The
Investigation of Convective Updrafts

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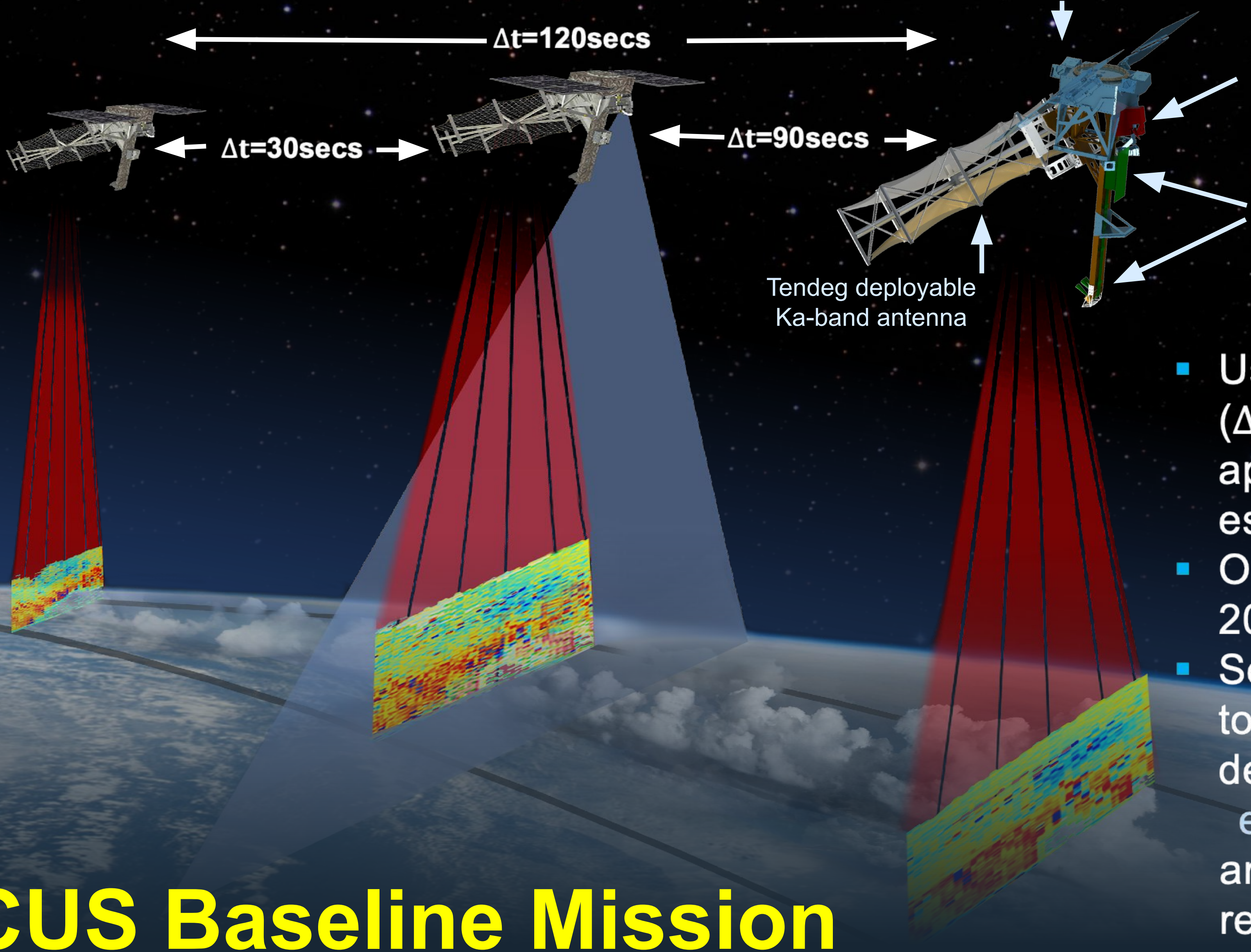
4 March 2023

The Investigation of Convective Updrafts

- The observations
- Why we chose this observation strategy
- How (do we know that) it “will work”
- What we will do with these observations, including 3 applications

4 March 2023

INCUS Baseline Mission



Δt=120secs

Δt=30secs

Δt=90secs

Blue Canyon Technologies X-SAT Venus commercial bus

JPL cross-track scanning microwave radiometer (middle spacecraft only) (TEMPEST-D heritage) - called the Dynamic Microwave Radiometer (DMR)

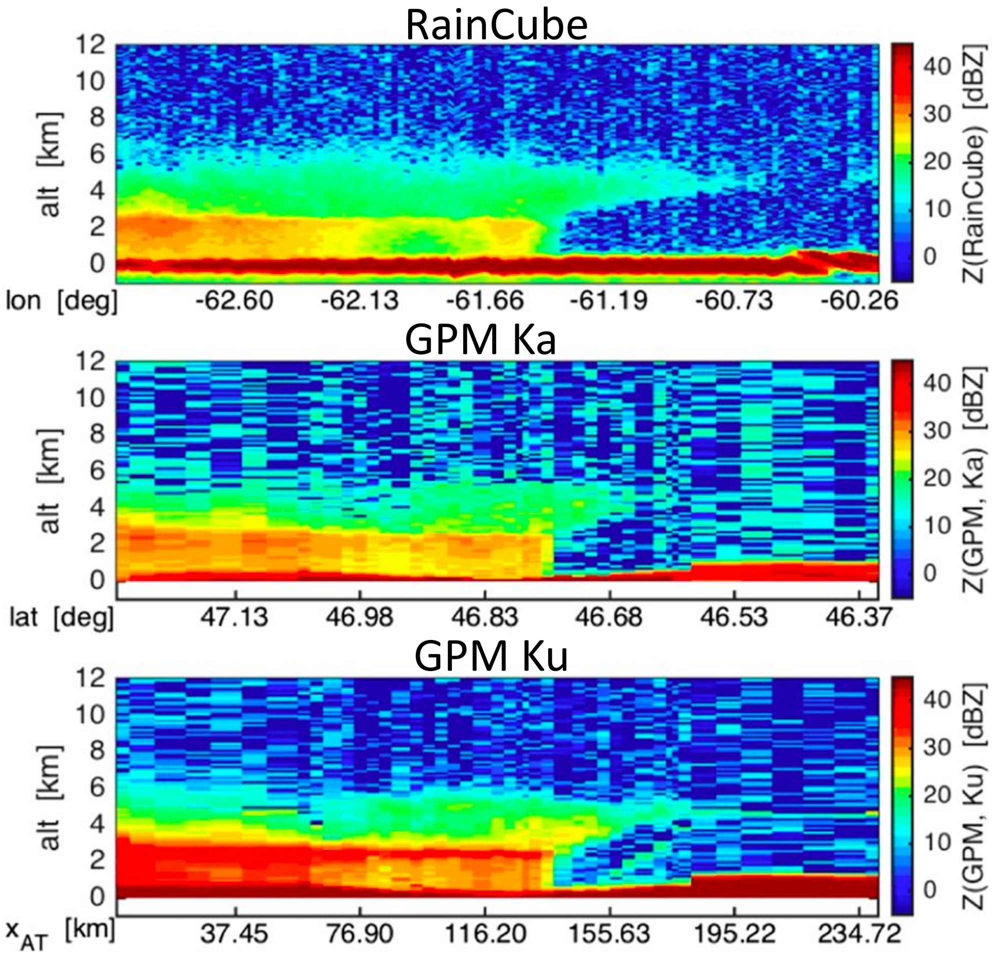
JPL Ka-band radar with 7 beams (RainCube heritage) – called the Dynamic Atmospheric Radar (DAR)

Tendeg deployable Ka-band antenna

- Use a novel time-differencing (Δt =30, 90 and 120 sec) approach to detect updrafts and estimate **Convective Mass Flux**
- Orbit over the global tropics from 2026 to 2028
- Segment global data according to reanalysis environment, then derive relations
  environment ⇒ **CMF** ⇒ storm
  and evaluate different model representations

RainCube heritage – in orbit 2018 to 2020

INVESTIGATION OF CONVECTIVE UPDRAFTS



25 January 2019 near PEI

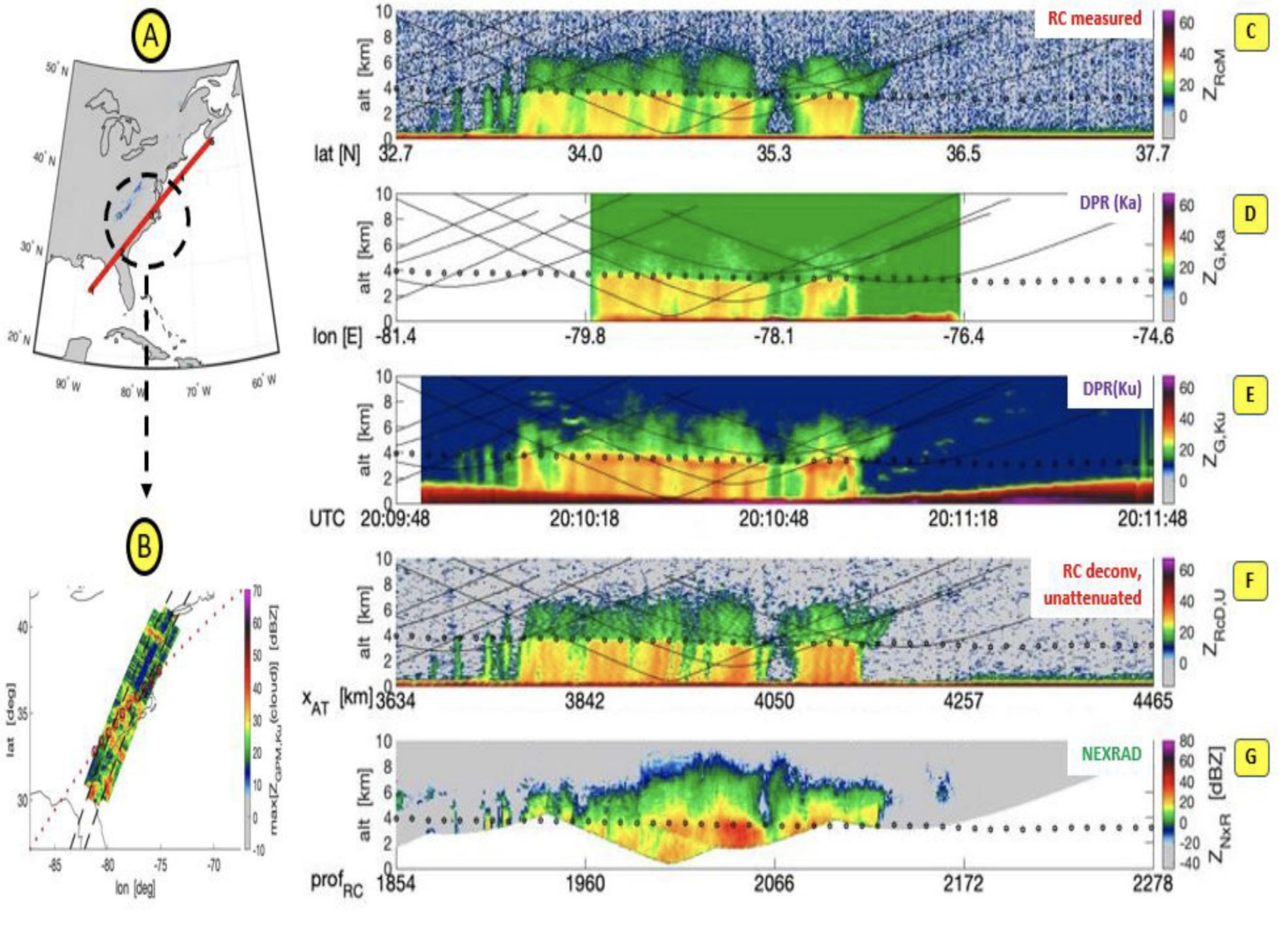
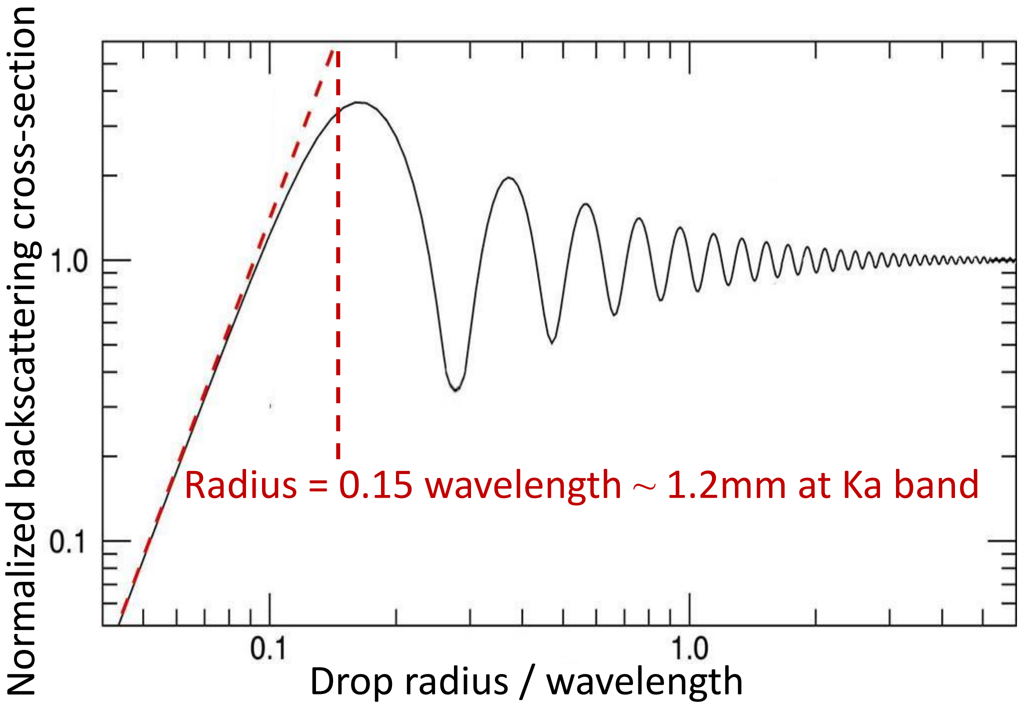


Fig. 7. "Ten eyes on a storm": collocations NEXRAD-to-RainCube-to-DPR over East Coast of the US: track of RainCube (A), and map of vertical maximum of $Z_{G,Ku}$ (B); curtain plots of Z_{RcM} (C), collocated DPR $Z_{G,Ka}$ (D) and $Z_{G,Ku}$ (E), RainCube's deconvolved and unattenuated $Z_{RcD,U}$ (F), and composite of NEXRAD observations Z_{NxR} (G).

Z_{ka} – Rain not monotonic



Radius = 0.15 wavelength ~ 1.2mm at Ka band

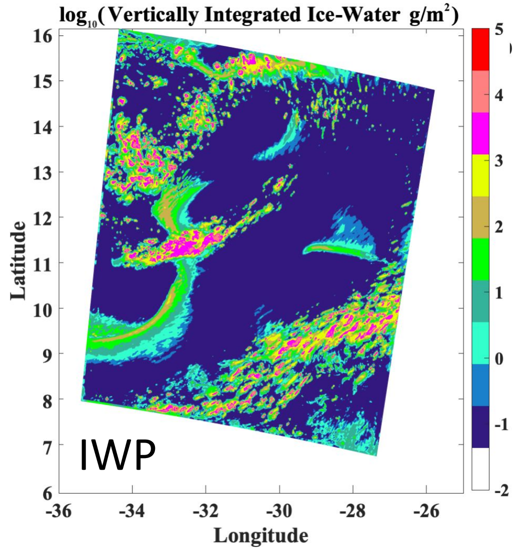
In spite of its name, RainCube is not ideal to observe **rain** …

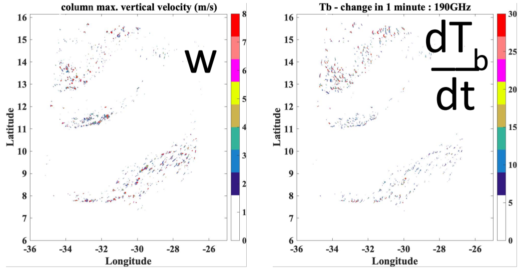
Instead, try to capitalize on the ability to formation-fly several identical copies …

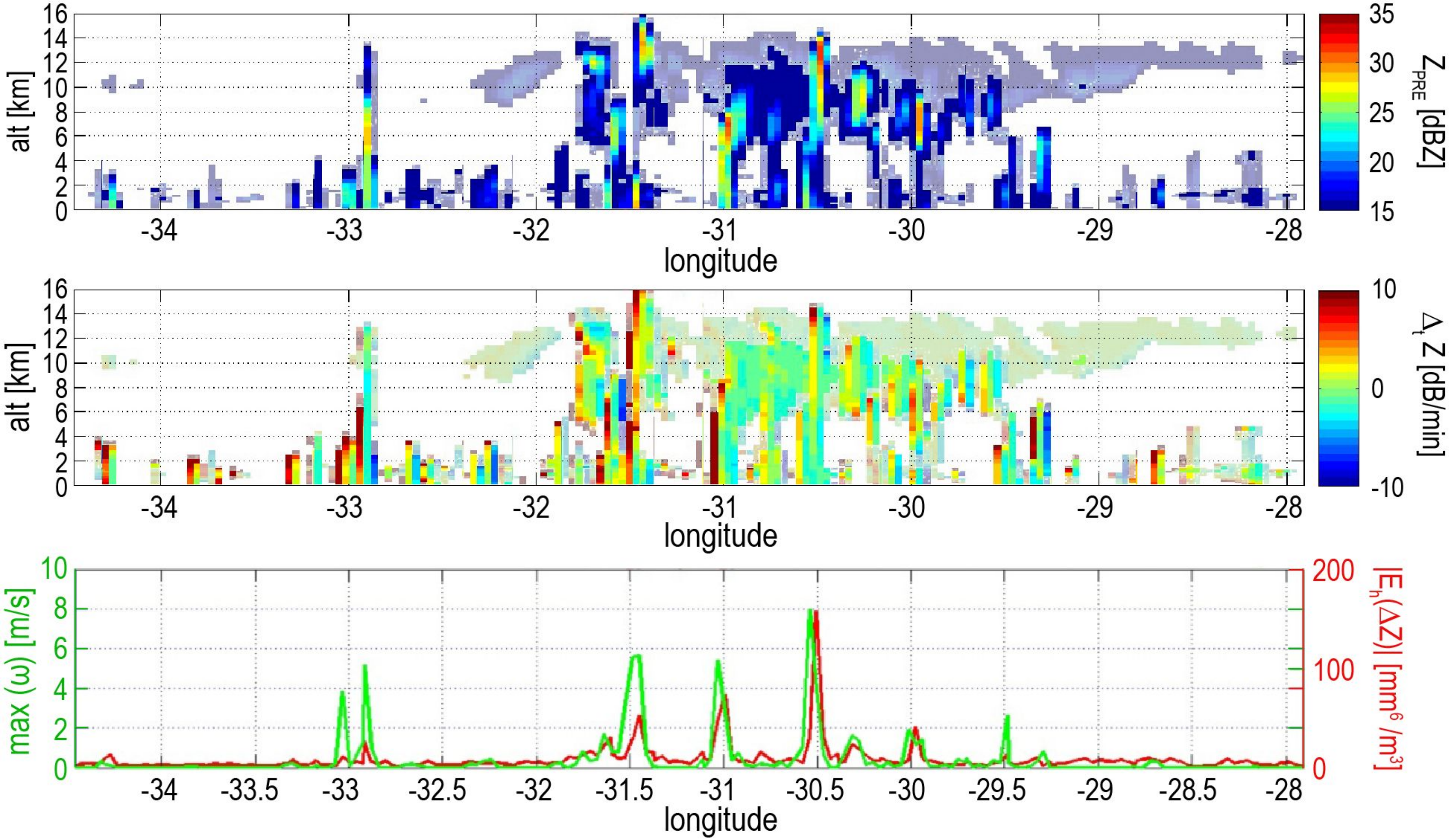
Z_{ka} – Rain not monotonic; Instead:

INVESTIGATION OF CONVECTIVE UPDRAFTS

Convection-permitting simulation of Isabel: 5 nested grids, 10sec output (D05 at 148m horizontal resolution)



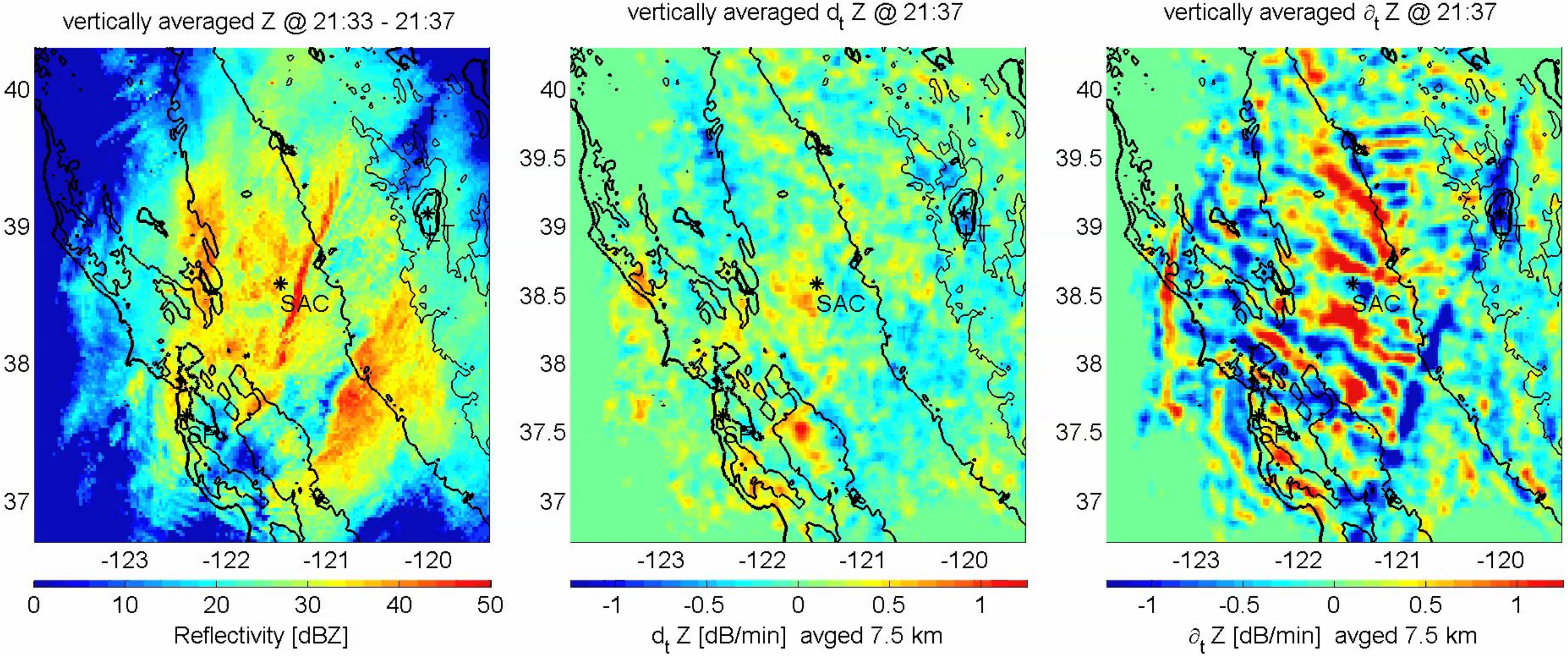




Earliest NEXRAD analyses

On 4 January 2008, from ~ 21:30 Z to 23:50 Z, with Δt ~ 4.3 minutes (showing the 250m et 1000m contours)

dbZ $\qquad$ $\dfrac{\partial \mathrm{dbZ}}{\partial t} + V \cdot \nabla \mathrm{dbZ}$ $\qquad$ $\dfrac{\partial \mathrm{dbZ}}{\partial t}$



Theoretical basis for retrieving w from (Z_t, $Z_{t+\Delta t}$)

Investigation of Convective Updrafts

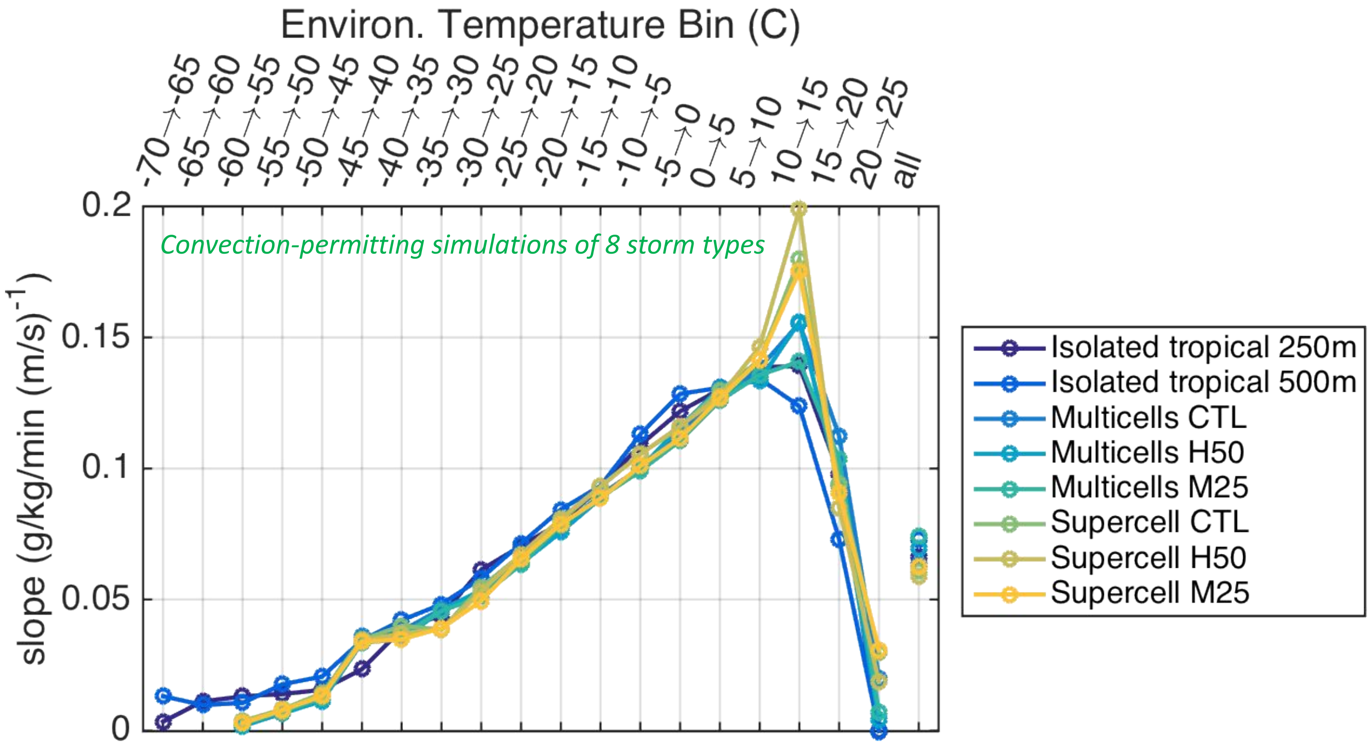
(Why and how) is the change in a vertical profile of Z related to the vertical transport?

Evolution equation for condensed water: $$\frac{\partial Q}{\partial t} + (u \cdot \partial Q/\partial x + v \cdot \partial Q/\partial y) + w\frac{\partial Q}{\partial z} = S_q$$

Simulations show that, in convective updrafts,

$$S_q = \alpha\, w$$

(Grant, van den Heever, et al, 2022)



Theoretical basis for retrieving w from (Z_t, $Z_{t+\Delta t}$)

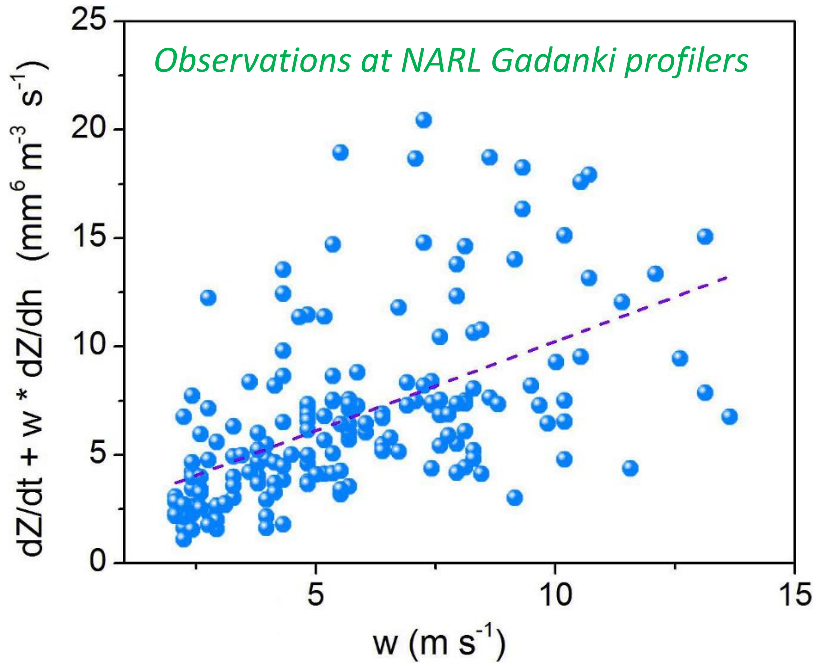
Investigation of Convective Updrafts

(Why and how) is the change in a vertical profile of Z related to the vertical transport?

Evolution equation for condensed water: $$w = \frac{\partial Q/\partial t + u\partial Q/\partial x + v\partial Q/\partial y}{\alpha - \partial Q/\partial h}$$

Observations confirm that, in convective updrafts,

$$S_q = \alpha\, w$$



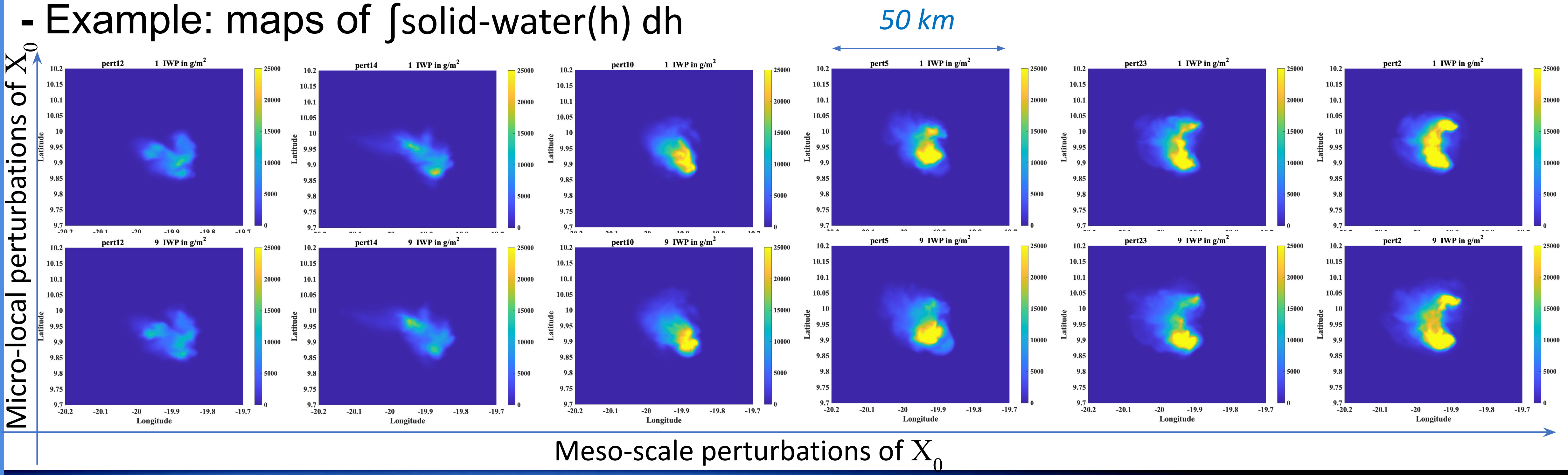
Parameter	L-band	VHF
Frequency	1.280 GHz	53 MHz
Antenna size	2.8 x 2.8 m^2	130 x 130 m^2
Beam width	5^o	3^o
Tx peak power	1.2 kW	~1 MW
Pulse width	0.25 - 8 msec	1-16 msec
Resolution	37.5 - 150 m	150 m
Lowest range	300 m	1500 m
Highest range	14 km*	21 km

Equivalence classes

Updrafts can appear quite different for slightly different initial states

- Convection is a turbulent process: $\begin{cases} dX_t = NS(X_t)\,dt \\ X_0 = E\{X\} \end{cases}$ modulo covariances at different scales

- Example: maps of ∫solid-water(h) dh



Objectives?

Updrafts can appear quite different for slightly different initial states

- What are the invariants of the convective updrafts A ?

Good idea for a set of goals:

- Characterize the conditional laws pr(A | environment)
  pr(storm high clouds ($\supset$ “size”) | A)
  pr(storm severity ($\supset$ precip) | A)

Detection, retrievals, compositing

So, in convective updrafts, $w = \dfrac{\partial Q/\partial t + u\partial Q/\partial x + v\partial Q/\partial y}{\alpha - \partial Q/\partial h}$

In practice, we do not have infinitesimal Δt, Δx, Δh, so we will use automatic learning instead, using simulated no-/yes- convection at 100m resolution in 20km domains, 3-minute duration.

This 1st step of the retrievals depends on using realistic physics. The 2nd depends on math to find the conditional mean w profile given a pair of measured reflectivity profiles:

- Harvest the updraft columns
- Discretize the range of h_{max} = highest h where Z > detection threshold => ~ 10 intervals
  Discretize the range of max-over-h-of $Z_{late} - Z_{early}$ => ~ 10 intervals
  Discretize the range of $\int Z(h)dh$ => ~ 10 intervals
- So then partition this reference dataset into 1000 subsets accordingly,
  indexed by N = 1 , … , 1000 :

Detection, retrievals, compositing

- Now apply optimal empirical learning to each reference data subset:

N=1

$$\left(\begin{matrix} \begin{bmatrix} Z_0(h_{40}) \\ Z_0(h_{39}) \\ \cdots \\ Z_0(h_1) \end{bmatrix} \begin{bmatrix} Z_1(h_{40}) \\ Z_1(h_{39}) \\ \cdots \\ Z_1(h_1) \end{bmatrix} ; \begin{bmatrix} Q_0(h_{40}) \\ Q_0(h_{39}) \\ \cdots \\ Q_0(h_1) \end{bmatrix} \begin{bmatrix} Q_1(h_{40}) \\ Q_1(h_{39}) \\ \cdots \\ Q_1(h_1) \end{bmatrix} \begin{bmatrix} w(h_{40}) \\ w(h_{39}) \\ \cdots \\ w(h_1) \end{bmatrix} \\ \cdots \qquad \updownarrow 10^3\text{s} \\ \begin{bmatrix} Z_0(h_{40}) \\ Z_0(h_{39}) \\ \cdots \\ Z_0(h_1) \end{bmatrix} \begin{bmatrix} Z_1(h_{40}) \\ Z_1(h_{39}) \\ \cdots \\ Z_1(h_1) \end{bmatrix} ; \begin{bmatrix} Q_0(h_{40}) \\ Q_0(h_{39}) \\ \cdots \\ Q_0(h_1) \end{bmatrix} \begin{bmatrix} Q_1(h_{40}) \\ Q_1(h_{39}) \\ \cdots \\ Q_1(h_1) \end{bmatrix} \begin{bmatrix} w(h_{40}) \\ w(h_{39}) \\ \cdots \\ w(h_1) \end{bmatrix} \end{matrix}\right) \quad \cdots$$

N=1000

$$\left(\begin{matrix} \begin{bmatrix} Z_0(h_{40}) \\ Z_0(h_{39}) \\ \cdots \\ Z_0(h_1) \end{bmatrix} \begin{bmatrix} Z_1(h_{40}) \\ Z_1(h_{39}) \\ \cdots \\ Z_1(h_1) \end{bmatrix} ; \begin{bmatrix} Q_0(h_{40}) \\ Q_0(h_{39}) \\ \cdots \\ Q_0(h_1) \end{bmatrix} \begin{bmatrix} Q_1(h_{40}) \\ Q_1(h_{39}) \\ \cdots \\ Q_1(h_1) \end{bmatrix} \begin{bmatrix} w(h_{40}) \\ w(h_{39}) \\ \cdots \\ w(h_1) \end{bmatrix} \\ \cdots \\ \begin{bmatrix} Z_0(h_{40}) \\ Z_0(h_{39}) \\ \cdots \\ Z_0(h_1) \end{bmatrix} \begin{bmatrix} Z_1(h_{40}) \\ Z_1(h_{39}) \\ \cdots \\ Z_1(h_1) \end{bmatrix} ; \begin{bmatrix} Q_0(h_{40}) \\ Q_0(h_{39}) \\ \cdots \\ Q_0(h_1) \end{bmatrix} \begin{bmatrix} Q_1(h_{40}) \\ Q_1(h_{39}) \\ \cdots \\ Q_1(h_1) \end{bmatrix} \begin{bmatrix} w(h_{40}) \\ w(h_{39}) \\ \cdots \\ w(h_1) \end{bmatrix} \end{matrix}\right)$$

Once these reference data subsets are ready,
apply e.g. **Kernel Flows** to each, in order to (find the warping vectors that) define the kernel $K_N(Z_0, Z_1; Z_0', Z_1')$ so that

$$\Sigma_n \, w^{(n)} \, K_N(Z_0, Z_1; Z_0^{(n)}, Z_1^{(n)})$$

is $\sim$ the average of all w profiles that underlie a given pair (Z_0, Z_1) of measured reflectivity profiles

4 objectives

Investigation of Convective Updrafts

Science Objective 1: ENV ⟹ Convective Mass Flux (profiles of w, J_{air} above 5000m AMSL)

Determine how the environmental properties of relative humidity, temperature, vertical wind shear and convective available potential instability CAPE) impact CMF in tropical convective storms as a function of storm type, lifecycle and diurnal cycle (Baseline and Threshold)

Science Objective 2: CMF ⟹ Anvil Clouds

Determine the relationship between the CMF in tropical convective storms and the properties of the anvil clouds they produce (Baseline and Threshold)

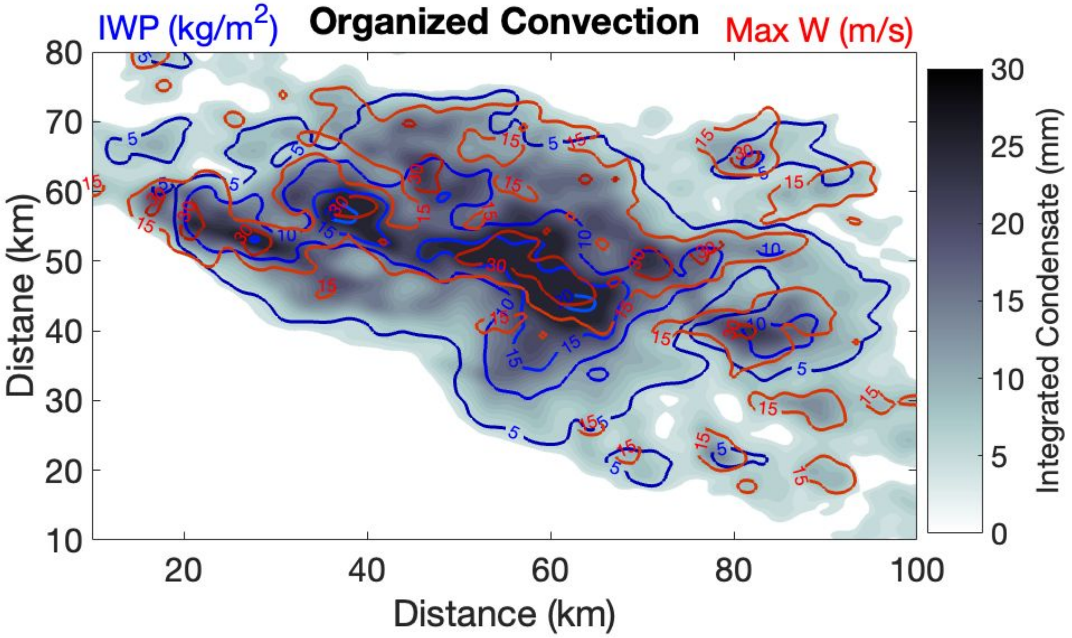
Science Objective 3: CMF ⟹ Extreme Weather

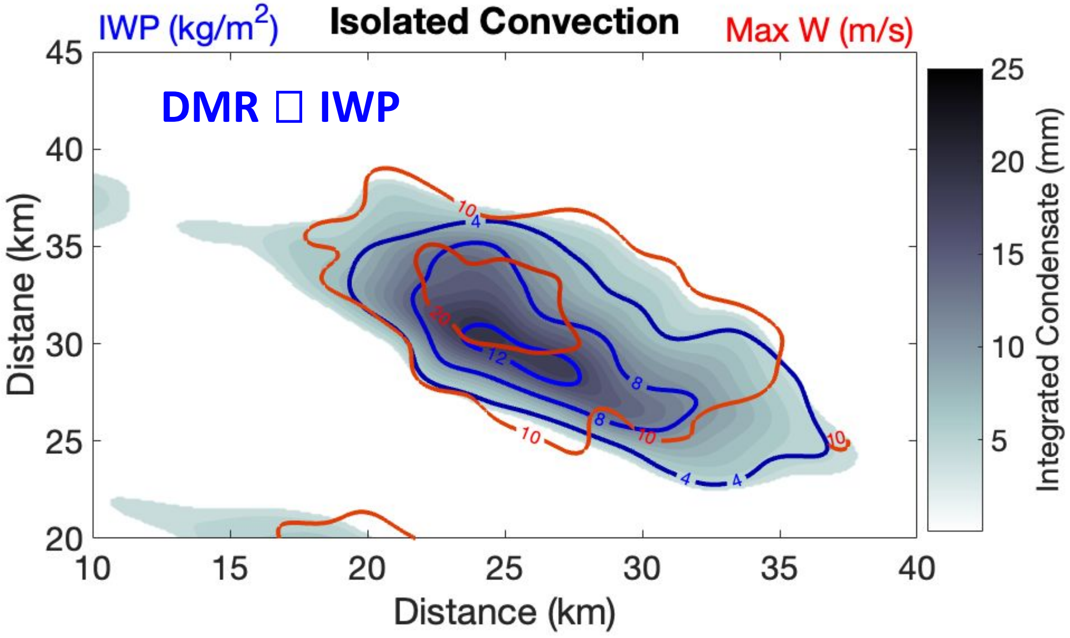
Determine the relationship between the CMF in tropical convective storms and the type and intensity of the weather they produce (Baseline)

Science Objective 4: CMF in Models

Evaluate the environmental-CMF relationships (Baseline and Threshold), CMF-high cloud relationships (Baseline and Threshold), and CMF-weather relationships (Baseline only), established in Science Objectives 1 – 3, in convective permitting models (CPMs), numerical weather predication (NWP) models and global climate models (GCMs).

Enhancing value of DAR using DMR





Although the resolution of DMR is coarser than that of these simulations, its estimates of the distribution of IWP over the storm allow us to replace

"The radar makes a handful of obs over the storm", with the much more powerful

"Radar observation *m* represents the Nth quintile in the storm distribution"

Enhancing value of DAR using DMR

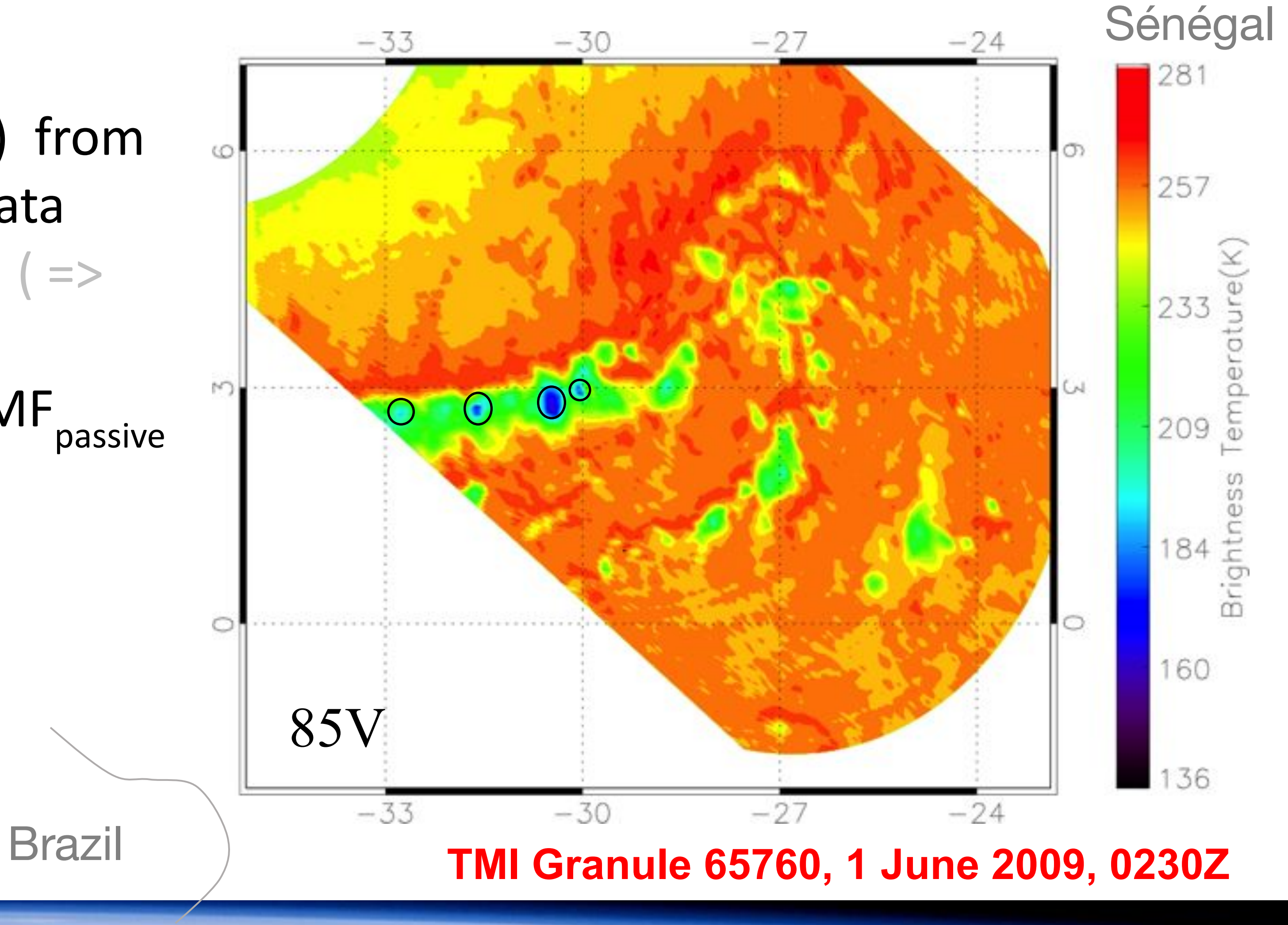
Promising ***prospect***:

1) Derive CMF$_{passive}$ = F(IWP, spatialχ) from the coincident radar+radiometer data
2) Integrate CMF$_{passive}$ over the storm (=> which CMF?)
3) Characterize the uncertainty in ∫ CMF$_{passive}$

⇒ For TCs?

⇒ For NWP?

⇒ Quantify the uncertainty as a function of radiometer (channels and) resolution



TMI Granule 65760, 1 June 2009, 0230Z

Application to nowcasting

Existing: Empirical reference database of ½-hourly anvil chronologies (from geo-IR mosaic)

$(s_0, s_1, s_2, \ldots, s_N)$

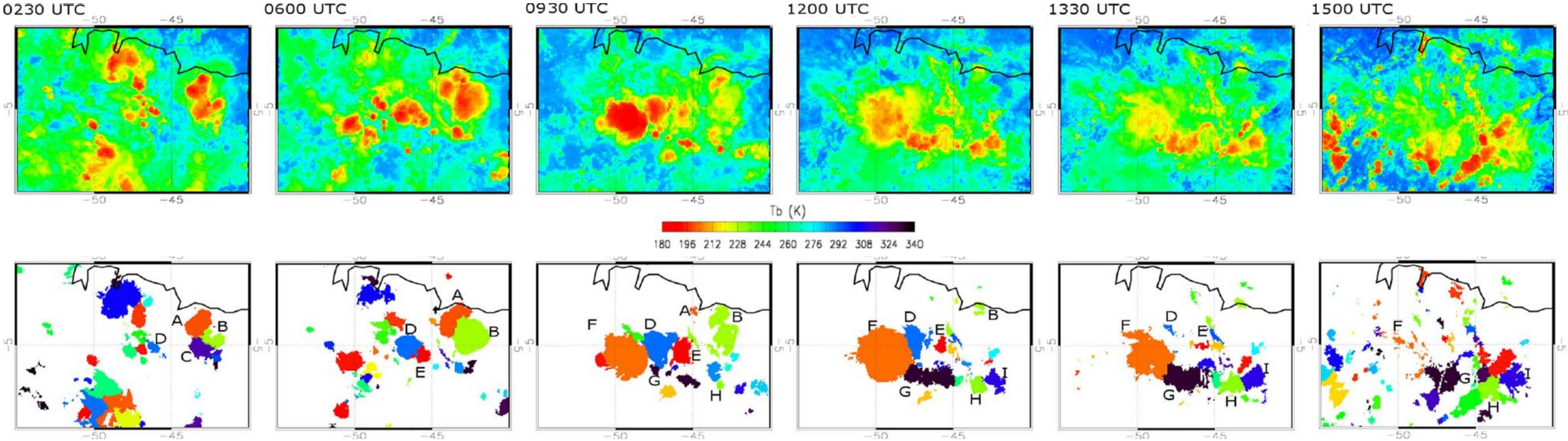
Entry s_n at step n^{th} time step consists of (anvil area, stats of pixel temperatures)

Learn to forecast next 12 ½-hour steps from past 12

INCUS: Inject most recent microwave (including time), and

Learn to forecast next 12 ½-hour steps from past 12 plus most-recent microwave

Application to nowcasting



A: (s_0, ………………………………………………………………, s_{14})

B: (s_0, ………………………………………………………………, s_{19})

C: (s_0, ……………………, s_6)

D: (s_0, ………………………………………………………………, s_{22})

E: (s_0, ………………………………………………………………, s_{16})

F: (s_0, ………………………………………………………………, s_{19})

G: (s_0, ………………………………………………………………, s_{17})

H: (s_0, ………………………………………………………………, s_{31})

I: (s_0, ………………………………………………………………, s_{25})

Application to nowcasting

Existing: Empirical reference database of ½-hourly anvil chronologies (from geo-IR mosaic)

Entry s_n at step n^{th} time step consists of (anvil area, stats of pixel temp)

Learn to forecast next 12 ½-hour steps from past 12

INCUS: Inject most recent microwave (including time), and

Learn to forecast next 12 ½-hour steps from past 12 **plus most-recent microwave**

Develop each observed chronology $(s_0, s_1, s_2, \ldots, s_N)$ into N+1 opportunities to learn:

$$(0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, s_0 \;;\; s_1, s_2, s_3, s_4, s_5, s_6, s_7, s_8, s_9, s_{10}, s_{11}, s_{12})$$

$$(0, 0, 0, 0, 0, 0, 0, 0, 0, 0, s_0, s_1 \;;\; s_2, s_3, s_4, s_5, s_6, s_7, s_8, s_9, s_{10}, s_{11}, s_{12}, s_{13})$$

$$(0, 0, 0, 0, 0, 0, 0, 0, 0, 0, s_0, s_1, s_2 \;;\; s_3, s_4, s_5, s_6, s_7, s_8, s_9, s_{10}, s_{11}, s_{12}, s_{13}, s_{14})$$

$$\ldots$$

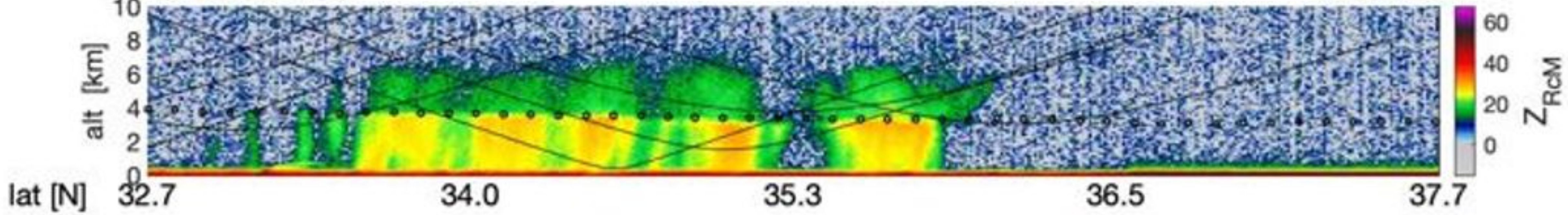
$$(s_{N-13}, s_{N-12}, s_{N-11}, s_{N-10}, s_{N-9}, s_{N-8}, s_{N-7}, s_{N-6}, s_{N-5}, s_{N-4}, s_{N-3}, s_{N-2} \;;\; s_{N-1}, s_N, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0)$$

$$(s_{N-12}, s_{N-11}, s_{N-10}, s_{N-9}, s_{N-8}, s_{N-7}, s_{N-6}, s_{N-5}, s_{N-4}, s_{N-3}, s_{N-2}, s_{N-1} \;;\; s_N, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0)$$

$$(s_{N-11}, s_{N-10}, s_{N-9}, s_{N-8}, s_{N-7}, s_{N-6}, s_{N-5}, s_{N-4}, s_{N-3}, s_{N-2}, s_{N-1}, s_N \;;\; 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0)$$

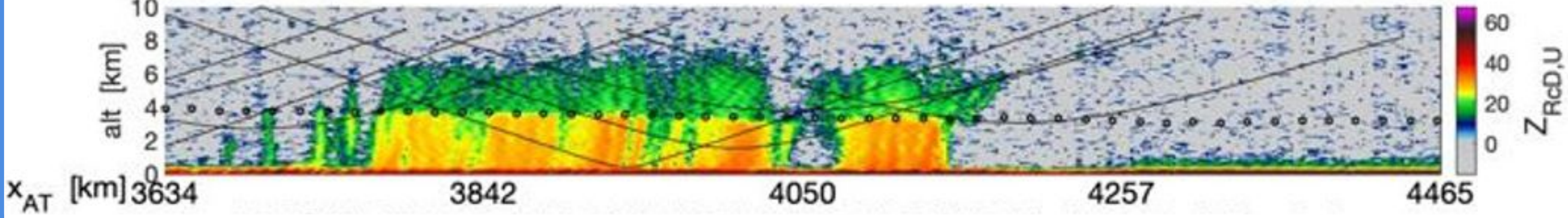
Upper levels (+evolution) in hi-res

RainCube calibrated reflectivity factors:



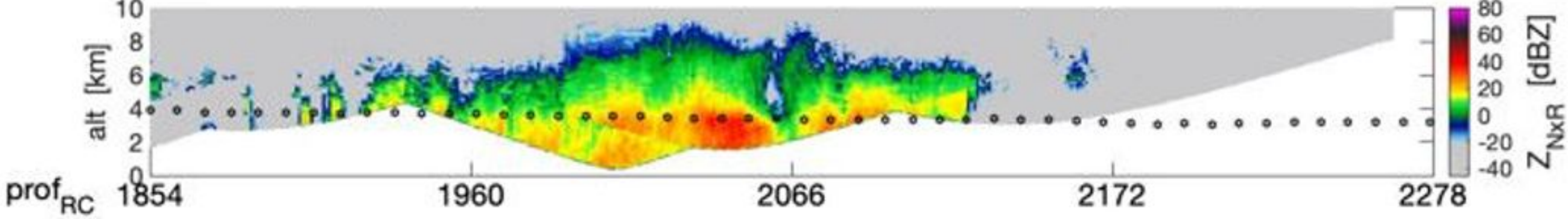
RainCube reflectivity factors deconvolved and “de-attenuated”:

At t = 0, 30, 120 seconds



NEXRAD composited reflectivity factors:

Every ~ 4.3 minutes



Summary

- 3 small Ka-band radars (~ 3km horizontal resolution, 250m vertical) + 1 mm-wave (MHS-like, highfrequency-ATMS-like) radiometer
- Radar swath ~ 10 km (7 overlapping FOVs)
- Scheduled to orbit 2026 – 2028, inclination TBD (by 2024) up to 66° latitude
- **Profiles of CMF** (i.e. w and J_{air}) and Z_{ka} at 30, 90, & 120 seconds **in the radar swath**
- Information “transferrable” to radiometer swath, to estimate storm-wide CMF ?

- Composite for 2-year data analysis (environment => CMF => storm)
- Application to nowcasting of rapidly evolving convection (à la WMO SCOPE Nowcasting)
- Systematic obs of the evolution of clouds above 5000m AMSL
- Application to NWP ? TCs ?

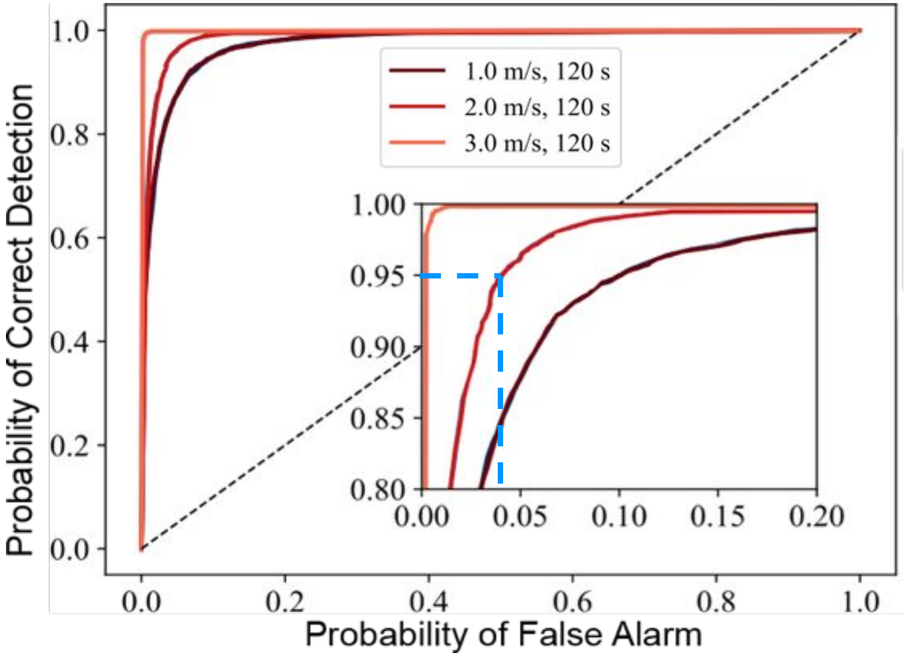
Back-up

INVESTIGATION OF CONVECTIVE UPDRAFTS

Back-up slide

Expected detection performance

For w_0=2m.s^{-1}, Q_0 = 0.05 g.kg^{-1}, Δt = 2 mins, z_1 = 2 dB, z_2 = 1dB, Z_{th} = 17dB



Analysis indicates that **Δt=120 seconds** allows for a **high (95%) probability of detection** with a **low (5%) probability of false alarm**

- Δt =2 minutes guarantees updraft detection but can it capture updraft variability?
- Δt = 30 secs limits variability over Δt ≤ 20%, sufficient to capture true value of the most variable (strongest) updraft velocities (w)