Signatures of Aerosol Indirect Effect (AIE) in the Long-term Satellite Climate Data Records (CDRs) over the Global Ocean

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Outline

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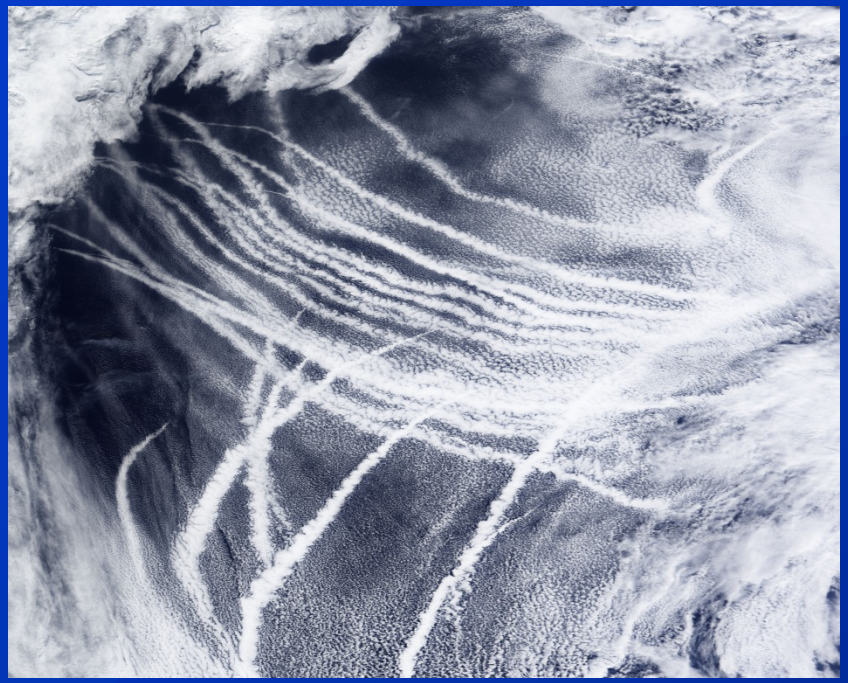
Signatures of Conventional Aerosol Indirect Effect (C-AIE)

- Polluted Cloud:
  - Microphysics: Small cloud droplets, high cloud optical depth, and more cloud water
  - Macrophysics: Less precipitation, increased cloud lifetime, and more cloud fraction
  - Radiation: Enhanced cloud albedo, more absorption, and less transmission
- Clean Cloud:
  - Microphysics: Large cloud droplets, low cloud optical depth, and less cloud water
  - Macrophysics: More precipitation, reduced cloud lifetime, and less cloud fraction
  - Radiation: Reduced cloud albedo, less absorption, and more transmission

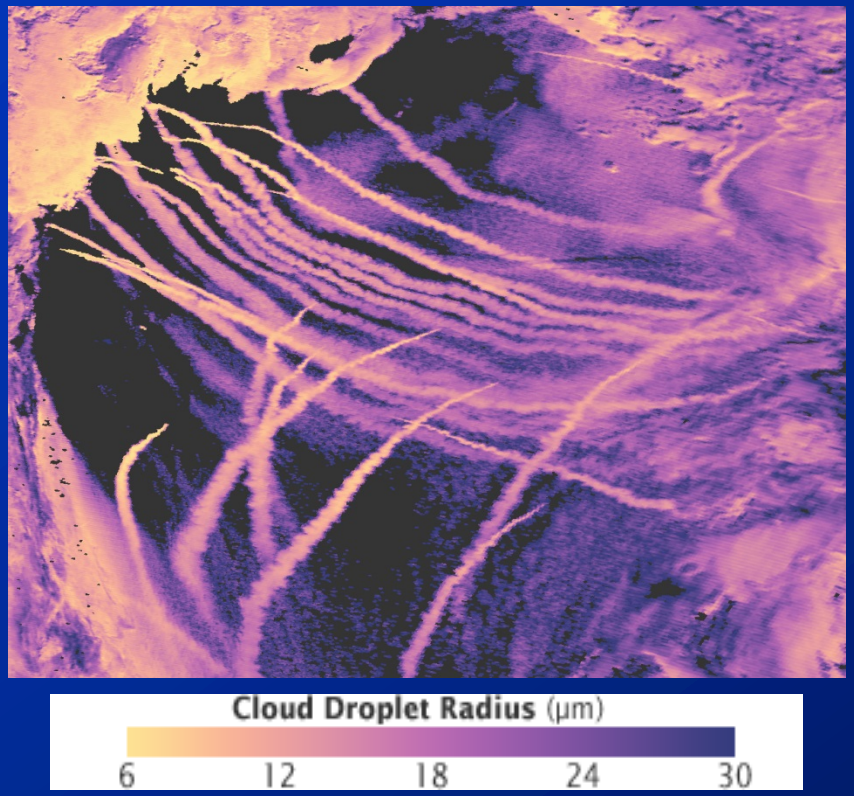
Instantaneous/Short-term Satellite and In-Situ Observations Have Confirmed These Signatures of C-AIE

(Ship Track Example)

Terra/MODIS Nature Color Image



Retrieved Cloud Droplet Radius Image



(March 4, 2009; The Northeast Pacific Ocean; Courtesy of NASA Earth Observatory)

Objective of Our Study

- One remaining question is: Do these signatures still exist in long-term averaged satellite observations?

- Answer to the question is critical for the climate consequence of AIE.

- Thus, the objective of this study is to identify the C-AIE signatures in the long-term satellite observations over the global ocean.

Satellite Data - 1 : AVHRR PATMOS-x Cloud CDRs

Cloud Types	Explanation	Note
Water	Warm liquid water cloud	Named as water cloud in our study
Supercooled	Supercooled liquid water cloud	Grouped as the same category (mixed cloud) in our study
Mixed	Supercooled liquid water and ice cloud	
Opague Ice	Thick ice cloud	
Ice	Thin cirrus cloud	Named as cirrus cloud in our study
Overlapping	Thin cirrus above low cloud	Grouped as the same category in our study
Overshooting	Ice cloud with overshooting tower due to deep convection	

Cloud Variables	Note	Temporal Coverage (Resolution)	Spatial Coverage (Resolution)
Cloud Droplet Effective Radius (CDER)	Directly retrieved	1978-2016 (daily orbit – Level-2b)	Global land & ocean (0.1°x0.1° – Level-2b)
Cloud Optical Depth (COD)	Directly retrieved		
Cloud Water Path (CWP)	Derived from CDER & COD		
Cloud Cover Fraction (CCF)	Directly retrieved		
Cloud Top Temp (CTT)	Directly retrieved		
Cloud Top Height (CTH)	Derived from CTT		

(Pavolonis et al., 2005; Walther et al., 2012; Heidinger et al., 2014)

Satellite Data – 2: AVHRR Aerosol CDR

Aerosol Variable	Note	Temporal Coverage (Resolution)	Spatial Coverage (Resolution)
Aerosol Optical Thickness (AOT)	Value is at 0.63 μm	1980-2016 (daily & monthly mean)	Global ocean only (0.1°x0.1°)

(Zhao et al., 2008, 2013, 2016; Chan et al., 2013)

Monthly and seasonally averaged cloud and aerosol products were derived from the cloud and aerosol CDRs and the product values from 1981 to 2011 (31-years/372-months) are used in the current study.

Analyzing Approaches

- Statistic Correlation Analysis
  - Consider AOT (τ) as a proxy of column aerosol concentration
  - Analyze the correlations between AOT and cloud variables, including CDER (r_e), COD (τ_c), CWP, CCF, CTT (or CTH).
- Linear Trend Analysis
  - Linear Trend (*LT*): ***LT* is the slope of linear regression line for the time series of aerosol or cloud variables. It is in the unit of absolute (or percentage) changes per decade or per year.**
  - Significance of *LT*:

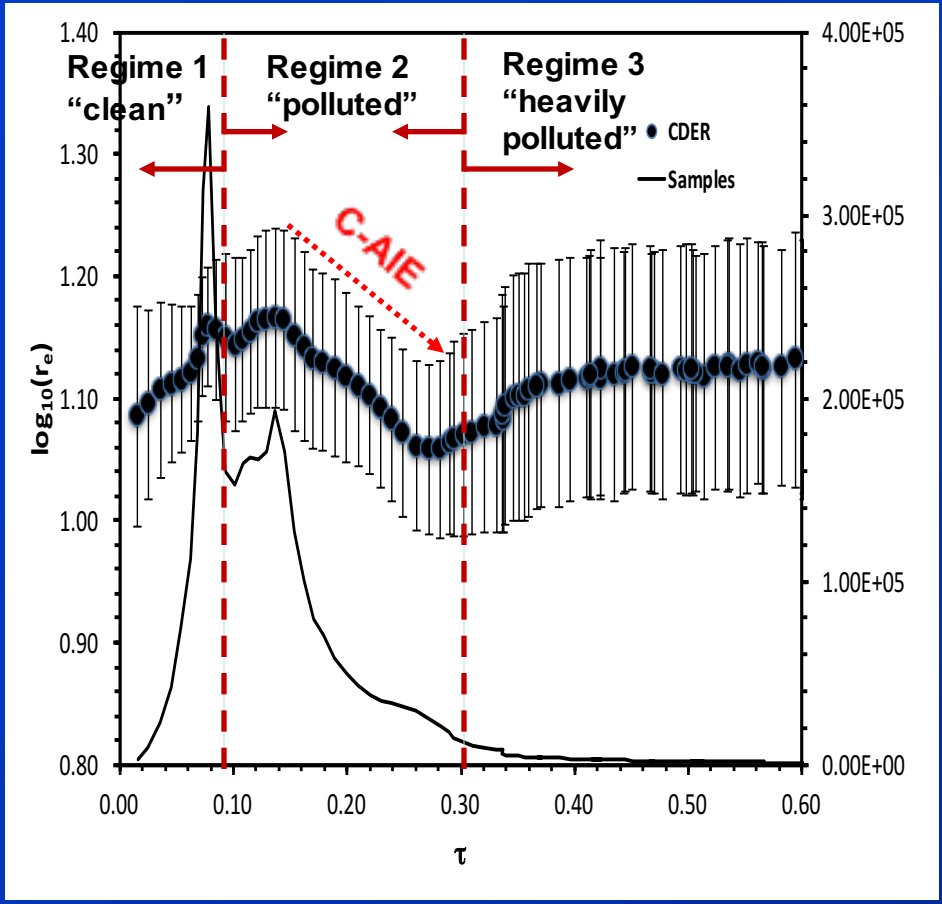
    Defined as *LT*/σ, σ is the standard deviation of the *LT*. *LT* is examined at 95% confidence (or 5% significance) level, which is corresponding to *LT*/ $\sigma \leq -2$ (negative trend) or *LT*/s ≥ 2 (positive trend).

Results

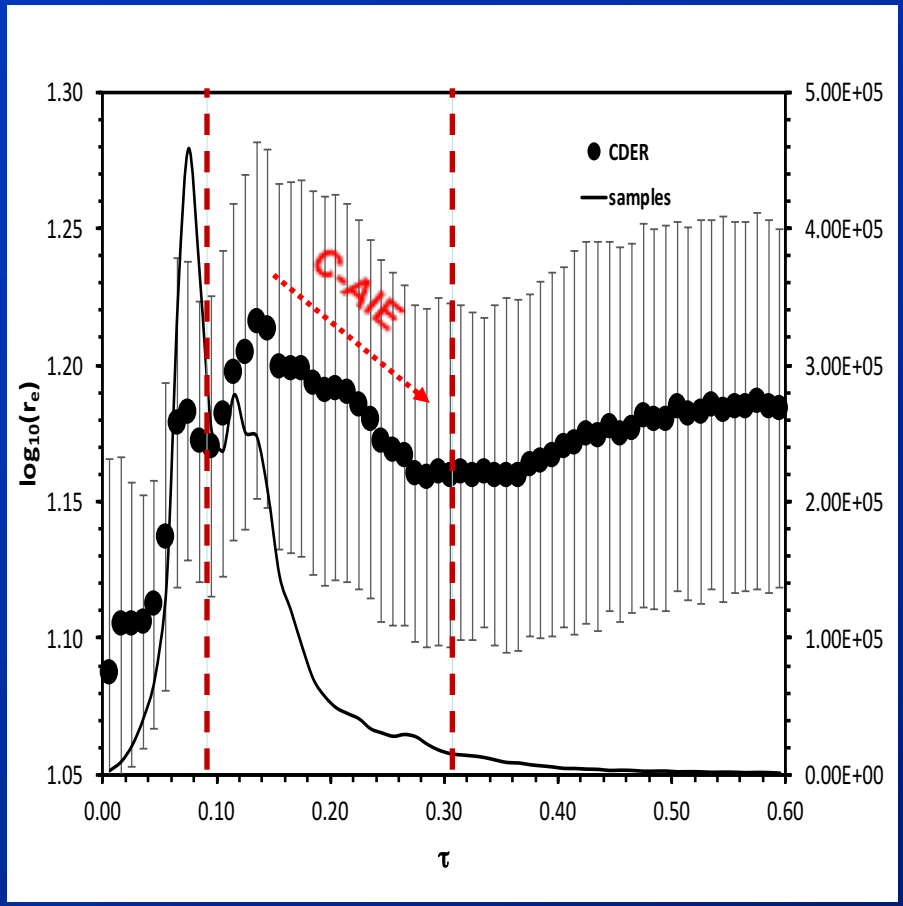
Three Regimes for AIE

(based on long-term averaged global monthly mean data)

Water Cloud (CDER vs AOT)



Mixed Cloud (CDER vs AOT)

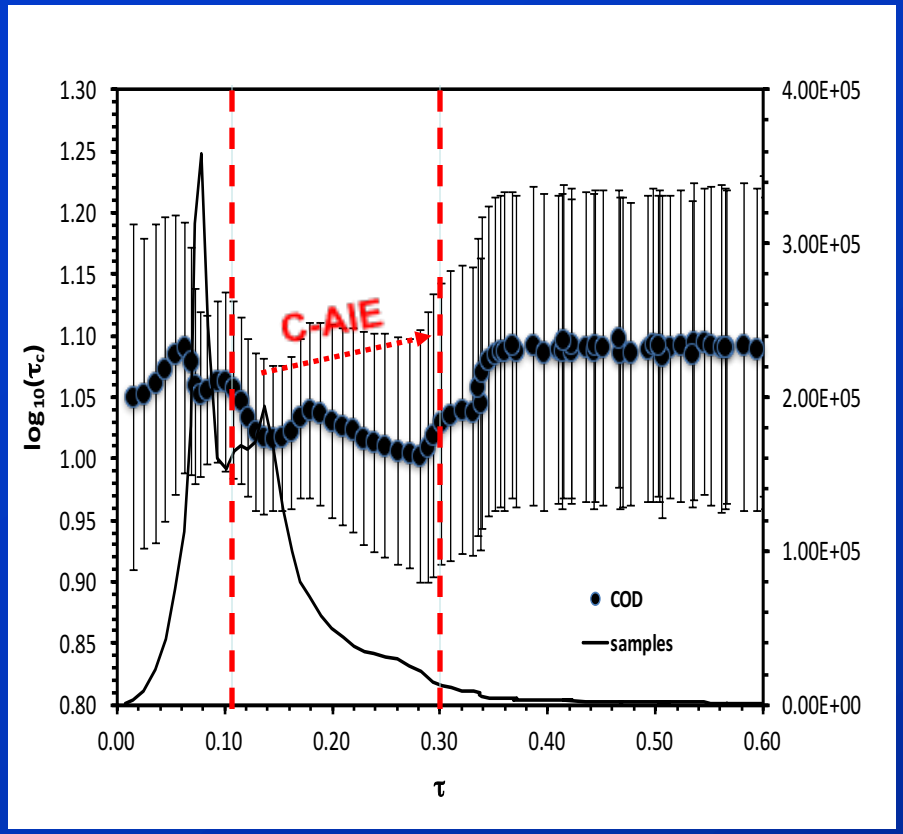


Regime 1: AOT < 0.1; Regime 2: 0.1 < AOT <0.3; Regime 3: AOT > 0.3

(Regime 2 shows the C-AIE signature of CDER & named as C-AIE sensitive regime)

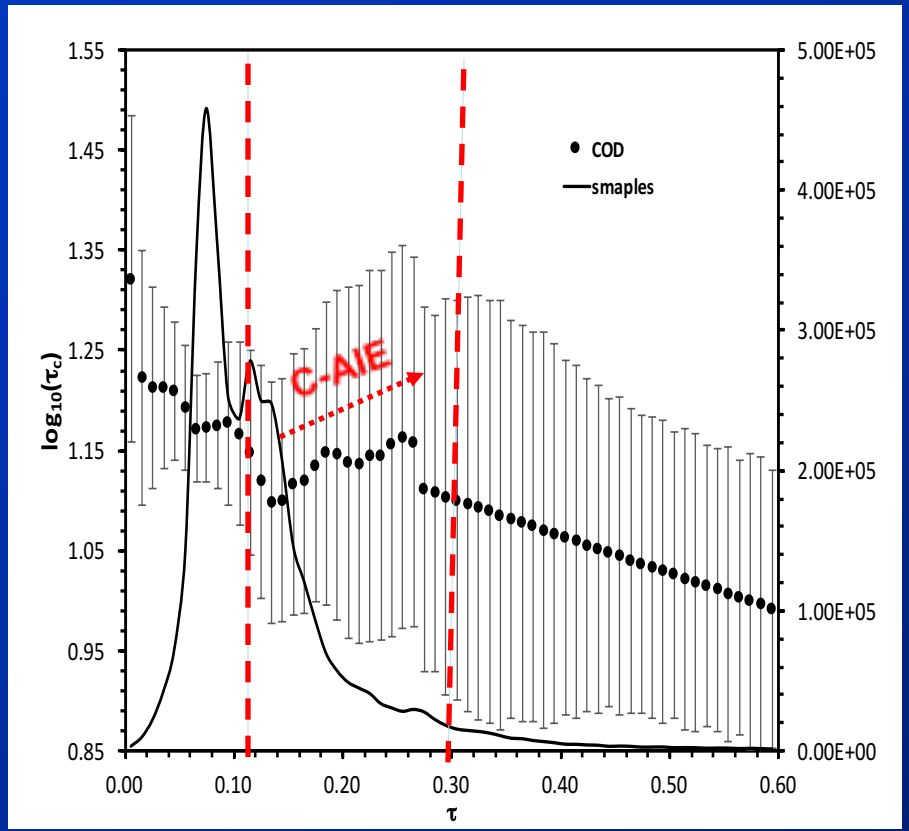
Case of Cloud Optical Depth (COD)

Water Cloud (COD vs AOT)



The C-AIE signature of COD in Regime 2 is vague

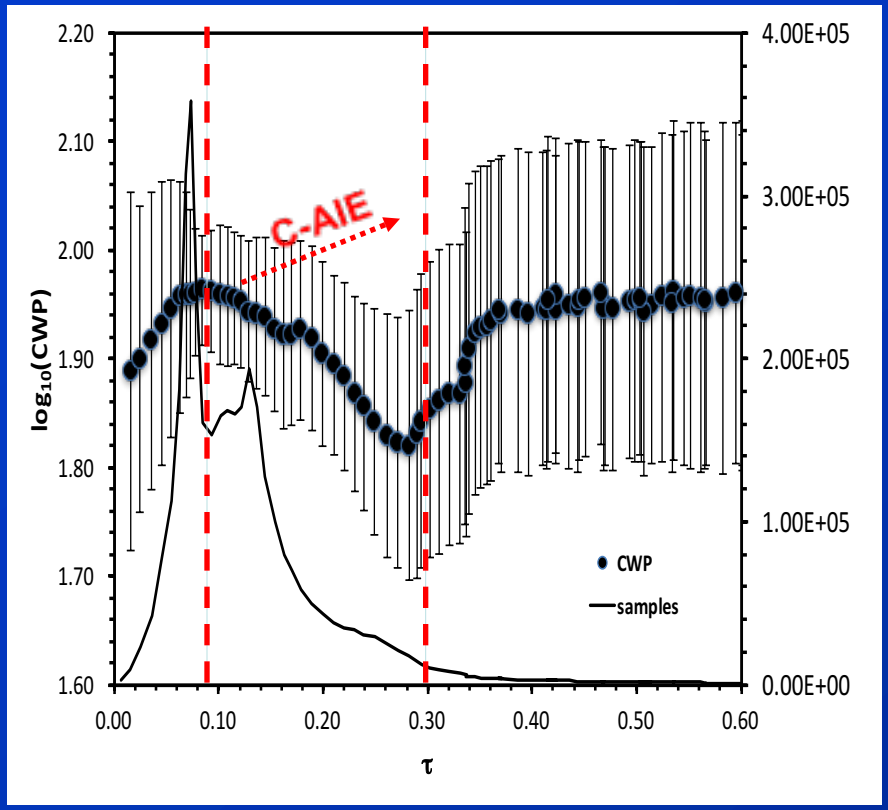
Mixed Cloud (COD vs AOT)



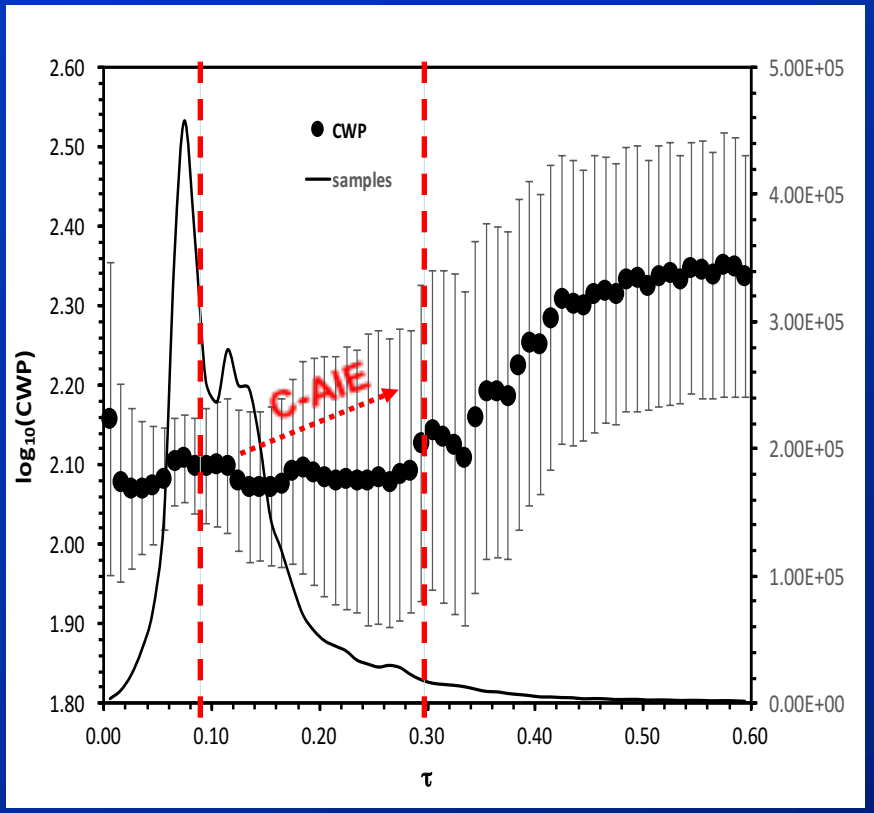
The C-AIE signature of COD in Regime 2 is distinct

Case of Cloud Water Path (CWP)

Water Cloud (CWP vs AOT)



Mixed Cloud (CWP vs AOT)

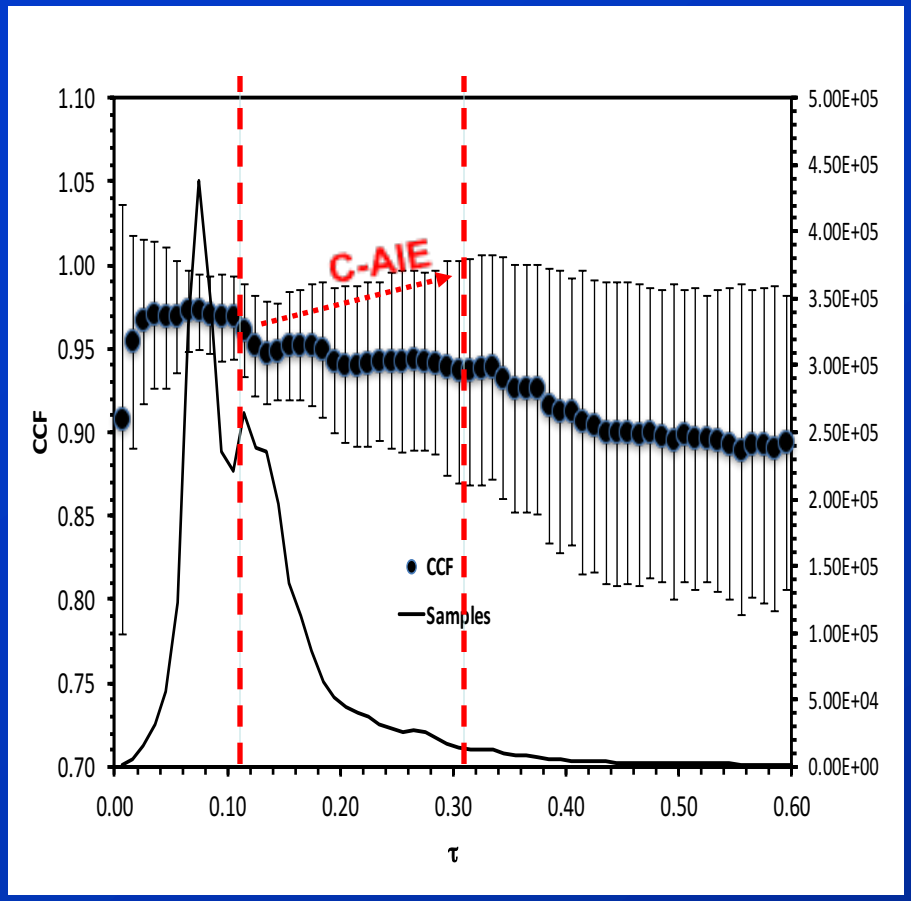


The C-AIE signature of CWP has disappeared in Regime 2 for both water & mixed cloud

$$\mathrm{CWP} = \frac{5}{9}\rho r_e \tau_c$$

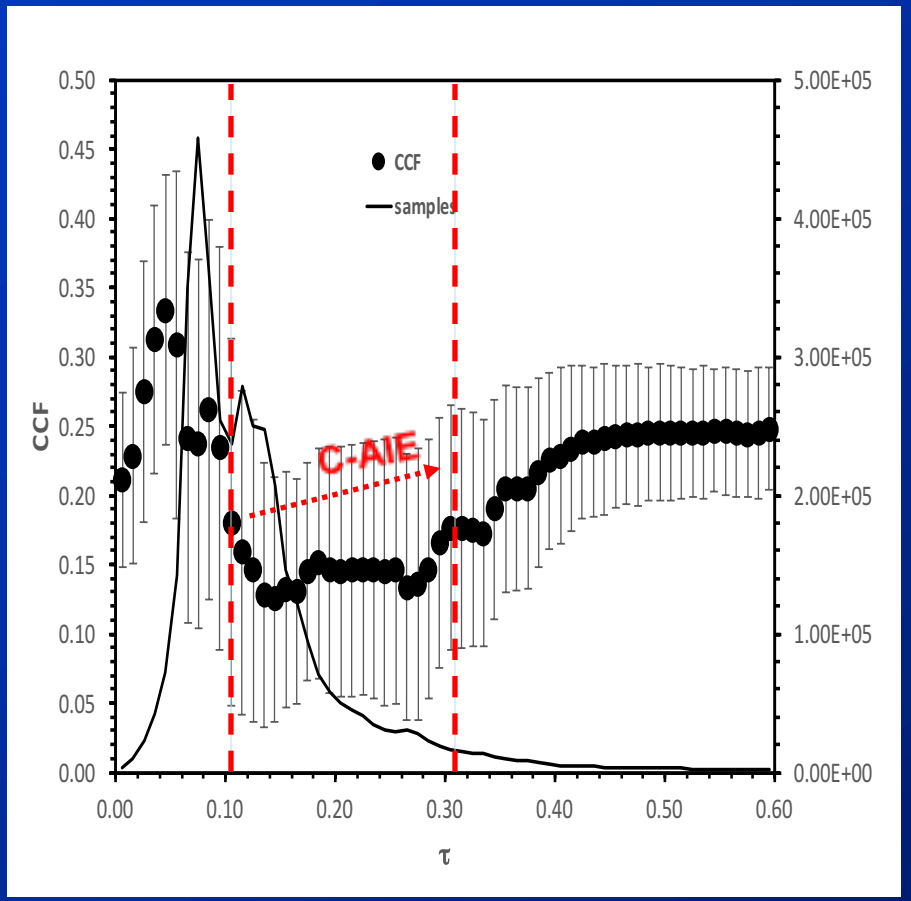
Case of Cloud Cover Fraction (CCF)

Water Cloud (CCF vs AOT)



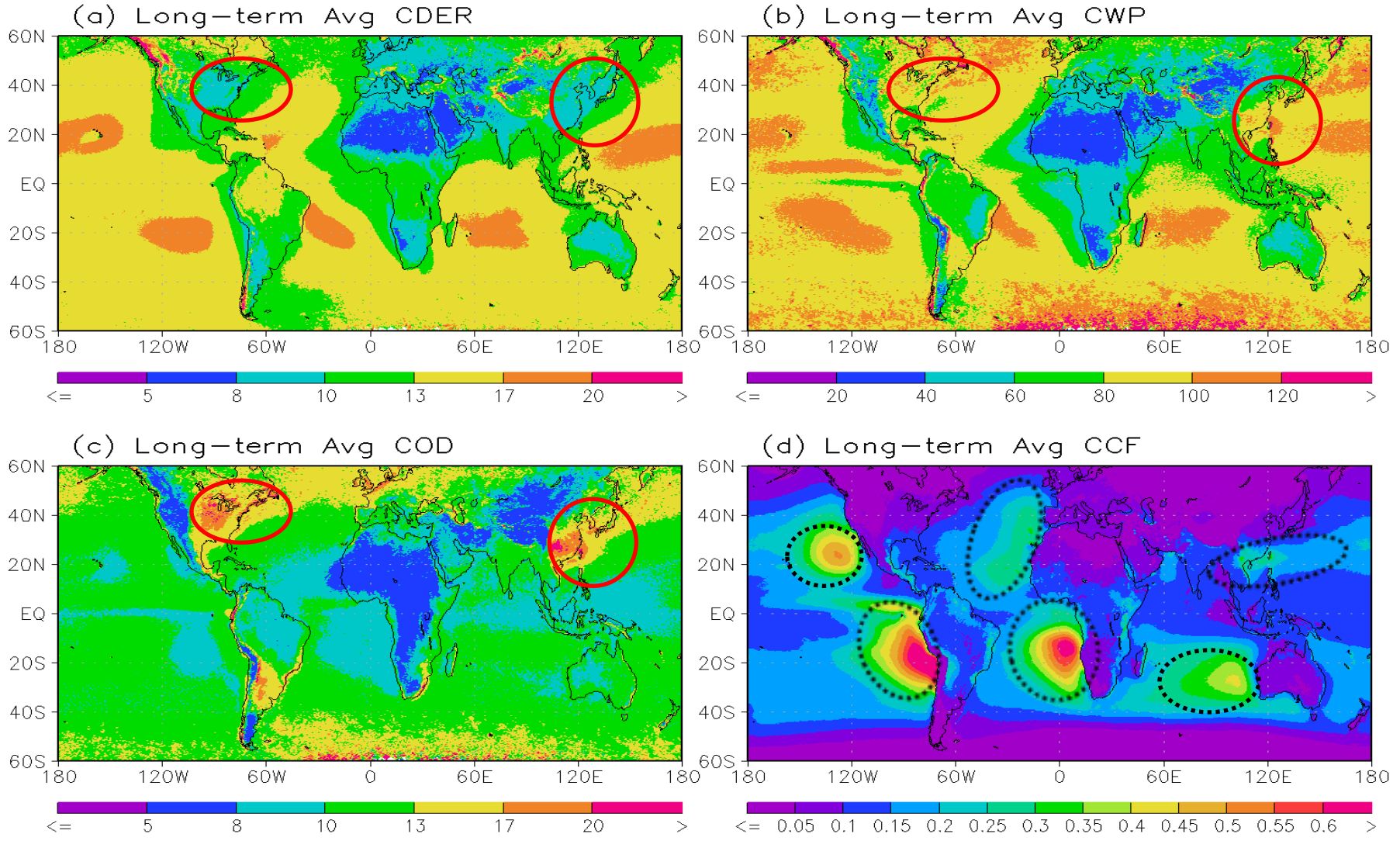
The C-AIE signature of CCF in Regime 2 is missing

Mixed Cloud (CCF vs AOT)



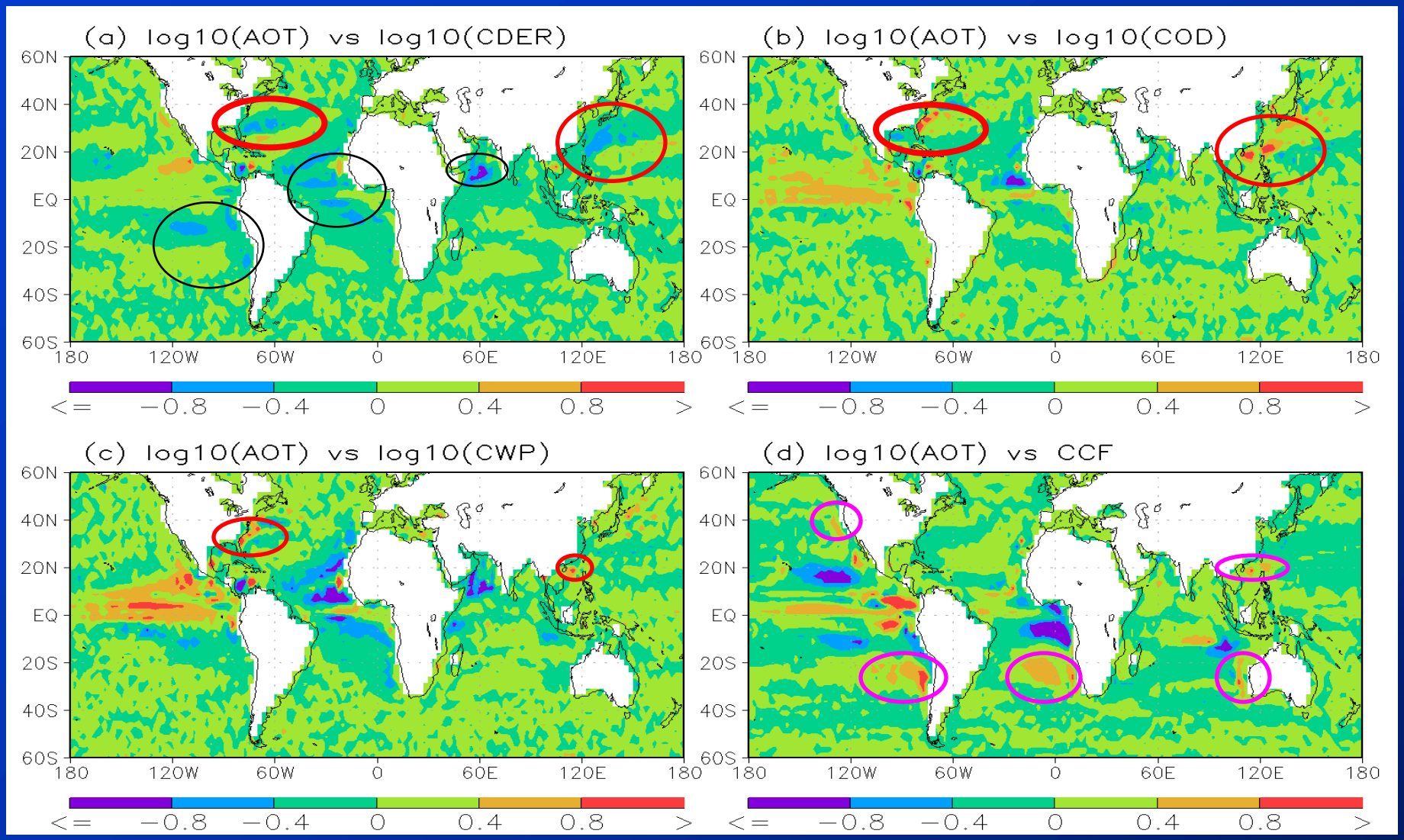
The C-AIE signature of CCF in Regime 2 is vague.

Example: Global Map of Long-term (1981-2011) Averaged Monthly Mean Water Cloud Variables

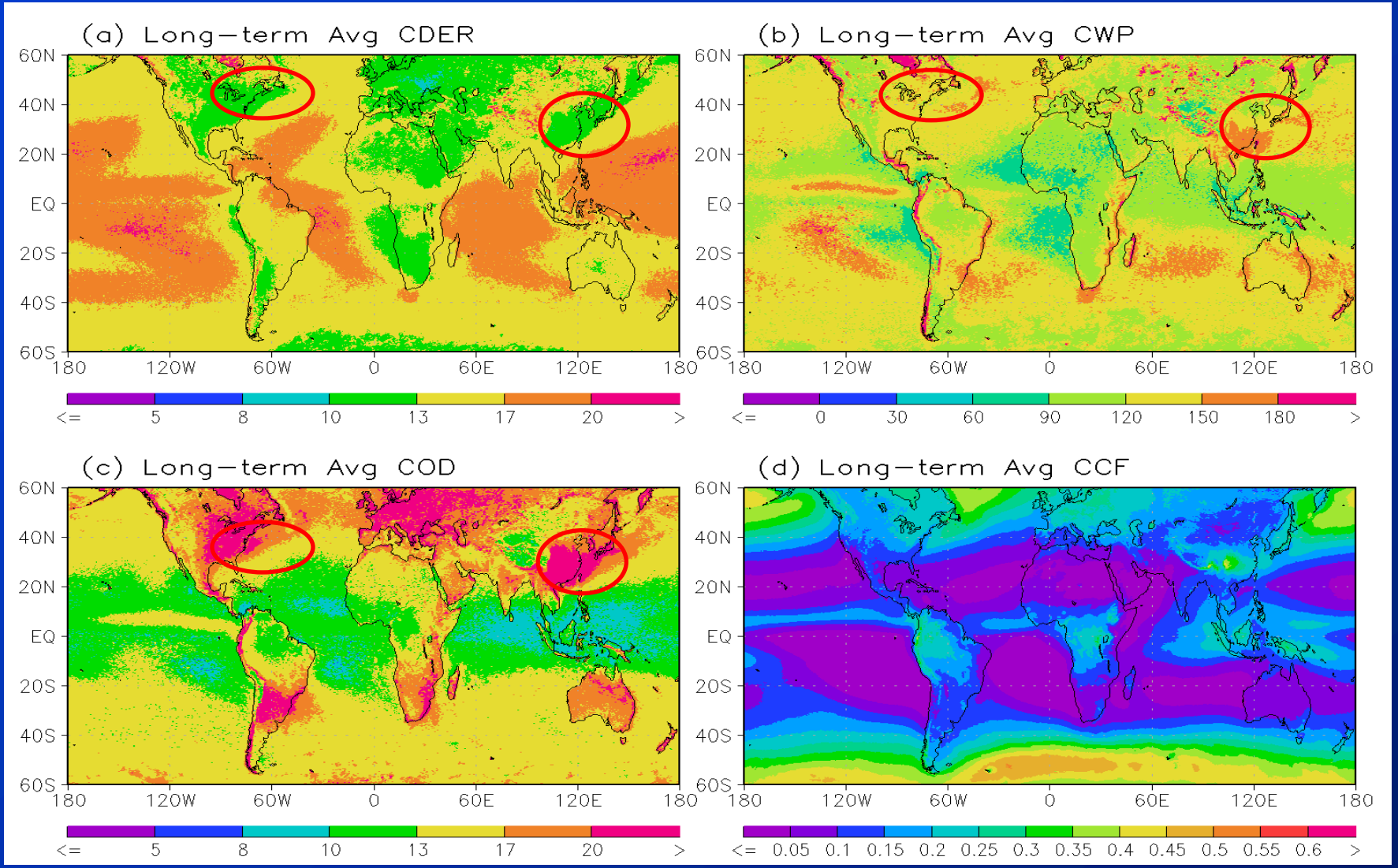


Linear Correlation Slope Map between AOT and Cloud Variables of Water Cloud

(Computed for 2.5°x2.5° grids from original 0.1°x0.1° grids)

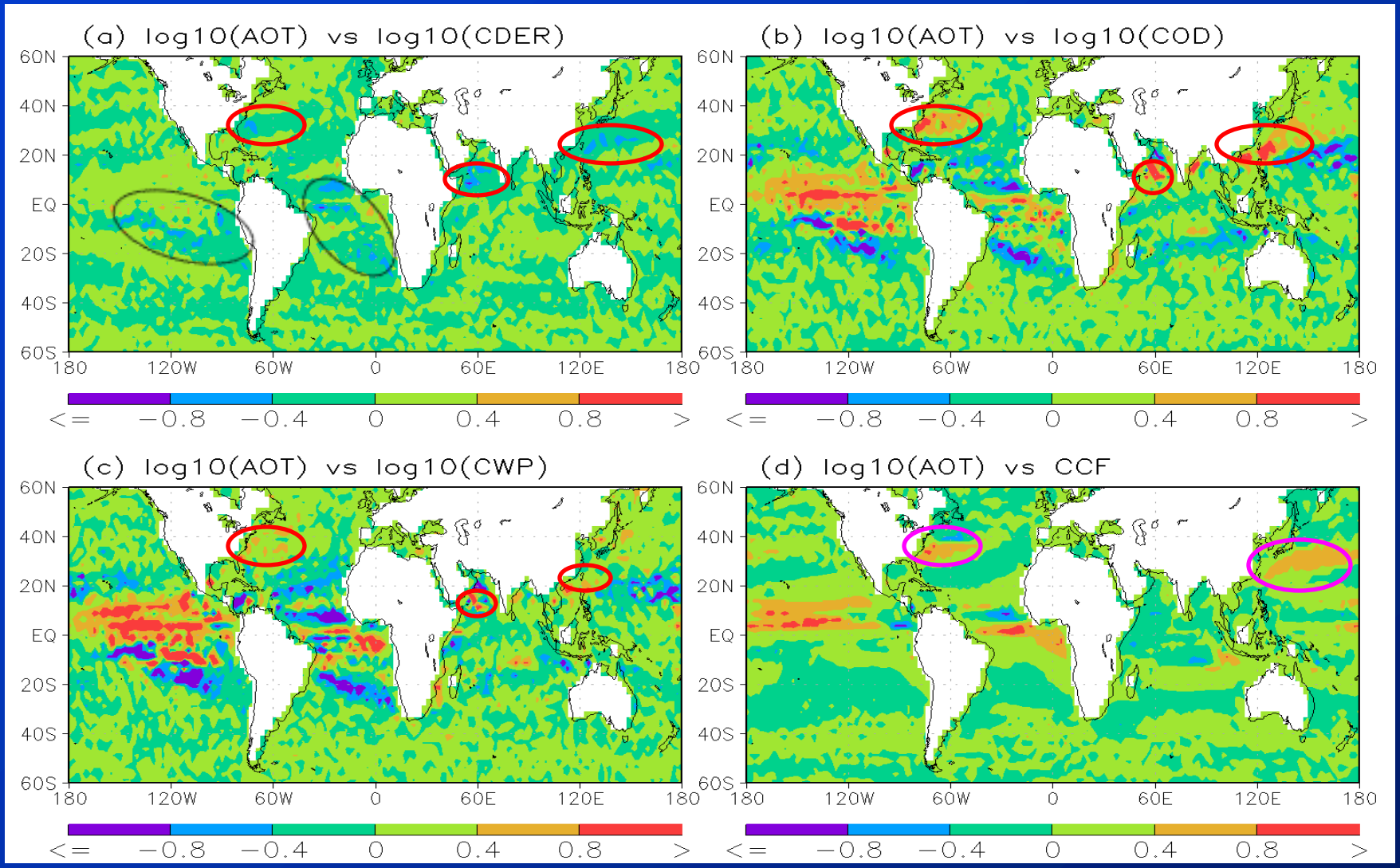


Example: Global Map of Long-term (1981-2011) Averaged Monthly Mean Mixed Cloud Variables



Linear Correlation Slope Map between AOT and Cloud Variables of Mixed Cloud

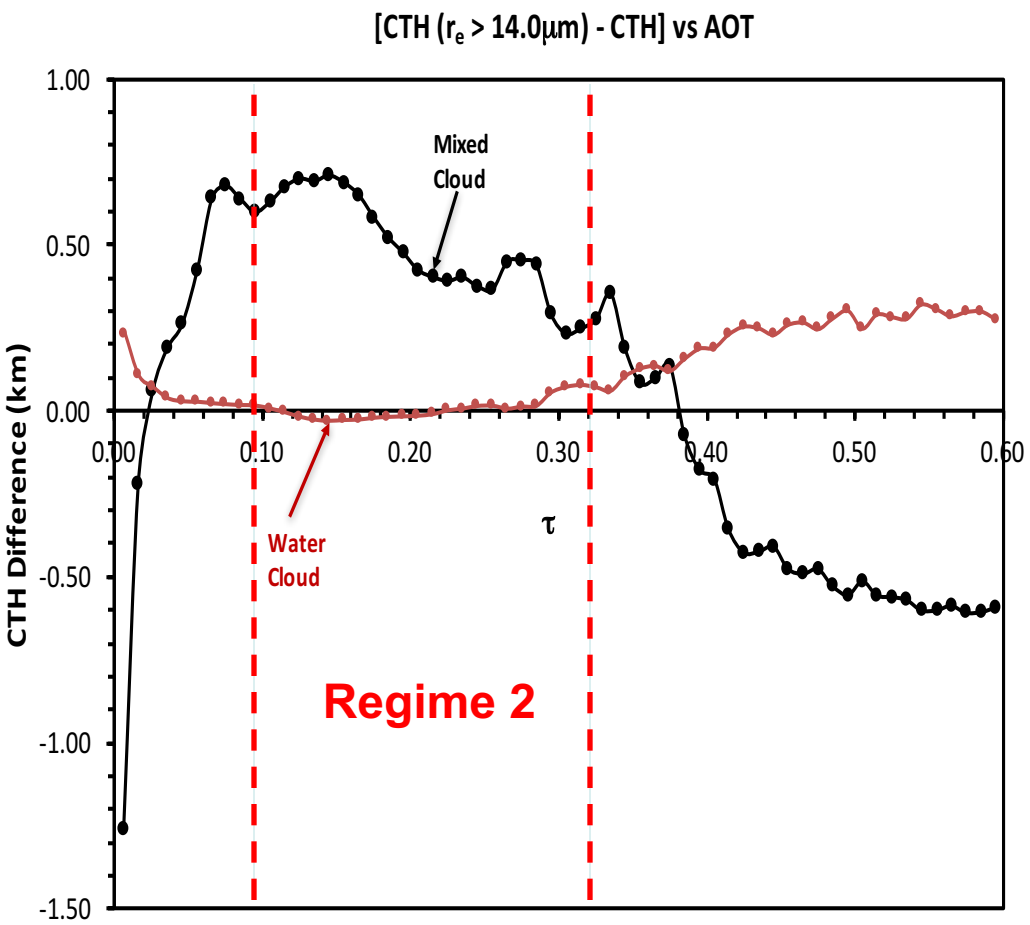
(Computed for 2.5°x2.5° grids from original 0.1°x0.1° grids)



Precipitation Efficiency Signature of C-AIE

(based on cloud top height (CTH) for CDER > 14 μm)

ΔCTH vs AOT



[based on long-term (1981-2011) averaged monthly mean data over global ocean]

For Mixed Cloud:

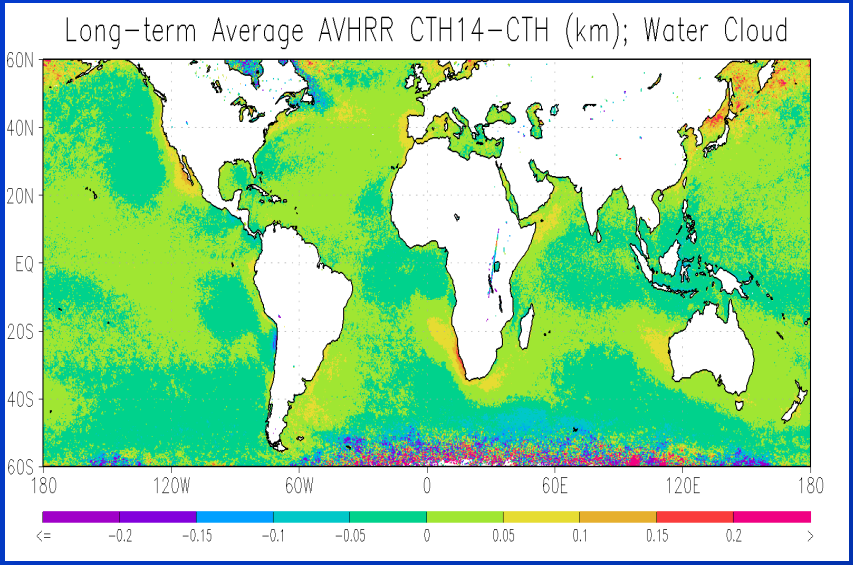
Precipitation efficiency is suppressed in C-AIE sensitive regime 2 since cloud droplets need to travel to higher altitude to grow up to rain drops.

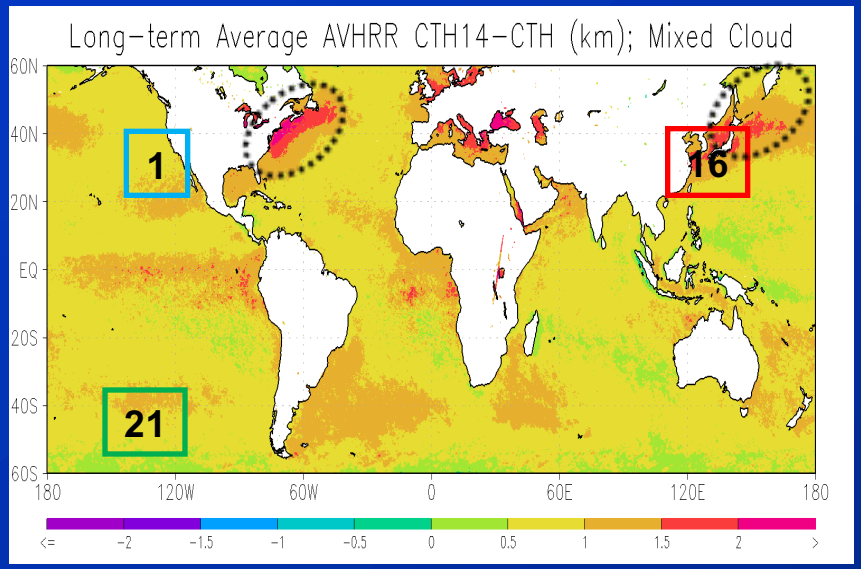
For Warm Water Cloud:

It is hard to infer the precipitation efficiency from ΔCTH since all clouds are capped by the top of PBL anyway.

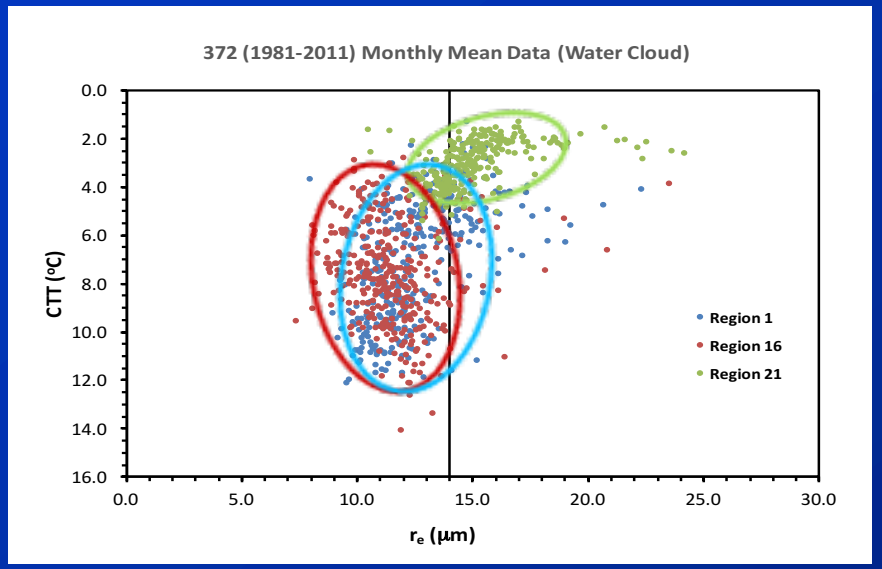
Reduced Precipitation Efficiency Signature of C-AIE

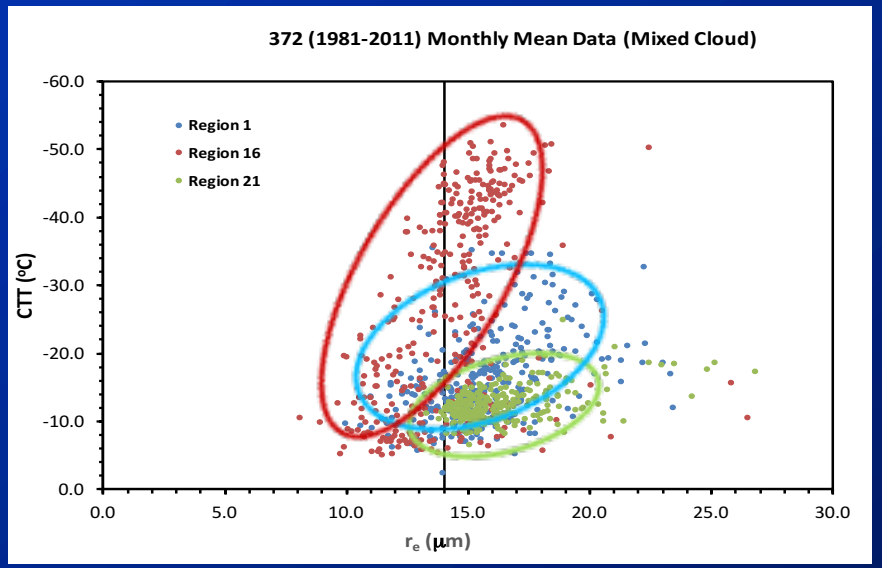
Global Map of ΔCTH





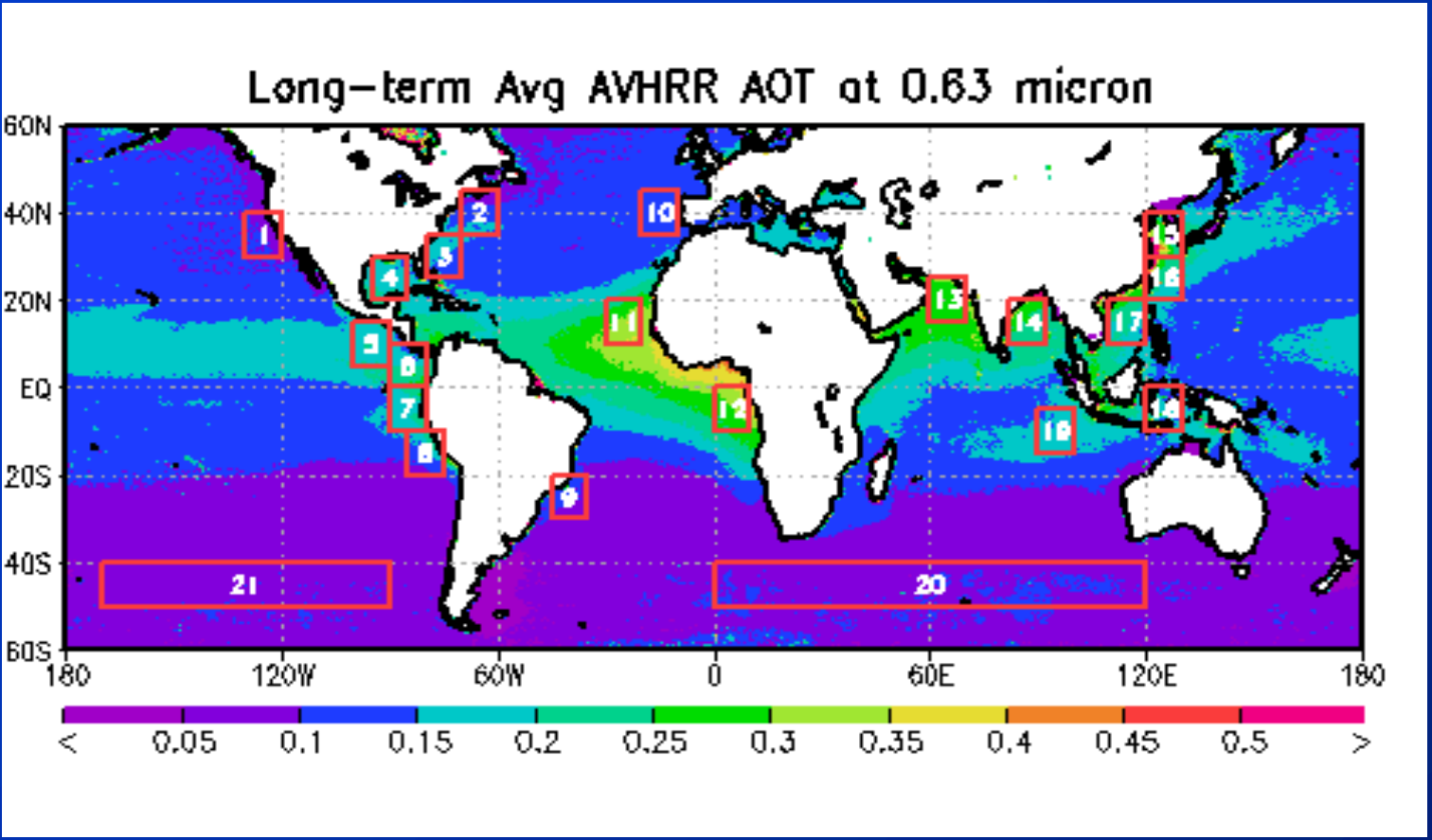
CTT vs r_e





Region Survey Study

Map of Long-term (1981-2011) Averaged Monthly Mean AOT over Ocean

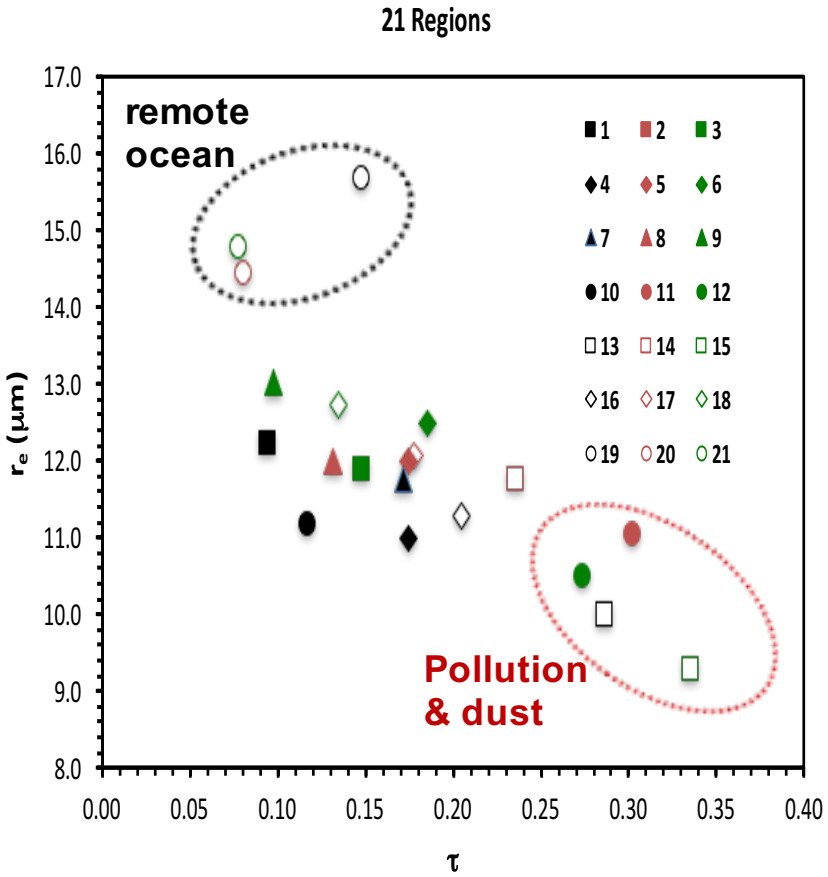


21 regions (red boxes) are selected for regional survey study later

Regional Survey (Water Cloud)

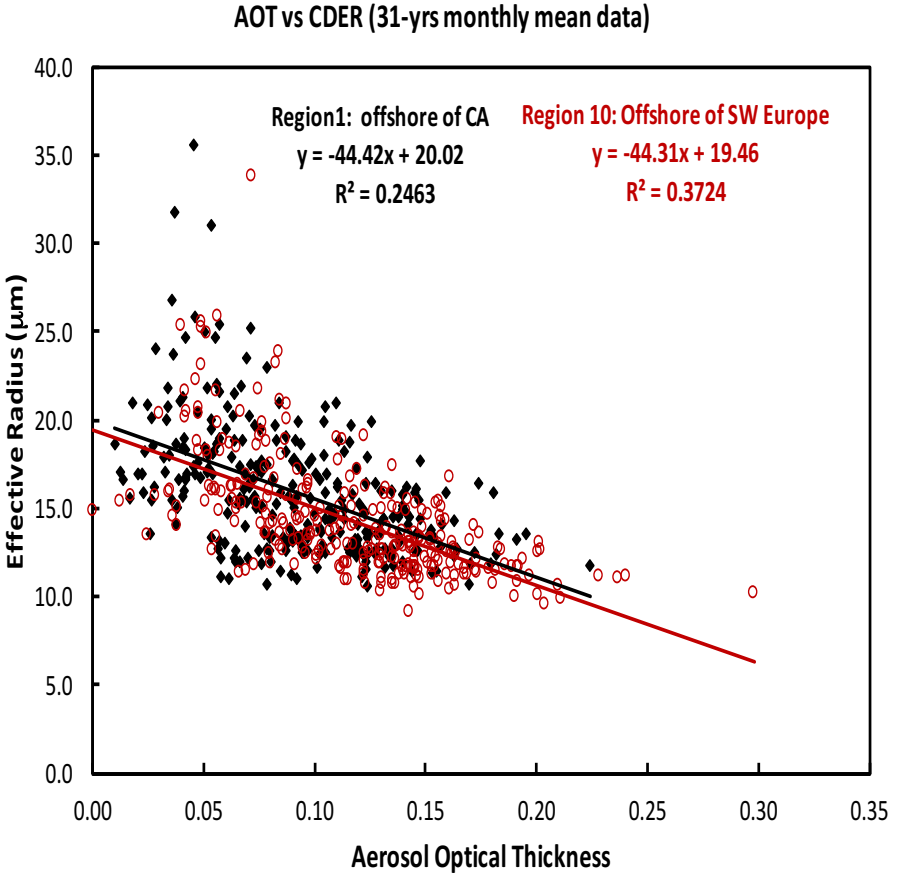
(Signature of C-AIE in CDER)

CDER vs AOT (Spatial Space)



(points are the long-term average of monthly mean data for the 21 regions)

CDER vs AOT (Temporal Space)

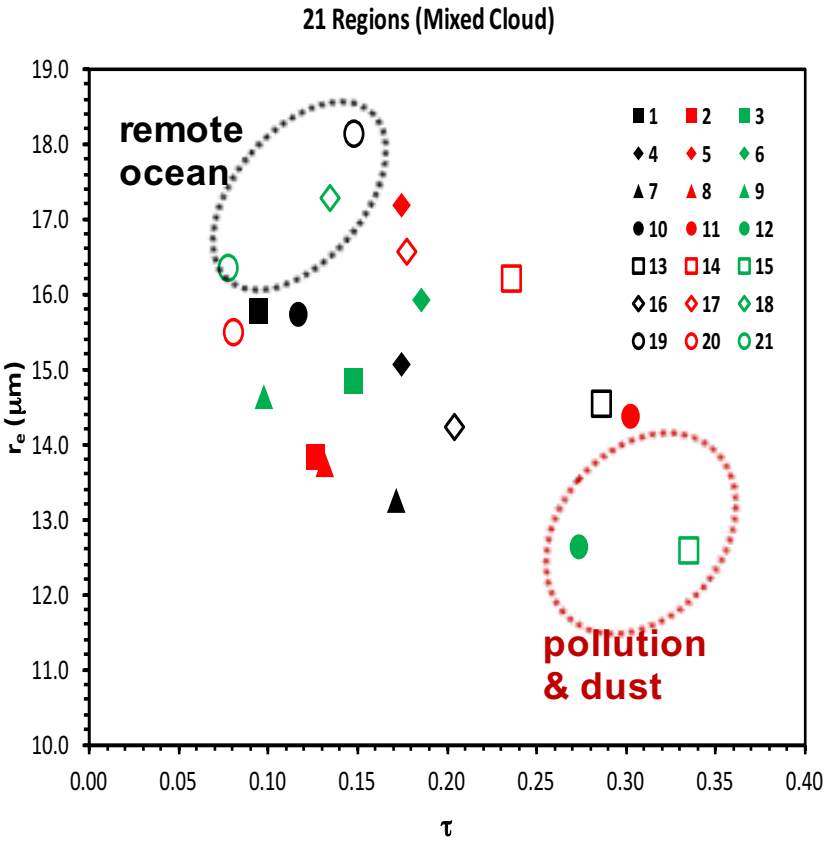


(points are monthly mean data from 1981 to 2011 for Region 1 & 10)

Regional Survey (Mixed Cloud)

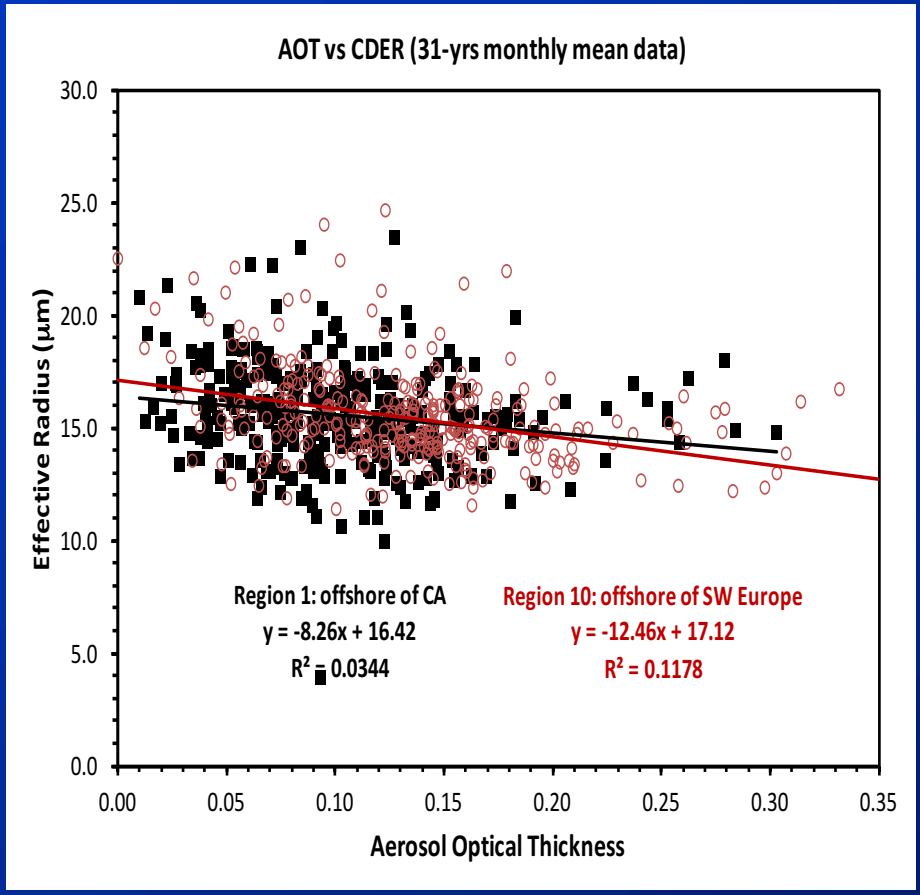
(Signature of C-AIE in CDER)

CDER vs AOT (Spatial Space)



(points are the long-term average of monthly mean data for the 21 regions)

CDER vs AOT (Temporal Space)



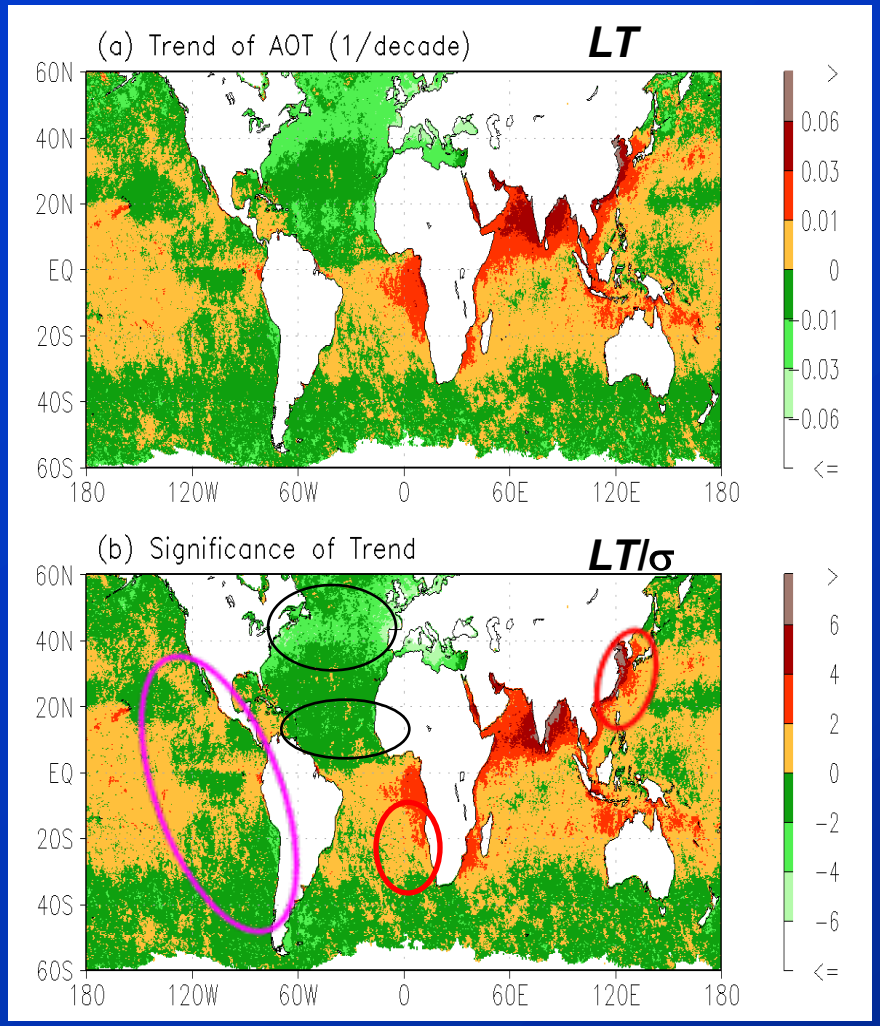
(points are monthly mean data from 1981 to 2011 for Region 1 & 10)

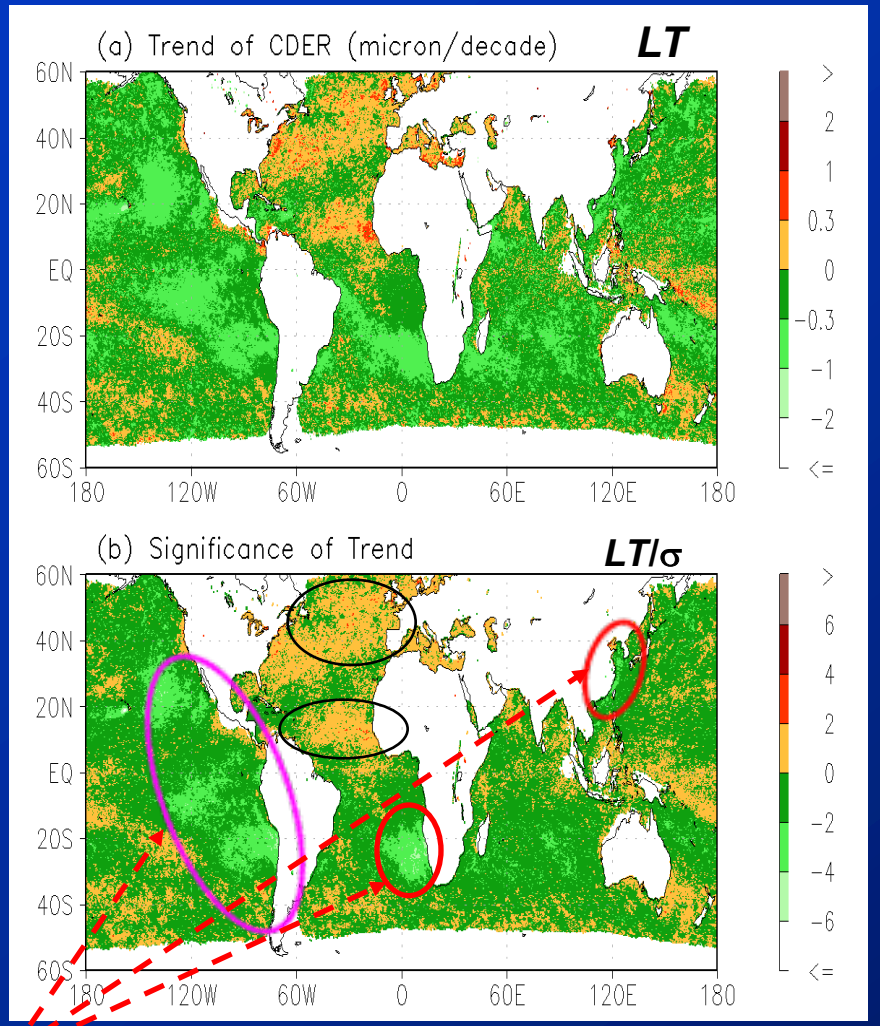
Linear Long-term Trend and Significance

(water cloud)

AOT

CDER



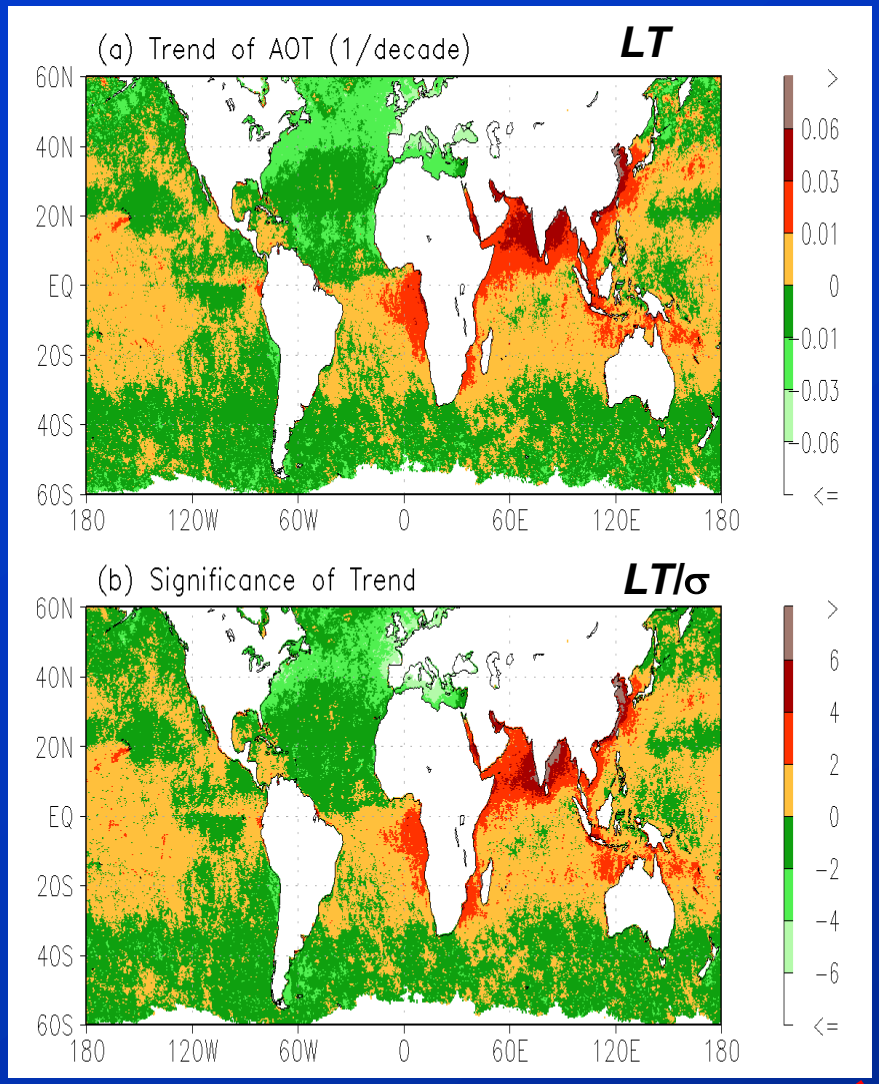


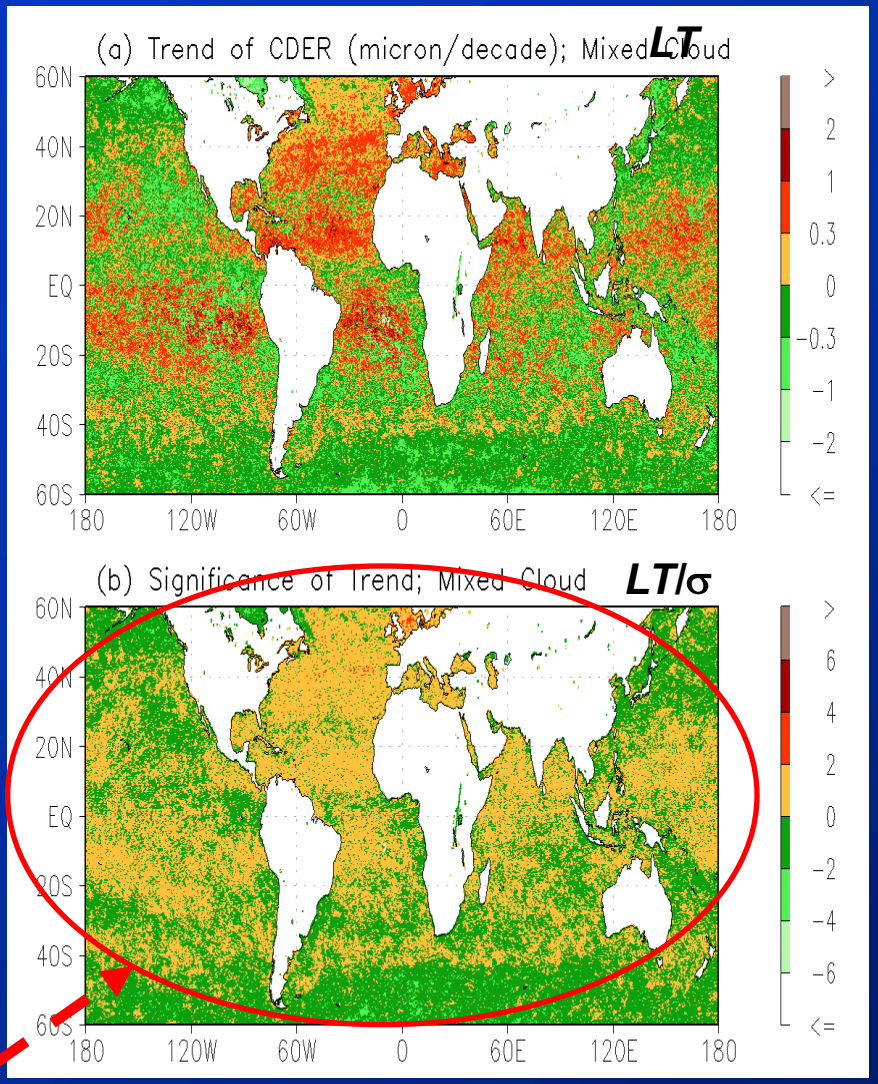
|*LT*/σ| > 2 indicates > 95% confidence level

Linear Long-term Trend and Significance

(mixed cloud)

AOT **CDER**





$|LT/\sigma| < 2$ indicates < 95% confidence level

Summary and Conclusions

- 31-years of aerosol and cloud CDRs from AVHRR satellite observations over the global ocean have been used to detect the signatures of C-AIE in the long-term averaged global satellite observations for the marine water and mixed clouds.
- Three AOT regimes have been identified to classify AIE over the global ocean. Regime 2 (0.1 <AOT<0.3) is named as C-AIE sensitive regime.
- C-AIE signature in CDER is evident in the long-term average for both water and mixed clouds but only the trend of water cloud signature is significant.
- C-AIE signature in COD is evident for the mixed cloud and somewhat noticeable for the water cloud. There is no significant trend of the signature for the both kinds of cloud.
- C-AIE signature in CWP (or CCF) is only noticeable in limited regions over the global ocean for both water and mixed clouds and there is no significant trend of the signature for the both kinds of cloud.
- C-AIE signature in the long-term averaged precipitation is evident only for the mixed cloud and there is no significant trend of the signature for the both kinds of cloud.

Acknowledgement

- **Collaborators:**
  - Dr. Andrew K. Heidinger (NOAA/NESDIS/STAR)
  - Dr. Andi Walther (CIMSS, UW-Madison)

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  - Climate Data Record (CDR) Program at NOAA/NESDIS/NCEI

Thank You!

Questions?