Radiative and Aerosol Indirect Effect Studies based on MODIS Cloud Regimes

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Motivation

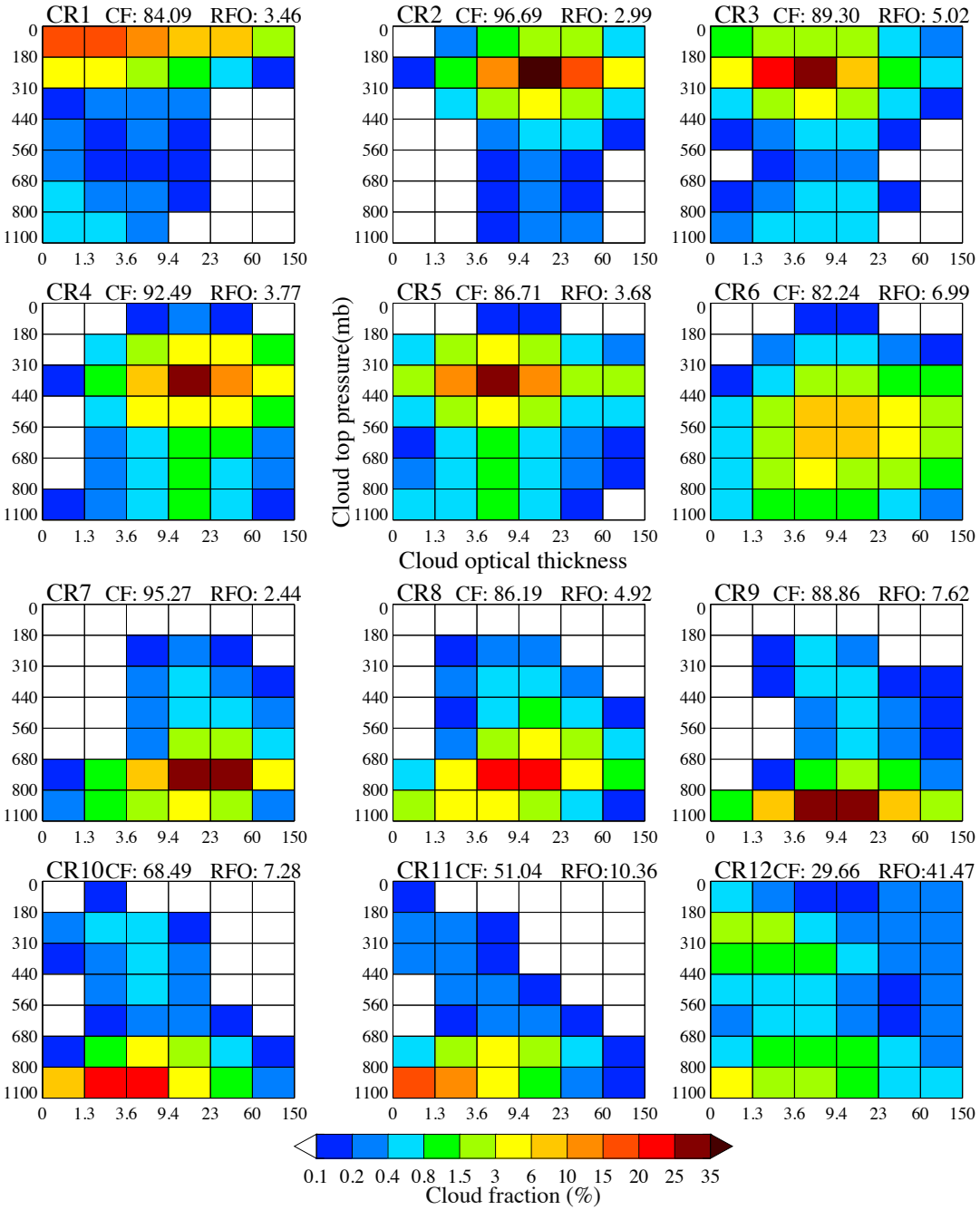
- Need to understand effects of clouds on Earth's Radiation Budget (ERB) – improve details of ERB-cloud coupling in GCMs
- Need to understand effects of aerosols on clouds and precipitation and eventually on ERB (again with representation of processes in GCMs in mind)
  - Problem poses obvious observational challenges
  - How to separate aerosol from all other effects?
- In both cases, breaking down the analysis by "regime" (groups of similar cloud conditions) may help
- At scales O(100km)^2 likely to encounter cloud "mixtures" rather than isolated cloud "types"
- Regimes pose <u>some</u> constraint on environmental conditions (similar clouds ←→similar environment)
- But how do we define regimes?
  - Exploiting cloud appearance (from passive obs) is a good starting point
- We adopt a "cloud regime" (CR) kind based on CTP-TAU joint histograms
  - Our CRs are based on MODIS (you may also know ISCCP "Weather States")

Datasets

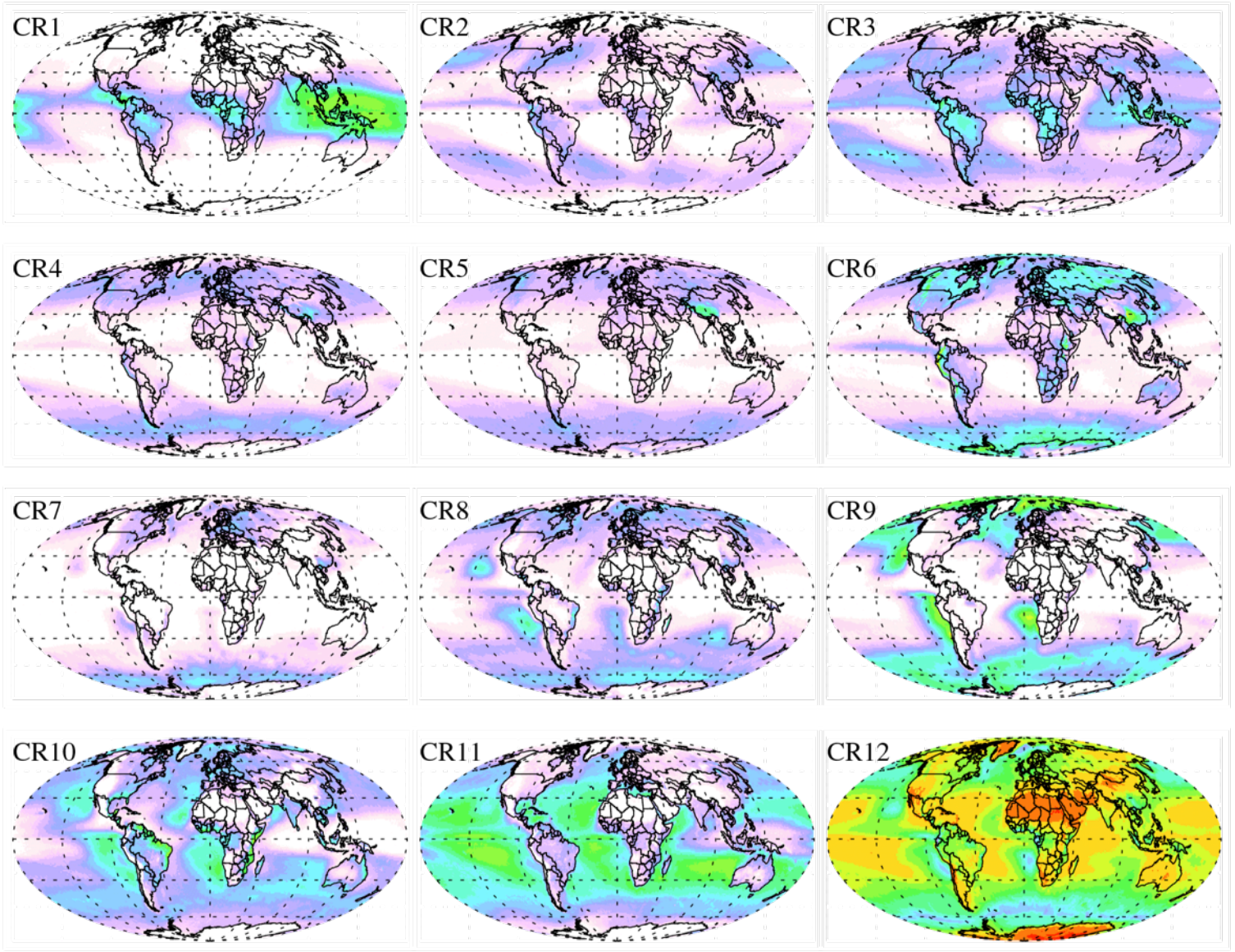
- ***12 years*** of Aqua-Terra L-3 daily (D3) 1° data
  - Collection 6
- Joint histograms of CTP-TAU
  - MODIS CRs from *k-means* clustering
- Other cloud variables: CF, CTP, TAU, REFF
- Dark Target AOD (and MERRA-2 AOD, 3-hr, not shown)
- CERES SYN1deg daily
- TMPA-3B42 surface precipitation (3-hr, 0.25°)
  - 50°S-50°N
- Collocated CloudSat-CALIPSO products


MODIS CRs

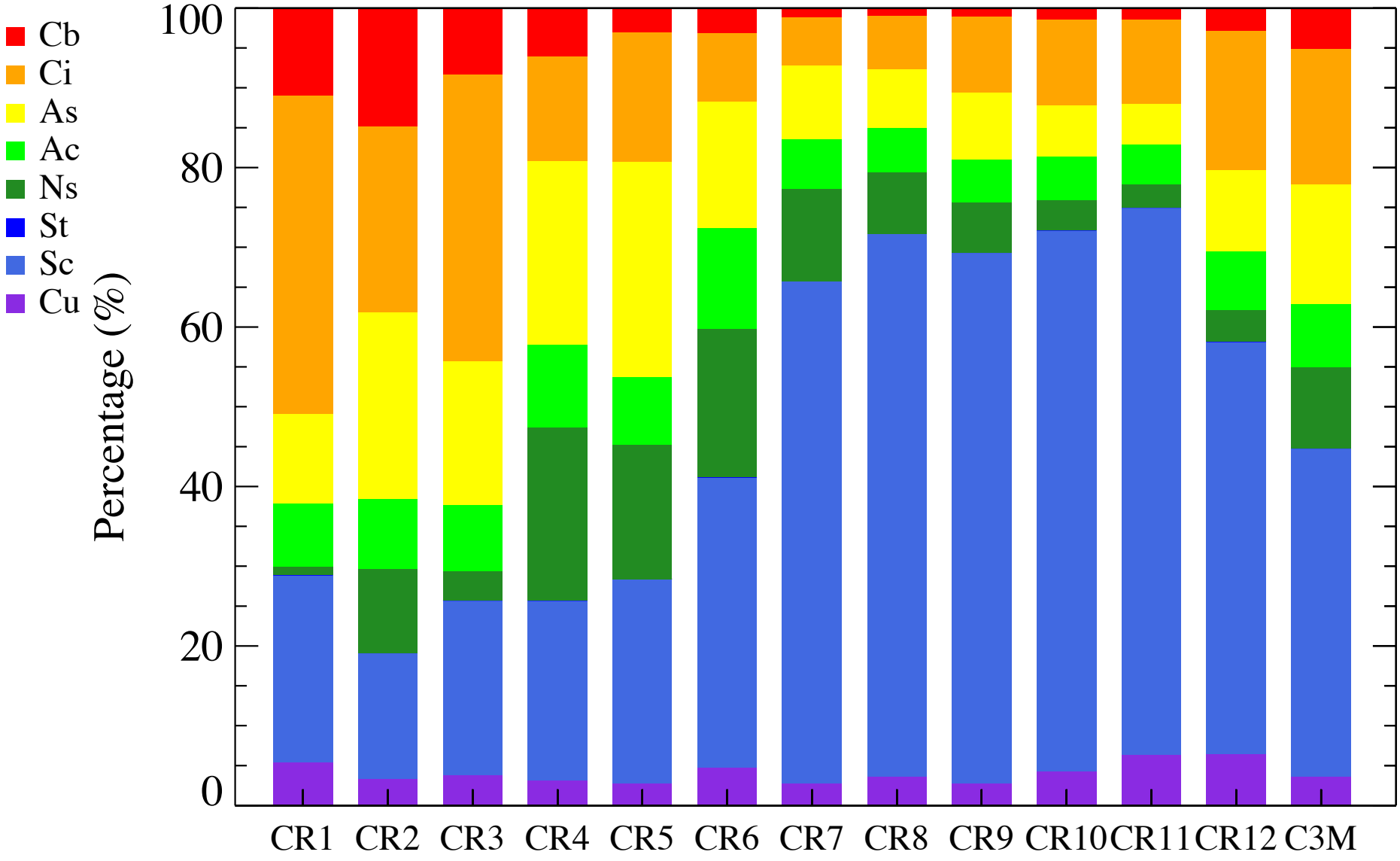
Global MODIS C6 CRs



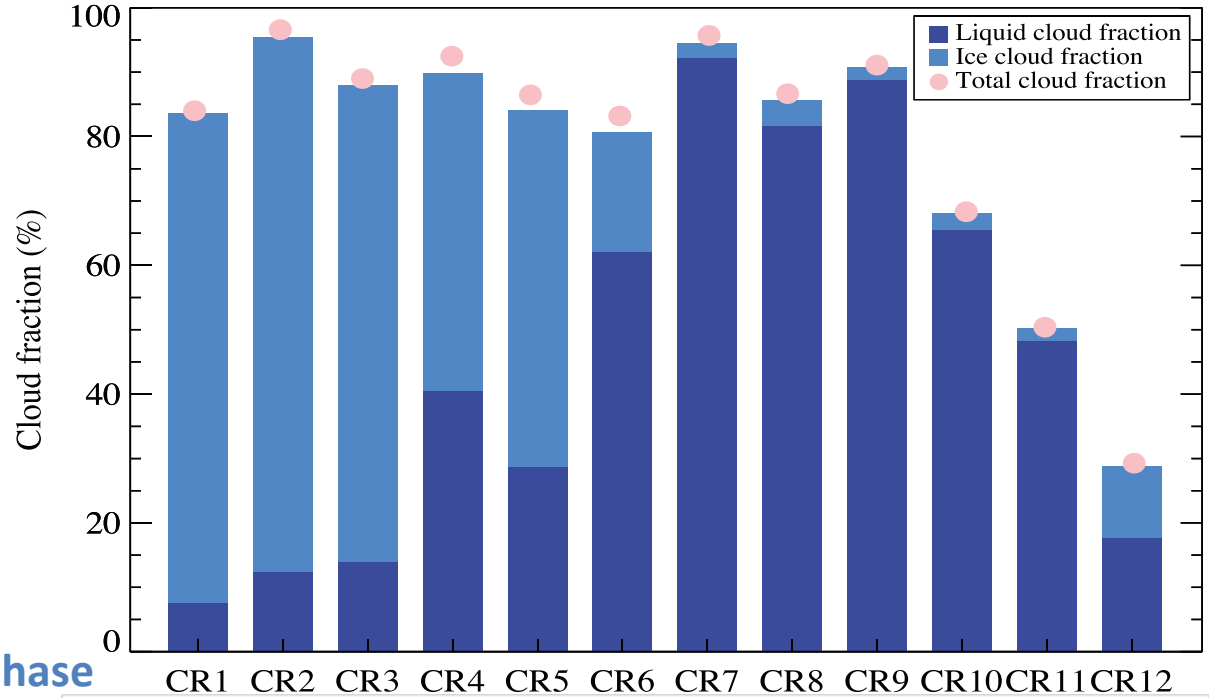
Where the CRs occur



(Aqua) CR cloud type breakdown per CloudSat

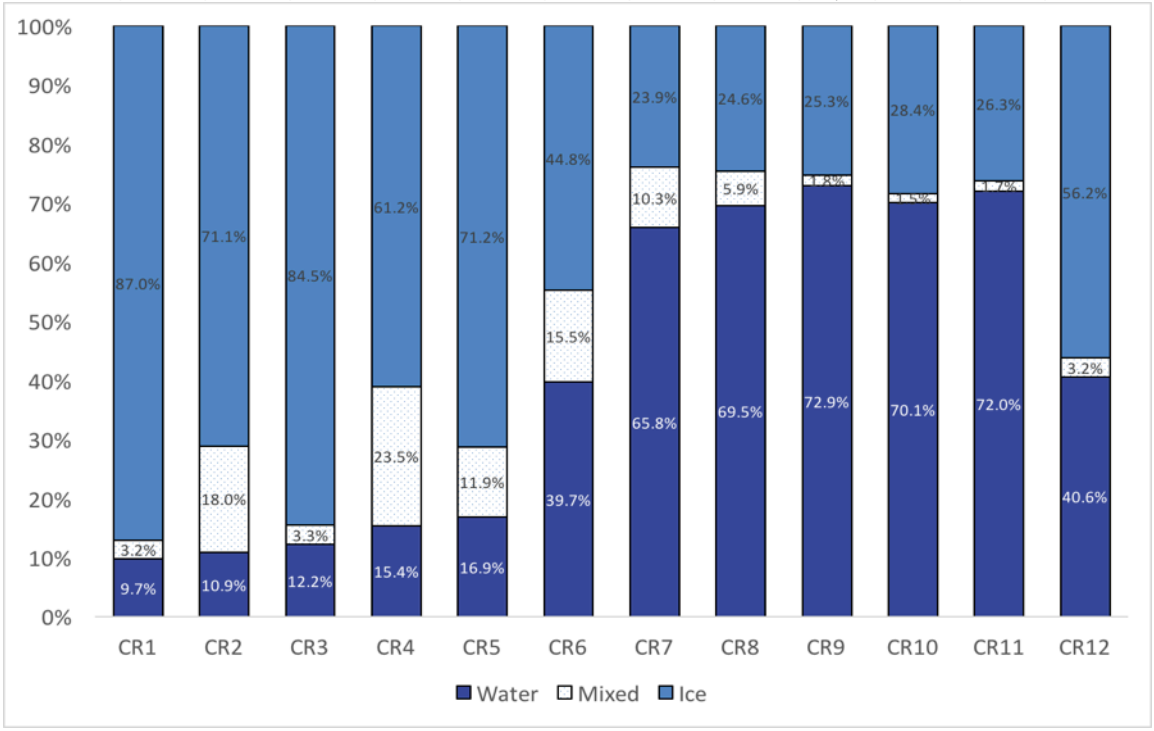


MODIS CF



CR thermodynamic phase

2B-CLDCLASS-LIDAR
* Cloud phase

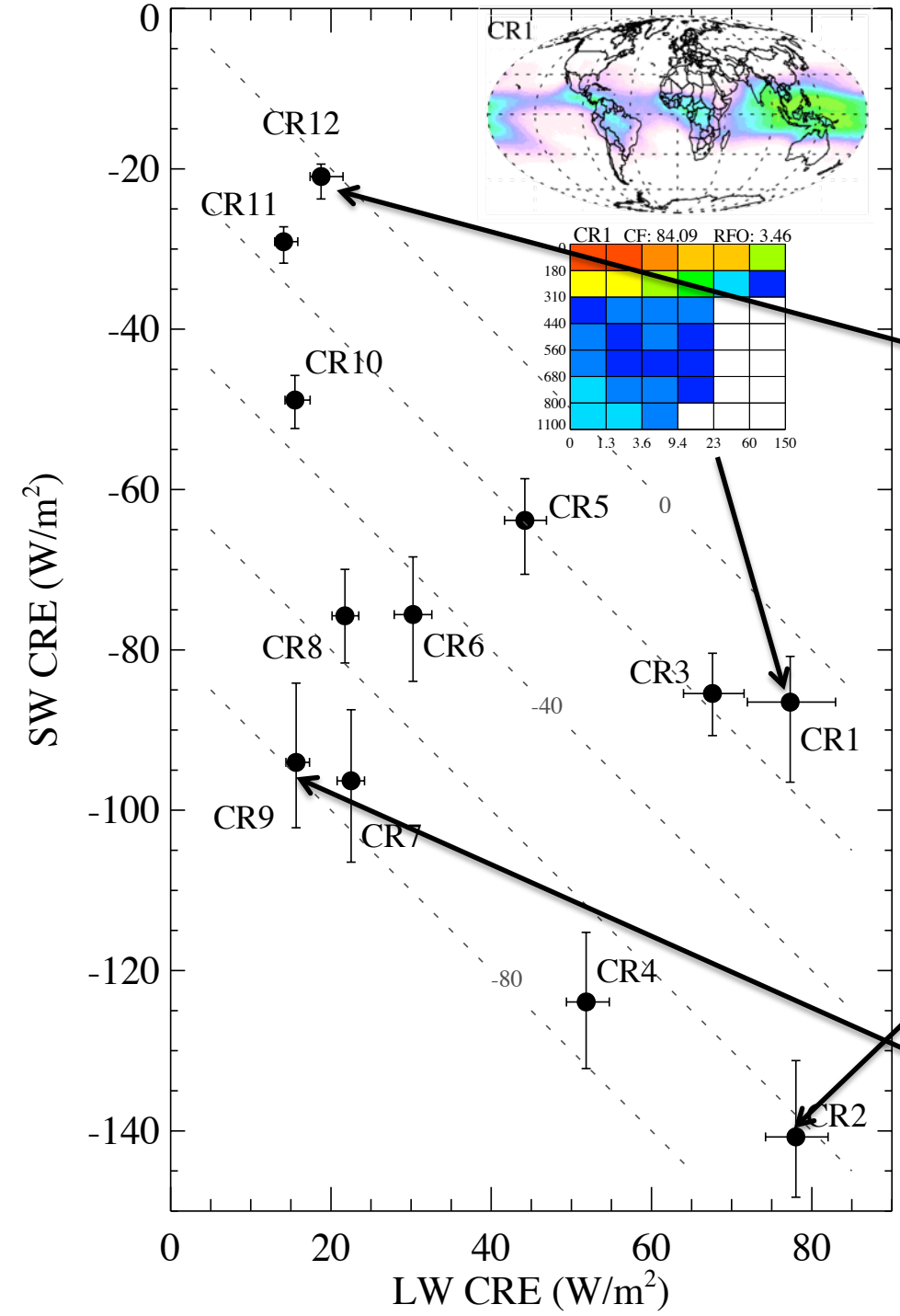


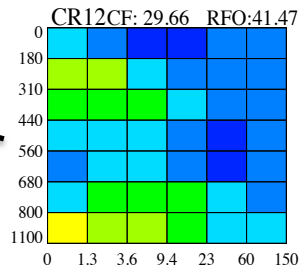
Radiative Effects by CR

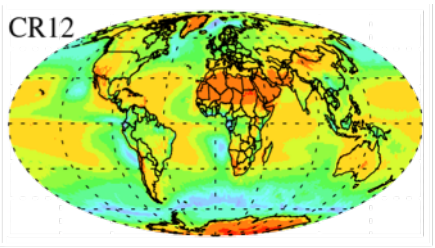
$$CRE = F_{all\text{-}sky} - F_{clr} = CF(F_{ovc} - F_{clr})$$

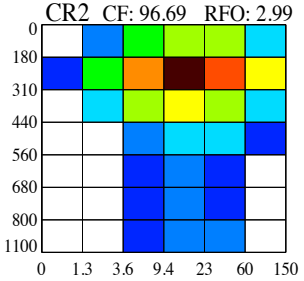
F is net=down-up flux

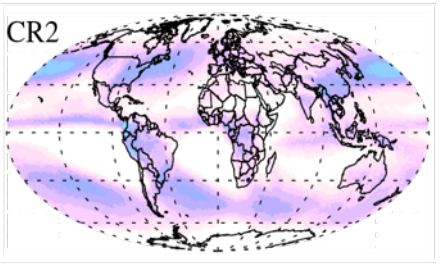
CRE from CERES SYN1deg-daily (CR_{Terra}=CR_{Aqua})

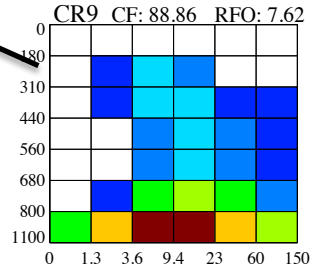


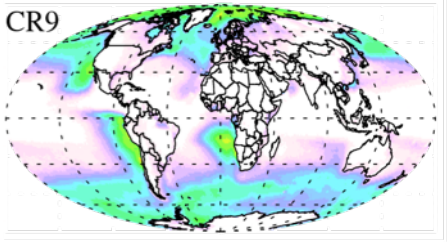




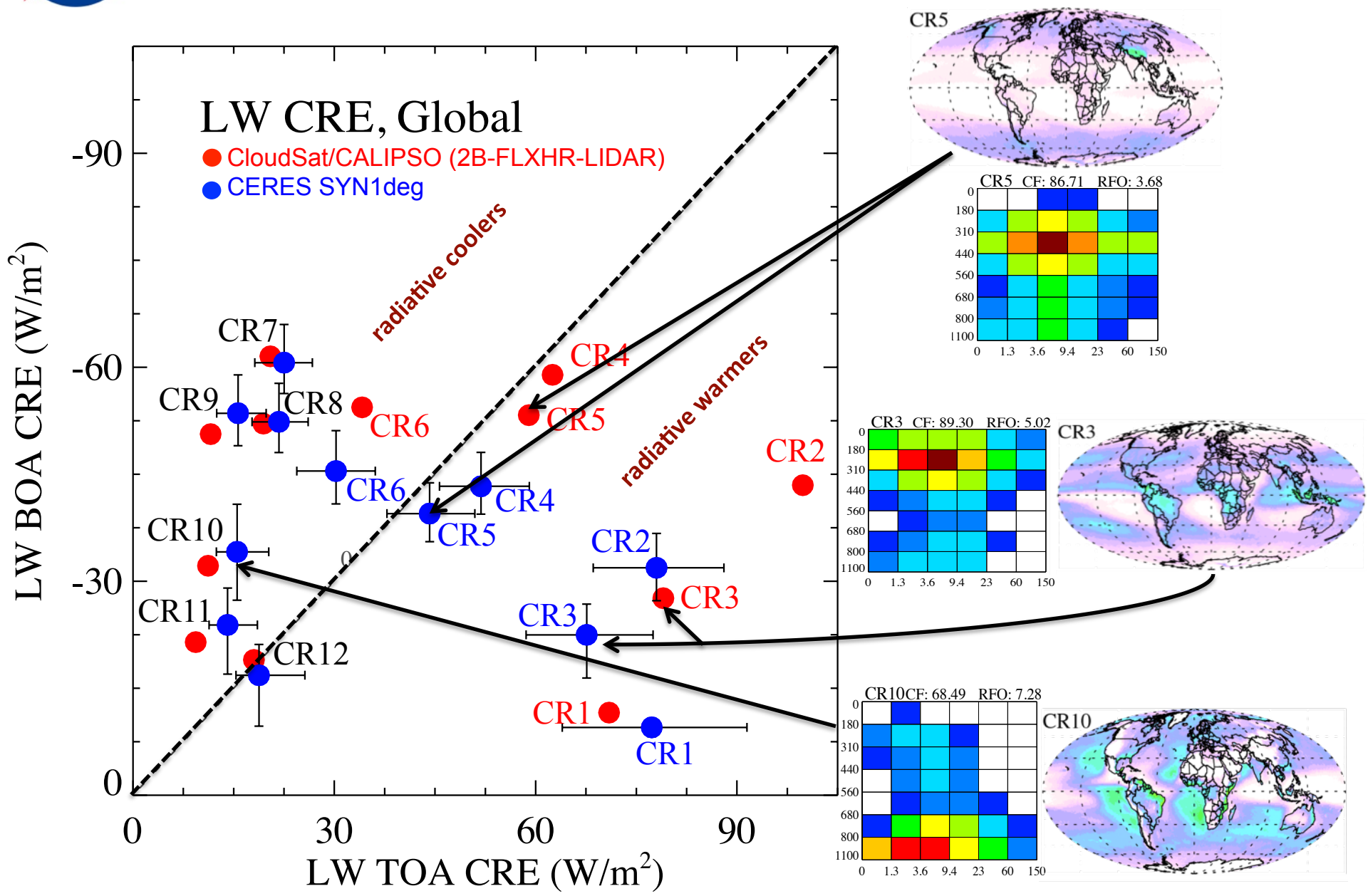




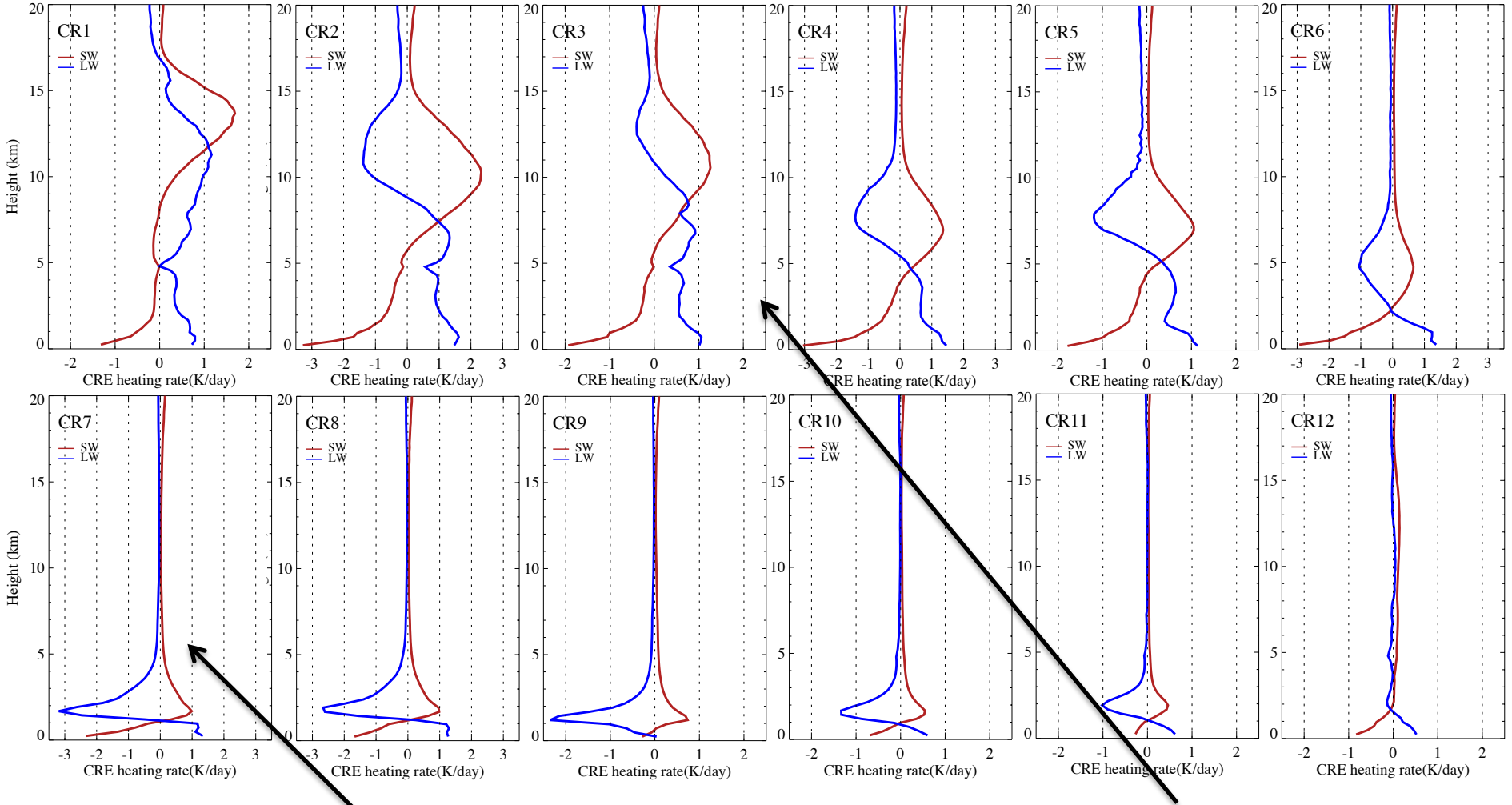


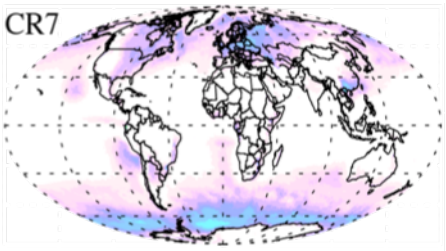


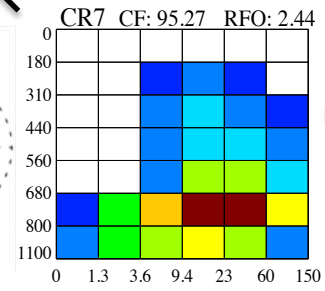
LW cooling or warming of atmospheric column



Vertical distribution of cooling and warming (LW and SW, Aqua CRs)

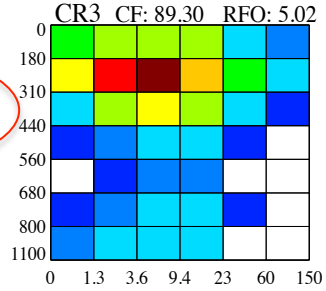


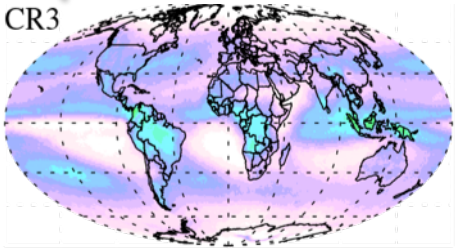




$$CRH = -\frac{1}{\rho C_p}\frac{dCRE}{dz}$$

CloudSat-CALIPSO (2B-FLXHR-LIDAR)





Summary and thoughts on CRE analysis

- CRs help us understand the contributions of the various prevailing cloud systems to the Earth Radiation budget
- Coherent picture between interpretation of the makeup (as viewed from passive or active) of the CRs and their radiative character
- CRs good framework to:
  - recognize cloud systems that provide radiative cooling or warming of the atmosphere
  - resolve vertical distribution of cloud cooling/warming radiative contributions
  - identify cloud systems contributing most to enhanced reflected solar and reduced emitted thermal infrared radiation to space

Oreopoulos et al. JGR 2016

Aerosol Indirect Effects by CR

Methodology

- Daily MODIS aerosol AOD defined for each gridcell from Terra and Aqua (when needed use immediate neighbor gridcells)
- Examine Precip, CF, CTP, TAU, REFF vs collocated aerosol
  - Relative AOD value; position within distribution (percentile) 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

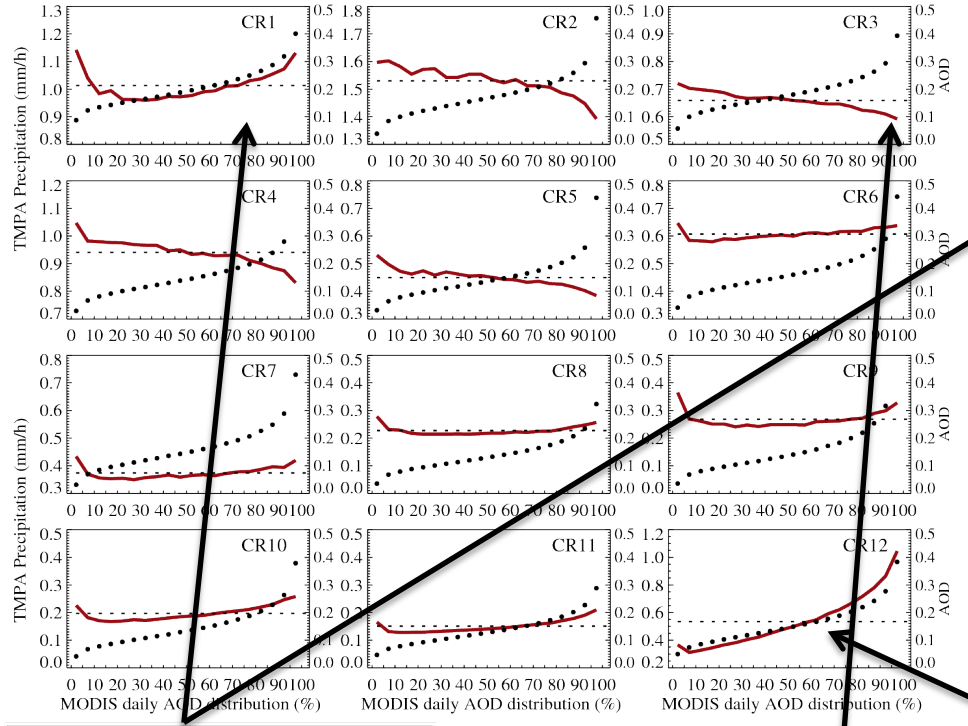
What are we searching for?

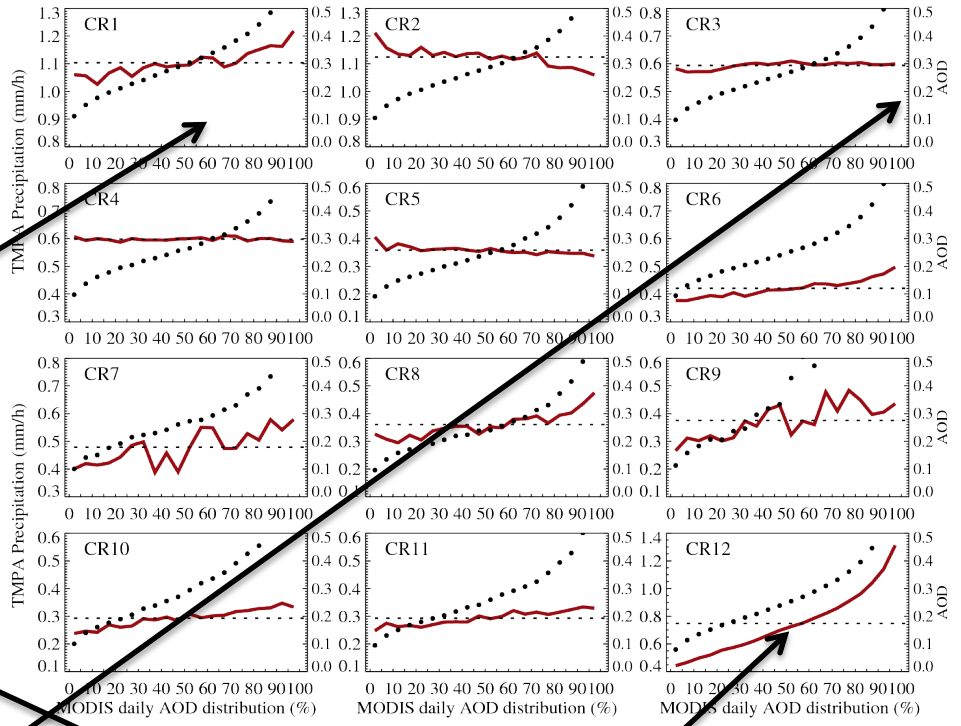
- Invigoration for (mostly) ice and mixed phase CRs
  - Precipitation increase with AOD (what about scavenging?)
  - CTP decrease with AOD
  - TAU increase with AOD (?)
- First indirect effect for (mostly) liquid CRs
  - TAU increase with AOD
  - REFF decrease with AOD
- Second indirect effect for (mostly)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

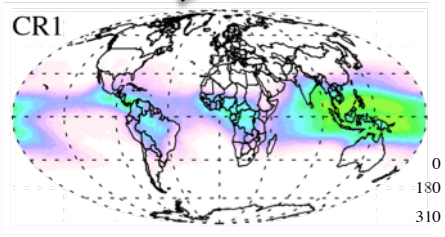
Are there land/ocean differences of precip vs aerosol?

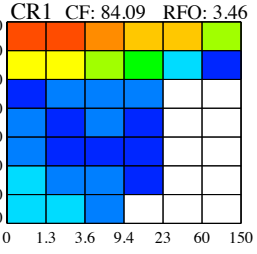
TMPA (P > 0)

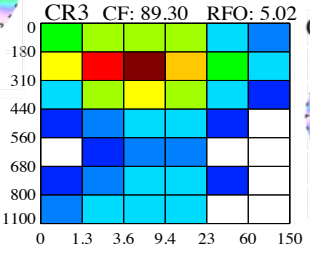
Ocean ***Land***

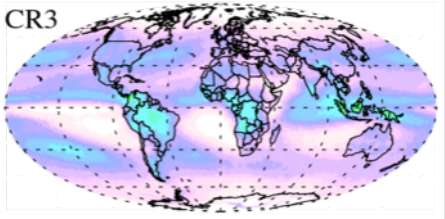


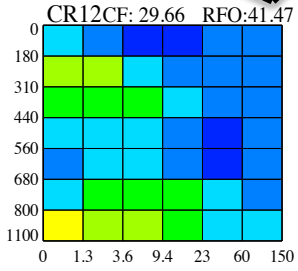


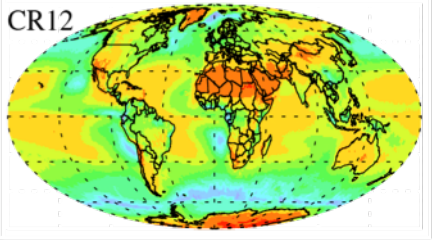






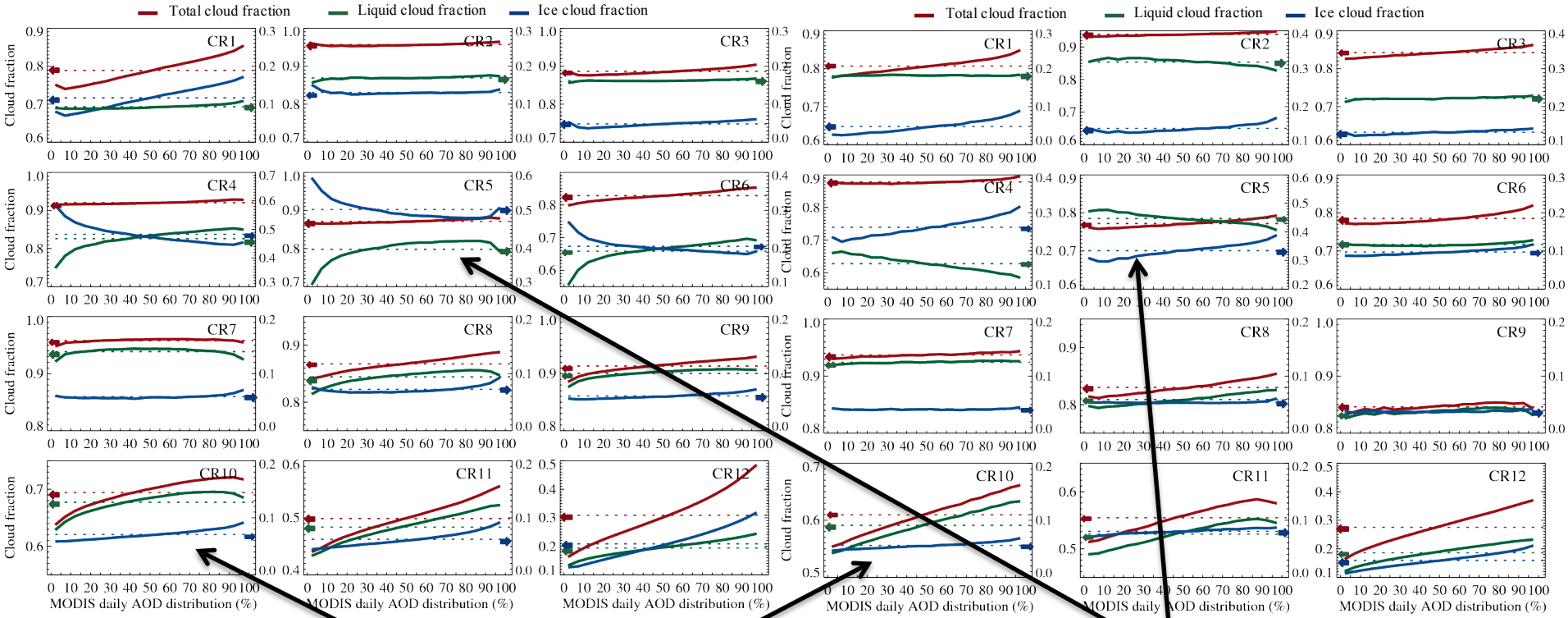


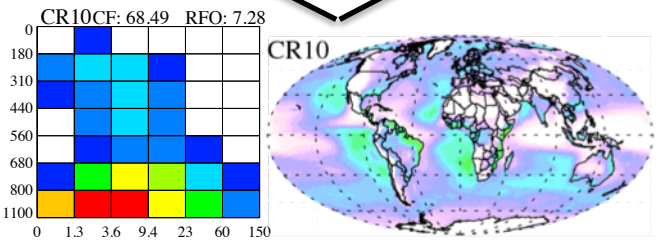


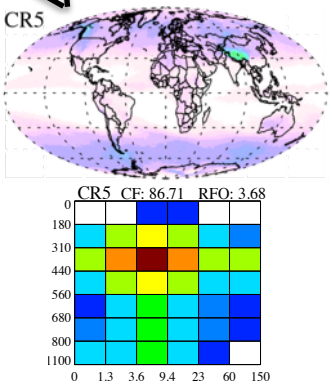


CF vs AOD percentile

Ocean ***Land***

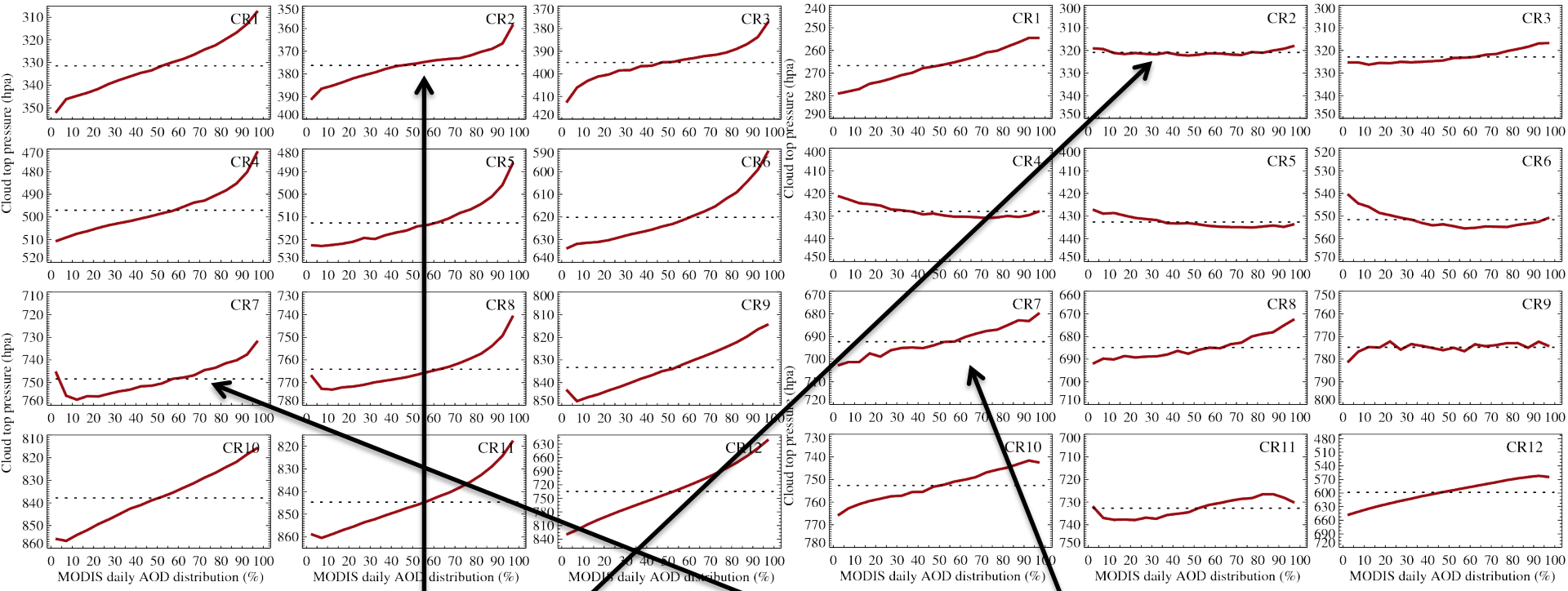


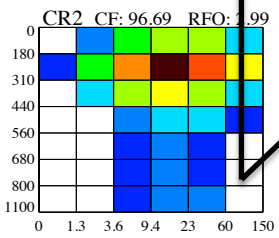


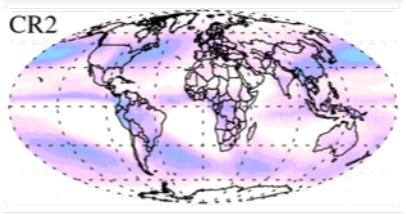


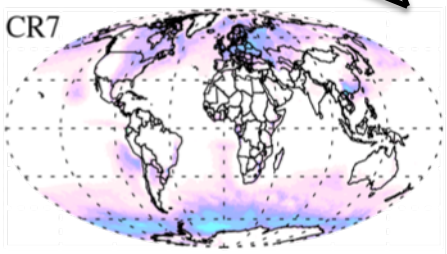
Cloud Top Pressure vs AOD percentile

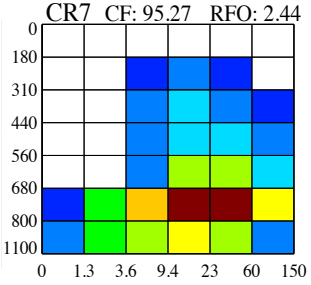
Ocean **Land**





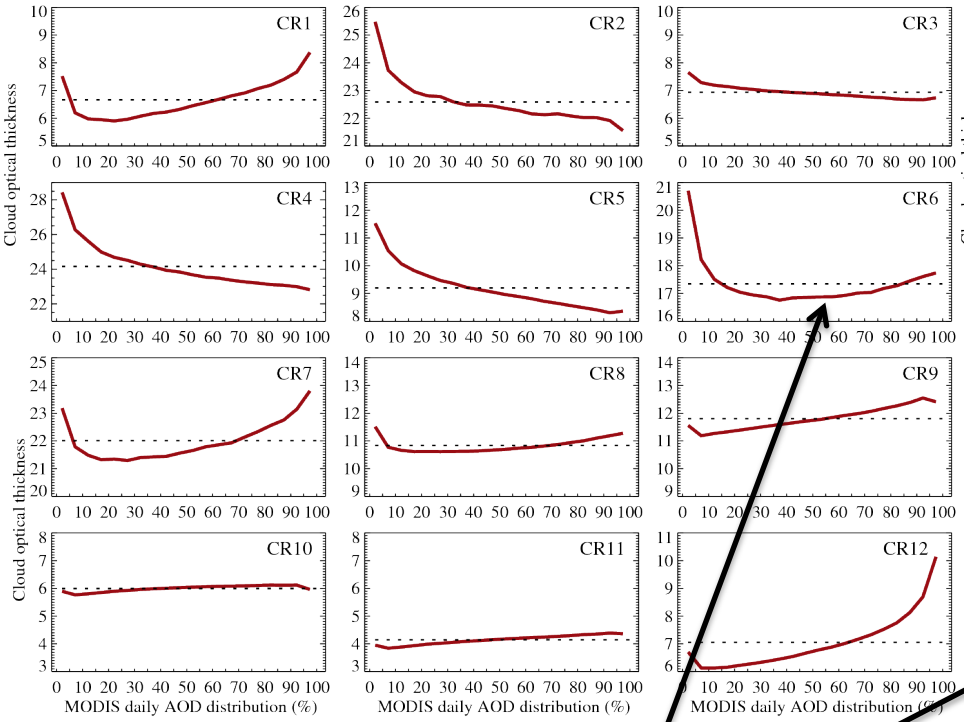


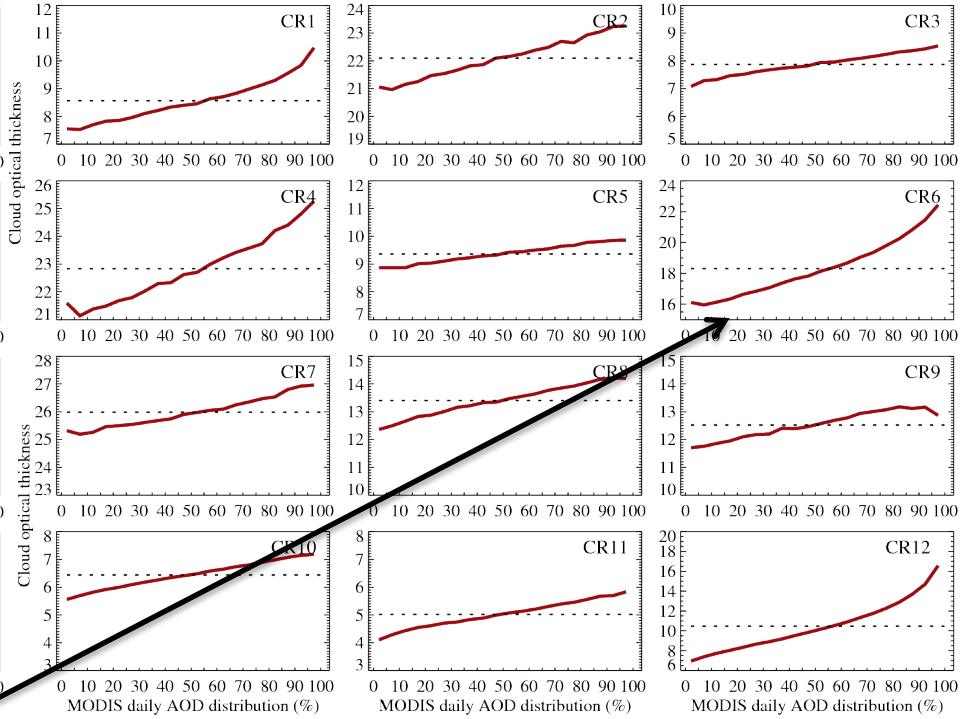


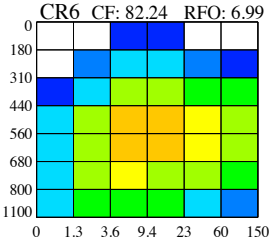


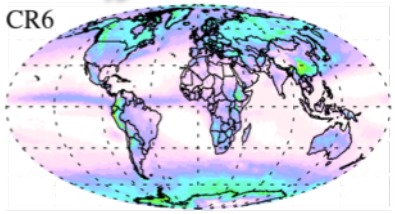
Cloud Optical Thickness vs AOD percentile

Ocean ***Land***



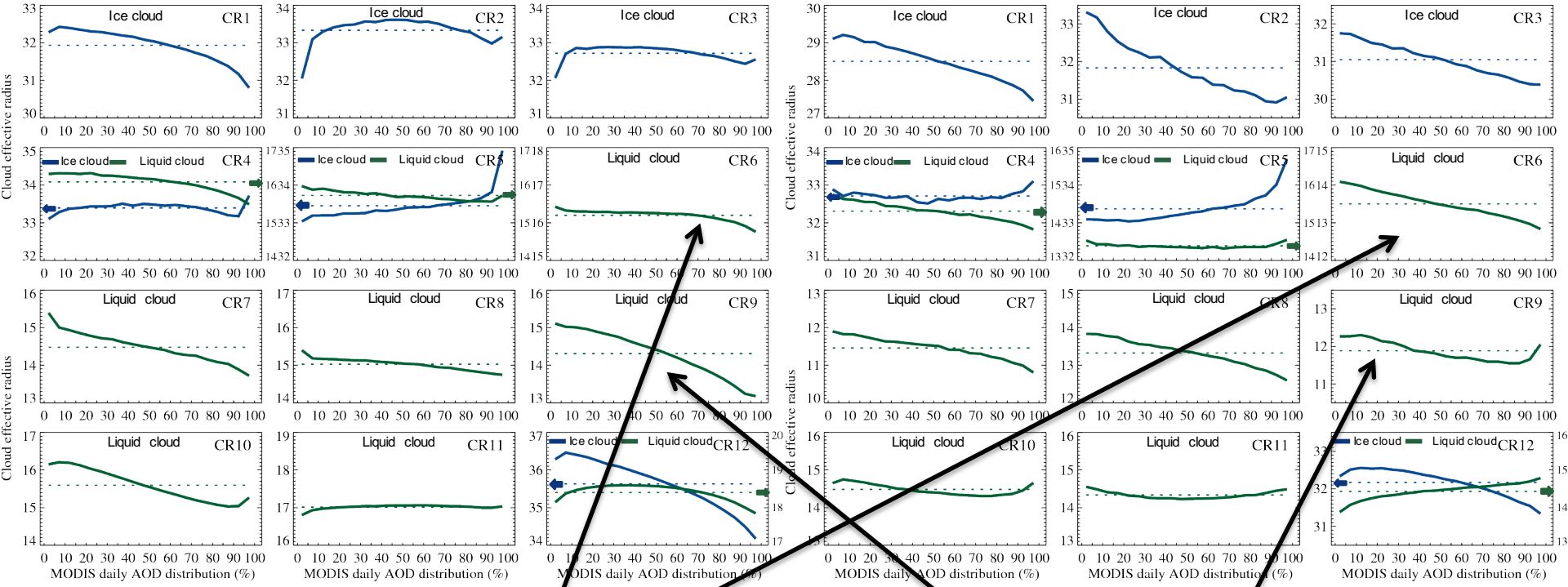


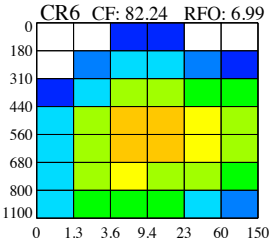


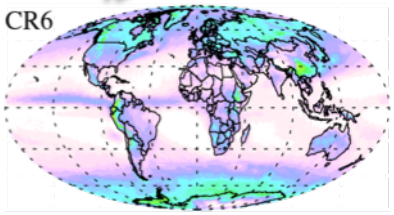


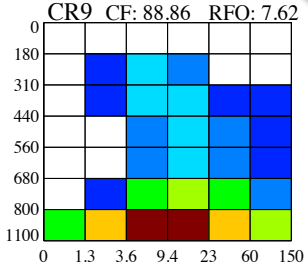
Cloud Effective Radius vs AOD percentile

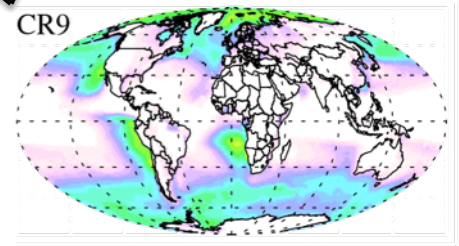
Ocean ***Land***











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	⇓		⇑		–		⇑	

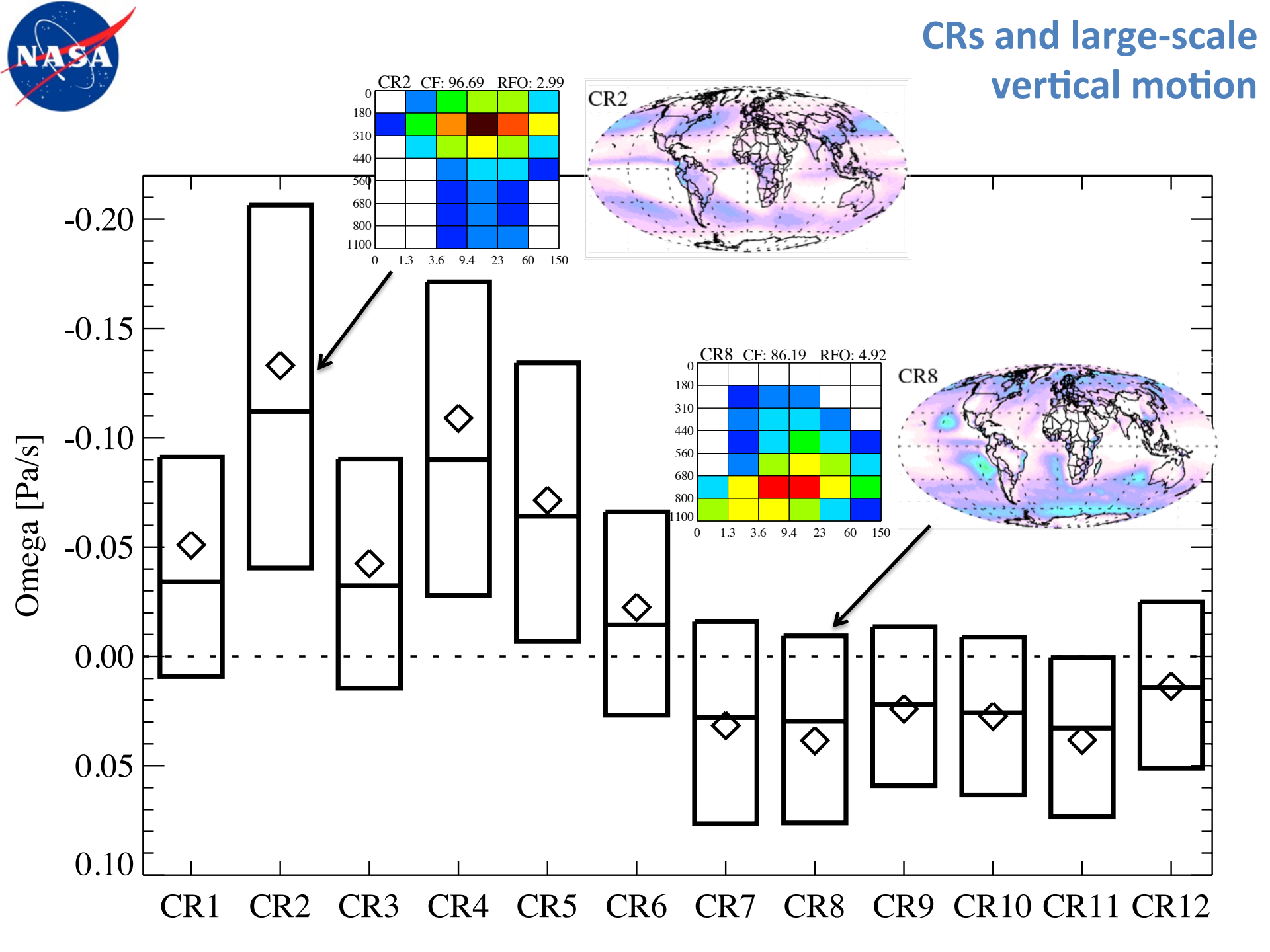
red arrow: consistent with invigoration; blue arrow: consistent with 1st and 2nd indirect effect

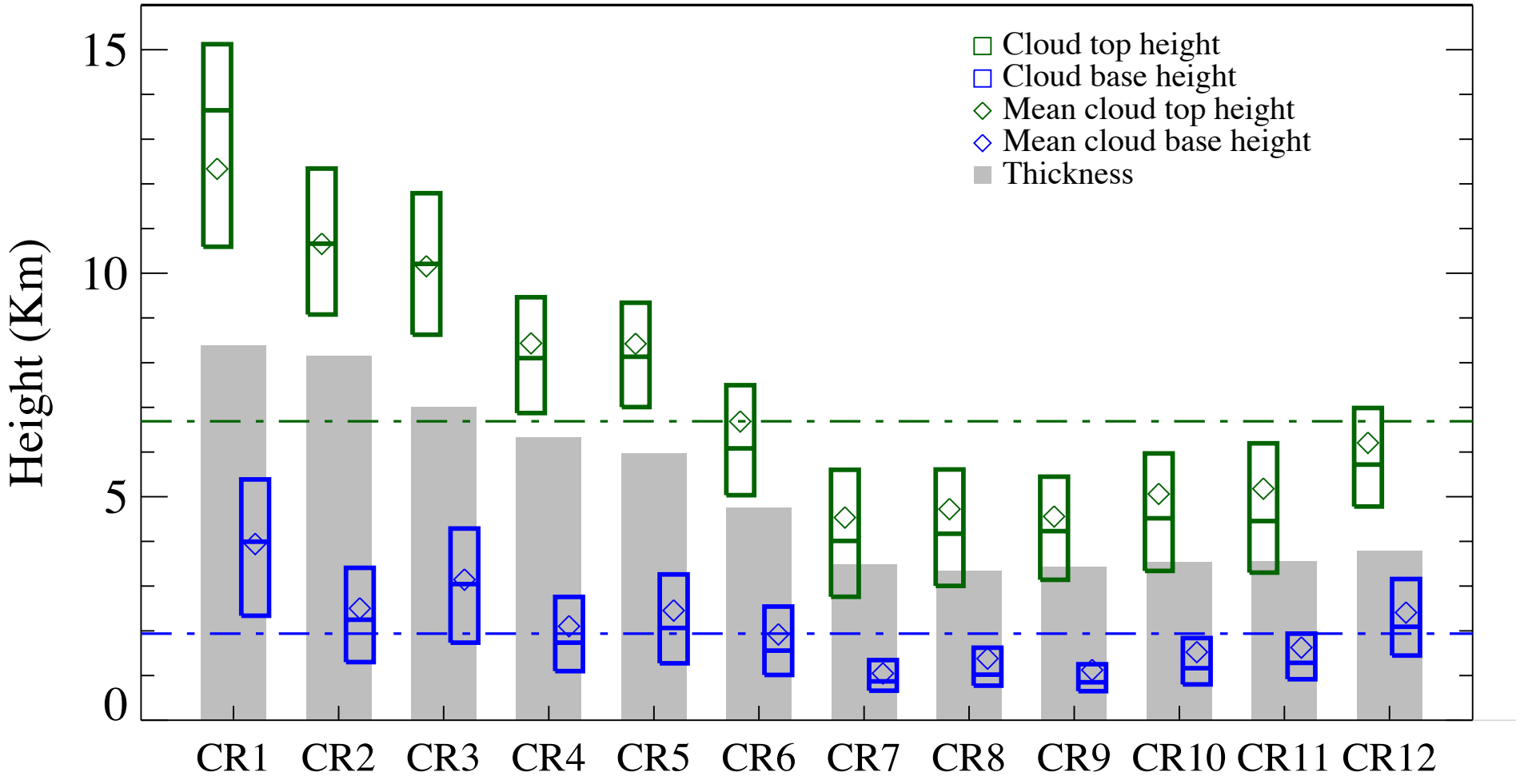
Summary and thoughts about IAE analysis

- A regime-based approach is suitable for studying aerosol-cloud-precipitation interactions
- Precipitation and cloud property variability with AOD seems very systematic (”good looking” curves)
  - *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?
- Other co-variations (non-aerosol), e.g., meteorology cannot be excluded (working on that right now!).

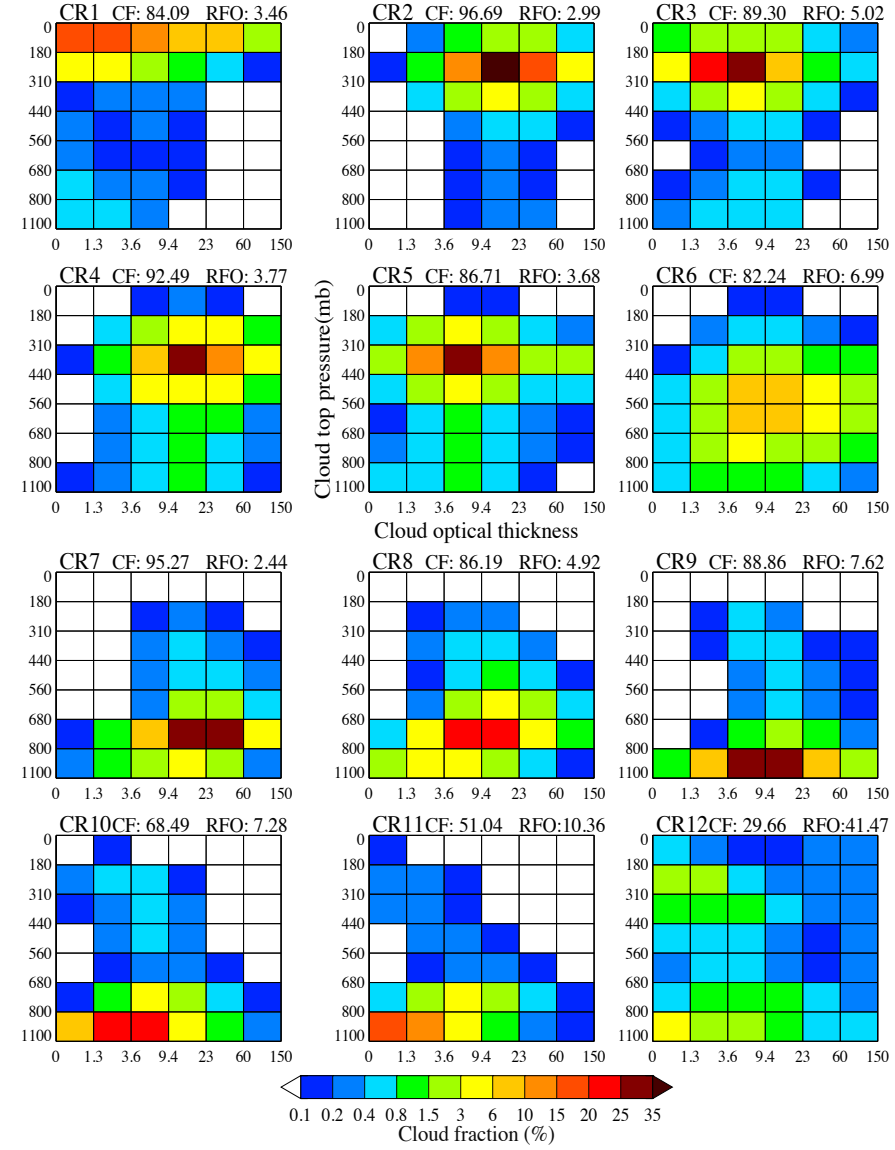
Additional Slides

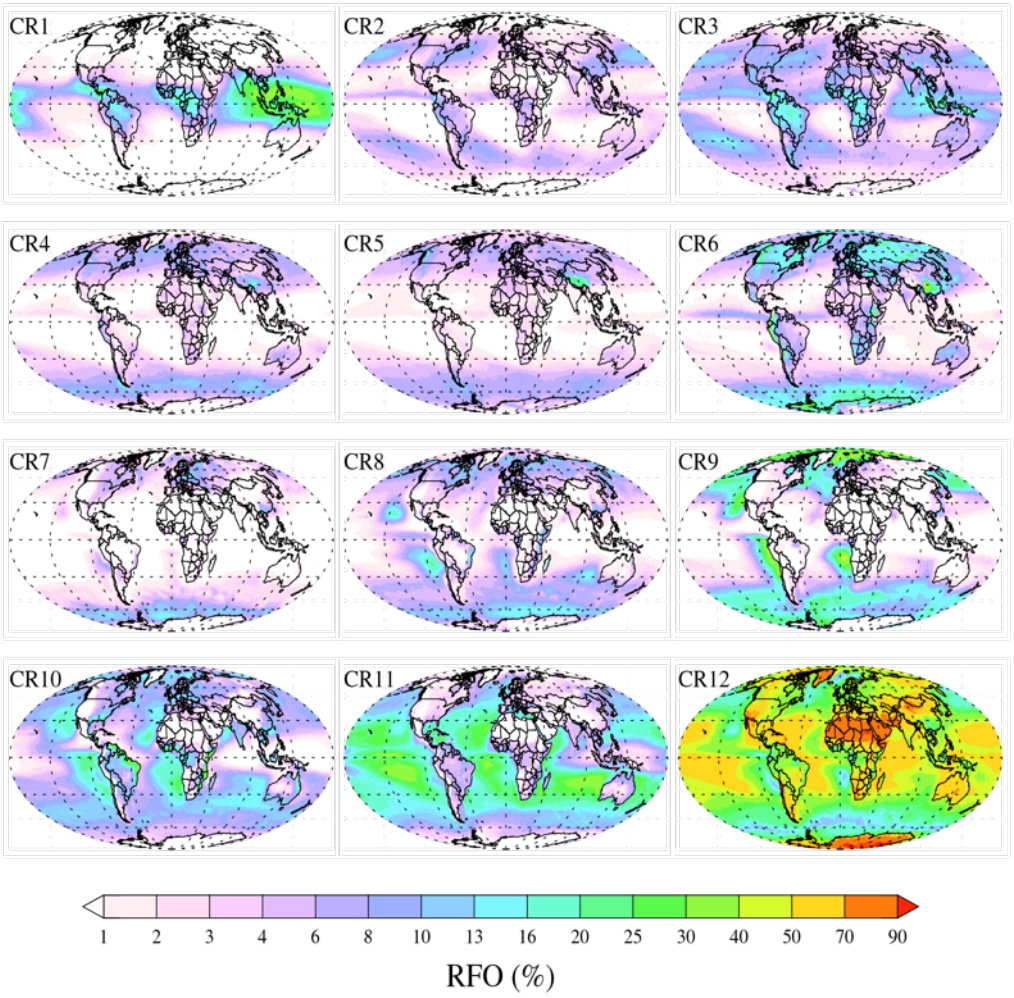
CRs and large-scale vertical motion




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

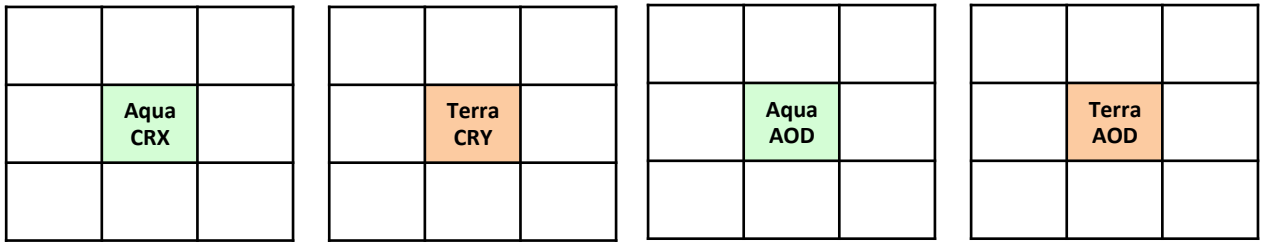
The full picture





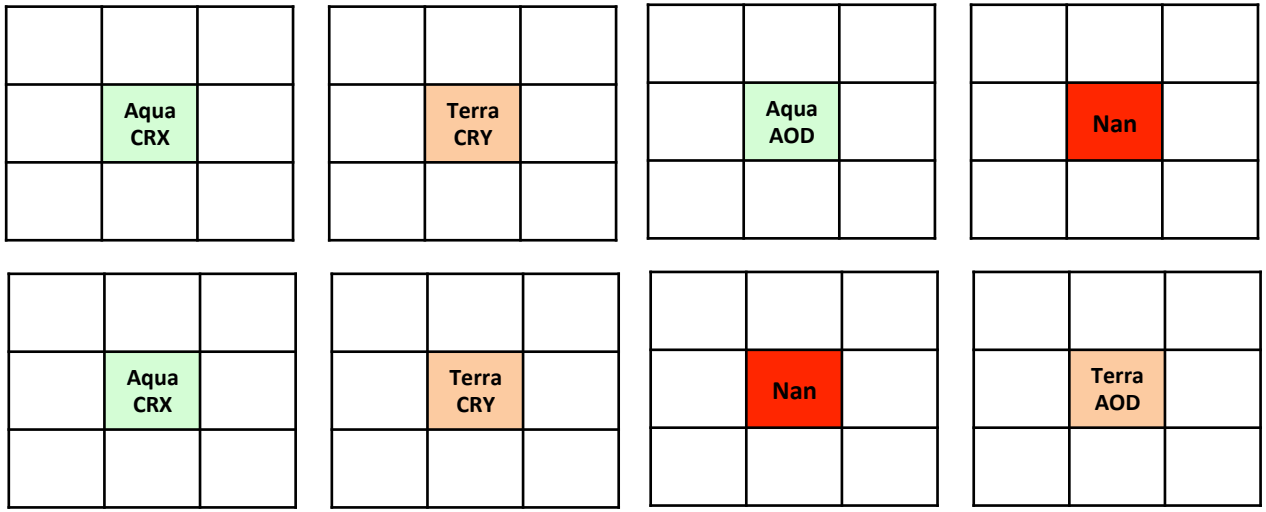
AOD Determination

1)



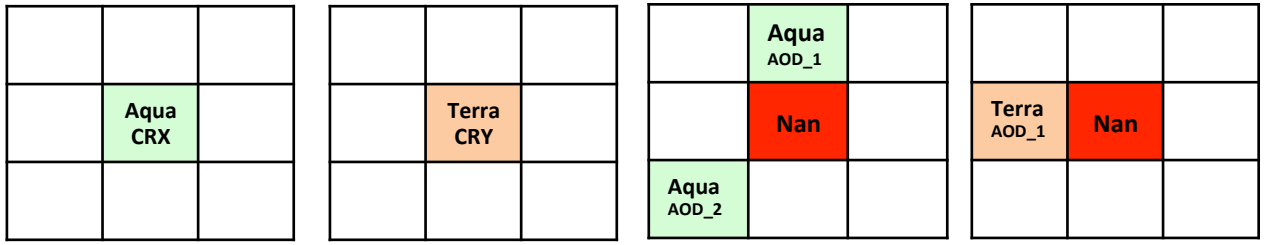
AOD = (Aqua AOD + Terra AOD) / 2.

2)



AOD = Aqua AOD OR AOD = Terra AOD

3)



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

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

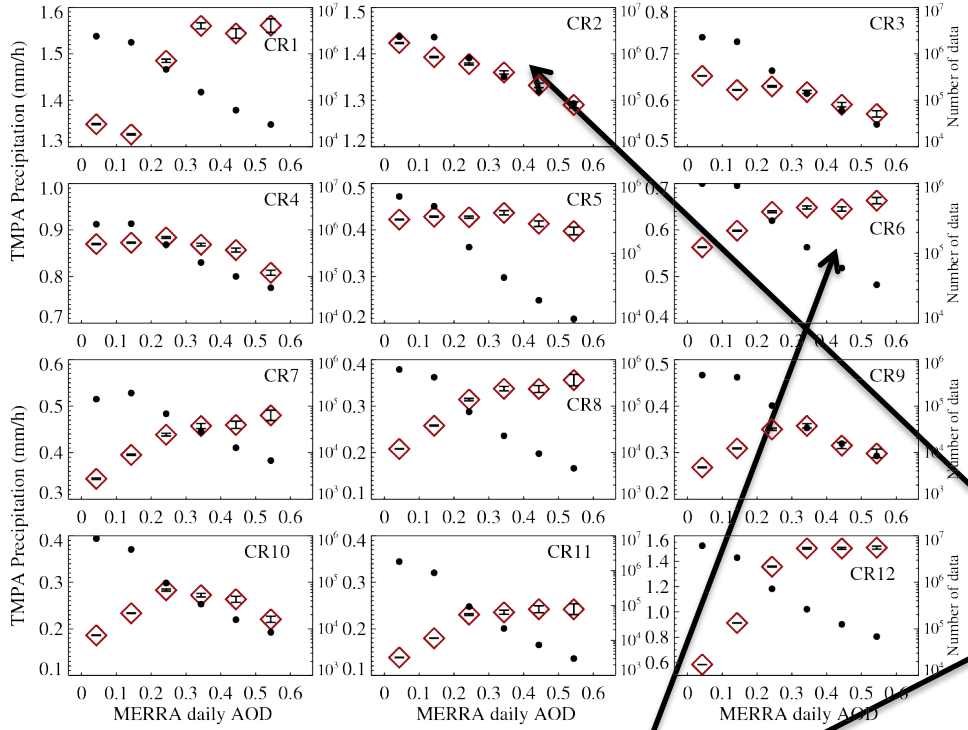
- I won’t show all results!

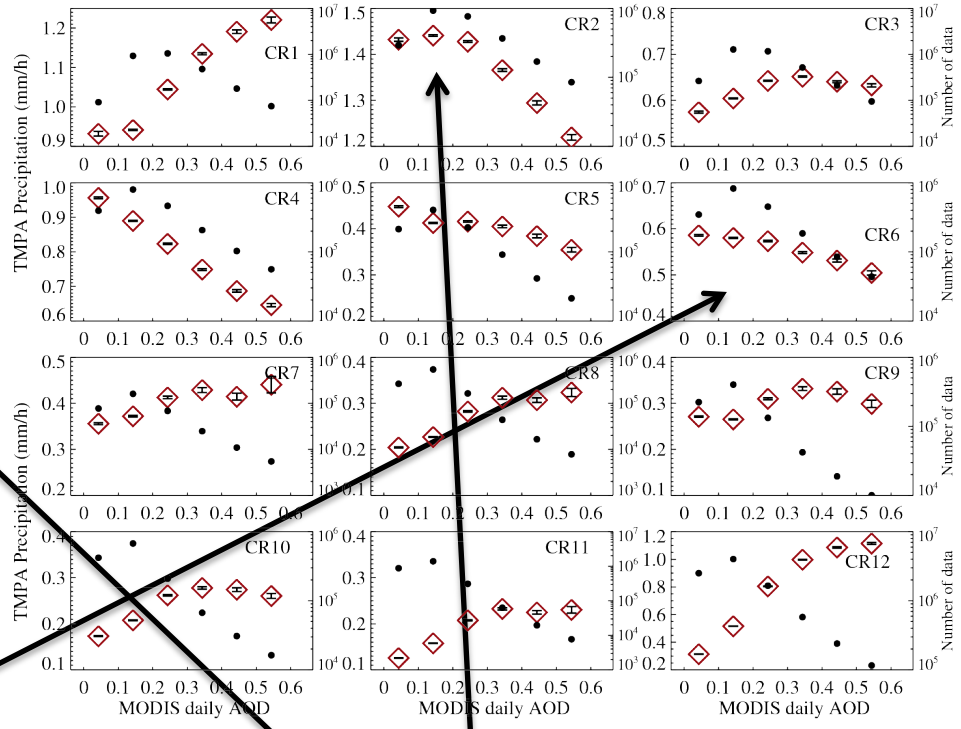
Does the AOD dataset matter?

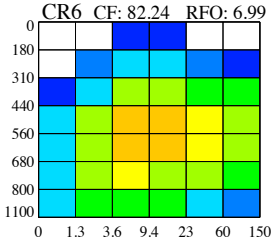
TMPA (P > 0)

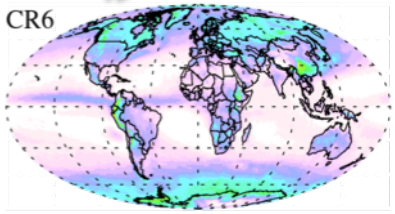
AOD data from Merra-2

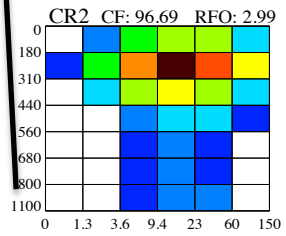
AOD data from MODIS

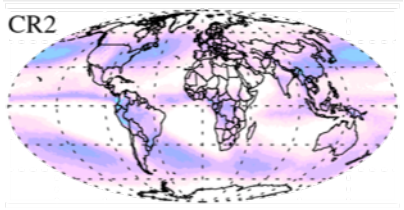










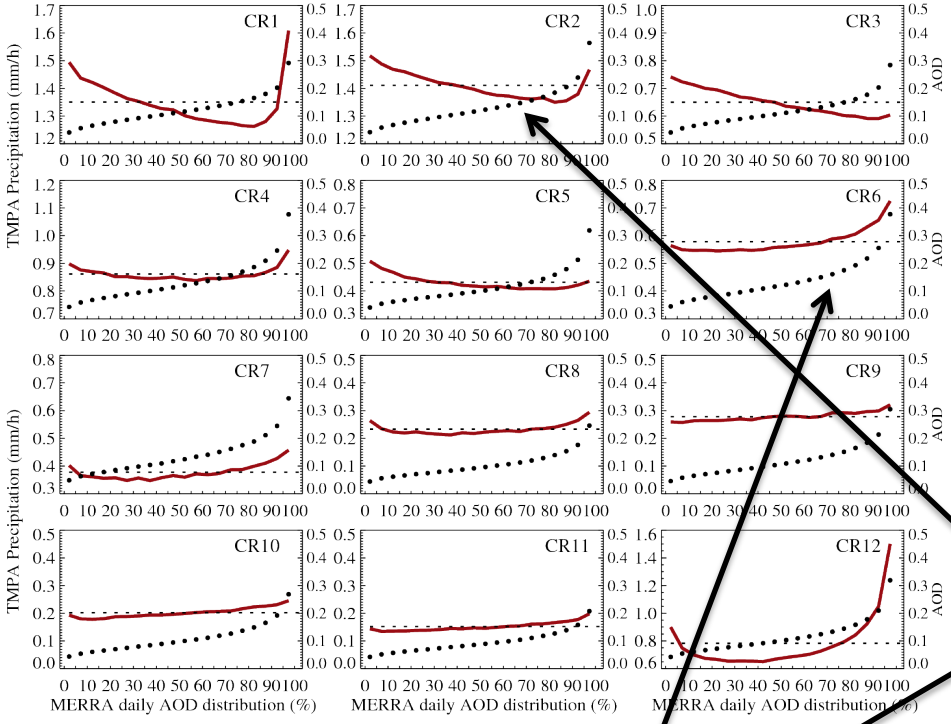


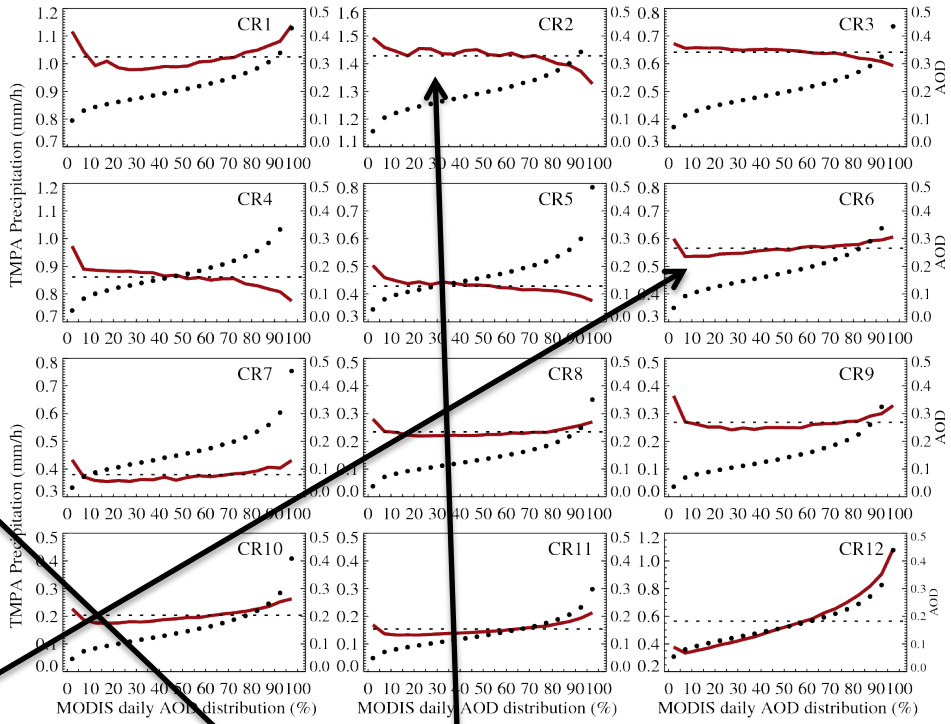
Does the AOD dataset matter?

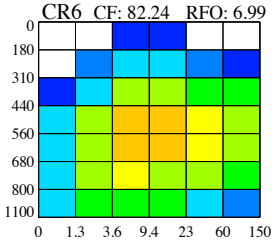
TMPA (P > 0)

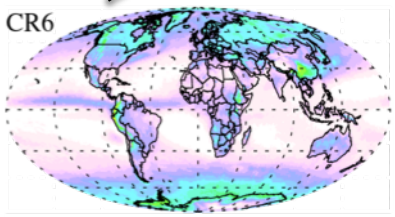
AOD data from Merra-2

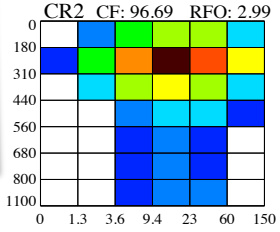
AOD data from MODIS

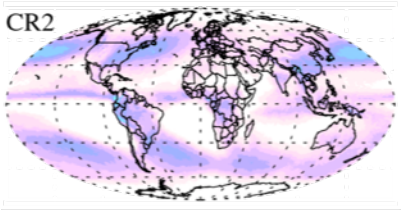






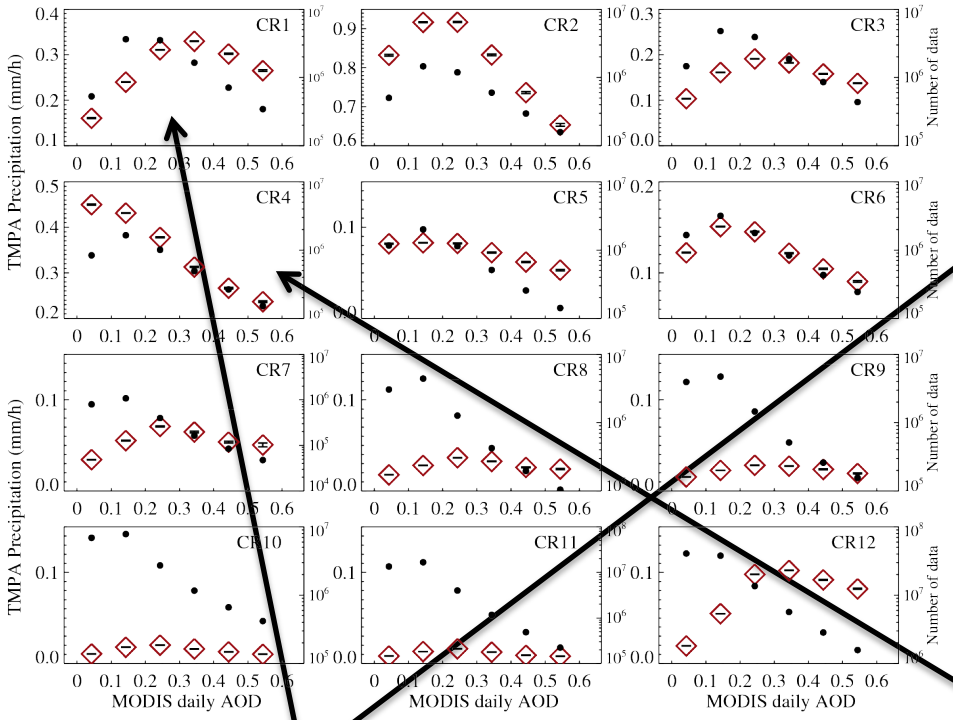


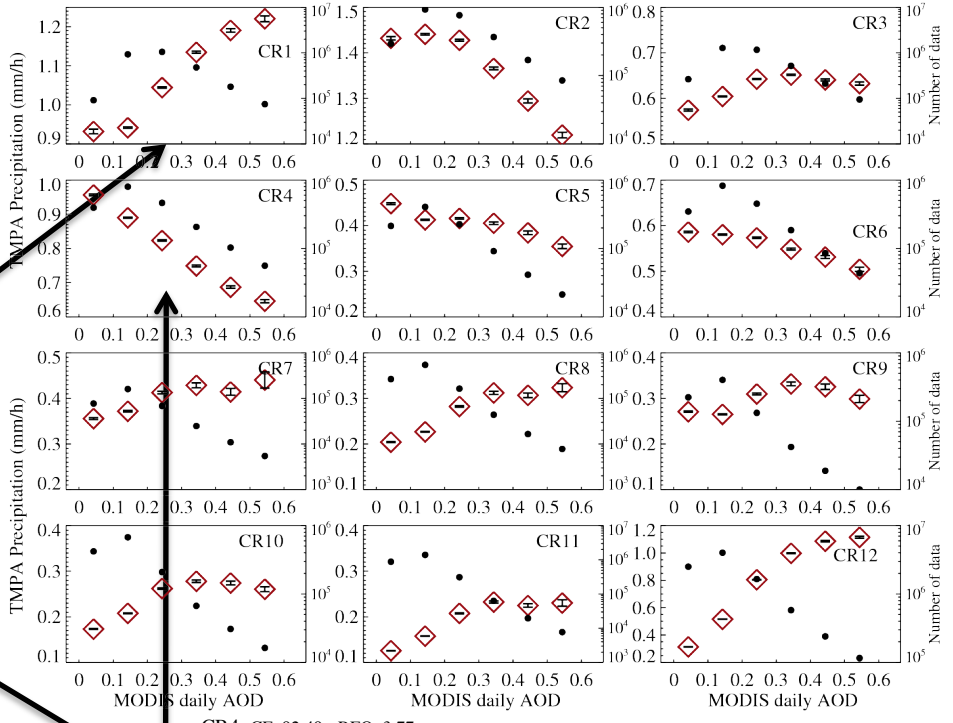


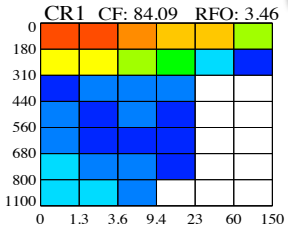


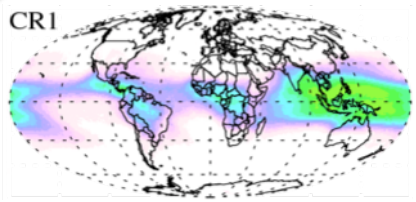
Does inclusion of non-precipitating matter?

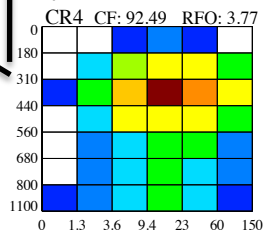
TMPA (P ≥ 0) *AOD data from MODIS* **TMPA (P > 0)**

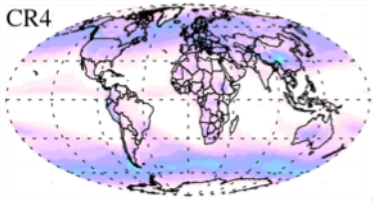










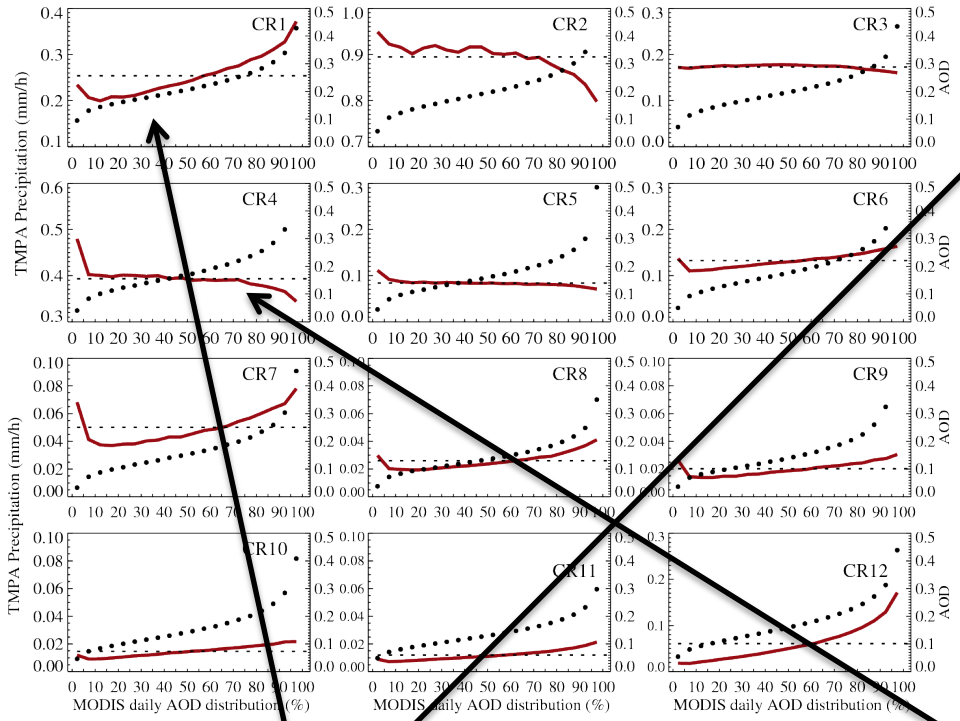


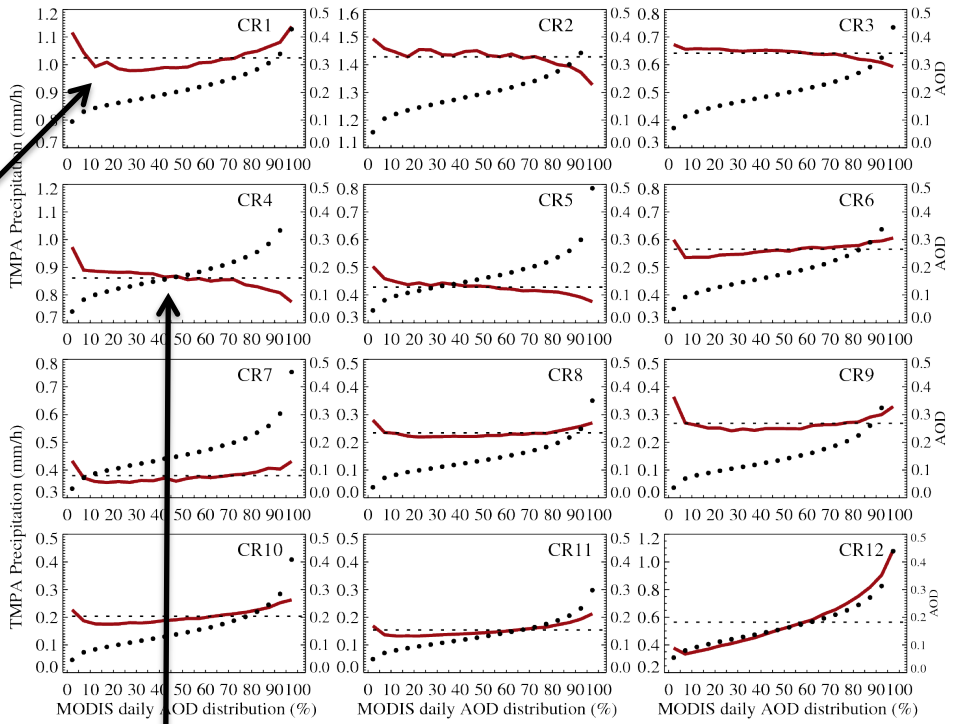
Does inclusion of non-precipitating matter?

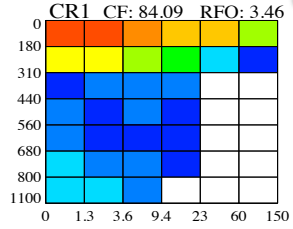
TMPA (P ≥ 0)

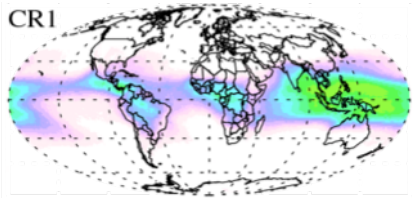
AOD data from MODIS

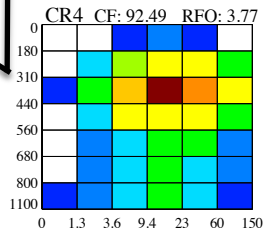
TMPA (P > 0)

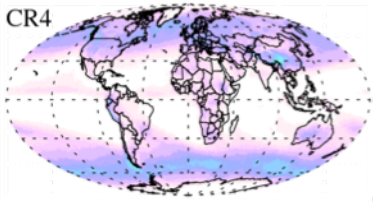












Ice regime : CR1- CR3
Liquid regime : CR6 – CR11
Mix regime : CR4 – CR5
CR12

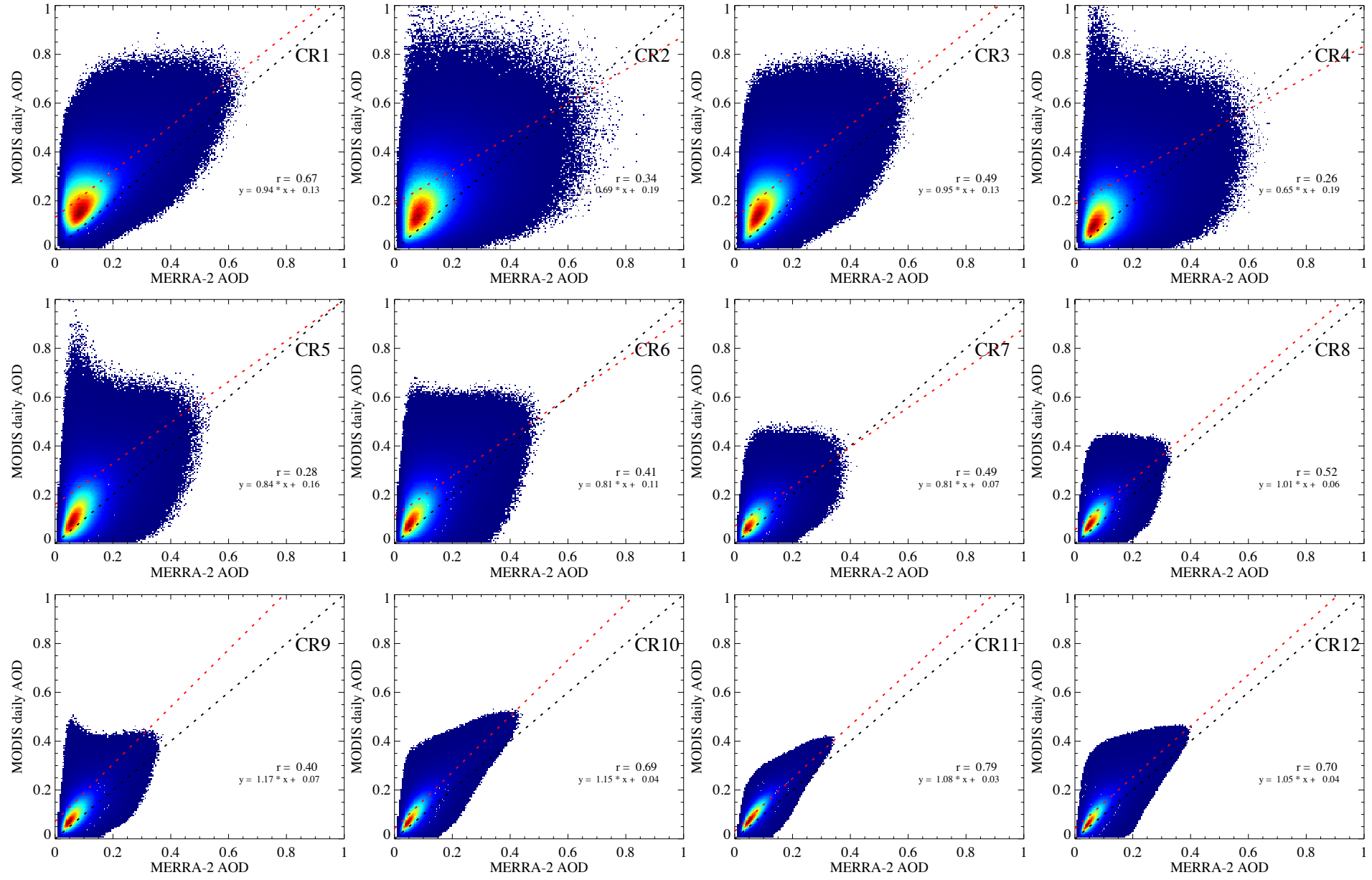
MODIS AOD absolute values

	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	⇓	⇑	–	⇑				

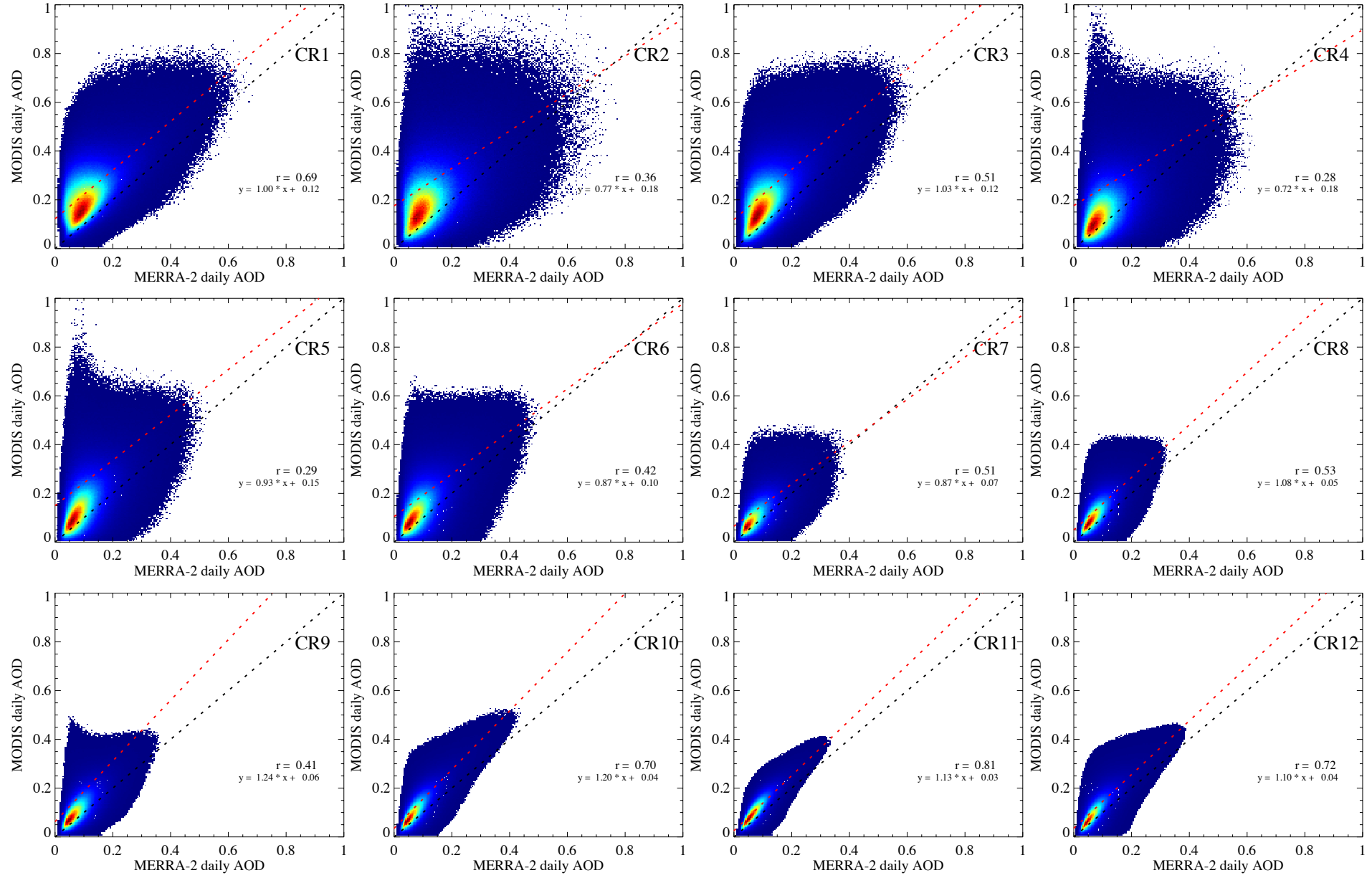
red arrow: consistent with invigoration; blue arrow: consistent with 1st and 2nd indirect effect



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



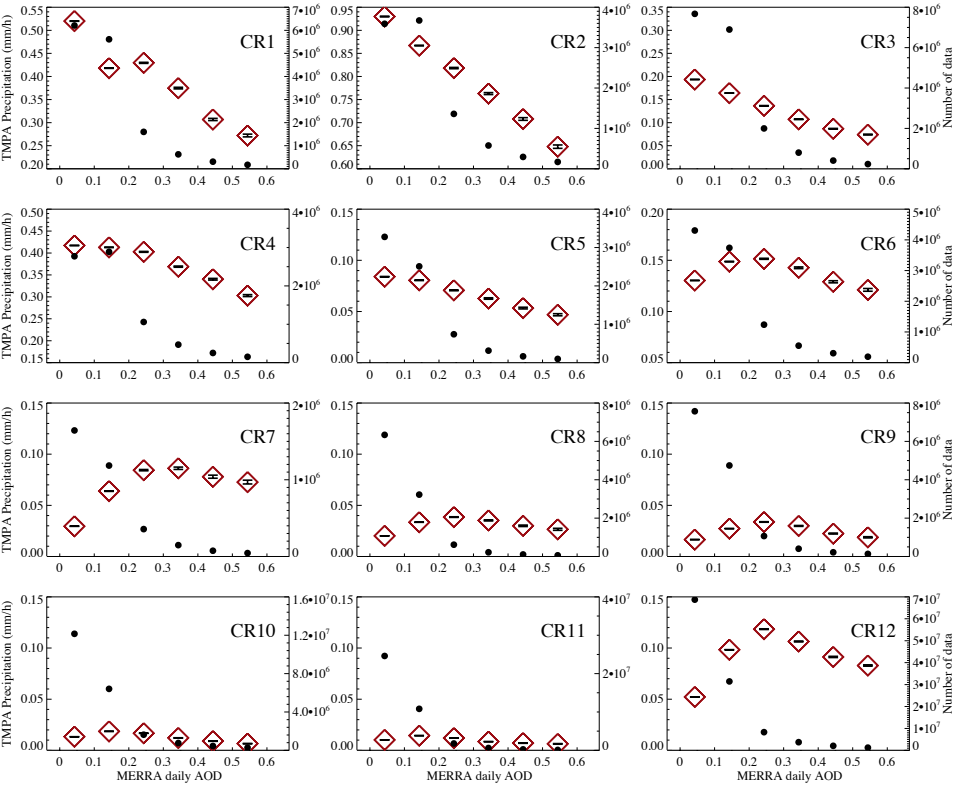
Comparison of MERRA-2 daily AOD to MODIS daily AOD over MODIS the spatial-temporal matching for 12-years.

MODIS daily AOD - MERRA2 daily AOD

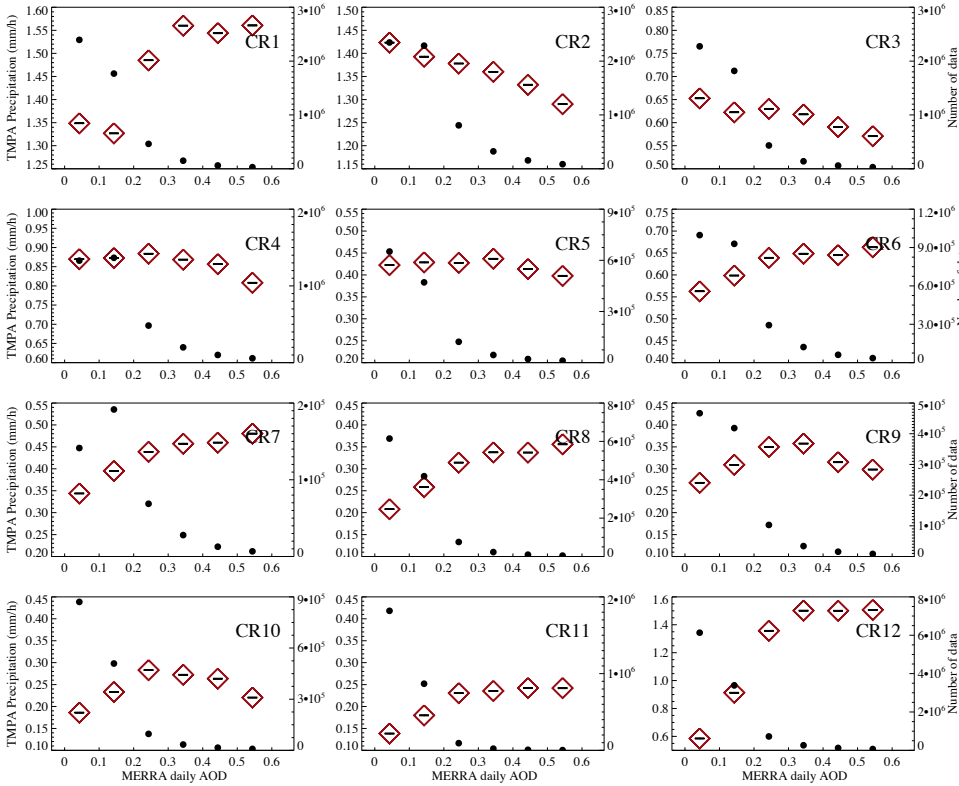
::: **MERRA-2 daily AOD = (MERRA-2 MYD AOD + MERRA-2 MOD AOD) / 2.**

AOD data from Merra-2

TMPA (P ≥ 0)

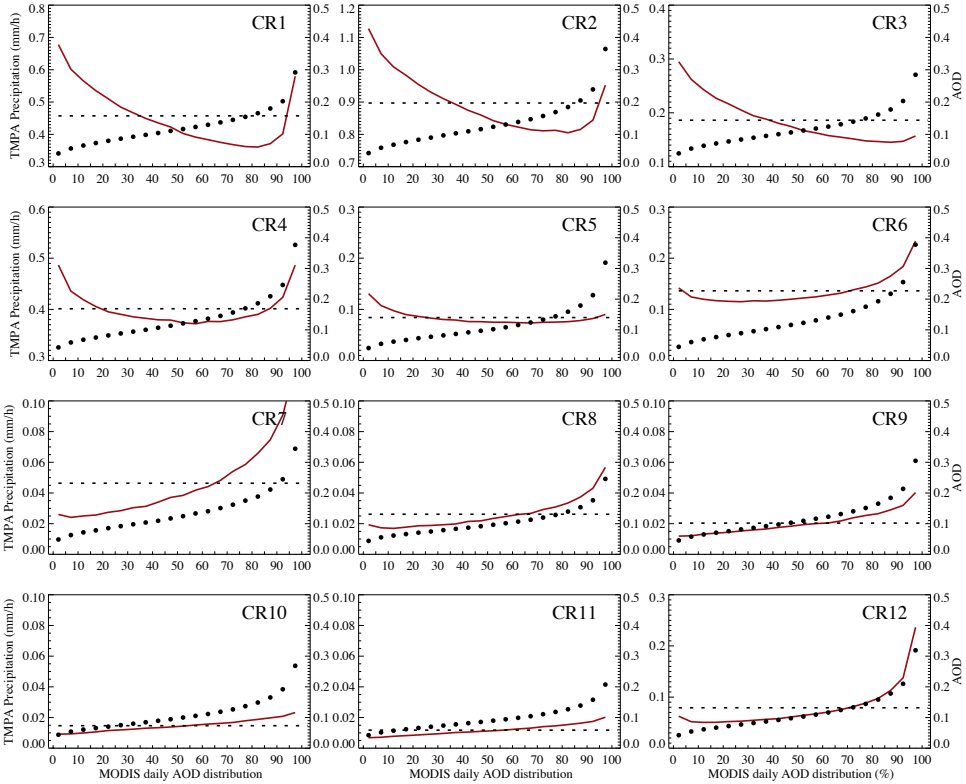


TMPA (P > 0)

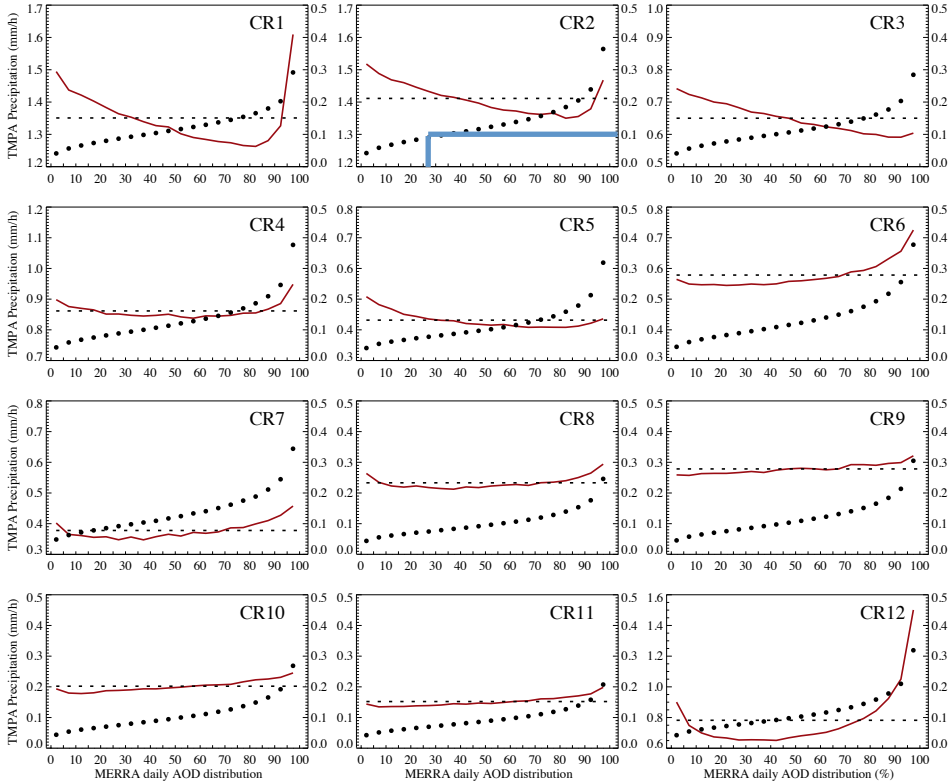


AOD data from Merra-2

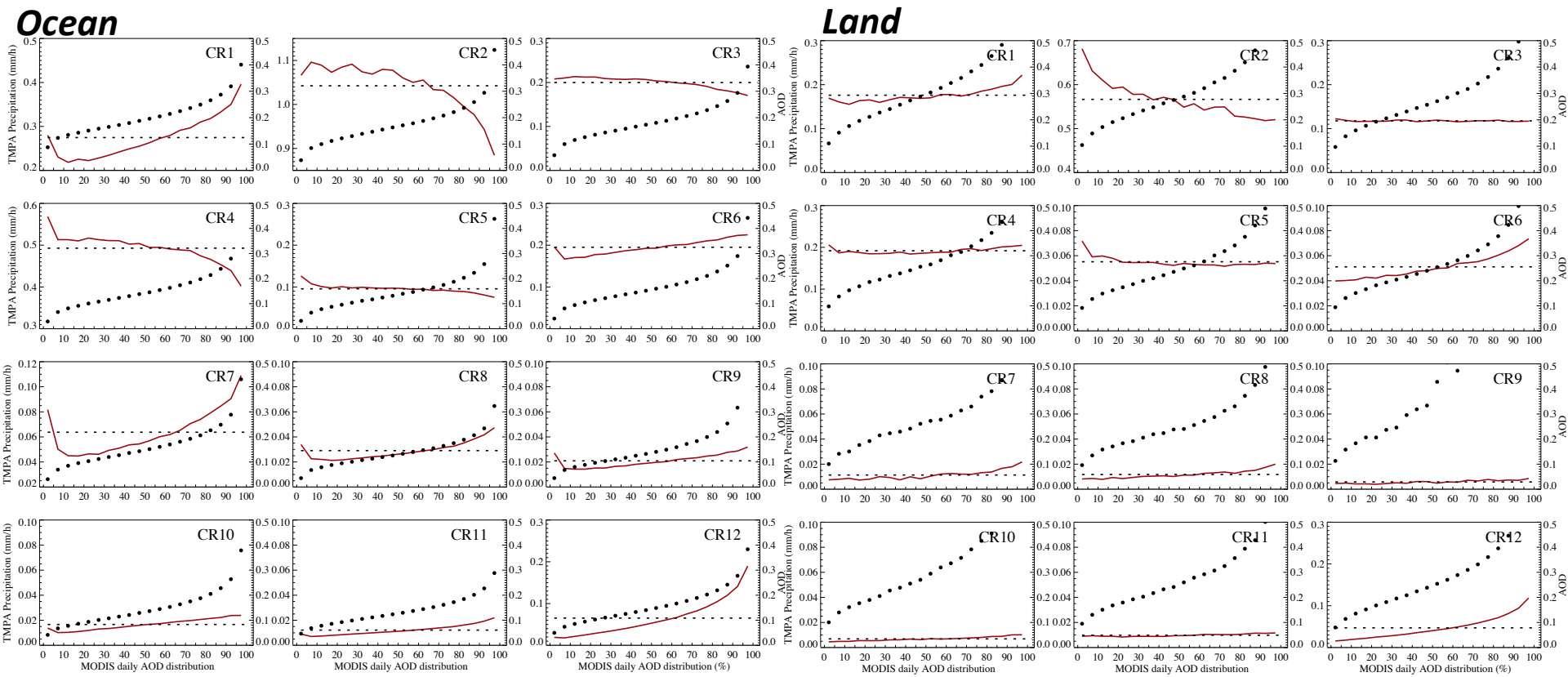
TMPA (P ≥ 0)



TMPA (P > 0)



TMPA (P ≥ 0)

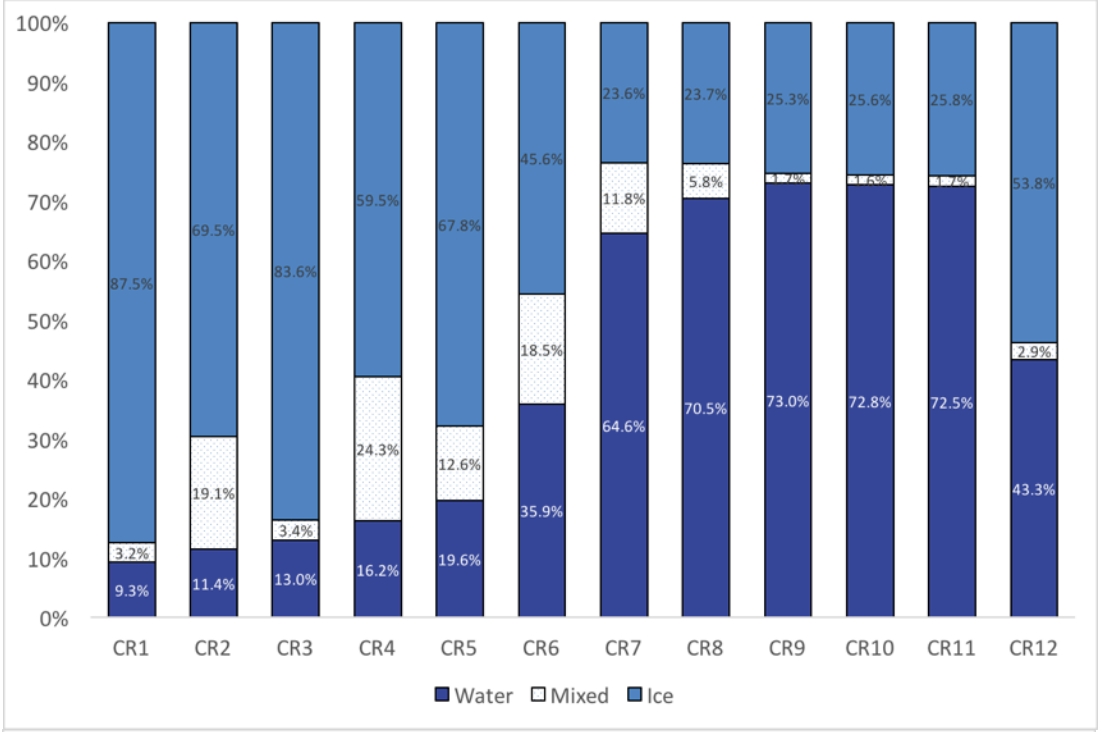


TMPA Precipitation (mm/h) as a function of AOD distribution(per grid per season). The horizontal dashed line is mean TMPA precipitation of each CR. The dots indicate mean AOD within their AOD distribution ranges.

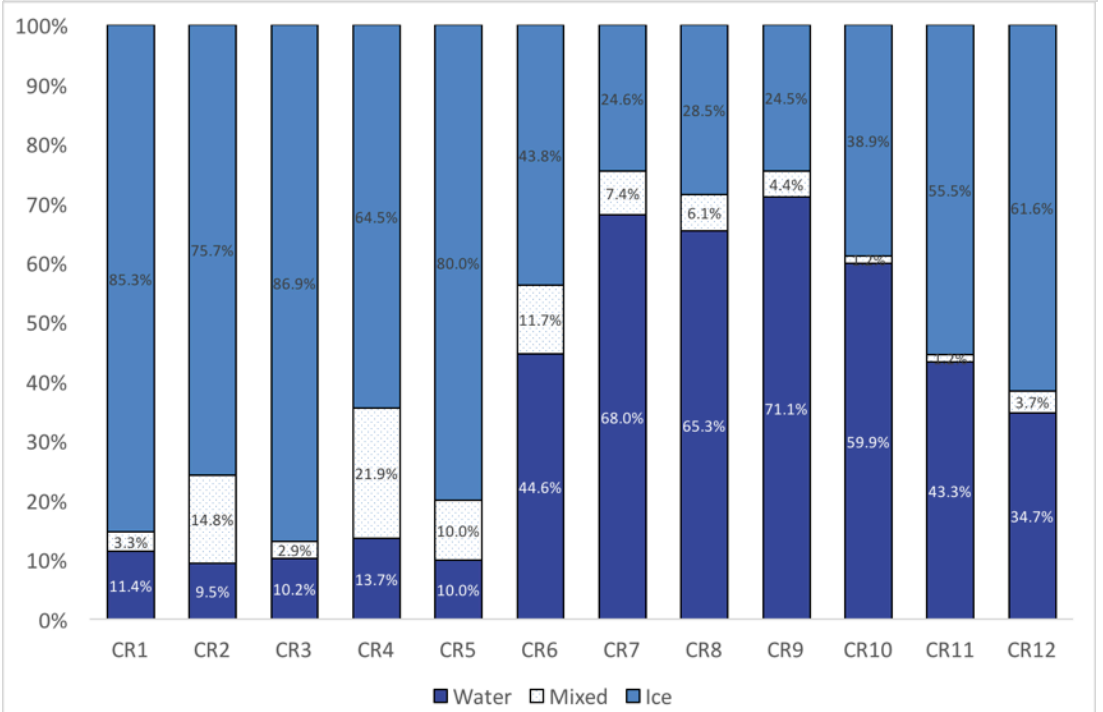
Minimum and maximum values of Y-axis(for TMPA) are different to each CR, but their interval is same.

2B-CLDCLASS-LIDAR
* Cloud phase

Ocean



Land

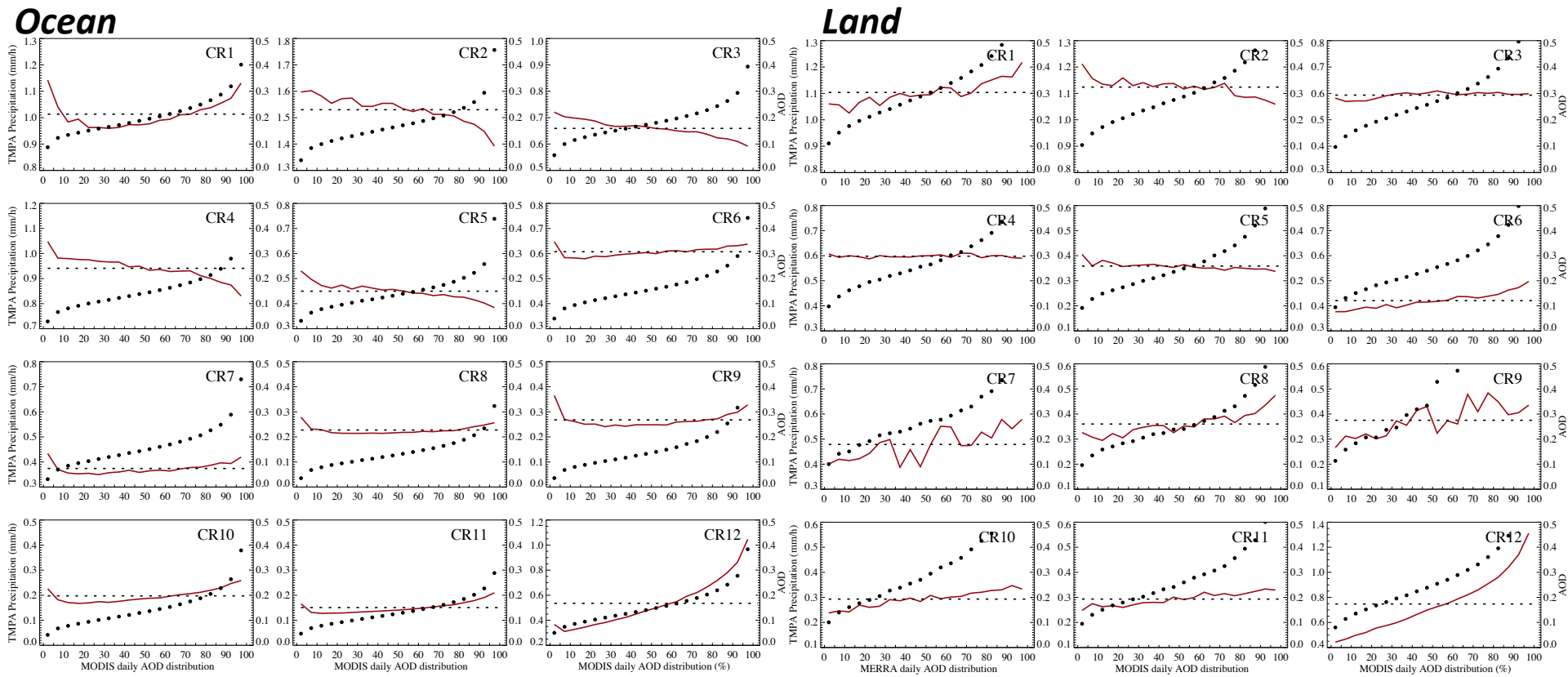


Aerosol-Cloud(CR)-Precipitation

Ocean/ Land

As a function of ***MODIS aod relative distribution***

TMPA (P > 0)



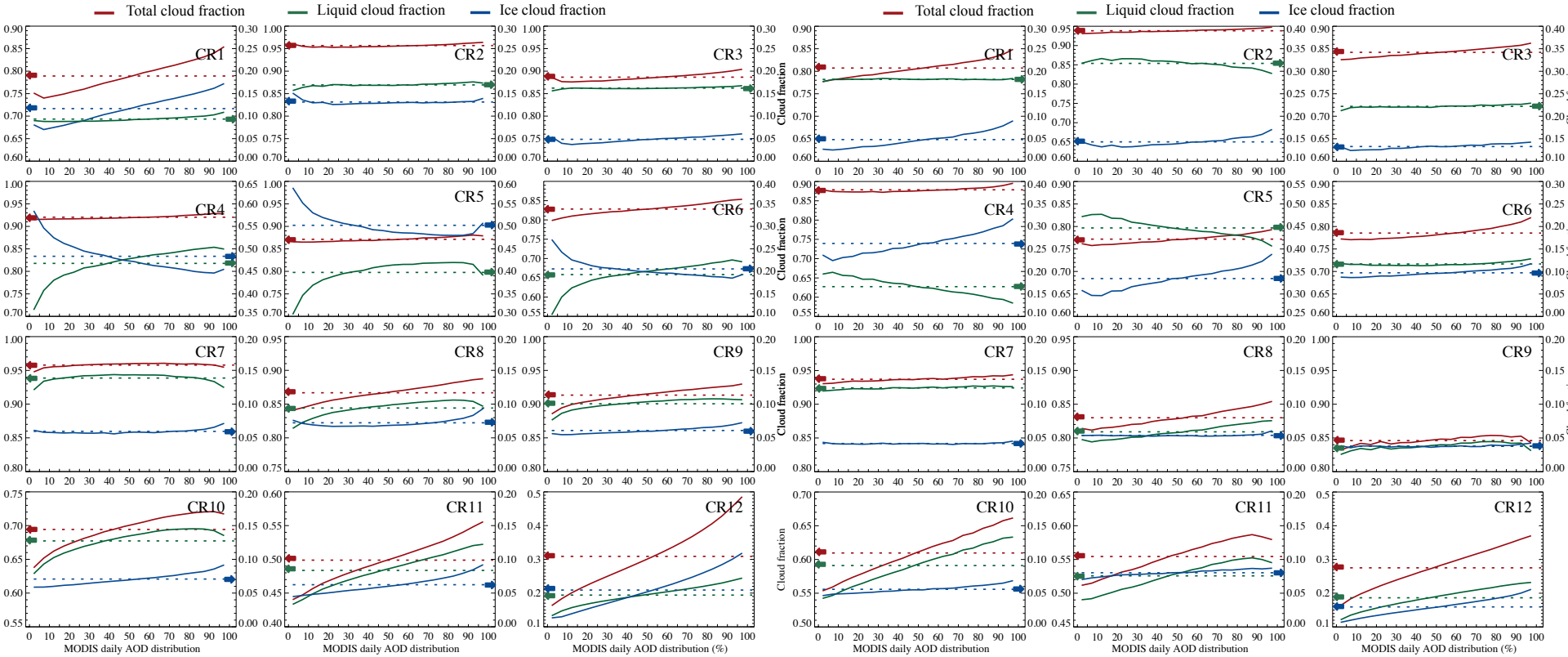
TMPA Precipitation (mm/h) as a function of AOD distribution(per grid per season). The horizontal dashed line is mean TMPA precipitation of each CR. The dots indicate mean AOD within their AOD distribution ranges.

Minimum and maximum values of Y-axis(for TMPA) are different to each CR, but their interval is same (max – min = 0.5) except CR12.

Cloud fraction

Ocean

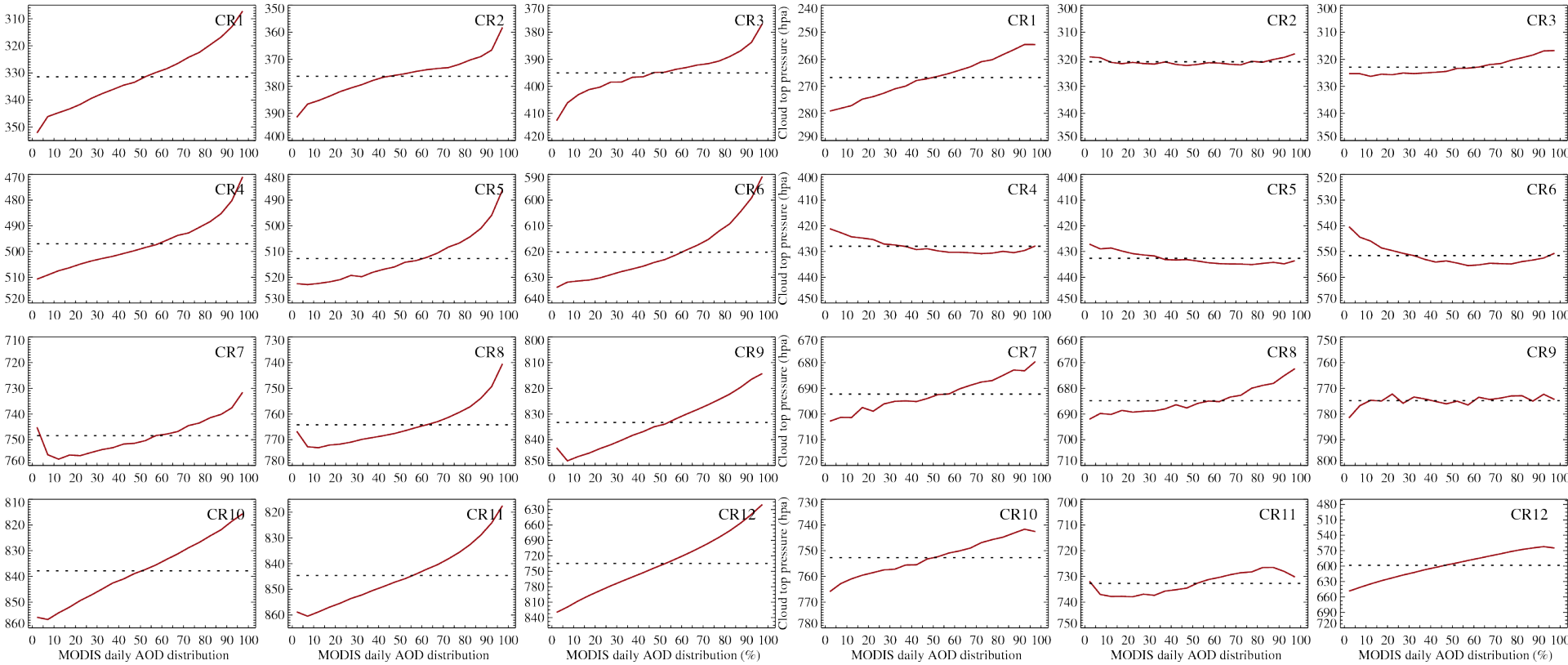
Land



Cloud fraction as a function of AOD distribution(per grid per season). The horizontal dashed line is mean cloud fraction of each CR. Minimum and maximum values of Y-axis are different to each CR.

Cloud top pressure

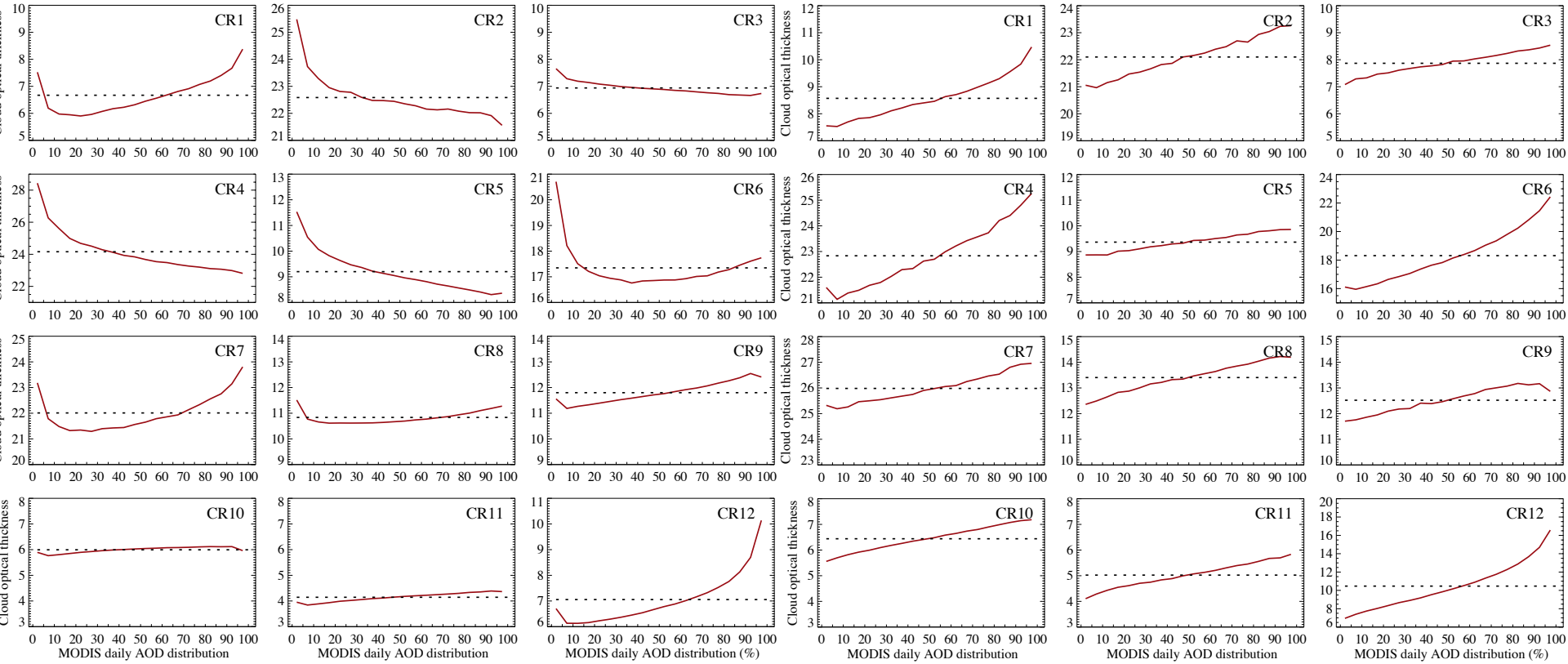
Ocean ***Land***



Cloud top pressure as a function of AOD distribution(per grid per season). The horizontal dashed line is mean cloud top pressure of each CR. Minimum and maximum values of Y-axis are different to each CR, but their interval are same except CR12.

Cloud optical thickness

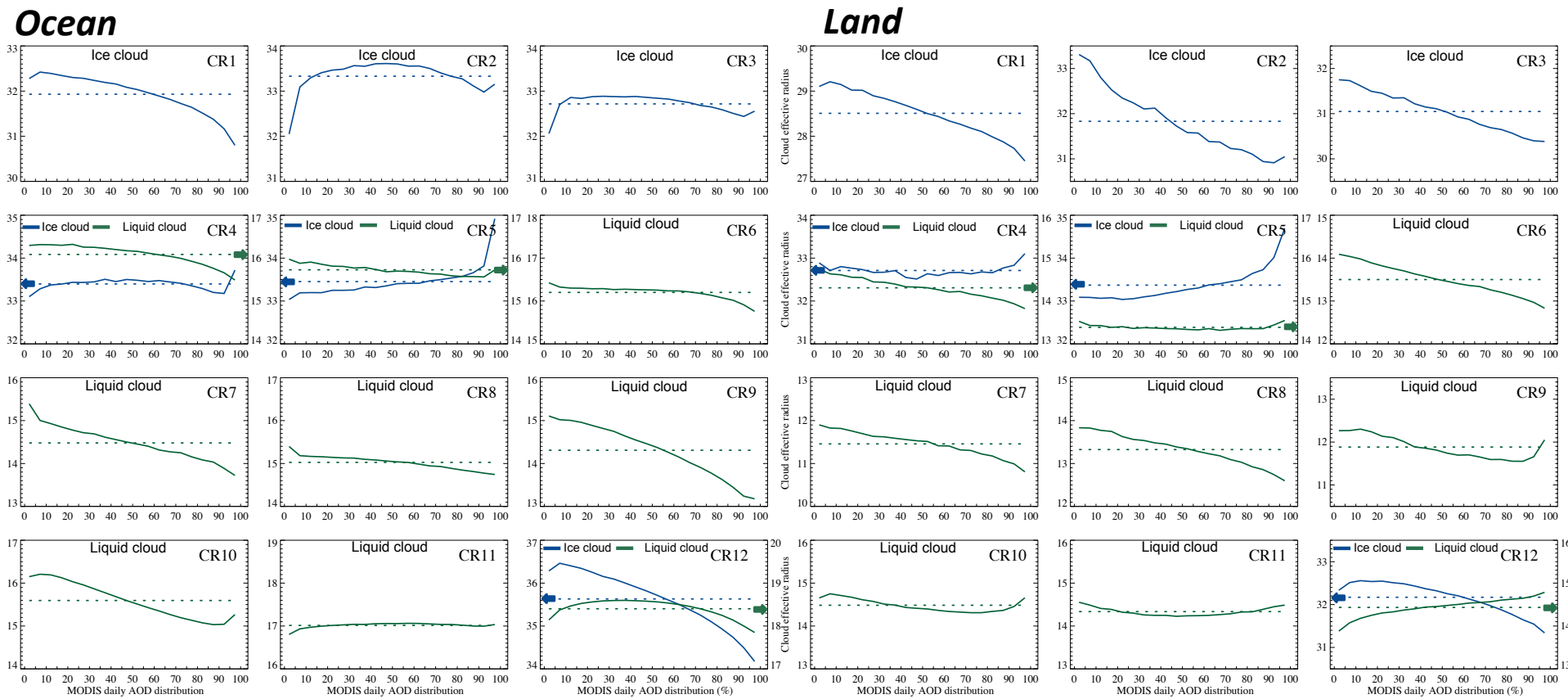
Ocean ***Land***



Cloud optical thickness as a function of AOD distribution(per grid per season). The horizontal dashed line is cloud optical thickness of each CR.

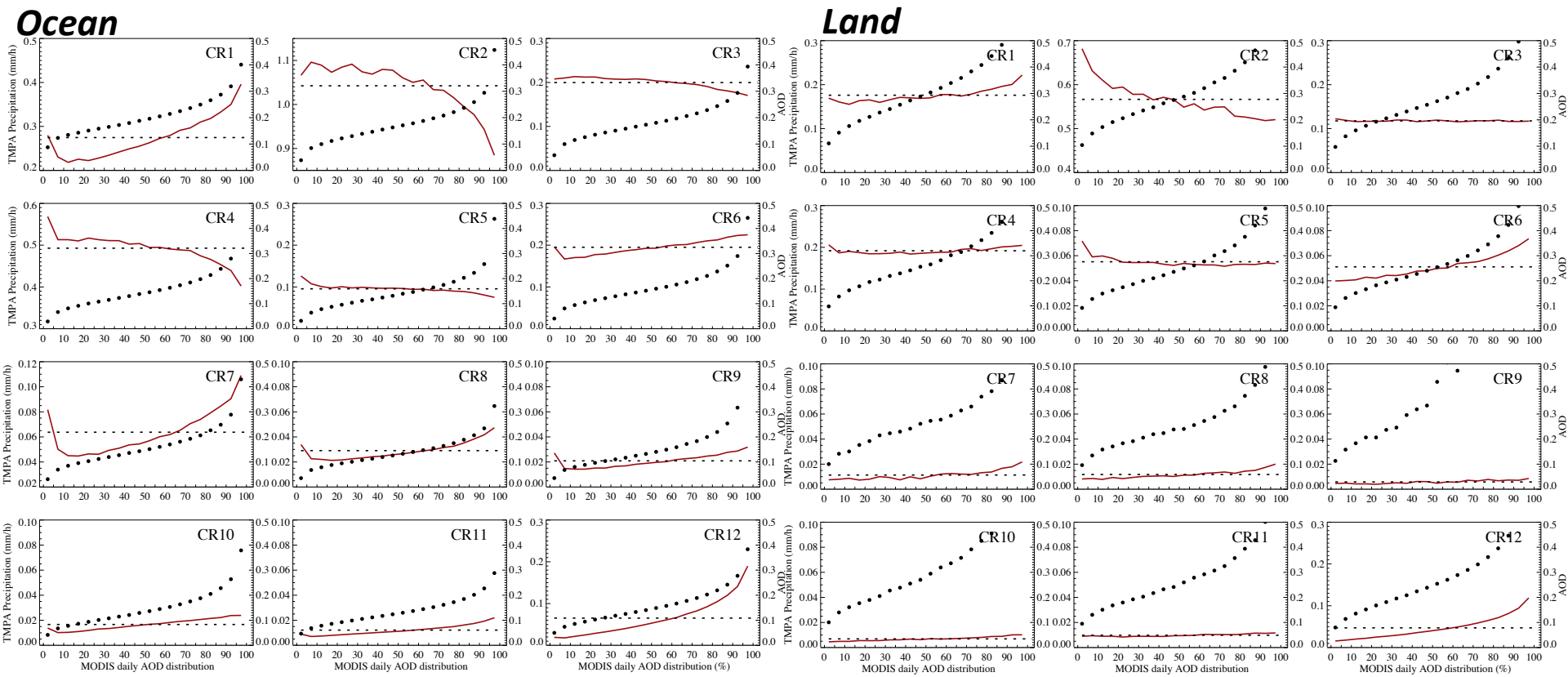
Minimum and maximum values of Y-axis are different to each CR.

Cloud effective radius (μm)



Cloud effective radius as a function of AOD distribution(per grid per season). The horizontal dashed line is cloud effective radius of each CR.

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.

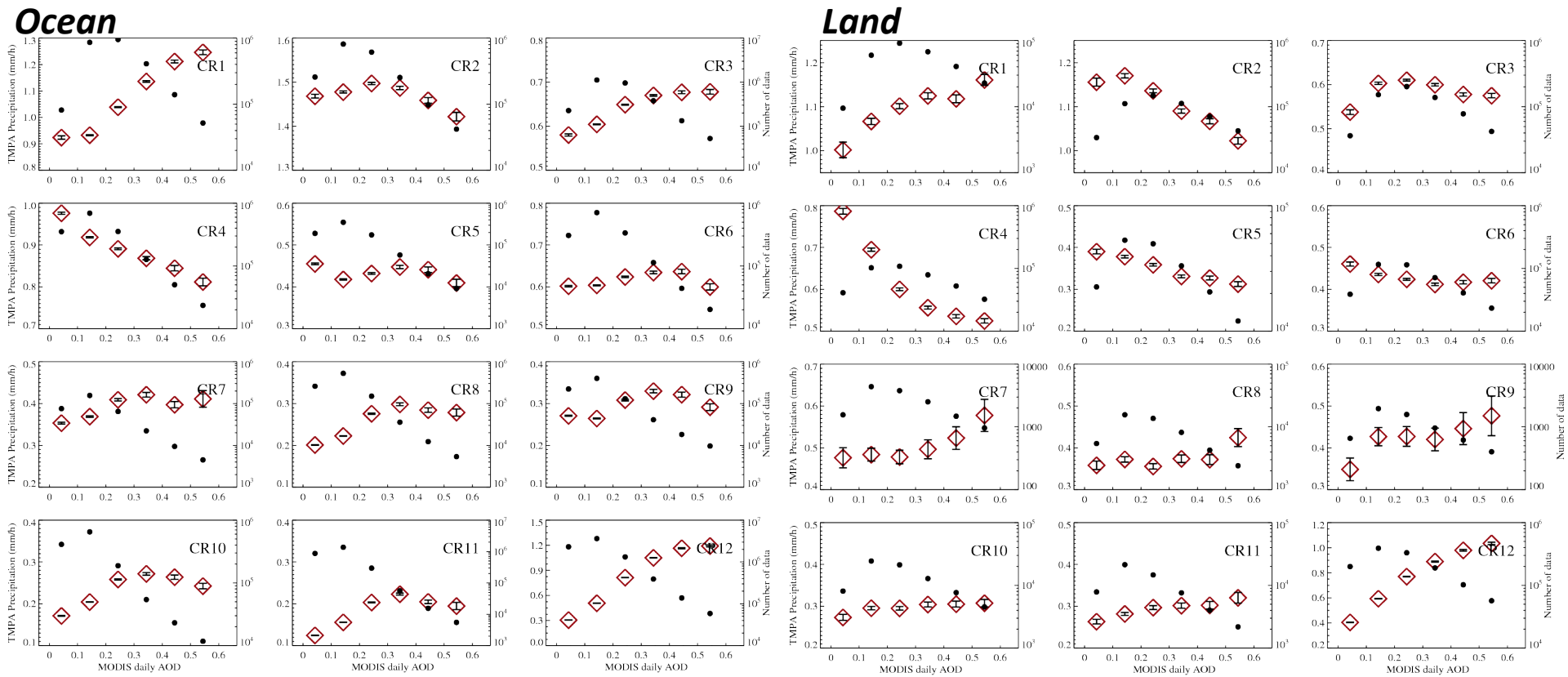
Minimum and maximum values of Y-axis(for TMPA) are different to each CR, but their interval is same.

Aerosol-Cloud(CR)-Precipitation

Ocean/ Land

As a function of ***daily MODIS absolute values.***

TMPA (P > 0)

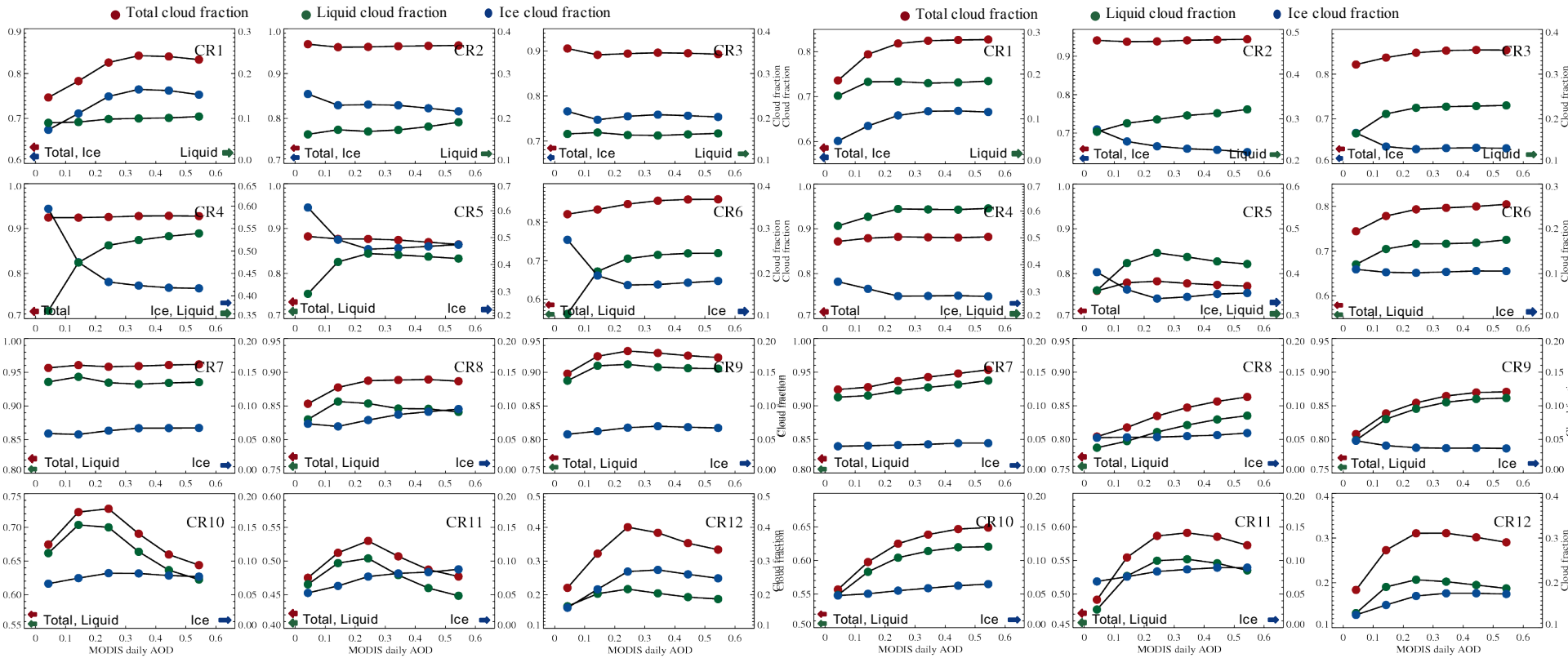


TMPA Precipitation (mm/h) as a function of MODIS daily AOD. Black dots mean number of data. The error bars indicate the standard error (SE) given by the standard deviation of the data divided by the square root of number of data.

Cloud fraction

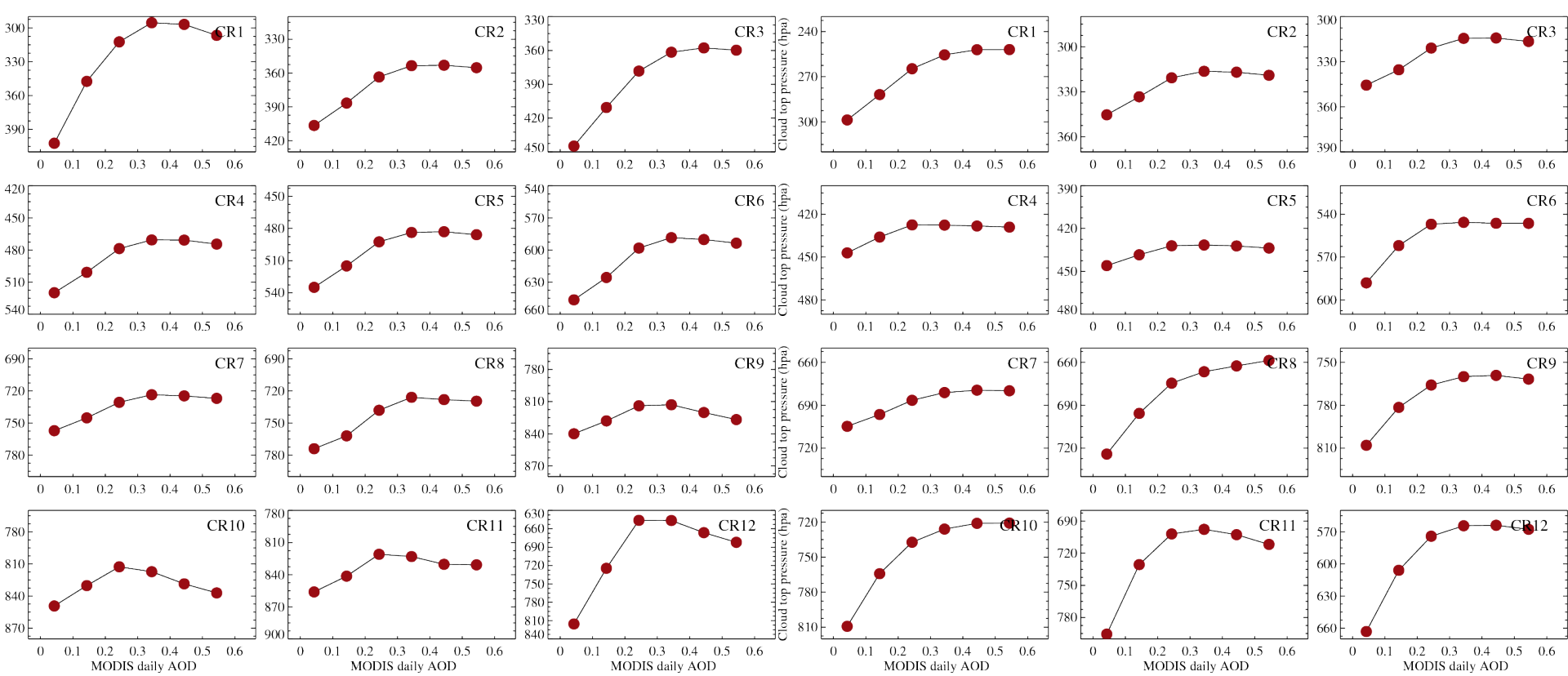
Ocean

Land



Cloud fraction as a function of daily MODIS AOD.

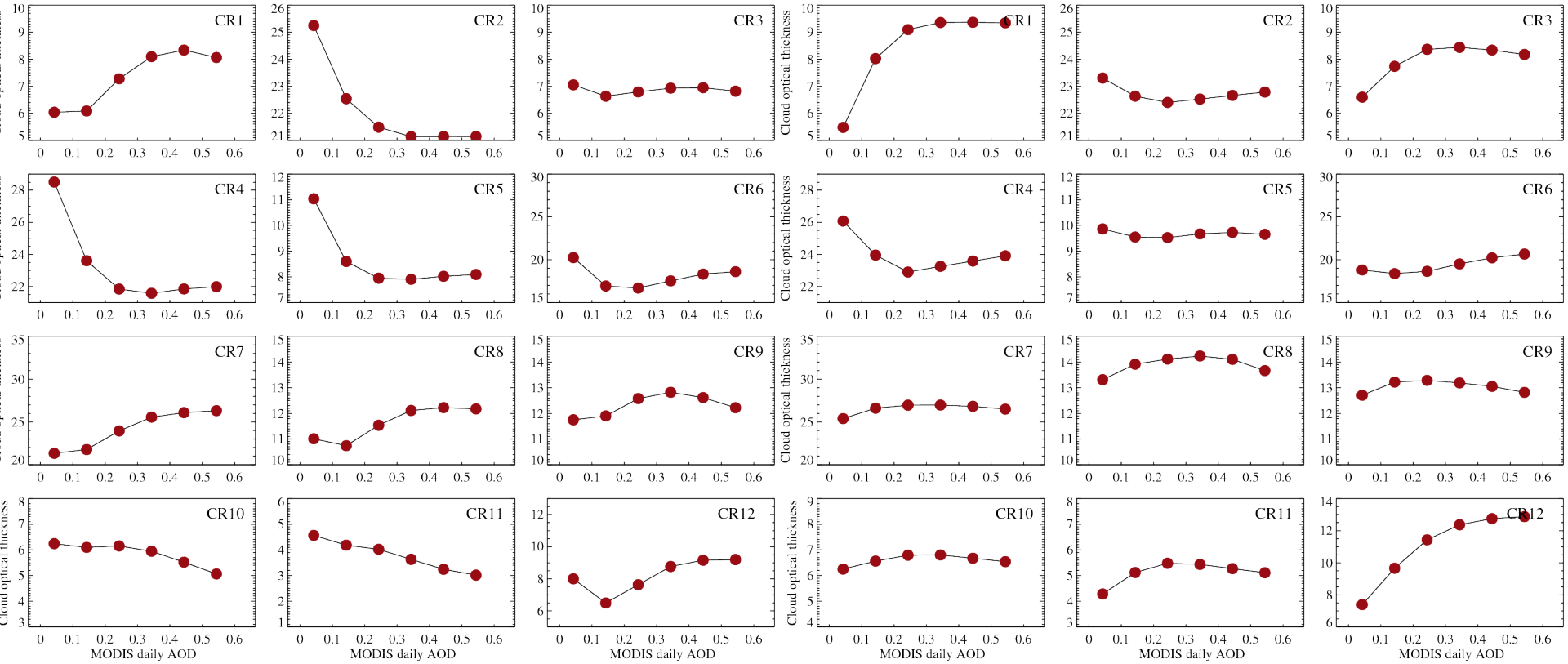
Cloud top pressure



Cloud top pressure as a function of MODIS daily AOD.

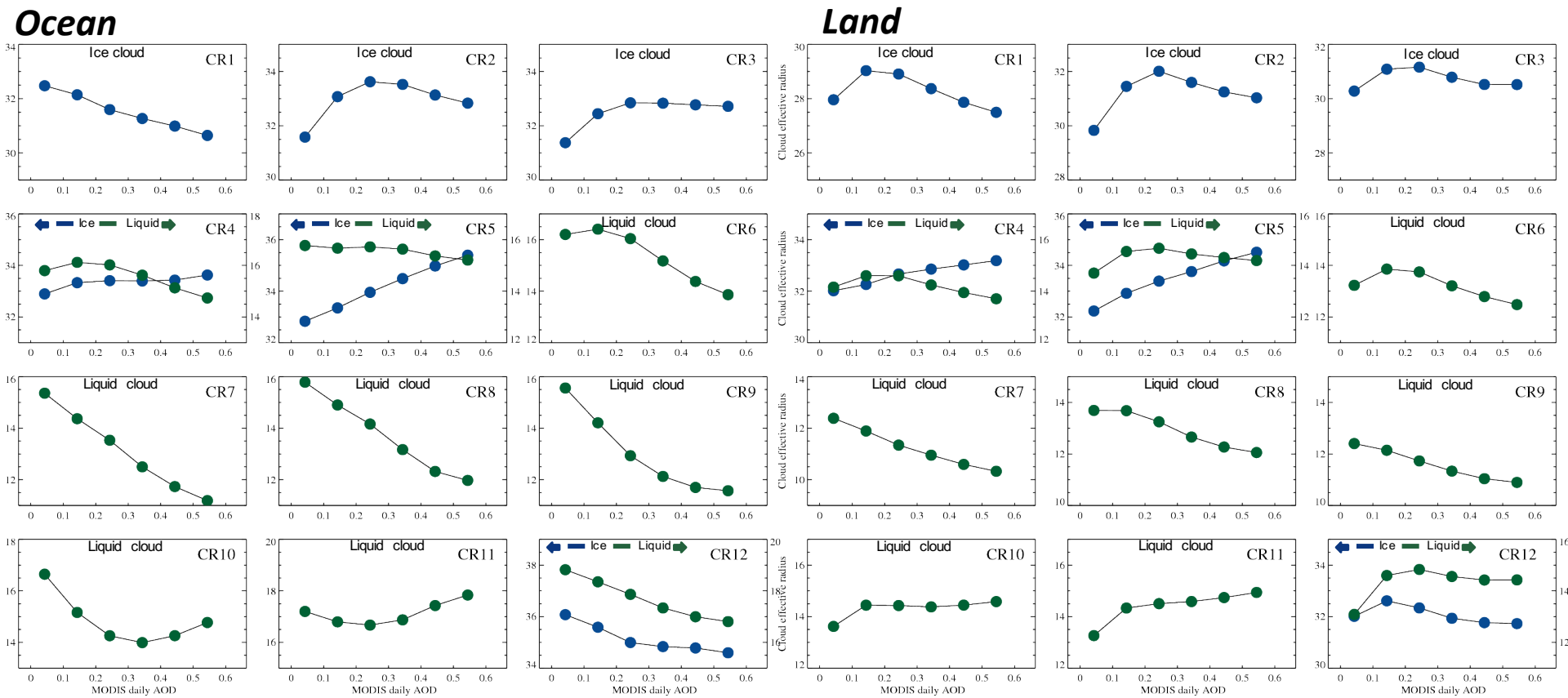
Cloud optical thickness

Ocean ***Land***



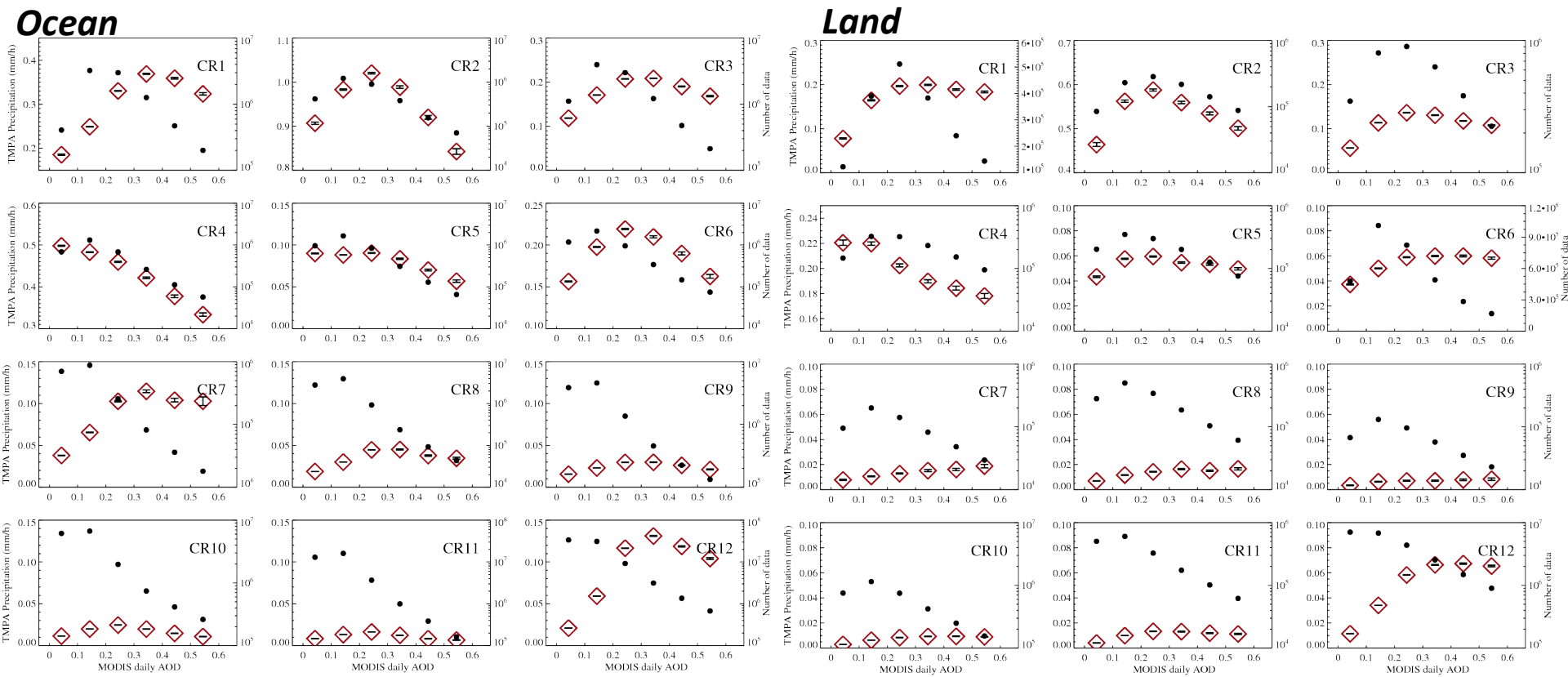
Cloud optical thickness as a function of MODIS daily AOD.

Cloud effective radius (μm)



Cloud effective radius as a function of MODIS daily AOD.

TMPA (P ≥ 0)



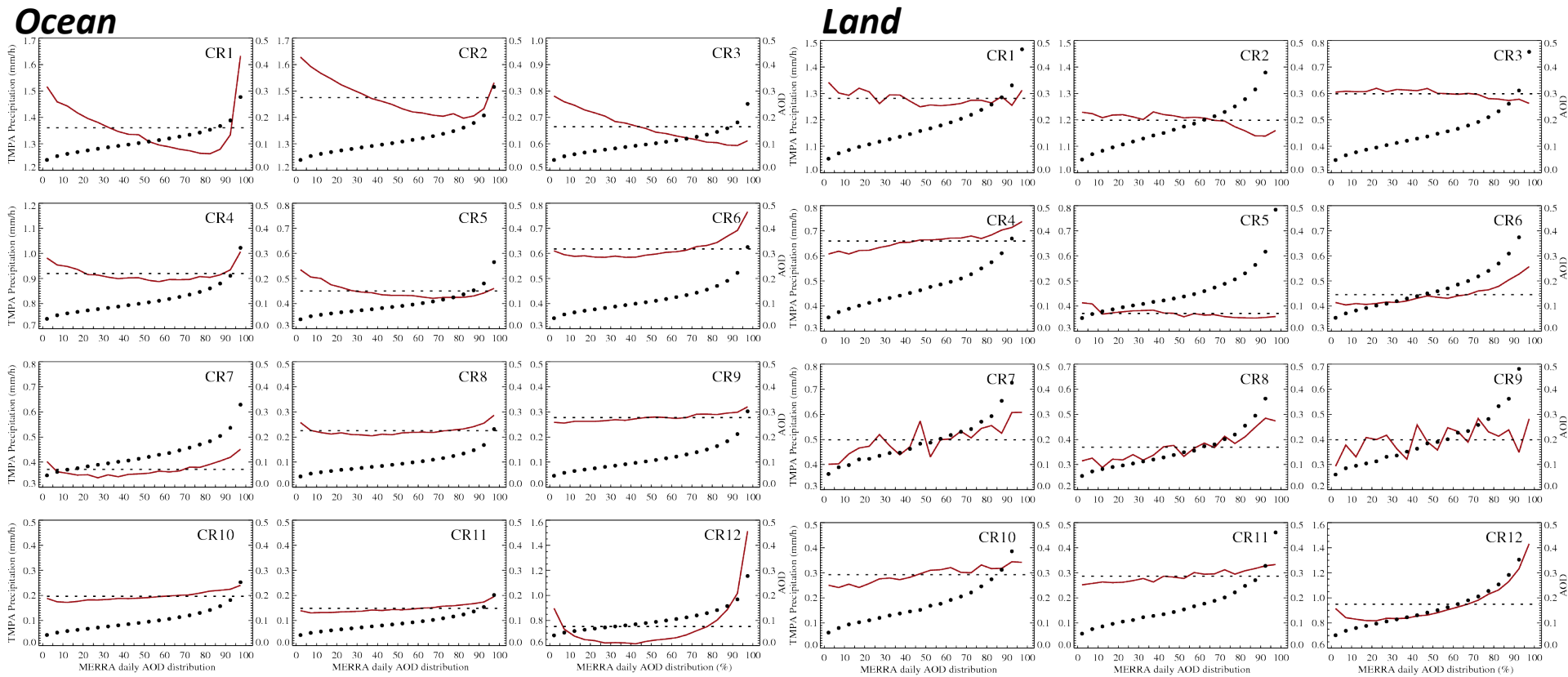
TMPA Precipitation (mm/h) as a function of MODIS daily AOD. Black dots mean number of data. The error bars indicate the standard error (SE) given by the standard deviation of the data divided by the square root of number of data.

Aerosol-Cloud(CR)-Precipitation

Ocean/ Land

As a function of ***daily MERRA aod relative distribution***

TMPA (P > 0)



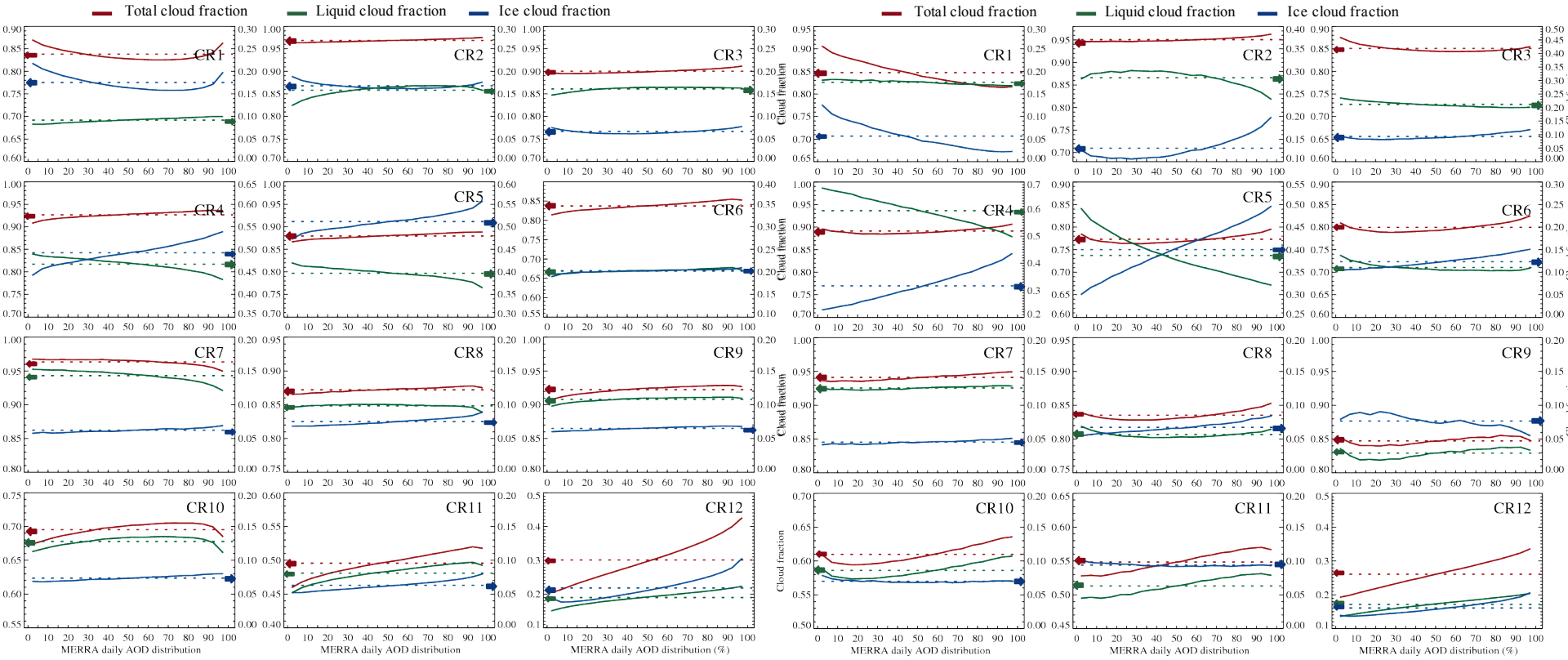
TMPA Precipitation (mm/h) as a function of AOD distribution(per grid per season). The horizontal dashed line is mean TMPA precipitation of each CR. The dots indicate mean AOD within their AOD distribution ranges.

Minimum and maximum values of Y-axis(for TMPA) are different to each CR, but their interval is same (max – min = 0.5) except CR12.

Cloud fraction

Ocean

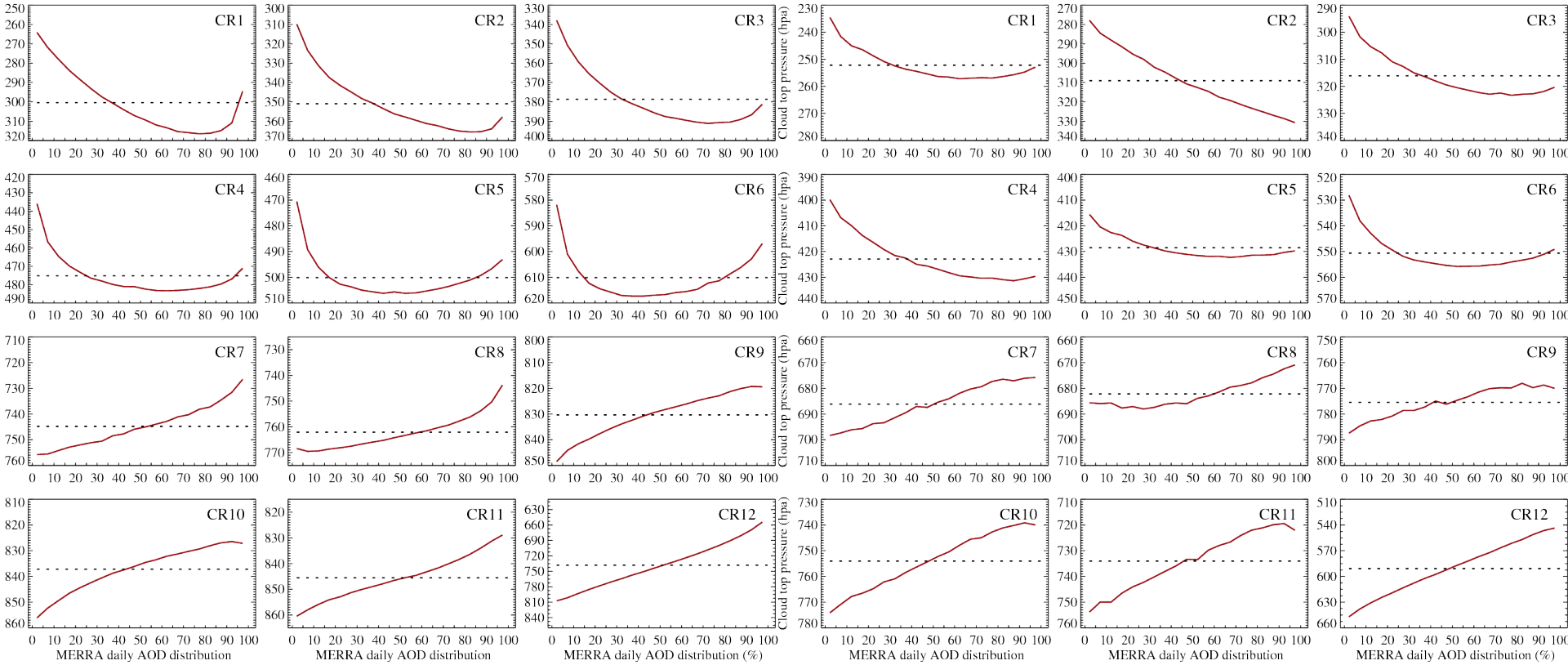
Land



Cloud fraction as a function of AOD distribution(per grid per season). The horizontal dashed line is mean cloud fraction of each CR. Minimum and maximum values of Y-axis are different to each CR.

Cloud top pressure

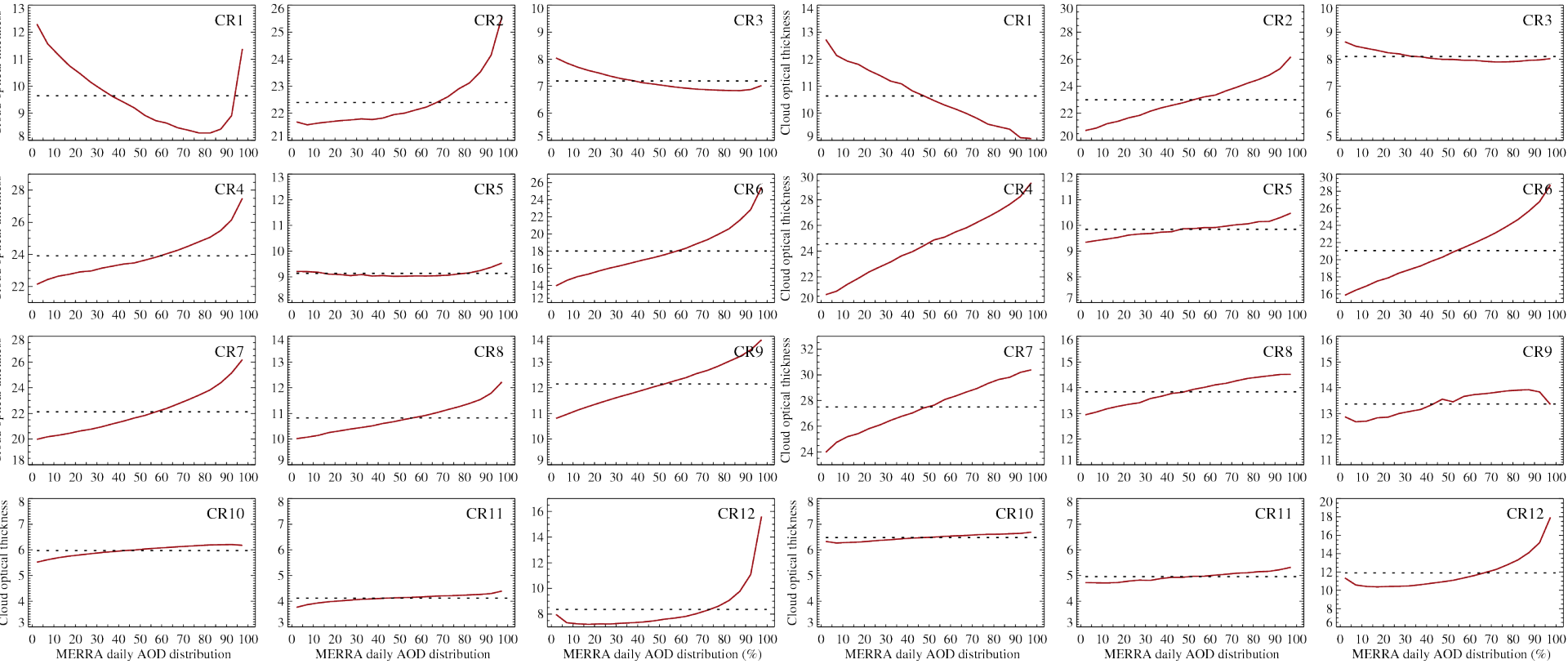
Ocean ***Land***



Cloud top pressure as a function of AOD distribution(per grid per season). The horizontal dashed line is mean cloud top pressure of each CR.

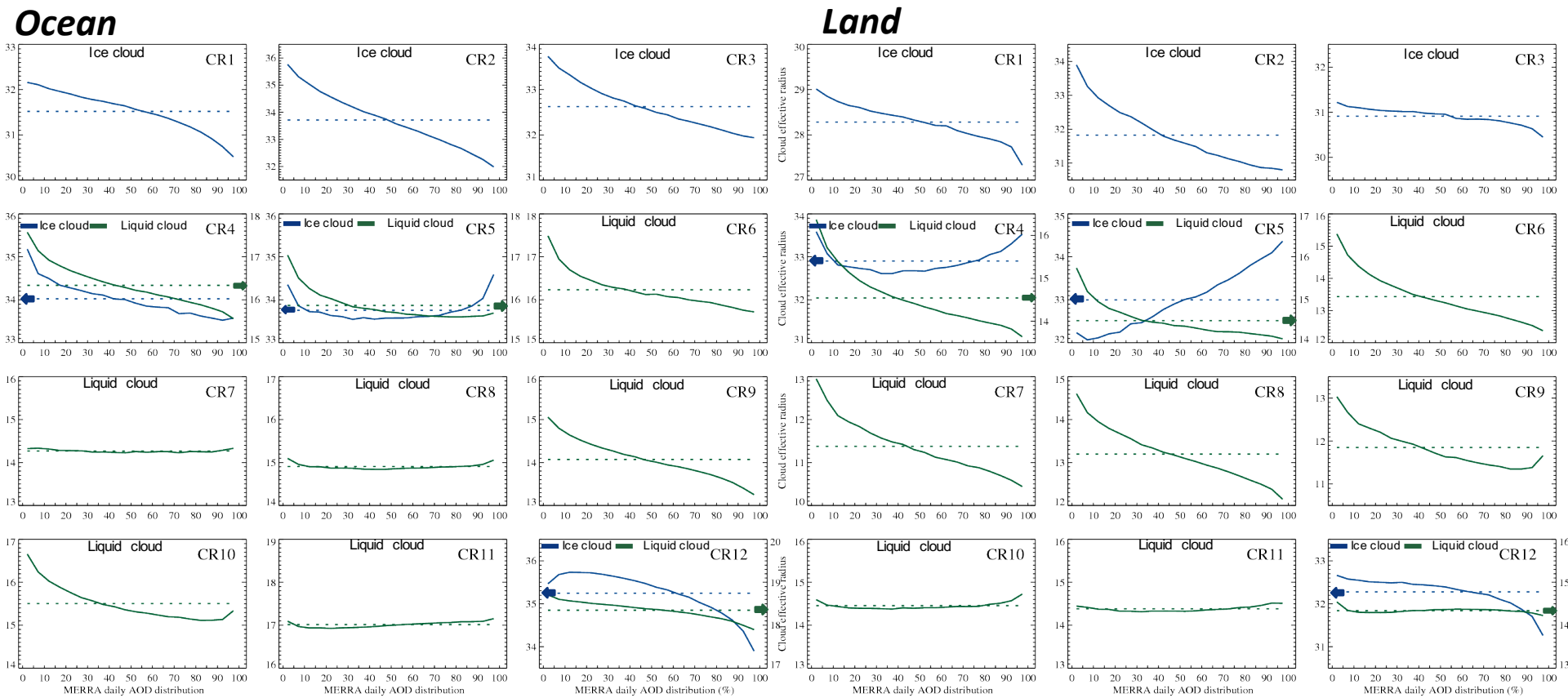
Cloud optical thickness

Ocean ***Land***



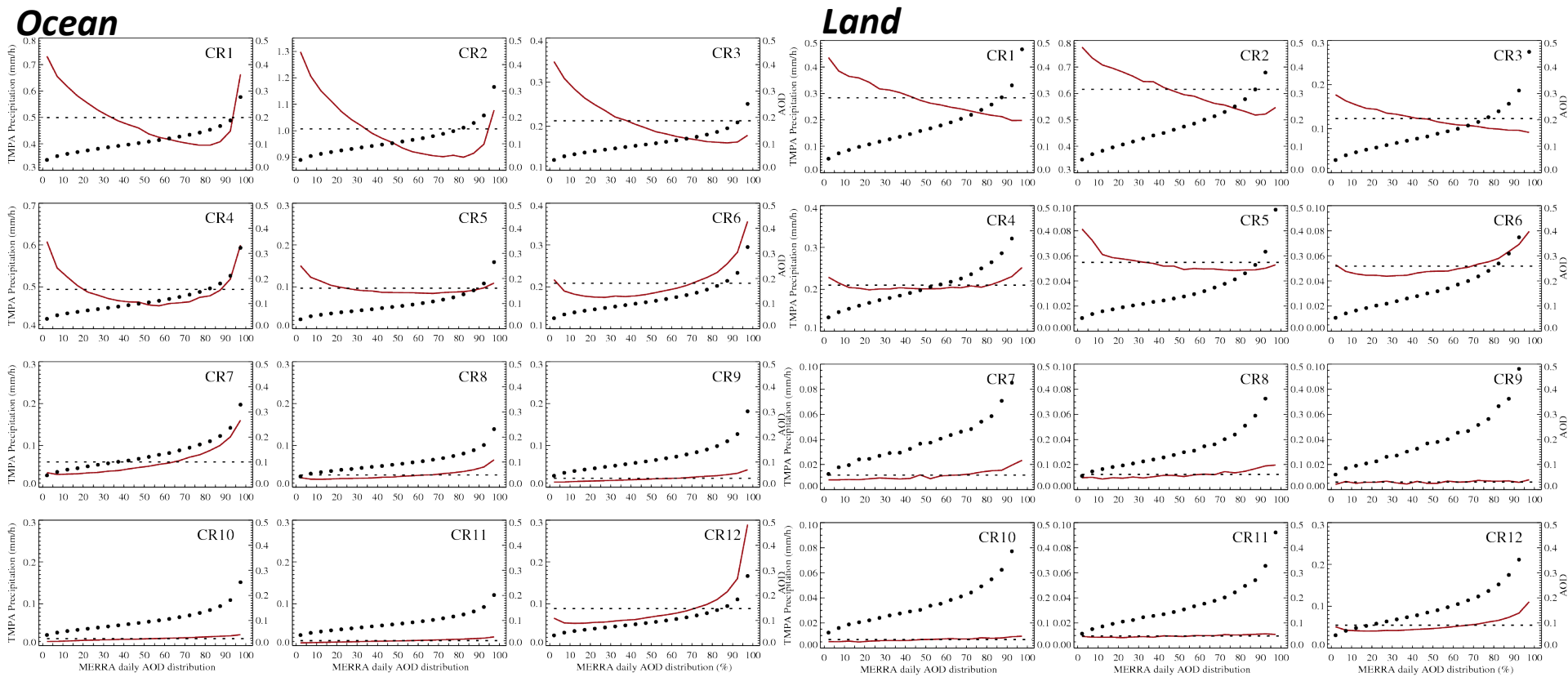
Cloud optical thickness as a function of AOD distribution(per grid per season). The horizontal dashed line is cloud optical thickness of each CR.

Cloud effective radius (μm)



Cloud effective radius as a function of AOD distribution(per grid per season). The horizontal dashed line is cloud effective radius of each CR.

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.

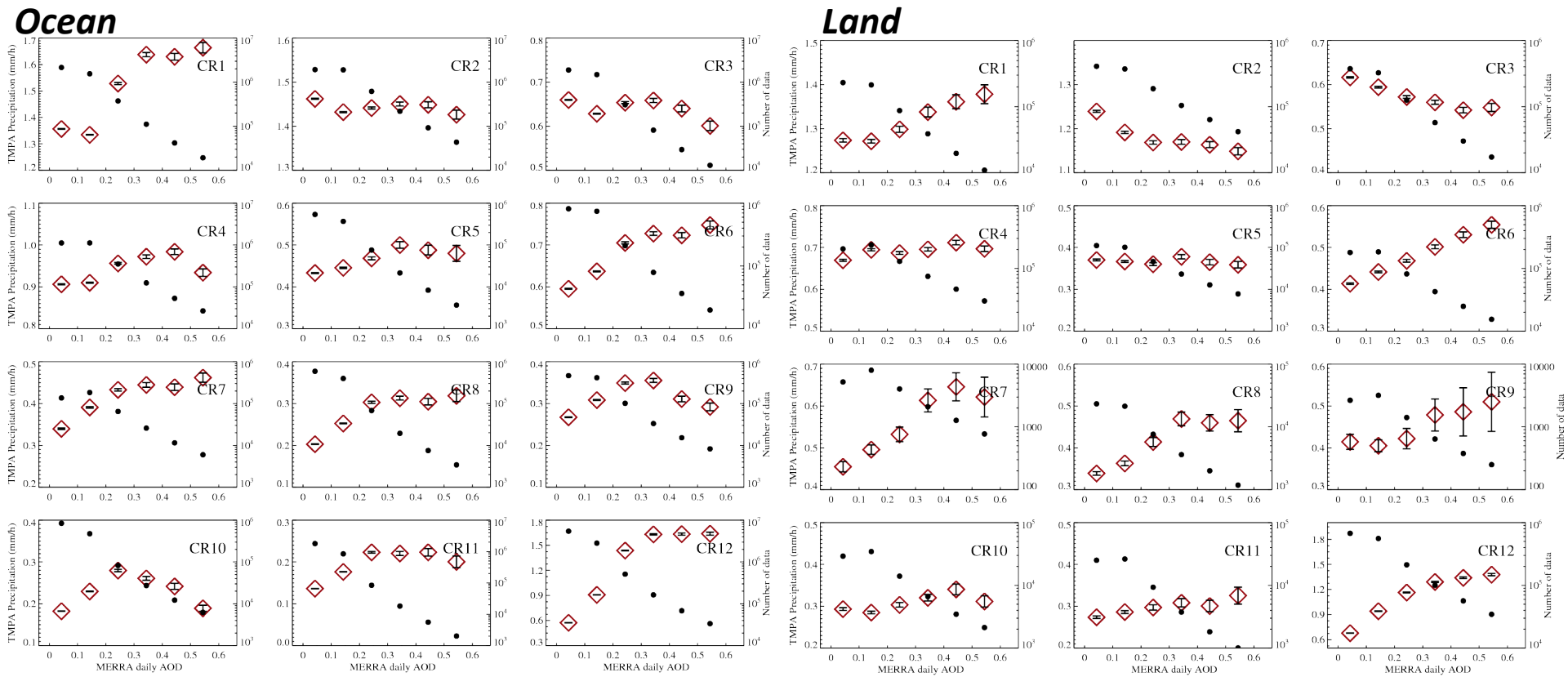
Minimum and maximum values of Y-axis(for TMPA) are different to each CR, but their interval is same.

Aerosol-Cloud(CR)-Precipitation

Ocean/ Land

As a function of ***daily MERRA absolute values.***

TMPA (P > 0)



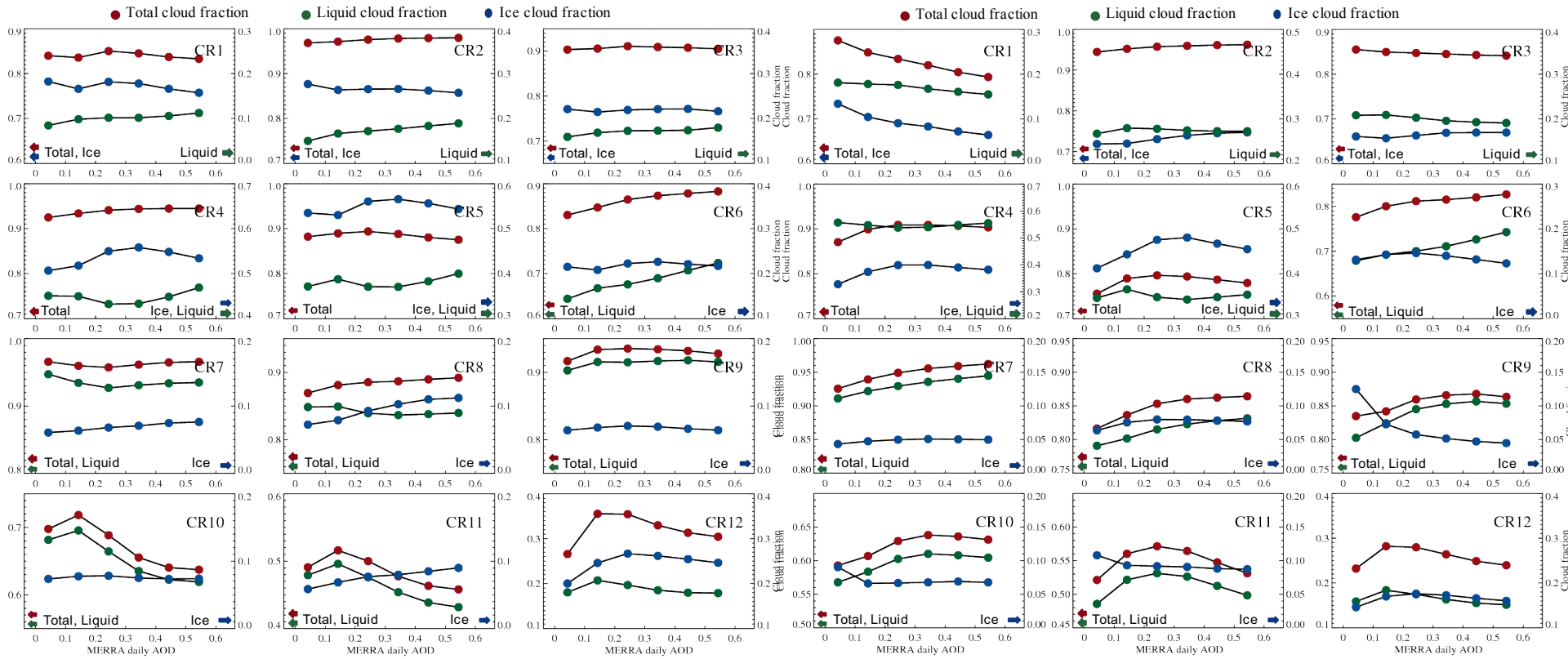
TMPA Precipitation (mm/h) as a function of AOD distribution(per grid per season). The horizontal dashed line is mean TMPA precipitation of each CR. The dots indicate mean AOD within their AOD distribution ranges.

Minimum and maximum values of Y-axis(for TMPA) are different to each CR, but their interval is same (max – min = 0.5) except CR12.

Cloud fraction

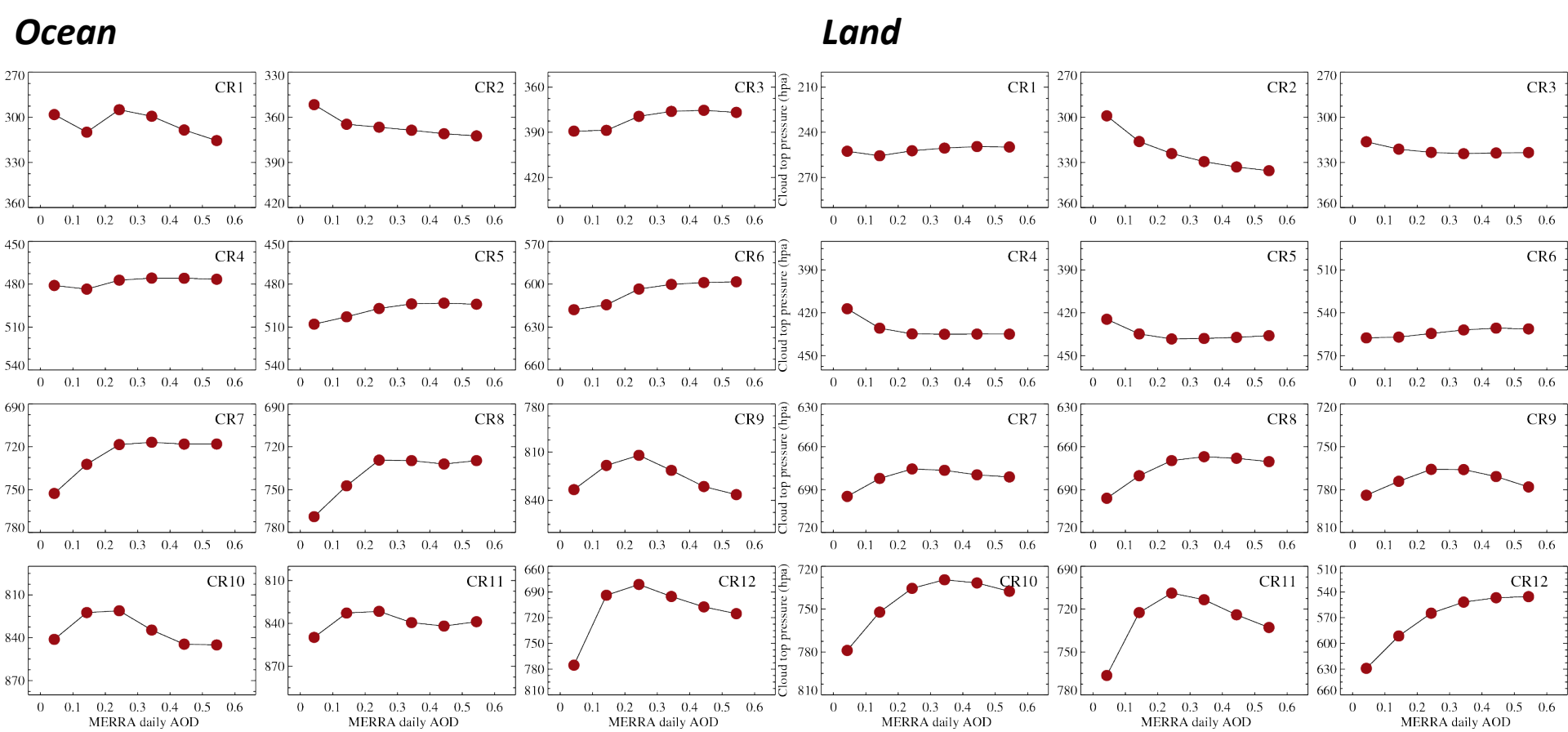
Ocean

Land



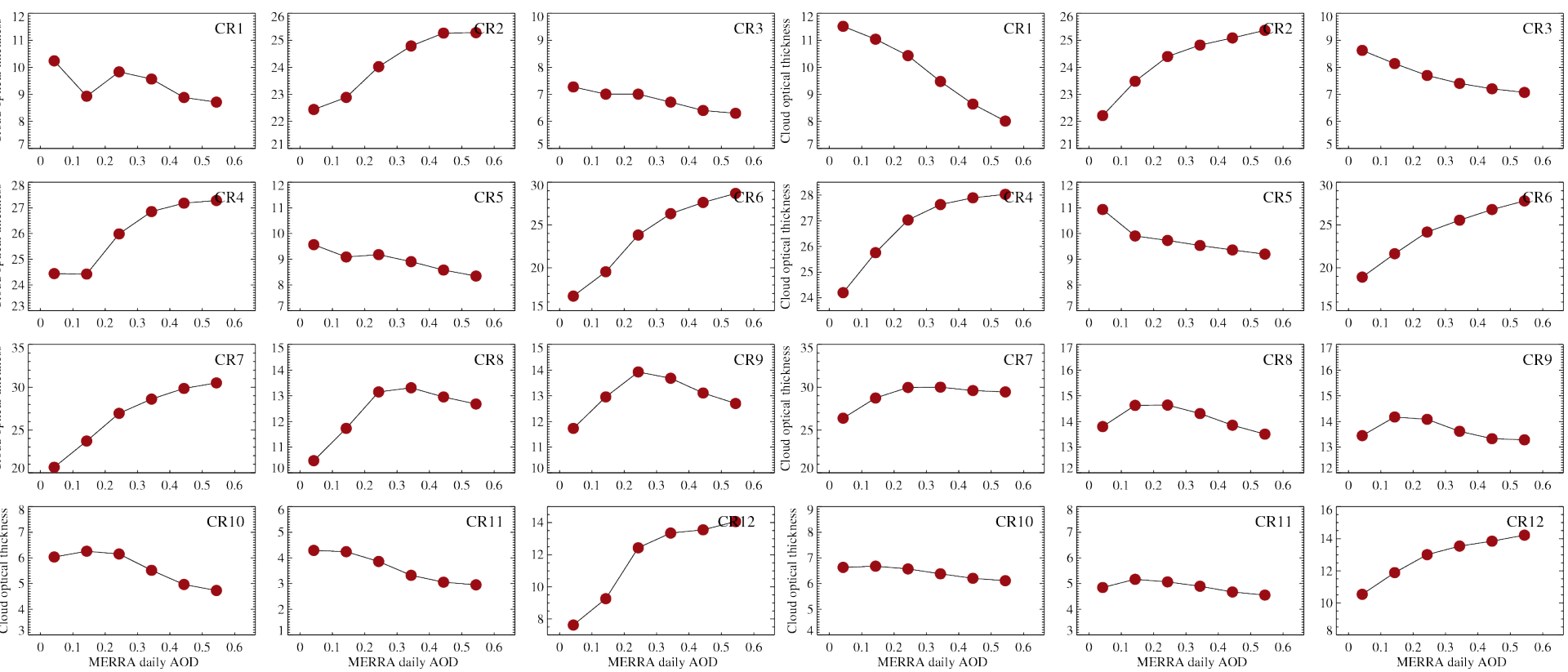
Cloud fraction as a function of AOD distribution(per grid per season). The horizontal dashed line is mean cloud fraction of each CR. Minimum and maximum values of Y-axis are different to each CR.

Cloud top pressure



Cloud top pressure as a function of AOD distribution(per grid per season). The horizontal dashed line is mean cloud top pressure of each CR. Minimum and maximum values of Y-axis are different to each CR, but their interval are same except CR12.

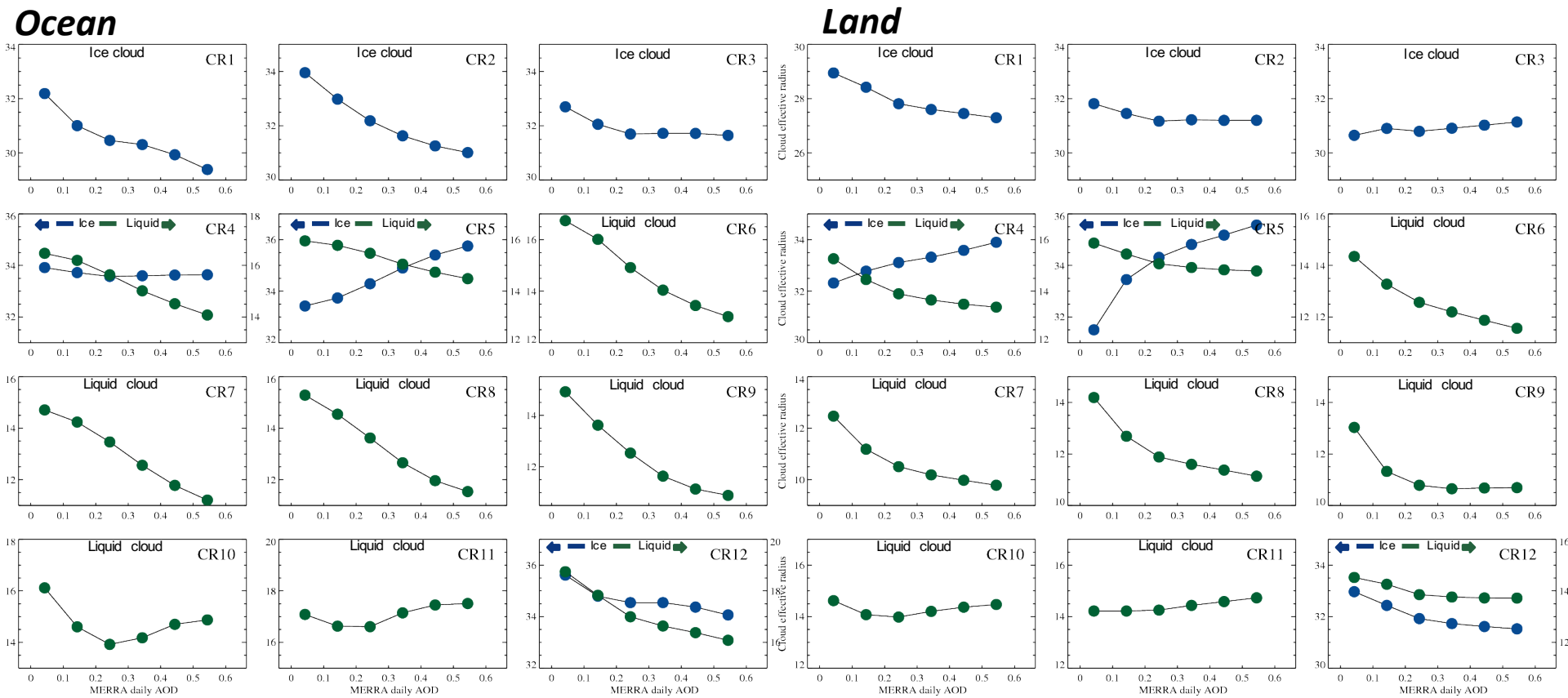
Cloud optical thickness



Cloud optical thickness as a function of AOD distribution(per grid per season). The horizontal dashed line is cloud optical thickness of each CR.

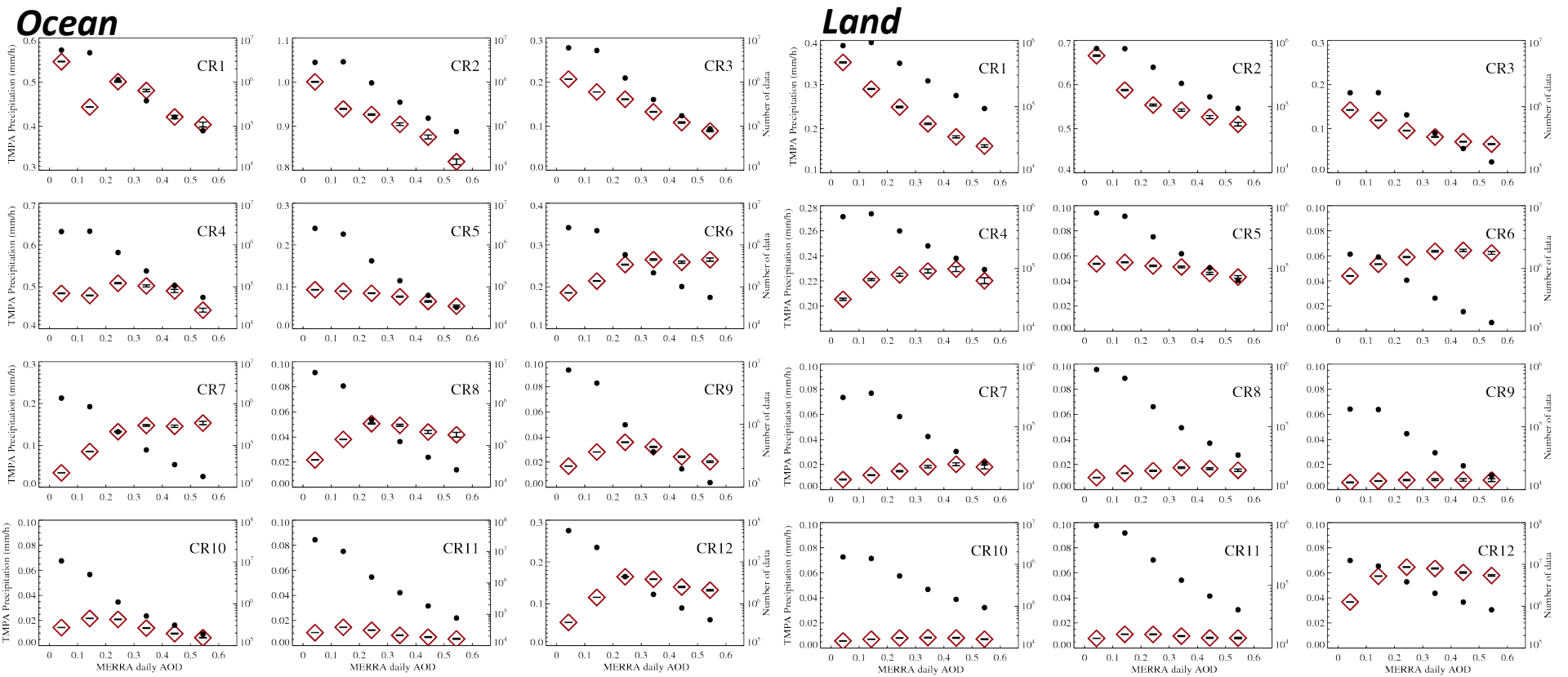
Minimum and maximum values of Y-axis are different to each CR.

Cloud effective radius (μm)



Cloud effective radius as a function of AOD distribution(per grid per season). The horizontal dashed line is cloud effective radius of each CR.

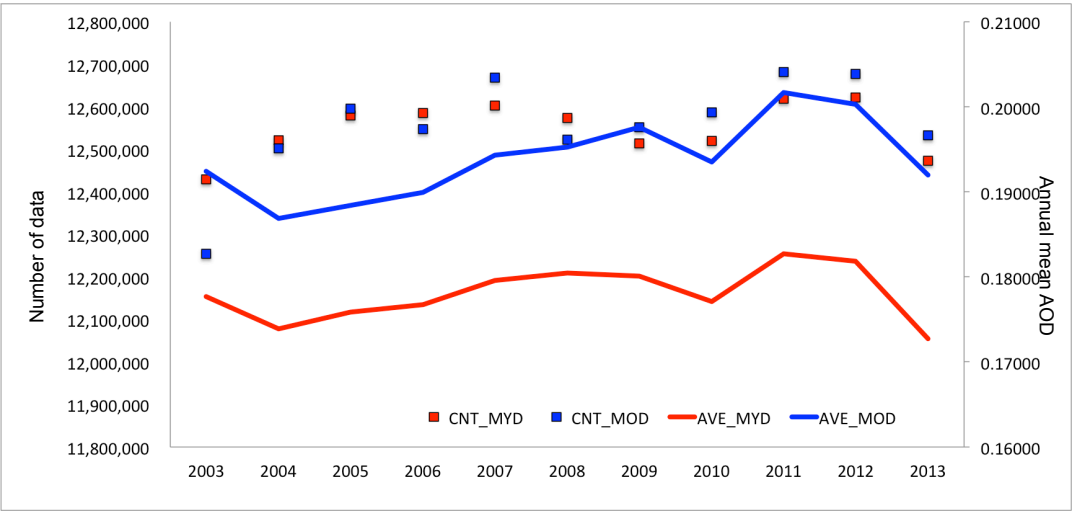
TMPA (P ≥ 0)



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.

-Annual mean MODIS AOD



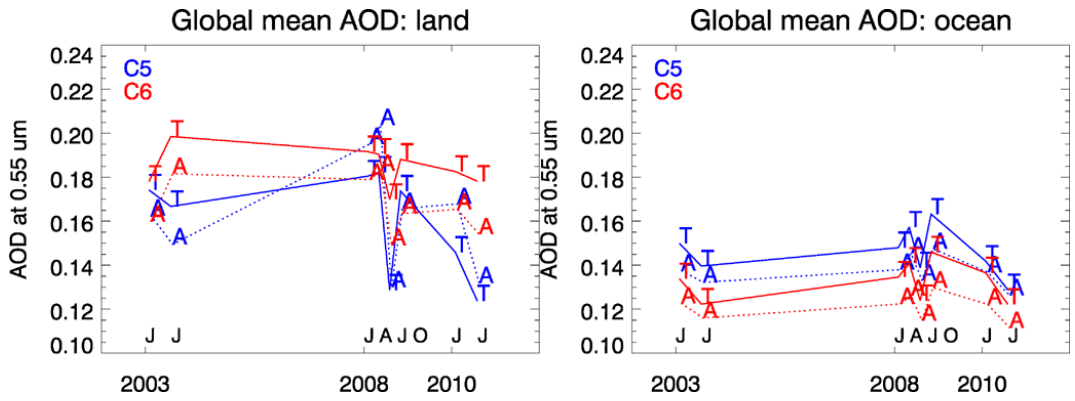


Fig. 23. Global monthly mean AOD for DT-land (left) and DT-ocean (right) for eight test months (January and July for 2003, 2008 and 2010, plus April and October 2008) as computed for Terra (T) versus Aqua (A), and C6 (red) versus C5 (blue).

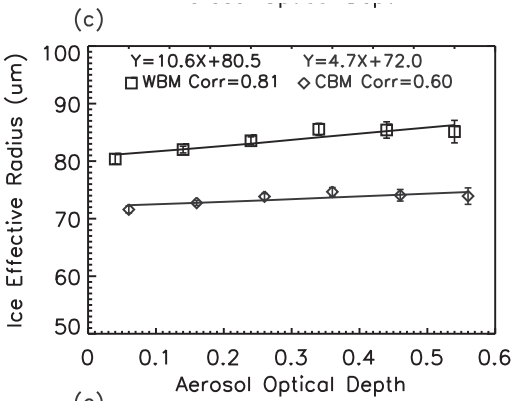
We restate here (from Sect. 2.4) that this is not a calibration or a trend paper. However, since we have already processed eight months of "test data" for both Terra and Aqua, we ask whether Terra/Aqua AOD inconsistencies might remain for C6. Following Tables 2 (for land) and 4 (for ocean), we calculate 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.

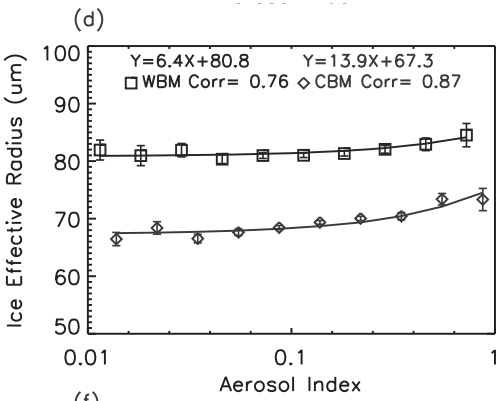
At this point, we cannot determine fully how the revised calibration efforts will impact global trends and divergence of Terra and Aqua. However, the preliminary result is that, in fact, the trending differences will most likely be mitigated by the new calibration effort. Unlike the situation in 2007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

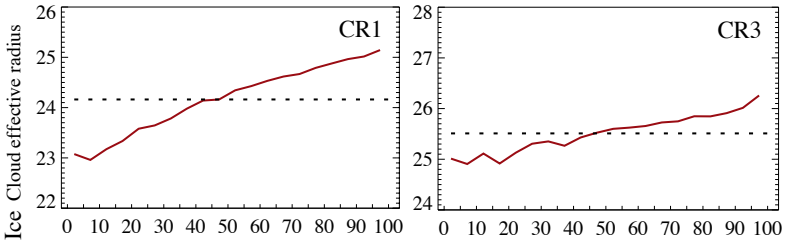
Levy et al., 2013

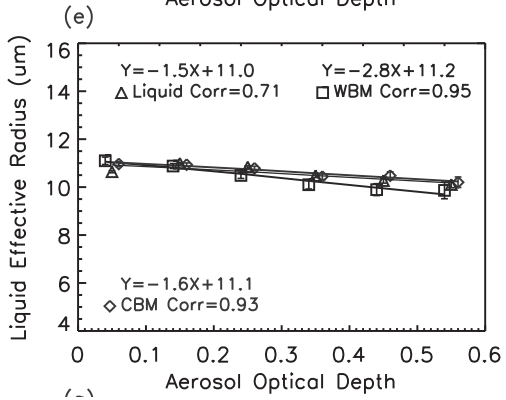
Land

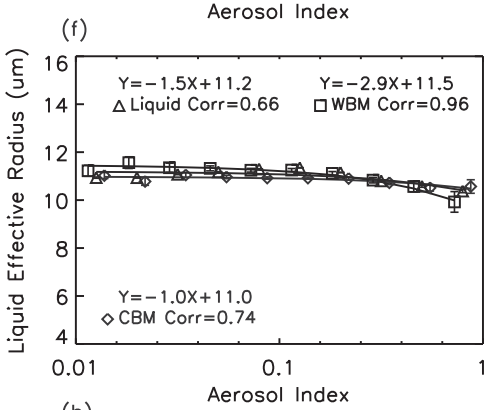
Ocean

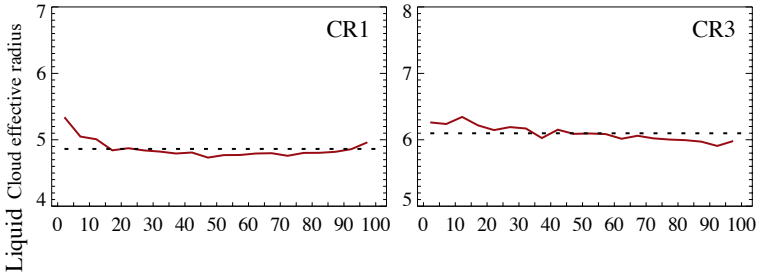








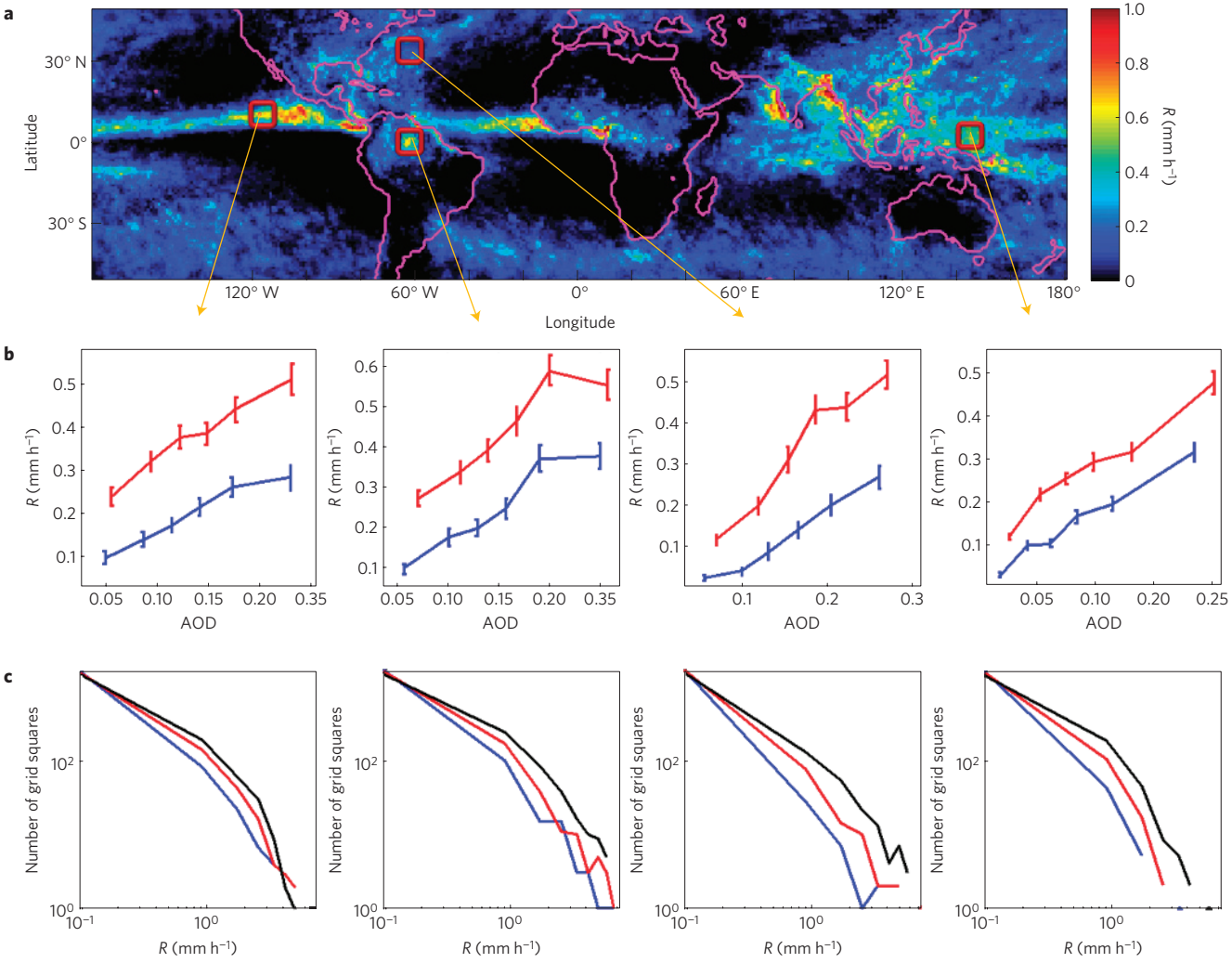


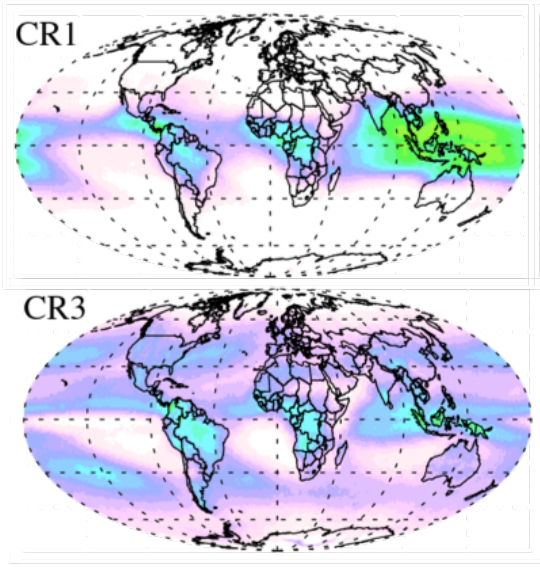


Peng et al., 2016

Region : Tropics (20S – 20N)

Aerosol from MODIS, CER from CloudSat CPR





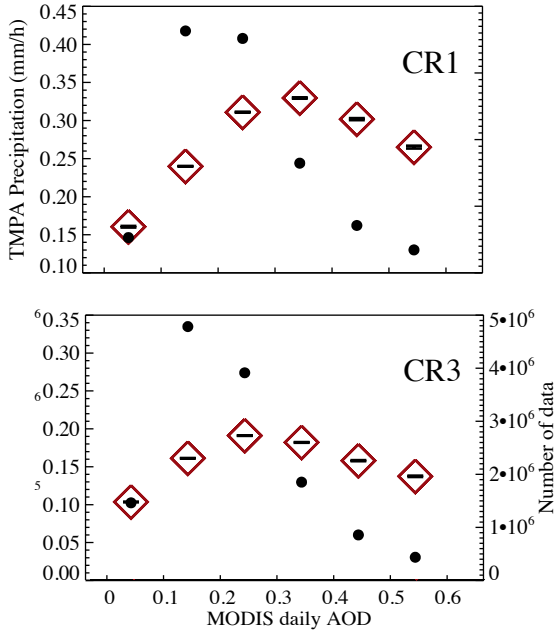
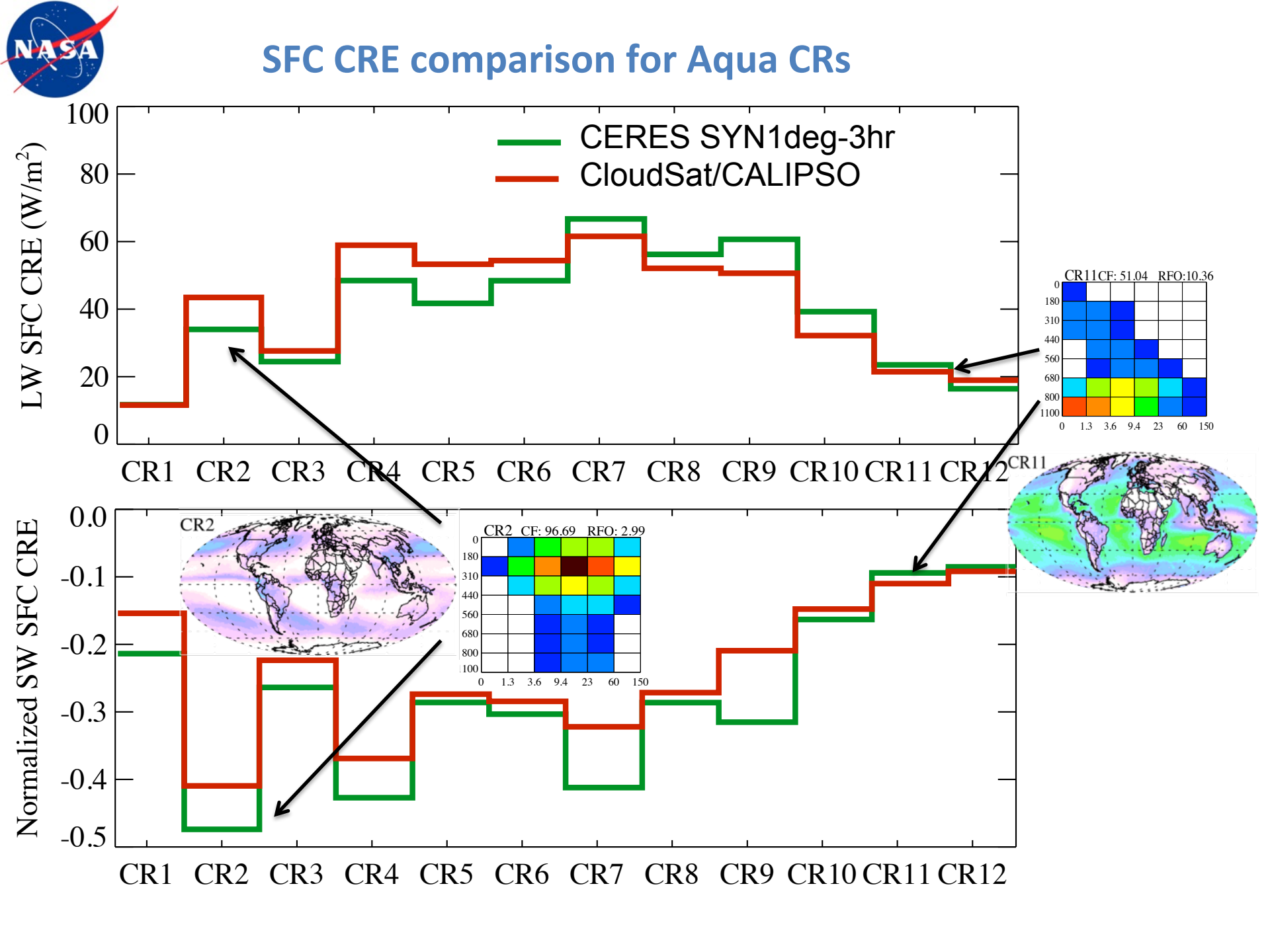


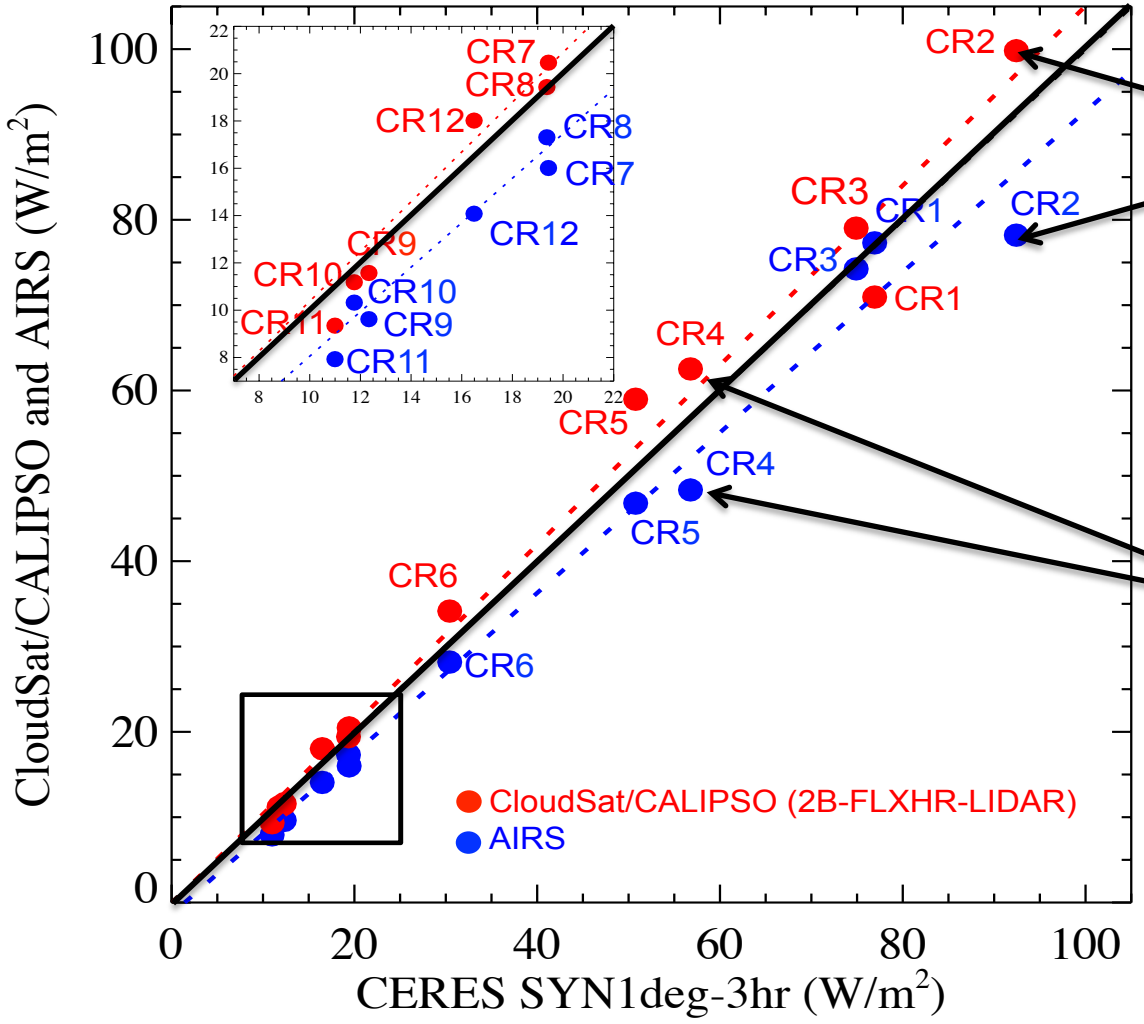
Figure 1 | 13:30 local-time map of rain rate (*R*) and the observed trend with aerosol loading in four selected regions. a, Map of the study area showing average *R* values during June, July and August 2007. **b**, The average *R* values are plotted for six aerosol-loading sets (blue, including zero *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.

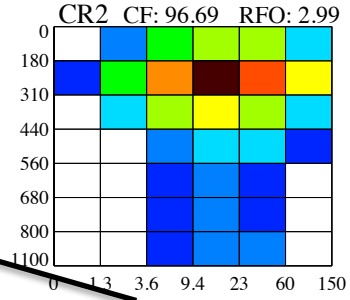
Koren et al., 2012

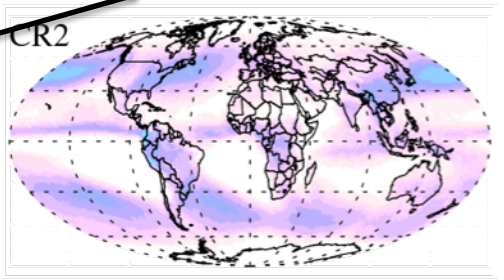
SFC CRE comparison for Aqua CRs

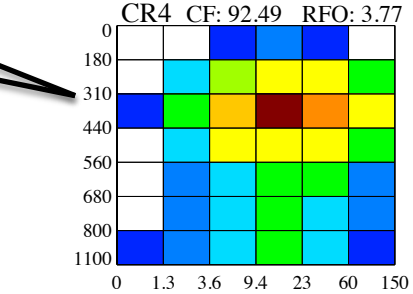


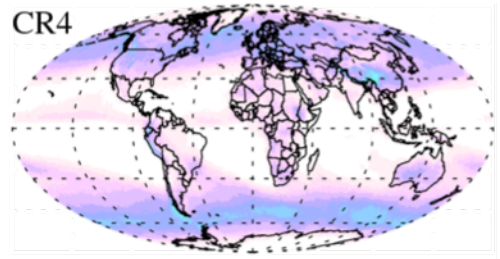
LW TOA CRE comparison for Aqua CRs (three datasets)











LW and SW TOA CRE comparison for Aqua CRs
CERES vs CloudSat-CALIPSO

Global contributions