

Studying the Sensitive Regimes and Active Regions of Aerosol Indirect Effect (**AIE**) for the **Ice Clouds** over the Global Oceans by Using Long-Term Satellite Observations

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AeroCom and AeroSat Workshop
College Park, MD, USA; Oct. 15-19, 2018

NOAA Satellite and Information Service | National Centers for Environmental Information





Outline

➤ **Background**

- **Observational Signatures of AIE for Ice Clouds**

➤ **Objective of This Study**

➤ **Long-term Satellite & Reanalysis Data Used**

- **AVHRR PATMOS-x Satellite Cloud Climate Data Records (CDRs)**
- **AVHRR Satellite Aerosol Climate Data Record (CDR)**
- **NCEP CFSR (version 3) Monthly Mean Product**

➤ **Analyzing Approaches & Results**

➤ **Summary and Conclusions**

➤ **Acknowledgement**



Background

- Our understanding on the aerosol indirect effect (**AIE**) of cold ice clouds is much meager than that of warm water clouds and with larger uncertainties.
 - **In microphysics**, we have less understanding on the correlation of aerosol loading with ice nuclei (IN) concentration comparing to cloud condensation nuclei (CCN) as well as the mechanisms of IN nucleation and the growth and multiplication of cloud ice particles.
 - **In macrophysics**, ice clouds are generally associated with more intensive cloud dynamics and thermodynamics comparing to water clouds, which may alter AIE in unconventional ways or even obscure the AIE so that it becomes undetectable by remote sensing observations.
- The **AIE** of ice clouds may emerge in more forms than the positive albedo and lifetime effects conventionally noticed in the observation of water clouds.



Observational Signatures of AIE for Ice Clouds

(e.g., Jensen and Toon, 1997; Rosenfeld, 2000; Chylek et al., 2006; Penner et al., 2009, Zhao et al. 2018)

- **Positive Twomey/Albedo Effect**
 - Increasing of aerosol loading and number concentration induces the generation of more cloud particles with smaller size and therefore enhance the cloud reflection of solar radiation if cloud water content stays nearly constant. Cloud optical thickness and cloud water/ice path increase accordingly.
- **Positive Albrecht/Lifetime Effect**
 - More smaller cloud particles due to positive Twomey effect result in reduced precipitation efficiency so that the cloud lifetime is elongated and more solar radiation is reflected by clouds.
- **Negative Twomey/Albedo Effect**
 - Adverse to the positive albedo effect when aerosol loading and number concentration increase.
- **Negative Albrecht/Lifetime Effect**
 - Adverse to the positive lifetime effect and induced by the negative Twomey effect
- These signatures were detected mainly from instantaneous and short term observations and have been confirmed by model simulations.



Objective of This Study

To detect and confirm the AIE signatures of ice cloud from **a climatology perspective** based on long-term satellite observations in view of long-term mean values of aerosol and cloud variables are with less noises comparing to their instantaneous or short-term averaged counterparts.

- Specifically, to identify the sensitive regimes of aerosol loading and active geolocations of AIE for ice clouds over the global oceans using NOAA long-term satellite climate data records (**CDRs**)

Satellite Data - 1 : AVHRR PATMOS-x Cloud CDRs

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

Cloud Types	Explanation	Note
Water	Warm liquid cloud	Grouped as “liquid cloud” (Zhao et al., 2017)
Supercooled	Supercooled liquid cloud	
Mixed	Supercooled liquid and ice cloud	Future development & study
Opaque Ice	Thick ice cloud	Grouped as “a single ice cloud” in the current study
Ice	Thin cirrus cloud	
Overshooting	Ice cloud with overshooting tower due to deep convection	
Overlapping	Thin cirrus above low cloud	Future development & study

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

Satellite Data – 2: AVHRR Aerosol CDR

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

AVHRR aerosol CDR is derived from Patmos-x clear-sky radiances

Aerosol Variable	Note	Temporal Coverage (Resolution)	Spatial Coverage (Resolution)
Aerosol Optical Thickness (AOT or τ)	Values at 0.63 and 0.85 μm	1980-current (daily & monthly mean)	Global ocean only (0.1°x0.1°)

Ångström Size Parameter: $\alpha = -\ln(\tau_{\lambda_1}/\tau_{\lambda_2})/\ln(\lambda_1/\lambda_2)$

Aerosol Index: $AIDX = \tau_{\lambda_1} \times \alpha$; ($\lambda_1 = 0.63\mu\text{m}$; $\lambda_2 = 0.85\mu\text{m}$)

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

NCEP CFSR (version3) Monthly Mean Product

(Saha et al., BAMS, 2010; ftp://nomads.ncdc.noaa.gov/CFSR/HP_monthly_means/)

Selected Meteorological Variables Used in Our Analyzing Study

Meteorological Variables	Note	Temporal Coverage (Resolution)	Spatial Coverage (Resolution)
Relative Humidity (RH ; %) (100, 150, 200, 250, 300, 400mb)	Averaging for 6 pressure levels	1979 – 2011 (monthly mean)	Original Data: Globe (0.5° x 0.5°) Derived Data: Globe (0.1° x 0.1°)
Vertical Velocity (VV ; Pa/s) (on 300mb pressure level)	VV > 0 (downward) VV < 0 (upward)		
Convective Available Potential Energy (CAPE ; J/kg)	in surface layer		

Analyzing Approaches

• Relationship Analysis

- Consider **AIDX** as a proxy of column aerosol concentration.
- Check the relationship between **AIDX** and six key cloud variables, including CPER (r_e), COD (τ_c), IWP, CCF, CTT, CTH, for AIE signatures

• AIE Sensitivity Analysis

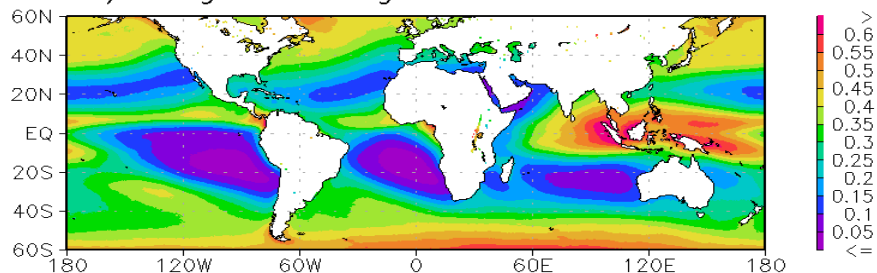
- $B = \Delta \log_{10}(\text{Cloud Variable}) / \Delta \log_{10}(\text{AIDX})$
Analyze the changing tendency of key cloud variables relative to the change of aerosol loading (AIDX)
- B is actually the slope of linear regression of $\log_{10}\{\text{Cloud Variable}\} = A + B * \log_{10}\{\text{AIDX}\}$

Results of Analyses

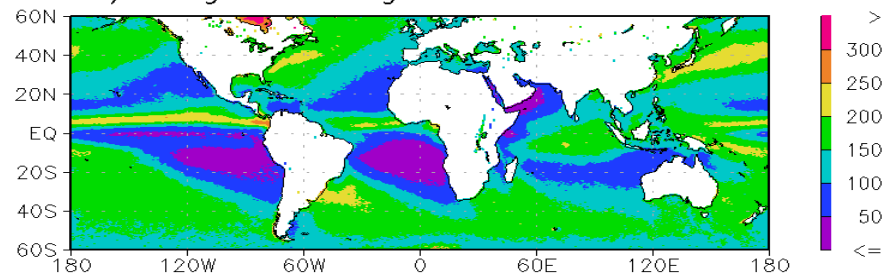
(for 31-years Long-term Averaged Data)

Global Distribution of Cloud Variables for Ice Clouds

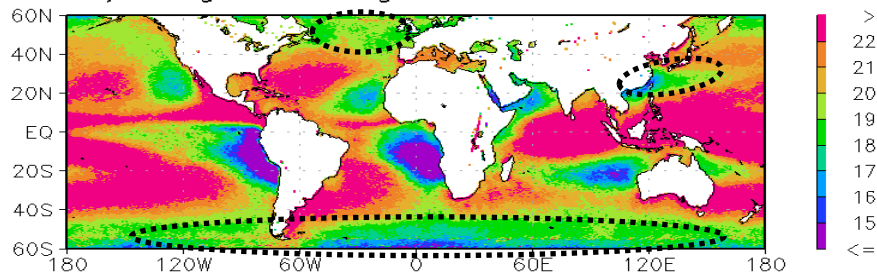
a) Long-term Avg CCF



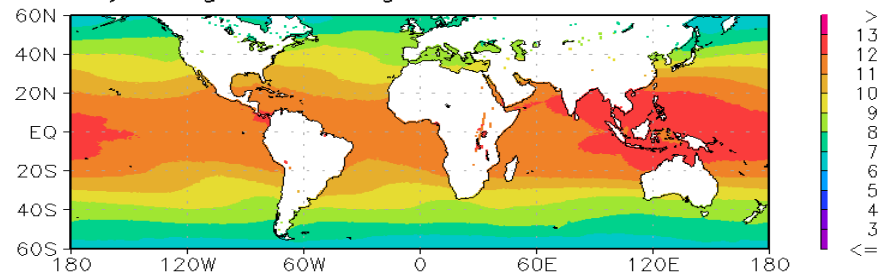
d) Long-term Avg IWP



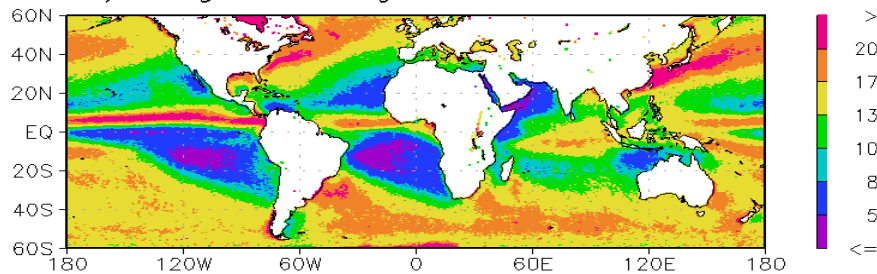
b) Long-term Avg CPER



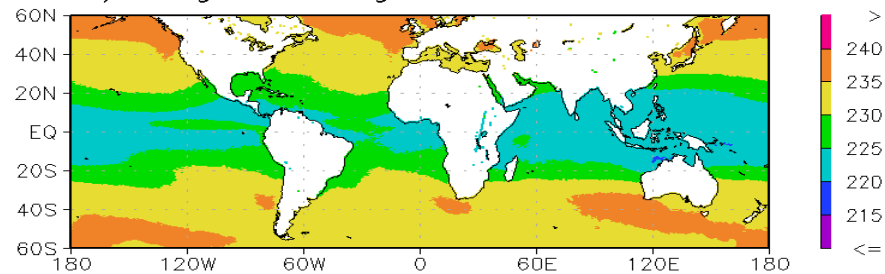
e) Long-term Avg CTH



c) Long-term Avg COD

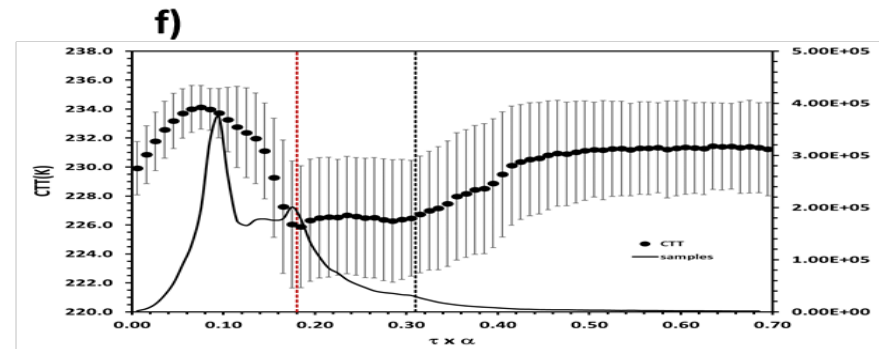
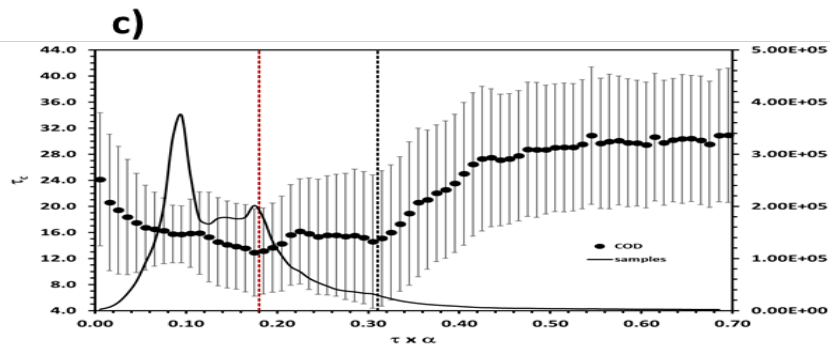
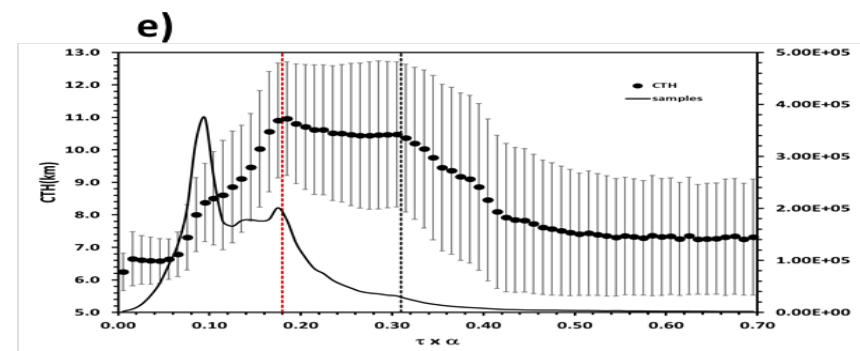
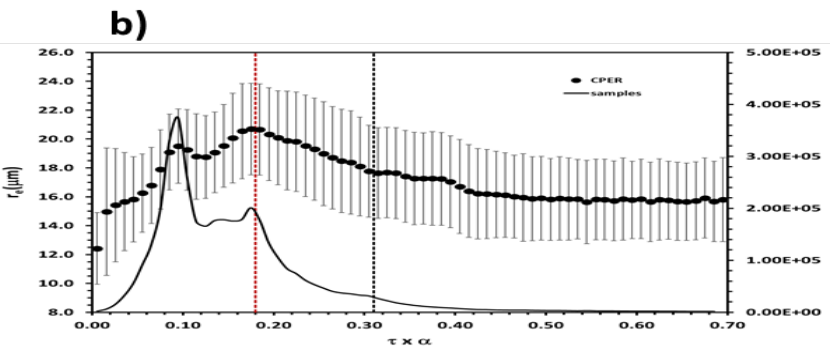
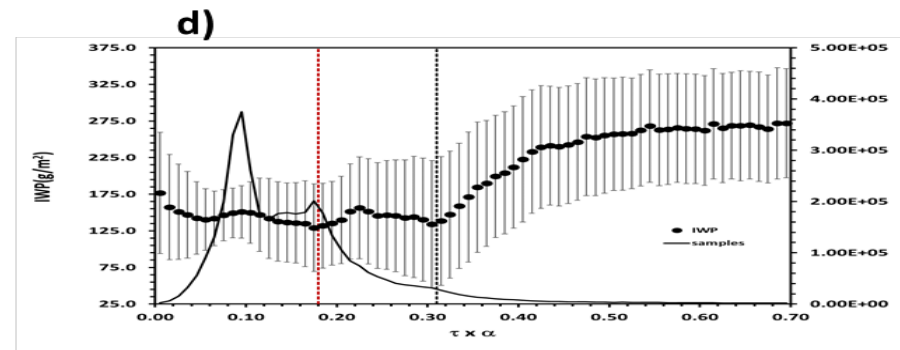
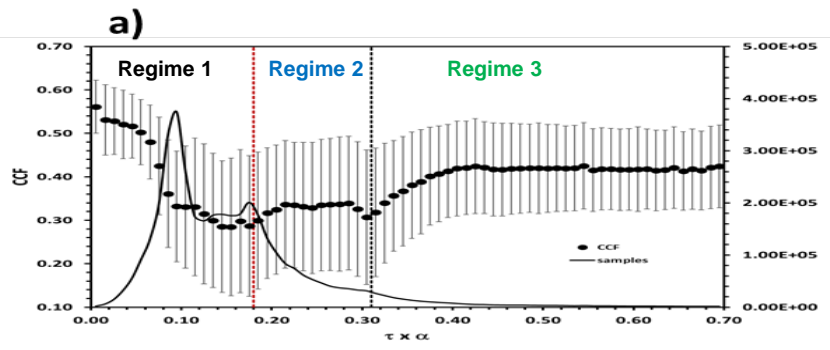


f) Long-term Avg CTT



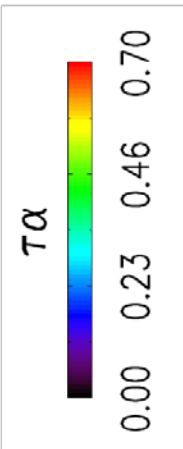
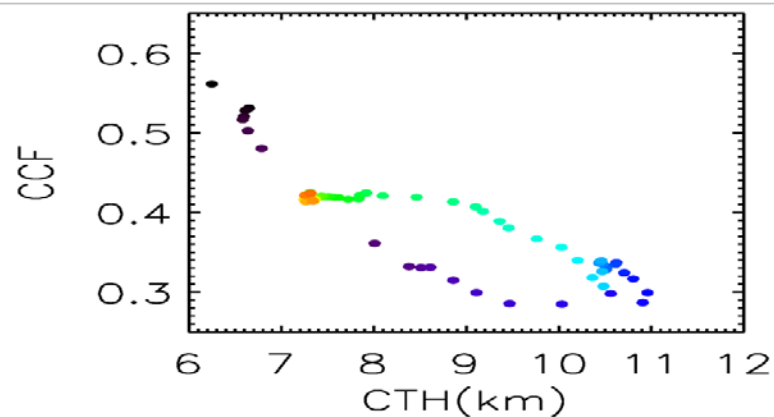
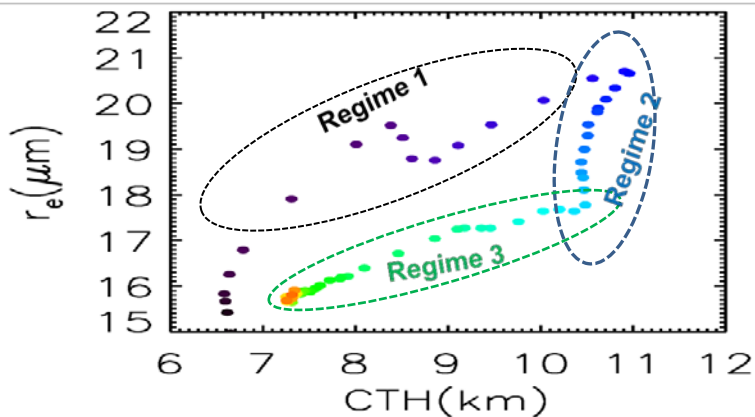
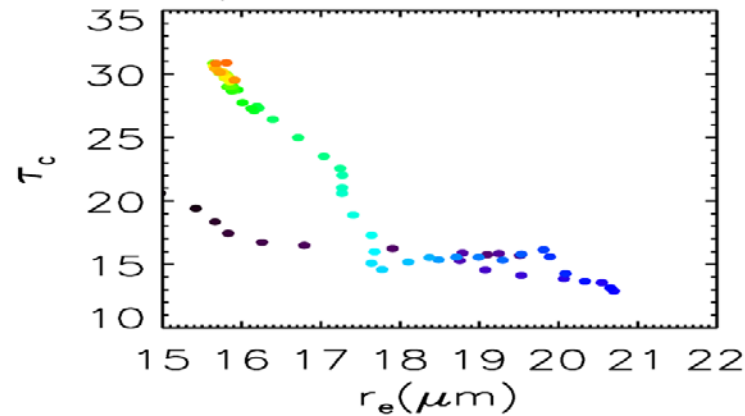
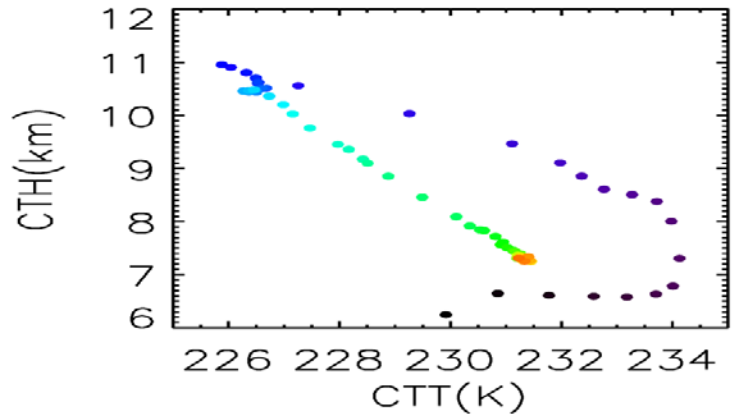
Three Regimes of Aerosol Effect on Ice Clouds

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



Three Regimes of Aerosol Effect on Ice Clouds

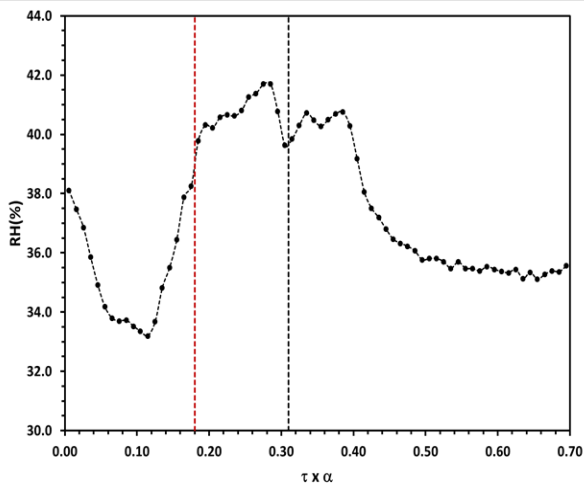
(based on long-term averaged global monthly mean data)



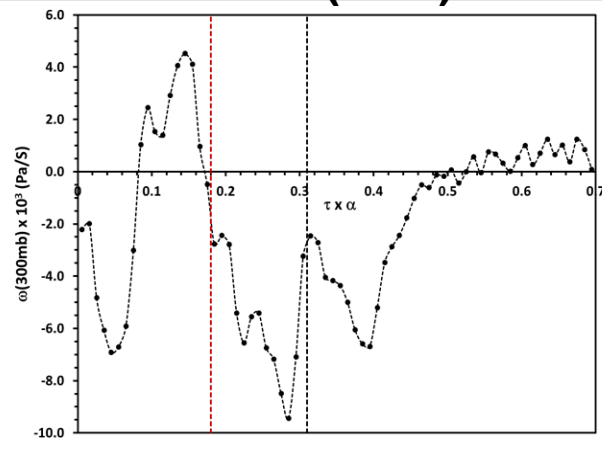
Regime 1: $\text{AIDX} < 0.18$ (clean air), sensitive regime of negative Twomey effect;
Regime 2: $0.18 < \text{AIDX} < 0.31$ (moderate aerosol loading), sensitive regime of positive Twomey effect .
Regime 3: $\text{AIDX} > 0.31$ (high aerosol loading), transition regime of cloud dynamics/thermodynamics from strong to weak.

Meteorological Condition of the Three Regimes

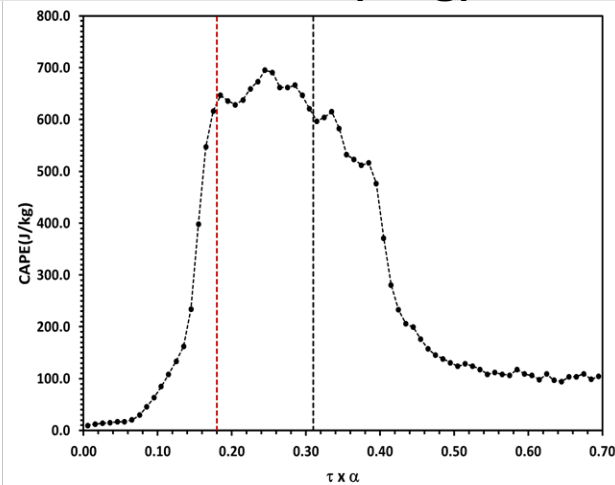
RH (%)



VV (Pa/s)



CAPE (J/kg)



Meteorological & Aerosol Variables

Regime 1

Regime 2

Regime 3

RH (%)

Low

High

High -> Low

VV (Pa/s)

Negative -> Positive

Negative

Negative -> Neutral

CAPE (J/kg)

Low -> High

High

High -> Low

AIDX

Low

Moderate

High





Features and Explanations of Regime 1

- Negative Twomey effect is indicated by **increasing CPER** together with **decreasing COD and IWP** when **AIDX** increases & negative cloud lifetime effect (**decreasing CCF** with **increasing AIDX**).
- Meteorological condition indicates the clouds are mainly in developing stage and the uplift motion can maintain sufficient supersaturation and cold temperature for heterogeneous freezing and the ice particles can also grow bigger (**large CPER**) due to less particles competing for water vapor and eventually precipitate out.
- The concurrent **increase of CTT and CTH** with increasing **AIDX** in the first section of this regime suggests the clouds are in an elevated inversion layer, which is often observed in the synoptic warm/cold front systems at high latitudes.



Features and Explanations of Regime 2

- A signature of positive Twomey effect is evident since **CPER decreases with increasing AIDX while COD, IWP, and CCF show a minor increase** at the beginning and stay nearly constant thereafter.
- More activated aerosols in liquid phase participate in the competition for water vapor so that their growth to larger cloud droplets is suppressed.
- Meteorological condition indicates the clouds are mainly in well developed stage with strong upward motion.
- Large amount of small droplets are lifted by strong upward motion to higher altitude (**high CTH**) in very cold temperature (**low CTT**) to trigger glaciation.

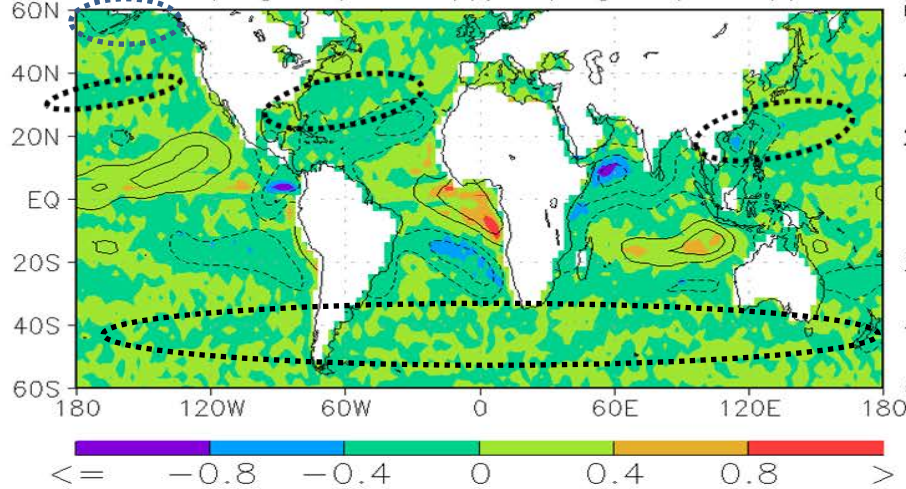


Features and Explanations of Regime 3

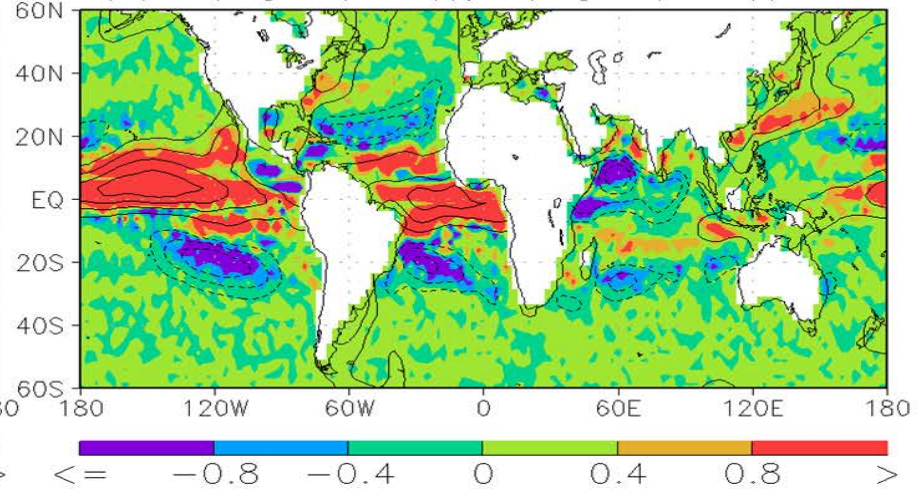
- Meteorological condition indicates the clouds are mainly in well developed stage at the beginning and gradually decay to the end, which is also concurred with the **highest COD and IWC and their concurrent rapid increase with increasing AIDX** at the beginning along with gradually **saturated CPER reduction**.
- Thus, the strong cloud dynamics and thermodynamics become dominant at the beginning of the regime, which may obscure the signatures of aerosol indirect effect accordingly.

Global Maps of the Sensitivity of Cloud Variables to Aerosol Loading Change (computed for $2.5^\circ \times 2.5^\circ$ grids from original $0.1^\circ \times 0.1^\circ$ grids)

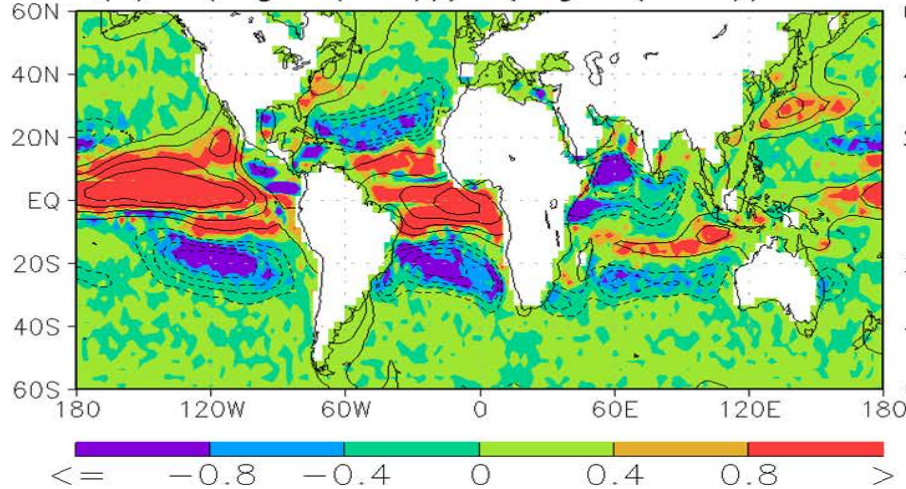
(a) $d(\log_{10}(\text{CPER}))/d(\log_{10}(\text{AIDX}))$



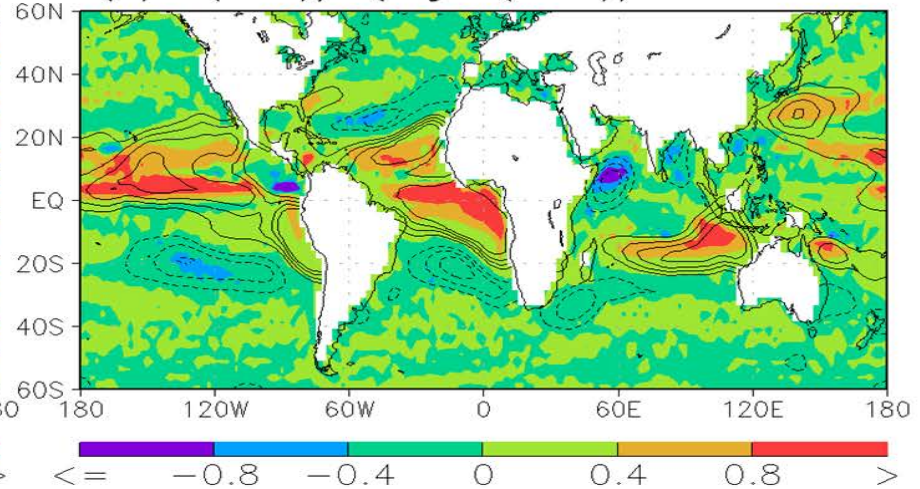
(b) $d(\log_{10}(\text{COD}))/d(\log_{10}(\text{AIDX}))$



(c) $d(\log_{10}(\text{IWP}))/d(\log_{10}(\text{AIDX}))$

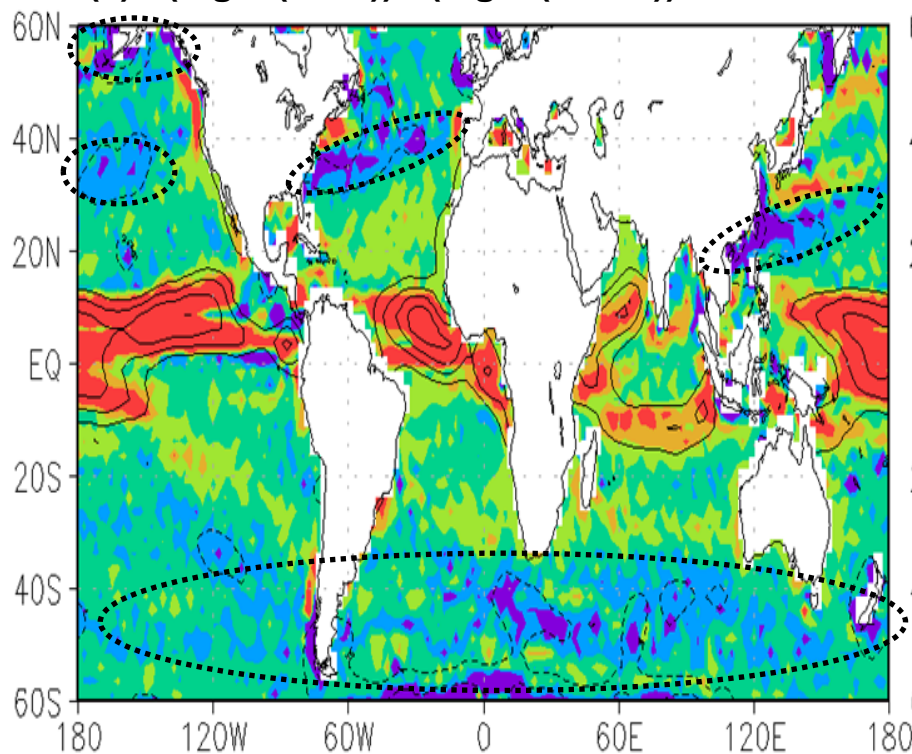


(d) $d(\text{CCF})/d(\log_{10}(\text{AIDX}))$

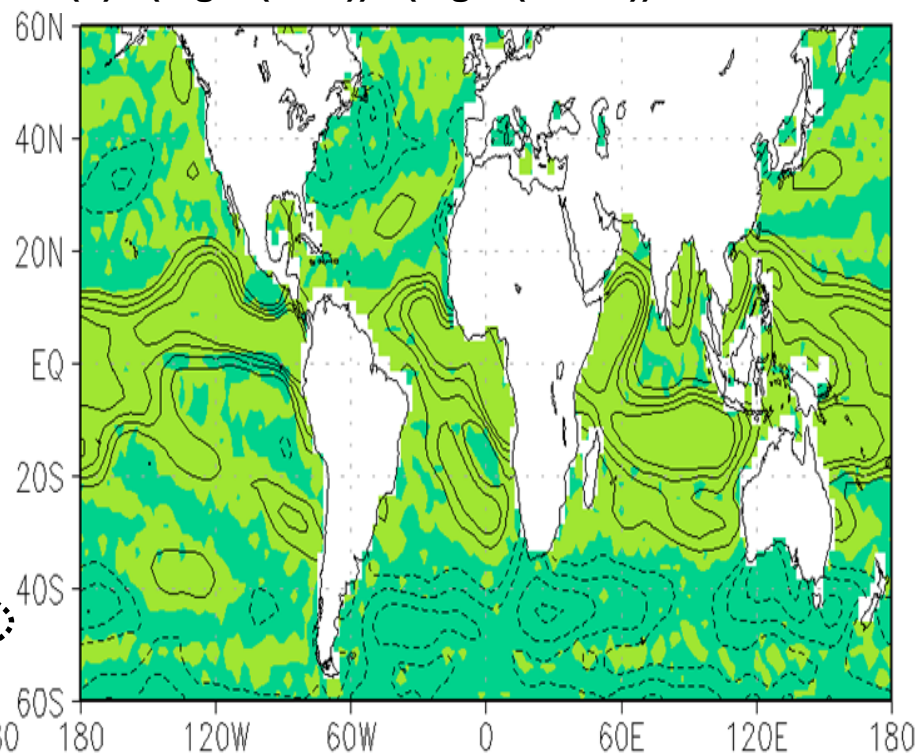


Global Maps of Linear Correlation Slope between Cloud Variables (computed for 2.5°x2.5° grids from original 0.1°x0.1° grids)

(a) $d(\log_{10}(\text{COD}))/d(\log_{10}(\text{CPER}))$



(b) $d(\log_{10}(\text{CCF}))/d(\log_{10}(\text{CPER}))$



Summary and Conclusions

- **AIE on marine ice clouds does manifest in the long-term mean of cloud variables over the global oceans as demonstrated by analyzing aerosol and cloud CDRs based on 31-year AVHRR satellite observations.**
- **Three AIDX regimes have been identified for aerosol effects on ice clouds:**
 - **Regime 1 ($AIDX < 0.18$) is the sensitive regime for negative albedo and lifetime effects**, which is mainly located in the regions with the uplift motion of synoptic weather systems and pristine air at middle/high latitudes.
 - **Regime 2 ($0.18 < AIDX < 0.31$) is the sensitive regime for positive albedo and lifetime effects**, is mainly located in the regions with the uplift motion of synoptic weather systems and relative high aerosols transported from continental sources or originated from rough ocean surface at middle/high latitudes.
 - **Regime 3 ($AIDX > 0.31$) is the sensitive regime for dynamic/thermodynamic effect (AIE may be obscured)**, which is mainly located in the tropical convergence zones with strong convective motion and high aerosol loadings due to dust, biomass burning, and marine aerosols.
- **The results are helpful for the improvement of AIE in climate models.**



Acknowledgement

•Collaborators:

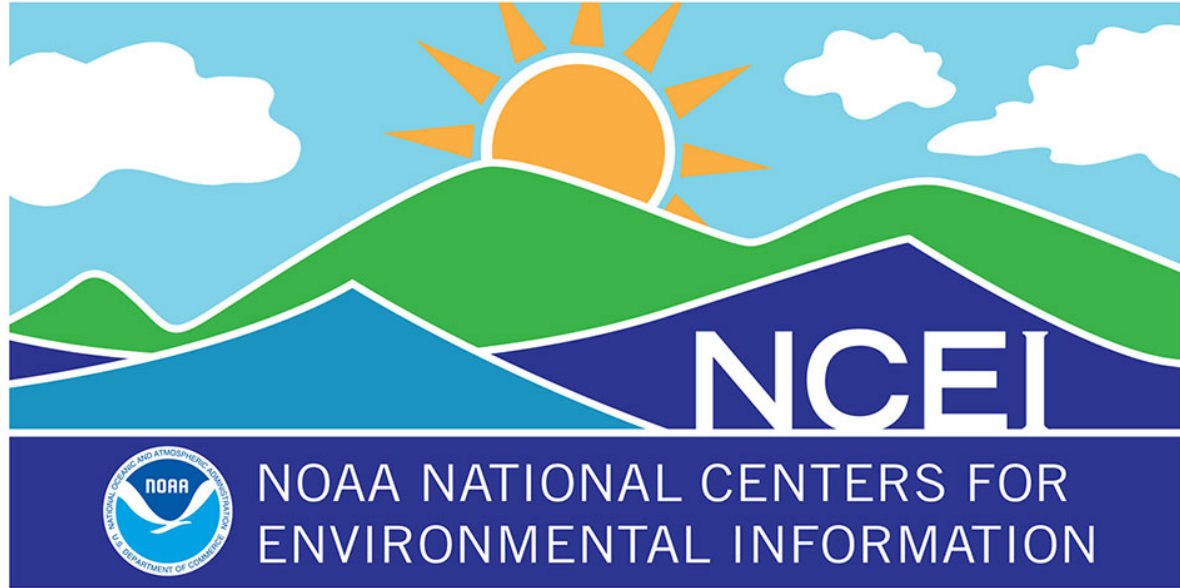
- Dr. Andrew K. Heidinger (NOAA/NESDIS/STAR)
- Dr. Yanggang Liu (DOE/BNL)
- Dr. Fangquan Yu (ASRC of SUNY at Albany)
- Dr. Zhanqing Li (UMCP)

•Funding Support:

- NOAA Climate Data Record (CDR) Program

Thank you!

Questions?



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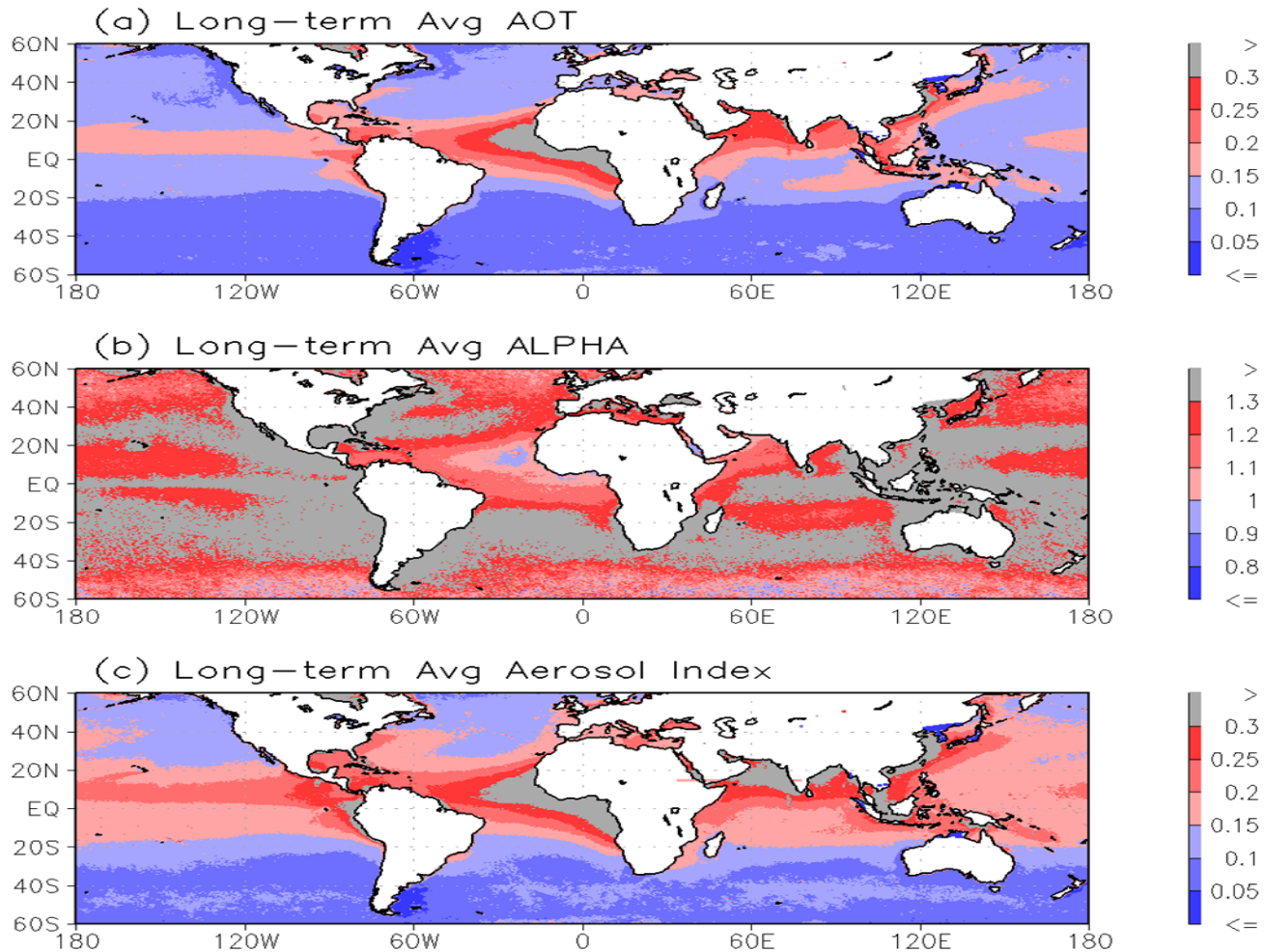


Backup Slides



Aerosol Global Distribution

Long-Term Average (1981-2011)

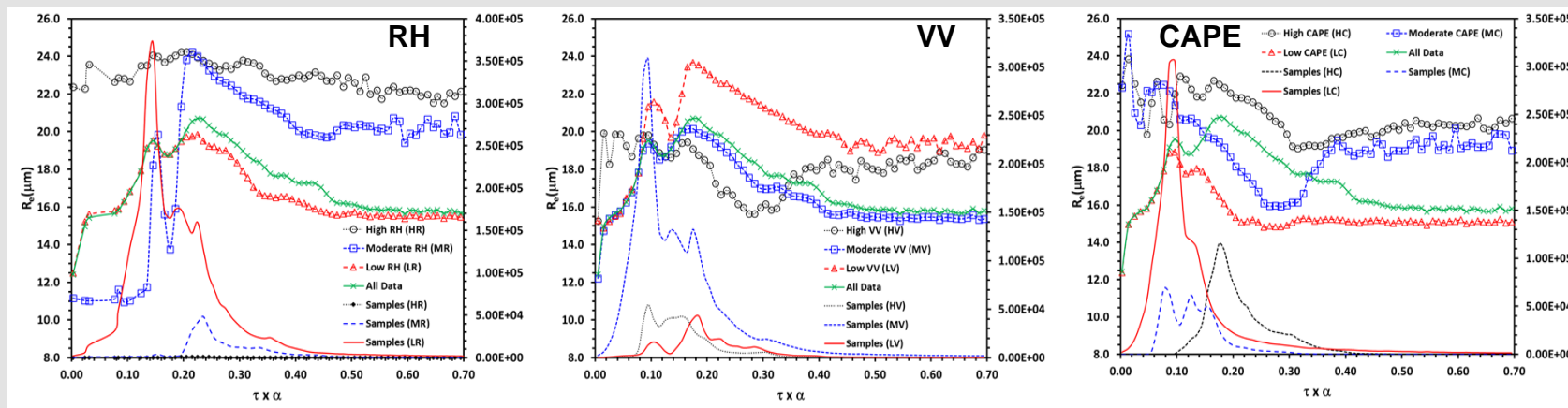


Meteorological Condition for the Three Regimes

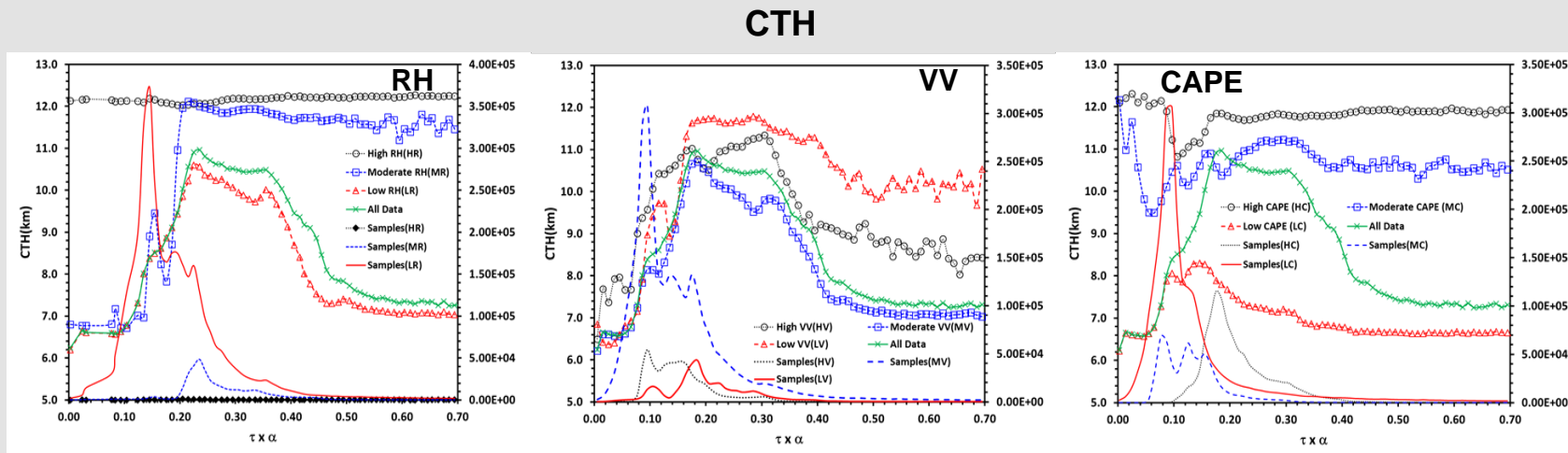
Specific Thresholds/Ranges Defined for Data Filtering

Meteorological Variables	Low Value (L)	Moderate Value (M)	High Value (H)
RH (%)	$RH \leq 45\%$	$45\% < RH < 65\%$	$RH \geq 65\%$
VV (Pa/s)	$VV \leq -0.02 \text{ Pa/s}$	$-0.02 \text{ Pa/s} < VV < 0.02 \text{ Pa/s}$	$VV \geq \text{Pa/s}$
CAPE (J/kg)	$CAPE \leq 100 \text{ J/kg}$	$100 \text{ J/kg} < CAPE < 450 \text{ J/kg}$	$CAPE \geq 450 \text{ J/kg}$

CPER



Meteorological Condition for the Three Regimes



Summary

Cloud Variables	Regime 1			Regime 2			Regime 3		
	RH	VV	CAPE	RH	VV	CAPE	RH	VV	CAPE
CPER (μm)	L	L->M	L->M	L	M&H	M&H	L	H->M	M->L
CTH (km)	L	L->M	L->M	L	M&H	M&H	L	H->M	M->L