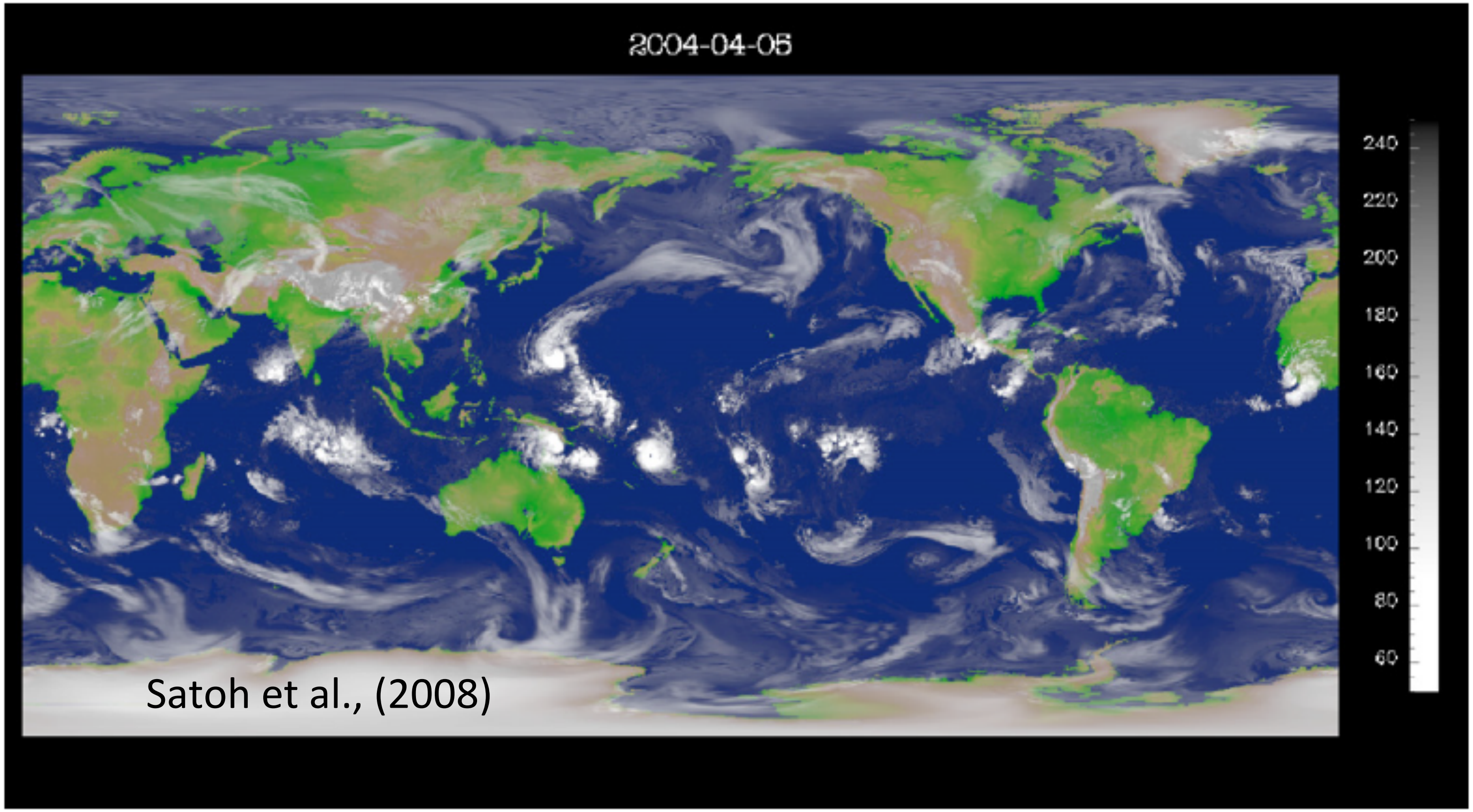
The ACE Clouds Science Traceability Matrix

Jay Mace, Simone Tanelli, Roger Marchand, Graeme Stephens,
Steve Ackerman, Steve Platnick, Dave Starr, Ann Fridlind

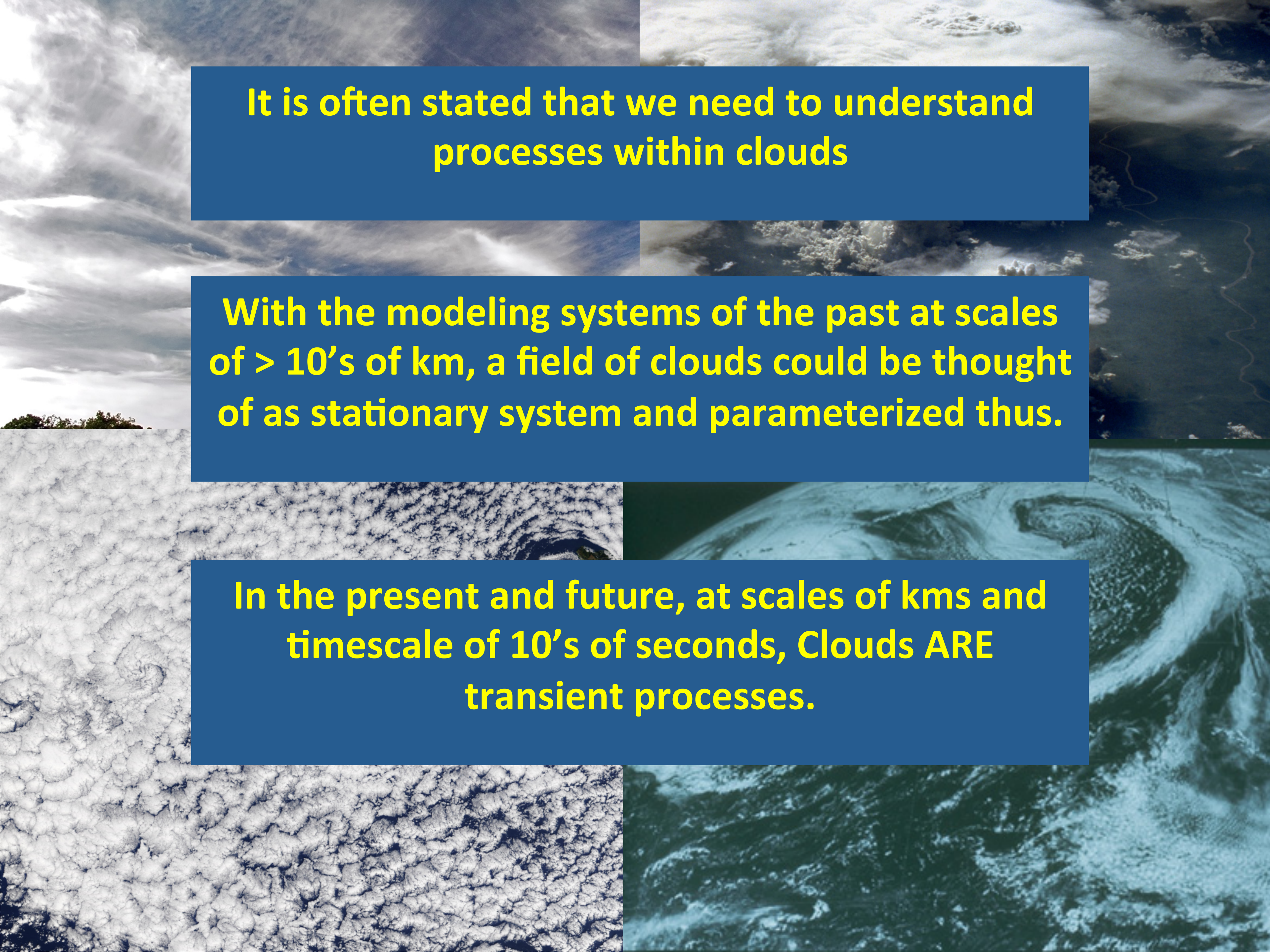
Global MODELS Are Evolving to Resolve Process…

Models are evolving rapidly toward global cloud resolving.

NICAM global cloud resolving model non-hydrostatic, ~3.5km global



As models progress down in scale and convective parameterizations are abandoned, the parameterization of *microphysical process* increasingly become the weak link.


It is often stated that we need to understand processes within clouds
With the modeling systems of the past at scales of > 10’s of km, a field of clouds could be thought of as stationary system and parameterized thus.
In the present and future, at scales of kms and timescale of 10’s of seconds, Clouds ARE transient processes.

A Few Statements by Sue Van Den Heever Regarding Sensitivity of CRM to Microphysical Processes:

Sensitivity to Graupel/Hail Parameterization:

- The peak stratiform and convective areas differed by 105% and 150% respectively
- Accumulated precipitation varied by a 558%
- (Adams et al., 2013)

Sensitivity to Riming of ice in Mixed Phase:

- Surface snowfall rates and totals vary by 200 – 300% due to differences between bin and bulk microphysical riming schemes
- (Saleeby and Cotton, 2008)

Sensitivity to Droplet Breakup in Rain:

- Small changes to droplet breakup parameters => 500-600% differences in precipitation rates
- (Morrison et al., 2012)

Sensitivity to Microphysical Scheme Complexity (# of moments):

- 300-400% differences in surface precipitation due to the number of moments predicted => feedbacks to storm dynamics

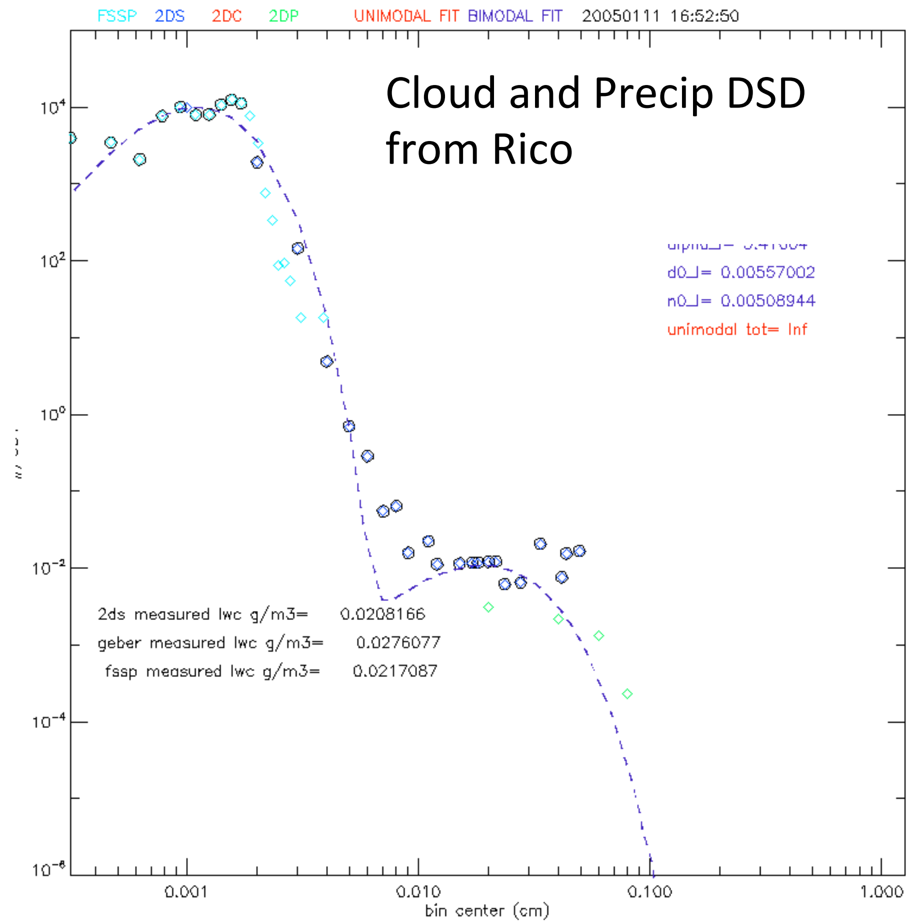
How are Microphysical Processes Resolved?

1. Recognize that by microphysics we mean distributions of particle size.

2. A distribution of particles require at least 2 independent parameters to define it – Droplet Number and Distribution mass for instance

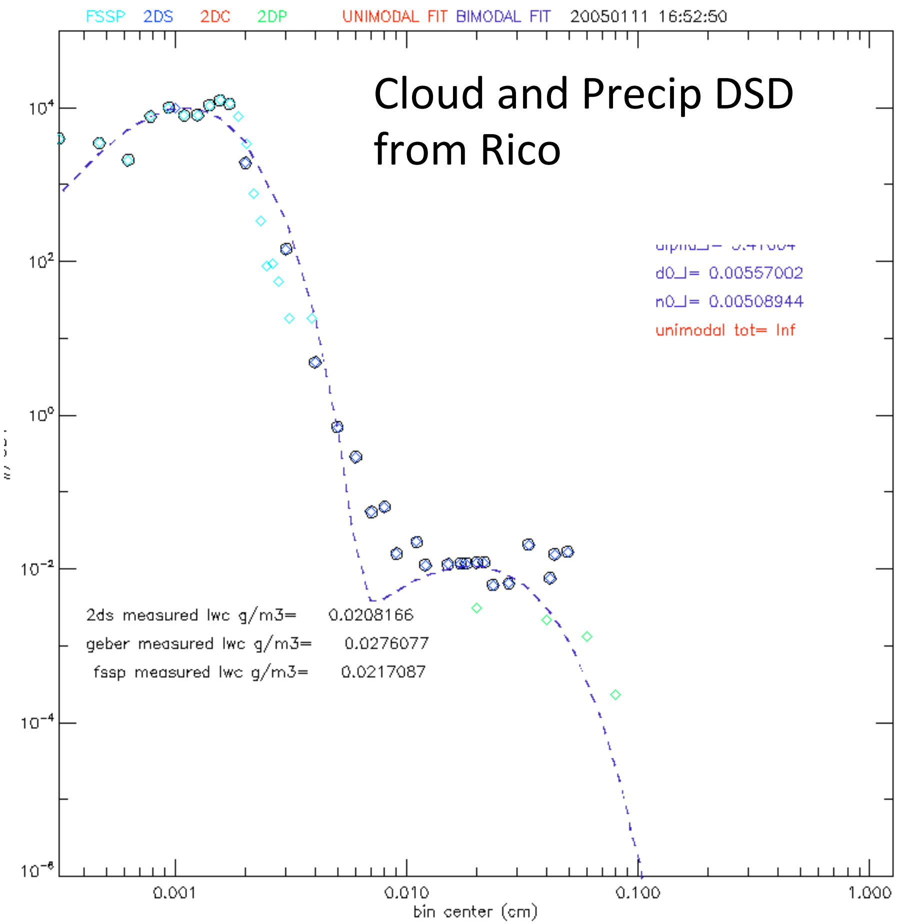
3. Process implies that the DSD is evolving – i.e. Cloud (aerosol) DSD is being converted to a Precip (cloud) DSD or vice versa

4. All this occurs in up (down)drafts or through droplet collection during sedimentation (accretion)



Rico Clouds (Rauber et al, 2008)

So to resolve process with measurements, information must be present to **constrain the droplet or particle modes that are undergoing change** ***in the vertical dimension***.



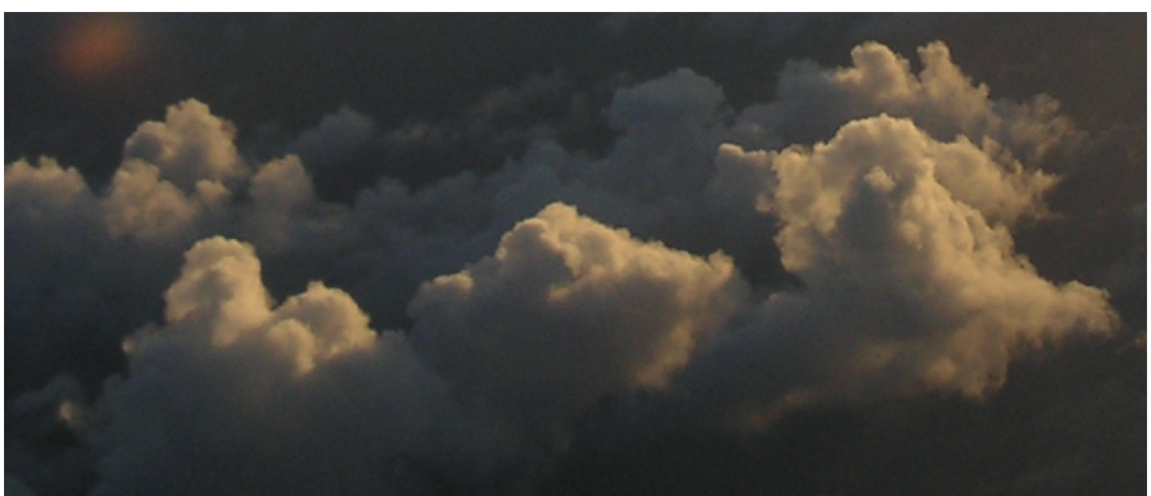
Precipitation is formed in clouds like this by the processes of

Autoconversion – growth of cloud mode droplets to precipitation size

$$\left(\frac{\partial q_r}{\partial t}\right)_{auto} = 1350 q_c^{2.47} N_c^{-1.79}$$

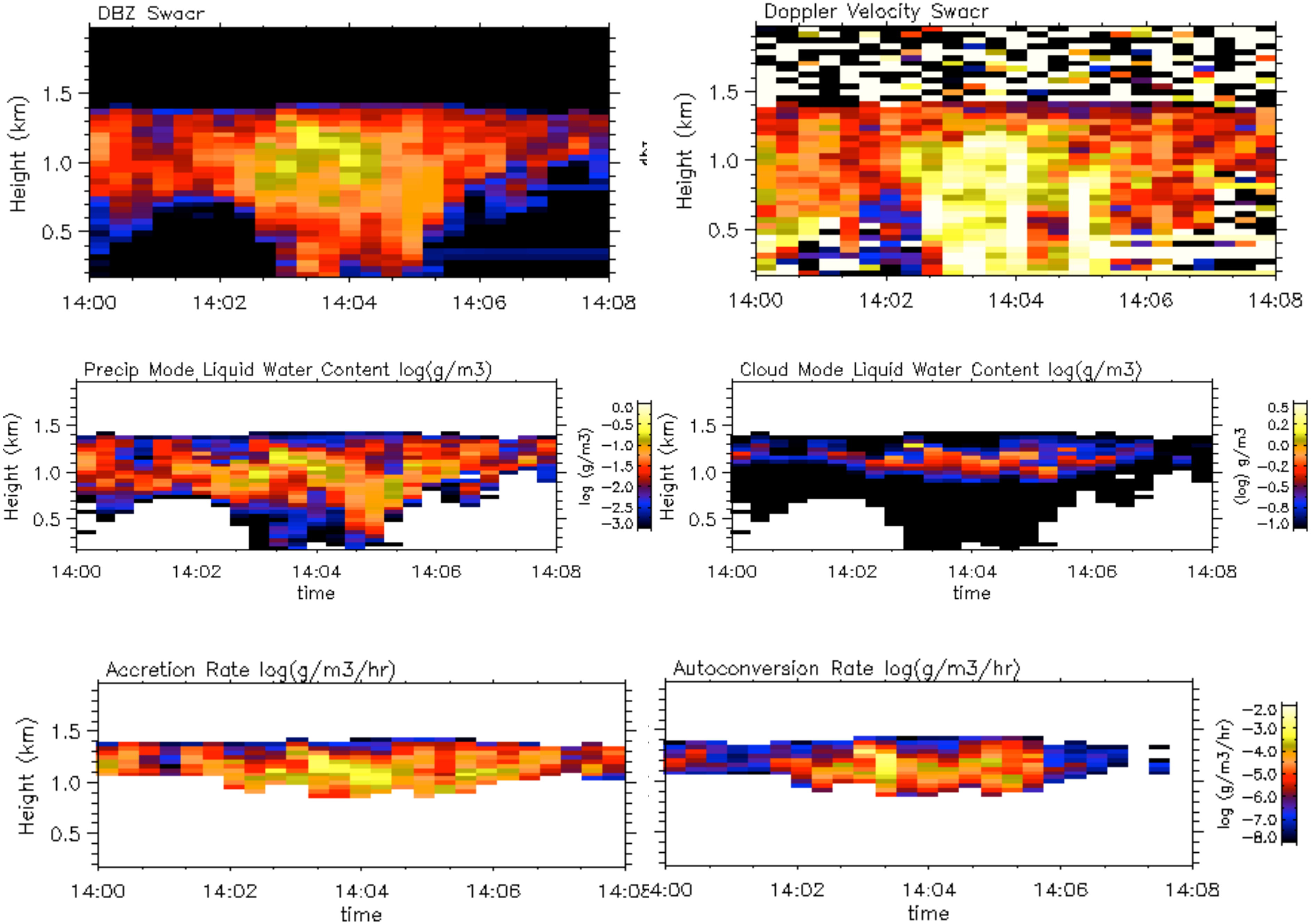
Accretion – collection of cloud drops by falling precipitation

$$\left(\frac{\partial q_r}{\partial t}\right)_{accre} = 57\left(q_c q_r\right)^{1.15}$$

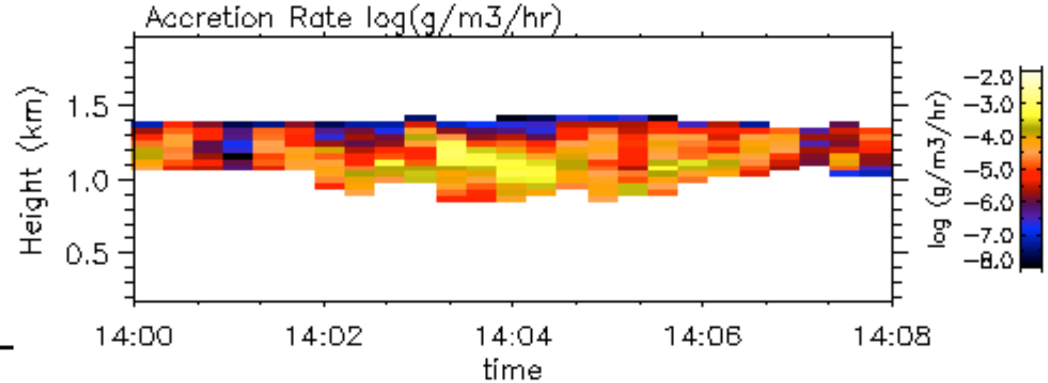


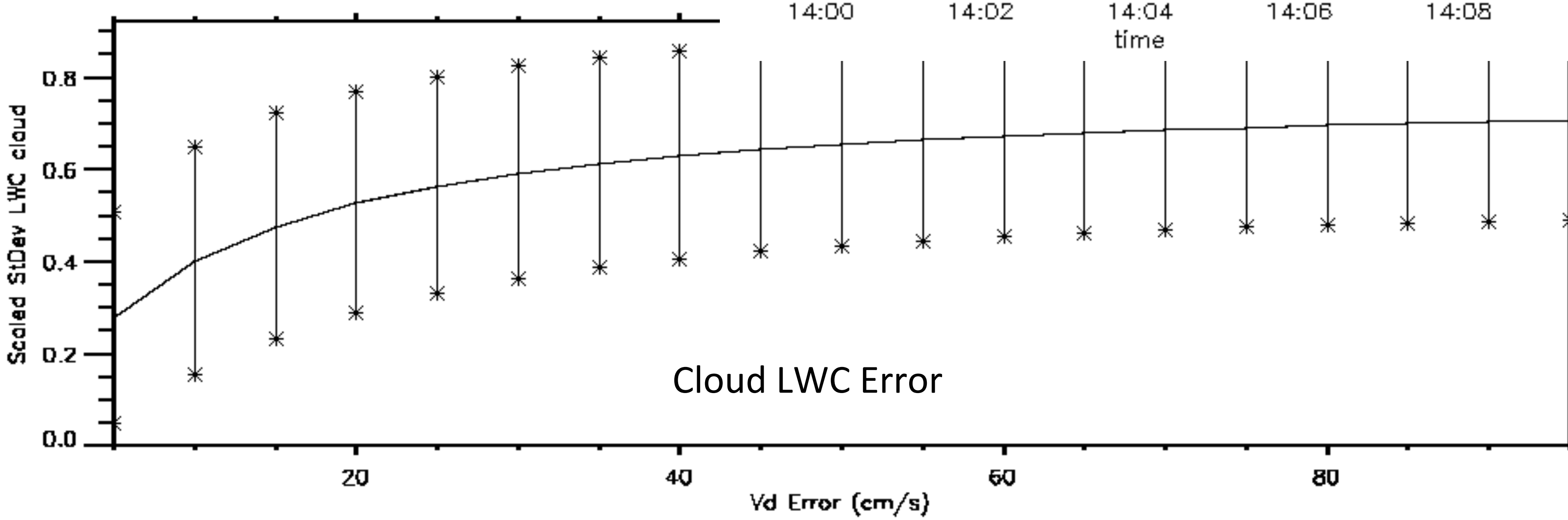
- Liquid clouds with high droplet number (1st indirect effect) have a slow autoconversion rate
- may never get to accretion (2nd aerosol indirect effect)

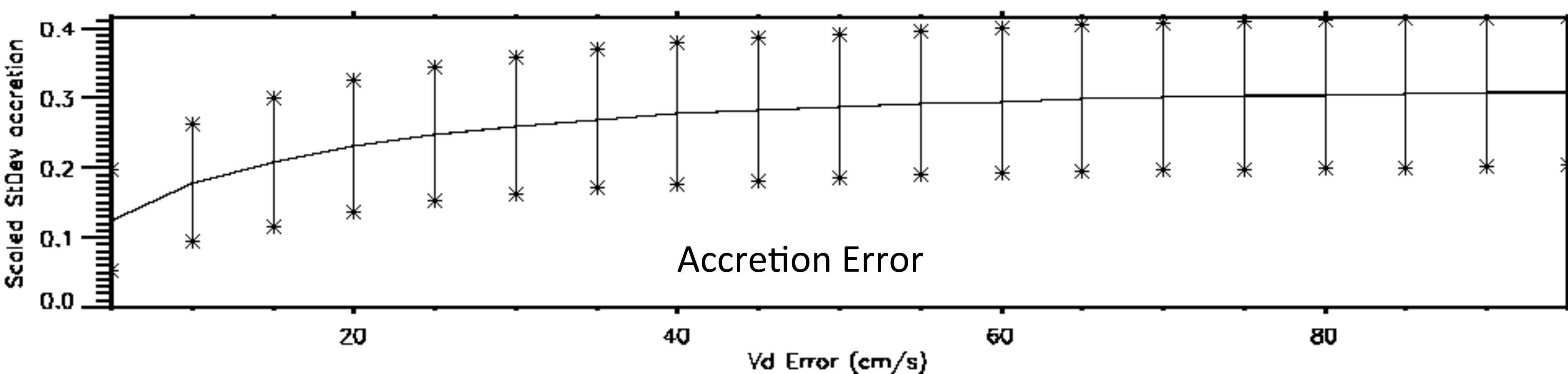
Example Case from Azores ARM Deployment: Lightly raining stratocumulus (1 mm/day)



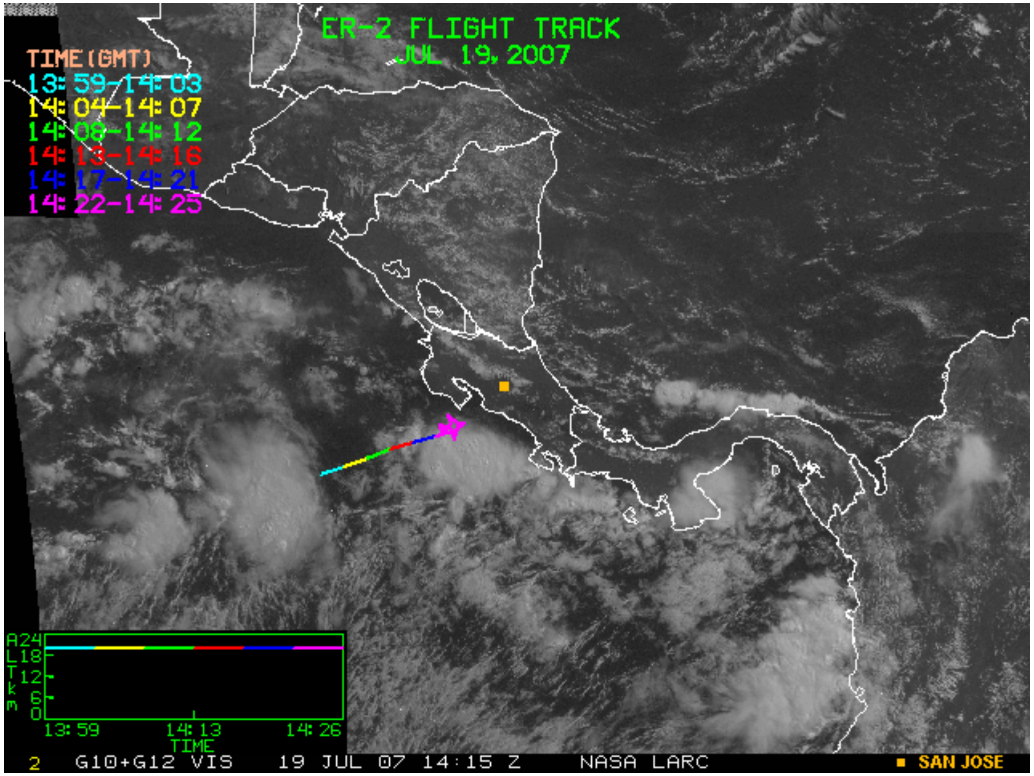
How are the errors sensitive to uncertainty in Doppler Velocity?

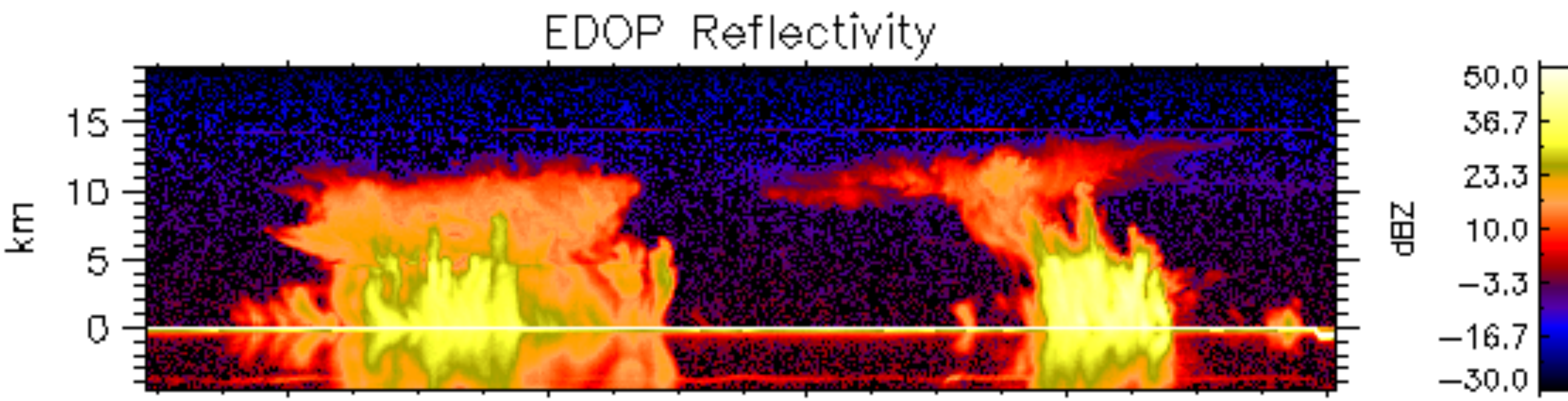






How it's done. An example from TC4





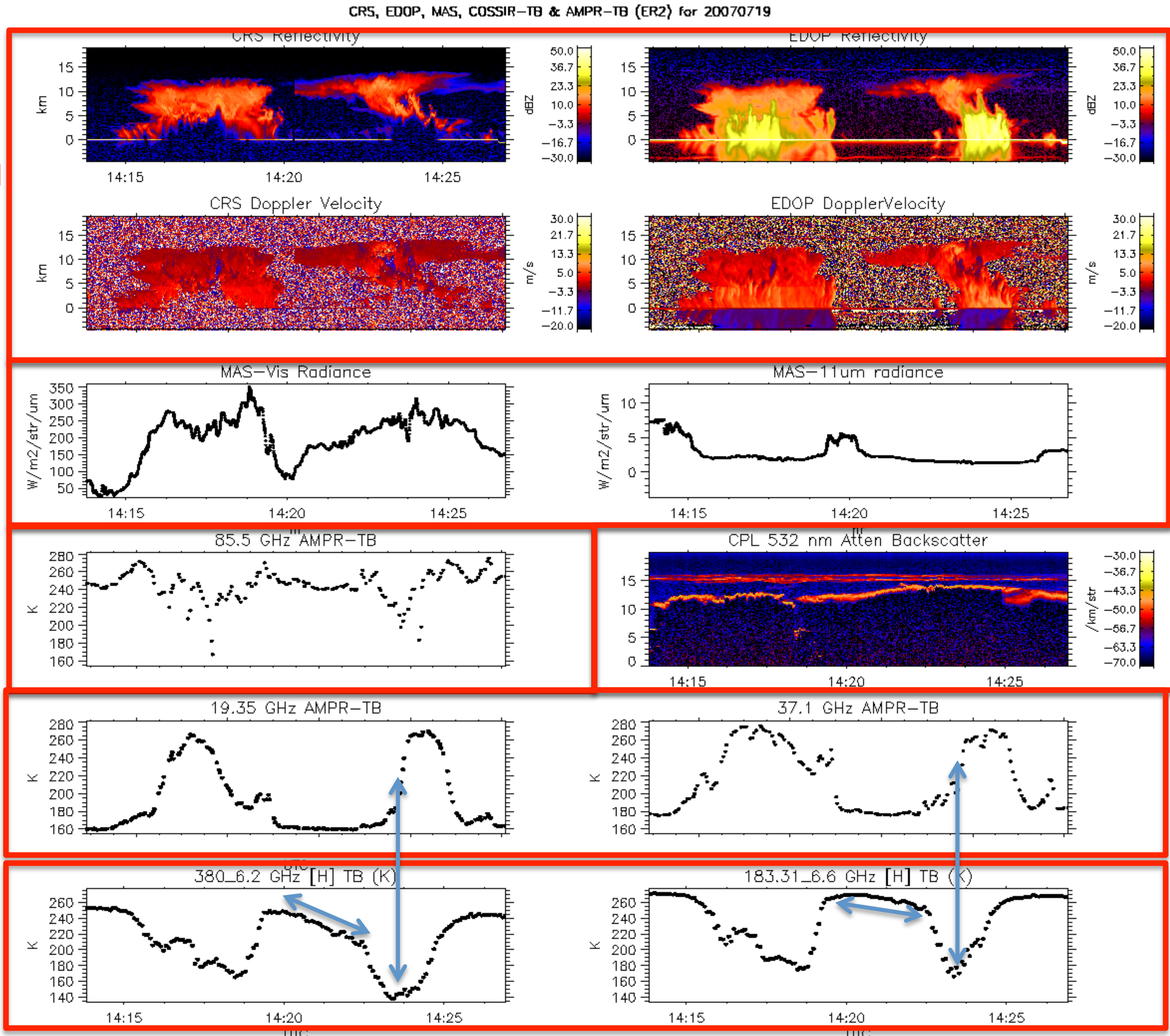
Radar Data Courtesy Gerry Heymsfield

Z and V at two freq constrain profile of precip, cloud, and vertical motion

Reflectance and Lidar backscatter constrain cloud near top

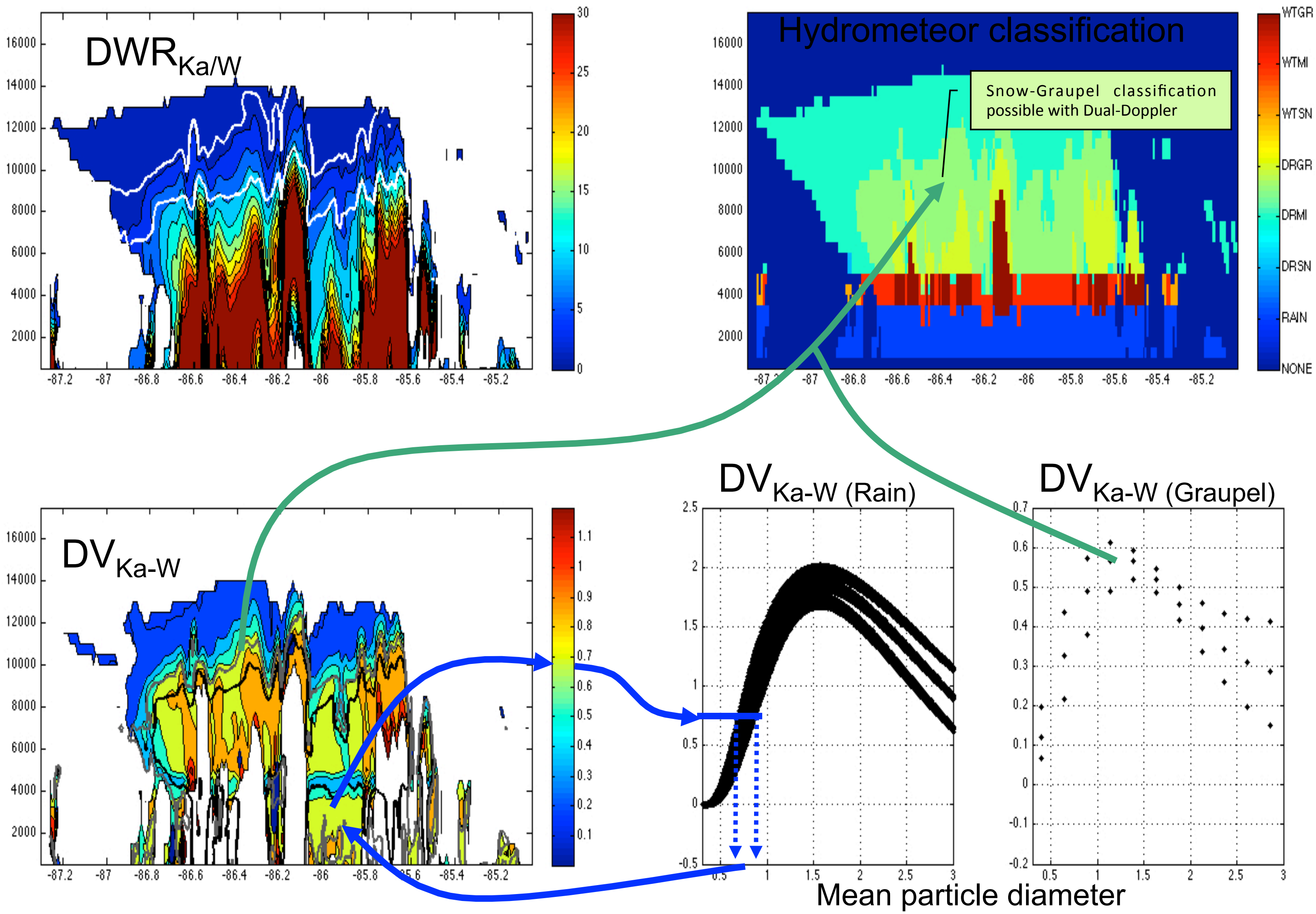
Ice scattering signatures at 85 GHz constrains cross sectional area of large ice

Low Freq Microwave constrains the liquid water path



Submm constrains ice water path

Dual-Doppler (Ka-W) measurement



ACE Clouds STM – Overall Approach

Approach: Define Cloud System-Specific Science Questions that will advance the science of the early '20's.

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Then determine what geophysical parameters (at what resolution and error tolerances) are needed to address a question.

⇩

What ***combination of measurements*** (within reasonable technological limitations) would provide the minimum geophysical parameters to address a questions?

⇩

What are the minimum requirements of measurements to derive the geophysical parameters for a question?

⇩

Collect the measurement requirements for each question and let the most stringent of those requirements define the overall measurement requirements for the ACE mission

Table 2.1 ACE Cloud Science Traceability Matrix

Category	Topical Themes	Geophysical Parameters and Error Tolerance Requirements[1]	Measurement and Instrument Requirements[2]
Morphology	Occurrence and macroscale structure (vertical and horizontal) of clouds and precipitation and interaction with large-scale meteorological and thermodynamic forcing.	(see parameter table below)	1. W Band Radar (Table 5.1) (1-19) 2. Ka Band Radar (Table 5.1) (1,2,3,5,7,9,10,11,14,19,20) 3. High Spectral Res. Lidar (Table 5.2) (1,2,4,7,10,12,17,15,20) 4. High-Resolution VIS-SWIR Imager (Table 5.3) (primary =1,2,11,15,16,18; assist = 10, 12, 17) 5. Wide Swath Vis-IR Imager (Table 5.3), (primary = 1,4,7,11,12 1,2,4,7,11,15,16,18; assist = 10, 12, 17) 6. Low Freq. Microwave (Table 5.4) (5,10,11,12,13,14,16,19, 5,11) 7. High Freq. Microwave (Table 5.5) (10,11,12,13, 11, 16)
Microphysics	Microphysical Processes that form, maintain, and cause changes to profiles of aerosol, clouds, precipitation and the interactions between them.		
Aerosol	The specific role of aerosol in modifying the occurrence and properties of clouds and precipitation.		
Energetics	Maintenance of and changes to the energetic balance of the atmosphere and earth system due aerosol, clouds, and precipitation.		

Geophysical Parameters and Error Tolerance Requirements[1]:

		Narrow Nadir Swath	Wide Swath
Morphology	1. Cloud Layer Detection	2%	5% (optical depth > 0.3)
	2. Cloud Top Height	250m (R), 100 m (G)	1500 m (ice) 1000 m (liq)
	3. Cloud Base Height	250m (R), 100 m (G)	
	4. Cloud Top Phase	5%	20%
	5. Precipitation Detection	10%	20%
	6. Vertical Motion		
	7. Multilayer Cloud Detection	5%	Detection of cirrus (τ~0.3–7 depending on geometry) over lower water cloud
	8. Cloud Phase Profile	20%	
	9. Precipitation Profile	10%	
Microphysics and Aerosol	10. Water Content Profile	10-25%	
	11. Cloud Water Path	10%	25%
	12. Cloud Particle Size Profile	10-25%	
	13. Precipitation Particle Size Profile	10%	
	14. Precipitation Rate Profile	20-50%	
Energetics	15. Cloud Column Optical Depth	10%	20%
	16. Layer Effective Radius	10%	20% (liq) 30% (ice)
	17. Extinction Profile	5%	
	18. Radiative Effect	10% or 25 W m^{-2}	10 W m^{-2} (TOA)
	19. Latent Heating	5 K day^{-1} km^{-1}	

Instrument	Measurement	Cloud Microphysical Constraint	Additional Information and Comments
Dual Frequency 94/35 GHz Radar	Radar Reflectivity	• Vertically resolved 6^{th} moment of cloud drop size distribution for particles less than 0.1 of the radar wavelength • Differential response to large hydrometeors	• Difference in response of 95/35 GHz radar reflectivity and Doppler velocity for larger particles (> ~0.3 mm) can be used to identify the presence of such particles and help characterize the microphysics of this part of the distribution. • Differential attenuation with respect to 94 GHz is likely to prove useful in identification of cloud and precipitation type (phase) and retrieval of precipitation water content.
	Doppler Velocity	• Vertically resolved $2^{nd}/3^{rd}$ moment of drop size distribution (reflectivity weighted) • Differential response in presence of large hydrometeors.	• Doppler velocity is a measure of total velocity of the cloud particles. In convective cores, the velocity is dominated by cloud vertical motion. In other conditions, the velocity can be separated into contributions from particle fall velocity and air motion (Dynamics). • Cloud liquid water drops generally fall too slowly to be measured via this technique but it is very useful for identification, and characterization of ice clouds, snow, drizzle, and rain.
	Differential Attenuation, Path Integrated and Vertical Profile	• Profile of Condensed Water • Total column liquid water path.	• One can use surface reflectance to estimate total attenuation in the radar in the column, when the radar is not totally attenuated. The attenuation is determined largely by the amount of liquid water (cloud and precipitation) in the column.

Instrument	Measurement	Cloud Microphysical Constraint	Additional Information and Comments
High Spectral Resolution Lidar (HSRL)	Extinction	• vertically resolved 2^{nd} moment of cloud drop size distribution in the upper 5 optical dpeths	• Produces extremely valuable direct evaluation of optically thin cloud and aerosol extinction. • Aerosol single scattering properties • Also provides information on cloud-top-height and more generally insight into structure of thin cloud.

Instrument	Measurement	Cloud Microphysical Constraint	Additional Information and Comments
High Resolution Multi-angle Imaging Polarimeter (UV, Visible, and Shotwave Infrared)	UV, Visible and shortwave infrared radiances at multiple view angles. Polarized reflectances at some visible wavelengths.	• Cloud phase near "cloud top" (in region of cloud where bulk of visible light is reflected) • Radiative-effective ice cloud-habit (constrains possible/likely cloud habit mixtures) near "cloud top". • Column albedo • 2^{nd} moment of drop size distribution near cloud top) • effective radius near cloud top.	• Multi-view-angle imagery can also be used with stereo-imaging technique to derive cloud top height. This approach is insensitive to calibration and does not rely on any assumptions regarding atmospheric temperature lapse rate. The approach works well except for exceptionally diffuse high clouds, representing a failure rate of only a few percent. 50 m resolution images can be used to determine cloud-top-height with precision of about 50 m assuming view angles at +/- 45 degrees from nadir.

Instrument	Measurement	Cloud Microphysical Constraint	Additional Information and Comments
Passive Low and High Frequency Microwave Radiometer Channels at: 10.65, 18.7, 23.8, 36.5, 89, 166.5, 183±3, 183±9 GHz	Brightness temperature	• Column liquid water path • Column water vapor path • Surface precipitation rate in wide swath • Ice cloud and ice precipitation • Important wide swath • Significant constraints for nadir viewing	• Column constraint • Will provide wide-swath / cloud system context to narrow-swath observations and in particular information on precipitation.
Passive Sub-mm Radiometer Channels at high frequency: 325.15, 448.00, 642.90, 874.40 GHz	Brightness temperature	• Column ice and particle size constraint for ice clouds; • proportional to the 3^{rd} moment of particle size distribution	• Column constraint • Will provide wide-swath / cloud system context to narrow-swath observations.

Instrument	Measurement	Cloud Microphysical Constraint	Additional Information and Comments
Wide-Swath Visible and Infrared Radiometers	Infrared radiances Vis reflectances	MODIS-like constraints for large swath and important for nadir viewing column constraints.	• Supply contextual information. • Infer cloud-top-heights and optical properties of the broad cloud system. • Support nighttime operations (IR approach can be used to estimate cloud top heights during day and night.) • Large 2.1 um vs. 3.7 um retrievals in boundary-layer clouds appear to provide detection of drizzle/precip. modes

So, depending on how you count, there are 7 instruments that are required to address the science questions relevant to aerosol, cloud, and precipitation.

Is this too much? Probably.

But from a science perspective, Let's look at the fundamental facts.

Aerosol, cloud and precipitation are THE ISSUES that drive uncertainty in climate change prediction. This is simply true.

If the community is serious about actually solving (accurately simulating climate change for the coming centuries), THESE ISSUES (aerosol, clouds, precipitation) MUST be dealt with.

ACE has always been conceived as the necessary *minimum* measurement suite to address the aerosol, cloud, and precipitation questions of the coming decade. The aerosol, cloud, and precipitation issues that plague climate models will NOT go away unless these measurements in some form are made.

But, Is ACE simply too big to be realized as formulated?.

Paraphrasing from Hal's talk: Flagship missions are non starters.

Consider a two platform solution:

Low Platform: Aerosol-Cloud

- HSRL
- PACE

High Platform: Cloud-Precip
(formation fly with MetOP SG)

- Multi Freq. Doppler Radar

Goal: Add a minimal Cloud Radar to the Low Platform
Goal: Add a minimal Backscatter Lidar to the High Platform

What fraction of the relevant science questions can be addressed by such a solution?

We should know this so the NRC knows before the next DS really gets going.

Consider that if we don't get it right with this DS, the next opportunity will be for missions to flown in the 2030's!

Instrument	Measurement	PSD Moment	Additional Information		Thin Ci	Thick Ice	Ice o/ liquid	Convection	Frontal	Cu/SC
HSRL Lidar	Extinction	2nd	MUST have independent Extinction							
94 GHz Radar	Z	6th d<0.3 mm	Combo of multi freq. Doppler will constrain the large particle modes very precisely							
	Vd	2nd/3rd weighted by 94 GHz Z								
35 GHz Radar	Z	6th d< 1 mm								
	Vd	2nd/3rd weighted by 35 GHz Z								
Low Freq Microwave	Column Liquid	3rd	Column constraint							
Sub mm (High Freq Microwave)	Column Ice and Size constraint	3rd	Column constraint							
Visible Imager	Vis Tau/re	2nd	Column constraint (Day)							
Thermal IR Imager	IR Emissivity	2nd to E=1	Column constraint (night)							
Polarimeter	Habit/phase									
Solar and IR Flux			Radiative Closure Column constraint							

Question is how much do each of these measurements contribute to each cloud classification?

Or

How much precision and accuracy is sacrificed by NOT having a measurement capability?

Instrument	Measurement	PSD Moment	Additional Information		Thin Ci	Thick Ice	Ice o/ liquid	Convection	Frontal	Cu/SC
HSRL Lidar	Extinction	2^{nd}	MUST have independent Extinction		?	?	?	?	?	?
94 GHz Radar	Z	6^{th} d<0.3 mm	Combo of multi freq. Doppler will constrain the large particle modes very precisely		?	?	?	?	?	?
	Vd	$2^{nd}/3^{rd}$ weighted by 94 GHz Z			?	?	?	?	?	?
35 GHz Radar	Z	6^{th} d< 1 mm			?	?	?	?	?	?
	Vd	$2^{nd}/3^{rd}$ weighted by 35 GHz Z			?	?	?	?	?	?
Low Freq Microwave	Column Liquid	3^{rd}	Column constraint		?	?	?	?	?	?
Sub mm (High Freq Microwave)	Column Ice and Size constraint	3^{rd}	Column constraint		?	?	?	?	?	?
Visible Imager	Vis Tau/re	2^{nd}	Column constraint (Day)		?	?	?	?	?	?
Thermal IR Imager	IR Emissivity	2^{nd} to E=1	Column constraint (night)		?	?	?	?	?	?
Polarimeter	Habit/phase				?	?	?	?	?	?
Solar and IR Flux			Radiative Closure Column constraint		?	?	?	?	?	?