The DOE ARM Cloud, Aerosol, and Complex Terrain Interactions (CACTI) Field Campaign

June 13, 2019
2019 ARM-ASR PI Meeting

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PNNL is operated by Battelle for the U.S. Department of Energy

CACTI: WHAT, WHERE, AND WHO?

Broad Overview

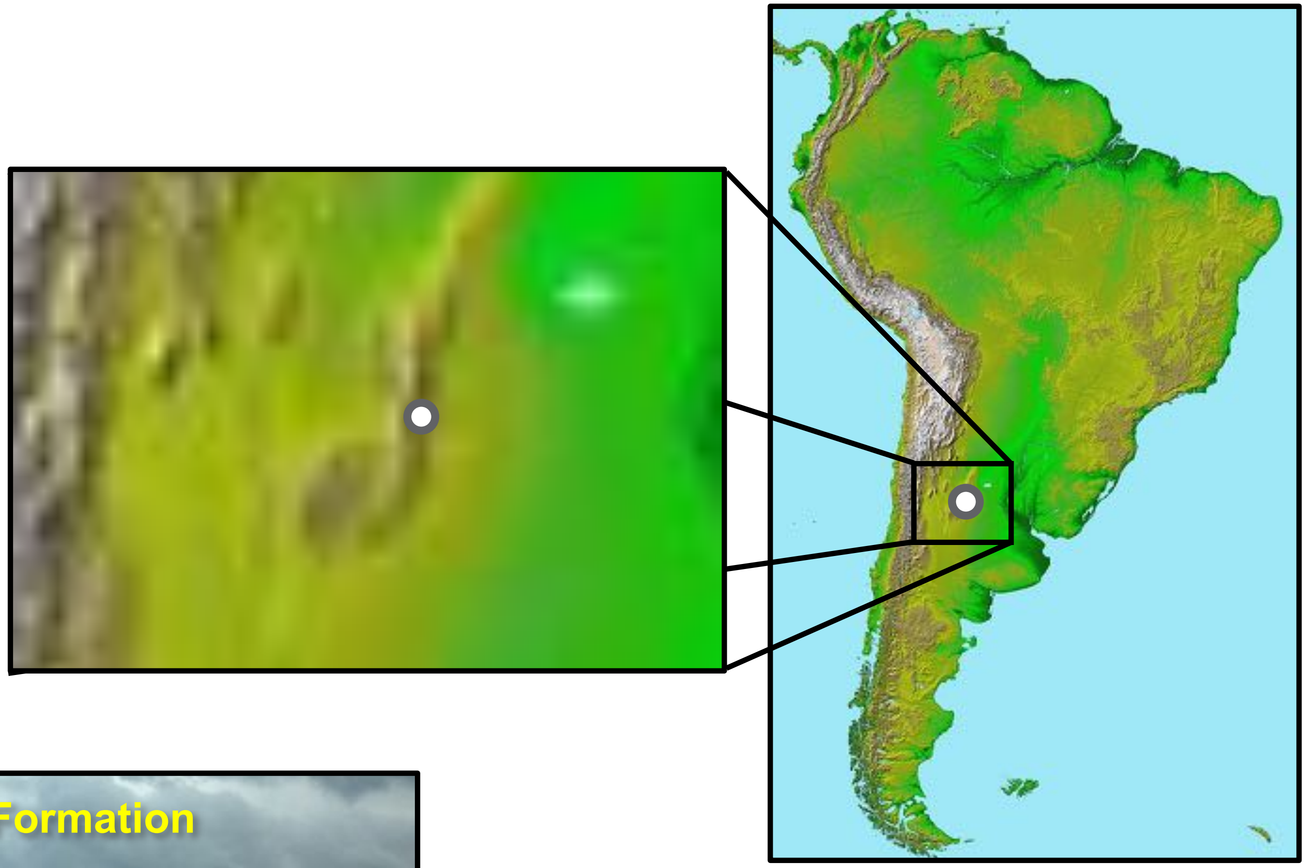
Timing: 15 October 2018 – 30 April 2019

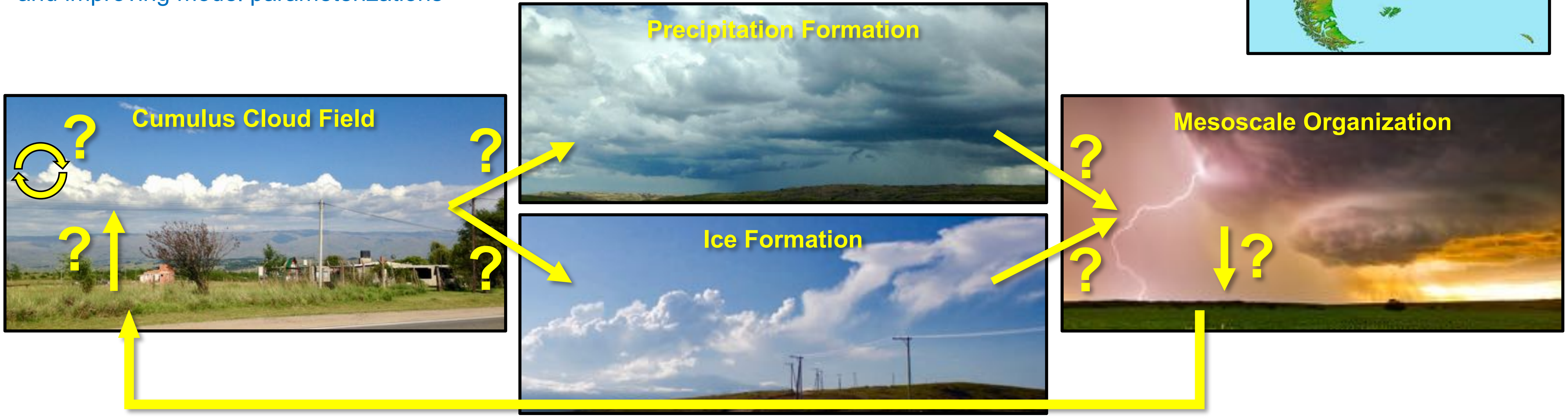
Location: Villa Yacanto, Argentina (32.1°S, 64.75°W)

Facilities: AMF-1 (> 50 instruments), C-SAPR2 radar, G-1 aircraft (IOP, > 50 in situ instruments), and supplemental AWS, photogrammetry and sounding sites

IOP was coincident with NSF-led RELAMPAGO field program from 1 Nov – 18 Dec 2018

Primary Goal: Quantify the sensitivity of convective cloud system evolution to environmental conditions for the purposes of evaluating and improving model parameterizations





Science Team

Principal Investigator

Adam Varble, Pacific Northwest National Laboratory

Co-Investigators

Stephen Nesbitt, University of Illinois

Edward Zipser, University of Utah

Greg McFarquhar, University of Illinois

Sonia Kreidenweis, Colorado State University

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Pavlos Kollias, McGill University

David Romps, Lawrence Berkeley National Laboratory

Eldo Avíla, Universidad Nacional de Córdoba

Paloma Borque, University of Illinois

Paola Salio, Universidad de Buenos Aires

Susan van den Heever, Colorado State University

Paul DeMott, Colorado State University

Robert Houze, Jr., University of Washington

Michael Jensen, Brookhaven National Laboratory

Ruby Leung, Pacific Northwest National Laboratory

David Gochis, National Center for Atmospheric Research

Christopher Williams, University of Colorado-Boulder/NOAA

With critical support from ARM infrastructure and management, INVAP (in country management), local land owners and government officials, NOAA (providing us GOES-16 rapid scan data for events), and NASA Langley (performing satellite retrievals for us).

Management, Infrastructure, Support

Critical In Country Support

INVAP, Servicio Meteorológical Nacional (SMN), Forecasting Team (Lynn McMurdie, SMN and student forecasters), local government officials in Villa Yacanto and Rio Cuarto, Universidad de Córdoba, Fuerza Aérea Argentina (Air Force), Aeropuertos Argentina 2000 (AA2000), Empresa Argentina de Navegación Aérea (EANA), and Gobierno de la Provincia de Córdoba

ARM Ground Facilities

Heath Powers, Tim Goering, Peter Argay: *AMF1 Operations Management*

Kim Nitschke: *Former AMF1 Manager*

Vagner Castro, Juarez Viegas, Tercio Silva, Bruno Cunha: *Site Technicians*

Nitin Bharadwaj, Joseph Hardin, Andrei Lindenmaier, Brad Isom, Pete Argay, and Todd Houchens: *Radar Engineering*

Stephen Springston, Art Sedlacek: *Aerosol Systems Engineering*

Many others: *Instrument Operations, Engineering, Data Mentorship*

ARM Aircraft Facility

Beat Schmid: *Facility Manager*

Jason Tomlinson: *Engineering Manager*

Mike Hubbell: *Flight Operations Manager/Pilot*

Clayton Eveland, Jon Ray, and Jen Armstrong: *Pilots*

Alyssa Matthews, Mikhail Pekour, Lexie Goldberger, Fan Mei, Matt Newburn, Kaitlyn Suski, Alla Zelenyuk-Imre, Mike Crocker, Luke Marx, Pete Carroll, Albert Mendoza, Dan Nelson, and Tom Hill: *Engineering, Operations, and Data Mentors*

ARM Infrastructure

Jim Mather, Nicki Hickmon, Jennifer Comstock, Sally McFarlane: *ARM Management*

Hanna Goss, Ryan Risenmay, Michael Wassem, Rolanda Jundt, Eric Francavilla, Robert Stafford, Cory Ireland: *Communications*

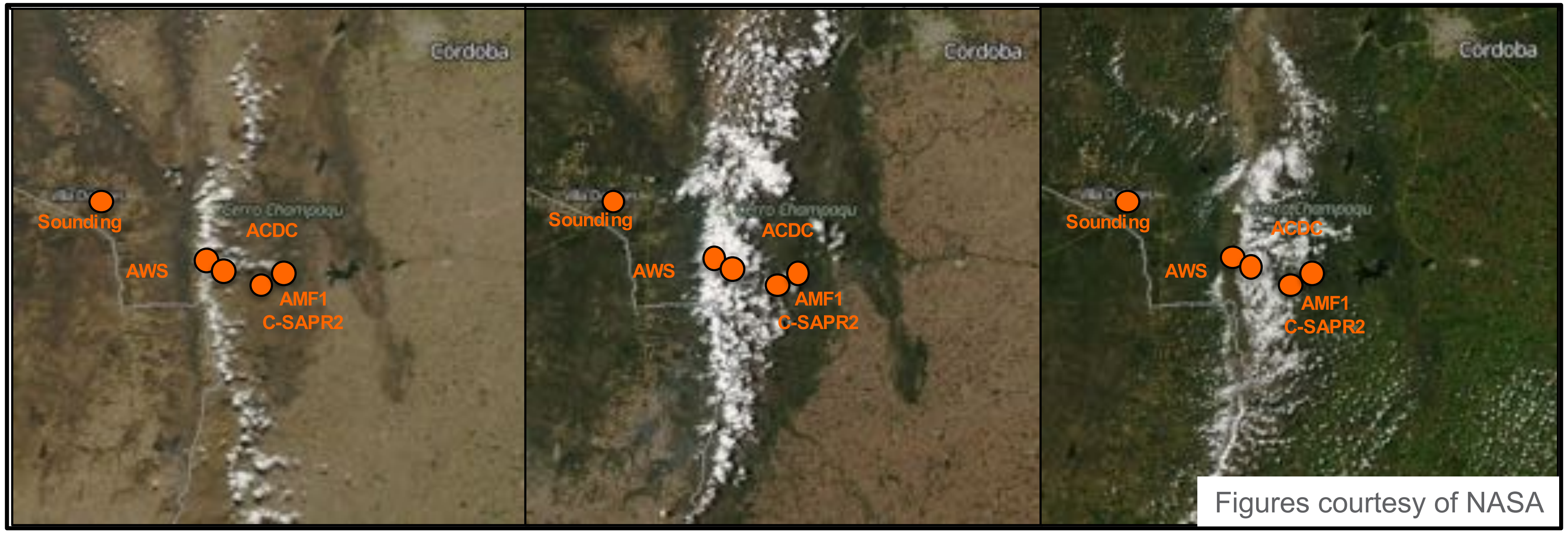
Giri Prakash, Cory Stuart, Maggie Davis, Rob Records, David Swank: *Data Flow and Storage*

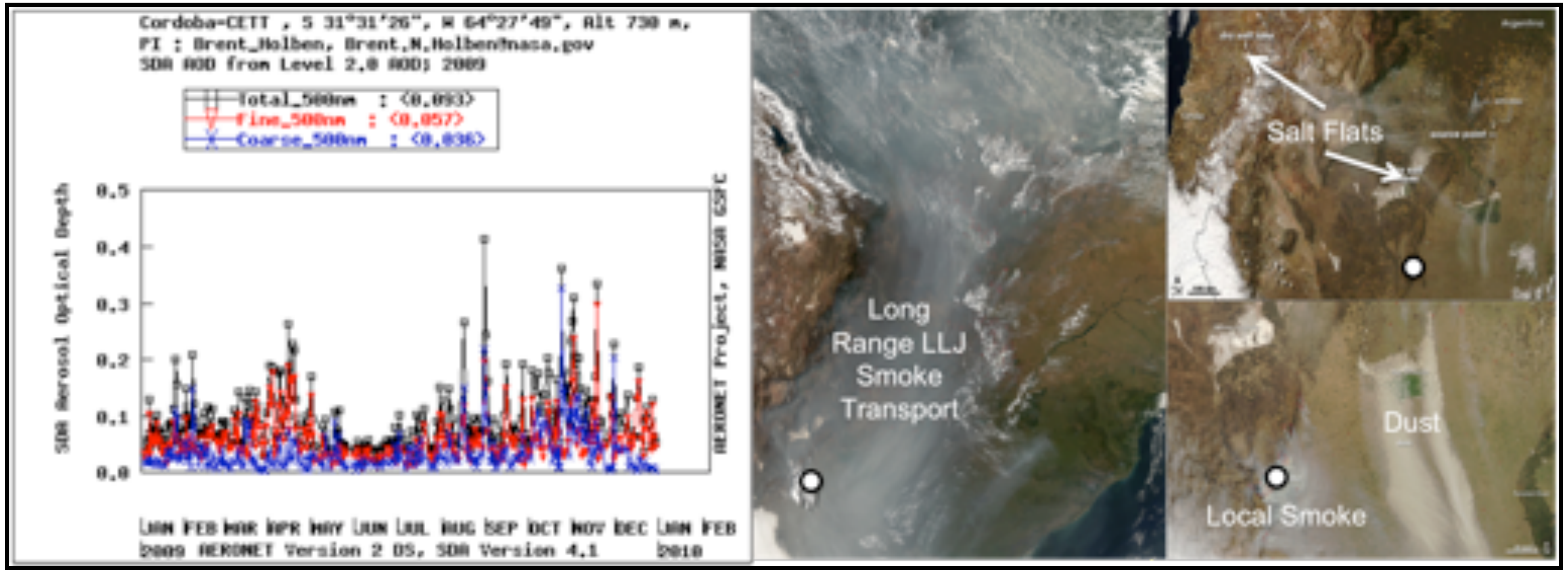
Adam Theisen, Ken Kehoe, Austin King, Sherman Beus: *Data Quality*

And so many others who contributed to engineering, import/export, installation, operations, communications, mentoring of instruments, and data quality/flow/storage without which CACTI would not exist!

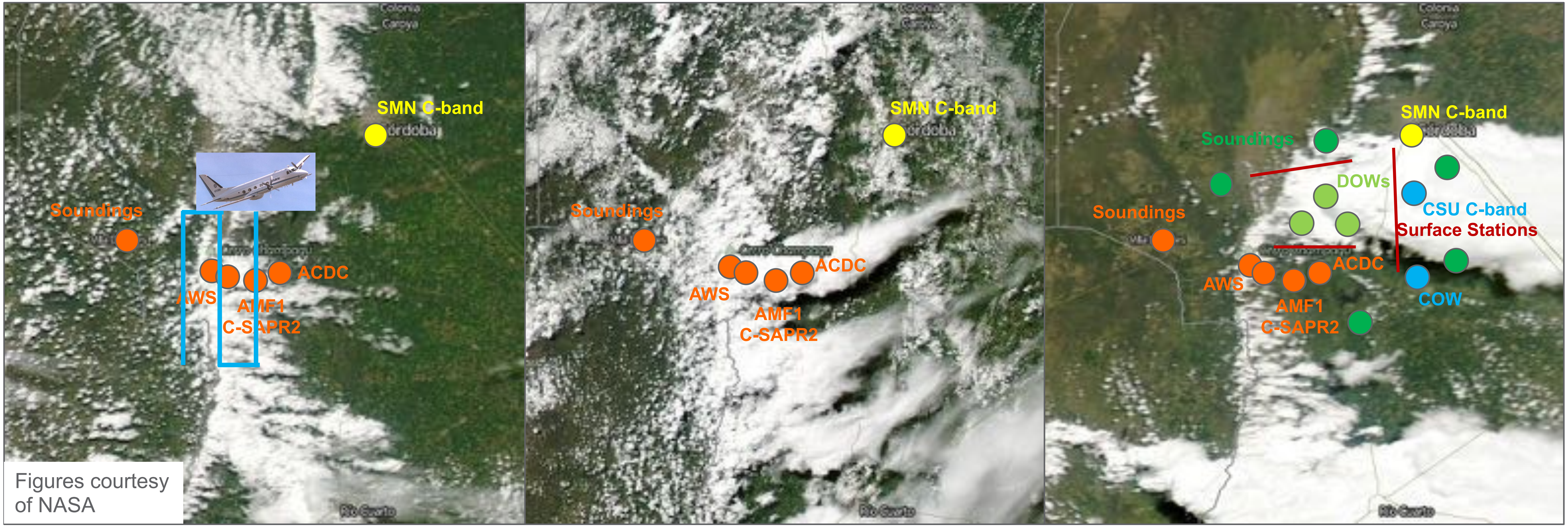
WHY ARGENTINA?

Experiment Rationale: Repeated Cumulus with Variable Aerosol and Land Surface Properties



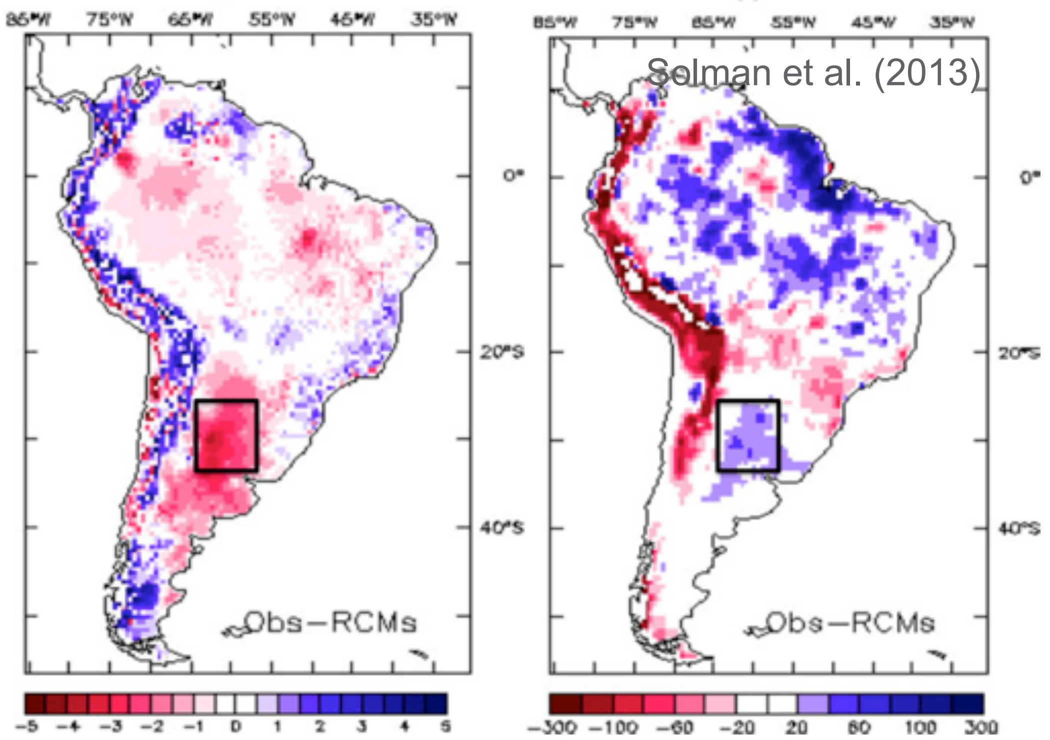


Experiment Rationale: Repeated Deep Convective Initiation

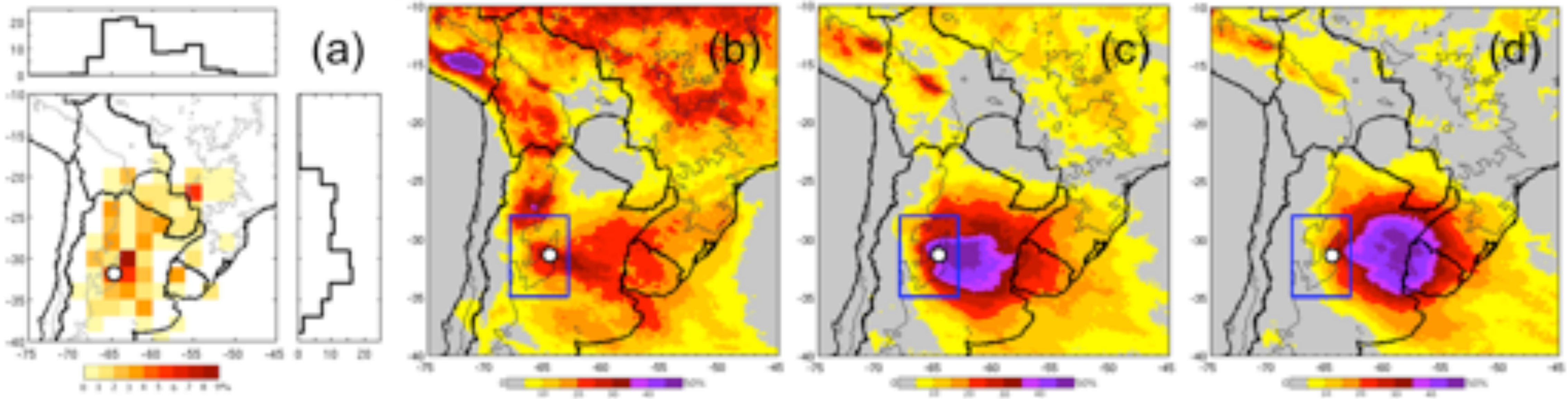


Experiment Rationale: Frequent Deep Convective Upscale Growth (Mesoscale Organization)

- Climate model ensemble mean 2-m temperature is warm-biased and precipitation is dry-biased in the summer from the Sierras de Córdoba eastward (right)
  - This is similar to the bias over the US Great Plains
- Also like the US Great Plains, an overwhelming majority of the precipitation in this region is produced by eastward propagating MCSs (bottom)



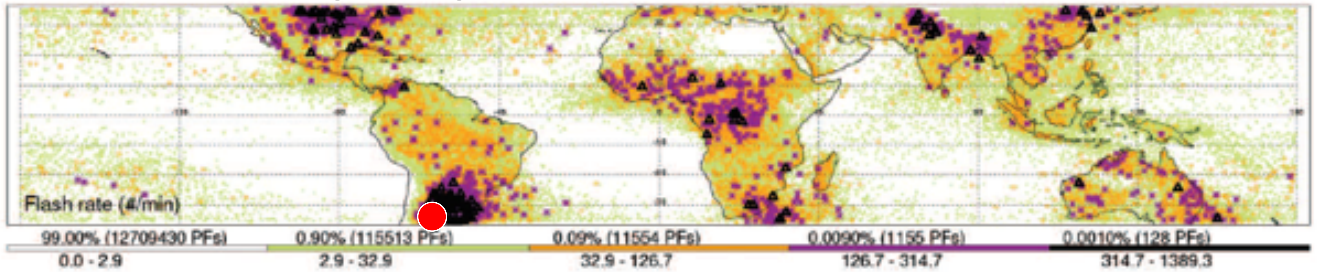
Time progression of cold cloud top temperature coverage for systems starting over the Sierras de Cordoba

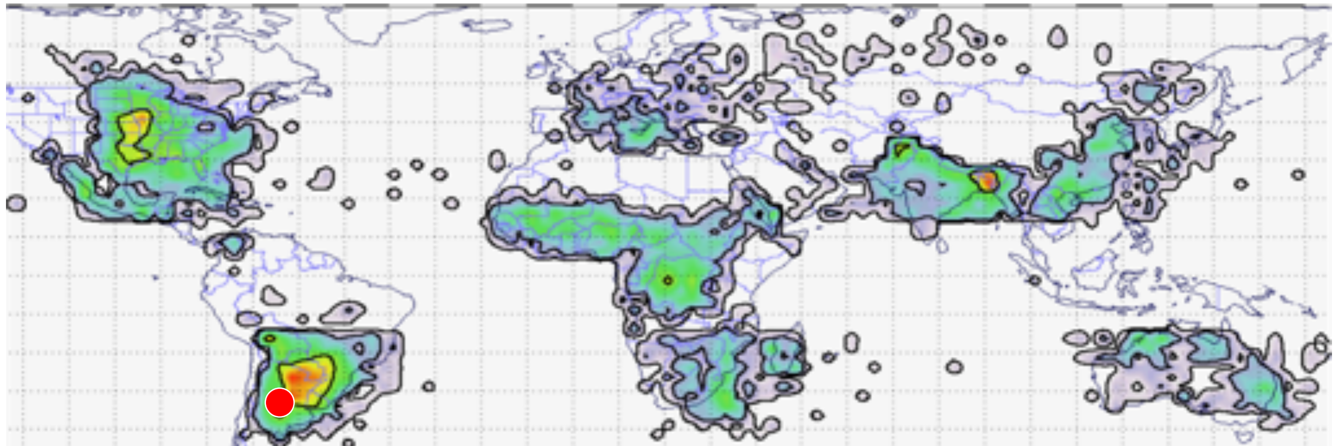


Vidal and Salio (2014)

Experiment Rationale: "Extreme" Deep Convection

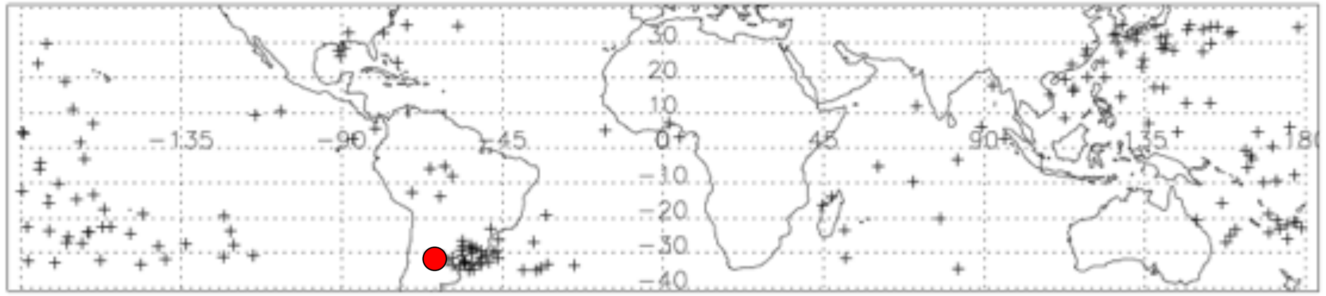
Most Extreme Lightning Flash Rates (Zipser et al. 2006)





Severe Hail Frequency Estimated from AMSR-E (Cecil and Blankenship 2012)

TRMM estimated systems with rainfall > 300,000 m³/s



C-band Reflectivity Vertical Cross-Section

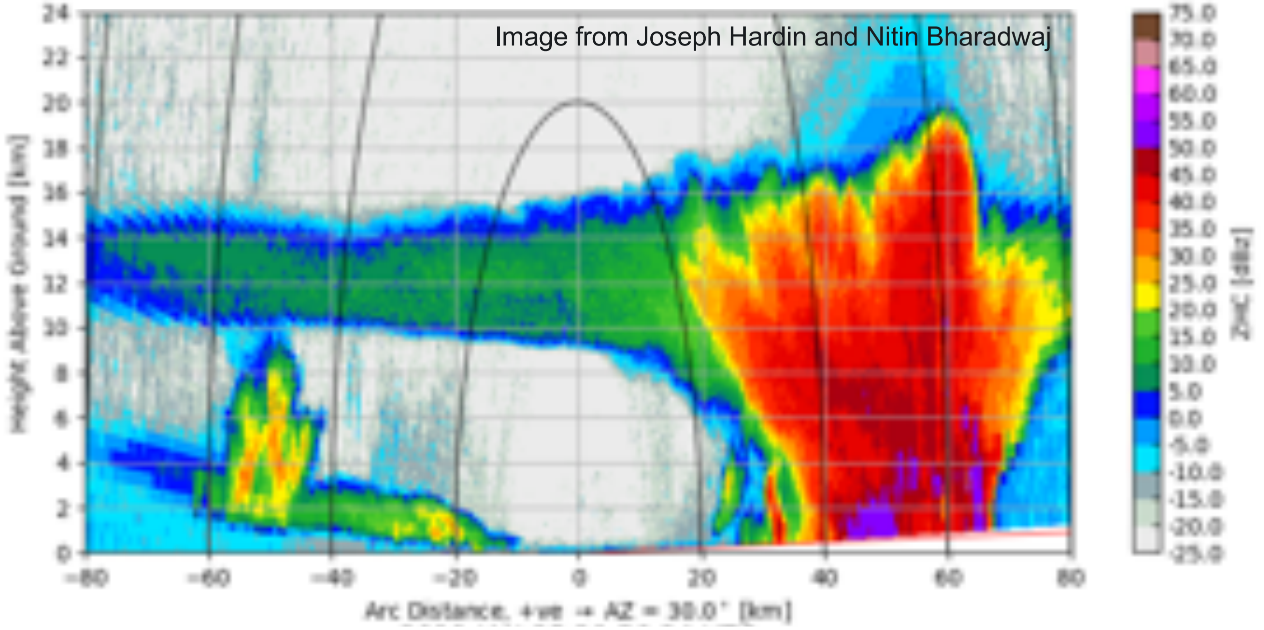


Photo and Video Courtesy of Paola Salio

CACTI OBJECTIVES

Pacific Northwest NATIONAL LABORATORY

Science Questions

1. How are the properties and lifecycles of orographically generated ~~boundary layer~~ clouds, including cumulus humulis, mediocris, congestus, and stratocumulus, affected by environmental kinematics, thermodynamics, aerosols, and surface properties?
   - How do these clouds types alter the lower free troposphere through detrainment?

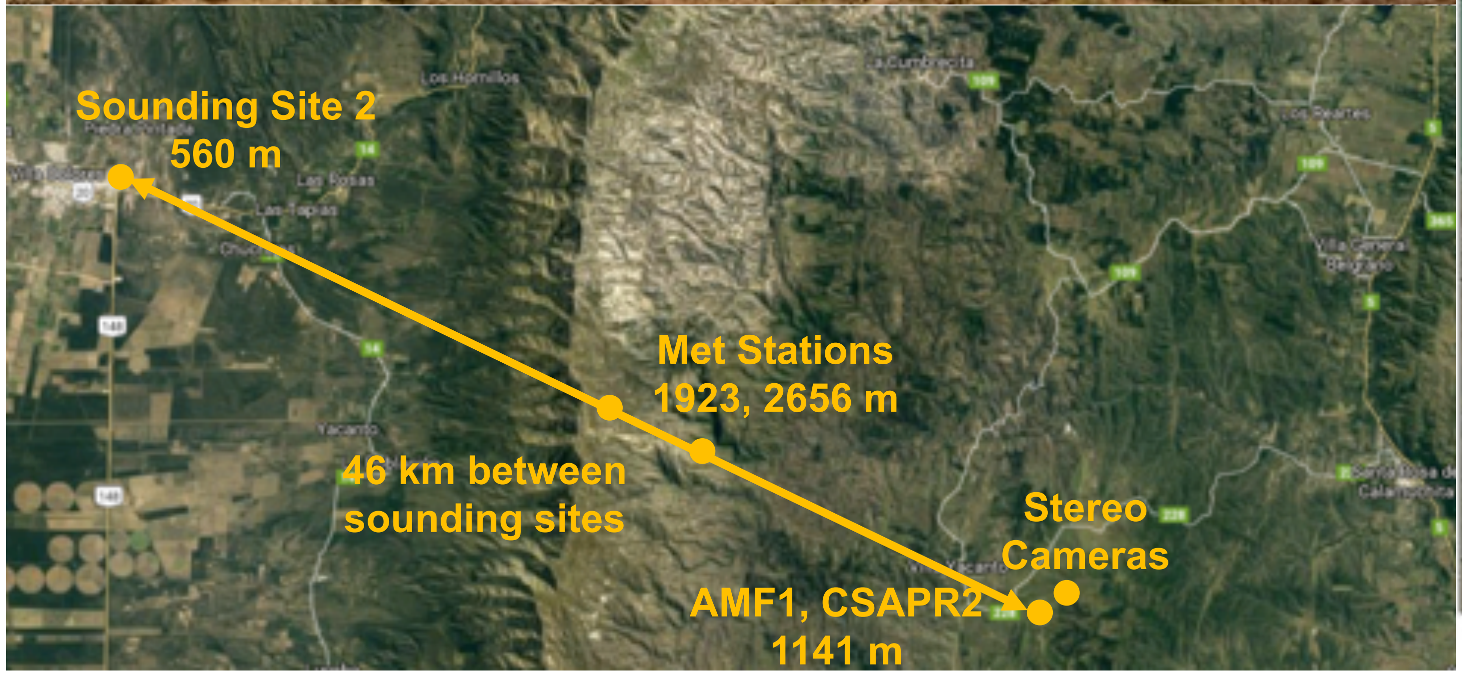
2. How do environmental kinematics, thermodynamics, and aerosols impact deep convective initiation, upscale growth, mesoscale organization, and system lifetime?
   - How are soil moisture, surface fluxes, and aerosol properties altered by deep convective precipitation events and seasonal accumulation of precipitation?

These questions are intentionally very general. The location in Argentina was primarily chosen because of its very high frequency of orographic convective clouds, specifically deep convective initiation and upscale growth, in a wide variety of environments uniquely observable from a fixed location.

CACTI MEASUREMENTS

Siting


Photo by Jason Tomlinson



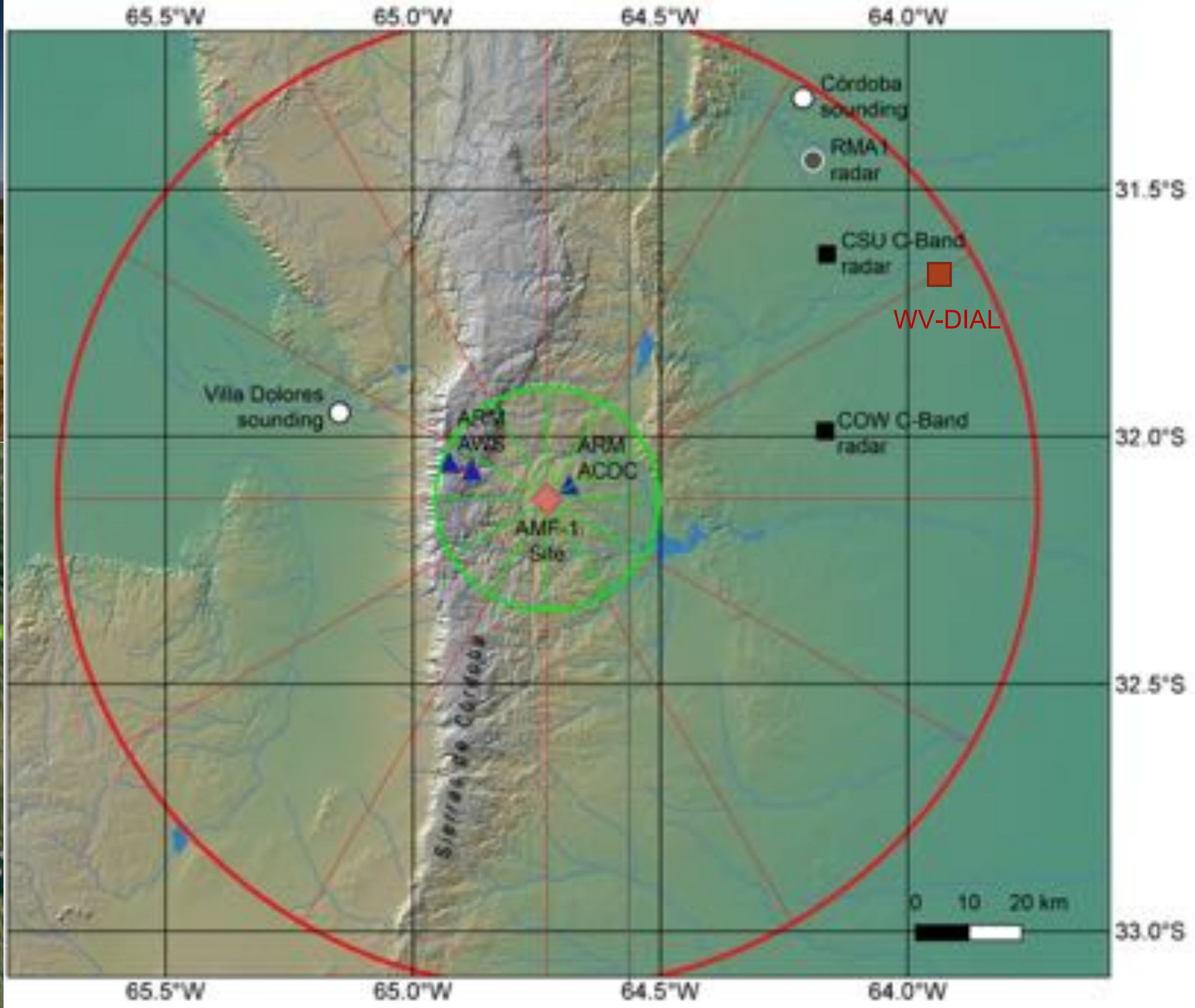


Figure courtesy of Steve Nesbitt

Siting


Photo by Jason Tomlinson


Photo by Paloma Borque

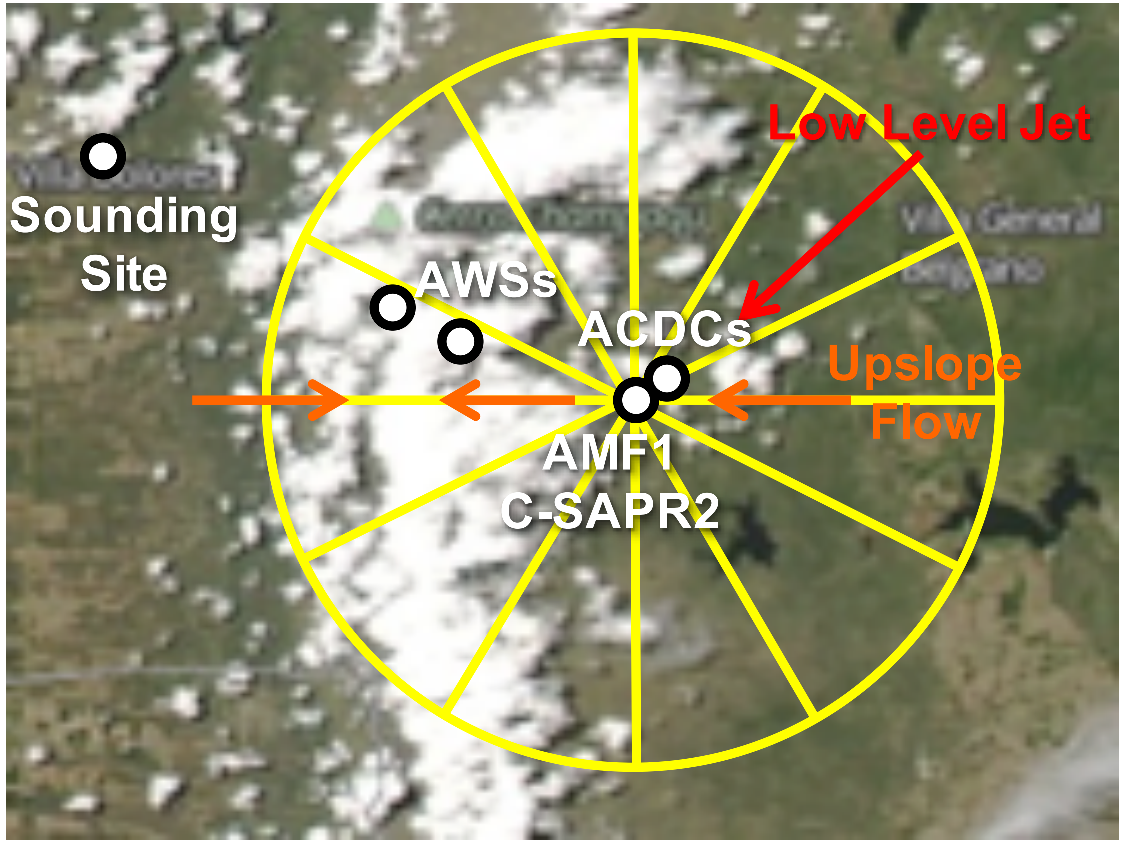
Ground Instrumentation

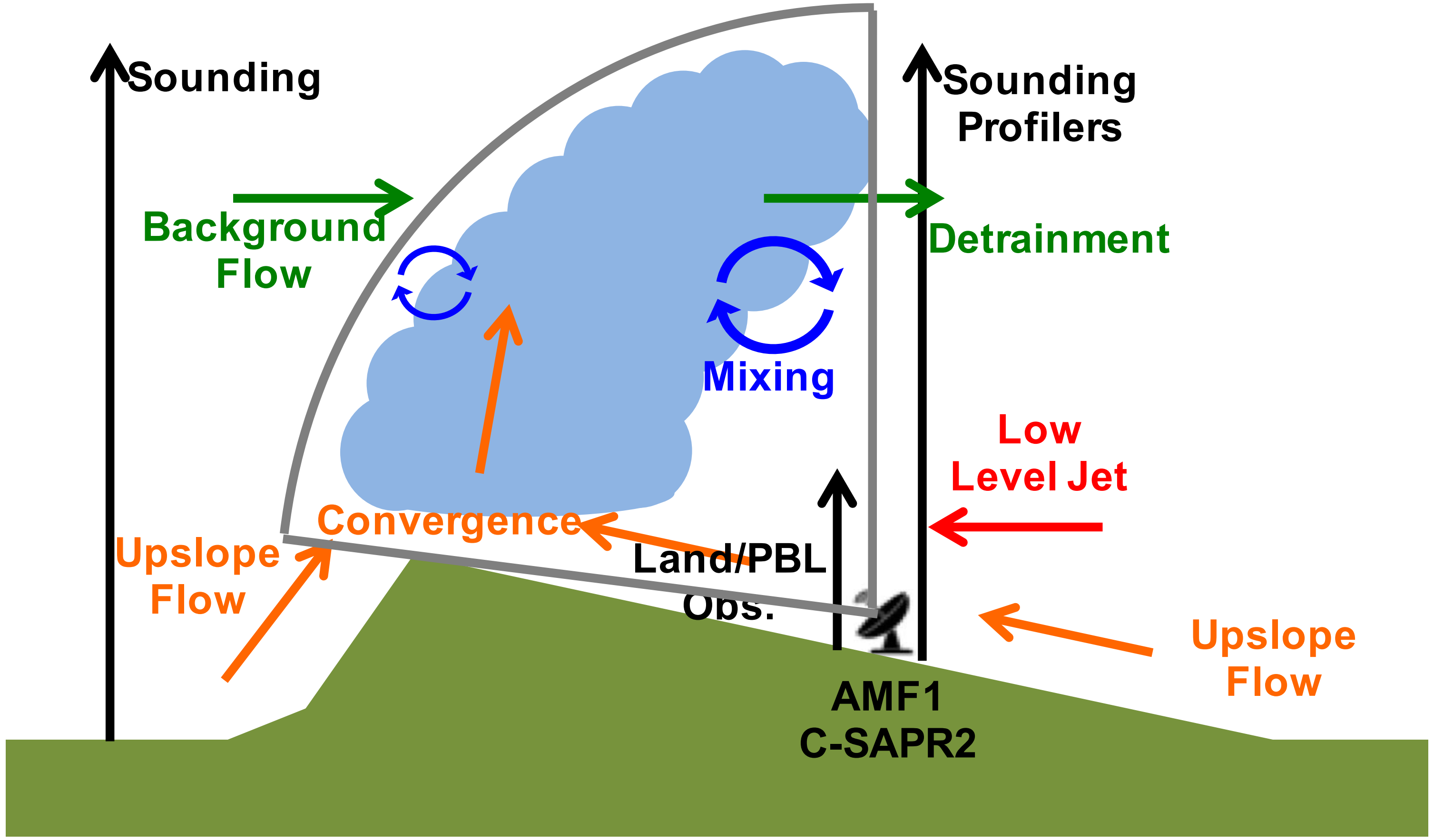
Property	Instrument
Hydrometeor radar reflectivity, Doppler velocity and spectra, cloud/precipitation kinematic and microphysical retrievals	C-band Scanning ARM Precipitation Radar (C-SAPR2) Ka/X-band Scanning ARM Cloud Radar (X/Ka-SACR) Ka-band ARM Cloud Radar (KAZR) Radar wind profiler (precipitation mode)
Heights of cloud bases and tops, cloud sizes and vertical velocities	ARM Cloud Digital Cameras (ACDC)
Cloud base height	Ceilometer
Cloud scene/fraction	Total Sky Imager (TSI)
Raindrop size distribution, fall speeds, rainfall	Laser disdrometer 2D video disdrometer (2DVD) Tipping bucket rain gauge Weighing bucket rain gauge Optical rain gauge
Liquid water path, precipitable water	2-Channel Microwave Radiometer (MWR-2C) 3-Channel Microwave Radiometer (MWR-3C) Microwaver Radiometer Profiler (MWR-P) High-Frequency Microwave Radiometer (MWR-HF)
Surface pressure, temperature, humidity, winds, visibility	Surface meteorological instrumentation
Vertical profiles of temperature, humidity, winds	Balloon-borne sounding system Radar wind profiler (wind mode) Microwave Radiometers
Boundary layer winds and turbulence	Doppler lidar Sodar
Surface latent and sensible heat fluxes, CO_2 flux, turbulence, soil moisture, energy balance	Eddy Correlation flux measurement system (ECOR) Surface Energy Balance System (SEBS)

Ground Instrumentation

Property	Instrument
Upwelling and downwelling radiation	Downwelling sky shortwave, infrared, and spectral radiometers Upwelling ground infrared and spectral radiometers Atmospheric Emitted Radiation Interferometer (AERI) Multifilter radiometer Multifilter Rotating Shadowband Radiometer (MFRSR) Infrared thermometer – ground and sky 2-Channel Narrow Field of View Zenith Radiometer Hemispheric Shortwave Array Spectroradiometer Zenith Shortwave Array Spectroradiometer
Aerosol backscattered radiation profile	Micropulse lidar Doppler lidar
Aerosol optical depth	Cimel Sun photometer Multifilter Rotating Shadowband Radiometer (MFRSR)
Cloud condensation nuclei concentration	Dual Column Cloud Condensation Nuclei (CCN) counter
Condensation nuclei concentration	Condensation Particle Counters (CPC, UCPC)
INP concentration	Filters for offline processing in CSU ice spectrometer
Aerosol chemical composition	Aerosol Chemistry Speciation Monitor (ACSM)
Black carbon	Single Particle Soot Photometer (SP2)
Aerosol extinction	Ambient and variable humidity nephelometers
Aerosol absorption	Particle Soot Absorption Photometer (PSAP)
Aerosol particle size distribution	Ultra-High Sensitivity Aerosol Spectrometer (UHSAS) Scanning Mobility Particle Sizer (SMPS) Aerodynamic Particle Sizer (APS)
O_3, CO, N_2O, H_2O concentration	Trace gas instrument system

Measurement Strategy





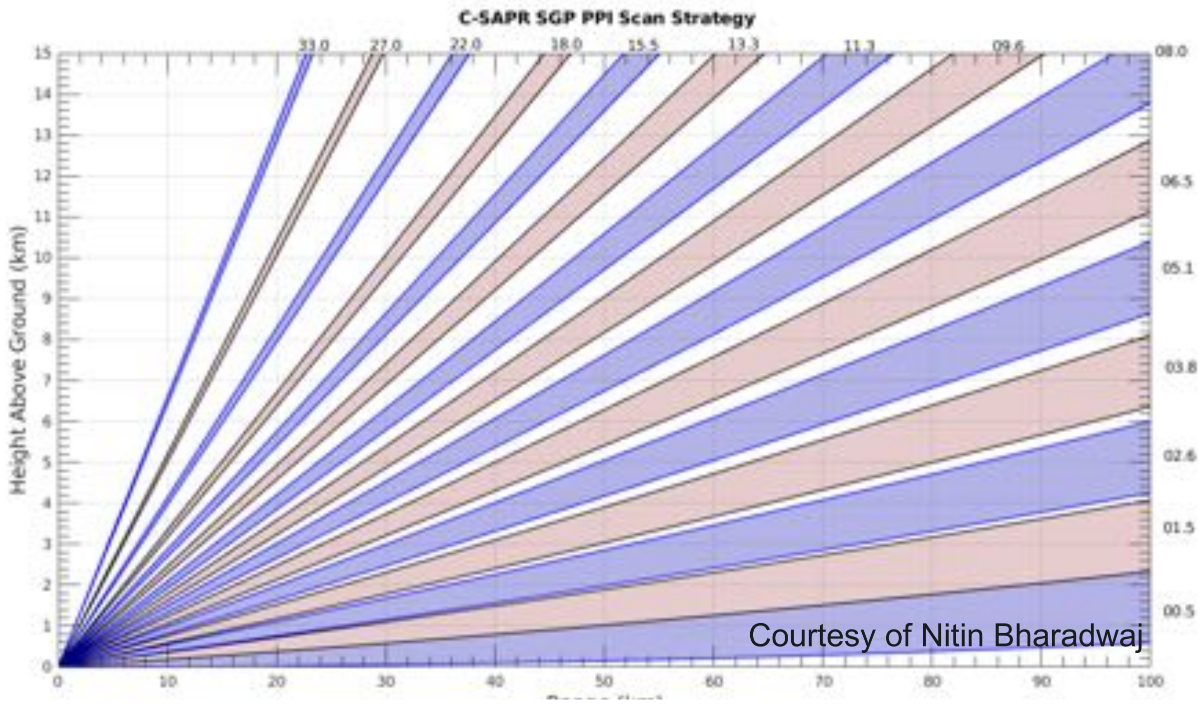
Measure cloud base inflow properties with in situ/remote sending measurements of clouds, precipitation, and cloud-detrained air properties in the free troposphere

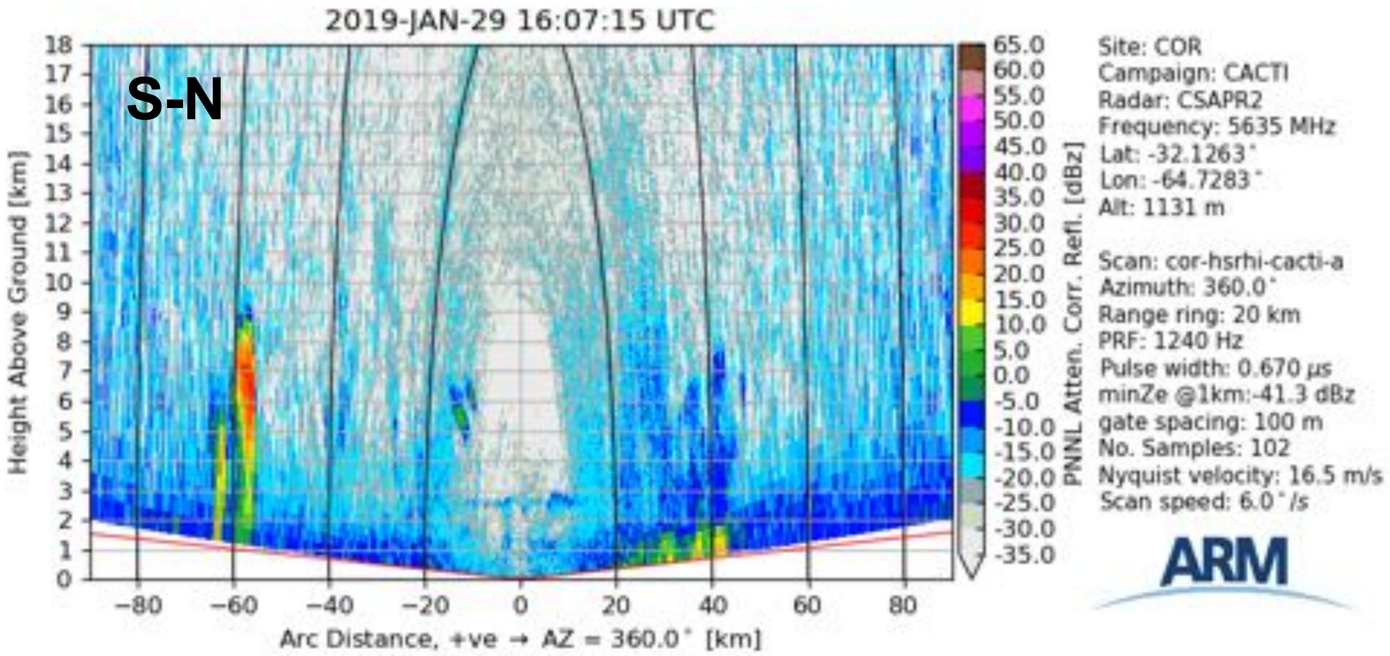
On site operations is limited to daytime (9 AM to 9 PM local – 12Z to 0Z) with 4-5 AMF site soundings (every 3-4 hours) and 2-3 upstream soundings (every 6 hours)

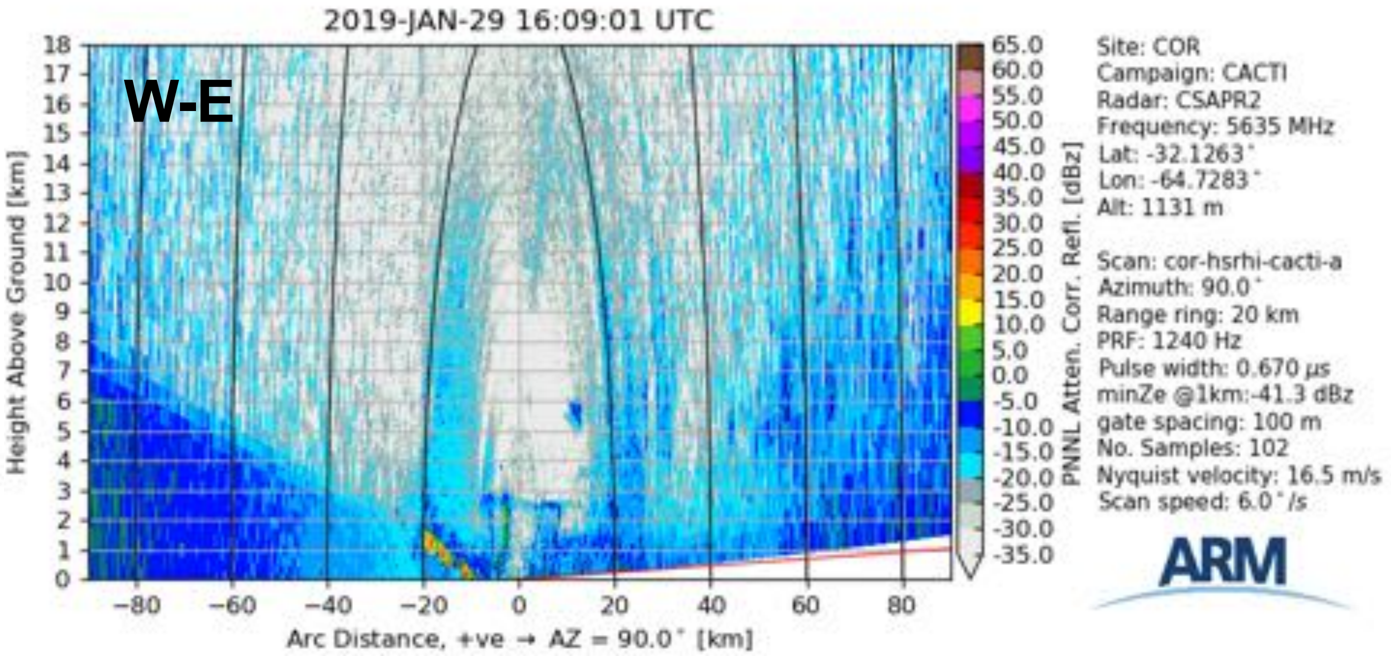
Two automated weather stations at higher elevations and stereo cameras to monitor cumulus evolution

C-SAPR2 Scans

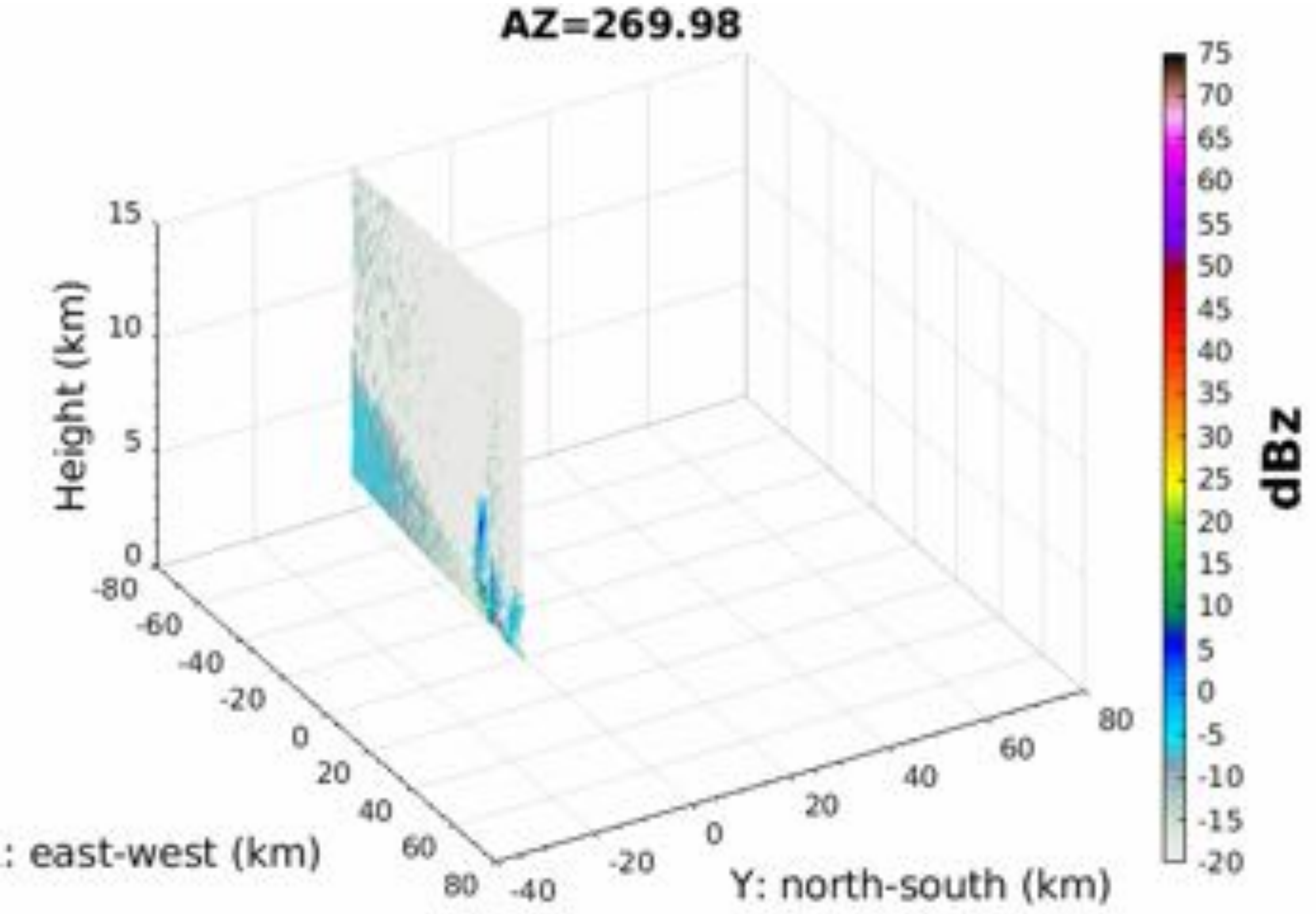
- 15-min update cycle (Oct 15-March 1)
  - 15-tilt PPI “volume”
  - ZPPI
  - 6-azimuth hemispheric RHI (HSRHI) pattern
  - Repeat 6-azimuth HSRHI pattern
- During the IOP, HSRHI patterns were occasionally replaced with sector RHIs targeting convective cells displaced from the AMF site
- Downtime: Dec 27-Jan 20, Feb 9-21, March 2-7
- Starting March 7th, only W-E HSRHIs were performed because of unfixable azimuthal rotation issue







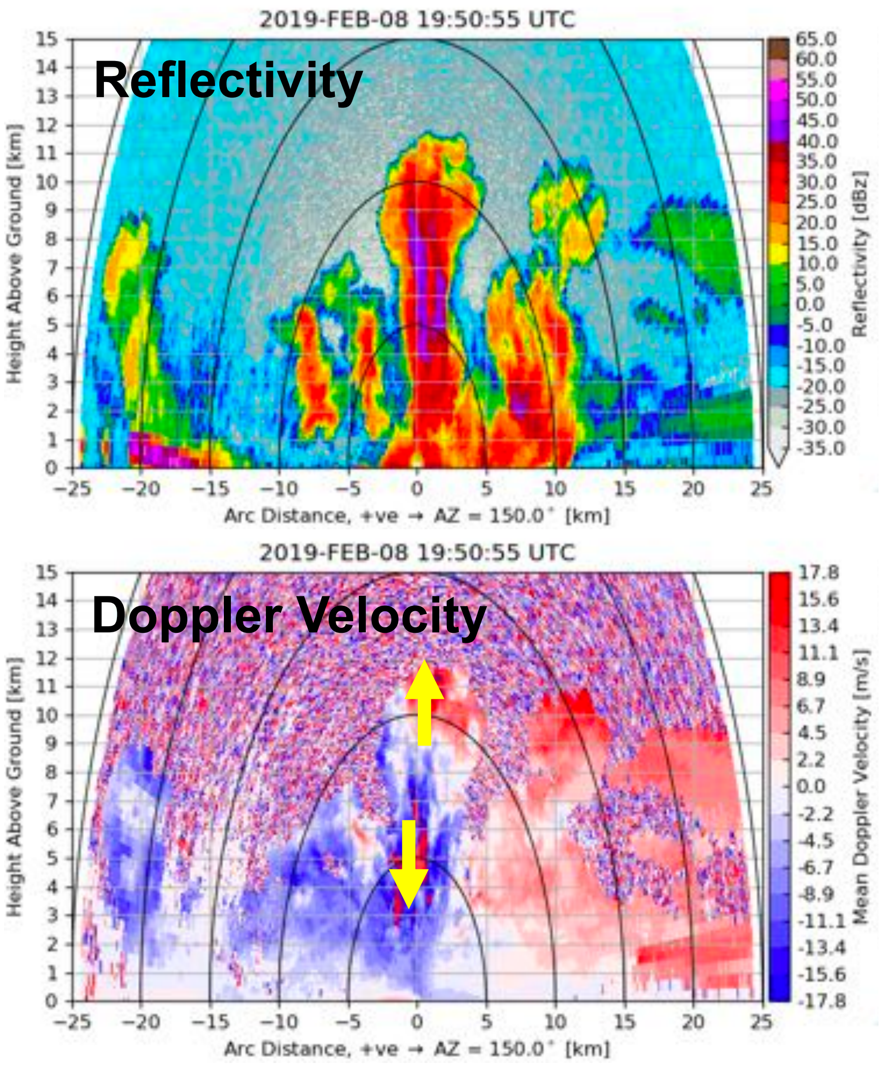
C-SAPR2 Scans



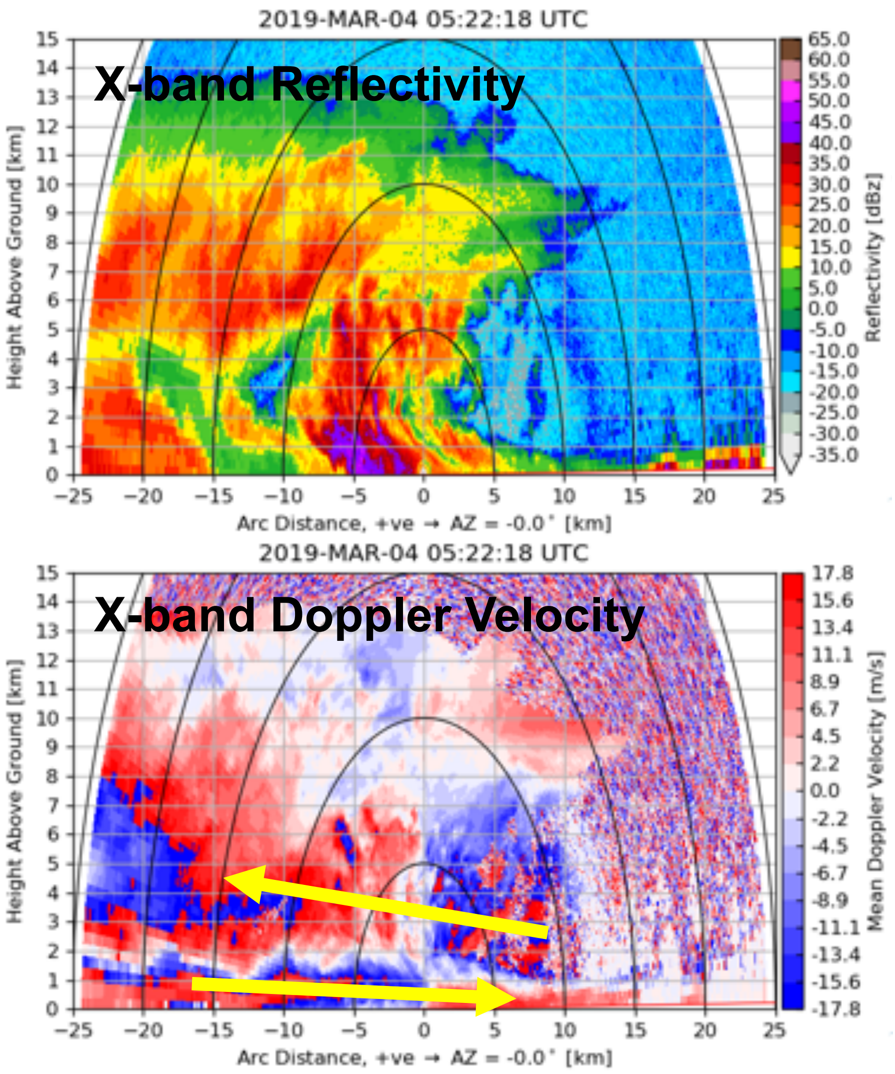
Courtesy of Nitin Bharadwaj

X-SACR Scans

- 15-min update cycle (Oct 15-Mar 5)
  - 30-deg sector RHI (every 3 deg between 240 and 270 deg) within stereo camera FOV
  - 6-azimuth hemispheric RHI (HSRHI) pattern
  - Repeat 6-azimuth HSRHI pattern
  - Repeat 6-azimuth HSRHI pattern again
- Only limited outages
- Starting March 5th, a 15 tilt PPI “volume” was put in place to replace the sector RHI and 1 HSRHI pattern because of problems with C-SAPR2
  - Oversampling was decreased and range was increased to 62 km to “replace” missing C-SAPR2 scans



Imagery from Nitin Bharadwaj and Joseph Hardin

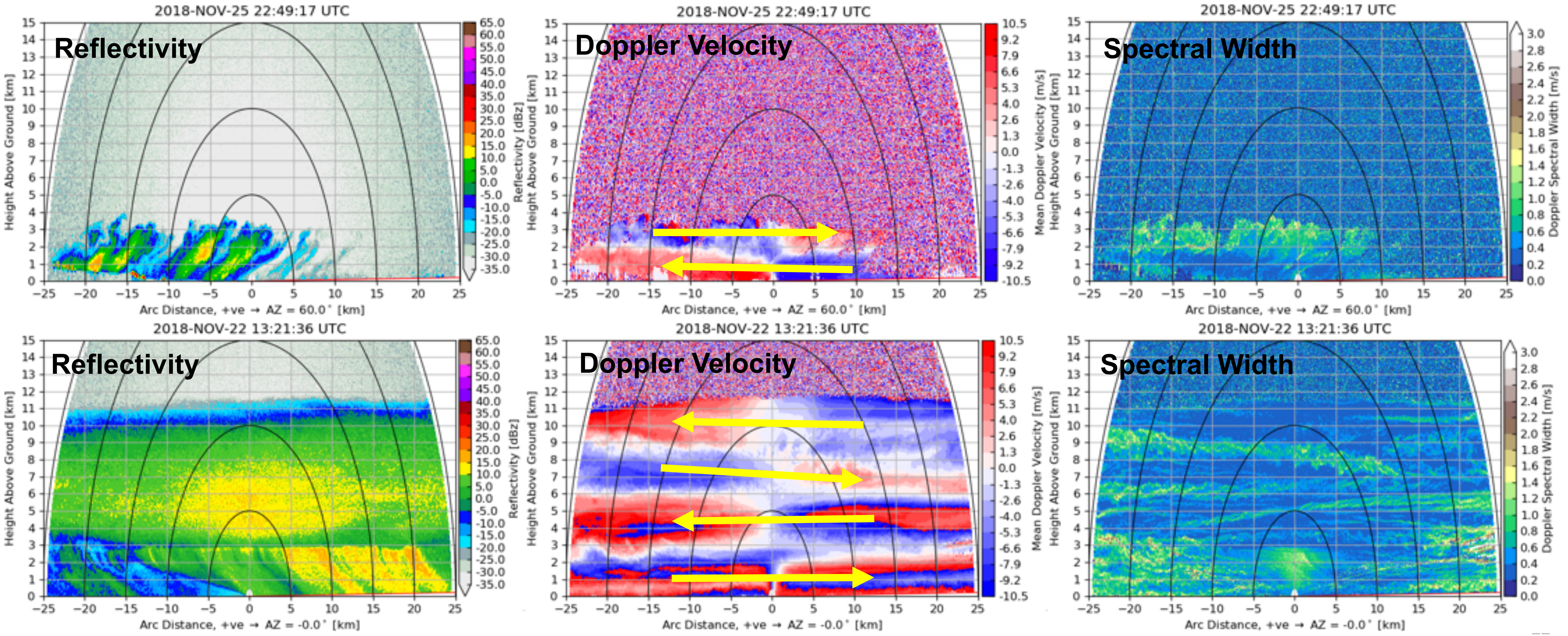


Images above from Joseph Hardin and Nitin Bharadwaj

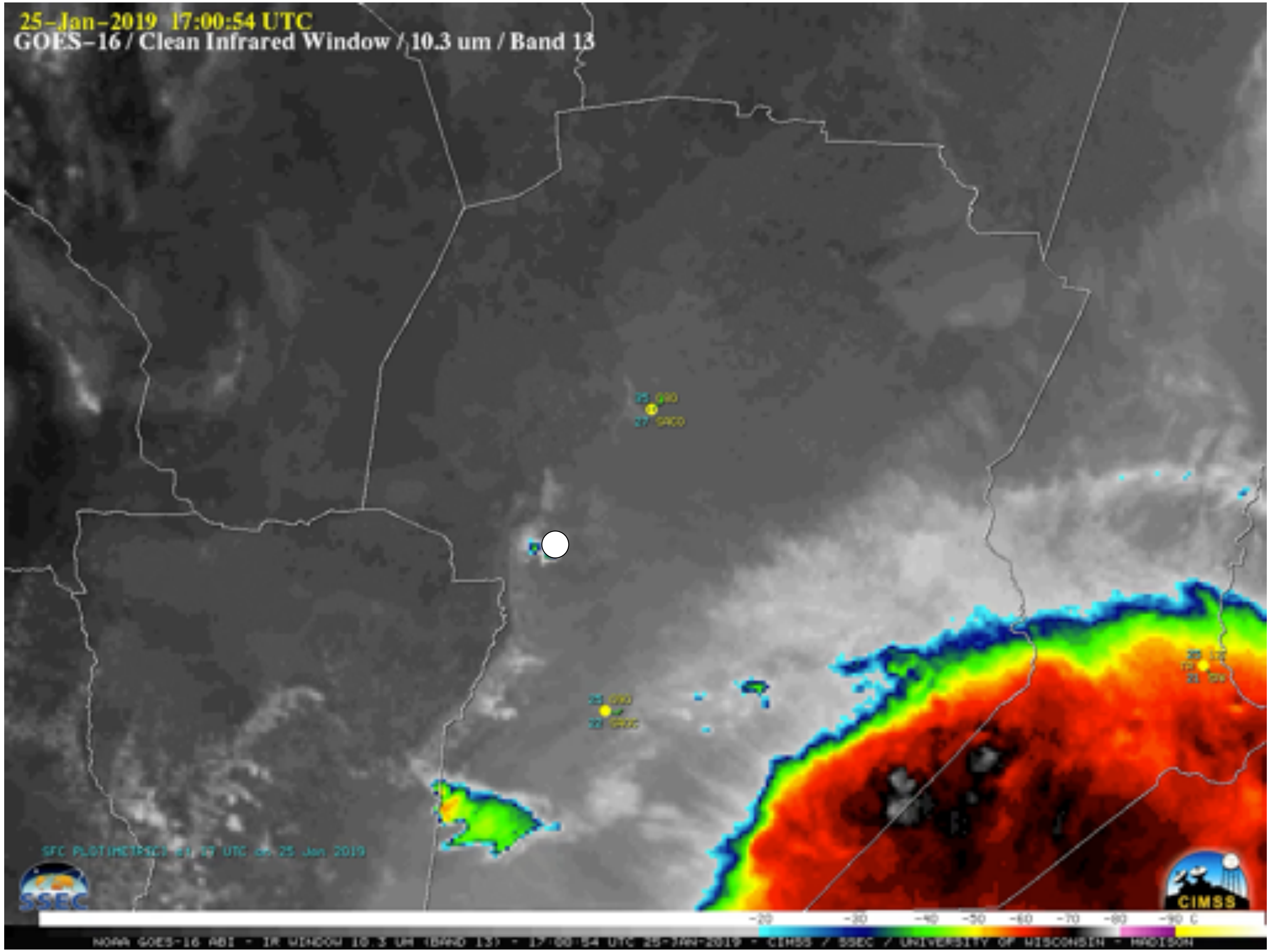
Ka-SACR Scans

- Same 15-min update cycle as X-SACR (Oct 15-March 5)
  - Sector RHI within Stereo Camera FOV
  - PPI volume replaced sector RHI and 1 HSRHI starting March 5

Imagery from Nitin Bharadwaj and Joseph Hardin



GOES-16 Products Courtesy of NOAA and NASA Langley



- 0.5-km visible and 2-km IR resolution
- 15-min temporal resolution
  - 1-min temporal resolution for many deep convective days
- Products from NASA Langley to be uploaded to the ARM archive:
  - Cloud Phase
  - Cloud Top Height, Temperature, and Pressure
  - Cloud Base Height and Pressure
  - Cloud Thickness
  - Optical Depth
  - Cloud Top Effective Radius
  - Liquid Water Path
  - Ice Water Path
  - Broadband Albedo
  - Broadband Longwave Flux
  - Overshooting Top Locations and Properties

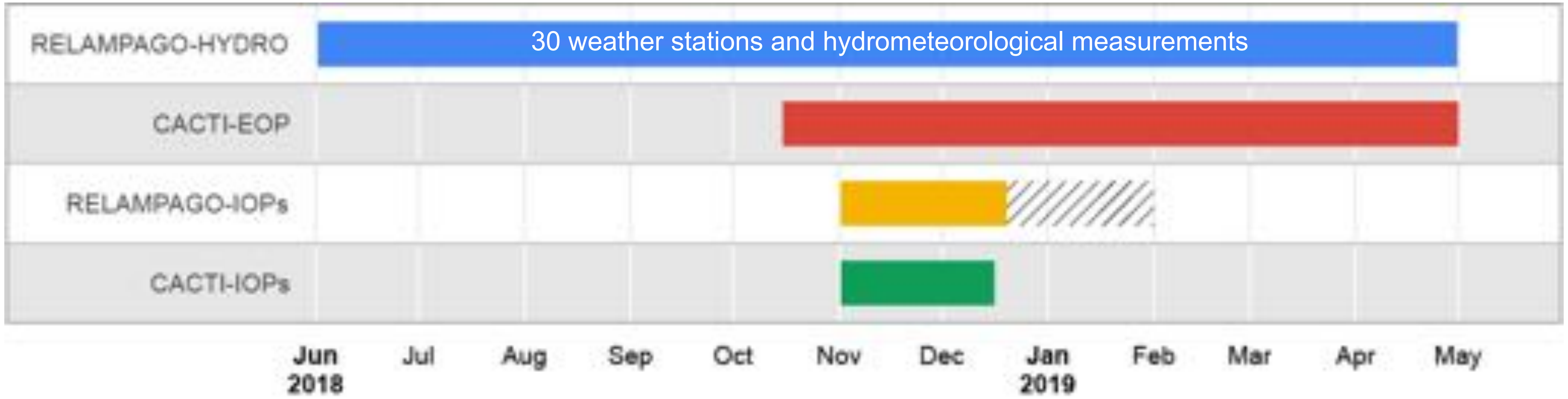
ARM Value Added and PI Product Plans

VAP	Measurement
AERINF	Longwave spectral radiances
QCRAD	QC'ed surface radiative fluxes
RADFLUX	Clear sky downwelling broadband radiation for computing CRE
AOP	Aerosol optical properties
AOD	Aerosol optical depth
AERIoe	Boundary layer temperature and humidity
DLPROF	3D wind profiles
PBLHT	Boundary layer height estimates
QCECOR	QC'ed latent and sensible surface fluxes
MWRRET	Precipitable water vapor and liquid water path estimates
INTERPSONDE	Temperature, humidity, pressure, and wind time-heights (no ECWMF)
MERGESONDE	Temperature, humidity, pressure, and wind time-heights (including ECMWF)
VARANAL	Large-scale advective tendencies
PCCPP	Cloud boundary locations and movements from stereo cameras
MPLCLDMASK	Cloud mask and depolarization ratio from micropulse lidar
KAZR-ARSCL	Cloud boundary time-heights with corrected KAZR reflectivity and velocity
CMAC2.0	Corrected radar measurements and retrievals
SatCORPS (Langley)	GOES-16 cloud retrievals at 1 or 15-min frequency depending on time period
ARMBE	Hourly best estimated climate relevant variables
Additional PI Products	Radar retrievals and Cartesian gridded products, and ice nucleating particle concentrations

Categorized Days: Overhead Clouds/Precipitation

Cloud Regime Over AMF Site	Dates
Cumulus Humulis, Congestus or Stratocumulus (183 out of 212 days)	October 1, 3, 4, 5, 6, 9, 10, 11, 12, 14, 16, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30 November 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 15, 16, 17, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30 December 1, 2, 3, 4, 5, 6, 7, 9, 10, 11, 12, 13, 14, 16, 17, 18, 19, 20, 21, 22, 25, 26, 27, 28, 29, 31 January 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 18, 19, 20, 21, 22, 23, 24, 25, 27, 28, 29, 30, 31 February 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 21, 22, 23, 24, 25, 26, 27 March 1, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 24, 25, 26, 27, 28, 29, 30, 31 April 1, 2, 4, 10, 11, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 29, 30
Deep Convection (80 out of 212 days)	October 14, 17, 18, 19, 22, 24, 25, 26, 28, 30, 31 November 3, 4, 5, 6, 10, 11, 12, 13, 17, 22, 26, 27, 29, 30 December 1, 2, 5, 6, 10, 13, 14, 18, 19, 20, 27, 28, 30 January 2, 3, 6, 9, 10, 13, 14, 15, 17, 22, 23, 24, 25, 26, 29, 30, 31 February 1, 8, 11, 12, 19, 21, 23, 24 March 4, 7, 8, 9, 15, 16, 17, 20, 25, 31 April 1, 15, 20, 21, 22, 24, 30
Surface Rainfall (96 out of 212 days)	October 1, 11, 12, 14, 17, 18, 19, 20, 22, 23, 24, 25, 26, 28, 30, 31 November 1, 3, 4, 5, 6, 7, 11, 12, 13, 22, 26, 27, 28, 29, 30 December 1, 2, 5, 10, 13, 14, 18, 19, 20, 27, 28, 30 January 2, 3, 6, 9, 10, 13, 14, 15, 17, 18, 22, 23, 25, 26, 29, 30, 31 February 1, 3, 8, 9, 11, 12, 22, 23, 24, 25, 26 March 4, 5, 8, 9, 11, 12, 14, 15, 16, 17, 19, 20, 26, 26, 31 April 1, 15, 20, 21, 22, 24, 25, 26, 27, 30

Combined Ground Resources with RELAMPAGO



- RELAMPAGO, a collaborative NSF-led campaign led by PI Steve Nesbitt, took place from **Nov 1 – Dec 18** overlapping the CACTI IOP period when the G-1 aircraft was in country and radar operators were at the AMF site
- RELAMPAGO deployed 2 C-band radars, 3 X-band DOWs, a water vapor DIAL lidar, 6 mobile radiosonde units, mobile met stations (pods), and lightning mapping arrays and electric field mills
- RELAMPAGO-Hydro (PIs Francina Dominguez, David Gochis, Marcelo Garcia) deployed a surface met/flux/stream gauge hydrology-focused regional network covering **all of CACTI**
- Argentina also supplied an operational C-band radar, many more radiosonde launches, and pre-existing regional met and hydrologic networks
- RELAMPAGO goals included bettering understanding of deep convective initiation, upscale growth, severe weather, lightning behavior, and regional hydrology.

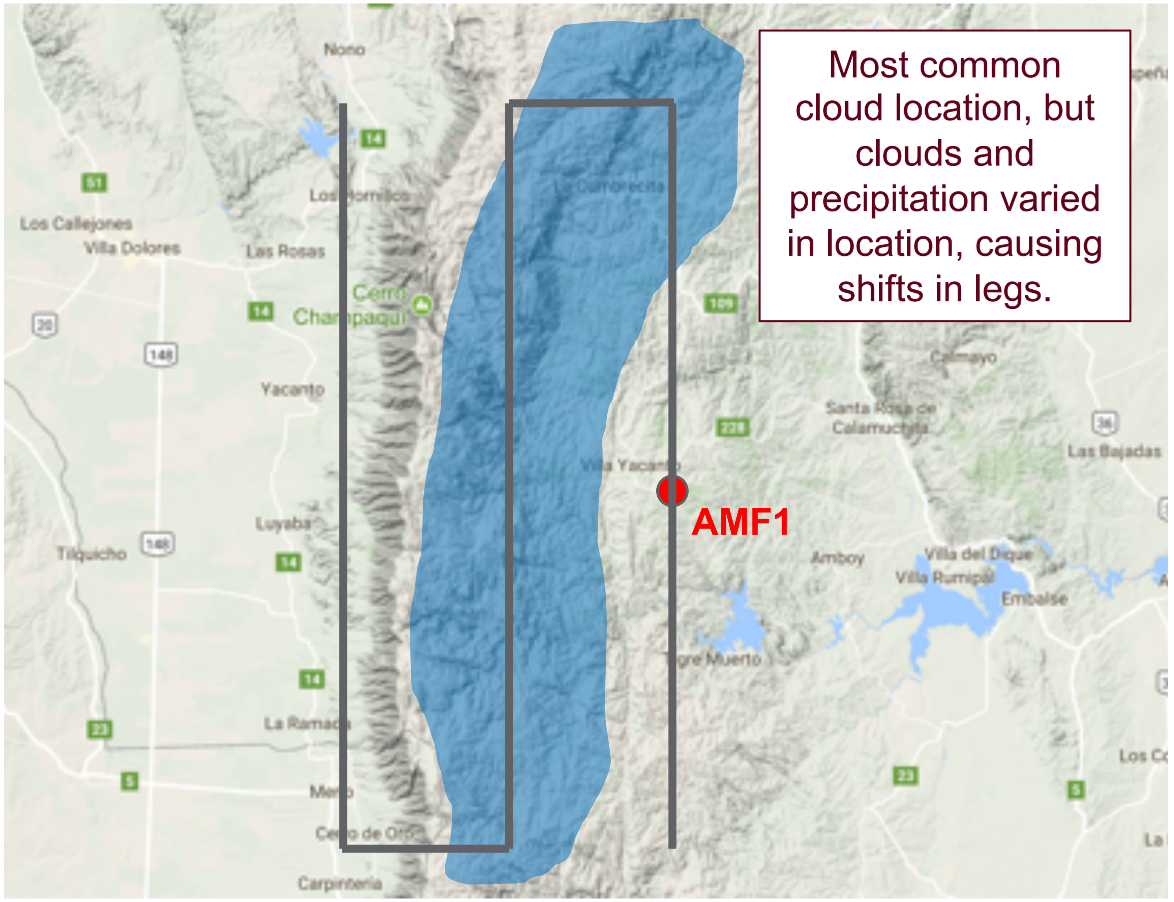
G-1 Flight Strategy

22 flights between November 4 and December 8, 2018

Timing: Mid morning to afternoon (2-4 hour flights)

Patterns: North-south, constant altitude legs with vertical spiral over the AMF1 for some flights

Altitudes: As low as possible in PBL, just below cloud base, mid cloud, and cloud top

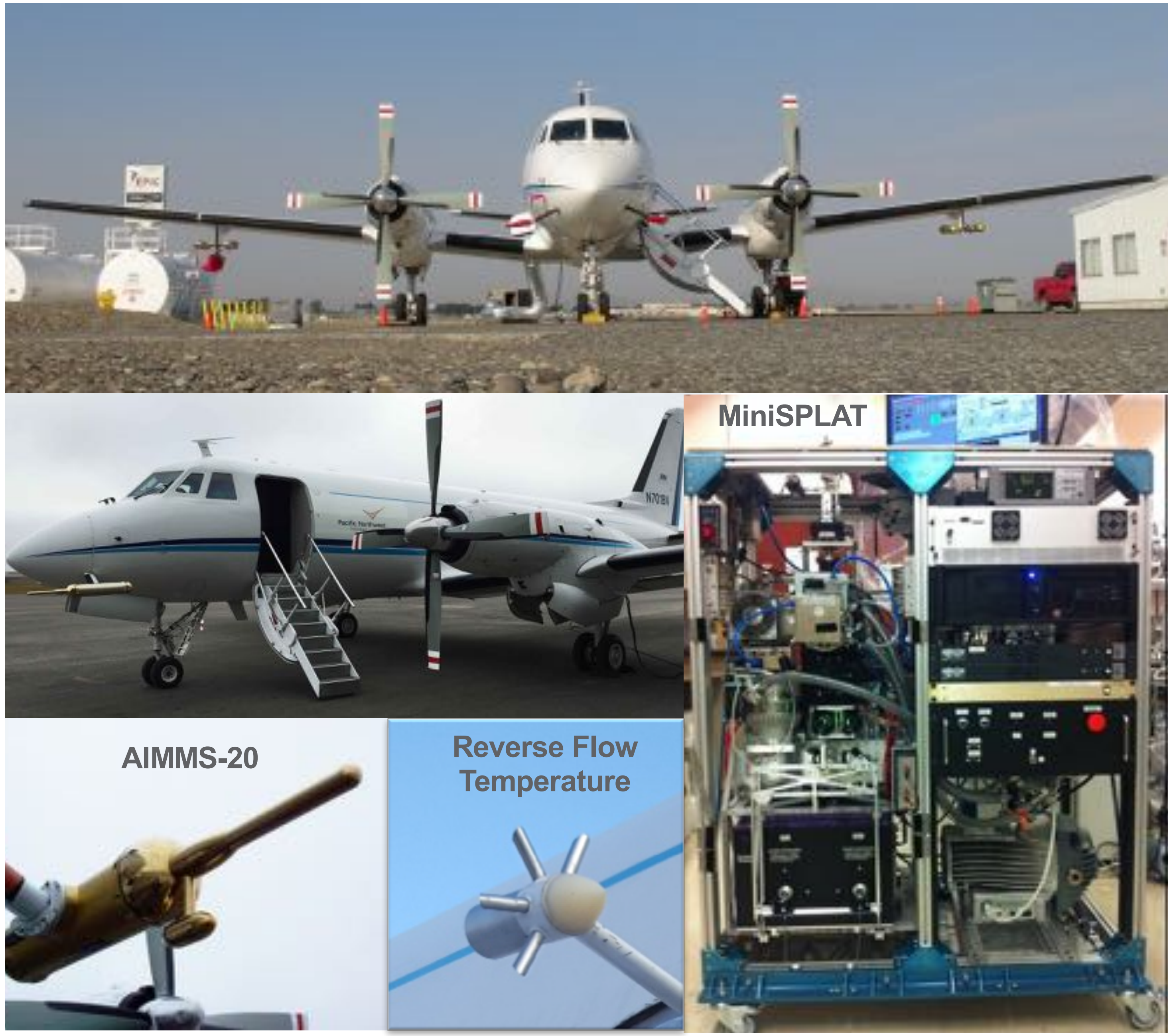


Objectives

1. Follow changes in aerosol properties from the surface to just below cloud base to in and out of clouds in the lower free troposphere
2. Measure high-resolution in situ relationships between convective cloud kinematic, microphysical, and macrophysical properties
3. Measure spatially varying thermodynamic, kinematic, and aerosol conditions in and around convective clouds including relationships with cloud microphysical and macrophysical evolution
4. Use measurements of hydrometeors and winds to fine tune radar retrievals of cloud properties

G-1 Instrumentation

Property	Instrument
Position/Aircraft parameters	Gust probe: Rosemount 1221F2
	AIMMS-20 GPS (Global Positioning System) DSM 232 C-MIGITS III (Miniature Integrated GPS/INS Tactical System) VN-200 GPS/INS
	Video Camera P1344
Meteorology	Aircraft Integrated Meteorological Measurement System (AIMMS-20)
	Tunable diode laser hygrometer (TDL-H)
	GE-1011B Chilled Mirror Hygrometer
	Licor LI-840A
	Rosemount 1201F1
	Rosemount E102AL
	Reverse flow temperature probe (100 Hz)
Aerosol optical properties	Single Particle soot Photometer (SP2)
	3-wavelength Integrating Nephelometer, Model 3563
	3-wavelength Particle Soot Absorption Photometer (PSAP)
	3-wavelength Single channel Tricolor Absorption Photometer (STAP)
Chemical composition	Single Particle Mass Spectrometer (MiniSPLAT II)
Trace Gas measurements	N2O/CO -23r
	O_3 Model 49i
	SO_2 Model 43i



Pacific Northwest
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G-1 Instrumentation

Property	Instrument
Hydrometeor size distribution	Fast Cloud Droplet Probe (F-CDP)
	Fast Forward Scattering Spectrometer Probe (F-FSSP)
	2-Dimensional Stereo Probe (2DS)
	High Volume Precipitation Sampler 3 (HVPS-3)
	Cloud Particle Imager (CPI)
	Cloud Imaging Probe (CIP)
	Cloud and Aerosol Spectrometer (CAS)
Cloud liquid water content	Particle Volume Monitor 100-A (PVM-100A)
	Multi-Element Water Content System (WCM-2000)
	Hot-wire probe from CAPS
Cloud extinction	Cloud Integrating Nephelometer (CIN)
Aerosol sampling	Aerosol Isokinetic Inlet
	Counterflow Virtual Impactor (CVI)
Aerosol size distribution	Ultra-high Sensitivity Aerosol Spectrometer (UHSAS)
	Scanning Mobility Particle Sizer (SMPS)
	Passive Cavity Aerosol Spectrometer (PCASP-100X)
	Optical Particle Counter (OPC) Model CI-3100
Aerosol number concentration	Ultrafine Condensation Particle Counter (UCPC) Model 3025A
	Condensation Particle Counter (CPC), Model 3772
Cloud condensation nuclei	Dual-column cloud condensation nuclei counters (CCN)
Ice nuclei concentration	Filter collections for CSU Ice Spectrometer

G-1 Flights

Primary Objective	# of Flights	Dates
Cumulus-Environment Interactions	8	Nov 16, 17, 20, 24, 25, 28 Dec 3, 7
Deep Convective Initiation	8	Nov 4, 6, 10, 12, 21, 29 Dec 4, 5
Microphysics Measurements Within Radar Scans	3	Nov 22 Dec 1, 2
Aerosol Characterization	3	Nov 14, 15 Dec 8

Photo by Jason Tomlinson

Photo by Jason Tomlinson

CACTI SCIENCE

Potential Research Topics

INTERACTIONS BETWEEN BOUNDARY LAYER CLOUDS AND THE ENVIRONMENT

- Land Surface Interactions
- Boundary Layer Interactions
- Free Tropospheric Interactions
- Aerosol Interactions

DEEP CONVECTIVE INITIATION AND ORGANIZATION

- Transition from Congestus to Cumulonimbus
- Dynamical, Microphysical, and Macrophysical Relationships
- Factors Controlling Mesoscale Organization
- Interactions with Aerosols and Land Surface Properties

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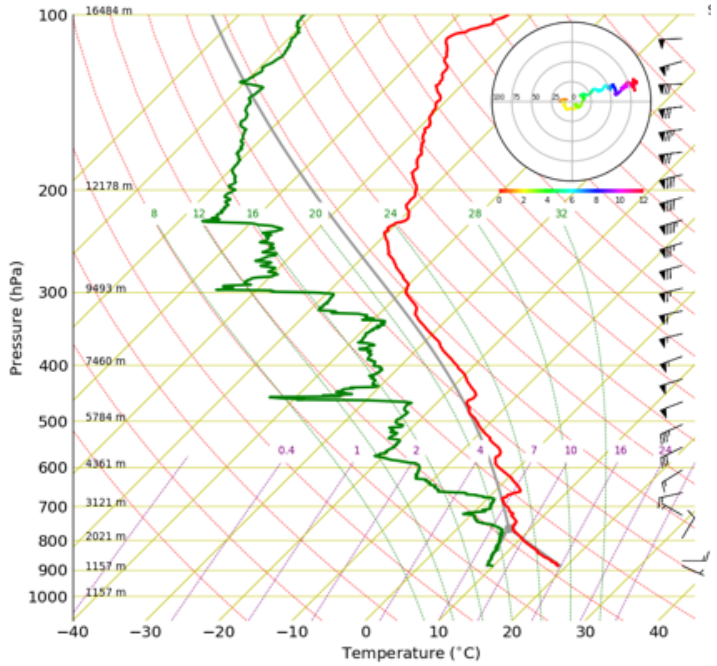
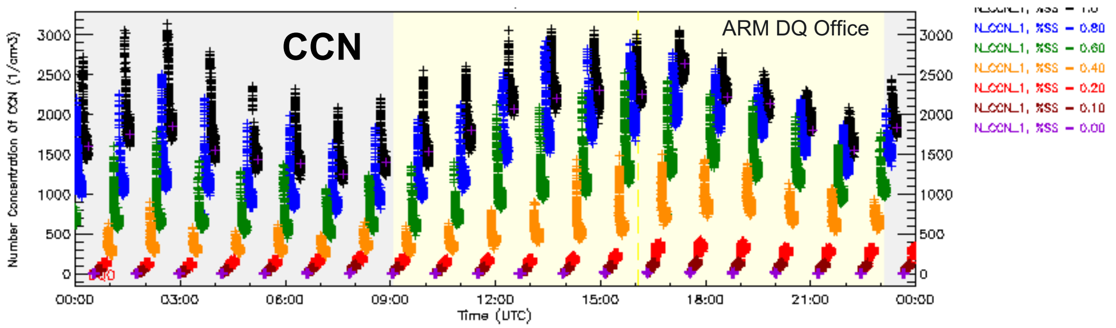
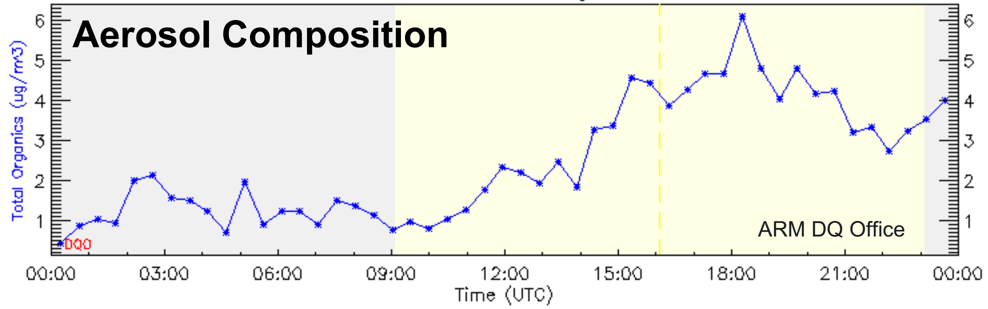
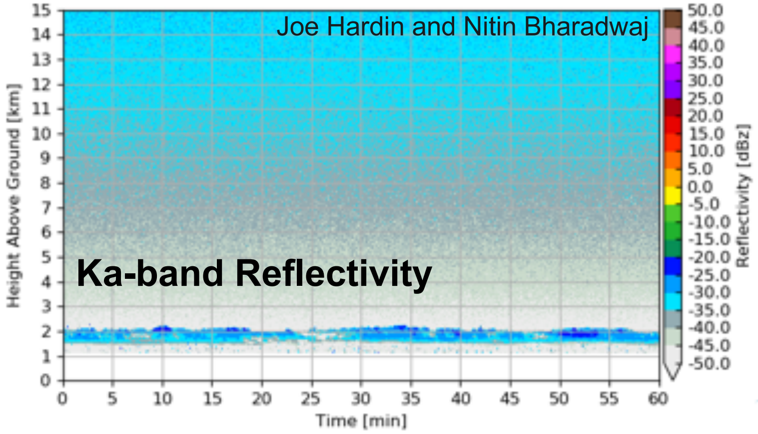
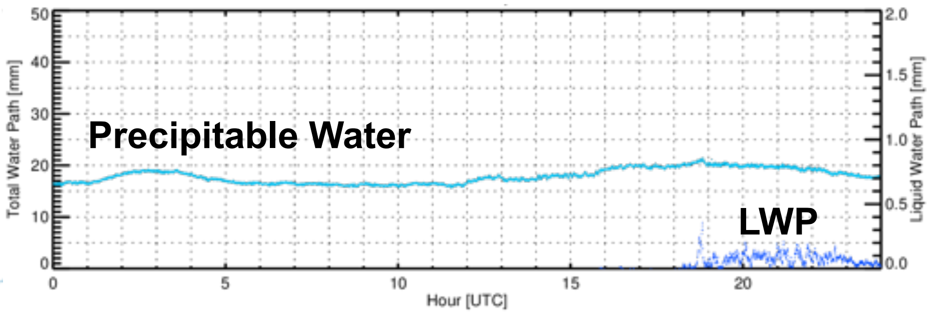
Land-Atmosphere-Aerosol-Cloud Interactions

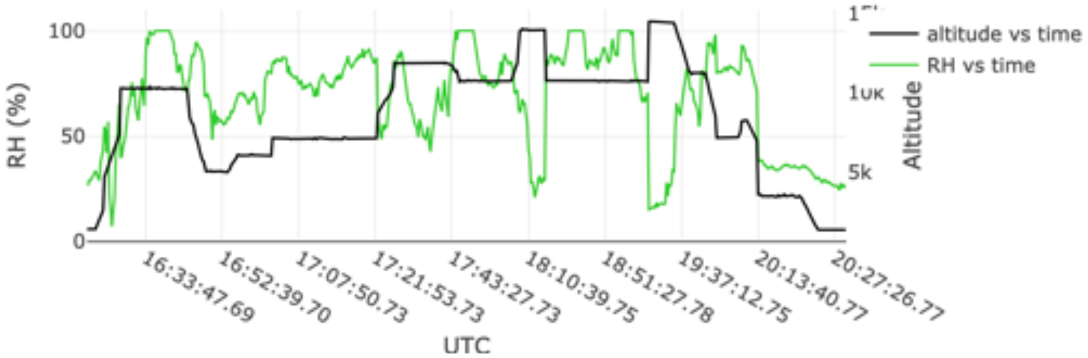




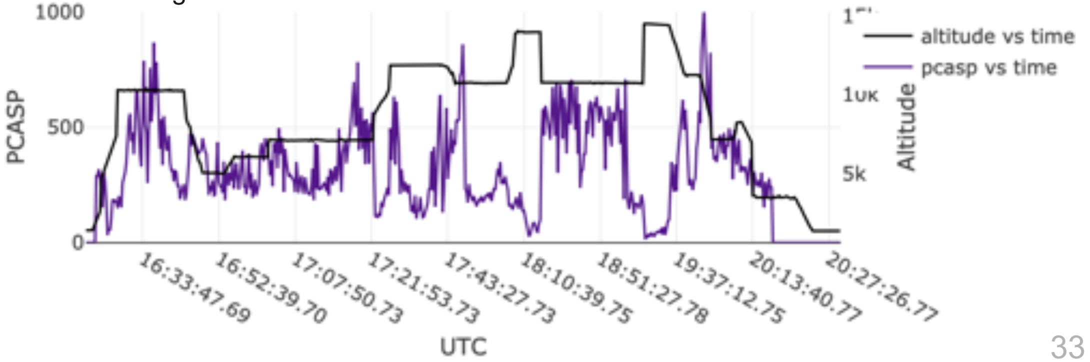


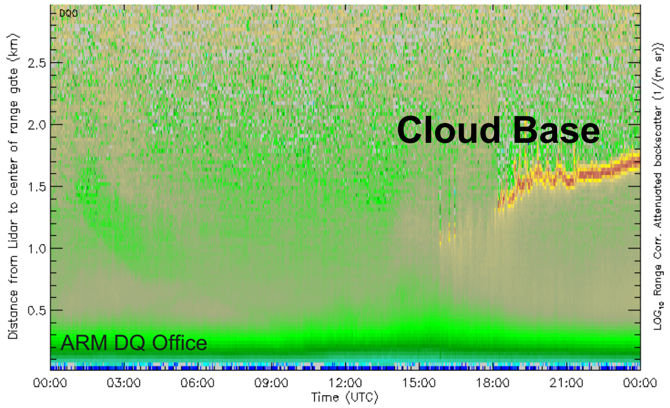


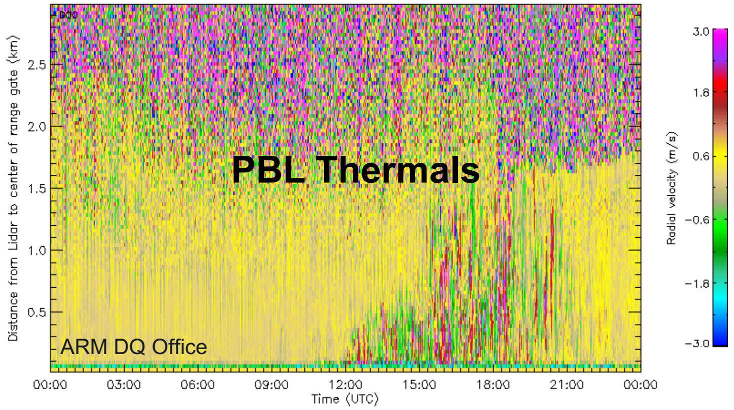




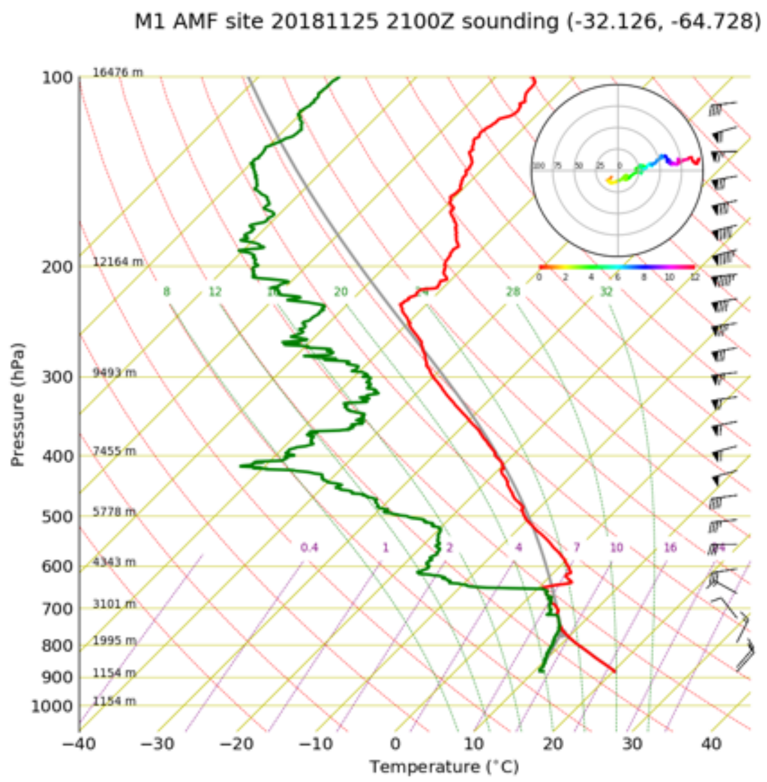
Images from AAF





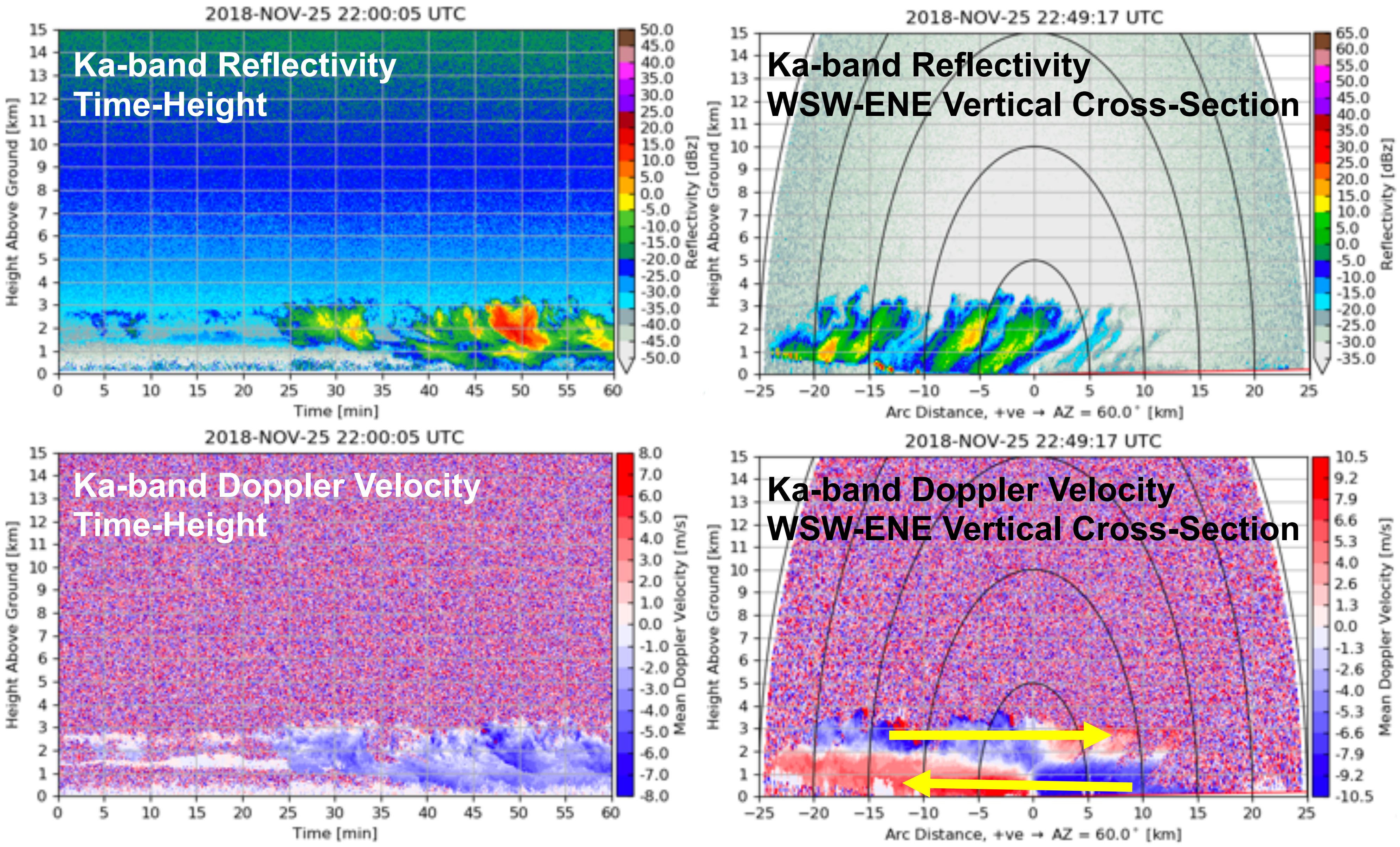


Shallow Convective Warm Rain



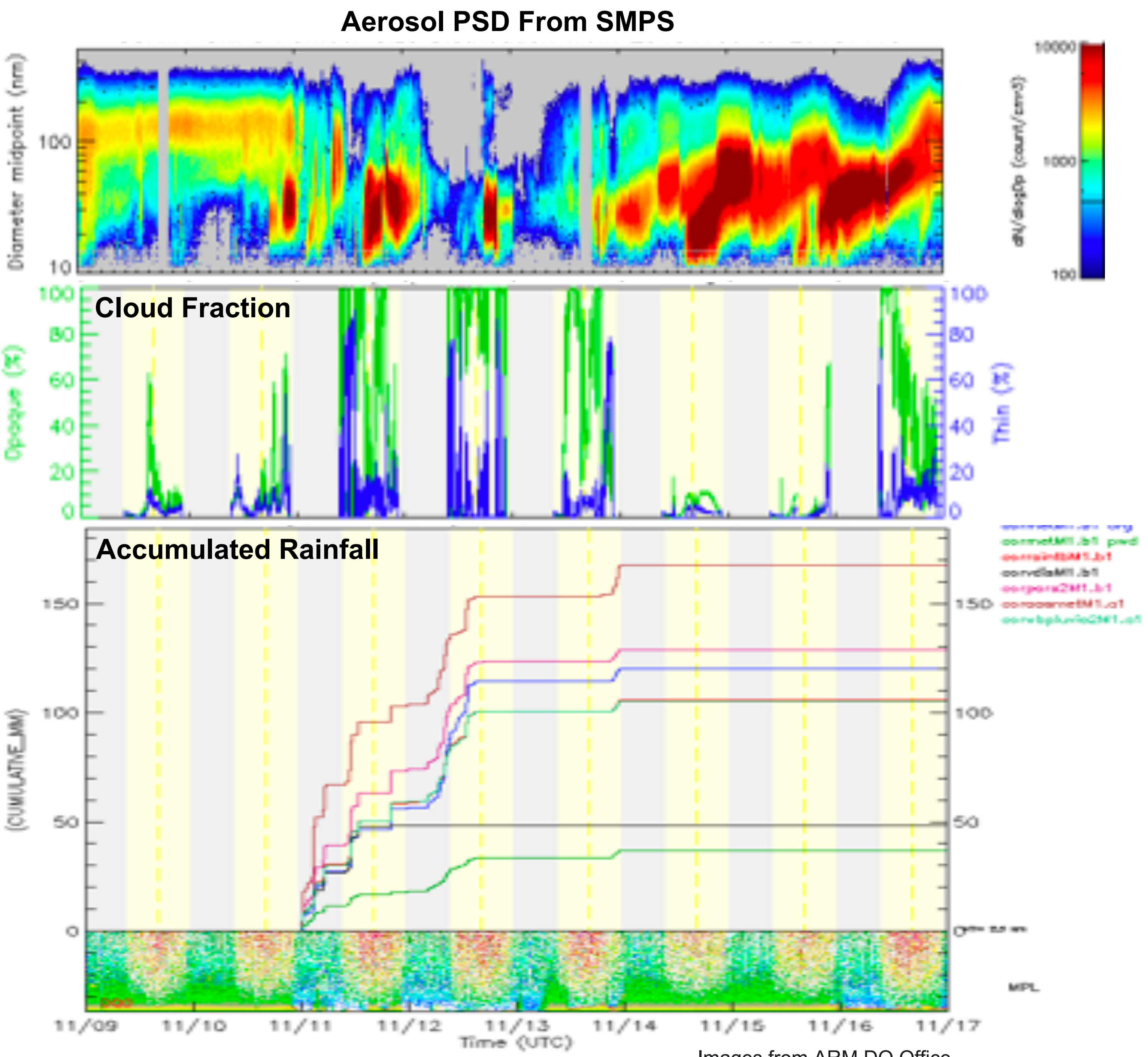
Appears to be PBL driven, but surface CCN@0.4% = 1500 cm^{-3}

Scanning radar shows moist layer above the PBL being pushed upward from upslope flow while vertically pointing radar shows cloud top convective circulations



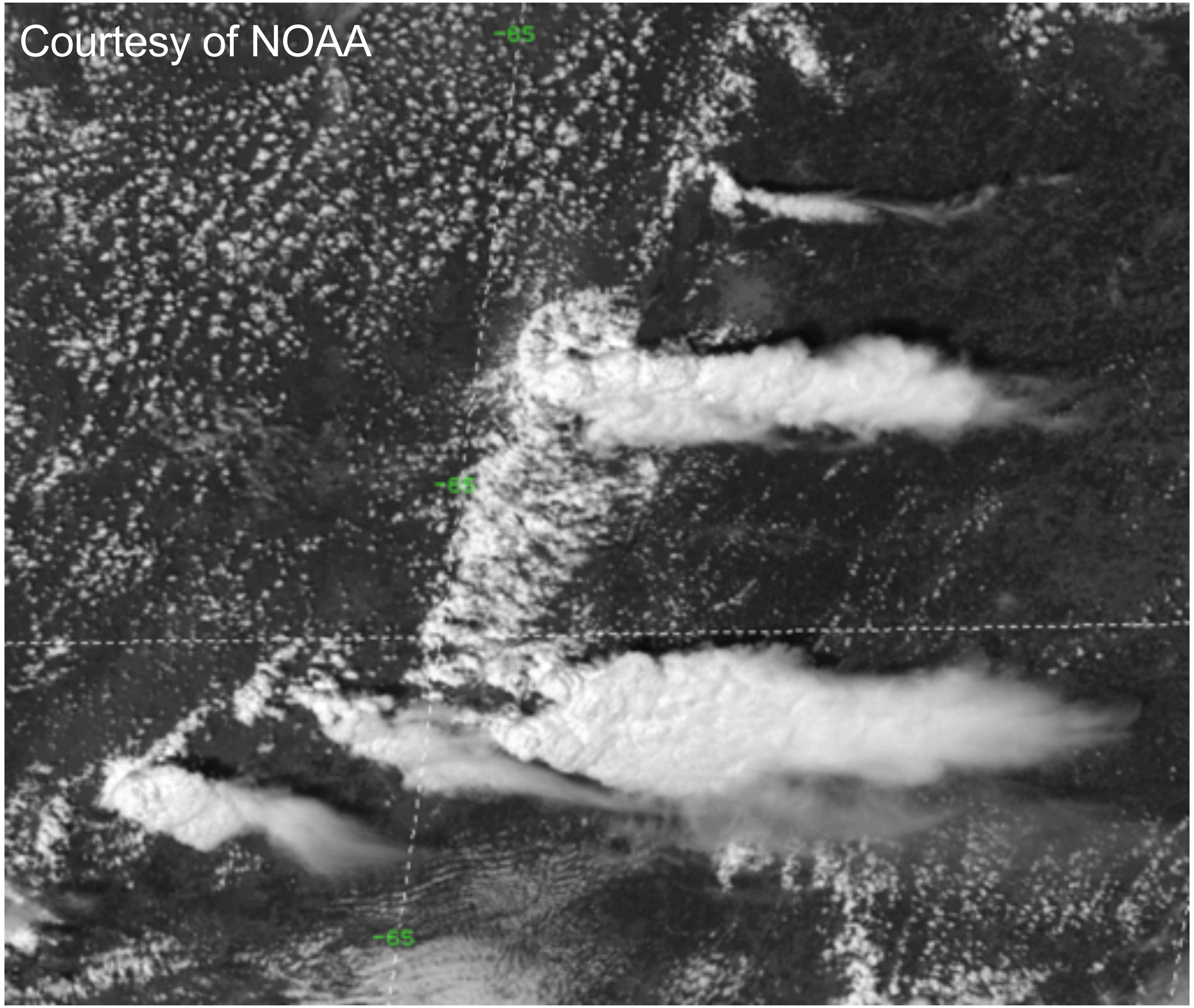
Images from Joseph Hardin and Nitin Bharadwaj

Aerosol-Precipitation Measurements



Images from ARM DQ Office

Shallow to Deep Transition



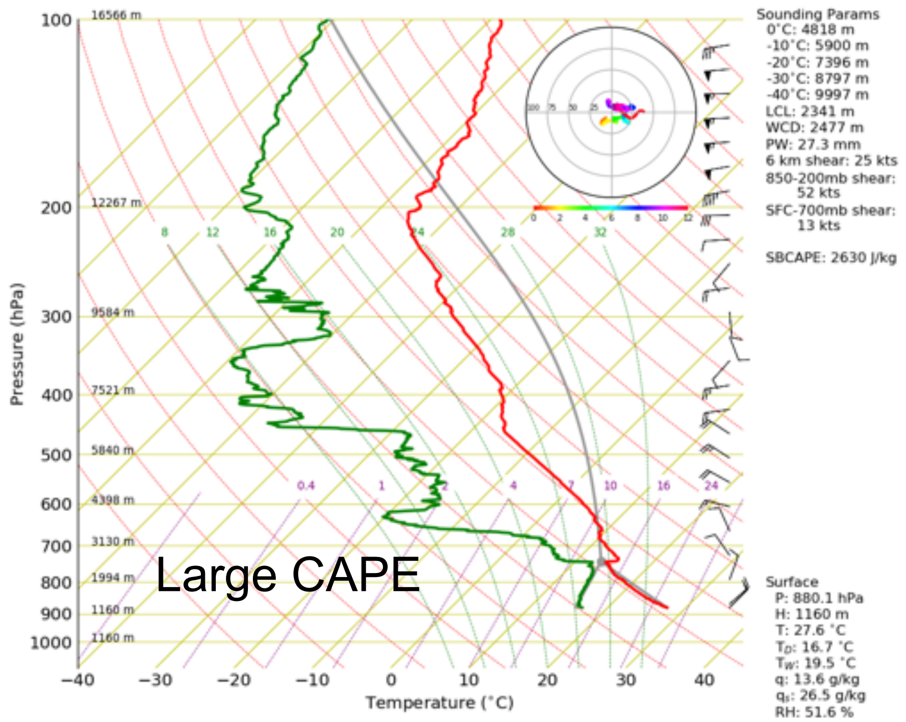
Shallow to Deep Transition

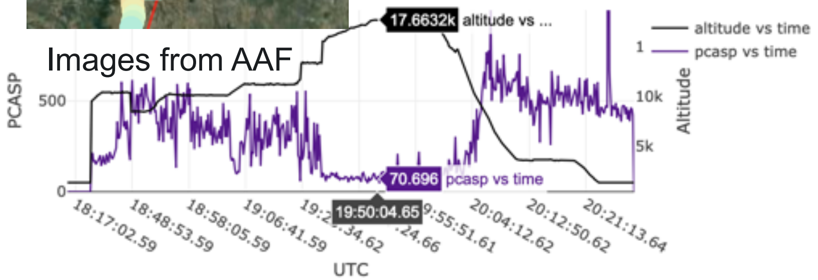
Shallow to Deep Transition

Shallow to Deep Transition

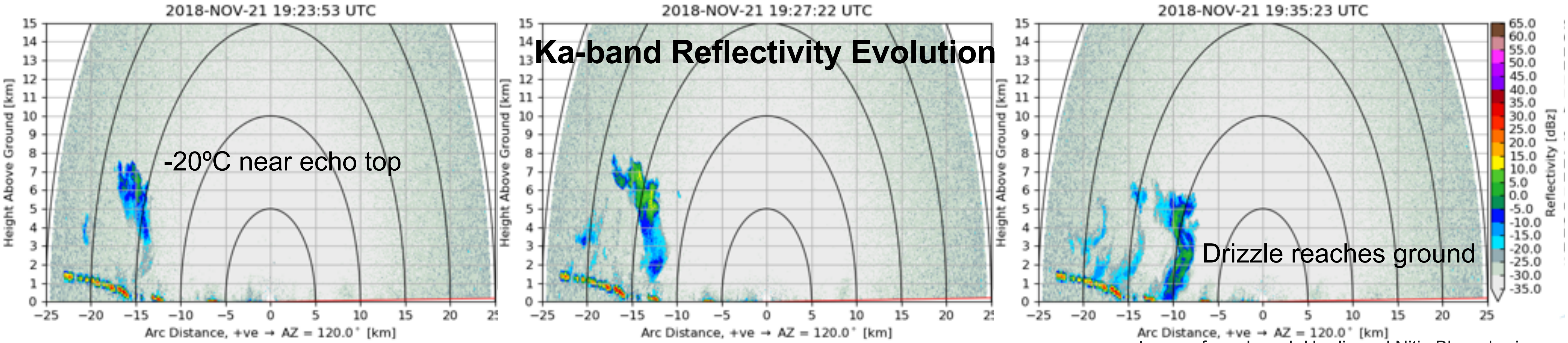
Shallow to Deep Transition

Ice Initiation





Ka-band Reflectivity Evolution



Images from Joseph Hardin and Nitin Bharadwaj

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Thank You

CACTI Background and Science Plan:
www.arm.gov/research/campaigns/amf2018cacti

CACTI Datasets (QC/retrievals in progress):
www.archive.arm.gov
www.arm.gov/research/campaigns/amf2018cacti

RELAMPAGO Field Catalog/Datasets:
https://www.eol.ucar.edu/field_projects/relampago

Contact: adam.varble@pnnl.gov