Measurements Needed to Advance Understanding of Aerosol-Cloud-Precipitation-Climate Interactions

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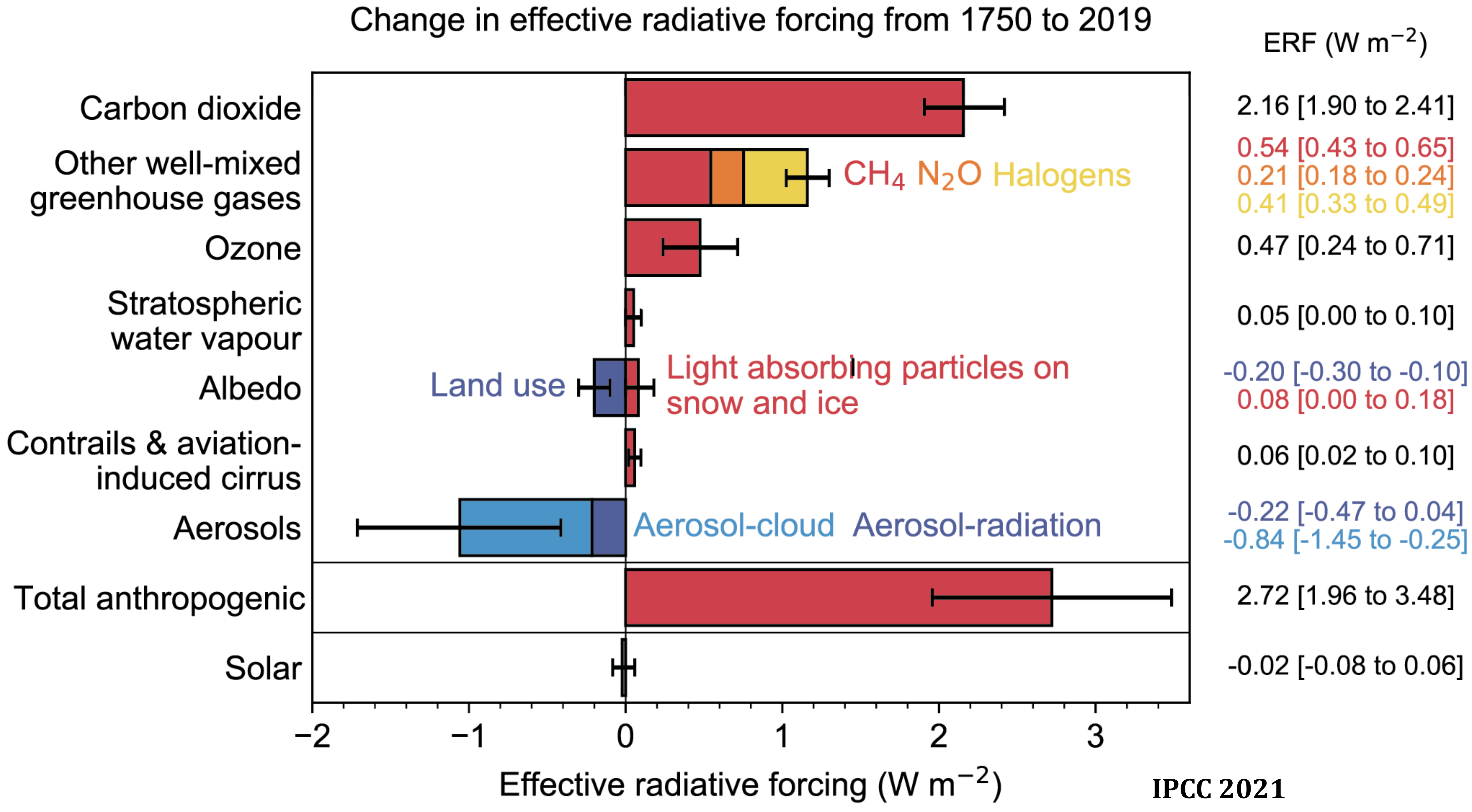
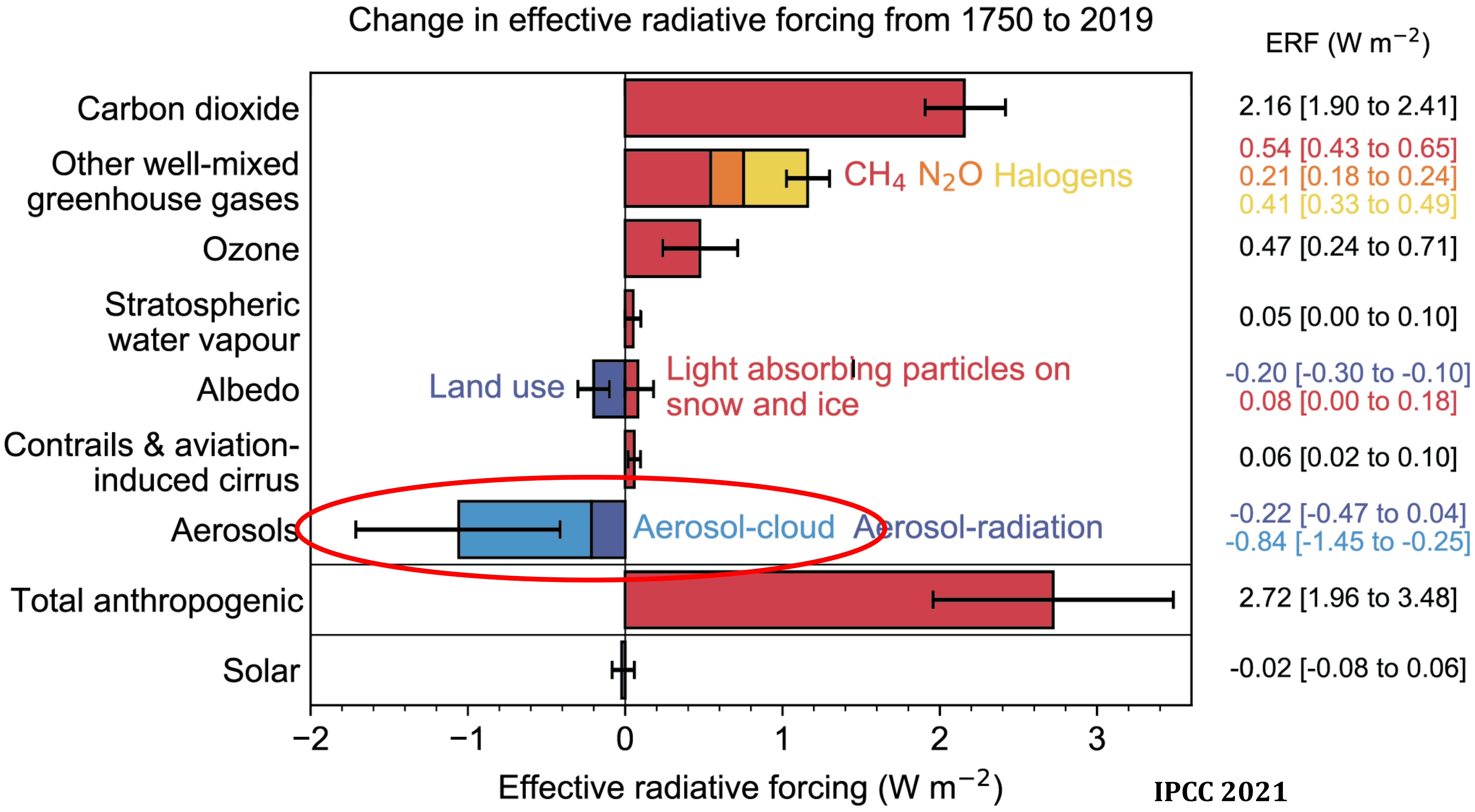
Aerosol-Cloud-Precipitation-Climate

- ***The most fundamental and complex problems in climate and weather research today are our poor understandings of the basic properties of clouds and our inability to determine quantitatively the many effects cloud processes have on weather and climate***

- **Work to investigate these problems requires an integrated approach using ground/air-based in-situ and remote sensing observations, satellite remote sensing and models with a variety of temporal and spatial scales**



Change in effective radiative forcing from 1750 to 2019
ERF (W m−2)
Carbon dioxide
2.16 [1.90 to 2.41]
Other well-mixed greenhouse gases
CH4 N2O Halogens
0.54 [0.43 to 0.65]
0.21 [0.18 to 0.24]
0.41 [0.33 to 0.49]
Ozone
0.47 [0.24 to 0.71]
Stratospheric water vapour
0.05 [0.00 to 0.10]
Albedo
Land use
Light absorbing particles on snow and ice
-0.20 [-0.30 to -0.10]
0.08 [0.00 to 0.18]
Contrails & aviation-induced cirrus
0.06 [0.02 to 0.10]
Aerosols
Aerosol-cloud
Aerosol-radiation
-0.22 [-0.47 to 0.04]
-0.84 [-1.45 to -0.25]
Total anthropogenic
2.72 [1.96 to 3.48]
Solar
-0.02 [-0.08 to 0.06]
−2
−1
0
1
2
3
Effective radiative forcing (W m−2)
IPCC 2021



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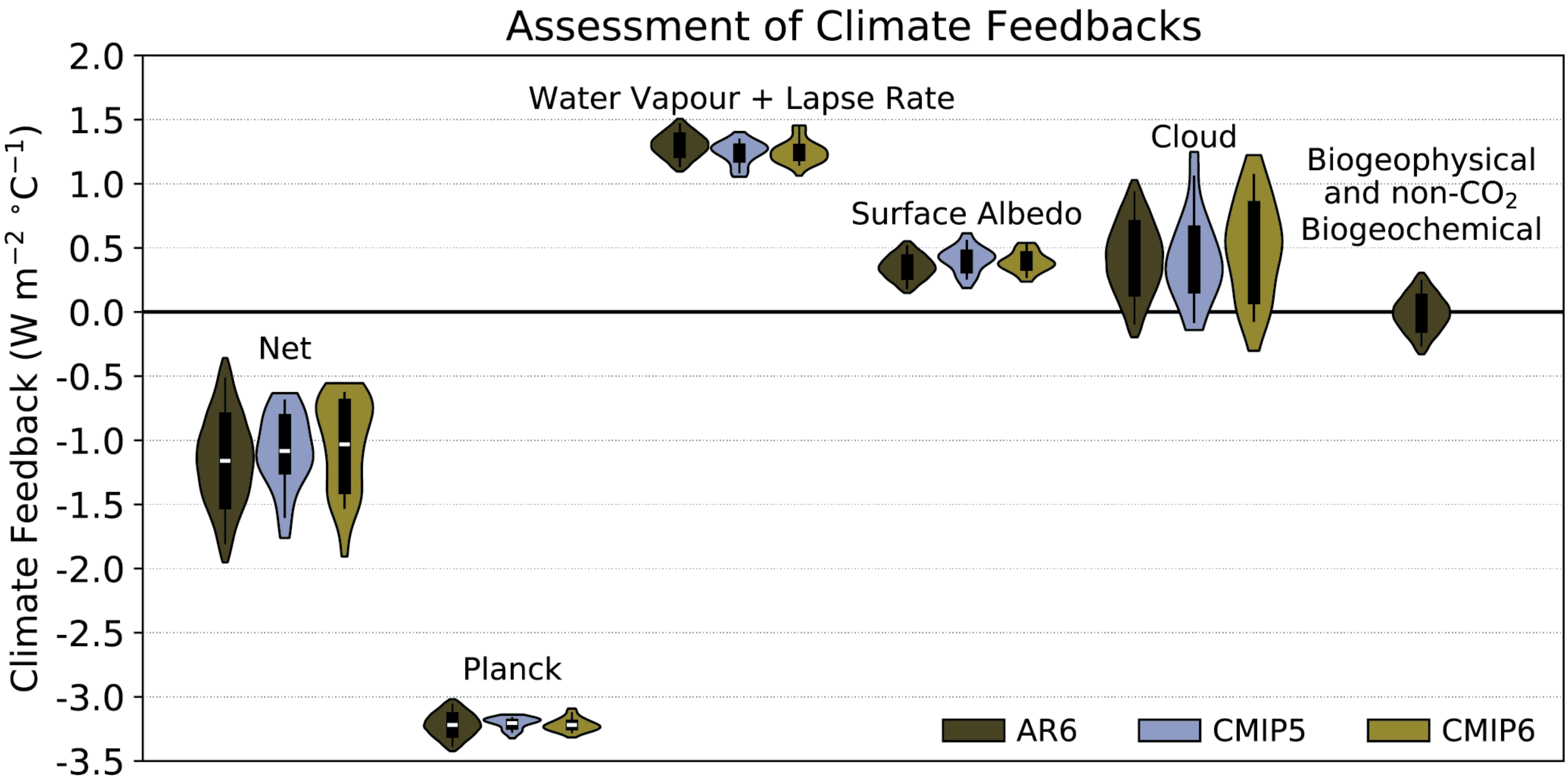
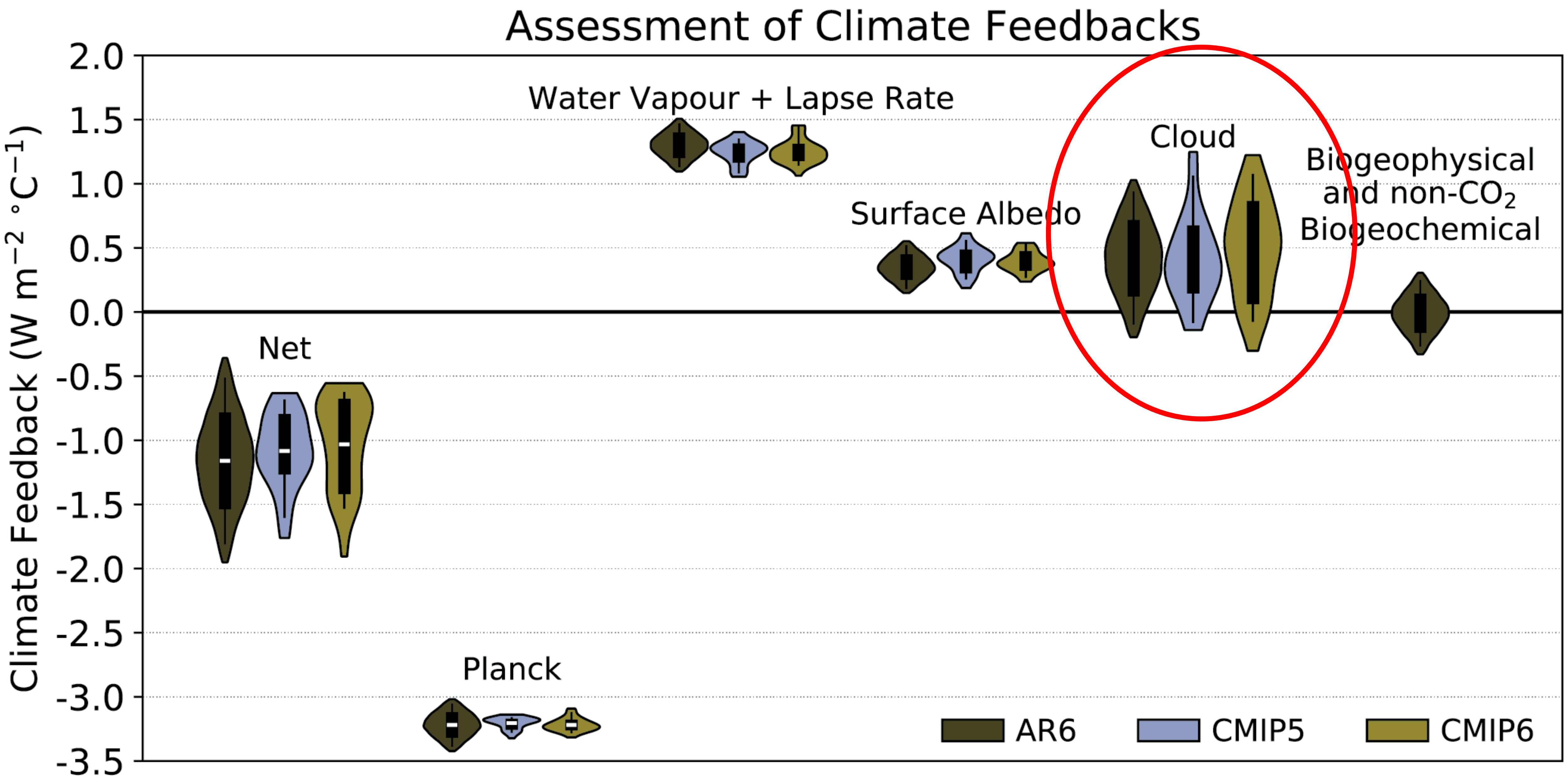


Assessment of Climate Feedbacks
Climate Feedback (W m^{-2} °C^{-1})
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
-2.0
-2.5
-3.0
-3.5
Net
Planck
Water Vapour + Lapse Rate
Surface Albedo
Cloud
Biogeophysical and non-CO_2 Biogeochemical
AR6
CMIP5
CMIP6

IPCC 2021


Assessment of Climate Feedbacks
Climate Feedback (W m^{-2} °C^{-1})
2.0
1.5
1.0
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0.0
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-1.0
-1.5
-2.0
-2.5
-3.0
-3.5
Water Vapour + Lapse Rate
Cloud
Biogeophysical and non-CO_2 Biogeochemical
Surface Albedo
Net
Planck
AR6
CMIP5
CMIP6

IPCC 2021

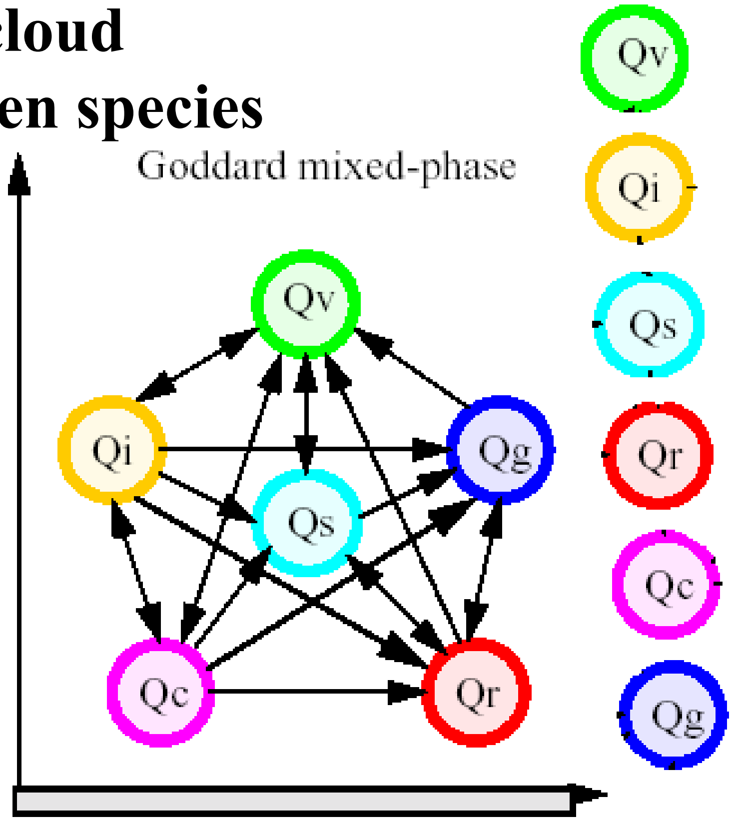
Role of Observations

- ***We need to improve our process-oriented understanding of aerosol-cloud-precipitation interactions***
- ***But, we observe aerosol, cloud, precipitation and radiative properties, not processes***
- **How can we link the two?**

What do models need from in-situ data?

Most cloud parameterization schemes predict 1- or 2- moments of a size distribution for a # of hydrometeor categories

These schemes require some information about cloud microphysics to calculate conversion rates between species



What do models need from in-situ data?

Most cloud parameterization schemes predict 1- or 2- moments of a size distribution for a # of hydrometeor categories

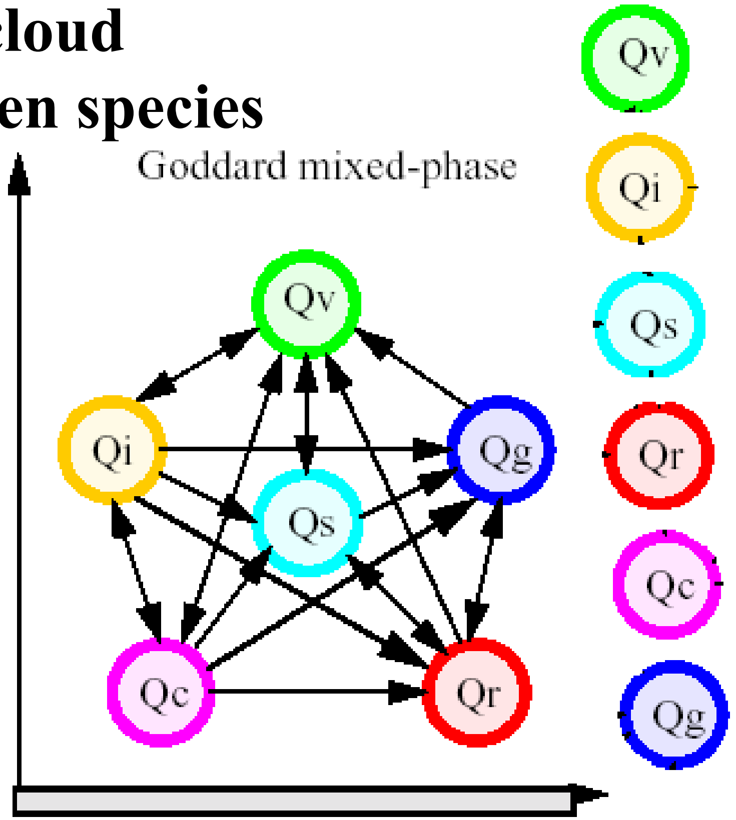
These schemes require some information about cloud microphysics to calculate conversion rates between species

$$N(D) = N_0 D^{\mu} e^{-\lambda D}$$
(size distribution)

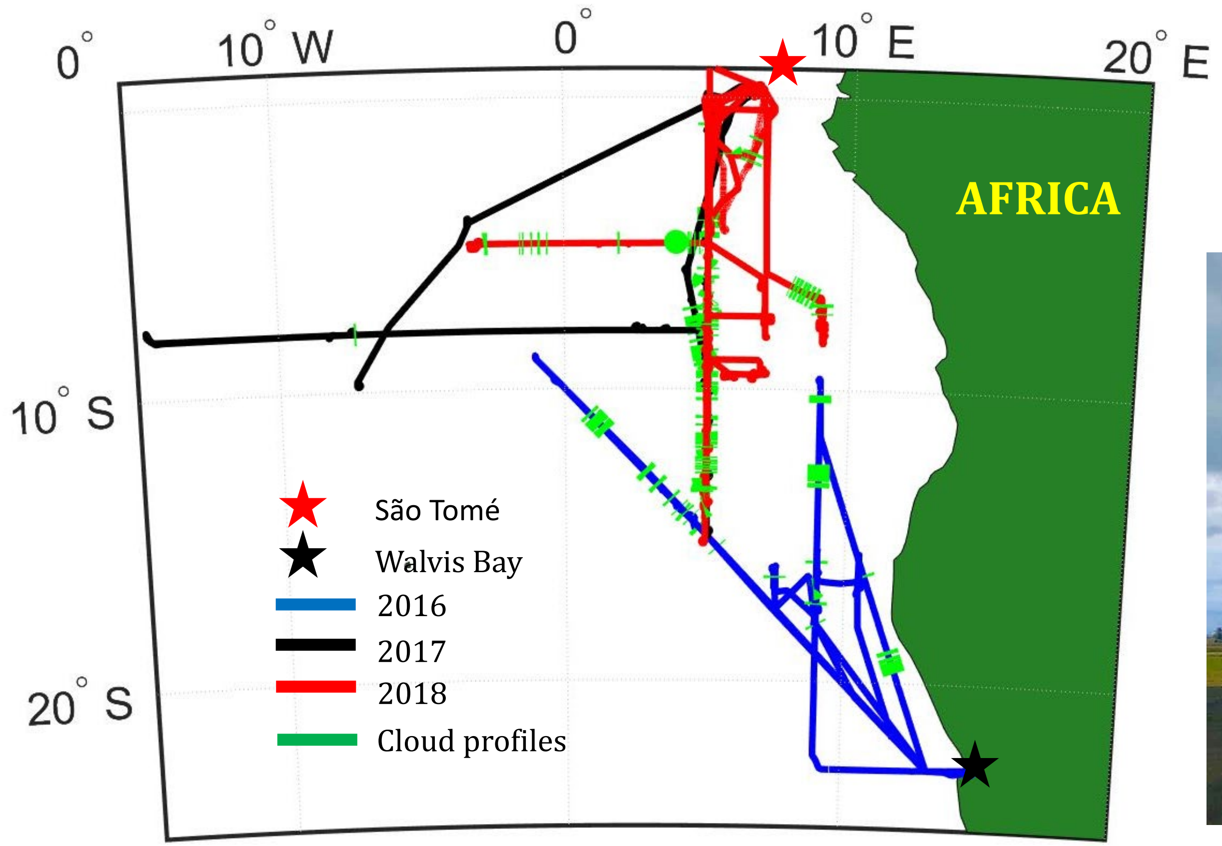
$m = \alpha D^{\beta}$ **(mass)**

$V = aD^{b}$ **(fall speed)**

$g, \omega_0 = f(T, IWC, r_e)$



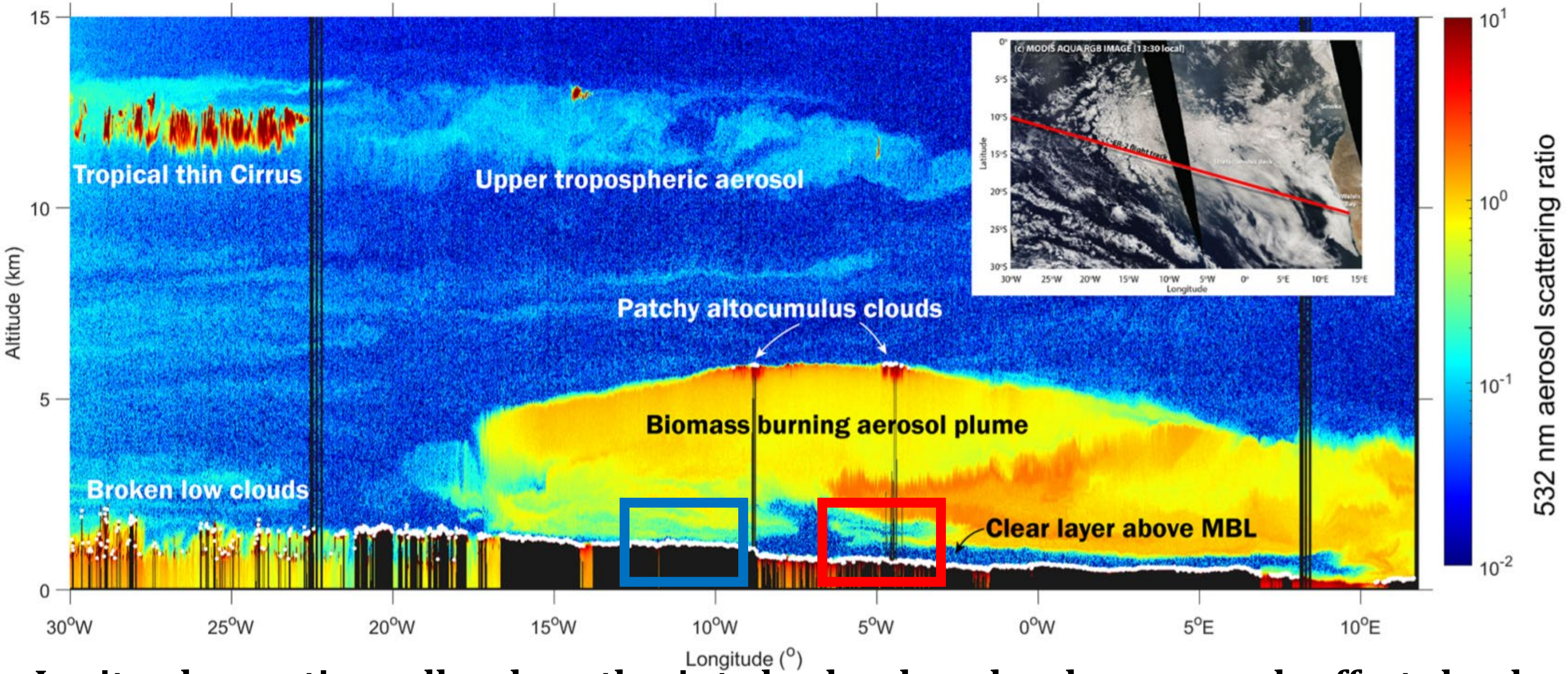
ORACLES: ObseRvations of Aerosols above CLouds and their intEractionS



ORACLES used aircraft to quantify how mixing of aerosols near tops of persistent stratocumulus deck off west coast of Africa affected cloud properties

Gupta et al., 2021

High Spectral Resolution LIDAR (HSRL-2)

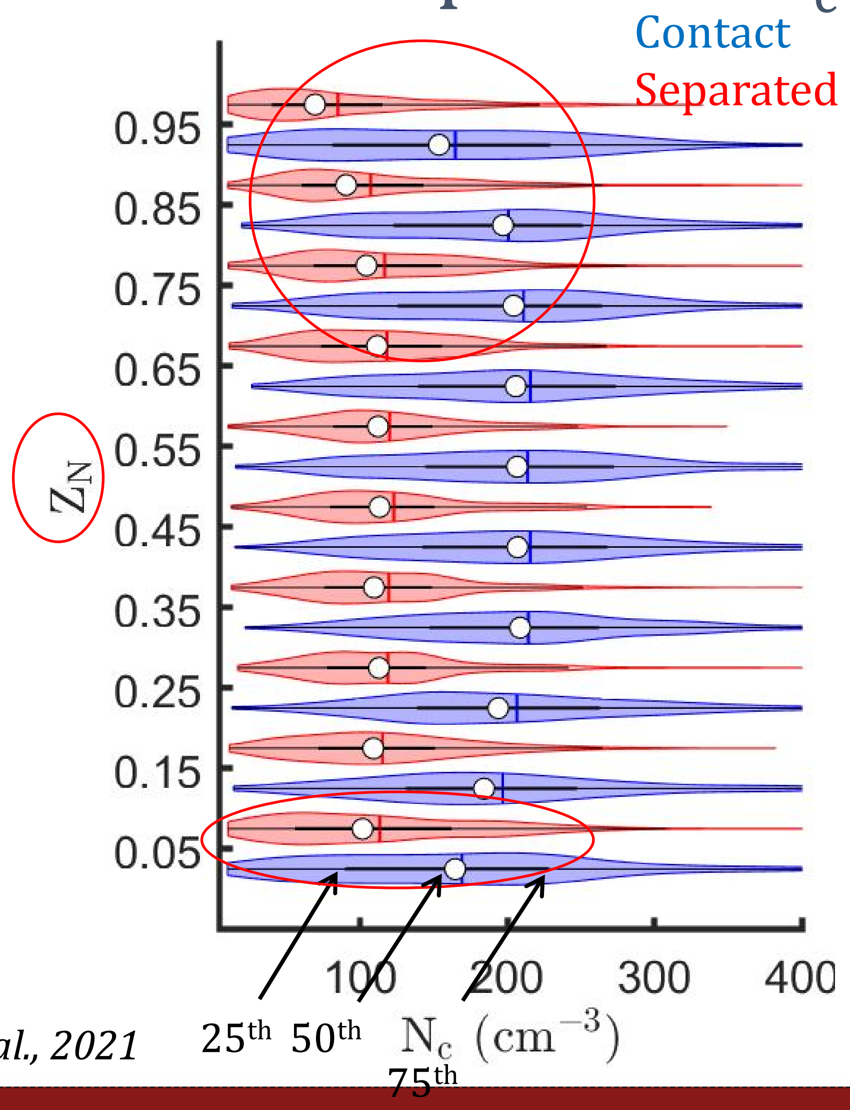


In situ observations allow hypothesis to be developed on how aerosols affect clouds

- **Synergy with modeling studies evaluated with observations required to quantify processes by which ACIs affect cloud properties; also evaluate remote sensing algorithms**

Redemann et al., 2021

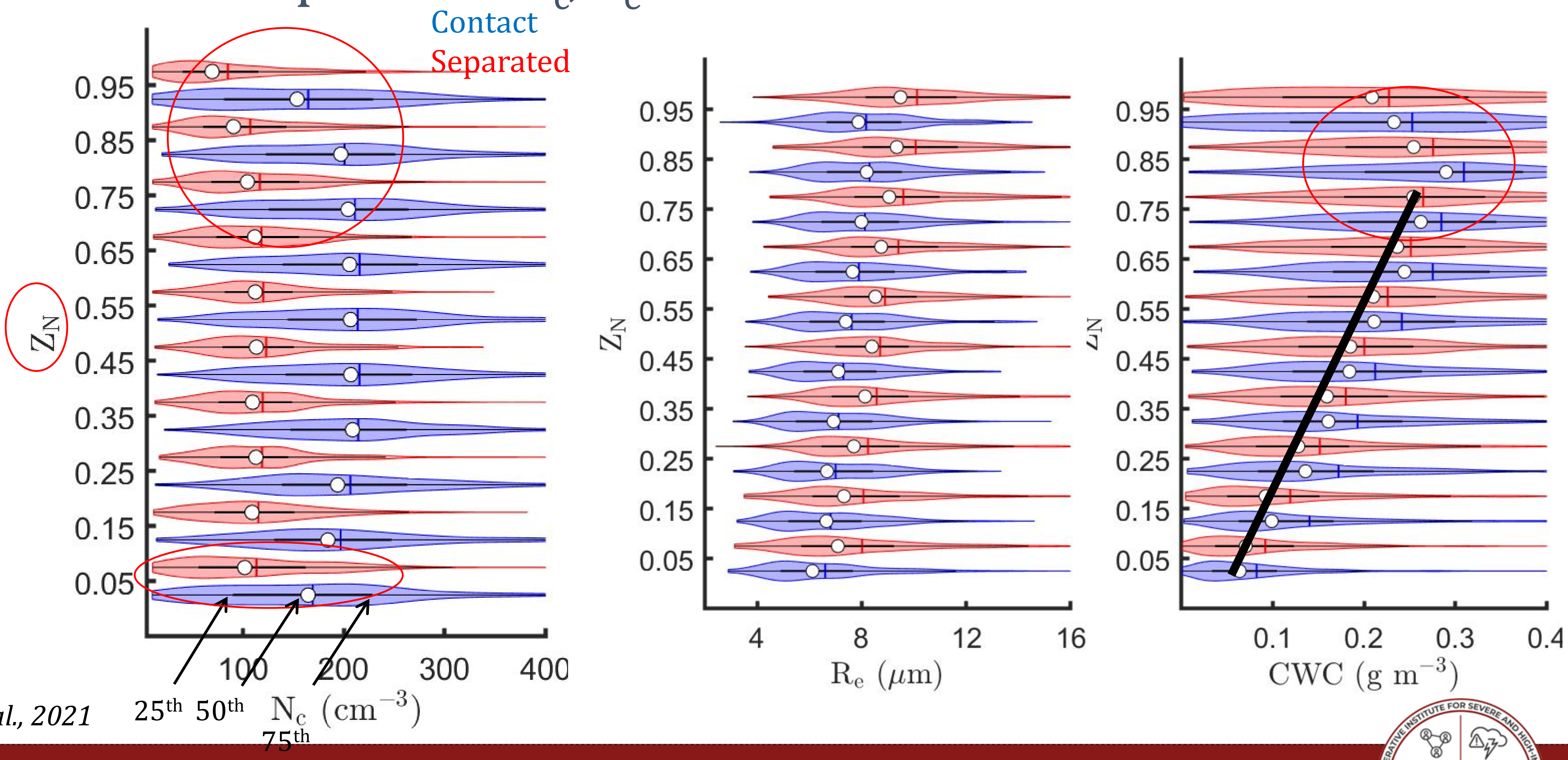
Vertical profile of N_c



Gupta et al., 2021

N_c for contact profiles 84 to 90 cm^{-3} higher. (95% confidence intervals; 2-sample t-test).

Vertical profile of N_c, R_e and CWC



Gupta et al., 2021

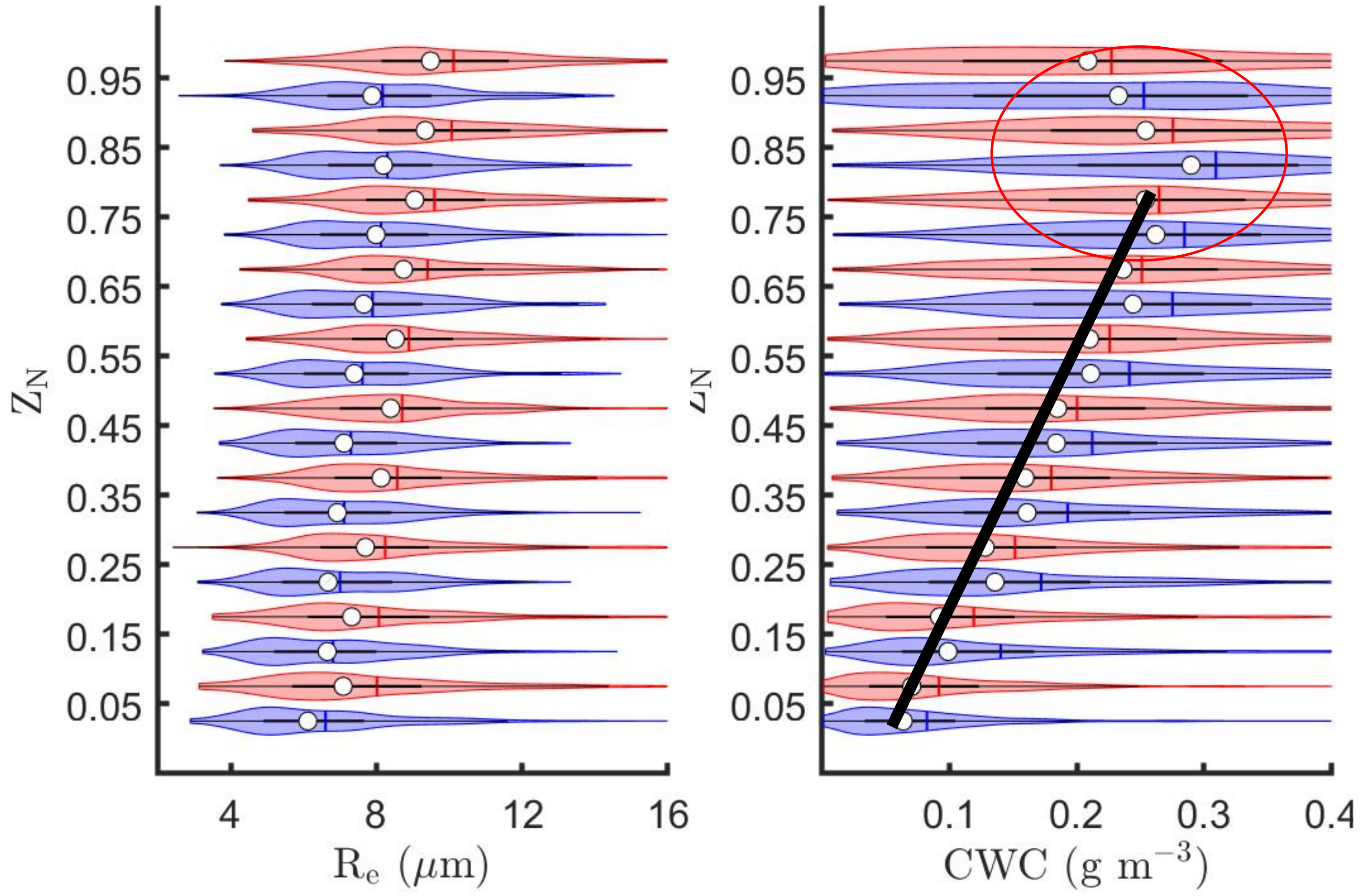
Vertical profile of N_c, R_e and CWC

Contact
Separated

R_e increased with height
- **7.1 to 9.5 μm**
- **6.1 to 7.9 μm**

CWC increased up to Z_N = 0.75, similar for contact and separated

Decrease in CWC near cloud top
- **Inhomogeneous mixing**



Future Observations

- **What observations do we need in future?**
- **Where/when do we need these observations?**
- **How do we need to collect these observations?**

Future Observations

- **What** observations do we need in future?
- **Where/when** do we need these observations?
- **How** do we need to collect these observations?
- **Science questions/hypotheses drive the answers to these questions**

Role of Models

SOCRATES observational requirement	To enhance our knowledge of SO aerosols, clouds and their interactions in a variety of synoptic settings and to narrow the uncertainties in representing key processes in climate models, a comprehensive dataset is needed that documents BL structure, and associated vertical distributions of liquid and mixed-phase cloud and aerosol (including CCN and IN) properties over the SO under a range of synoptic settings.
SOCRATES modeling requirement	For such a dataset to have broad impact on climate modelling, the modelling community must be an integral part of the SOCRATES design and be involved in a systematic confrontation of leading climate models with SOCRATES data, e. g. using short-term hindcasts as in VOCALS model assessment (Wyant et al. 2014).

- **Important for modeling community be involved from very beginning of project**

McFarquhar et al. 2020

Science Traceability Matrix (STM)

- In any specific campaign, need STM

Table 3.1-3. ORACLES Science Traceability Matrix (Table A.30-3)

Priority	Science Objectives	Scientific Measurement Requirements: Parameter	Scientific Measurement Requirements: Accuracy	Instrument Functional Requirements (**bold** font indicates instruments that meet or exceed measurement requirements)	
Threshold	**Aerosol direct effects:** S01-1 (Aerosol spatial evolution) S01-2 (Aerosol-induced radiative fluxes) S01-3 (Seasonal aerosol variation) **Aerosol semi-direct effects:** S02-1 (Relative vertical distribution) S02-2 (Aerosol-cloud heating rates) S02-3 (Cloud changes due to aerosol-induced heating)	**Aerosol:**			
		AOD at UV-VIS-SWIR	±0.02 or 5%	**4STAR** (0.01-0.02), **RSP** (0.02), AirMSPI, **HSRL-2** (0.01), eMAS, **AERONET** (0.01-0.02)	S01-1 S01-2
		AAOD at UV-VIS-SWIR	±0.02 for AOD>0.1	**4STAR** + **SSFR** (0.02), RSP, AirMSPI, HSRL, eMAS, **HiGEAR, AERONETT** (0.02)	S01-1 S01-2 S02-2
		Aerosol spectral refractive index at UV-VIS-SWIR	±0.02 for real part	4STAR + SSFR, RSP, AirMSPI, HSRL, eMAS, **AERONET** (0.02)	S01-1
		Aerosol/CCN size distribution, r_{eff}	±0.07 μm±7%	**HiGEAR** (10% number, 5% size), RSP	S01-1 S03-1
		Aerosol number conc. profile	50%	**HiGEAR** (10%), HSRL-2	S01-1 S03-1
		Chemical composition	Speciation (BC, volatile, refractory)	**HiGEAR-AMS** (35%), **SP2** (25%) RSP	S01-1 S03-1
		Aerosol extinction/absorption profile	±0.025 km^{-1} in ext	**HiGEAR** (0.005 in ext), **HSRL-2** (0.01 ext), 4STAR	S01-1 S02-1
		Single Scattering Albedo (SSA)(profile or layer)	±0.028	**HiGEAR** (0.03), HSRL-2, RSP, AirMSPI, **4STAR + SSFR** (0.02 in midvis), **AERONET** (~0.03)	S01-1 S01-2 S02-1 S02-2
		Gases:			
		CO, CO_2, H_2O, O_3	±10 ppbv CO	**COMA** (2 ppbv CO), facility, HiGEAR	S03-1 S01-1
		Cloud/Drizzle/Precipitation:			
		Cloud fractional cover	±0.05	**eMAS (0.05), ACR+APR-2, AirMSPI (0.05), MODIS/SEVIRI (0.05)**	S02-3 S01-2
Baseline	**Aerosol indirect effects:** S03-1 (Mixing survey) S03-2 (Cloud changes due to aerosol mixing) S03-3 (Cloud changes due to aerosol-suppressed precipitation)	Cloud top/bottom height	±100 m	**ACR+APR-2 (60 m), HSRL-2 (33 m), AirMSPI**	A S01-2
		Particle Size Distribution/Composition	±20%	**CAPS-CAS**, **PDI** (20%), CVI, CDP	S02-2 S02-3 S03-2
		COD	±10%	**eMAS** (5-10%), **SSFR**, RSP, AirMSPI, 4STAR	S02-2 S02-3 S03-2 S03-3
		r_{eff}	±20%	**eMAS** (10-20%), RSP, AirMSPI, SSFR, 4STAR, *in situ* **probes** (20%)	
		Liquid water content (LWC/LWP)	±0.05 g m^{-3} / 10 g m^{-2}	**King probe, CAPS-LWC, PDI** (20% LWC), **ACR+APR-2** (10 gm^{-2} LWP)	S02-3 S03-2 S03-3
		Thermodynamics		Facility	S02-3
		Precipitation microphysics/rate	±0.4 mm/day (rate)	**2D-S, CAPS-CIP, PDI+HVPS3 (0.2 mm/day), eMAS+ACR+APR-2 (0.2 mm/day)**	S03-3
		Radiation:			
		Spectral Solar Flux	±3%	**SSFR** (3%, 0.5-7% for differentials)	S01-1 S02-2
		Visible-SWIR Degree of Linear Polarization	±0.5%	**RSP** (0.2%), **AirMSPI** (0.5%)	S01-2 S02-2 S03-2
		Visible, SWIR, Thermal IR Radiance / Brightness	±5-10% in radiance, ±0.5 K for IR	**eMAS** (5% in radiance, 0.5 K for mid- and window-IR, 1-2 K for 13+ μm)	S02-3

Investigation Functional Requirements (A = all)

Requirement	
Observations:	
Intensive, multi-aircraft field campaigns	A A A
Measurements on routine flight track along 15°S, sampling at least 40 hrs (~200 100 km^2 model grid boxes) to enable statistical comparisons to climate models	S01-1 S03-1
Sampling that permits assessments of variability in aerosol and cloud properties within climate model grid cells (100 km^2) for multiple adjacent cells	A A A
3 airborne campaigns in different months of BB season	S01-3 S02-1 S03-1
In situ and remote sensing obs of aerosol layers above (and entrained into) low-level Sc deck	A A A
Coincident obs of underlying cloud macro- and microphysical properties	A A
Measurement of FT-to-PBL mixing	S03-1
Modeling:	
Large eddy simulations to integrate observations for process scale understanding of aerosol-cloud interactions.	A A
Regional chemistry-aerosol climate modeling for field planning, to integrate observations to constrain direct, semi-direct and indirect effects, and to separate aerosol and meteorological effects on clouds	A A A
Global climate modeling to determine impacts of BB aerosols on radiation budget and global circulation	A A A

Priority:

Critical, Important, Nice to Have

Threshold or Baseline

Table 3.1-3. ORACLES Science Traceability Matrix (Table A.30-3)

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Threshold	**Aerosol direct effects:**	**Aerosol:**			
	S01-1 (Aerosol spatial evolution)	AOD at UV-VIS-SWIR	±0.02 or 5%	**4STAR** (0.01-0.02), **RSP** (0.02), AirMSPI, **HSRL-2** (0.01), eMAS, **AERONET** (0.01-0.02)	S01-1 S01-2
	S01-2 (Aerosol-induced radiative fluxes)	AAOD at UV-VIS-SWIR	±0.02 for AOD>0.1	**4STAR + SSFR** (0.02), RSP, AirMSPI, HSRL,eMAS,**HiGEAR, AERONETT** (0.02)	S01-1 S01-2 S02-2
		Aerosol spectral refractive index at UV-VIS-SWIR	±0.02 for real part	4STAR + SSFR, RSP, AirMSPI, HSRL, eMAS, **AERONET** (0.02)	S01-1
	S01-3 (Seasonal aerosol variation)	Aerosol/CCN size distribution , r_{eff}	±0.07 µm±7%	**HiGEAR** (10% number, 5% size), RSP	S01-1 S03-1
		Aerosol number conc. profile	50%	**HiGEAR** (10%), HSRL-2	S01-1 S03-1
	Aerosol semi-direct effects:	Chemical composition	Speciation (BC, volatile, refractory)	**HiGEAR-AMS** (35%), **SP2** (25%) RSP	S01-1 S03-1
	S02-1 (Relative vertical distribution)	Aerosol extinction/absorption profile	±0.025 km^{-1} in ext	**HiGEAR** (0.005 in ext), **HSRL-2** (0.01 ext), 4STAR	S01-1 S02-1
		Single Scattering Albedo (SSA)(profile or layer)	±0.028	**HiGEAR** (0.03), HSRL-2, RSP, AirMSPI, **4STAR + SSFR** (0.02 in midvis), **AERONET** (~0.03)	S01-1 S01-2 S02-1 S02-2
	S02-2 (Aerosol-cloud heating rates)	**Gases:**			
		CO, CO_2, H_2O, O_3	±10 ppbv CO	**COMA** (2 ppbv CO), facility, HiGEAR	S03-1 S01-1
	S02-3 (Cloud changes due to aerosol-induced heating)	**Cloud/Drizzle/Precipitation:**			
		Cloud fractional cover	±0.05	**eMAS (0.05), ACR+APR-2, AirMSPI (0.05), MODIS/SEVIRI (0.05)**	S02-3 S01-2
Baseline		Cloud top/bottom height	±100 m	**ACR+APR-2 (60 m), HSRL-2 (33 m), AirMSPI**	A S01-2
		Particle Size Distribution/Composition	±20%	**CAPS-CAS , PDI** (20%), CVI, CDP	S02-2 S02-3 S03-2
	Aerosol indirect effects:	COD	±10%	**eMAS** (5-10%), **SSFR**, RSP, AirMSPI, 4STAR	S02-2 S02-3 S03-2 S03-3
	S03-1 (Mixing survey)	r_{eff}	±20%	**eMAS** (10-20%), RSP, AirMSPI, SSFR, 4STAR, *in situ* **probes** (20%)	
	S03-2 (Cloud changes due to aerosol mixing)	Liquid water content (LWC/LWP)	±0.05 g m^{-3} / 10 g m^{-2}	**King probe, CAPS-LWC, PDI** (20% LWC), **ACR+APR-2** (10 gm^{-2} LWP)	S02-3 S03-2 S03-3
		Thermodynamics		Facility	S02-3
	S03-3 (Cloud changes due to aerosol-suppressed precipitation)	Precipitation microphysics/rate	±0.4 mm/day (rate)	**2D-S, CAPS-CIP, PDI+HVPS3 (0.2 mm/day), eMAS+ACR+APR-2 (0.2 mm/day)**	S03-3
		Radiation:			
		Spectral Solar Flux	±3%	**SSFR** (3%, 0.5-7% for differentials)	S01-1 S02-2
		Visible-SWIR Degree of Linear Polarization	±0.5%	**RSP** (0.2%), **AirMSPI** (0.5%)	S01-2 S02-2 S03-2
		Visible, SWIR, Thermal IR Radiance / Brightness	±5-10% in radiance, ±0.5 K for IR	**eMAS** (5% in radiance, 0.5 K for mid- and window-IR, 1-2 K for 13+ µm)	S02-3

Investigation Functional Requirements (A = all)

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Intensive, multi-aircraft field campaigns	A A A
Measurements on routine flight track along 15°S, sampling at least 40 hrs (~200 100 km^2 model grid boxes) to enable statistical comparisons to climate models	S01-1 S03-1
Sampling that permits assessments of variability in aerosol and cloud properties within climate model grid cells (100 km^2) for multiple adjacent cells	A A A
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In situ and remote sensing obs of aerosol layers above (and entrained into) low-level Sc deck	A A A
Coincident obs of underlying cloud macro- and microphysical properties	A A
Measurement of FT-to-PBL mixing	S03-1
Modeling:	
Large eddy simulations to integrate observations for process scale understanding of aerosol-cloud interactions.	A A
Regional chemistry-aerosol climate modeling for field planning, to integrate observations to constrain direct, semi-direct and indirect effects, and to separate aerosol and meteorological effects on clouds	A A A
Global climate modeling to determine impacts of BB aerosols on radiation budget and global circulation	A A A

Science Objective:

E.g., Aerosol direct or indirect effects

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Table 3.1-3. ORACLES Science Traceability Matrix (Table A.30-3)

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Threshold	**Aerosol direct effects:** S01-1 (Aerosol spatial evolution) S01-2 (Aerosol-induced radiative fluxes) S01-3 (Seasonal aerosol variation) **Aerosol semi-direct effects:** S02-1 (Relative vertical distribution) S02-2 (Aerosol-cloud heating rates) S02-3 (Cloud changes due to aerosol-induced heating)	**Aerosol:**			**Observations:** Intensive, multi-aircraft field campaigns A A A Measurements on routine flight track along 15°S, sampling at least 40 hrs (~200 100 km² model grid boxes) to enable statistical comparisons to climate models S01-1 S03-1 Sampling that permits assessments of variability in aerosol and cloud properties within climate model grid cells (100 km²) for multiple adjacent cells A A A 3 airborne campaigns in different months of BB season S01-3 S02-1 S03-1 *In situ* and remote sensing obs of aerosol layers above (and entrained into) low-level Sc deck A A A Coincident obs of underlying cloud macro- and microphysical properties A A Measurement of FT-to-PBL mixing S03-1 **Modeling:** Large eddy simulations to integrate observations for process scale understanding of aerosol-cloud interactions. A A Regional chemistry-aerosol climate modeling for field planning, to integrate observations to constrain direct, semi-direct and indirect effects, and to separate aerosol and meteorological effects on clouds A A A Global climate modeling to determine impacts of BB aerosols on radiation budget and global circulation A A A
		AOD at UV-VIS-SWIR	±0.02 or 5%	**4STAR** (0.01-0.02), **RSP** (0.02), AirMSPI, **HSRL-2** (0.01), eMAS, **AERONET** (0.01-0.02) — S01-1 S01-2	
		AAOD at UV-VIS-SWIR	±0.02 for AOD>0.1	**4STAR + SSFR** (0.02), RSP, AirMSPI, HSRL, eMAS, **HiGEAR, AERONETT** (0.02) — S01-1 S01-2 S02-2	
		Aerosol spectral refractive index at UV-VIS-SWIR	±0.02 for real part	4STAR + SSFR, RSP, AirMSPI, HSRL, eMAS, **AERONET** (0.02) — S01-1	
		Aerosol/CCN size distribution, r_{eff}	±0.07 μm±7%	**HiGEAR** (10% number, 5% size), RSP — S01-1 S03-1	
		Aerosol number conc. profile	50%	**HiGEAR** (10%), HSRL-2 — S01-1 S03-1	
		Chemical composition	Speciation (BC, volatile, refractory)	**HiGEAR-AMS** (35%), **SP2** (25%) RSP — S01-1 S03-1	
		Aerosol extinction/absorption profile	±0.025 km^{-1} in ext	**HiGEAR** (0.005 in ext), **HSRL-2** (0.01 ext), 4STAR — S01-1 S02-1	
		Single Scattering Albedo (SSA)(profile or layer)	±0.028	**HiGEAR** (0.03), HSRL-2, RSP, AirMSPI, **4STAR + SSFR** (0.02 in midvis), **AERONET** (~0.03) — S01-1 S01-2 S02-1 S02-2	
		Gases:			
		CO, CO_2, H_2O, O_3	±10 ppbv CO	**COMA** (2 ppbv CO), facility, HiGEAR — S03-1 S01-1	
		Cloud/Drizzle/Precipitation:			
		Cloud fractional cover	±0.05	**eMAS (0.05), ACR+APR-2, AirMSPI (0.05), MODIS/SEVIRI (0.05)** — S02-3 S01-2	
Baseline	**Aerosol indirect effects:** S03-1 (Mixing survey) S03-2 (Cloud changes due to aerosol mixing) S03-3 (Cloud changes due to aerosol-suppressed precipitation)	Cloud top/bottom height	±100 m	**ACR+APR-2 (60 m), HSRL-2 (33 m), AirMSPI** — A S01-2	
		Particle Size Distribution/Composition	±20%	**CAPS-CAS , PDI** (20%), CVI, CDP — S02-2 S02-3 S03-2	
		COD	±10%	**eMAS** (5-10%), **SSFR**, RSP, AirMSPI, 4STAR — S02-2 S02-3 S03-2 S03-3	
		r_{eff}	±20%	**eMAS** (10-20%), RSP, AirMSPI, SSFR, 4STAR, *in situ* **probes** (20%) — S02-2 S02-3 S03-2 S03-3	
		Liquid water content (LWC/LWP)	±0.05 g m^{-3} / 10 g m^{-2}	**King probe, CAPS-LWC, PDI** (20% LWC), **ACR+APR-2** (10 gm^{-2} LWP) — S02-3 S03-2 S03-3	
		Thermodynamics		Facility — S02-3	
		Precipitation microphysics/rate	±0.4 mm/day (rate)	**2D-S, CAPS-CIP, PDI+HVPS3 (0.2 mm/day), eMAS+ACR+APR-2 (0.2 mm/day)** — S03-3	
		Radiation:			
		Spectral Solar Flux	±3%	**SSFR** (3%, 0.5-7% for differentials) — S01-1 S02-2	
		Visible-SWIR Degree of Linear Polarization	±0.5%	**RSP** (0.2%), **AirMSPI** (0.5%) — S01-2 S02-2 S03-2	
		Visible, SWIR, Thermal IR Radiance / Brightness	±5-10% in radiance, ±0.5 K for IR	**eMAS** (5% in radiance, 0.5 K for mid- and window-IR, 1-2 K for 13+ μm) — S02-3	

Science Measurement Requirements

Parameter and Accuracy needed

Table 3.1-3. ORACLES Science Traceability Matrix (Table A.30-3)

Priority	Science Objectives	Scientific Measurement Requirements: Parameter	Scientific Measurement Requirements: Accuracy	Instrument Functional Requirements (bold font indic[illegible] that meet or exceed measurement requirements)		Investigation Functional Requirements (A = all)	
Threshold	**Aerosol direct effects:**	**Aerosol:**					
	S01-1 (Aerosol spatial evolution)	AOD at UV-VIS-SWIR	±0.02 or 5%	**4STAR** (0.01-0.02), **RSP** (0.02), AirMSPI, **HSRL-2** (0.01), eMAS, **AERONET** (0.01-0.02)	S01-1 S01-2		
	S01-2 (Aerosol-induced radiative fluxes)	AAOD at UV-VIS-SWIR	±0.02 for AOD>0.1	**4STAR** + **SSFR** (0.02), RSP, AirMSPI, HSRL,eMAS,**HiGEAR, AERONETT** (0.02)	S01-1 S01-2 S02-2	**Observations:** Intensive, multi-aircraft field campaigns	A A A
		Aerosol spectral refractive index at UV-VIS-SWIR	±0.02 for real part	4STAR + SSFR, RSP, AirMSPI, HSRL, eMAS, **AERONET** (0.02)	S01-1		
	S01-3 (Seasonal aerosol variation)	Aerosol/CCN size distribution, r_{eff}	±0.07 µm±7%	**HiGEAR** (10% number, 5% size), RSP	S01-1 S03-1	Measurements on routine flight track along 15°S, sampling at least 40 hrs (~200 100 km^2 model grid boxes) to enable statistical comparisons to climate models	S01-1 S03-1
		Aerosol number conc. profile	50%	**HiGEAR** (10%), HSRL-2	S01-1 S03-1		
	Aerosol semi-direct effects:	Chemical composition	Speciation (BC, volatile, refractory)	**HiGEAR-AMS** (35%), **SP2** (25%) RSP	S01-1 S03-1		
	S02-1 (Relative vertical distribution)	Aerosol extinction/absorption profile	±0.025 km^{-1} in ext	**HiGEAR** (0.005 in ext), **HSRL-2** (0.01 ext), 4STAR	S01-1 S02-1	Sampling that permits assessments of variability in aerosol and cloud properties within climate model grid cells (100 km^2) for multiple adjacent cells	A A A
		Single Scattering Albedo (SSA)(profile or layer)	±0.028	**HiGEAR** (0.03), HSRL-2, RSP, AirMSPI, **4STAR + SSFR** (0.02 in midvis), **AERONET** (~0.03)	S01-1 S01-2 S02-1 S02-2	3 airborne campaigns in different months of BB season	S01-3 S02-1 S03-1
	S02-2 (Aerosol-cloud heating rates)	**Gases:**					
		CO, CO_2, H_2O, O_3	±10 ppbv CO	**COMA** (2 ppbv CO), facility, HiGEAR	S03-1 S01-1	*In situ* and remote sensing obs of aerosol layers above (and entrained into) low-level Sc deck	A A A
		Cloud/Drizzle/Precipitation:					
	S02-3 (Cloud changes due to aerosol-induced heating)	Cloud fractional cover	±0.05	**eMAS (0.05), ACR+APR-2, AirMSPI (0.05), MODIS/SEVIRI (0.05)**	S02-3 S01-2		
Baseline		Cloud top/bottom height	±100 m	**ACR+APR-2 (60 m), HSRL-2 (33 m), AirMSPI**	A S01-2	Coincident obs of underlying cloud macro- and microphysical properties	A A
		Particle Size Distribution/Composition	±20%	**CAPS-CAS , PDI** (20%), CVI, CDP	S02-2 S02-3 S03-2	Measurement of FT-to-PBL mixing	S03-1
	Aerosol indirect effects:	COD	±10%	**eMAS** (5-10%), **SSFR**, RSP, AirMSPI, 4STAR	S02-2 S02-3 S03-2 S03-3	**Modeling:** Large eddy simulations to integrate observations for process scale understanding of aerosol-cloud interactions.	A A
	S03-1 (Mixing survey)	r_{eff}	±20%	**eMAS** (10-20%), RSP, AirMSPI, SSFR, 4STAR, *in situ* **probes** (20%)			
	S03-2 (Cloud changes due to aerosol mixing)	Liquid water content (LWC/LWP)	±0.05 g m^{-3} / 10 g m^{-2}	**King probe, CAPS-LWC, PDI** (20% LWC), **ACR+APR-2** (10 gm^{-2} LWP)	S02-3 S03-2 S03-3	Regional chemistry-aerosol climate modeling for field planning, to integrate observations to constrain direct, semi-direct and indirect effects, and to separate aerosol and meteorological effects on clouds	A A A
		Thermodynamics		Facility	S02-3		
	S03-3 (Cloud changes due to aerosol-suppressed precipitation)	Precipitation microphysics/rate	±0.4 mm/day (rate)	**2D-S, CAPS-CIP, PDI+HVPS3 (0.2 mm/day), eMAS+ACR+APR-2 (0.2 mm/day)**	S03-3		
		Radiation:				Global climate modeling to determine impacts of BB aerosols on radiation budget and global circulation	A A A
		Spectral Solar Flux	±3%	**SSFR** (3%, 0.5-7% for differentials)	S01-1 S02-2		
		Visible-SWIR Degree of Linear Polarization	±0.5%	**RSP** (0.2%), **AirMSPI** (0.5%)	S01-2 S02-2 S03-2		
		Visible, SWIR, Thermal IR Radiance / Brightness	±5-10% in radiance, ±0.5 K for IR	**eMAS** (5% in radiance, 0.5 K for mid- and window-IR, 1-2 K for 13+ µm)	S02-3		

Instrument Functional Requirements

What Instrument meets requirements

Table 3.1-3. ORACLES Science Traceability Matrix (Table A.30-3)

Priority	Science Objectives	Scientific Measurement Requirements: Parameter	Scientific Measurement Requirements: Accuracy	Instrument Functional Requirements (**bold** font indicates instruments that meet or exceed measurement requirements)	
Threshold	**Aerosol direct effects:** S01-1 (Aerosol spatial evolution) S01-2 (Aerosol-induced radiative fluxes) S01-3 (Seasonal aerosol variation) **Aerosol semi-direct effects:** S02-1 (Relative vertical distribution) S02-2 (Aerosol-cloud heating rates) S02-3 (Cloud changes due to aerosol-induced heating)	**Aerosol:**			
		AOD at UV-VIS-SWIR	±0.02 or 5%	**4STAR** (0.01-0.02), **RSP** (0.02), AirMSPI, **HSRL-2** (0.01), eMAS, **AERONET** (0.01-0.02)	S01-1 S01-2
		AAOD at UV-VIS-SWIR	±0.02 for AOD>0.1	**4STAR** + **SSFR** (0.02), RSP, AirMSPI, HSRL, eMAS, **HiGEAR, AERONETT** (0.02)	S01-1 S01-2 S02-2
		Aerosol spectral refractive index at UV-VIS-SWIR	±0.02 for real part	4STAR + SSFR, RSP, AirMSPI, HSRL, eMAS, **AERONET** (0.02)	S01-1
		Aerosol/CCN size distribution, r_{eff}	±0.07 μm±7%	**HiGEAR** (10% number, 5% size), RSP	S01-1 S03-1
		Aerosol number conc. profile	50%	**HiGEAR** (10%), HSRL-2	S01-1 S03-1
		Chemical composition	Speciation (BC, volatile, refractory)	**HiGEAR-AMS** (35%), **SP2** (25%) RSP	S01-1 S03-1
		Aerosol extinction/absorption profile	±0.025 km^{-1} in ext	**HiGEAR** (0.005 in ext), **HSRL-2** (0.01 ext), 4STAR	S01-1 S02-1
		Single Scattering Albedo (SSA)(profile or layer)	±0.028	**HiGEAR** (0.03), HSRL-2, RSP, AirMSPI, **4STAR + SSFR** (0.02 in midvis), **AERONET** (~0.03)	S01-1 S01-2 S02-1 S02-2
		Gases:			
		CO, CO_2, H_2O, O_3	±10 ppbv CO	**COMA** (2 ppbv CO), facility, HiGEAR	S03-1 S01-1
		Cloud/Drizzle/Precipitation:			
		Cloud fractional cover	±0.05	**eMAS (0.05), ACR+APR-2, AirMSPI (0.05), MODIS/SEVIRI (0.05)**	S02-3 S01-2
Baseline	**Aerosol indirect effects:** S03-1 (Mixing survey) S03-2 (Cloud changes due to aerosol mixing) S03-3 (Cloud changes due to aerosol-suppressed precipitation)	Cloud top/bottom height	±100 m	**ACR+APR-2 (60 m), HSRL-2 (33 m), AirMSPI**	A S01-2
		Particle Size Distribution/Composition	±20%	**CAPS-CAS**, **PDI** (20%), CVI, CDP	S02-2 S02-3 S03-2
		COD	±10%	**eMAS** (5-10%), **SSFR**, RSP, AirMSPI, 4STAR	S02-2 S02-3 S03-2 S03-3
		r_{eff}	±20%	**eMAS** (10-20%), RSP, AirMSPI, SSFR, 4STAR, *in situ* **probes** (20%)	
		Liquid water content (LWC/LWP)	±0.05 g m^{-3} / 10 g m^{-2}	**King probe, CAPS-LWC, PDI** (20% LWC), **ACR+APR-2** (10 gm^{-2} LWP)	S02-3 S03-2 S03-3
		Thermodynamics		Facility	S02-3
		Precipitation microphysics/rate	±0.4 mm/day (rate)	**2D-S, CAPS-CIP, PDI+HVPS3 (0.2 mm/day), eMAS+ACR+APR-2 (0.2 mm/day)**	S03-3
		Radiation:			
		Spectral Solar Flux	±3%	**SSFR** (3%, 0.5-7% for differentials)	S01-1 S02-2
		Visible-SWIR Degree of Linear Polarization	±0.5%	**RSP** (0.2%), **AirMSPI** (0.5%)	S01-2 S02-2 S03-2
		Visible, SWIR, Thermal IR Radiance / Brightness	±5-10% in radiance, ±0.5 K for IR	**eMAS** (5% in radiance, 0.5 K for mid- and window-IR, 1-2 K for 13+ μm)	S02-3

Investigation Functional Requirements (A = all)

Observations:
- Intensive, multi-aircraft field campaigns — A A A
- Measurements on routine flight track along 15°S, sampling at least 40 hrs (~200 100 km^2 model grid boxes) to enable statistical comparisons to climate models — S01-1 S03-1
- Sampling that permits assessments of variability in aerosol and cloud properties within climate model grid cells (100 km^2) for multiple adjacent cells — A A A
- 3 airborne campaigns in different months of BB season — S01-3 S02-1 S03-1
- *In situ* and remote sensing obs of aerosol layers above (and entrained into) low-level Sc deck — A A A
- Coincident obs of underlying cloud macro- and microphysical properties — A A
- Measurement of FT-to-PBL mixing — S03-1

Modeling:
- Large eddy simulations to integrate observations for process scale understanding of aerosol-cloud interactions. — A A
- Regional chemistry-aerosol climate modeling for field planning, to integrate observations to constrain direct, semi-direct and indirect effects, and to separate aerosol and meteorological effects on clouds — A A A
- Global climate modeling to determine impacts of BB aerosols on radiation budget and global circulation — A A A

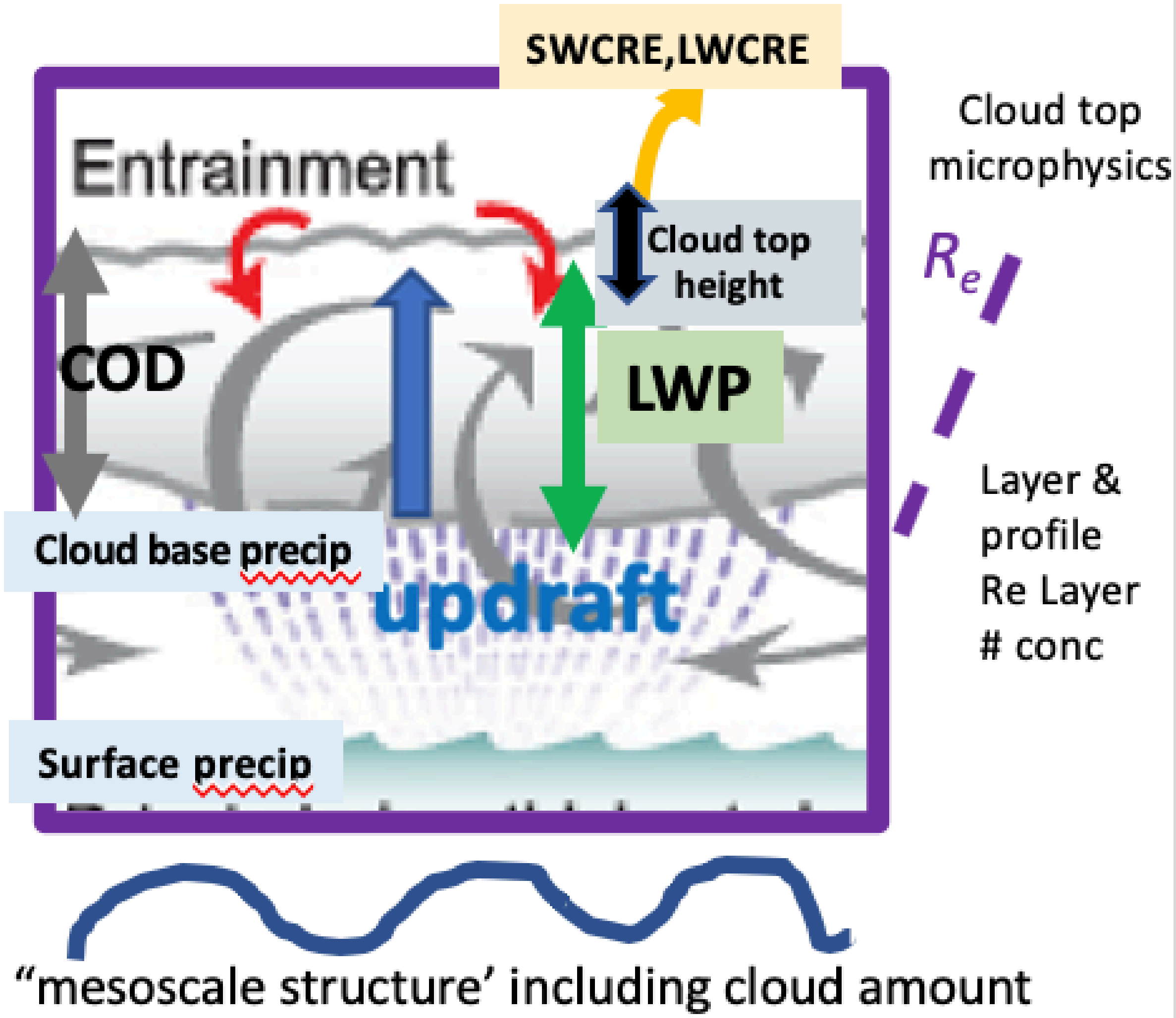
Investigation Functional Requirements

What flight tracks needed (or related modeling, satellite studies)

Science Questions: ACI and low clouds

- How do vertical distributions of aerosols affect cloud formation and evolution?
  - How can effects due to variation in meteorology be separated from aerosol effects?
- How is precipitation initiated in shallow cumulus clouds in 30-minute time periods?
- In mixed-phase clouds, what controls depth, amount & longevity of supercooled liquid water & initiation of ice?
  - Why do mixed-phase clouds persist?
  - What is role of secondary ice production processes & what controls development of precipitation?
- What controls open-closed cell transitions in Sc?

Science Questions: ACI and low clouds



- **Need high frequency data on cloud, aerosol, precipitation, radiative & surface fluxes**
- **Profiles through boundary layer and free troposphere**
- **Statistical sampling in multiple aerosol & meteorological regimes at different stage of evolution**

Aerosol Indirect Effects: Low Clouds

- **Measurement Requirements:**
  - Vertical profiles of aerosols in vicinity of cloud and their activation properties
    - CCN, INPs, Aerosol PSDs, composition/hygroscopicity, optical depth, scattering and absorption properties, mixing scenarios in both boundary layer & free troposphere
  - Environmental properties that control aerosol activation
    - Vertical velocity, in-cloud supersaturation, activation spectra (CCN = f(SS), INP = f(Ssi, T), turbulent fluxes of energy and moisture, vertical profile of boundary layer structure, 3-d winds for dynamics, high frequency T, q, w, u, v
  - Cloud size-resolved and bulk properties
    - Vertical profiles of bulk LWC and TWC, bulk extinction, size, shape and phase distributions of cloud particles, precipitation, spacing of cloud particles (homogeneous/inhomogeneous mixing), cloud fraction, high-resolution images, single particle scattering
  - Radiative Properties
    - Broadband up and down irradiance, high resolution spectral up and down, broadband and spectral albedo, cloud optical depth
  - Multi-wavelength/polarimetric remote sensing data to give context of observations

Aerosol Indirect Effects: Convective Clouds

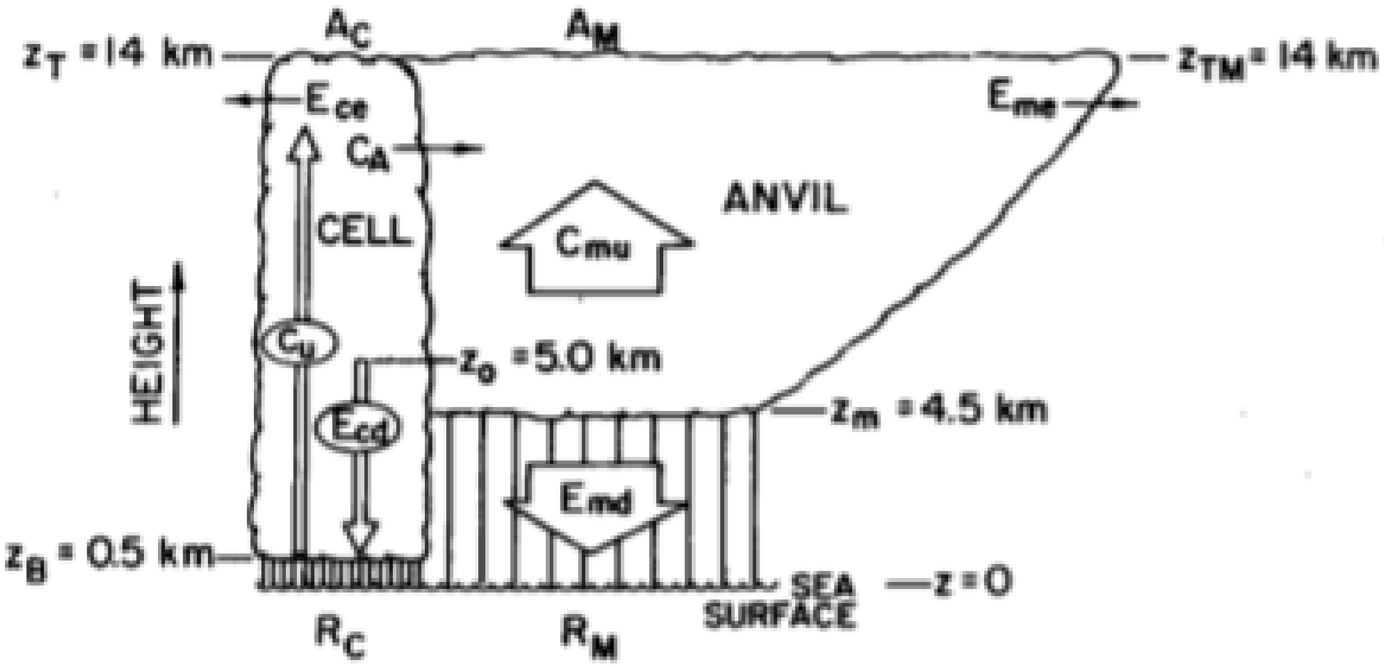


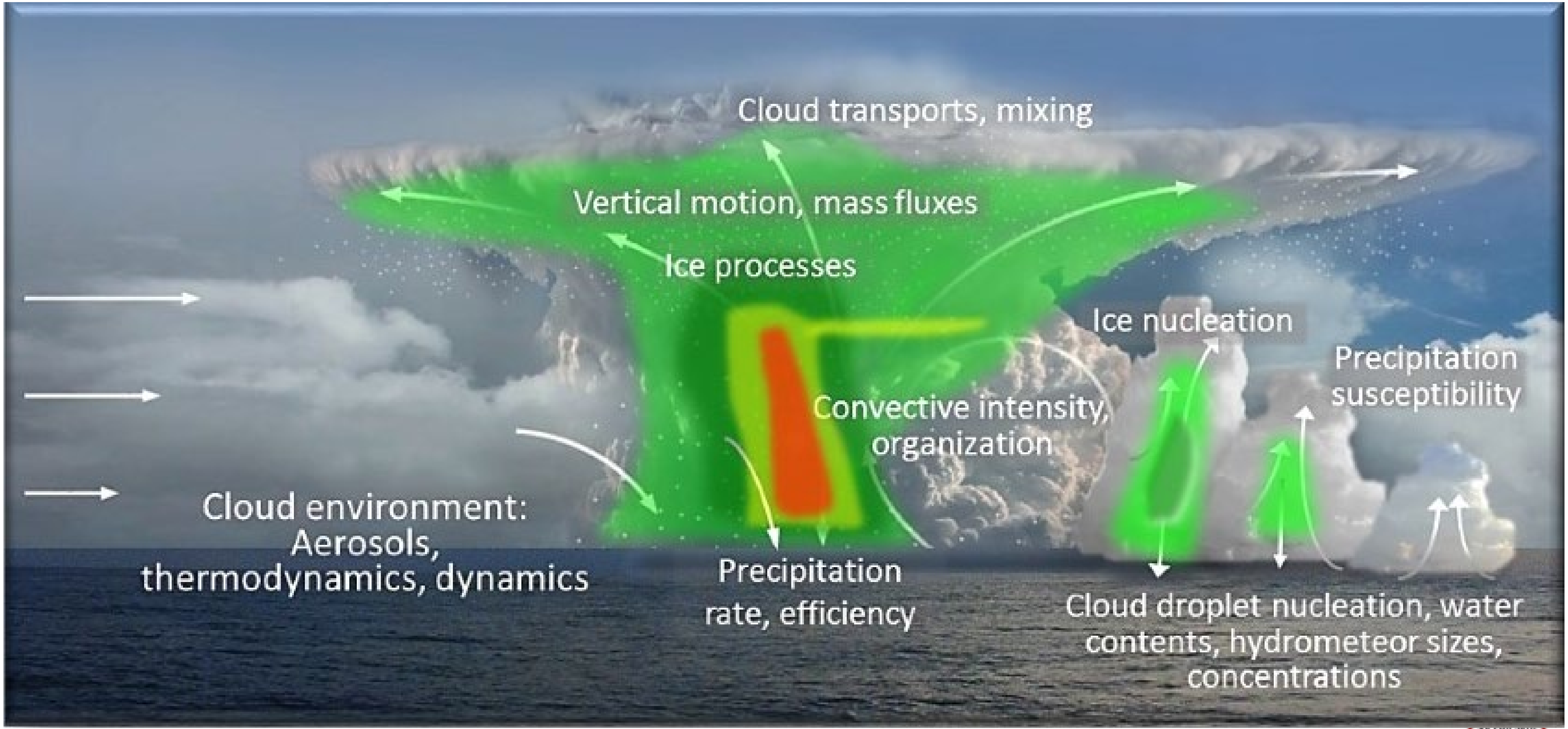
FIG. 2. Schematic vertical cross section of the idealized mesoscale system showing sources and sinks of condensed water. Symbols are defined in Section 2 of the text.

Leary and Houze 1980

Science Questions: ACI and convective clouds

- **How are the properties of anvil clouds generated coupled to that of convection producing them?**
  - **How are convective properties coupled to environmental conditions?**
  - **How will properties of clouds/convection vary in a warming environment?**
  - **What controls evolution of cirrus (anvil/cirrus evolution)?**
- **What is impact of aerosols on convective evolution and on deep clouds?**
- **What controls precipitation efficiency?**
- **To what extent can seeding of clouds impact precipitation?**

Aerosol Indirect Effects: Convective Clouds

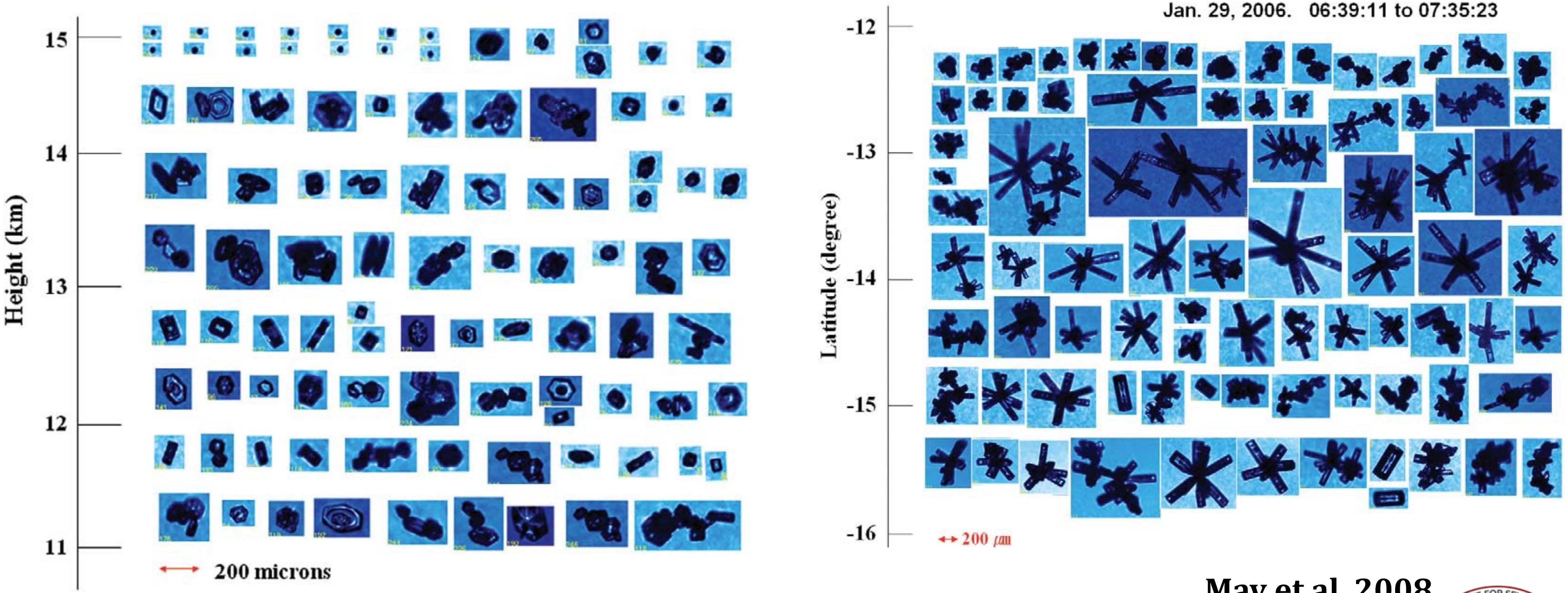


Aerosol Indirect Effects: Convective Clouds

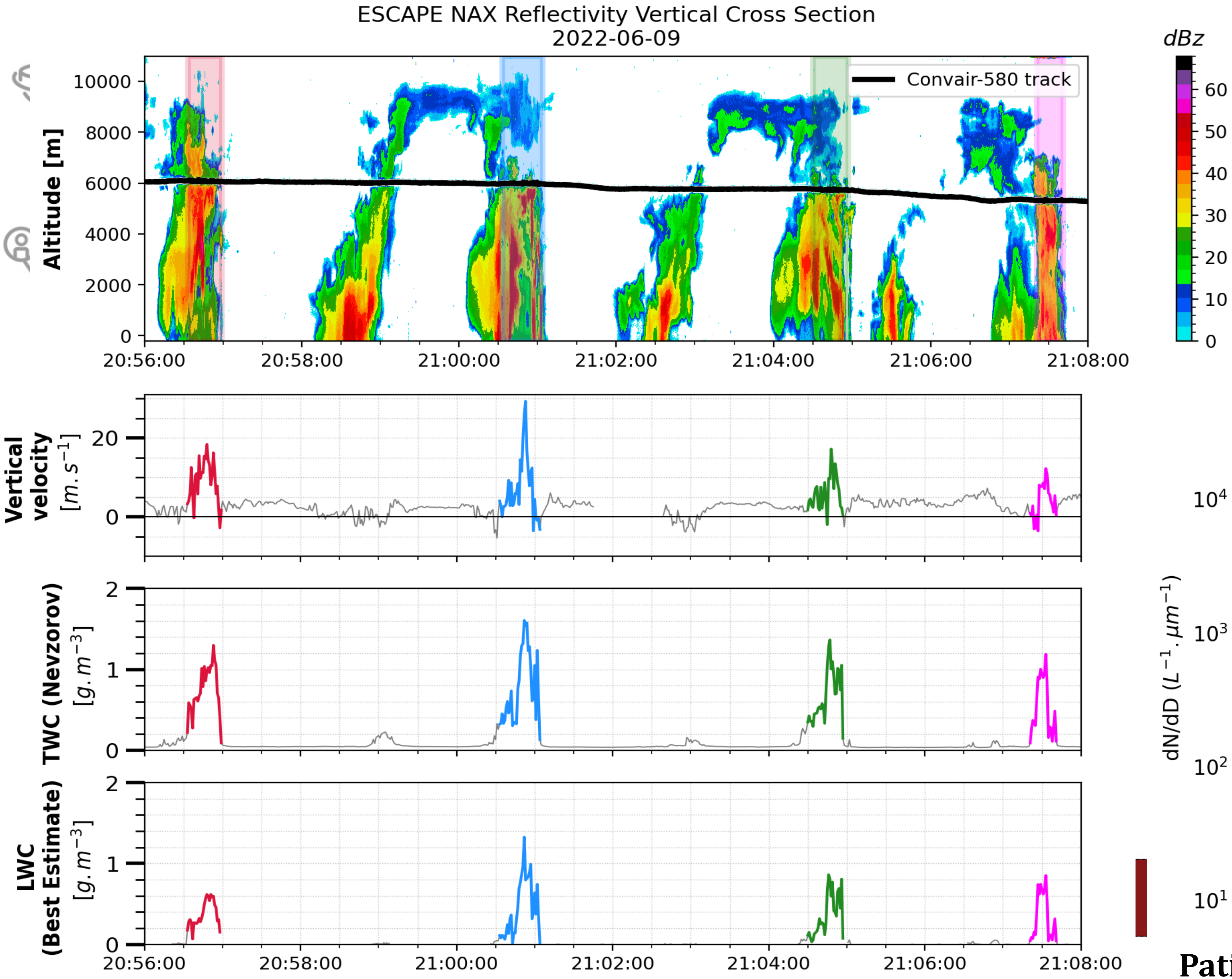
- **Measurement Requirements:**
  - Environmental conditions
    - Large-scale and small-scale environmental thermodynamics and kinematics, surface properties & fluxes, mesoscale structure, T, q, u, v, w, cloud top T,
  - Convective core properties
    - Age of convection, size of core, height of maximum vertical motion, magnitude of vertical motion, ice mass flux, Maximum Z, position from fronts, cloud cover, cloud top phase, lightning, melting layer height
  - Cloud size-resolved and bulk properties
    - Vertical profiles of bulk LWC and TWC, bulk extinction, size, shape and phase distributions of cloud particles, scattering properties, spacing of cloud particles (homogeneous/inhomogeneous mixing), ice water path, derived microphysical property rates
  - Aerosol Properties
    - Aerosol loading and properties, CCN, INP, Aerosol SDs, scattering properties, hygroscopicity, Angstrom exponent, AOD
  - Radiative Properties
    - Broadband up and down irradiance, high resolution spectral up and down, broadband and spectral albedo, cloud optical depth
  - Remote Sensing
    - Multi-wavelength/polarimetric data required to give context (phased array radar?)

Aerosol Indirect Effects: Convective Clouds

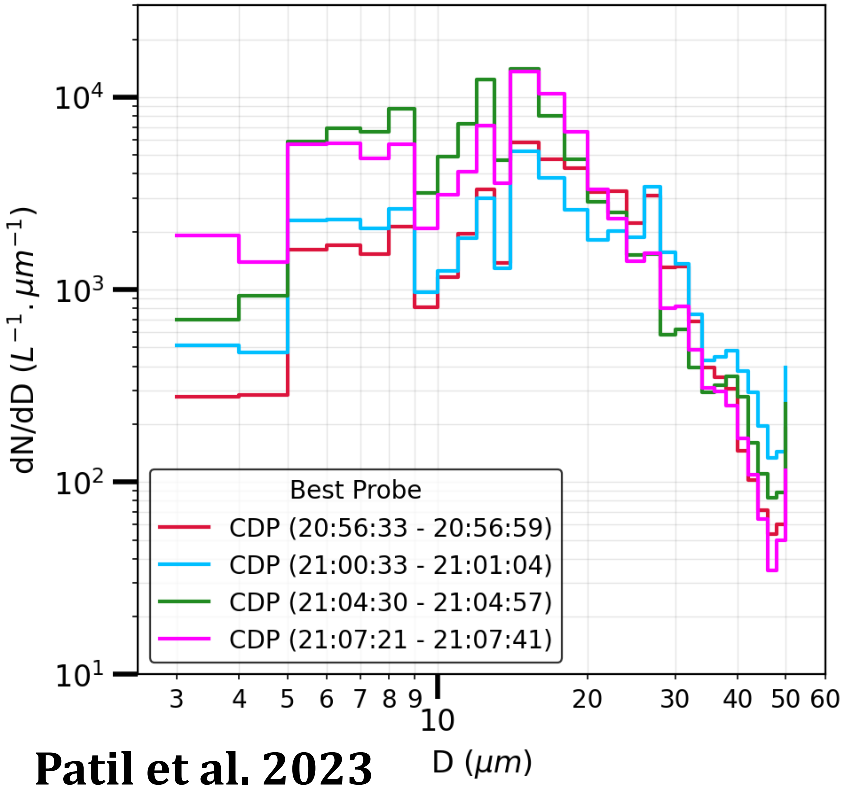
- **What controls evolution of microphysics from fresh anvil to aged anvil?**



May et al. 2008



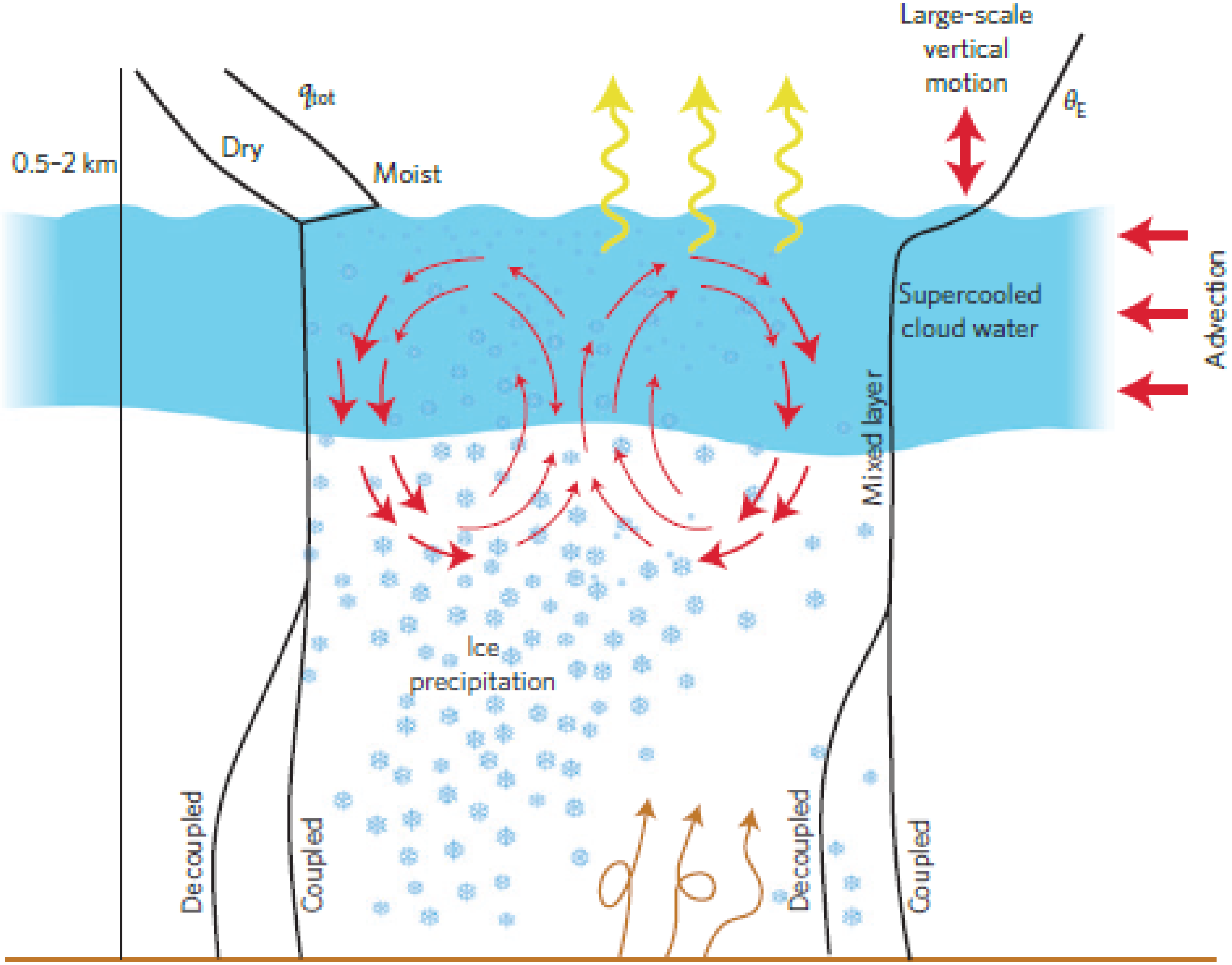
Especially need observations in intense updrafts such as these 30 m s^{-1} updrafts sampled during ESCAPE



Patil et al. 2023

Mixed-Phase Clouds

Morrison et al. 2012



Radiative Cooling
- Drives buoyant production of turbulence
- Forces direct condensation within inversion layer
- Requires minimum amount of cloud liquid water

Microphysics
- Liquid forms in updrafts and sometimes within the inversion layer
- Ice nucleates in cloud
- Rapid ice growth promotes sedimentation from cloud

Dynamics
- Cloud-forced turbulent mixed layer with strong narrow downdrafts, weak broad updrafts, and q_{tot} and θ_E nearly constant with height
- Small-scale, weak turbulence in cloudy inversion layer
- Large-scale advection of water vapour important

Surface Layer
- Turbulence and q contributions can be weak or strong
- Sink of atmospheric moisture due to ice precipitation
- Surface type (ocean, ice, land) influences interaction with cloud

Figure 3 | A conceptual model that illustrates the primary processes and basic physical structure of persistent Arctic mixed-phase clouds. The main features are described in text boxes, which are colour-coded for consistency with elements shown in the diagram. Characteristic profiles are provided of total water (vapour, liquid and ice) mixing ratio (q_{tot}) and equivalent potential temperature (θ_E). These profiles may differ depending on local conditions, with dry versus moist layers/moisture inversions above the cloud top, or coupling versus decoupling of the cloud mixed layer with the surface. Cloud-top height is 0.5–2 km. Although this diagram illustrates many features, it does not fully represent all manifestations of these clouds.

Mixed-Phase Clouds

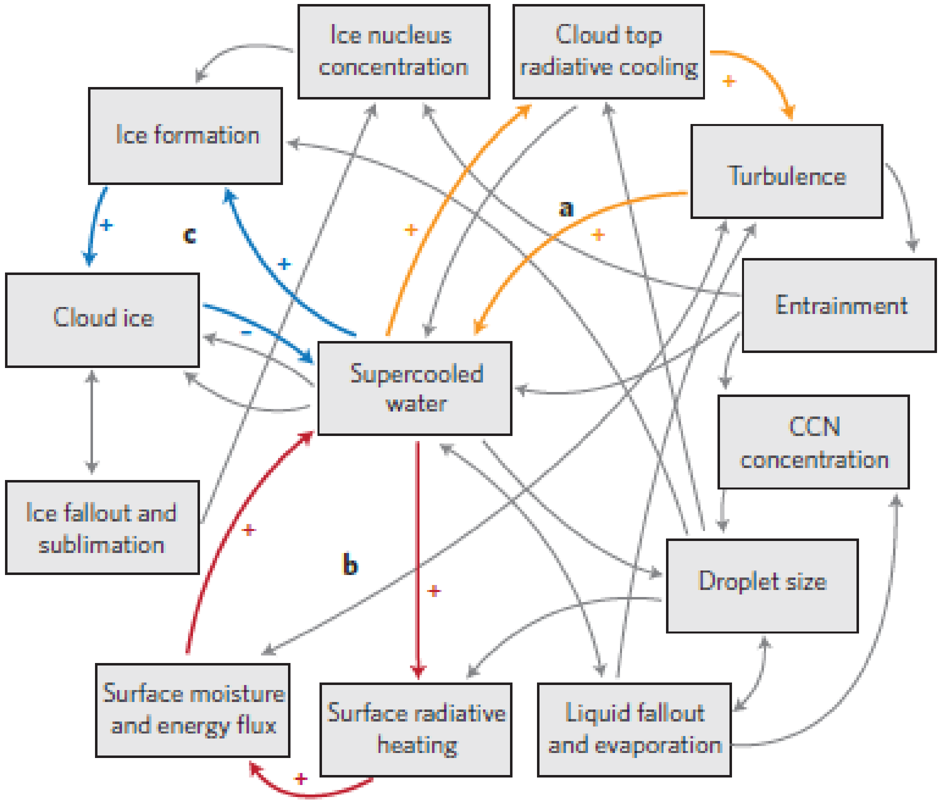


Figure 2 | Processes associated with Arctic mixed-phase clouds are linked through a complex web of interactions and feedbacks. In this diagram, the arrows signify the direction of influence of interactions between various physical quantities and processes. Not all important associations are included. Three specific interaction pathways (labelled a, b and c) are highlighted by coloured arrows and discussed in greater depth in the text. Signs (+ or -) indicate the expected response (increase or decrease) of the receiving element.

Morrison et al. 2012

- **Need to make measurements of physical properties that affect all these properties!**
  - **Similar to what previously listed, with special emphasis on transitions between phases and development of precipitation**
  - **Supercooling**
  - **Lagrangian transitions of air masses (how aerosols evolve and effect cloud, and feedback on clouds and precipitation)**
  - **Vertical profiles M(D), V(D), ρ(D), habit distribution and variability**
  - **Scattering/absorption properties at multiple λ**
  - **Precipitation rate/remote sensing**
  - **Environmental characteristics (large-scale and mesoscale)**

Where can we improve?

- In-situ measurements in deep convection
  - Critically needed for evaluating remote sensing retrievals and process studies
- Routine deployment of UAS
  - Routine statistics and 3-d mesonet
  - Ability to measure in lower boundary layer
  - Swarms of UAS to make measurements in multiple locations simultaneously
- Lagrangian sampling
  - Eulerian sampling is good for determining what properties are present, but falls short on deducing processes responsible for those properties
- Funding limitations
  - Perceived pressure to keep project small to maximize changes of success
  - Need multiple measurements (aerosols including composition, clouds, remote sensing) to get complete picture of processes
  - Are good projects not being funded due to aircraft/funding availability?
- Accurate measurements of humidity/supersaturation inside cloud
  - Needed to test invigoration hypothesis proposed by Rosenfeld/Fan

Where can we improve?

- Measurements of single-particle mass and fall velocity
    - m(D) and V(D) relations for ice crystals critical for model development
- Measurements of small ice crystals
    - Progress in understanding crystal shattering and depth of field limitations has been made, but high temporal resolution of ice crystals with D < 100 μm are still problematic (holographic & single-scattering probes help)
- Understanding cloud probes
    - Multiple analysis packages exist, and can give different results
    - Needs to be some standardization/benchmarking
    - Impact of cloud probe mounting location uncertain
- Observations over oceans
    - Coastal areas not representative of oceanic regions

Where can we improve?

- High Temporal/Spatial Frequency Observations
  - Many processes take place on fine time scales, and there can be significant inhomogeneities in fine spatial scales (e.g., turbulence and entrainment mixing very important)
  - Resolve homogeneous vs. inhomogeneous mixing
  - Fine-scale mixing of mixed-phase clouds
- Laboratory studies
  - Useful for supplementing field observations because can be better able to understand temporal evolution of processes
- Undersampled regions in world
  - Southern Ocean, polar regions, African continent, tropical oceans, wildfires, cryosphere interactions
  - Always need meteorological context of observations
- Capacity building
  - Need to engage early career scientists/grad students in all aspects of project (design, data collection, analysis)
  - Need to ensure funding and seats on aircraft

Aerosol Indirect Effects: Convective Clouds

- Goal:
  - Relate vertical motion within convective storms and associated cloud and precipitation structures to
    - Storm life cycle
    - Local environment thermodynamic and kinematic properties (T, q, wind shear)
    - Ambient aerosols
    - Surface properties
    - Latent heating profiles
    - Inflow → Convective drafts → microphysics → outflow characteristics → radiative effects
    - How does this contribute to transport of energy, heat and moisture
  - Coupling between vertical velocity, aerosols & microphysics
  - Convective detrainment and lifetime are also very important
  - Anvil cirrus life cycle