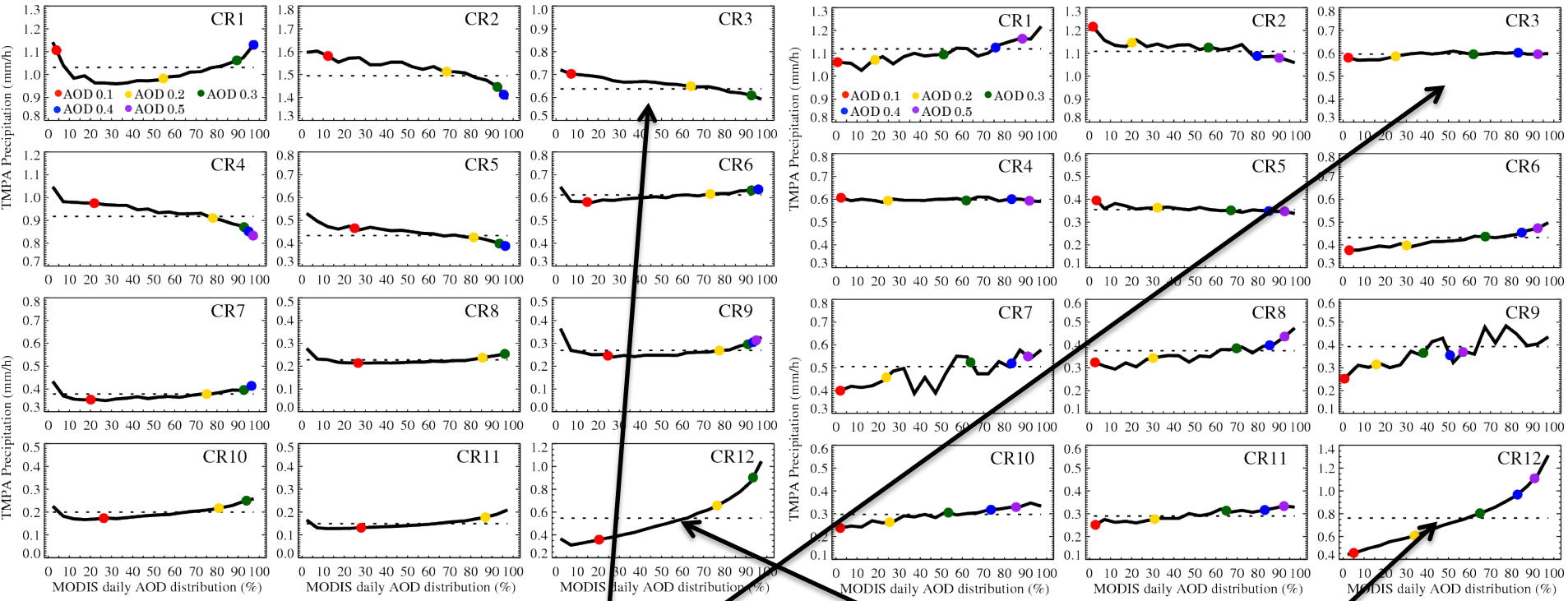


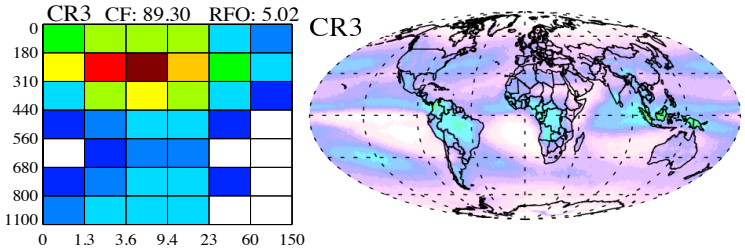


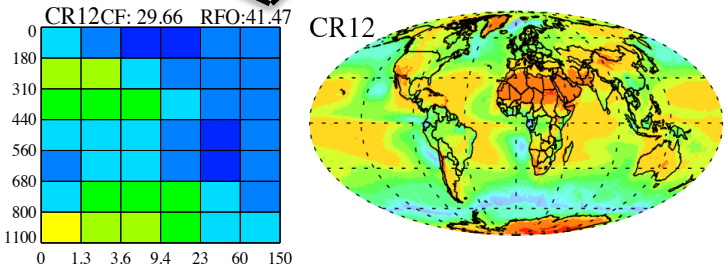
Are there land/ocean differences of precip vs aerosol?

TMPA (P > 0)

Ocean ***Land***



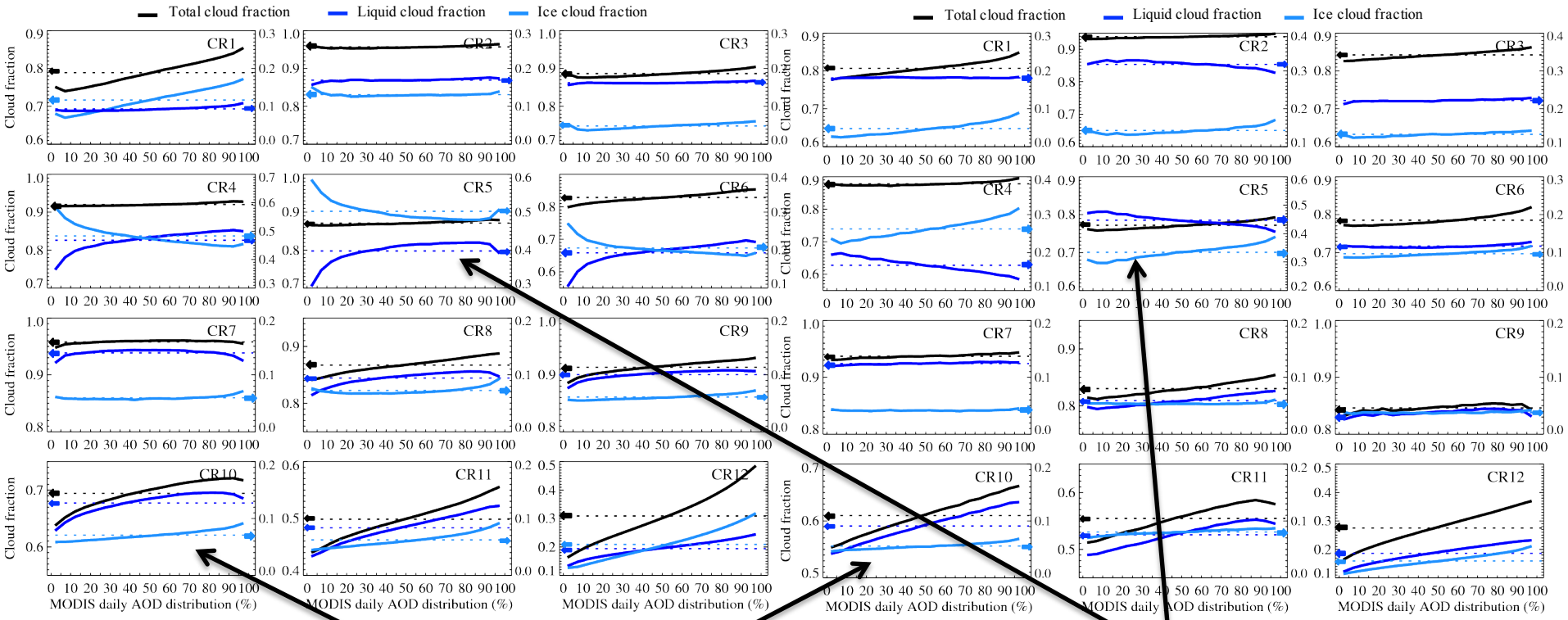


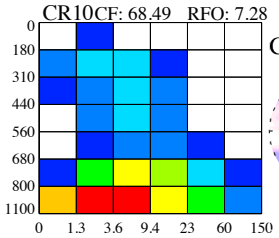


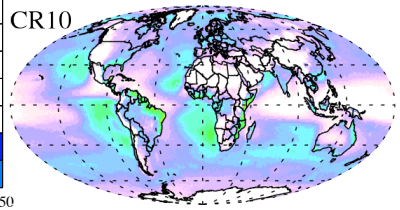
Cloud properties

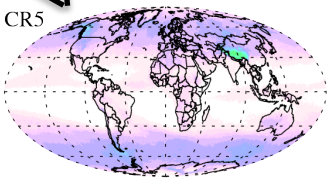
How does CF change with AOD?

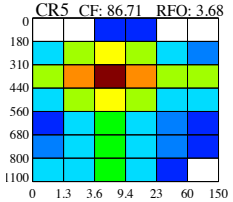
Ocean ***Land***



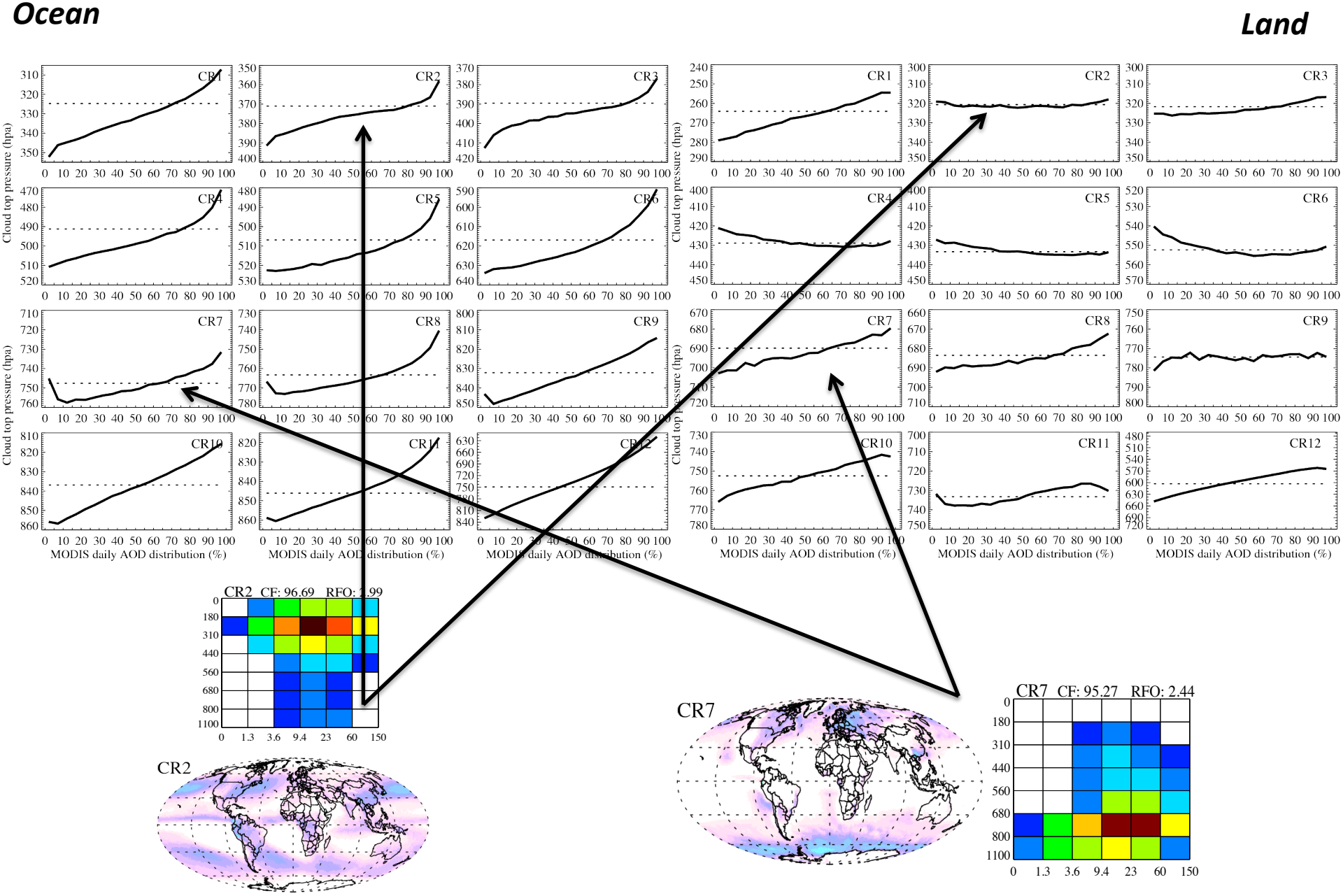






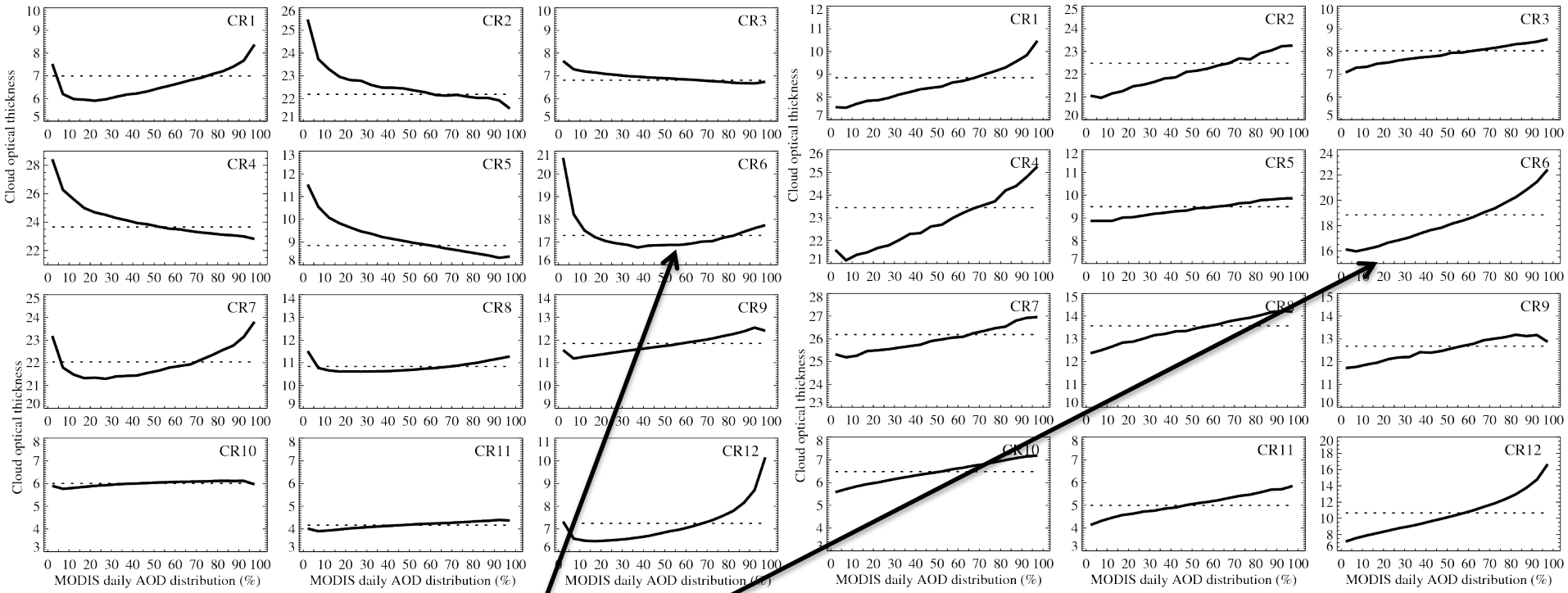


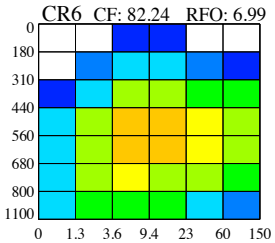
How does cloud top height change with AOD?

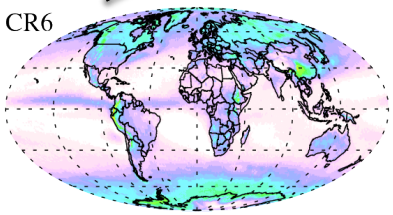


How does cloud opacity change with AOD?

Ocean ***Land***

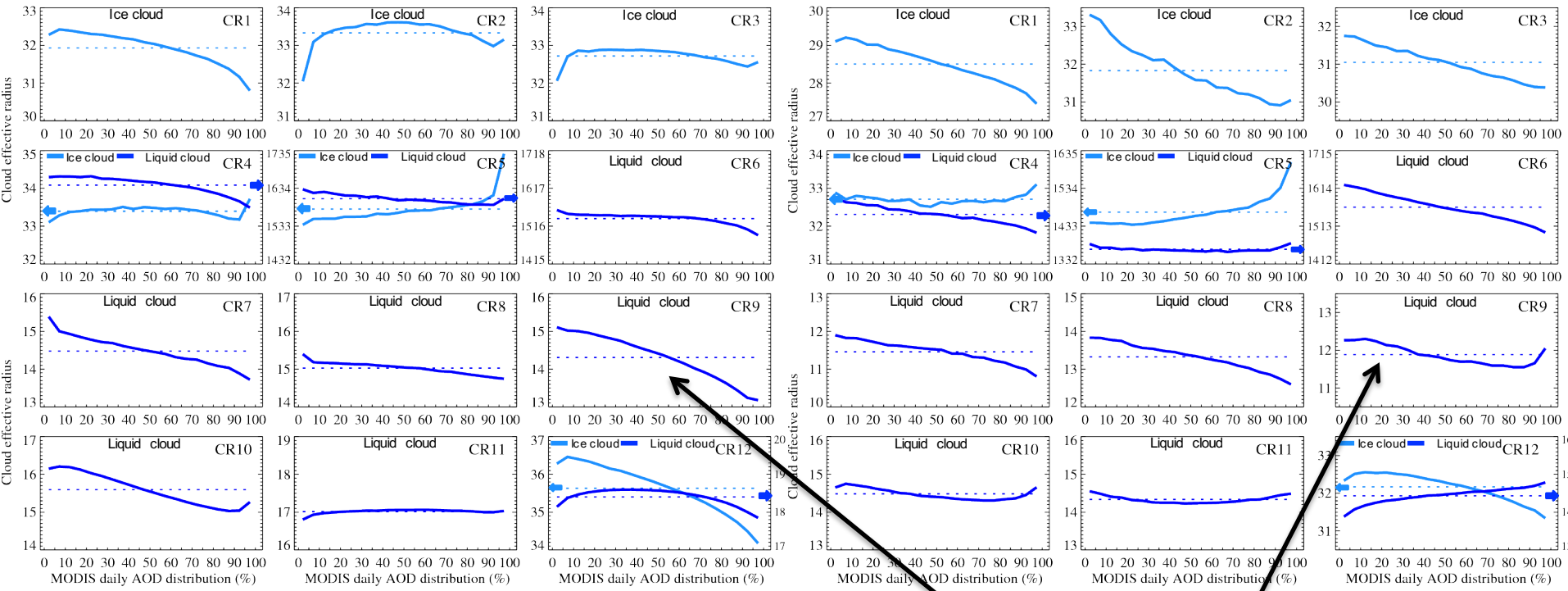


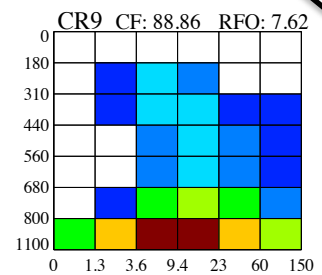


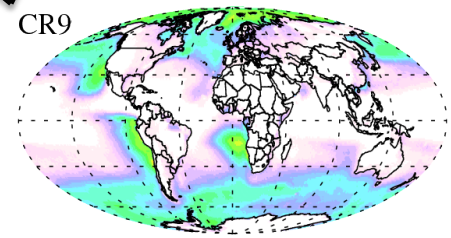


How does particle size change with AOD?

Ocean ***Land***







Summary

Ice regime : CR1- CR3
Liquid regime : CR6 – CR11
Mix regime : CR4 – CR5
CR12

MODIS AOD distribution

	ICE		LIQ		MIX		CR12	
	Land	Ocean	Land	Ocean	Land	Ocean	Land	Ocean
P>0	–		⇑	–	–	⇓	⇑	
CF	⇑		⇑		–		⇑	
CTH	⇑		⇑		⇓	⇑	⇑	
COT	⇑	–	⇑		⇑	⇓	⇑	
CER	⇓	–	⇓		–		–	
P≥0	–		–	⇑	–	⇓	⇑	

MERRA AOD distribution

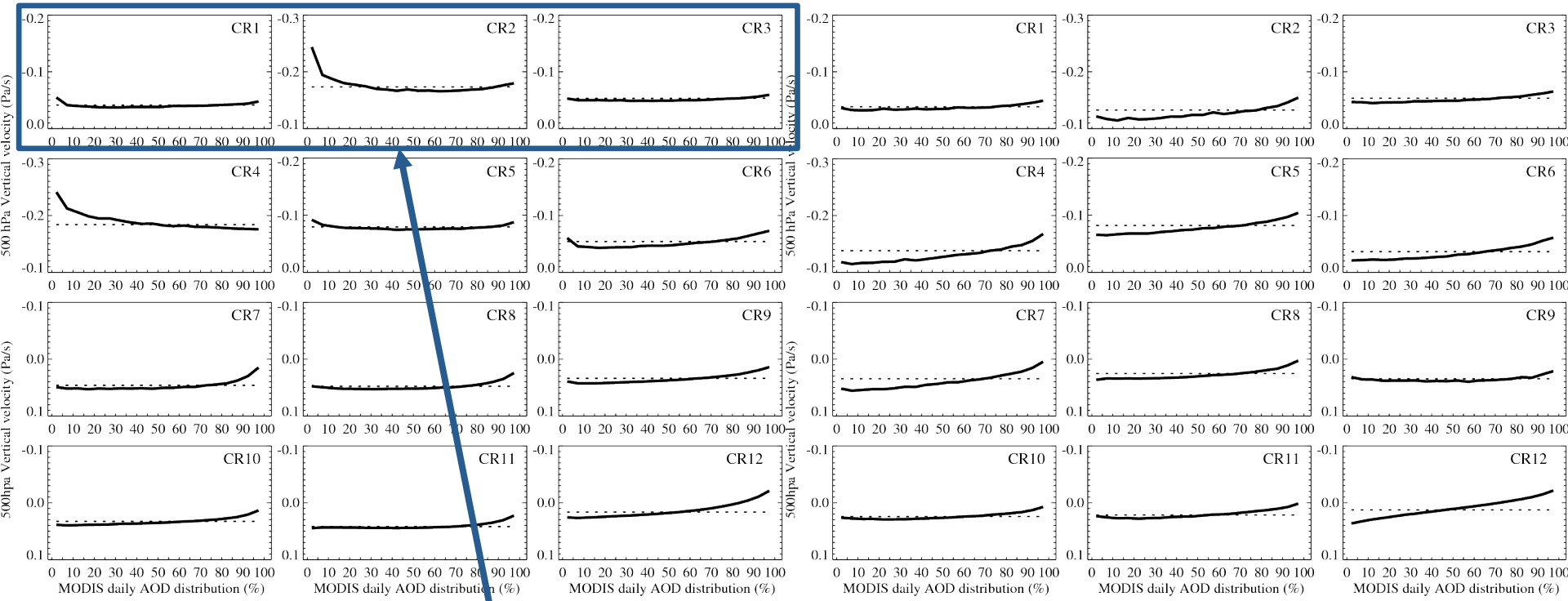
	ICE		LIQ		MIX		CR12	
	Land	Ocean	Land	Ocean	Land	Ocean	Land	Ocean
P>0	–	⇓	⇑	⇑	–	⇓	⇑	
CF	–		⇑		–		⇑	
CTH	⇓		⇑		⇓		⇑	
COT	–		⇑		⇑		⇑	
CER	⇓		⇓		–		–	
P≥0	⇓		⇑		–		⇑	

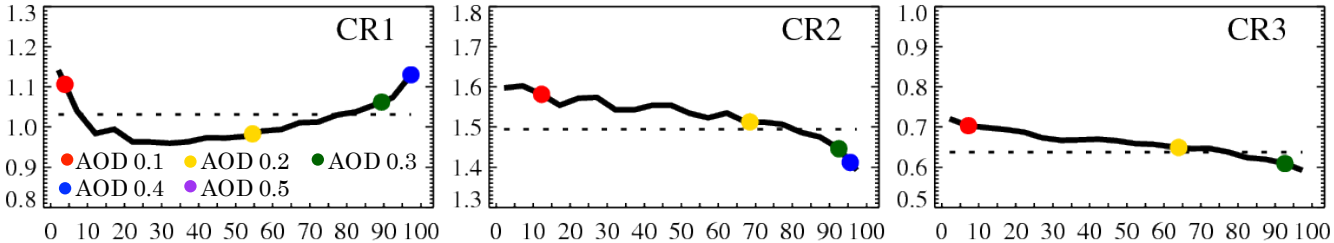
red arrow: consistent with invigoration; blue arrow: consistent with 1st and 2nd indirect effect

Role of Meteorology

How much does vertical motion change across AODs?

Ocean ***Land***



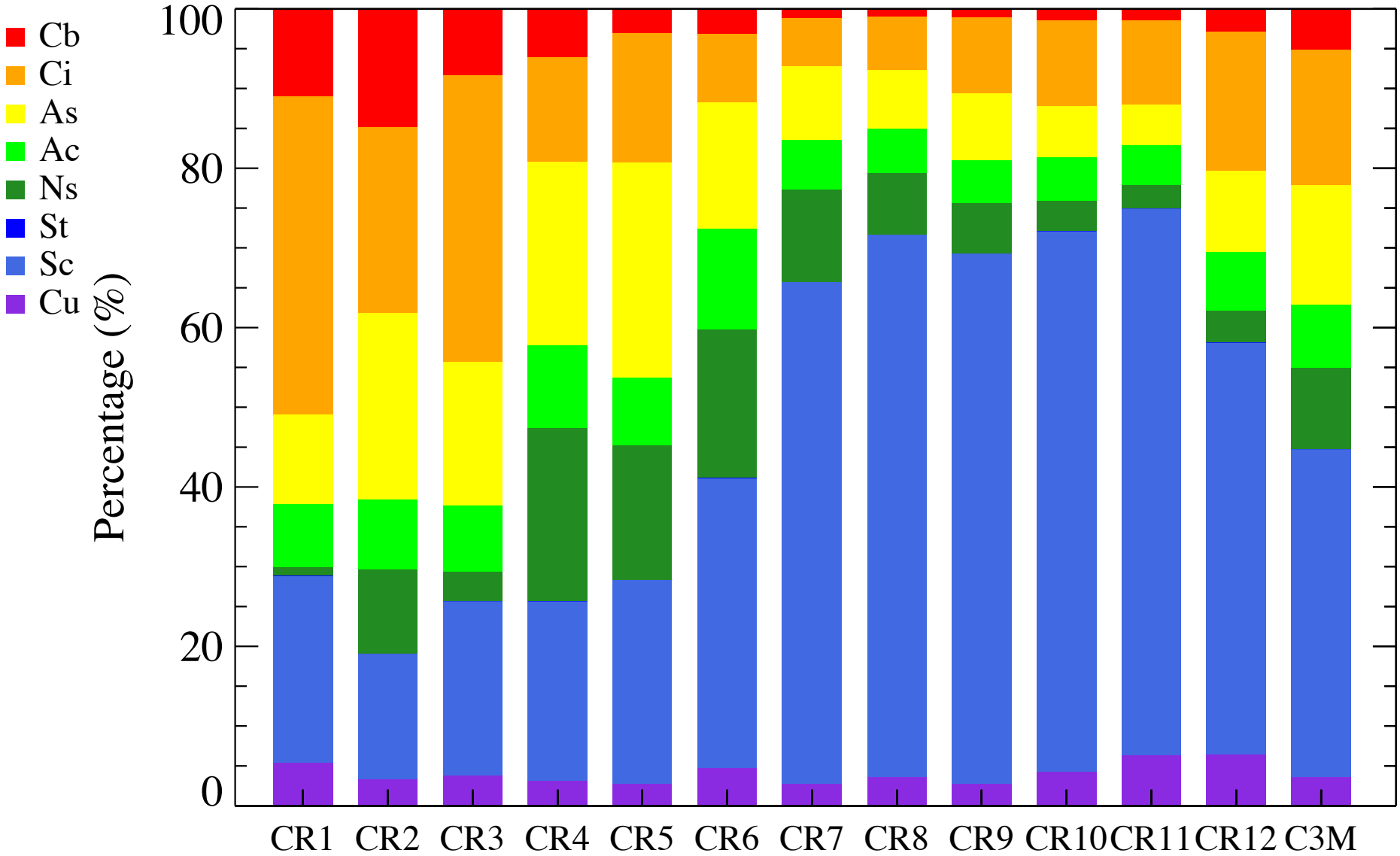


Is this progress, Yoram?

- A regime-based approach is suitable for studying aerosol-cloud-precipitation interactions on (near) global scalers
- Precipitation and cloud property variability with AOD seems very systematic (”good looking” curves)
- According to MODIS:
  - *No clear sign of invigoration (scavenging interferes?)*
  - *Aerosol indirect effects (increased CF, REFF) in liquid CRs*
  - *Cloud tops always rise with aerosol over ocean*
  - *TAU always increases with aerosol over land*
  - *Land-ocean contrasts are substantial*
  - *Low CF CR exhibits consistent behavior worth exploring further*
- Results should be interpreted with sampling and retrieval quality issues in mind. Is re-analysis AOD more appropriate?
- Meteorological co-variations (non-aerosol) currently investigated

Additional Slides

(Aqua) CR cloud type breakdown per CloudSat



Ice regime : CR1- CR3
Liquid regime : CR6 – CR11
Mix regime : CR4 – CR5
CR12

MODIS AOD absolute values

	ICE		LIQ		MIX		CR12	
	Land	Ocean	Land	Ocean	Land	Ocean	Land	Ocean
P>0	–		⇑		⇓		⇑	
CF	⇑		⇑		–		–	
CTH	⇑		⇑		⇑		⇑	–
COT	–		–		⇓		⇑	
CER	–		⇓		–		⇓	
P≥0	⇑		⇑		⇓		⇑	

MERRA AOD absolute values

	ICE		LIQ		MIX		CR12	
	Land	Ocean	Land	Ocean	Land	Ocean	Land	Ocean
P>0	–		⇑		–		⇑	
CF	–		⇑		–		–	
CTH	⇓		⇑		⇓	–	⇑	
COT	–		⇑		–		⇑	
CER	⇓		⇓		–		–	
P≥0	⇓		⇑		–		⇑	

red arrow: consistent with invigoration; blue arrow: consistent with 1st and 2nd indirect effect

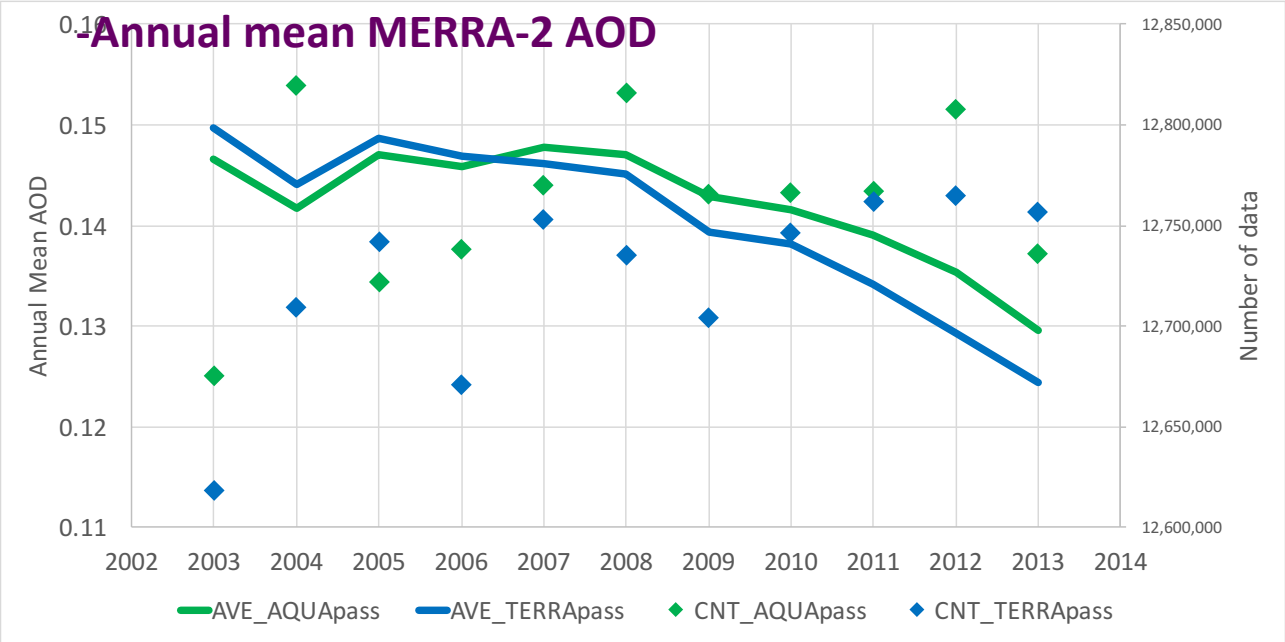
Analysis permutations

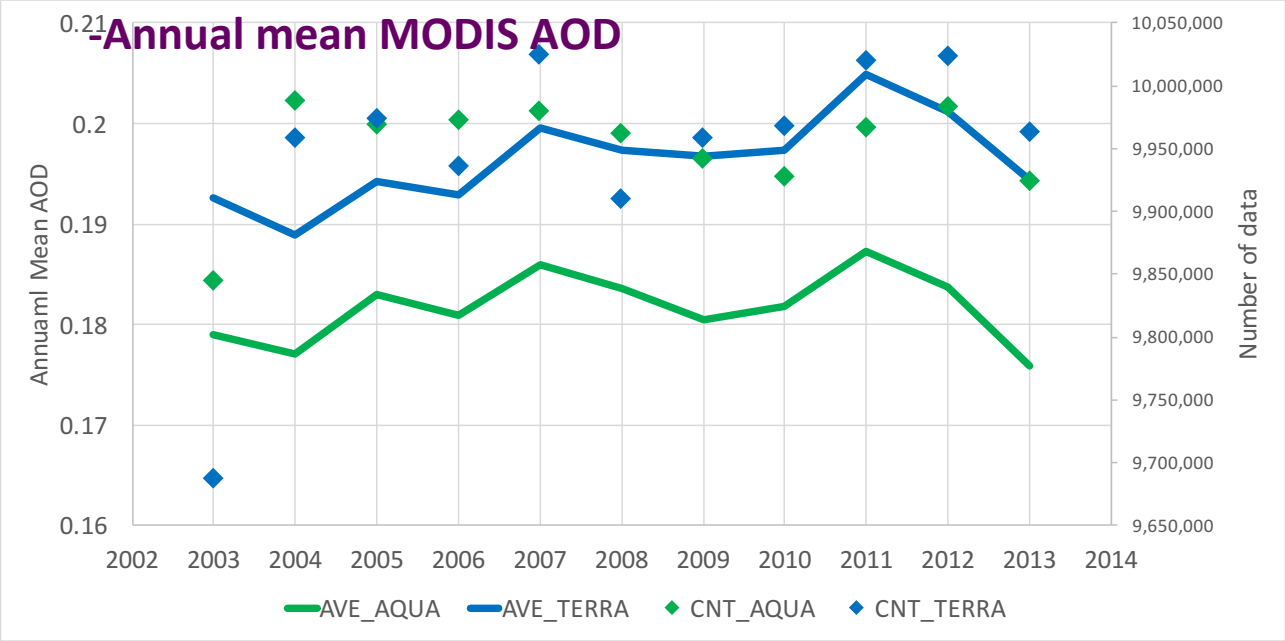
- Aerosol “low” vs high”: absolute/relative
- Aerosol from MODIS C6 or MERRA-2
- For precip: Ignore or not non-precipitating gridcells
- Global vs land/ocean breakdown
- For cloud properties: Separate by phase

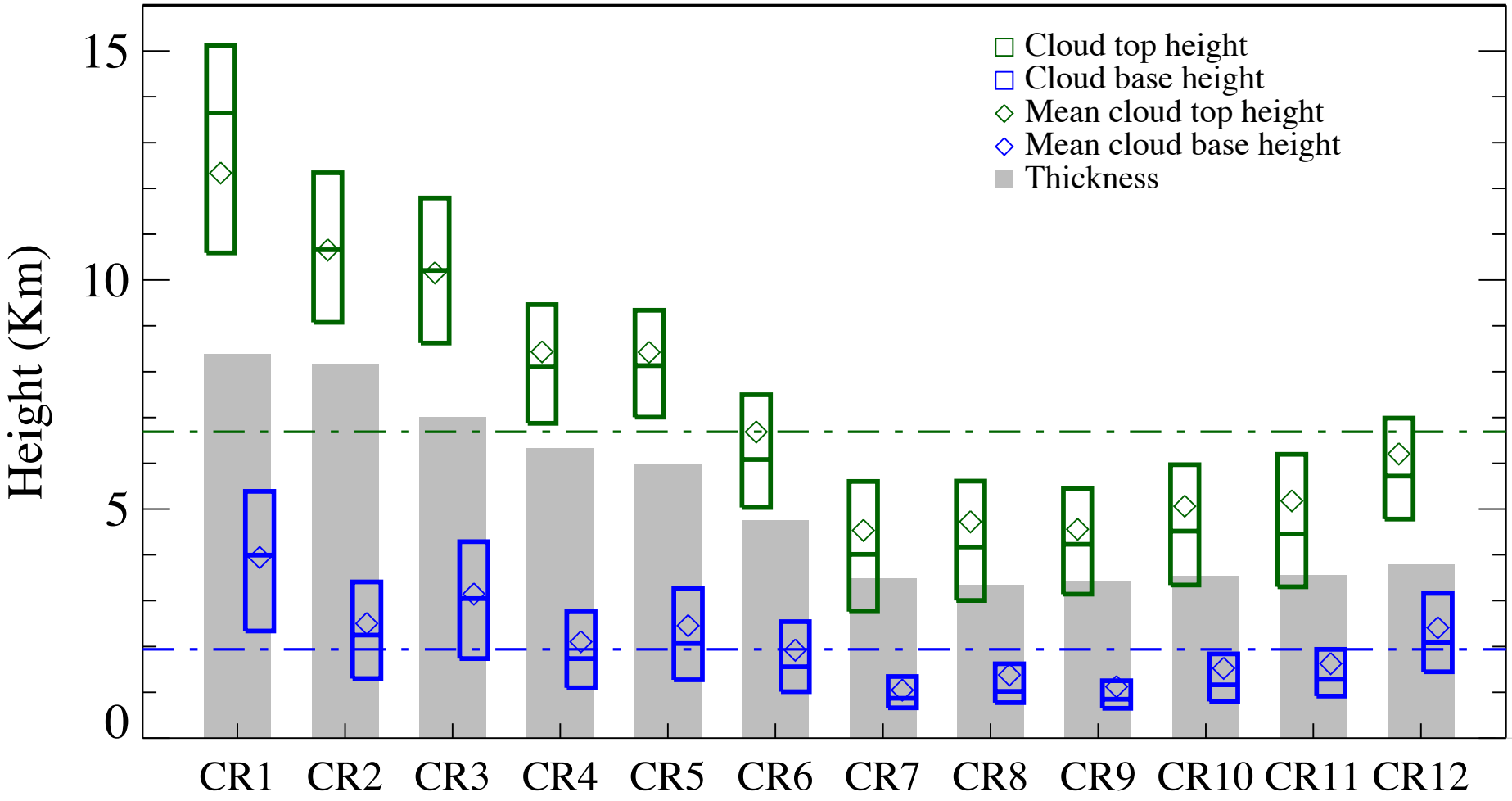
- I won’t show all results!

MODIS-MERRA-2 aerosol comparison (2)

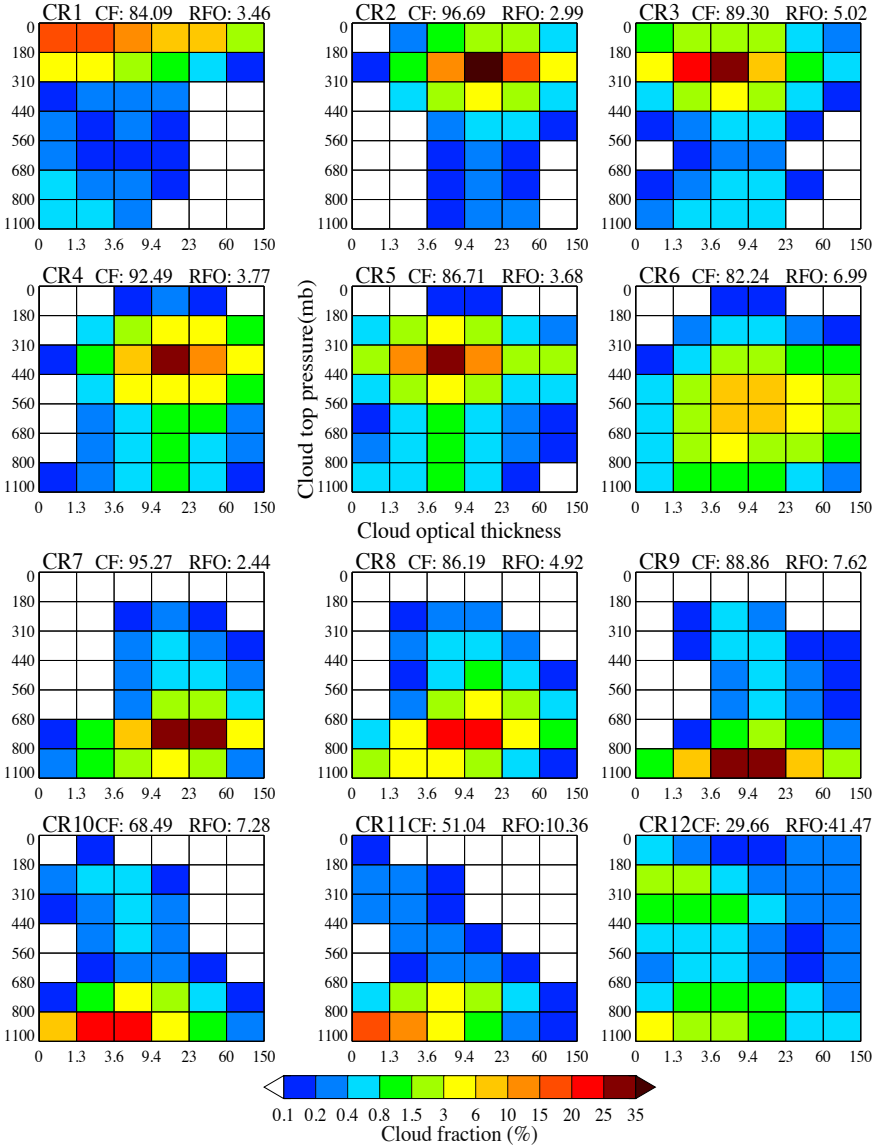
50S-50N

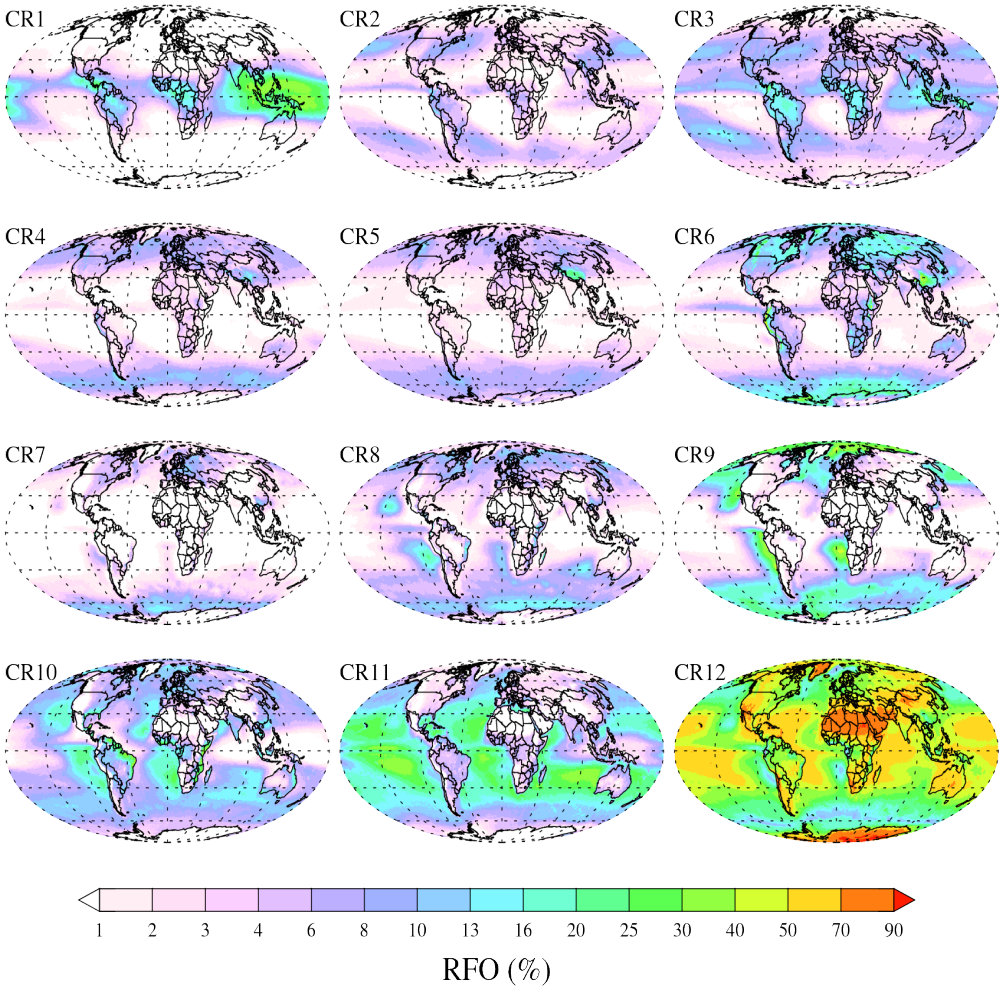


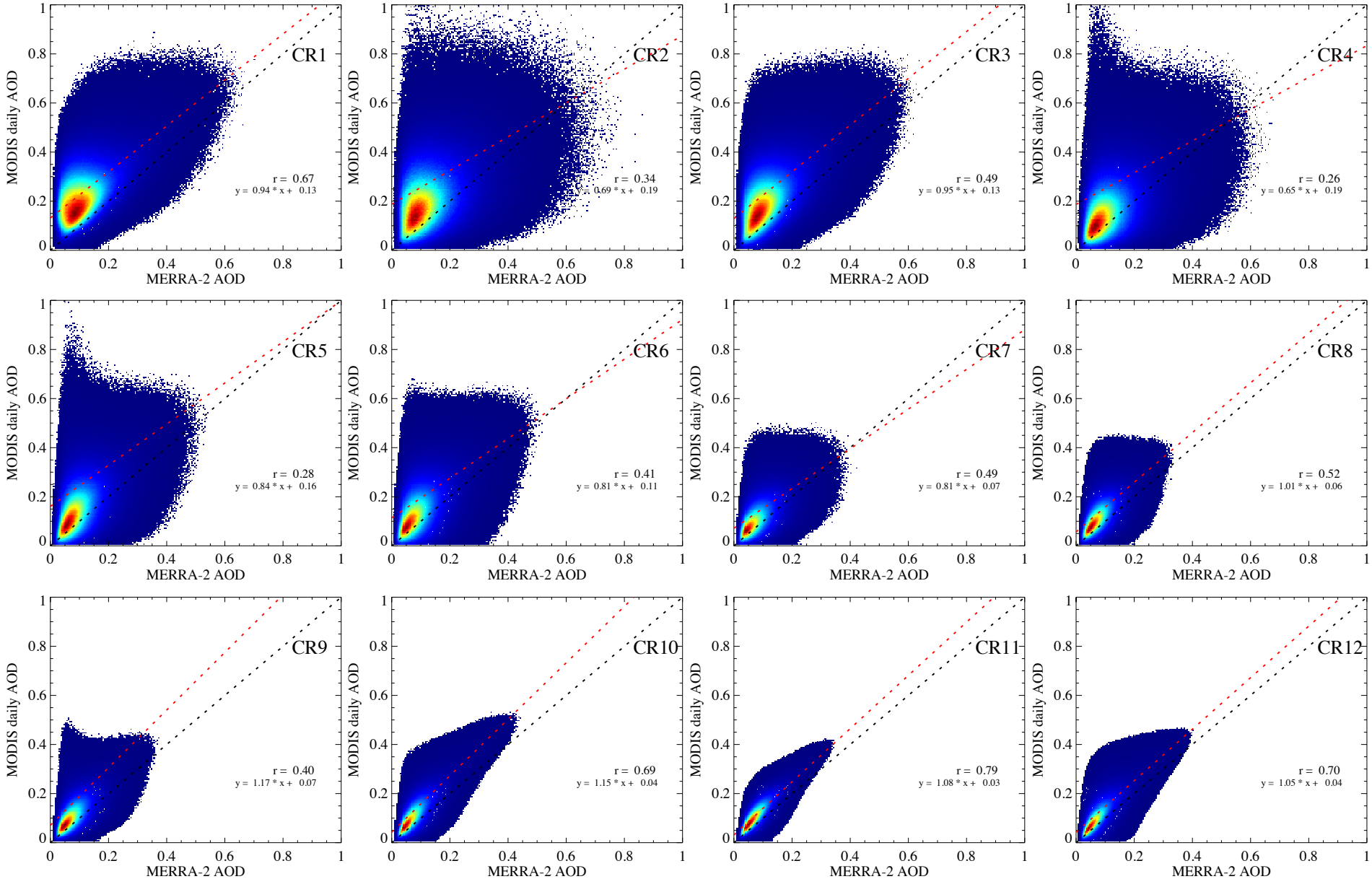



Cloud top height
Cloud base height
Mean cloud top height
Mean cloud base height
Thickness
Height (Km)
15
10
5
0
CR1
CR2
CR3
CR4
CR5
CR6
CR7
CR8
CR9
CR10
CR11
CR12

The full picture



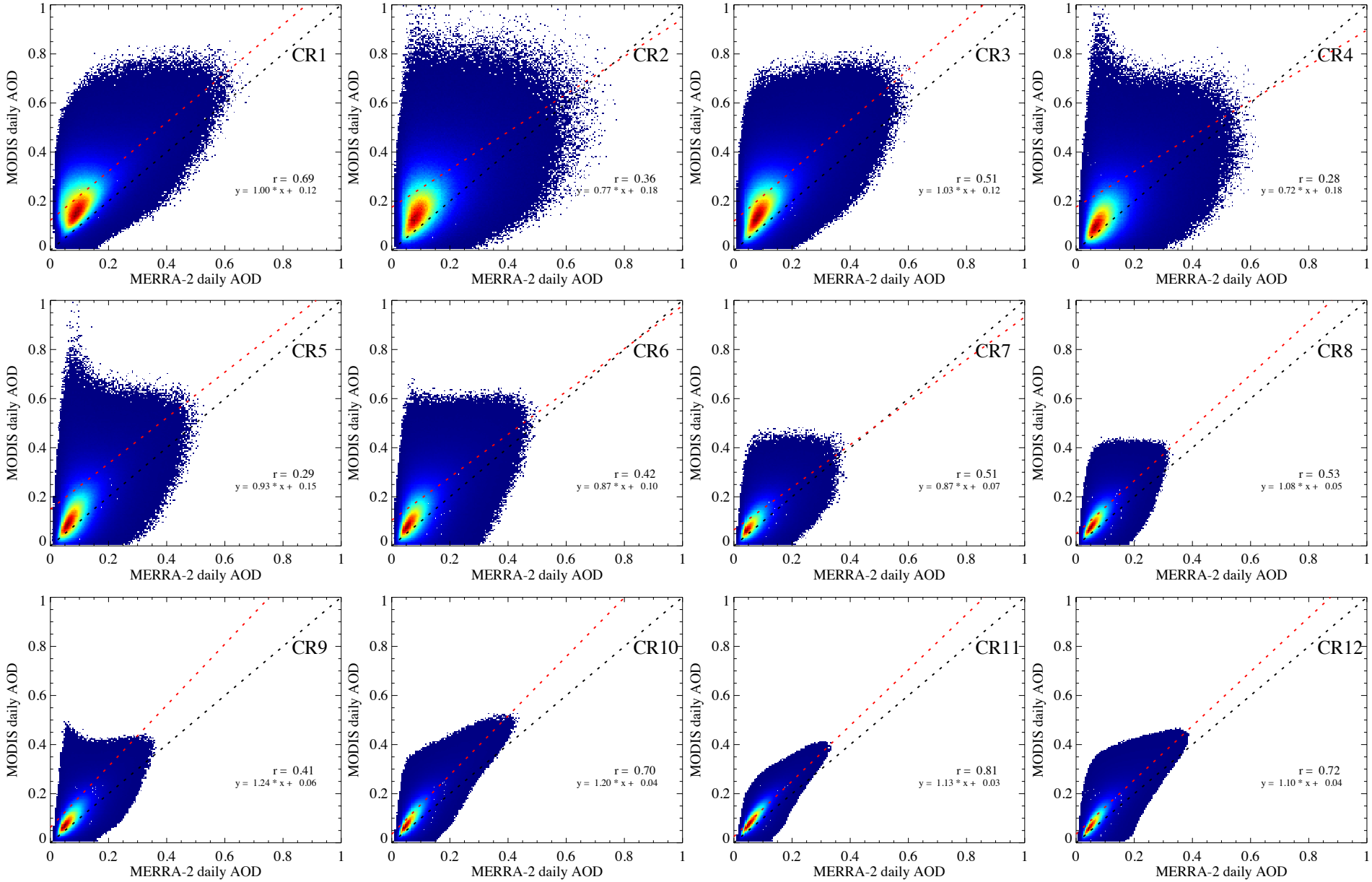




Comparison of MERRA-2AOD to MODIS daily AOD over MODIS the spatial-temporal matching for 12-years.

MODIS daily AOD - MERRA2AOD aqua passing time

MODIS daily AOD - MERRA2 AOD terra passing time



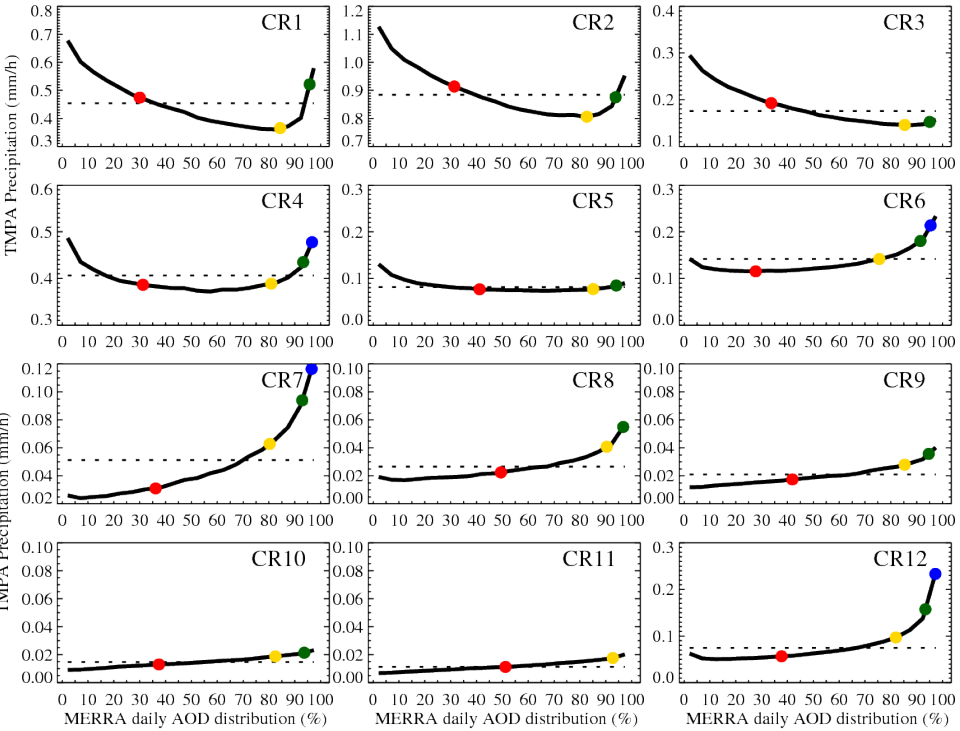
Comparison of MERRA-2 daily AOD to MODIS daily AOD over MODIS the spatial-temporal matching for 12-years.

MODIS daily AOD - MERRA2 daily AOD

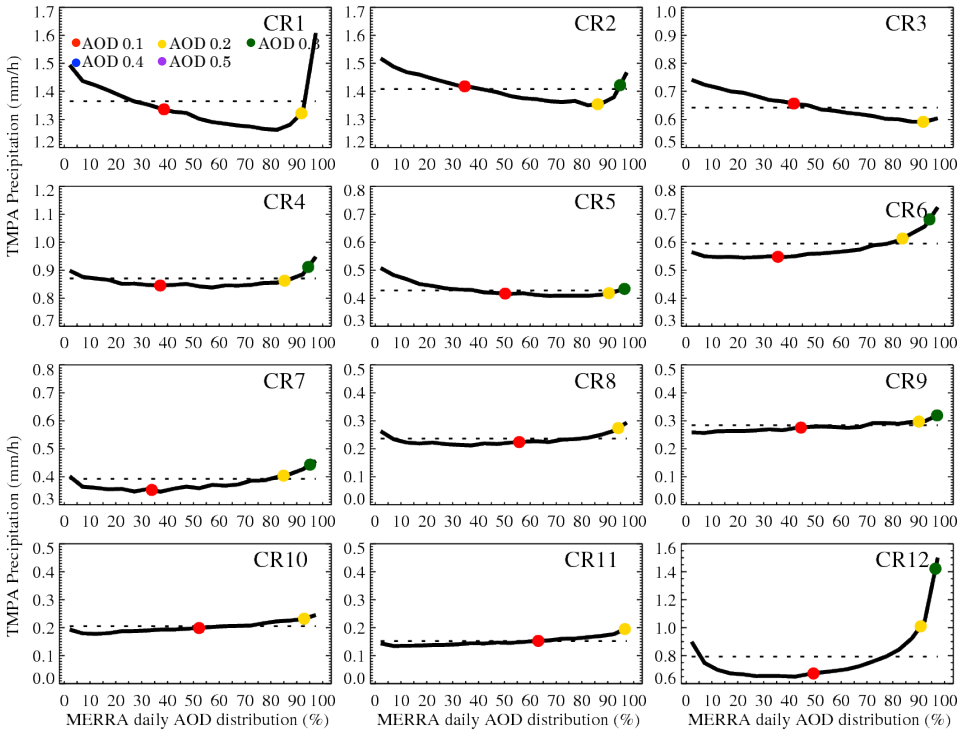
::: **MERRA-2 daily AOD = (MERRA-2 MYD AOD + MERRA-2 MOD AOD) / 2.**

AOD data from Merra-2

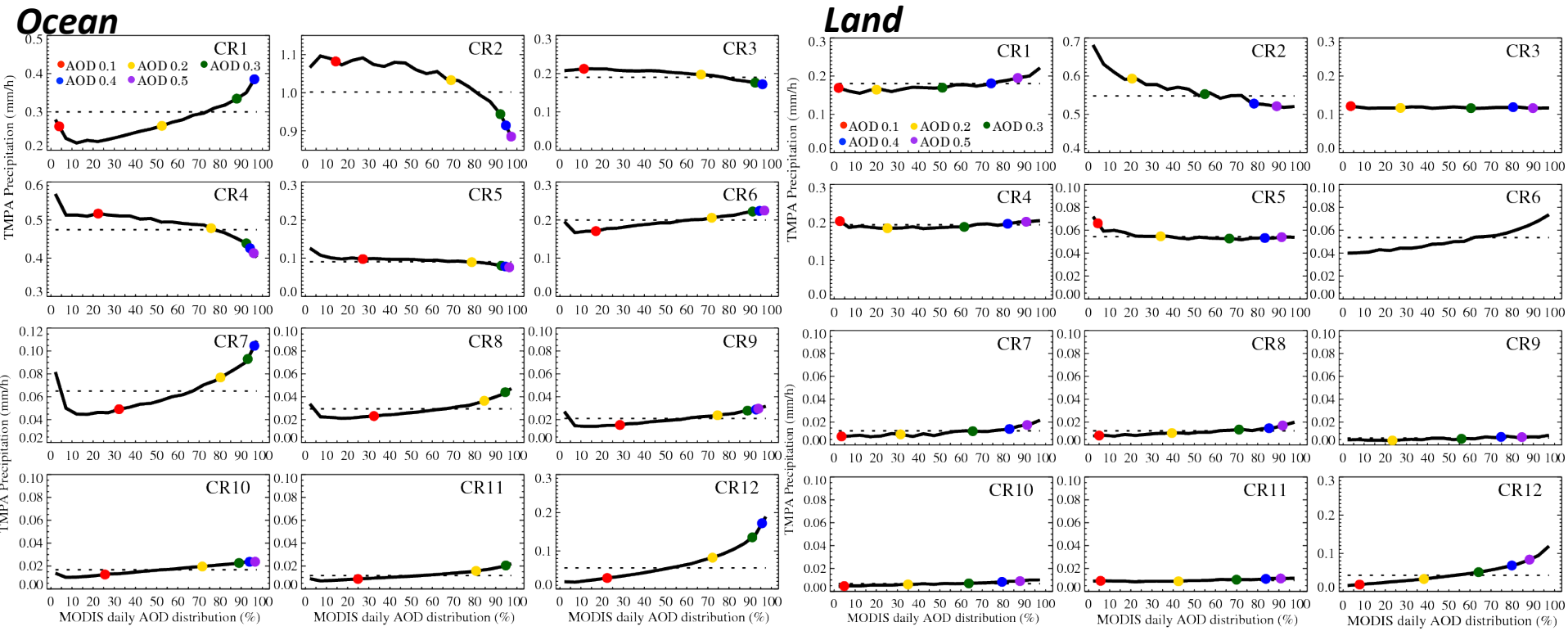
TMPA (P ≥ 0)



TMPA (P > 0)



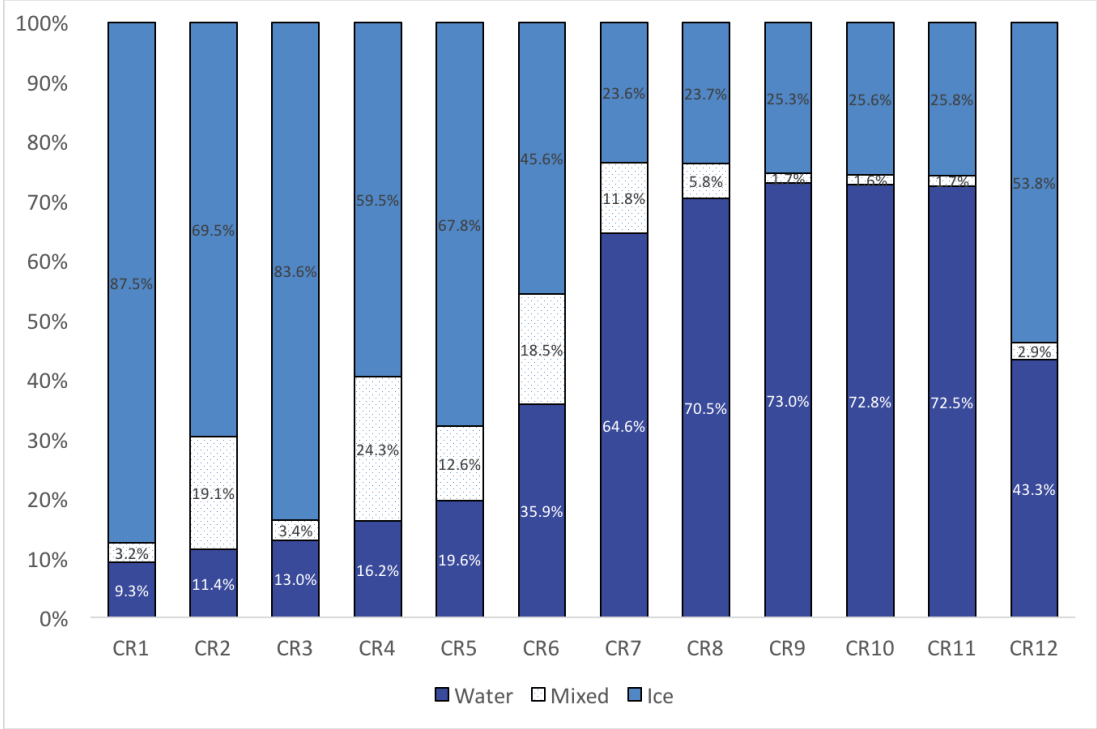
TMPA (P ≥ 0)



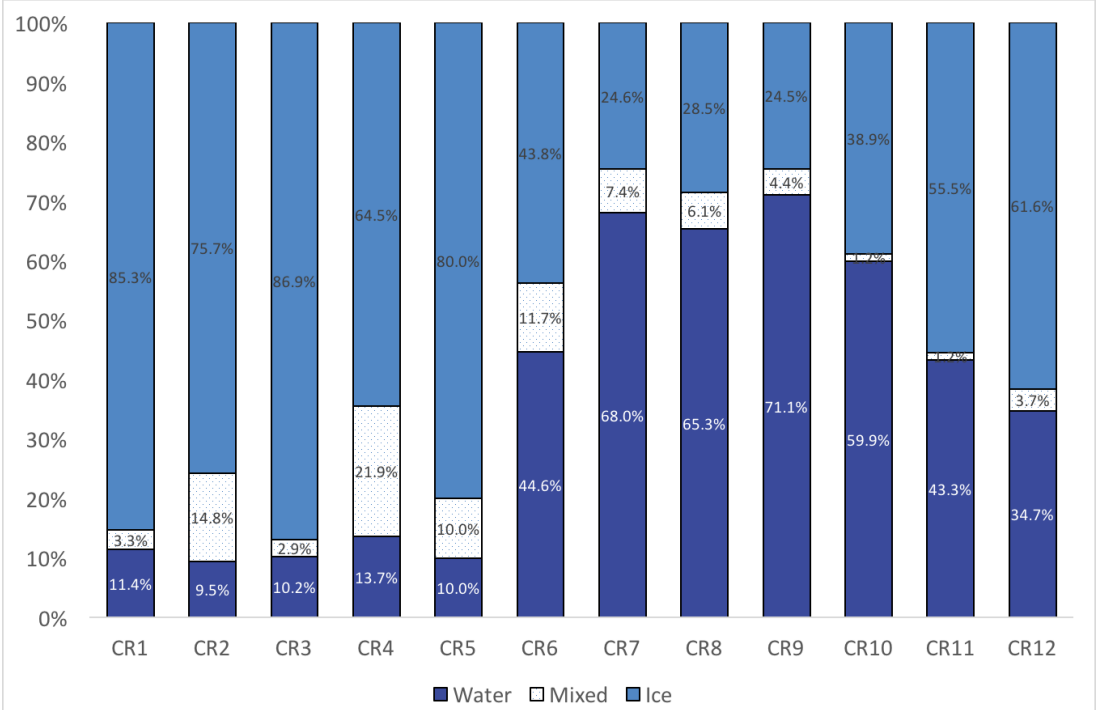
TMPA Precipitation (mm/h) as a function of AOD distribution(per grid per season). The horizontal dashed line is mean TMPA precipitation of each CR. The dots indicate mean AOD within their AOD distribution ranges.
Minimum and maximum values of Y-axis(for TMPA) are different to each CR, but their interval is same.

2B-CLDCLASS-LIDAR
* Cloud phase

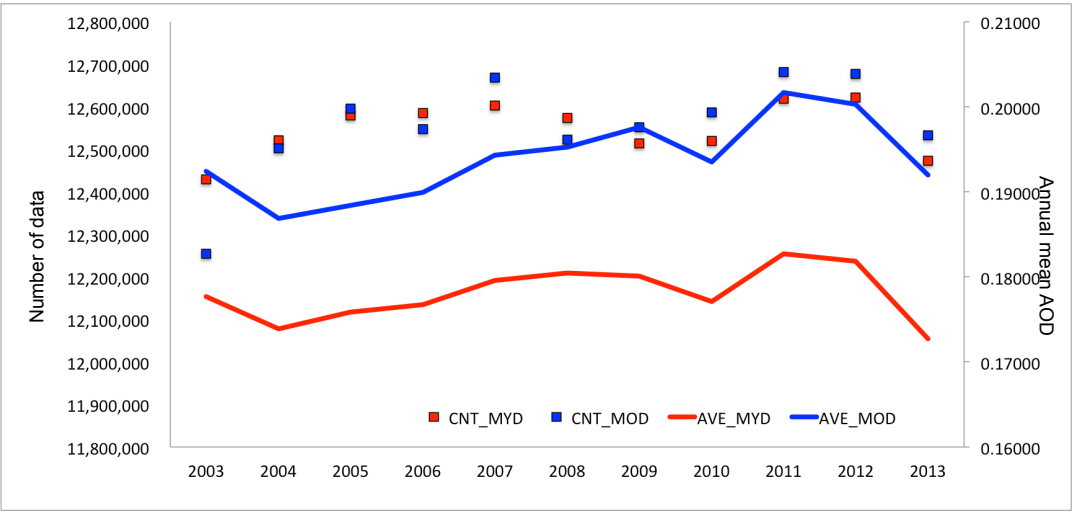
Ocean



Land



-Annual mean MODIS AOD



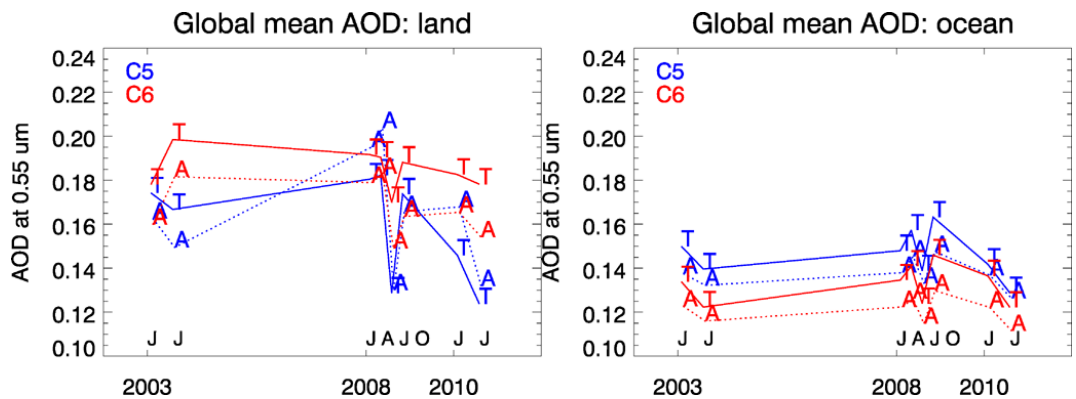


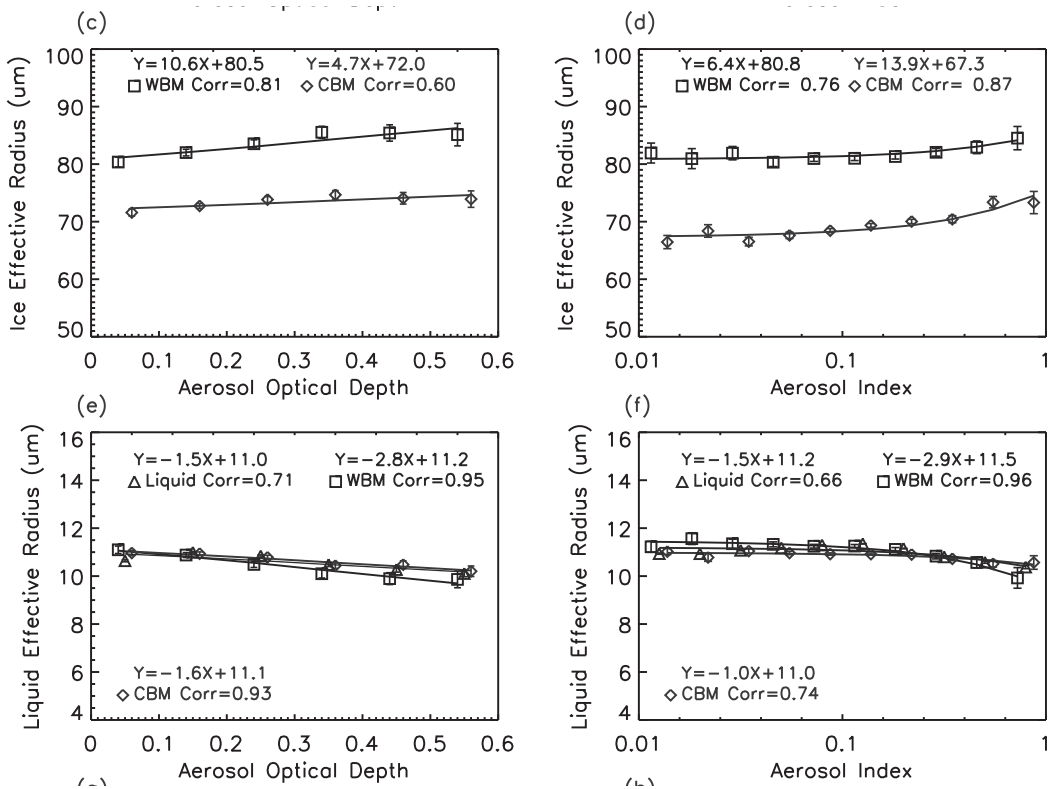
Fig. 23. Global monthly mean AOD for DT-land (left) and DT-ocean (right) for eight test months (January and July for 2003, 2008 and 2010, plus April and October 2008) as computed for Terra (T) versus Aqua (A), and C6 (red) versus C5 (blue).

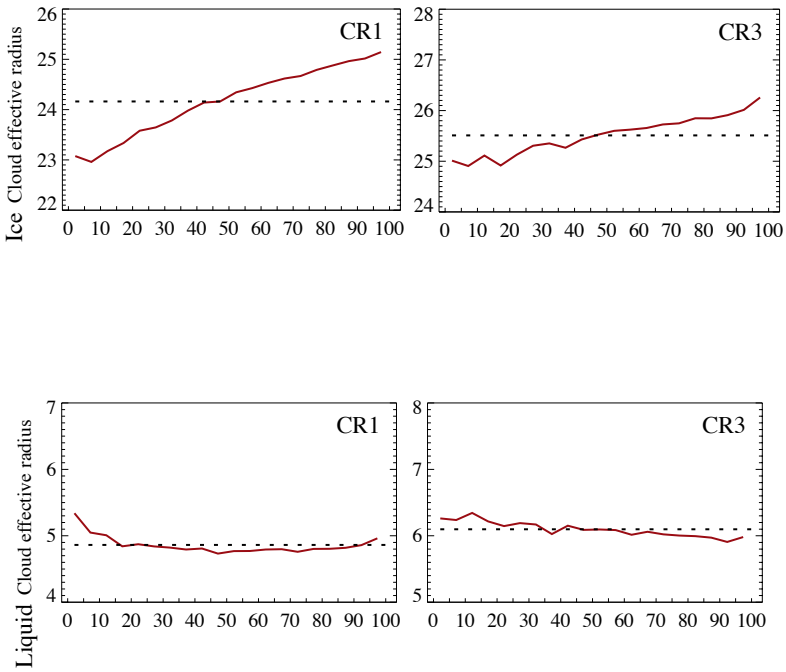
We restate here (from Sect. 2.4) that this is not a calibration or a trend paper. However, since we have already processed eight months of "test data" for both Terra and Aqua, we ask whether Terra/Aqua AOD inconsistencies might remain for C6. Following Tables 2 (for land) and 4 (for ocean), we calculate global, monthly mean AOD for each month, for Terra and Aqua separately, and for both C5 and expected C6 data. The results are plotted as Fig. 23, where C5 (C6) is plotted in blue (red), and Terra and Aqua are plotted as "T" and "A". Over land (left panel), it is clear that M_T and M_A did not well track each other for C5, and that $M_T > M_A$ in 2003, but reversed for 2008 and 2010. Even though the retrieval algorithm was updated for C6, the identical DT-land algorithm is still being used for both sensors' data. For C6, we should expect to see better tracking of M_T with M_A, although an offset of ~ 0.015 remains. Over the ocean (right panel), there will be a significant drop of 0.018 in all months, however the ~ 0.01 offset (described by Remer et al., 2008) will remain for C6. Reducing the Terra/Aqua offset is a topic of future study, but a vicarious gain correction (e.g Franz et al., 2007) may be an option.

At this point, we cannot determine fully how the revised calibration efforts will impact global trends and divergence of Terra and Aqua. However, the preliminary result is that, in fact, the trending differences will most likely be mitigated by the new calibration effort. Unlike the situation in 2007 when the C5 aerosol algorithms were put into operation after testing only on C4 inputs, for C6, we are accounting for expected upstream changes.

Levy et al., 2013

Land Ocean

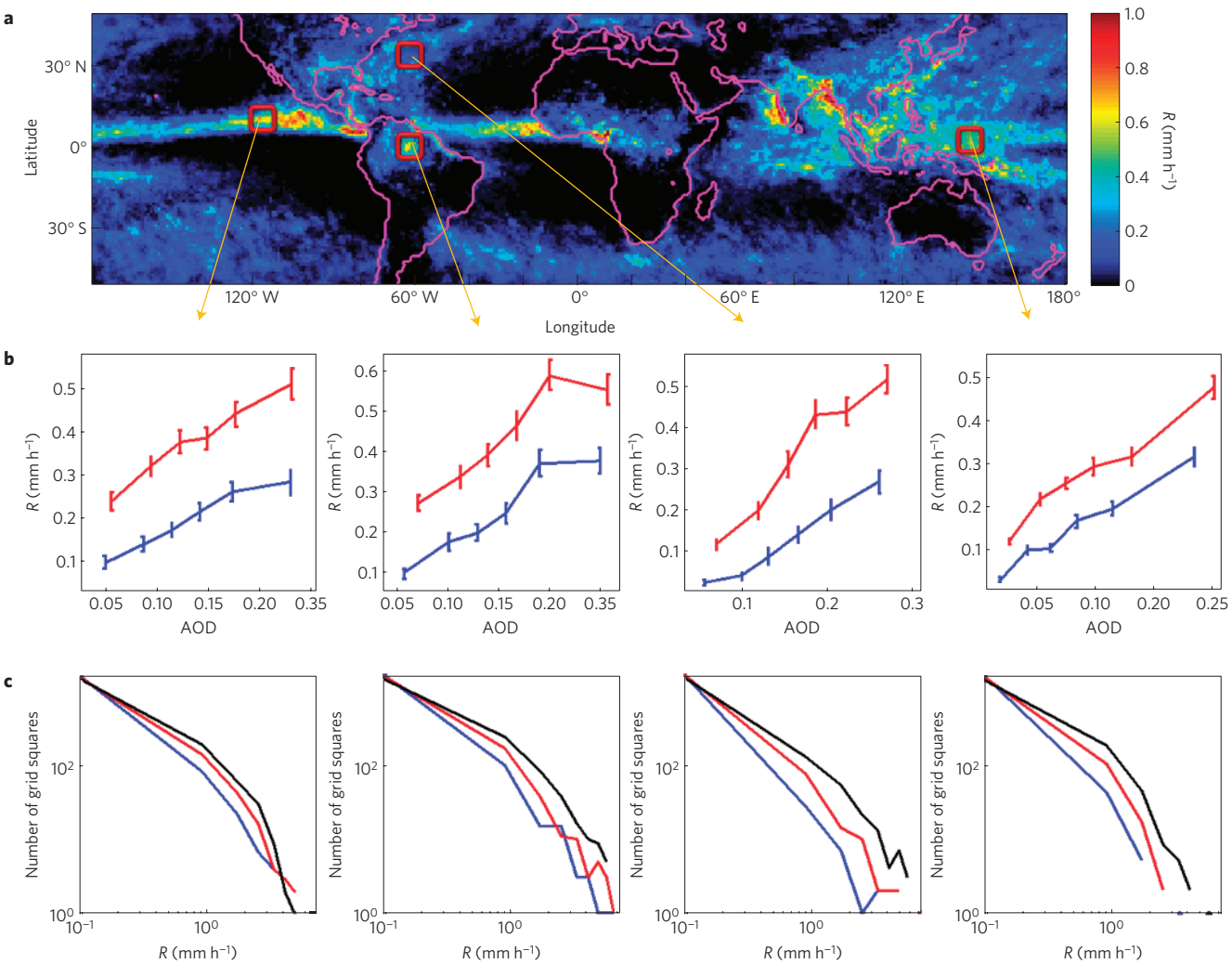




Peng et al., 2016

Region : Tropics (20S – 20N)

Aerosol from MODIS, CER from CloudSat CPR



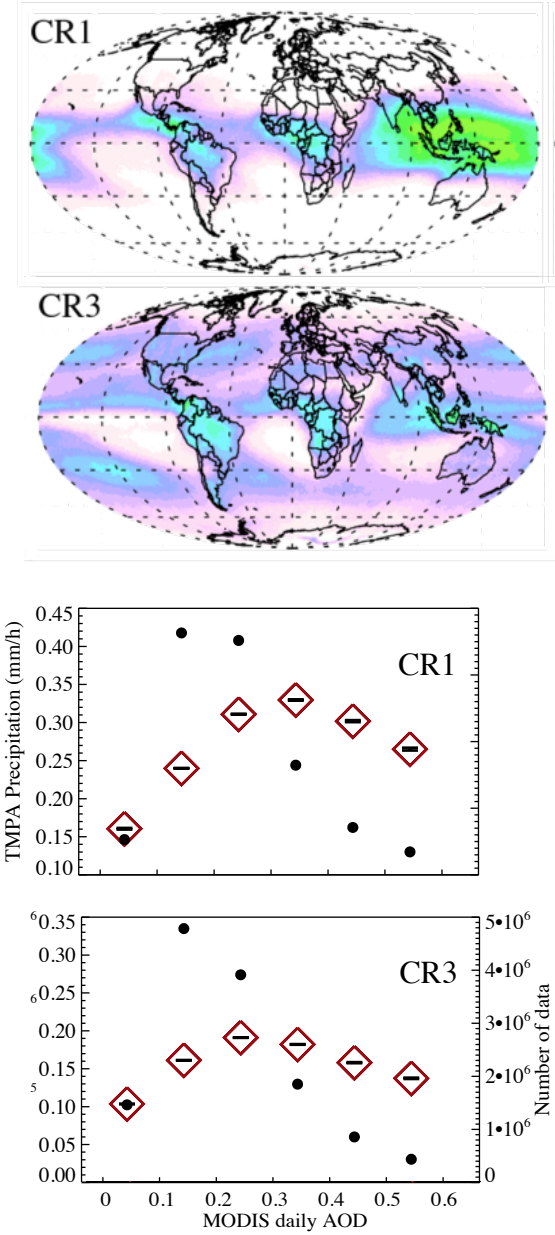


Figure 1 | 13:30 local-time map of rain rate (*R*) and the observed trend with aerosol loading in four selected regions. a, Map of the study area showing average *R* values during June, July and August 2007. **b**, The average *R* values are plotted for six aerosol-loading sets (blue, including zero *R* grid squares; red, without zero *R* grid squares). Vertical bars represent the standard error. **c**, *R* histograms are plotted for three aerosol-loading sets (average AOD: blue 0.07, red 0.12, black 0.22). Note the *R* intensification as a function of AOD in all cases.

Koren et al., 2012