Objective 3: Storm Dynamics

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Outline

- **Background and Traceability to Decadal Survey**
- **Statement of Objective-3 and Overarching Science Questions**
- **Approach to addressing science objective**
  - **Geophysical Variables**
- **Desired Geophysical Variable Capabilities**
  - **Example observables**
- **Outstanding questions, work in progress**

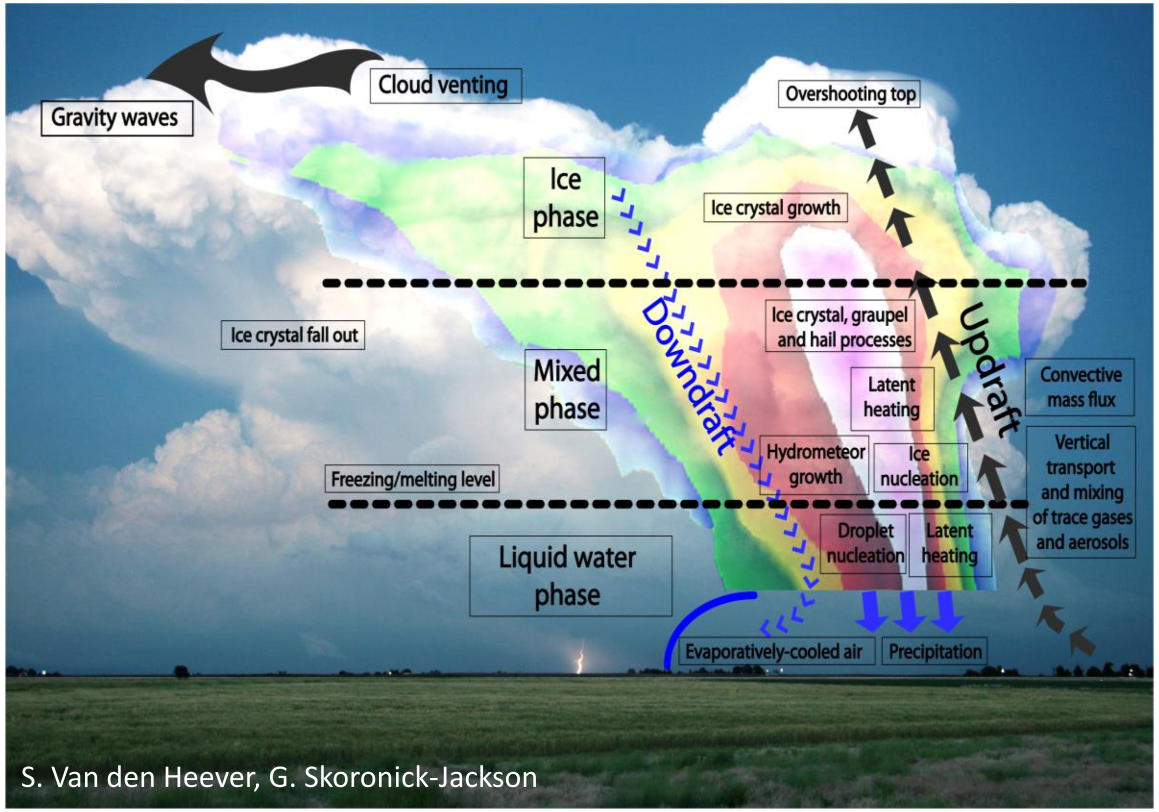
Overarching A-CCP Goal	A+CCP	A	CCP	2017 DS Most Important Very Important	Goals
Understand the processing of water and aerosol through the atmosphere and develop the societal applications enabled from this understanding.				C-2a,C2g, W-1a, W-2a	**G1** Cloud Feedbacks Reduce the uncertainty in low- and high-cloud climate feedbacks by advancing our ability to predict the properties of low and high clouds.
				C-2a* C-2g, C2-h*, C-5c*, H-1b, W-1a*, W-2a*, W-4a	**G2** Storm Dynamics Improve our physical understanding and model representations of cloud, precipitation *and dynamical processes* within storms.
				H-1b, W1-a, W-3a, S-4a	**G3** Falling Snow Quantify the rate of falling snow at middle to high latitudes to advance understanding of its role in cryosphere-climate feedbacks.
				W-1a, W-5a, C-5a	**G4** Aerosol Processes Reduce uncertainty in key processes that link aerosols to weather, climate and air quality related impacts.
		D I		C-2h, C-5c	**G5** Aerosol Radiative Forcing Reduce the uncertainty in Direct (D) and Indirect (I) aerosol-related radiative forcing of the climate system.

Goal only fully realizable via combined mission.

A or CCP makes meaningful contribution to goal

A-CCP Aerosols and Clouds-Convection-Precipitation Study

Goal 2: Storm Dynamics Background



Climate: Convective clouds and associated processes are *fundamental to Earth system* transports/exchanges of fresh water, mass, and energy, between the surface and atmosphere.

Modeling and Prediction: Global NWP at cloud resolving scales is imminent……However, weaknesses exist in representations of coupled convective dynamic (drafts) and microphysical *processes*:

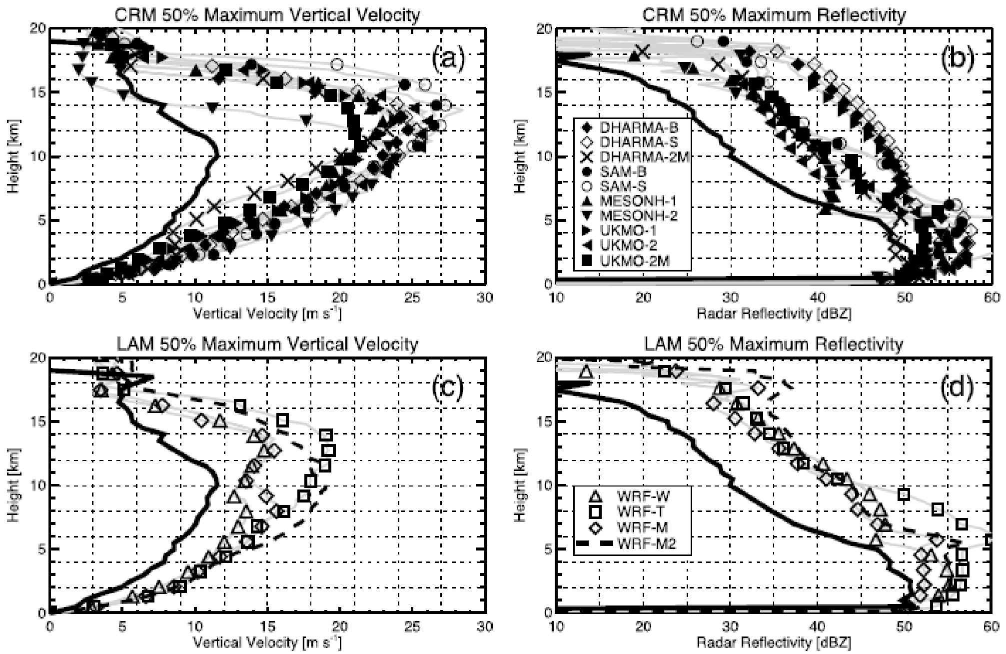
Documented impacts on precipitation initiation, intensity, frequency, and location, transports, diabatic heating, storm intensity, lifecycle, and organization, and cloud feedbacks in the climate system.

Priority: Improve global observation of the fundamental process **coupling** between convective cloud **vertical motion** (dynamics), **microphysics**, and **precipitation** production across a **full range of cloud environments (including aerosol background) and meteorological regimes**

A-CCP Aerosols and Clouds-Convection-Precipitation Study

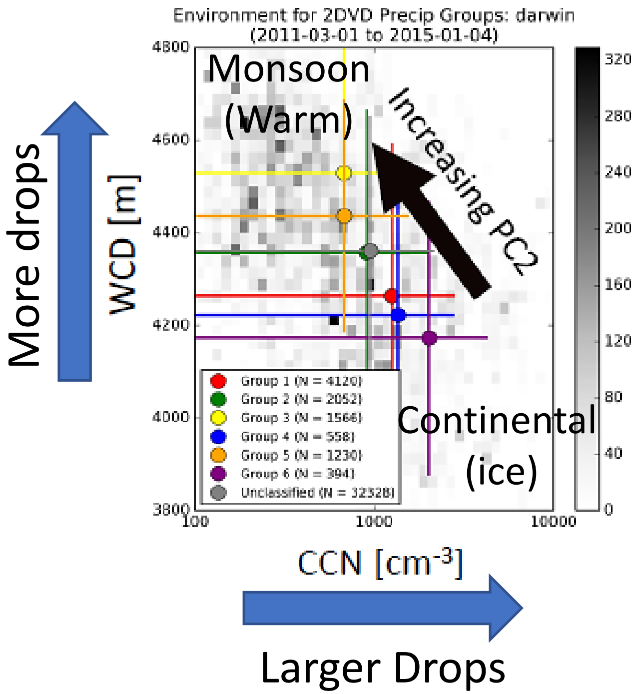
Goal 2: Storm Dynamics Background

Poor updraft prediction impacts microphysics

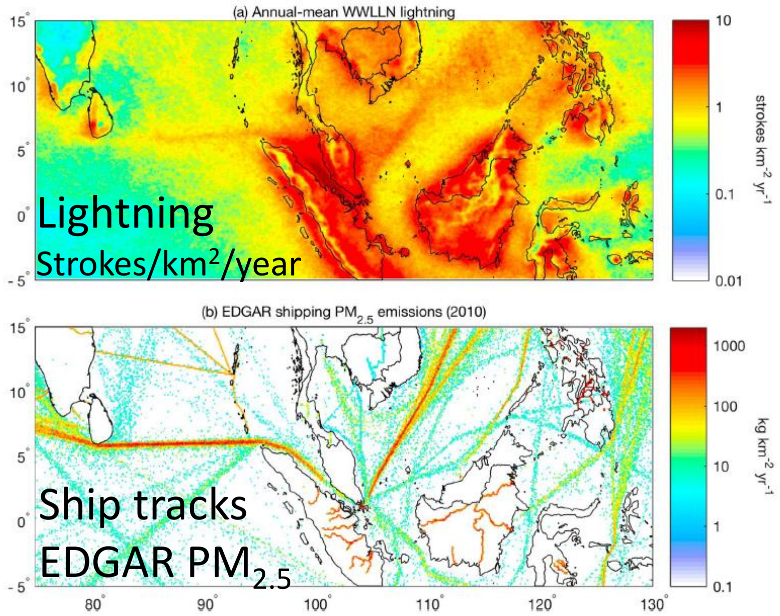


"Therefore, *overly intense simulated updrafts* may additionally be a product of unrealistic *interactions between convective dynamics, parameterized microphysics*……." Varble et al., 2014 JGR.

Regime and Aerosol Modification of Convective Processes?



Precipitation size distribution varies with convective regime as does aerosol…..Dolan et al. 2018 (AGU).



Thorton et al., 2017 GRL.

CAPE+precipitation studies do not *conclusively* explain ocean-land lightning difference.

How does aerosol alter convective physical processes (microphysics, dynamics)?

A-CCP Aerosols and Clouds-Convection-Precipitation Study

Goal 2 Broader Context: Trace to Decadal Survey Topics

- Weather
  - Overarching needs for *coupled Earth system model evolution* and improved weather, climate prediction:
    - Observations of *moist convection and precipitation processes* on convective scales
    - Observations to assess *impacts of convective organization on the larger circulation* (sub/seasonal prediction)
      - **W-1a** Boundary layer process impacts on weather, hydrologic, and air quality forecasts.
      - **W-4a** Measure *vertical motion in deep convection, heavy precipitation rates* to *improve model forecasts* of extreme precipitation, convective *transports*/redistribution of mass, moisture, momentum, chemical species.
      - **W-2a** Improved prediction of natural low-frequency modes of weather/climate variability tied in part to improved *process* understanding, assimilation/*models* of convection, mesoscale organization, circulation impact
- Climate:
  - Uncertainties in climate forcing and sensitivity associated with cloud feedbacks
    - Connect *cloud and convection processes* to atmospheric circulation
    - Improved understanding/representation of *affects of aerosols* on clouds and climate response
      - **C-2a** High cloud feedbacks ("shaped by *convective processes*", coupling of cloud, precipitation, aerosols)
      - **C-2g** Quantify the contribution of the UTLS to climate feedbacks and change (how composition changes affect)
      - **C-2h, 5c** Quantify the effect that aerosol has on cloud (indirect aspects).
- Hydrologic Cycle and Water Resources
  - Coupling of water and energy cycles in the context of a dynamic "Earth systems approach"
    - **H-1b** Quantify rates of *precipitation, phase (rain and snow/ice),* worldwide, convective and orographic scales…….

Storm Dynamics: Science Question and Objective 3

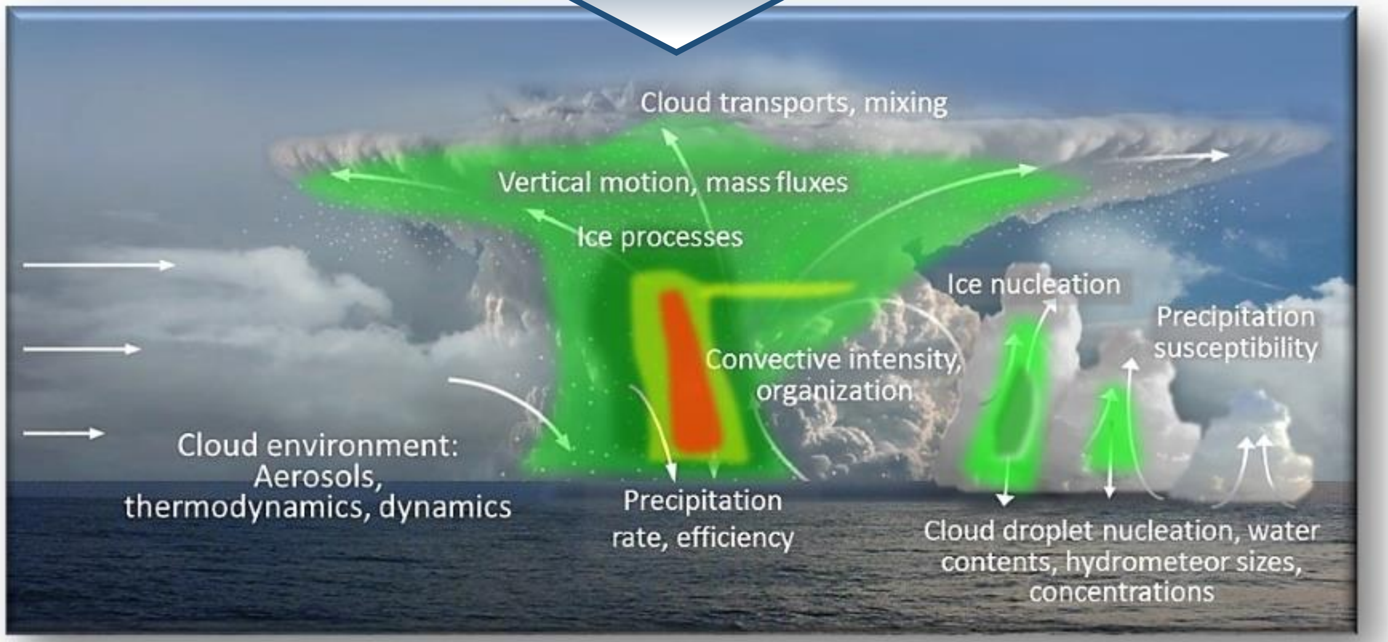
A+CCP	A	CCP	Goal	Example Science Question	Objectives
			G2 Storm Dynamics *Improve our physical understanding and model representations of cloud, precipitation and dynamical processes within storms.*	*How do different convective storm systems contribute to the vertical mixing and transports of heat, water, and other constituents within the atmosphere and how do these transports relate to the cloud and precipitation properties of storms?*	**O3** Convective Storm Systems **Minimum:** Relate vertical motion within convective storms and their cloud- and precipitation-structures to a) storm life cycle, b) local environment thermodynamic and kinematic factors such as temperature, humidity, and vertical wind shear, c) ambient aerosols, and d) surface properties. **Enhanced**: Relate vertical motion within convective storms and their cloud- and precipitation-structures to a) **latent heating profiles**, b) storm life cycle, c) local environment thermodynamic and kinematic factors such as temperature, humidity, and vertical wind shear, d) ambient aerosols, and e) surface properties.

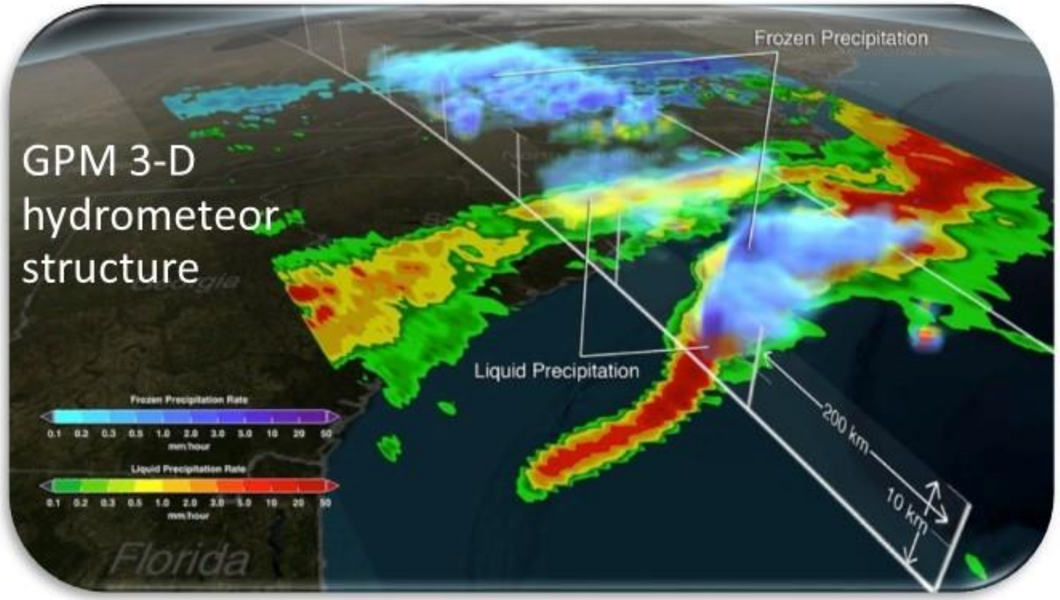
A-CCP Aerosols and Clouds-Convection-Precipitation Study

Storm Dynamics Approach

Advance from reflectivity profile/structure "snapshots" and mapping requirements for precipitation rate (TRMM, CloudSat, GPM) to measure **observational proxies for coupled dynamic and microphysical *processes***

"Processes"- physics that evolve convective cloud systems in the context of impacts on atmospheric circulation and composition; e.g., environment - updraft - cloud - precipitation - downdrafts - storm organization - diabatic heating - transports/detrainment





Key geophysical observation(s): Coincident global ***convective-scale vertical motion (Doppler or related proxy)*** column hydrometeor structure, precipitation rate, phase, and type, surrounding aerosol profile, set in context of PoR convective storm coverage and tendency, and dynamic and thermodynamic environments.

Program of Record

Mission	Orbit	Objective-3 Related Sensors	Agency	Ops Years
GPM	LEO (407 km) 65º incl.	Radar: DPR (Ka, Ku-Band) Microwave radiometer (imager): GMI (10-183 GHz)	NASA, JAXA	2014-2032 (+/-5)
EarthCARE* *Depends on launch date	LEO (393 km) Polar	Radar: CPR (W-Band, Doppler) / Lidar: ATLID (355 nm; HSRL) Vis/IR: MSI (0.67 - 12.0 μm, 7 channel)	ESA, JAXA	2021(?)-2026*
NOAA 20*, JPSS (2-4) *7-year design life	LEO (824 km) Polar	Microwave radiometer (sounder): ATMS (23.8 - 183 GHz) Vis/IR: VIIRS (412-12 μm, 22 bands) IR Sounder: CrIS	NOAA/NASA/ EUMETSAT	2017 - 2038
EPS/MetOP-SG-A 1-3	LEO (835 km) Polar	Microwave radiometer (sounder): MWS (23.8 - 229 GHz) IR Sounder: IASI-NG (3.62-15.5 μm; 12 bands) Vis/IR: MetImage (0.343 - 13.3 μm; 20 channels) Polarimeter: 3MI (0.41 - 2.1 μm)	EUMETSAT/CNES/ ESA	2022 - 2042
EPS/MetOP-SG-B 1-3	LEO (835 km) Polar	Microwave radiometer (imager): MWI (18.7 - 183.3 GHz) ICI (183 - 664 GHz)	EUMETSAT/CNES/ ESA	2022 - 2042
WSF-M	LEO, Polar	Microwave radiometer (imager)- Modified GMI	DoD	2022 - (?)
GOES 16-19	GEO	Vis/IR: ABI(0.47-13.3 μm;16 channels) Lightning:GLM (Optical .777 μm)	NOAA/NASA	2017 - 2038
Himawari	GEO	Vis/IR: AHI (0.455 - 13.3 μm; 16 channels)	JMA	2014 - 2031
MTG I (1-4)	GEO	Vis/IR: FCI (0.44 -13.3 μm; 16 channels), Lightning: LI (Optical;.777 μm)	EUMETSAT/ESA	2021 - 2038
GEO-KOMPSAT (2A, 2B*)	GEO	Vis/IR: AMI (0.47 - 13.3 μm; 16 channels) *Vis/NIR: GOCI-II (0.38-0.87 mm + panchromatic; 13 channels)	KARI/KMA/NIER	2018 - 2029+

A+CCP	A	CCP	Objectives
			O3 Convective Storm Systems **Minimum:** Relate vertical motion within convective storms and their cloud- and precipitation-structures to a) storm life cycle, b) local environment thermodynamic and kinematic factors such as temperature, humidity, and vertical wind shear, c) ambient aerosols, and d) surface properties. **Enhanced:** Relate vertical motion within convective storms and their cloud- and precipitation-structures to a) **latent heating profiles**, b) storm life cycle, c) local environment thermodynamic and kinematic factors such as temperature, humidity, and vertical wind shear, d) ambient aerosols, and e) surface properties.

A+CCP Potential Enabled Applications

- PEA1 Severe Storm Forecasting & Modeling (NOAA, NCAR, Private Industry)
- PEA2 Aerosol & Precipitation Interaction (NWS, NOAA, CTM, AQ agencies)
- PEA3 Climate Modeling (NOAA, CTM, EPA, state AQ agencies, policy makers)
- PEA5 Geospatial Information & Analytics (IBM, DoD, public companies)
- PEA6 Aviation Industry and Safety: (NOAA, FAA, DoD, DoE, Volcanic DoE, Ash Advisory Centers, Airlines, private industry)
- PEA9 Hydrologic Modeling (FEWS NET, World Bank, FAO, USDA Resource/Mgmt comm.)
- PEA10 Agricultural Modeling & Monitoring (USDA, ClimateCorp, ag. Comm./planners)
- PEA11 Health & Ecological Forecasting & monitoring (CDC, NOAA, Red Cross, World Bank, public/private sector)
- PEA12 Disaster Monitoring, Modeling, & Assessment (FEMA, NOAA, Red Cross, FAO, US Army, reinsurance, NGOs)

A	CCP	ODO	POR	Potential – Enabled Apps	Geophysical Variables (Minimum / Enhanced)	Qualifiers
	√			1,2,3	Vertical air velocity	Above 5km, |>2 m/s|
√	√		(√)	1,2,3,5,6	Cloud top height	
√			(√)	1,2,3,5,6	Cloud top temperature	
	√		(√)	1,2,3,5,6,9-12	Precipitation rate profile	
	√		(√)	1,2,3,5,6,9-12	Precipitation phase profile	Liquid/mixed/frozen
	√		(√)	1,2,3,6	Cloud vertical structure	E.g., reflectivity-profile above 5 km
	√		(√)	1,2,3,5,6,9-12	Ice water path	
	√		(√)	1,2,3,5,6,9-12	Convective classification	Org./intensity/depth
	√		(√)	1,2,3,5,6,9-12	Stratiform/convective precipitation discrimination	Conv./Stratiform
			√		Cloud lifecycle categories	
			√		Diurnally resolved cloud cover and cloud top height	
√				1,2,3,5,6	Aerosol extinction profile	
√		S	(√)	1,2,3,5,6	AOD	Column, PBL
			√		Synoptic scale motion	Environmental shear
			√		Environmental thermodynamic profiles	
	√		(√)	1,3	Latent heating profile	Instantaneous estimate
	√		(√)	1,2,3,5,6,9-12	Precipitation particle size	
	√		(√)		2D Surface Precipitation Rate	Mapped precip. rate
	√			1,2,3,5,6,9-12	Convective core size	
√				1,2,3,5,6	Aerosol effective radius	Profile
√				1,2,3,5,6	Aerosol non-sphericity	Profile & column
√				1,2,3,5,6	AAOD	Profile
			√		Lightning	

O3 Convective Storm Systems Geophysical Variables (1 of 3)	Desired Capability						Examples of Observables	Notes
	Range	Uncertainty	Scales					
			XY	Z	T	Swath		
Minimum / Enhanced	IMPORTANT: ***Desired Capabilities and Observables are preliminary***. Click here for additional information.							
Vertical air velocity	2-25 m/s 2-50 m/s	2 m/s	3 km 1 km	250 m	Instantaneous*	Nadir 20 km	Doppler shifted radial velocity, time differenced reflectivity (ΔZ~2 dBZ, 90sec); Height ≥ 5 km	Δx resolution marginal for convective updraft; capture mean level at/or above maximum mass flux; (E) will enable either or both improved sampling, resolution, and/or limited scan.
Cloud top height	6 - 20km	100m	2 km 1 km	100m			VIS backscatter	Expect to address this from lidar backscatter
Cloud top temperature	260-170K	2K	2 km 1 km	N/A			VIS backscatter, IR PoR	Cloud height from lidar, temperature matched to sounding; else PoR and broader context
Ice water path	0.2 -10 kg m^{-2}	100%	3 km 1 km	N/A			Radar reflectivity (> 14 GHz); VIS-SWNIR reflection, DFR, VIS backscatter	Combined radar/lidar has heritage
Convective classification	≥ 3-classes	N/A	5 km	N/A		wide	VIS/IR Geostationary PoR, multi-freq. microwave, radar reflectivity profile	Identify by org. (MCS, isolated conv, multi-cell etc.) and/or intensity (weak, moderate, intense), depth (shallow, moderate, deep) etc.
Cloud lifecycle categories	≥ 3 phases	N/A	5 km	N/A		wide	VIS/IR Geostationary PoR	e.g., Cu, mature, decaying; alternatively, MCS approach such as Roca et al., 2017 and refs therein
Diurnally resolved cloud top height	6 -20 km	1000 m	2 km	500m		wide	VIS/IR Geostationary PoR	PoR IR estimates boost uncertainty
Diurnally resolved cloud cover	0.05-1.00	5%	2 km	N/A		wide	VIS/IR Geostationary PoR	For context only
Precipitation rate profile	2-50 mm/hr 2-100 mm/hr	<100%	3 km 1 km	250m		Nadir 20 km	radar reflectivity >14 GHZ, µwave radiances (ocean only),	Lower freq radar for heavier rains; Near surface estimate can come from the profile lowest bin.
Cloud vertical structure	0.5 - 20 km	N/A	3 km 1 km	250m			Radar reflectivity profile (>14 GHZ) above melting layer (ML) ~ 5 km.	Minimum confined to above melting layer and ~coincident with vertical velocity measurement

O3 Convective Storm Systems Geophysical Variables (2 of 3)

O3 Convective Storm Systems Geophysical Variables (2 of 3)	Desired Capability						Examples of Observables	Notes
	Range	Uncertainty	Scales					
			XY	Z	T	Swath		
Minimum / **Enhanced**	**IMPORTANT**: Desired Capabilities and Observables are preliminary. Click here for additional information.							
Precipitation phase profile	liquid, solid, mixed		≤3 km	250 m	Instantaneous	Nadir / 20 km	Z profile, bright band, ΔV_r, pol. radar linear depolarization ratio (LDR; e.g., Ka > ~-15 dB), differential reflectivity ΔZ~2dBZ , dual-frequency ratio (e.g., Ka/W, Ku/Ka, Ku/W), polarimetric VIS backscatter	Basic separation of liquid and frozen in stratiform most straight forward. However, this would include approach for convective clouds, mixed phase, and the associated profile. Melting layer ID is implicit.
Stratiform/convective precipitation discrimination	0-100%	10 %	3 km	N/A			Radar reflectivity profile	3 types- C, S, Other. Better with multiple radar frequencies (E), vertically- resolved Doppler vertical motion
Aerosol extinction profile	Sfc-18 km	25%	10 m	100 m		Nadir	Backscatter profiles at VIS	Vicinity of convection
AOD (column, PBL)	0.03 - 4	15%	2 km / 1 km			20 km	Multi-angle radiance (UV,VIS) – 5%, multi-angle DOLP (x%) - Multispectral radiance in UV (aerosol absorption)- VIS (AOD, fine mode aerosol over water) - SWIR (surface properties and cirrus screening) - 5%	
Synoptic scale motion							From met analysis (PoR)	Dynamics
Environmental thermodynamic profiles							From met analysis (PoR)	Temperature, humidity, instability profiles/indices
Latent heating profile	-50-100 K/hr	30%	≤3 km	250 m	Instantaneous	Nadir or swath	Radar reflectivity profile, C/S type, Doppler velocity, time differenced reflectivity (ΔZ~2 dBZ, 90sec)	Instantaneous estimate with velocity constraint; Highly derived from combination of sources

O3 Convective Storm Systems Geophysical Variables (3 of 3)		Desired Capability						Examples of Observables	Notes
		Range	Uncertainty	Scales					
				XY	Z	T	Swath		
Minimum	**Enhanced**	**IMPORTANT**: Desired Capabilities and Observables are preliminary. Click here for additional information.							
Precipitation particle size		0.4-4.0 mm*	0.5 mm	≤3 km	250 m	Instantaneous	Nadir	Radar reflectivity, attenuation, dual-frequency ratio (DFR), combined TB and reflectivity/DFR.	*Characteristic water equivalent diameter (e.g., D_m, D_0 etc.). D_m largely < 3 mm (e.g., Gatlin et al., 2015); multi-frequency best.
2D Surface Precipitation Rate		0.5-50 mm/hr	< 50% @1 mm/hr; < 25% @>10 mm/hr	≤ 25 km	N/A		>500 km	Scanning passive μwave, >85 GHz	Contributes to horizontal mapping of precip. Uncertainty similar to GPM L1 Requirements.
Convective core size		25-400km^2	25 km^2	≤3 km	N/A		20 km	Radar reflectivity, microwave TB	Limited scanning or mapping implied
Aerosol effective radius profile		0.1–0.5	±20% when extinction exceeds 0.05 km^{-1}						
Aerosol non-sphericity									
AAOD									
Lightning								PoR; group/flash rates, flash area, length, energy	Geo, LEO and ground-based sensors

Objective 3: Convective Storms

Potential Enabled Application Example

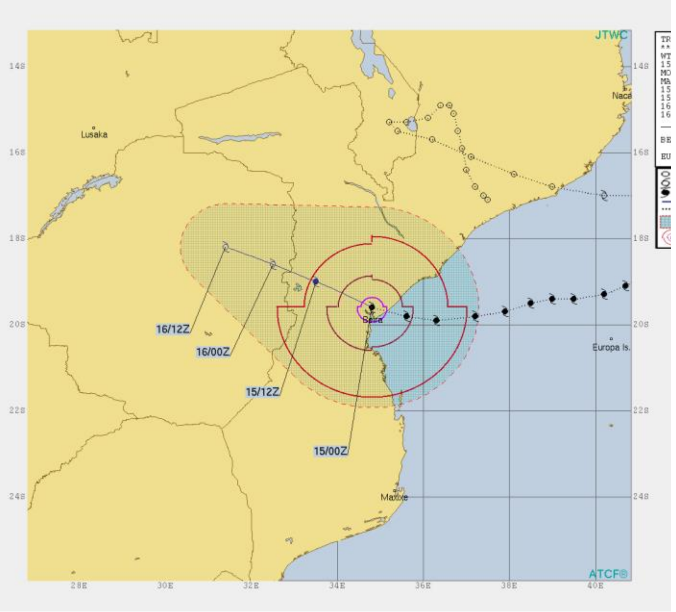
- **Severe Storm Forecasting and Modeling**: Observations of aerosols, cloud properties, and precipitation are used by the weather modeling and forecasting communities to predict hurricane and mid-latitude cyclone development, intensity, and track and associated precipitation type and amount

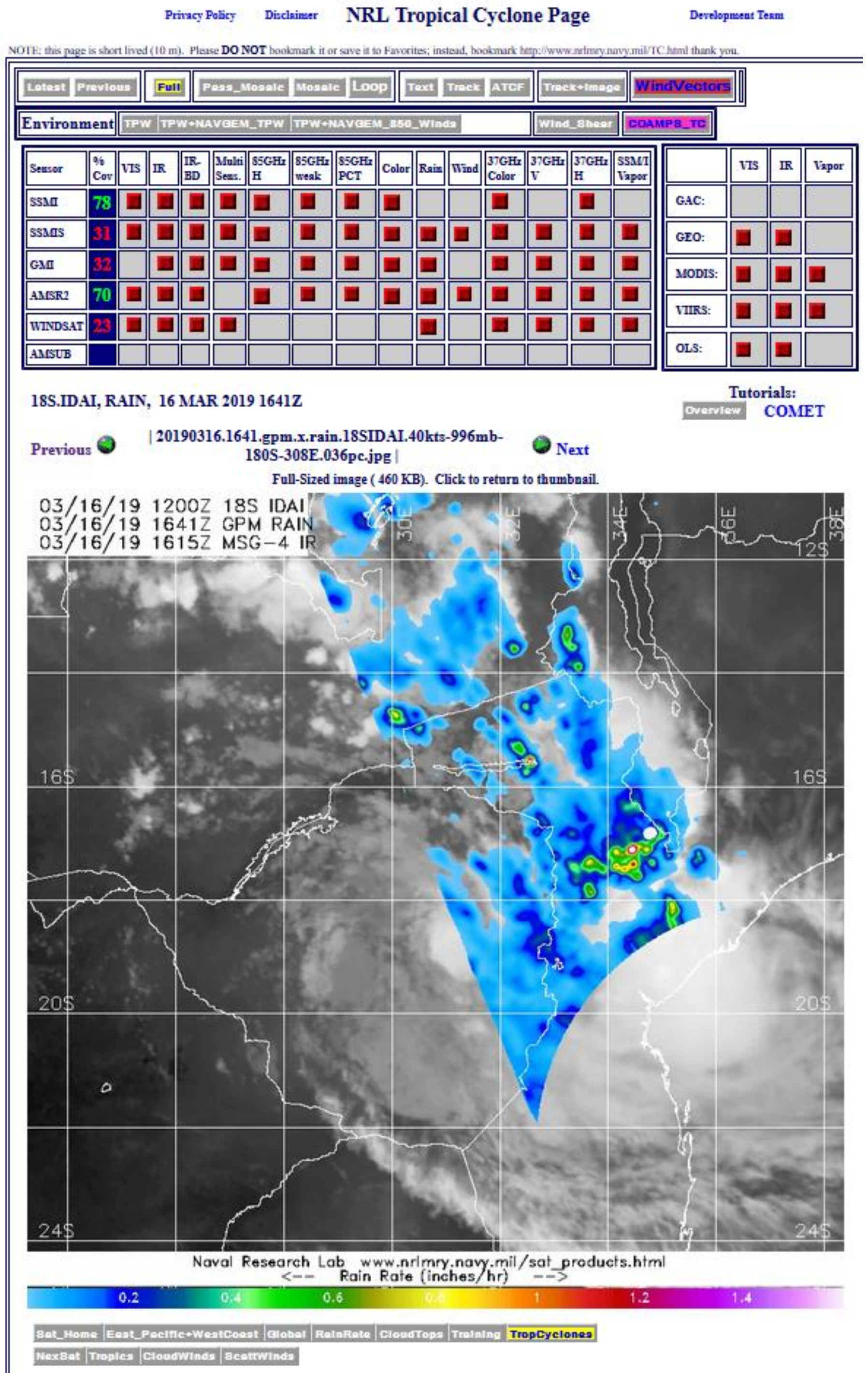
- **Relevant Geophysical Properties:** Cloud height, depth, surface precipitation, brightness temps

- **Partners**: NWP Modeling Communities, NOAA, Disasters planning communities

A+CCP has the potential to provide more information on convective events to inform storm intensification forecasting

NRL Tropical Cyclone Page
https://www.nrlmry.navy.mil





Develop Sub-Orbital Needs and Approaches

Potential gap(s) in orbiting instrument capability may dictate targeted sub-orbital sampling.

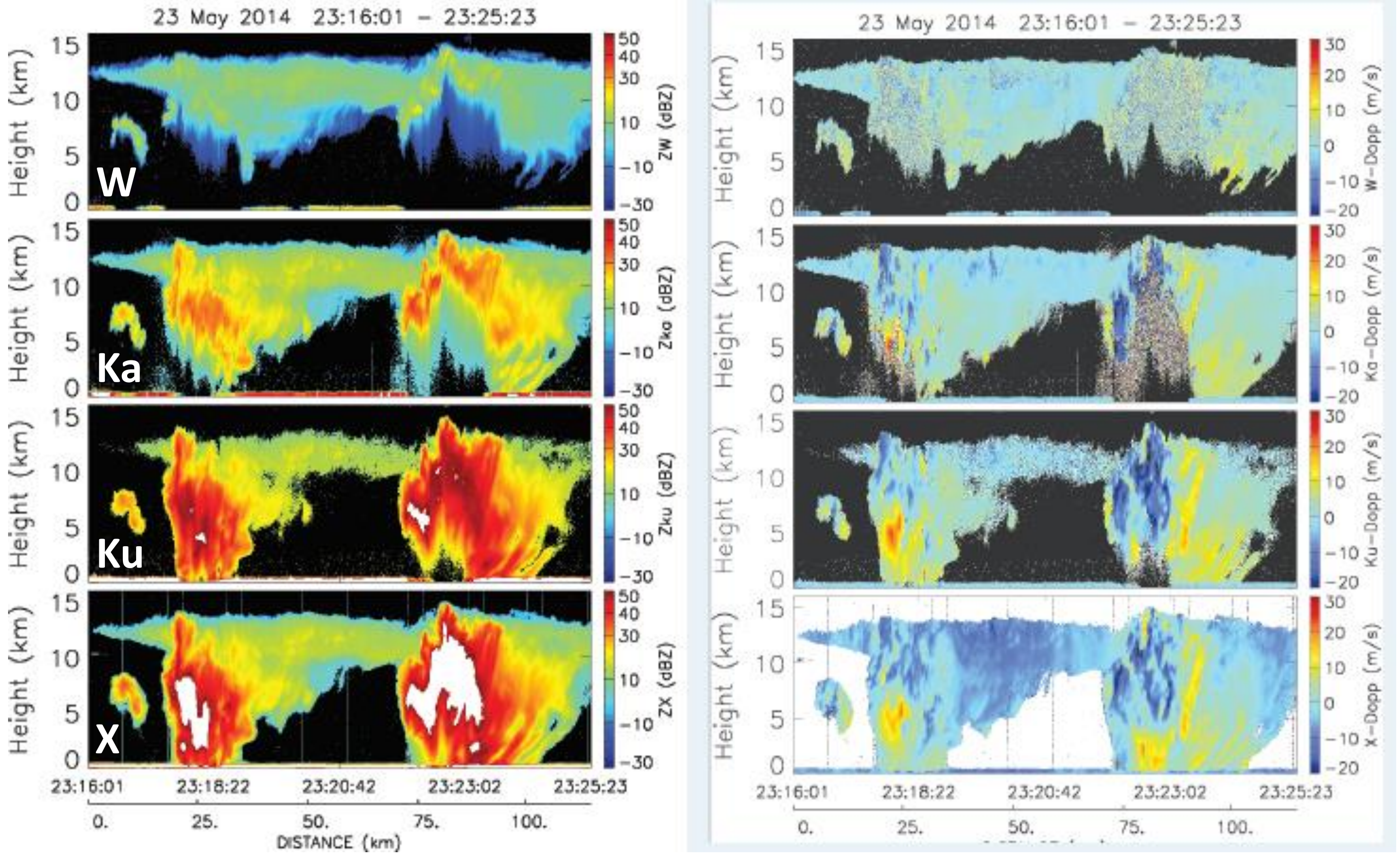
Example (*one*)- severe storms: Tail of intensity distribution but large impact!

Problem: Excessive attenuation/multiple scattering at higher radar frequencies- requires multi-parameter Doppler radar sampling at longer wavelengths.

Sub-orbital possibilities: Multi-platform airborne active/passive remote sensing, in situ environment, coordinated *and combined* with ground-based research rapid-scanning Doppler/polarimetric radar and supporting instrument networks (temporal sampling)

4-Frequency radar sampling from ER-2; IPHEx severe storm

Reflectivity (dBZ) | Doppler Velocity (m/s)



Heymsfield et al., 2017

Outstanding, Ongoing, and Next Steps

Geophysical variable adjustments and other issues need resolution based on SCC and community inputs

- Missing variables?
- Should cloud phase be included in the O3 minimum in addition to precipitation phase profile? If so, is "cloud top phase" more appropriate for this objective?
- Need to better define "convective classification" and "convective lifecycle" GVs.

Incorporate SIT "reality checks" on GV desired capabilities (ranges, uncertainties, resolution)

More detailed specification of PoR contribution(s)

Better define candidate observables and associated measurement specs

Value Framework

Utility assignment to GVs

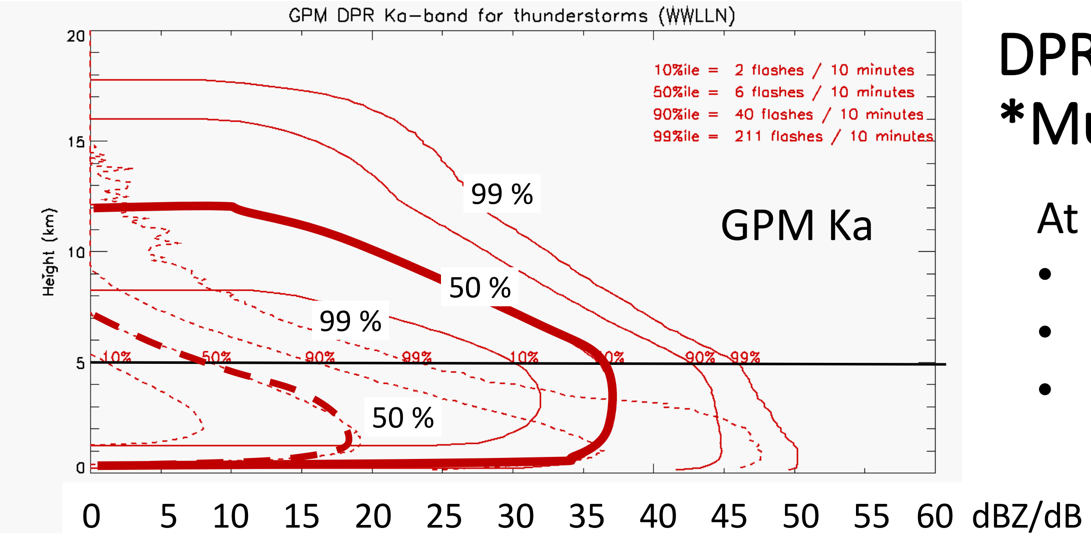
SIT Quality metrics for observables/measurements (literature, model/field campaign OSSEs etc.)

Initial architectural studies

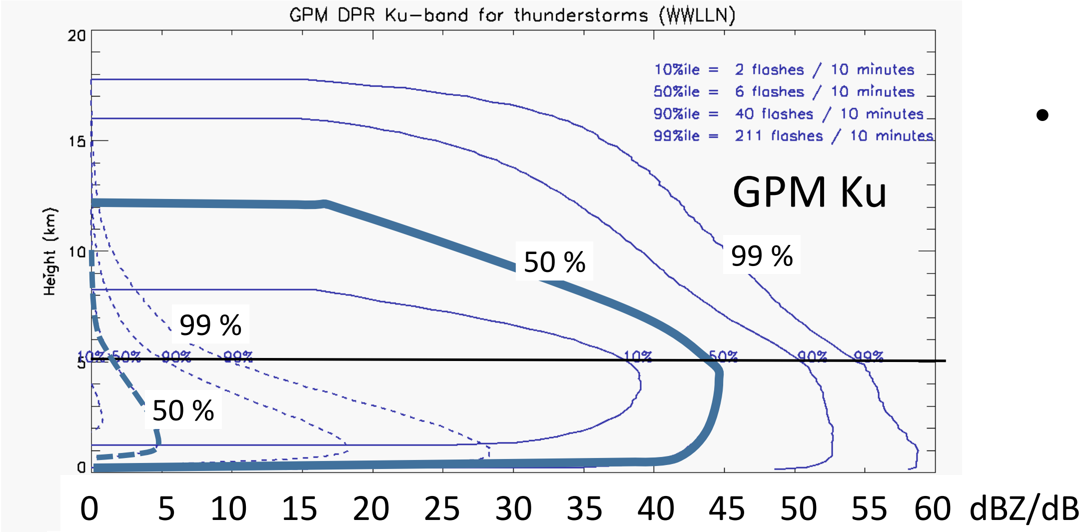
Identify potential "sub-orbital" components

BACKUP/EXTRA

GPM Estimate of Impact on Convective Storm Profiles if Limited to Ka-Band Radar



Corrected Z (dBZ; solid); Attenuation (dB; dashed)



Corrected Z (dBZ; solid); Attenuation (dB; dashed)

DPR *two- way* attenuation in thunderstorms (Z_m - Z_c)
*Multiple scattering not accounted for…..

At an ***altitude of 5 km***:

- For typical (50th %) thunderstorms, Ka has ~8 dB attenuation
- For moderate (90th %) thunderstorms, Ka has ~15 dB attenuation
- For strong (99th %) thunderstorms, Ka has ~22 dB attenuation

- For Ku, these numbers are 1.5, 5, and 10 dB, respectively (at 5 km)

Dan Cecil, NASA MSFC and ACCP-SIT