High-resolution Numerical Simulations of Tropical Convection for the NASA INCUS Mission

Itinderjot (I.T.) Singh[1], Jennie Bukowski[1], Peter J. Marinescu[1], Leah Grant[1], Rachel Storer[2], Gabrielle Leung[1], and Susan van den Heever[1]

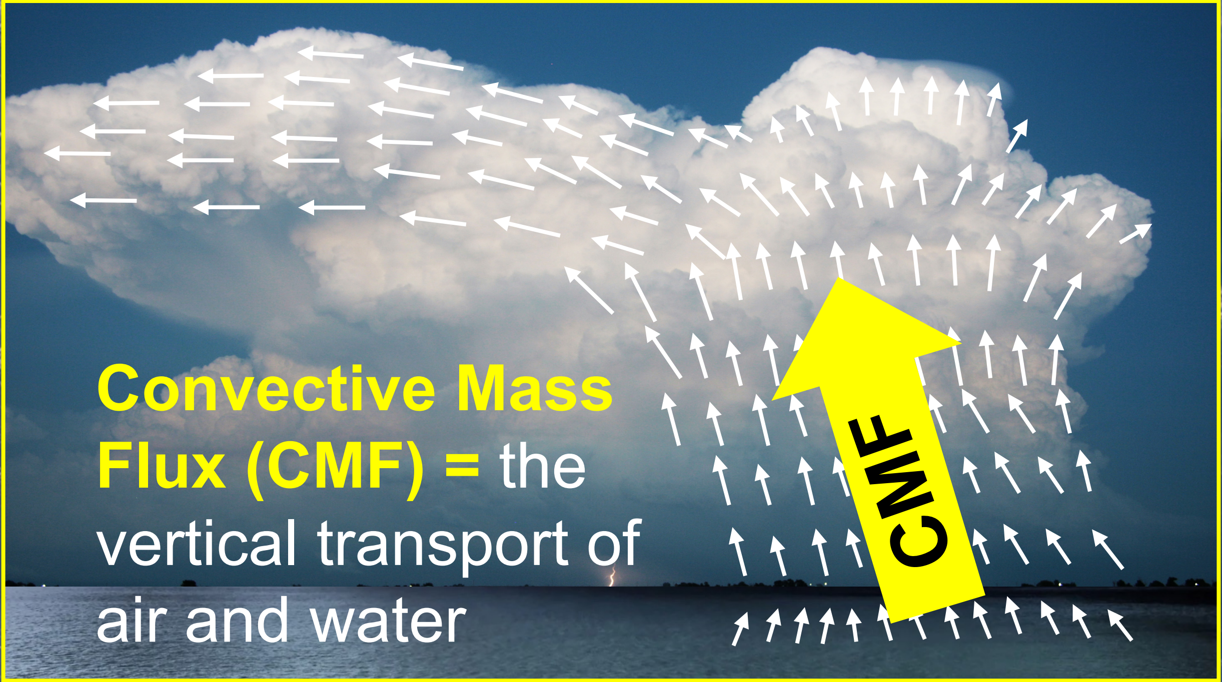
1 Colorado State University
2 University of California – Los Angeles; NASA Jet Propulsion Laboratory

This work is supported by INCUS, a NASA Earth Venture Mission, funded by NASA's Science Mission Directorate and managed through the Earth System Science Pathfinder Program Office under contract number 80LARC22DA011.

INCUS - INvestigation of Convective UpdraftS

Overarching Goal:
To understand why, when and where tropical convective storms form, and why only some storms produce extreme weather.

First global systematic investigation into CMF and its evolution within deep tropical convection



Convective Mass Flux (CMF) = the vertical transport of air and water

Image: NASA Earth Observatory (https://www.flickr.com/photos/nasa2explore/14991571998/)

INCUS Science Objectives

INVESTIGATION OF CONVECTIVE UPDRAFTS

Objective 1: ENV → CMF

Determine the predominant environmental properties controlling CMF in tropical convective storms

Objective 2: CMF → High Clouds

Determine the relationship between CMF and high anvil clouds (critical to cloud-climate feedbacks)

Objective 3: CMF → Current and Future Weather

Assess the relationship between CMF and type and intensity of the weather produced

Objective 4: CMF in Models

Evaluate these CMF observationally determined relationships in weather and climate models.


Image: van den Heever


Image: NASA ISS

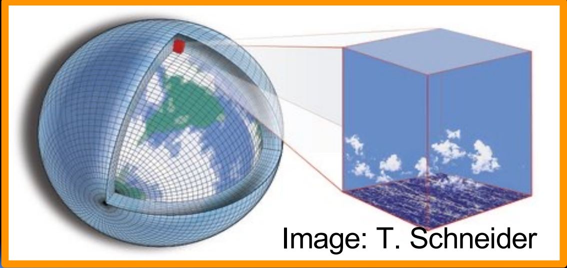
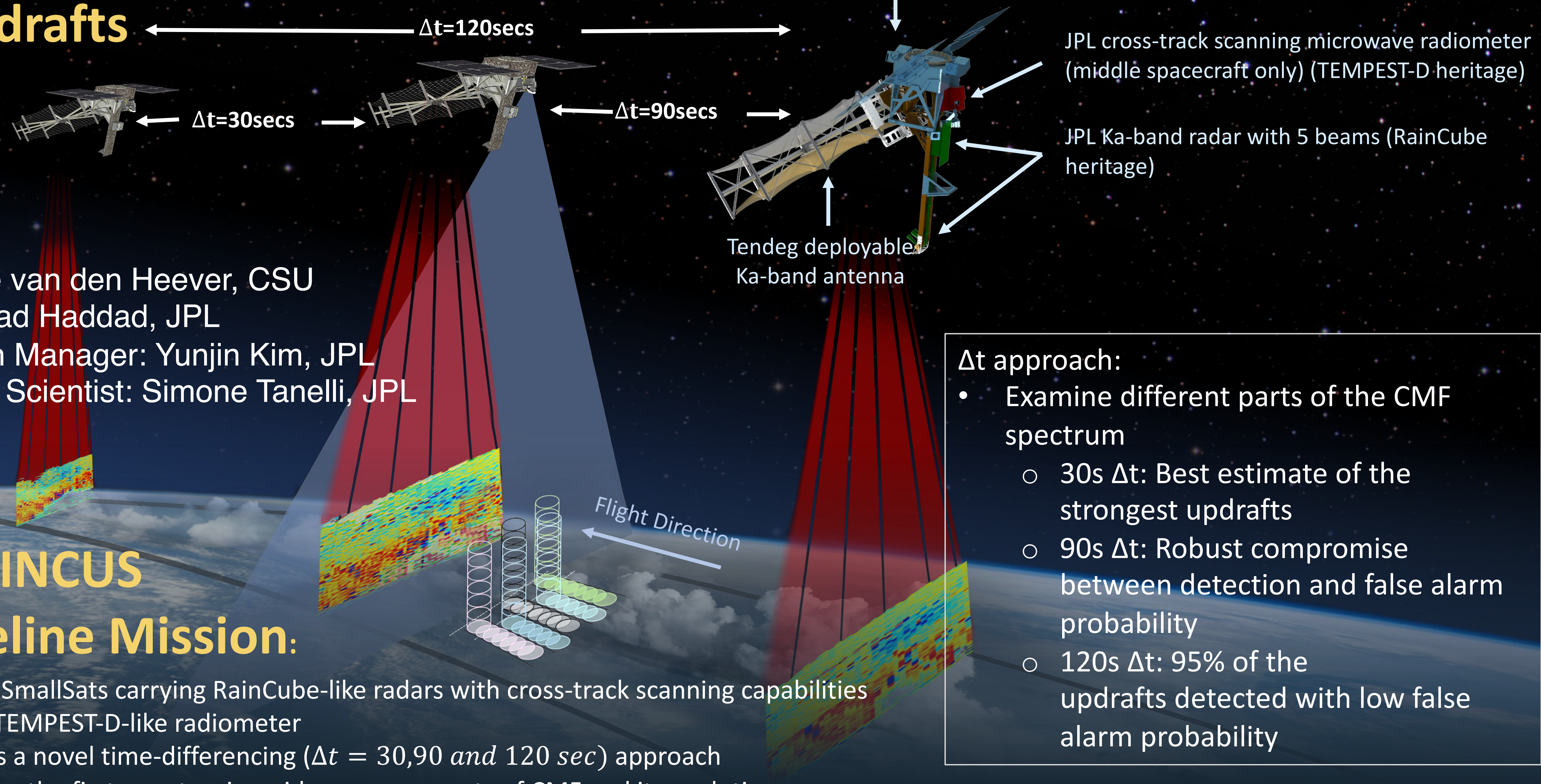


Image: T. Schneider

INCUS Investigation of Convective Updrafts



PI: Sue van den Heever, CSU
DPI: Ziad Haddad, JPL
Mission Manager: Yunjin Kim, JPL
Project Scientist: Simone Tanelli, JPL

The INCUS Baseline Mission:

- Flies 3 SmallSats carrying RainCube-like radars with cross-track scanning capabilities and a TEMPEST-D-like radiometer
- Applies a novel time-differencing ($\Delta t = 30{,}90\ and\ 120\ sec$) approach
- Provides the first ever tropics-wide measurements of CMF and its evolution

Δt approach:

- Examine different parts of the CMF spectrum
  - 30s Δt: Best estimate of the strongest updrafts
  - 90s Δt: Robust compromise between detection and false alarm probability
  - 120s Δt: 95% of the updrafts detected with low false alarm probability

INCUS Algorithm Workflow

INVESTIGATION OF CONVECTIVE UPDRAFTS

Cloud Model Simulations

Extensive database of LES simulations of convection in diverse environments

→ **Cloud Object Tracking**

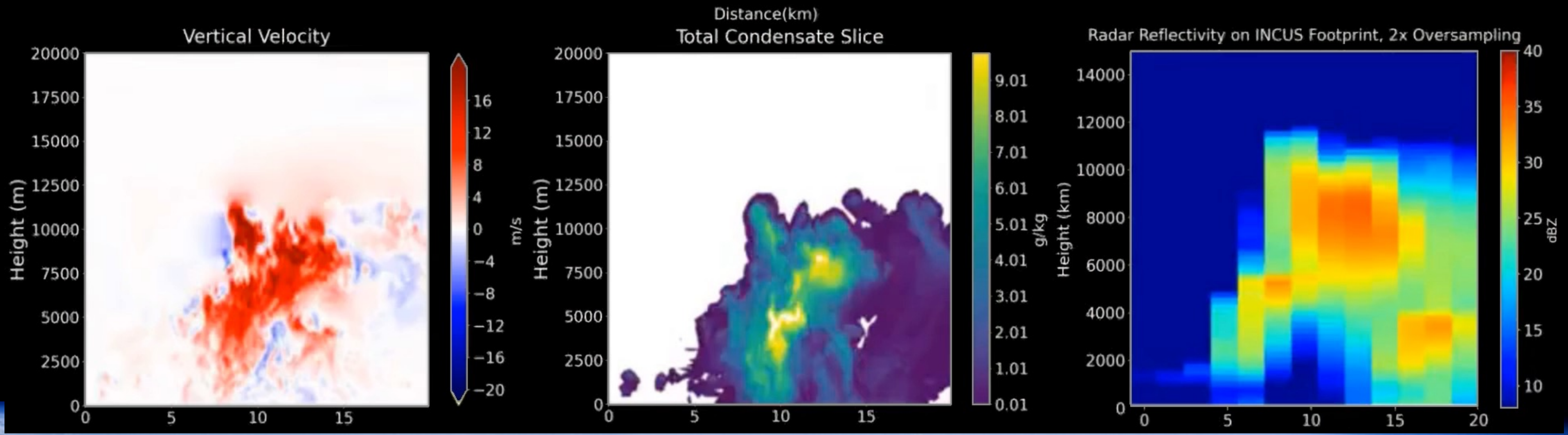
Track millions of modeled updrafts and their environment using *tobac*

→ **Radar and Radiometer Forward Model**

Model data converted to INCUS Ka-band radar reflectivity (Z) and microwave Brightness Temperature (T_b)

→ **Algorithm and Product Development**

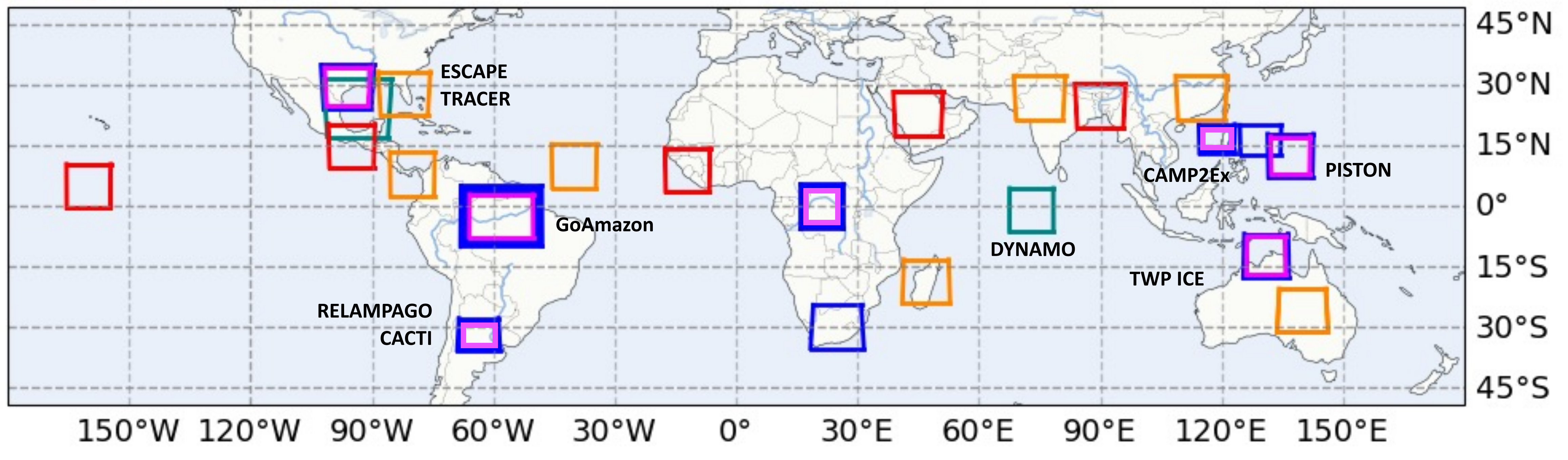
ML approaches to map time-separated Z profiles and MW Tb to various CMF metrics



INCUS LES Simulation Database

- 21 completed and/or currently running simulations
  - 13 case studies, 7 aerosol sensitivity tests, 3 microphysics schemes, 2 different models
  - Simulations chosen due to availability of observations and regions with varying convective clouds types, organization, and environments

RAMS Complete   RAMS In-Progress   WRF In-Progress   Up Next   Future



More than 40 case studies in total!

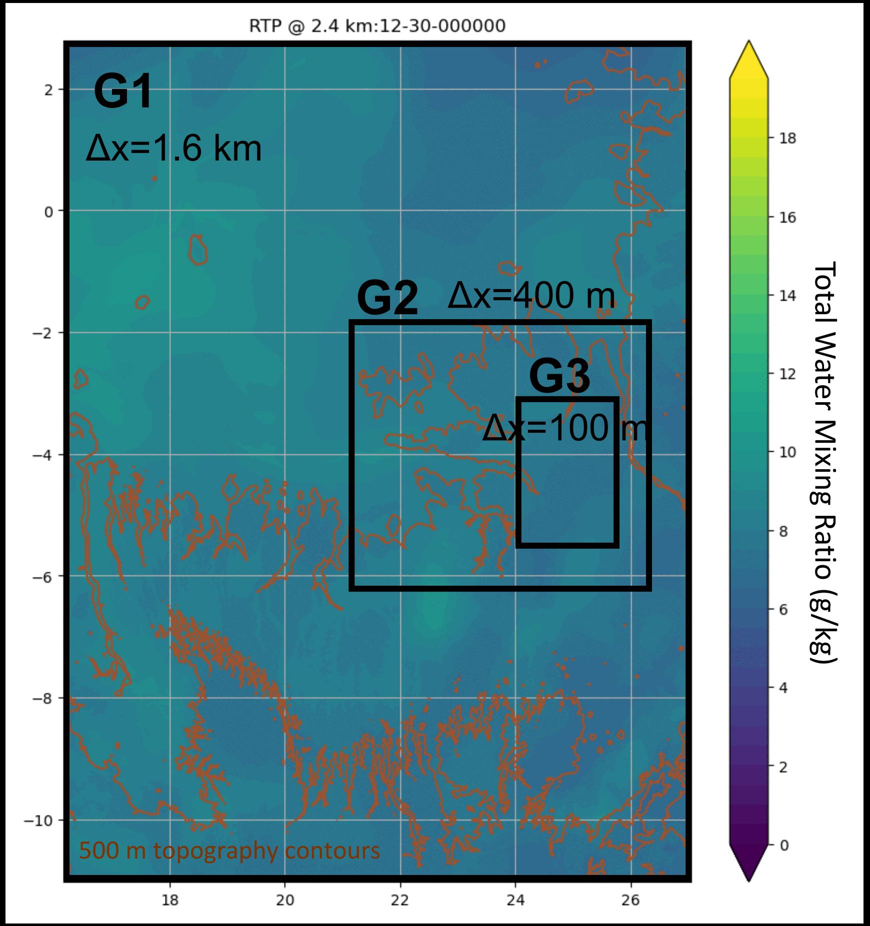
Investigation of Convective Updrafts

INCUS LES: Domains and Structure

INVESTIGATION OF CONVECTIVE UPDRAFTS

- Diverse convective storm database to train INCUS algorithm
- Large Eddy Simulation (LES) Models
  - Regional Atmospheric Modeling System (RAMS)
  - Weather Research and Forecasting Model (WRF)
    - Morrison & Thompson aerosol-aware microphysics
- Simulation details
  - 230 vertical levels / maximum Δz of 125 m
  - Same physics suite for all runs
  - >1.5 petabytes of storage for model data
- Development of "Model Statistics Package"
  - Analyze very high-res data across WRF & RAMS

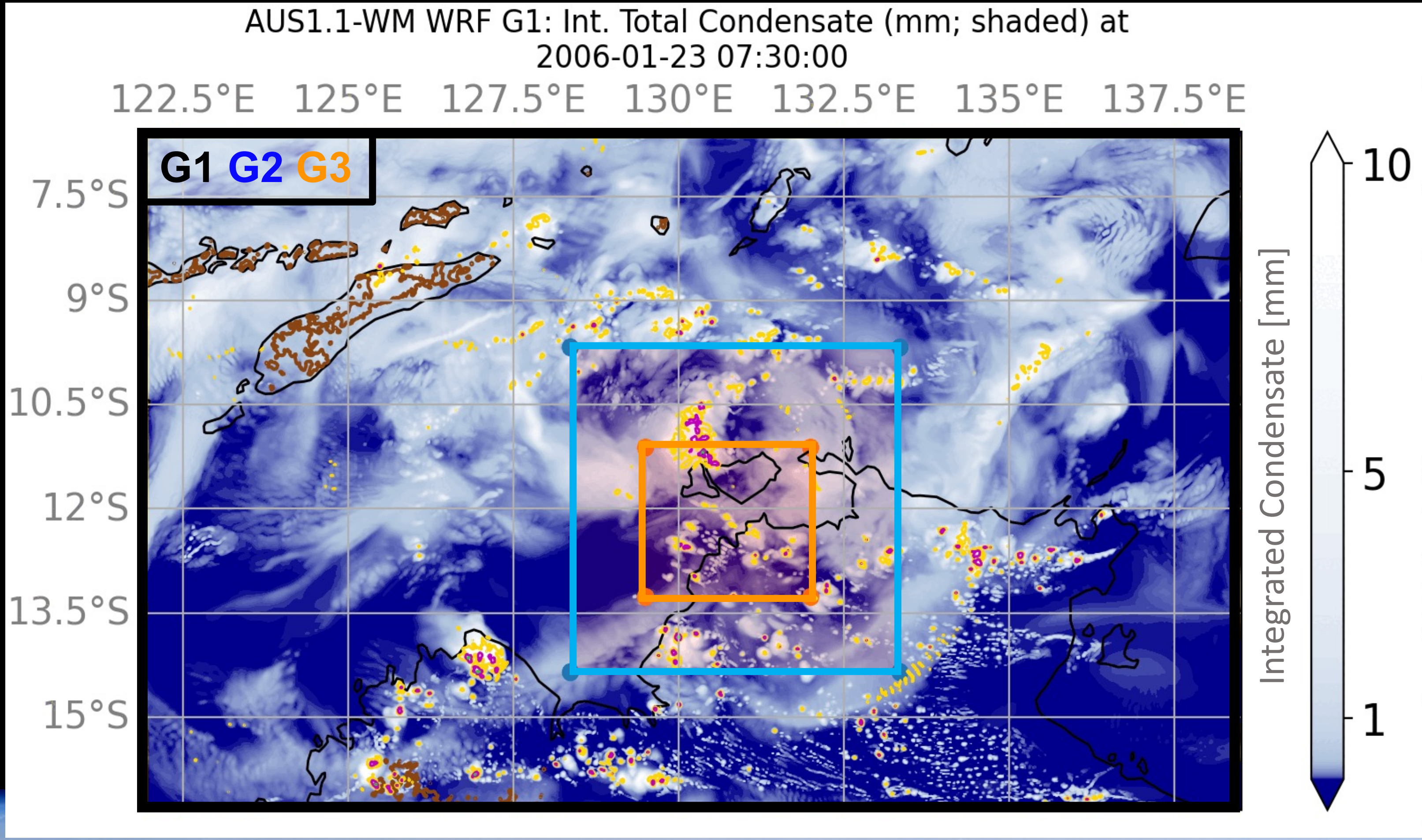
Total Water Mixing Ratio – 2.4 km AGL



[1]Cotton et al., 2003; Saleeby and van den Heever, 2013; [2]Skamarock et al., 2008; [3]Hersbach et al., 2020

INCUS LES: Domains and Structure

- G1 (1.6 km) - AUS1.1 WRF-Morrison (TWP-ICE)



Updraft Contours

2 m/s

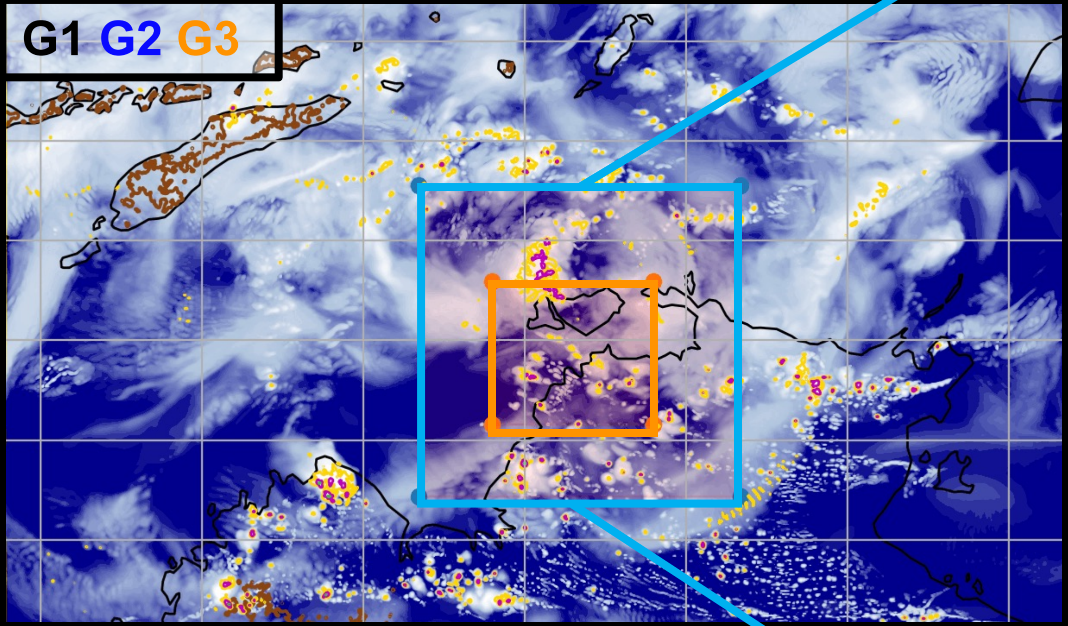
10 m/s

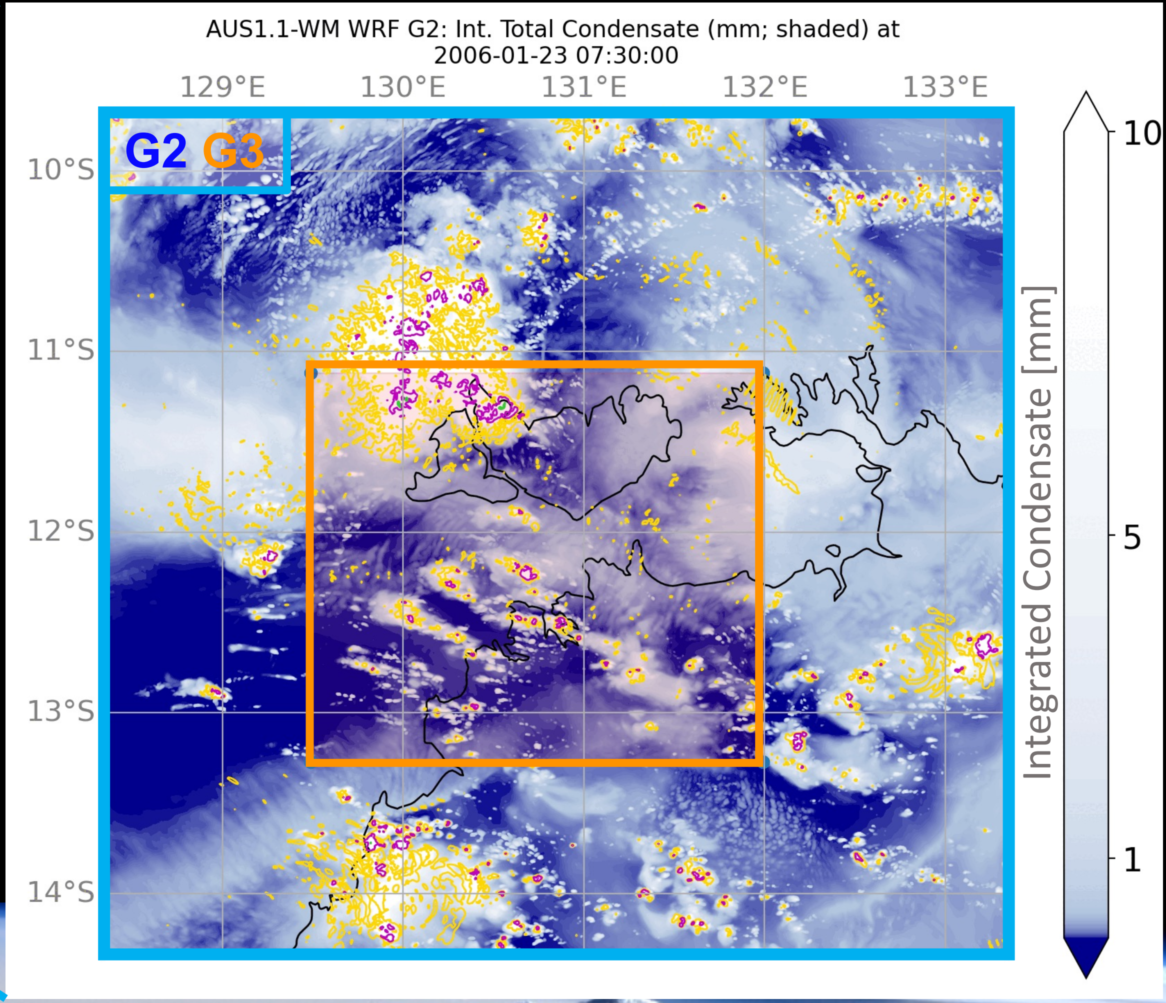
30 m/s

INCUS LES: Domains and Structure

INVESTIGATION OF CONVECTIVE UPDRAFTS

- G2 (400 m) - AUS1.1 WRF-Morrison (TWP-ICE)

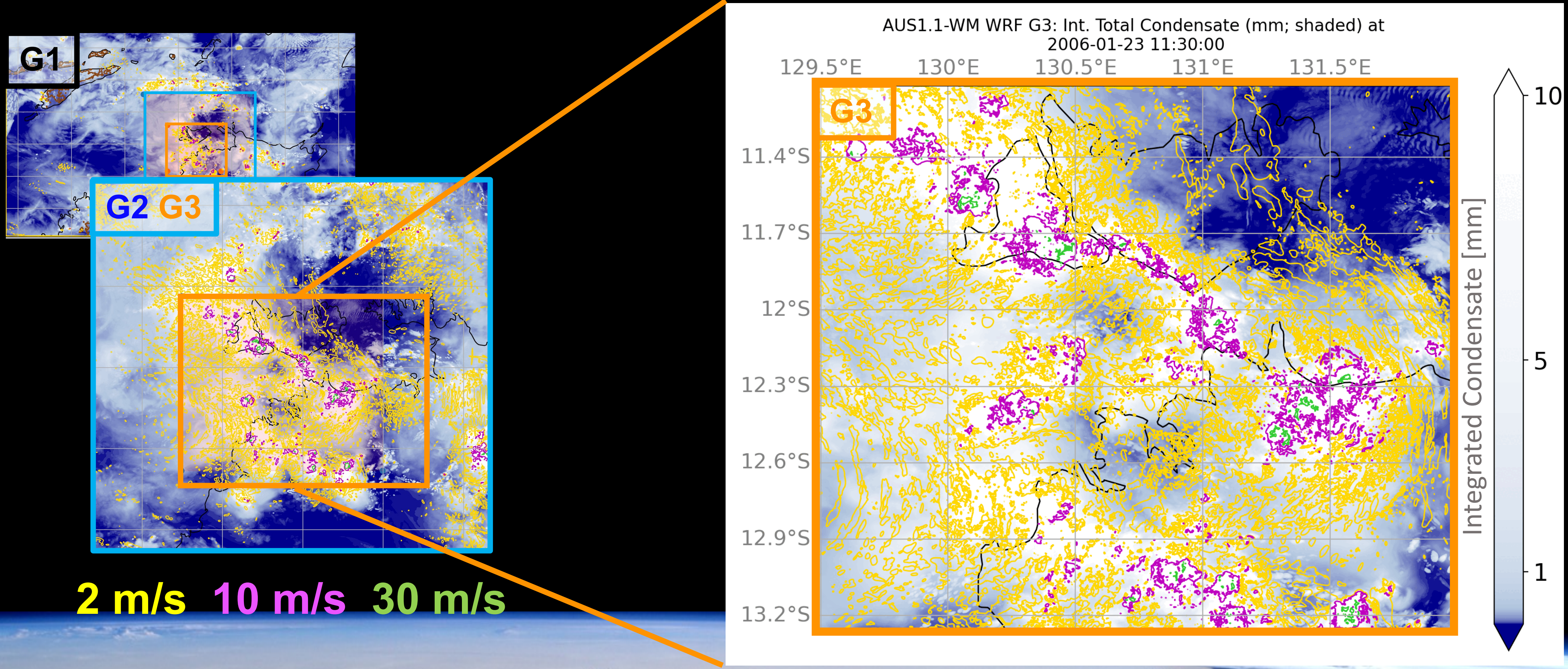




2 m/s 10 m/s 30 m/s

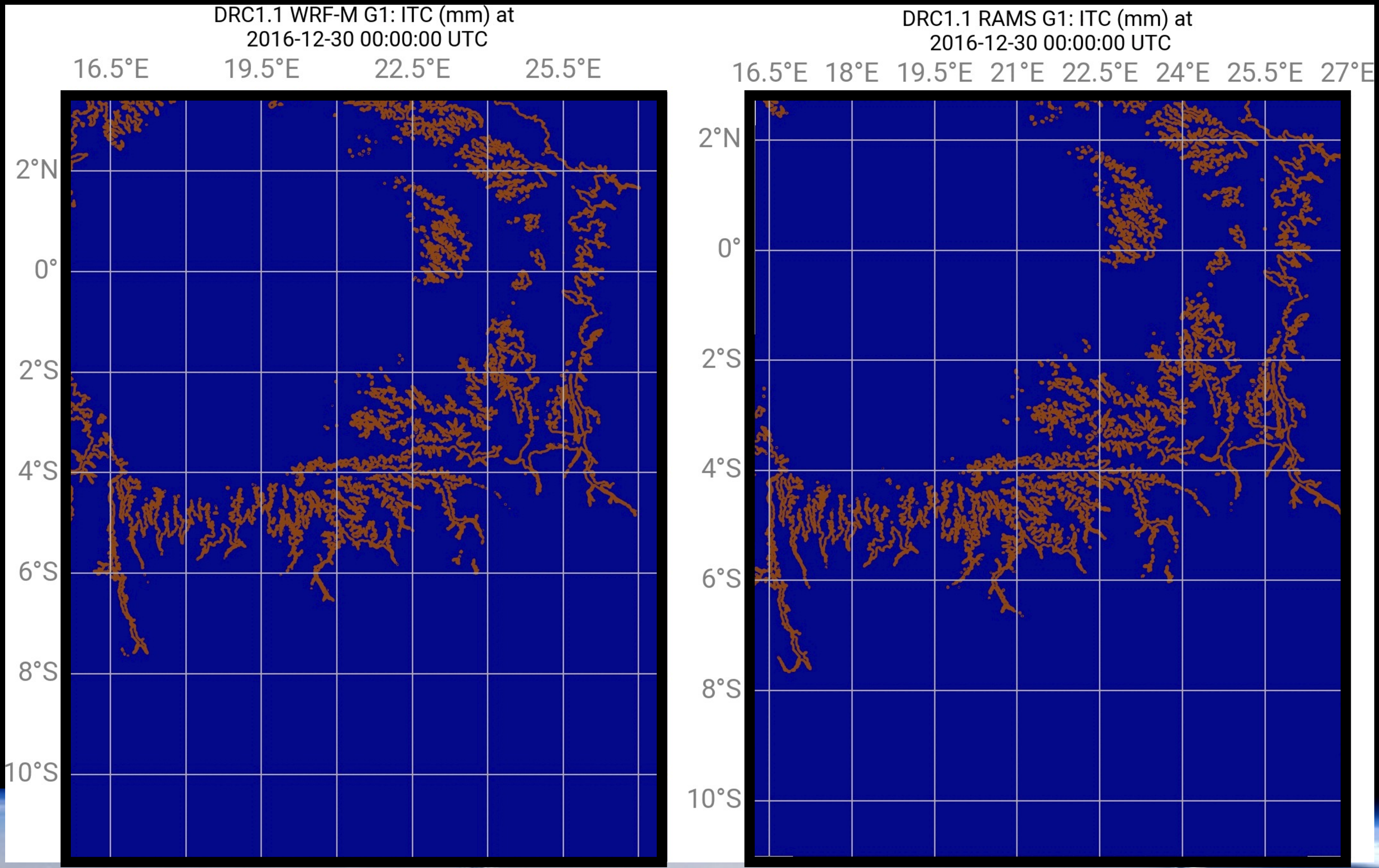
INCUS LES Simulation Database

- G3 (100 m) - AUS1.1 WRF-Morrison (TWP-ICE)



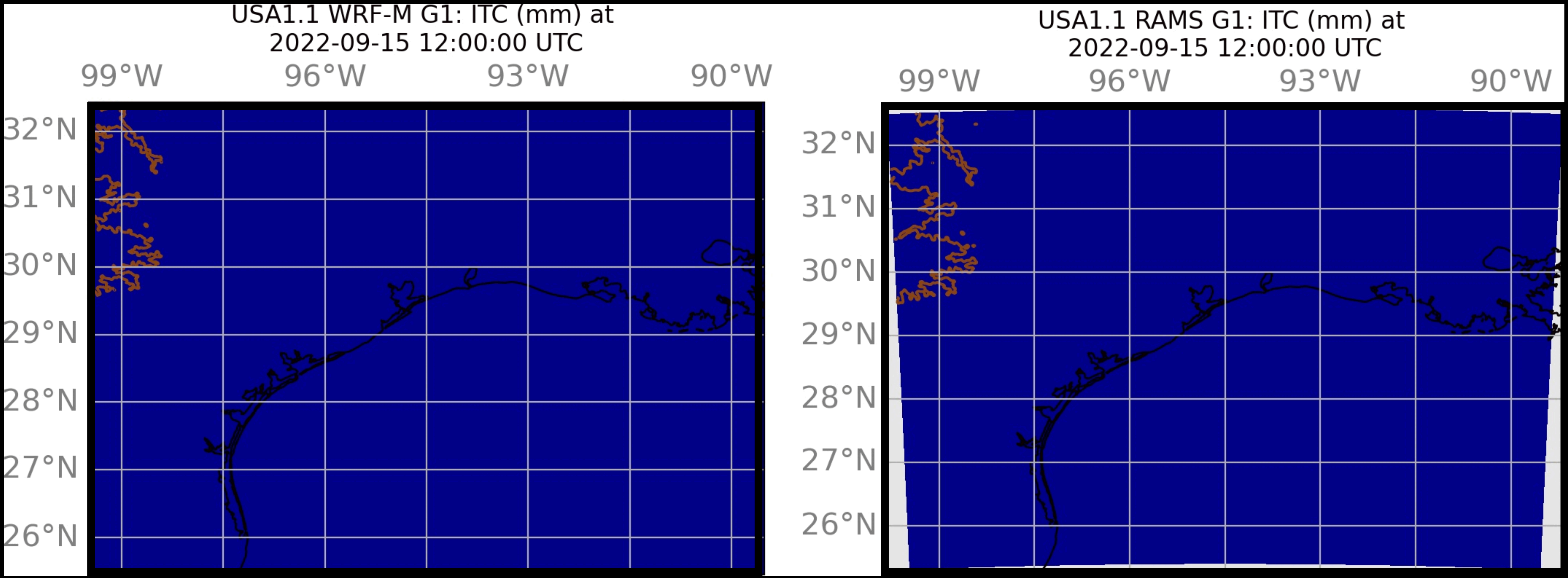
Simulation Animations – Scattered convection in Congo

- G1 (1.6 km) -DRC1.1 WRF-Thompson v. RAMS



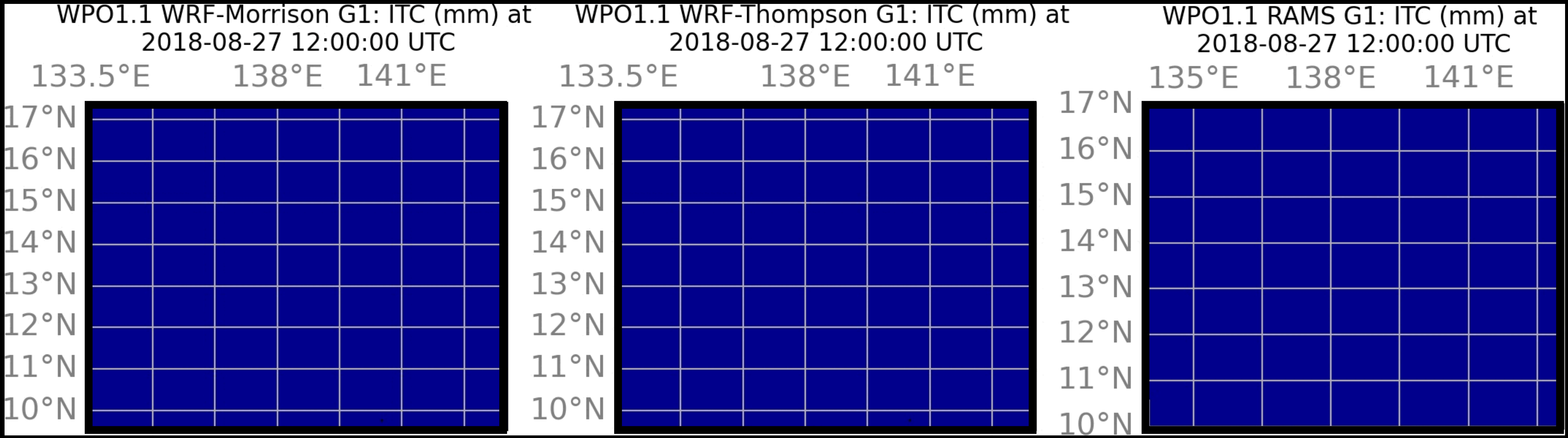
Simulation Animations – TRACER Case (US)

- G1 (1.6 km) - USA1.1 WRF-Morrison v. RAMS



Simulation Animations – PISTON Case (Western Pacific)

- G1 (1.6 km) - WPO1.1 WRF-Morrison v. WRF-Thompson v. RAMS



- Less agreement across models for isolated & scattered convection
  - Boundary layer schemes differ in WRF & RAMS among many other differences

Model Statistics Package – G1 Updrafts

INVESTIGATION OF CONVECTIVE UPDRAFTS

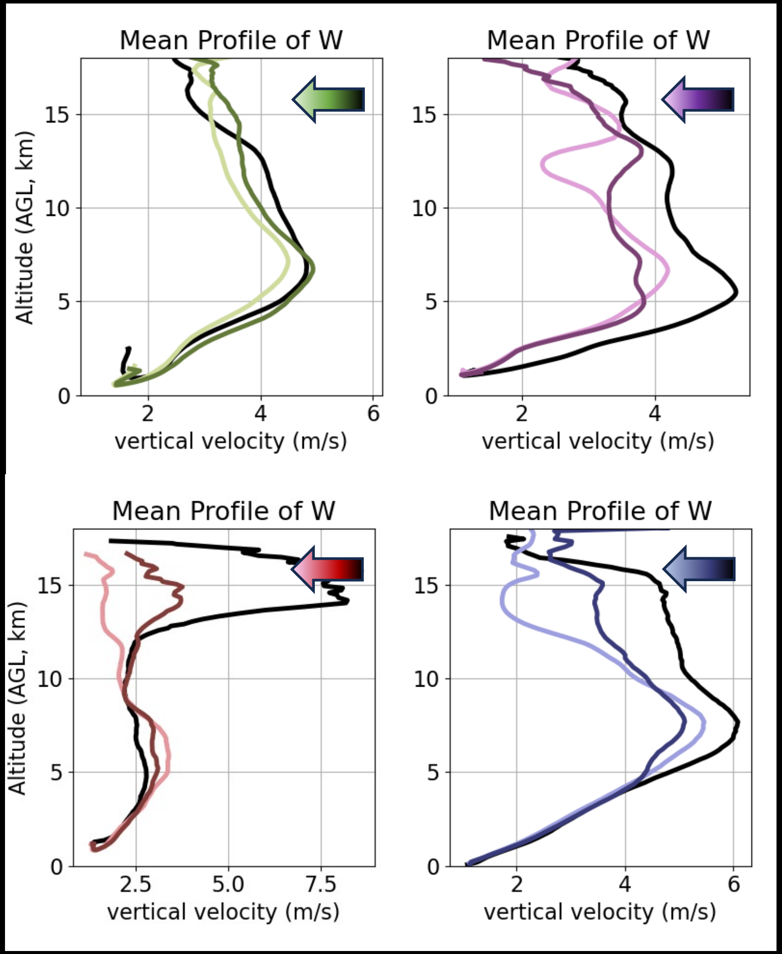
Argentina *Organized Continental*

Congo *Scattered Continental*

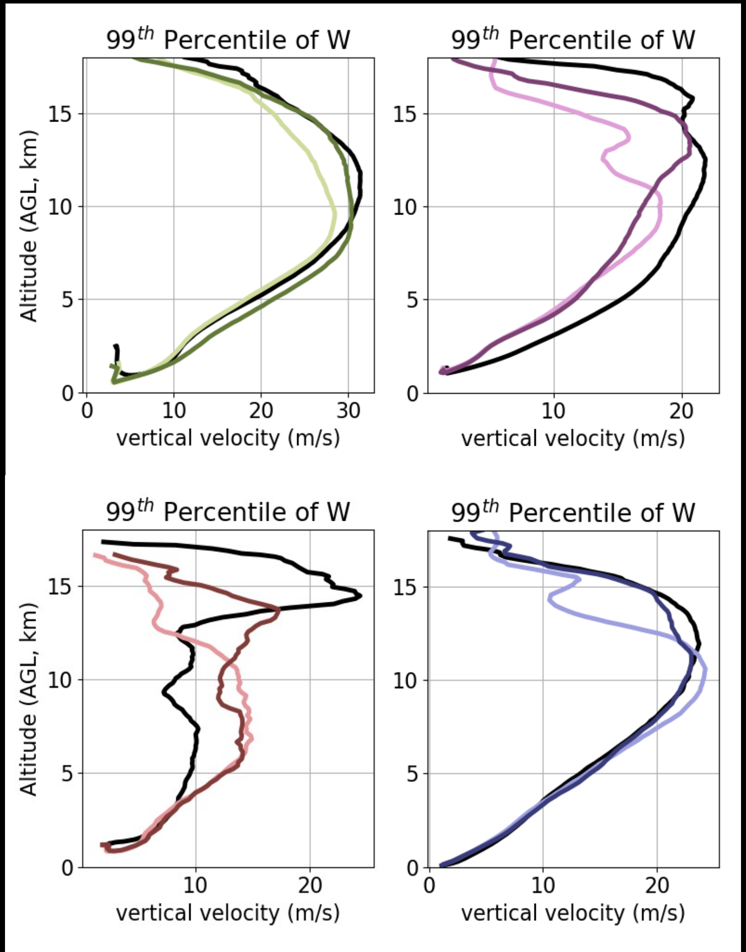
Philippines *Organized Maritime*

Western Pacific *Isolated Maritime*

Mean Updraft Velocity Profiles



Extreme Updraft Profiles



Black: RAMS Dark: WRF Thompson Light: WRF Morrison

INCUS Algorithm Workflow

Cloud Model Simulations

Extensive database of LES simulations of convective systems in diverse environments

Cloud Object Tracking

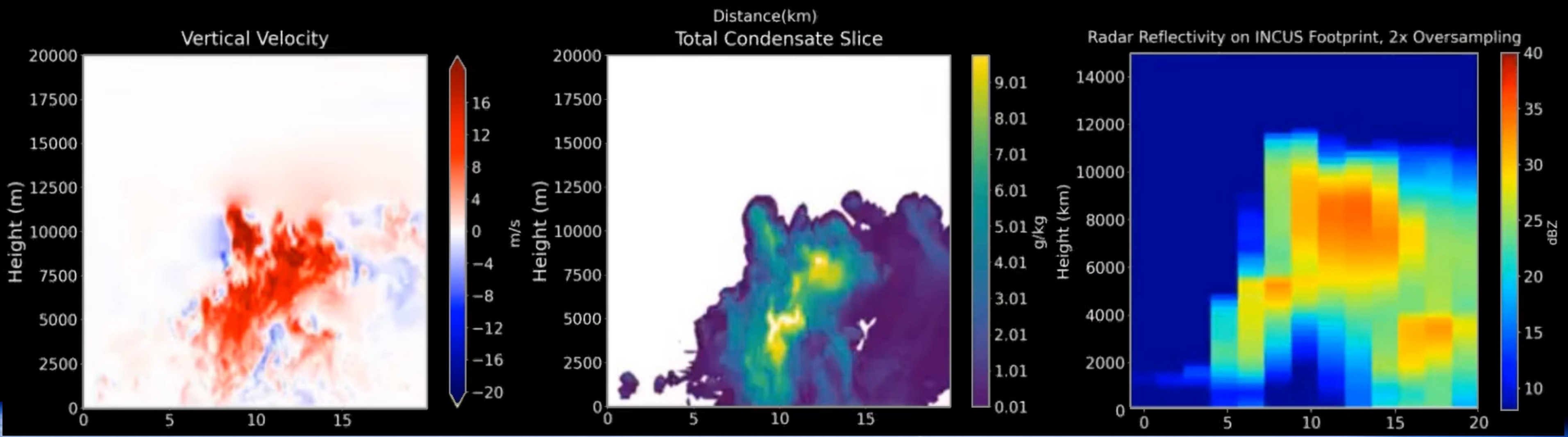
Track millions of modeled updrafts and their environment using *tobac*

Radar and Radiometer Forward Model

Model data converted to INCUS Ka-band radar reflectivity (Z) and microwave Brightness Temperature (T_b)

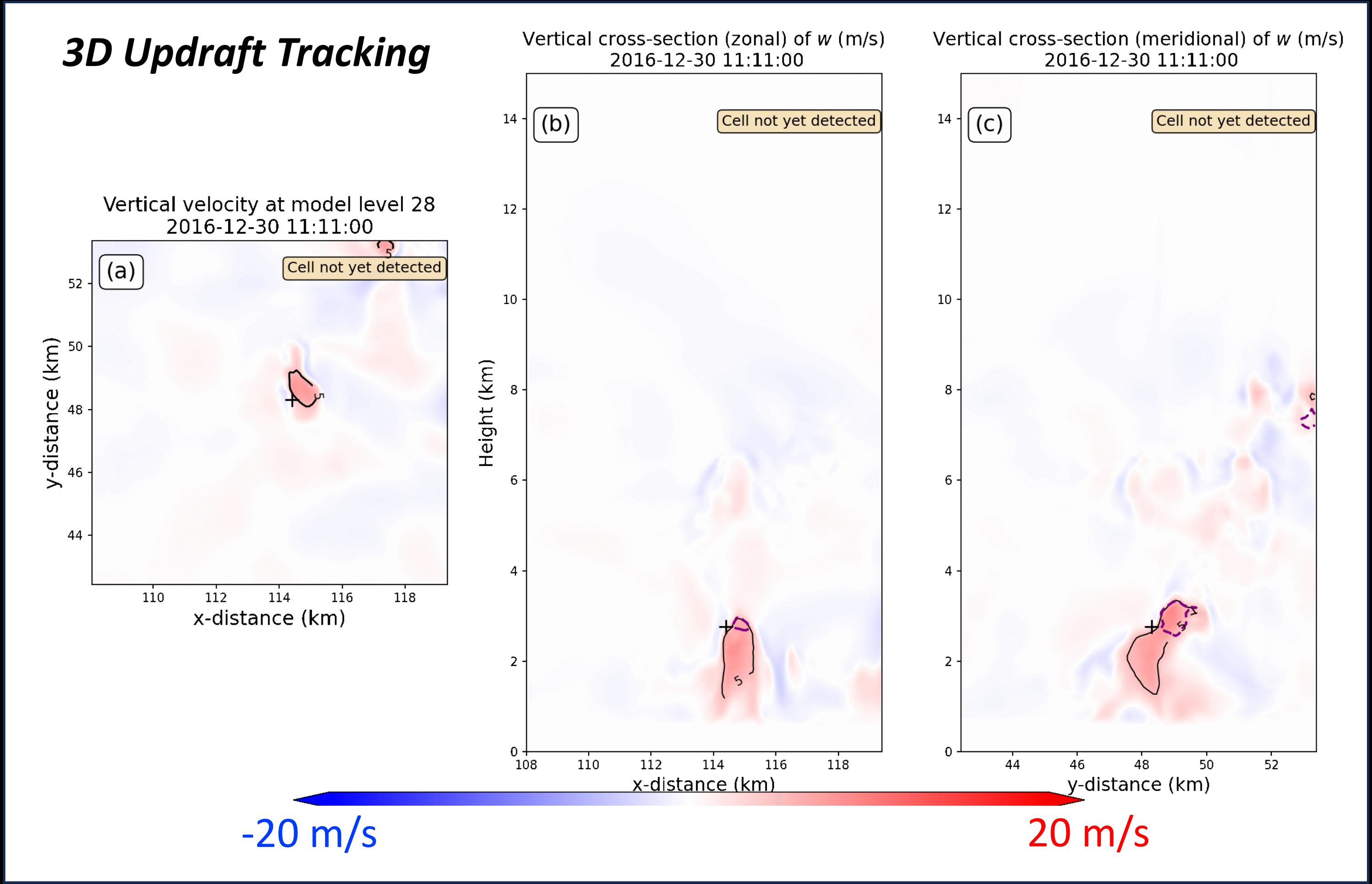
Algorithm and Product Development

ML approaches to map time-separated Z profiles and MW Tb to various CMF metrics



Tracking Updrafts in LES Model Data

- Tracking is completed with *tobac v1.5**
  - 3-dimensional tracking on simulated vertical velocity data
  - Multiple thresholds for feature identification
    - 1,2,3,4,....,50 m s^{-1}
- Updrafts at 100 m grid spacing are transient & chaotic



*Heikenfeld et al., 2019; Sokolowsky, Freeman et al. (in prep)

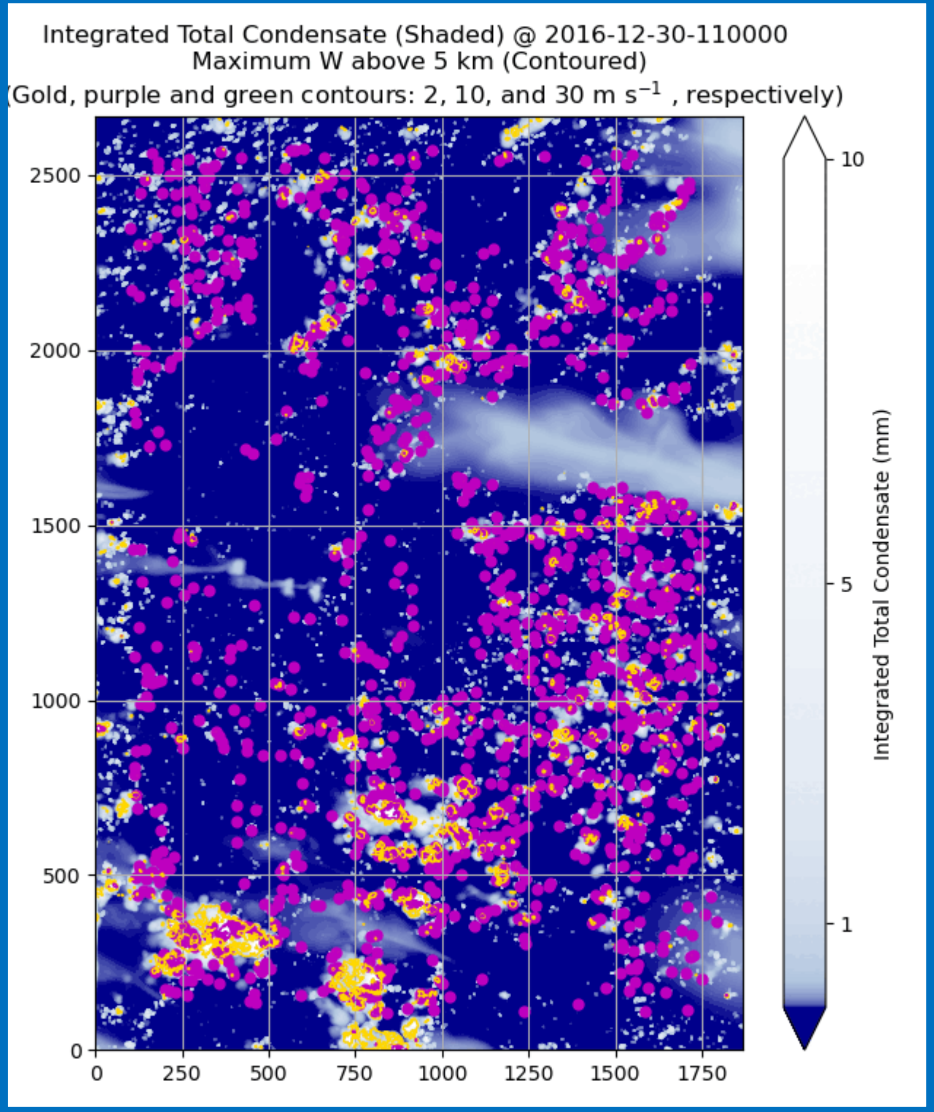
Tracking Updrafts in LES Model Data

INVESTIGATION OF CONVECTIVE UPDRAFTS

Simulation	Mode	Individual Updrafts Tracks	# of 2-min Periods (no overlap)
ARG1.1-R	MCS	27,013	61,214
ARG1.2-R	Terrain	24,456	55,418
AUS1.1-R	MCS	19,359	57,588
BRA1.2-R	MCS	15,870	46,027
RSA1.1-R	Terrain/Scattered	15,168	57,693
PHI2.1-R	MCS	14,532	48,250
DRC1.1-R	Scattered	9,019	38,585
PHI1.1-R	Scattered	5,537	18,049
BRA1.1-R	Scattered	3,048	13,417
USA1.1-R	Scattered	3,451	18,428
WPO1.1-R	Scattered	1,834	10,409
Total		**139,288**	**425,078**

> 425,000 2-min segments if using non-overlapping 2-min periods from the 11 case study simulations

+ 2-min segments from WRF Morrison and Thompson simulations



Ongoing Science - Modeling Team

- IT Singh: Quantifying the length scales of variability in tropical convective environments
- Jennie Bukowski: Relationship between convective mass flux and anvil properties; microphysics effects on updrafts & anvils
- Peter Marinescu: Sub-grid convective environment variability within reanalysis data; timescales of variability of vertical velocity and its budget components
- Gabrielle 'Bee' Leung: Dependence of precipitation and vertical velocity on grid spacing
- Rachel Storer: Idealized modeling to understand the sensitivity of $\Delta Z \rightarrow w$ mapping to microphysical process rates and parameters

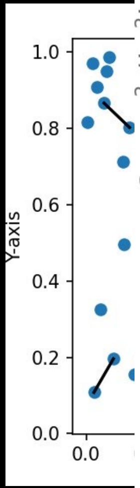
And a lot more!

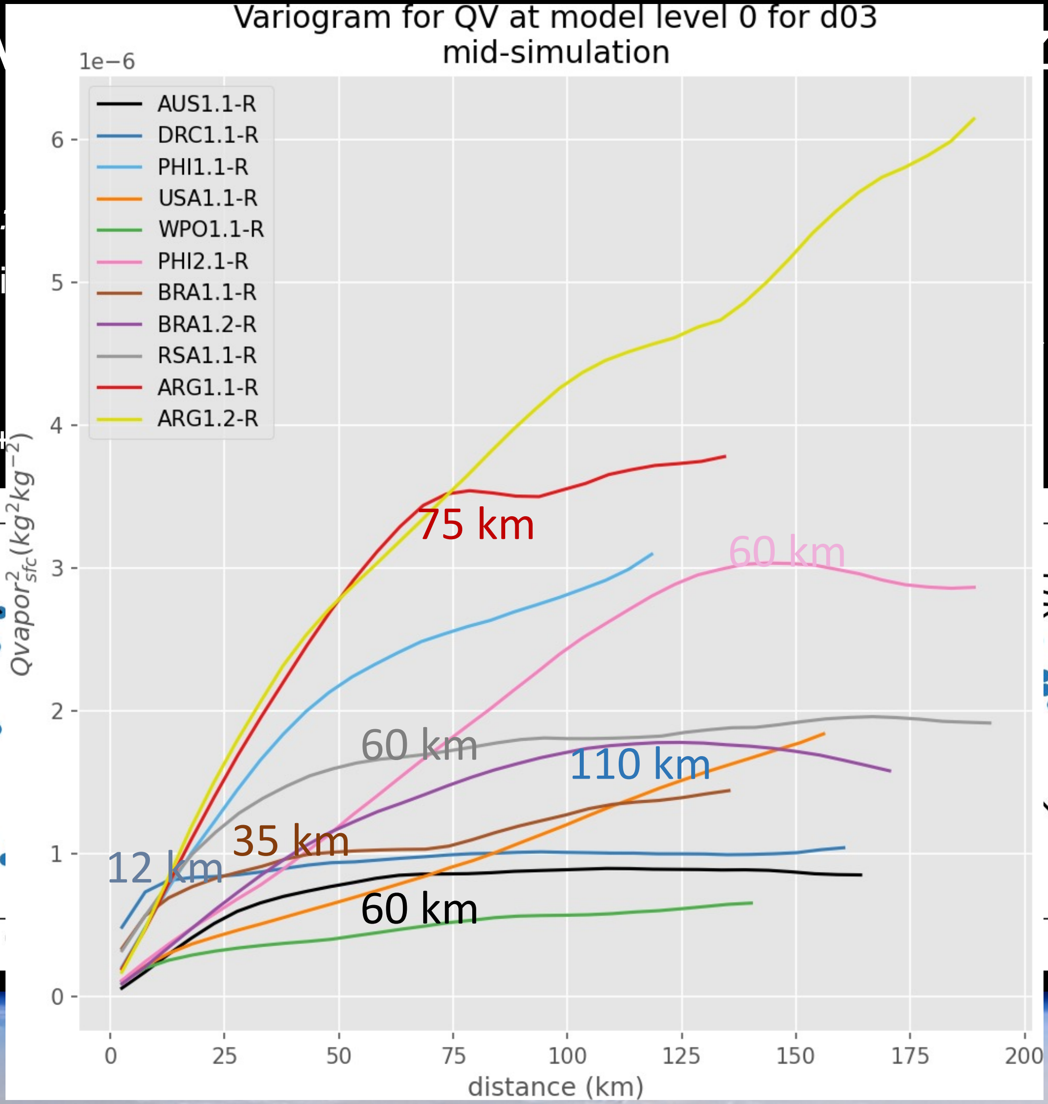
Ongoing Science - Spatial scales of variability in convective environments

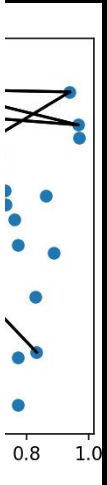
- Using v… …zontal spatial …

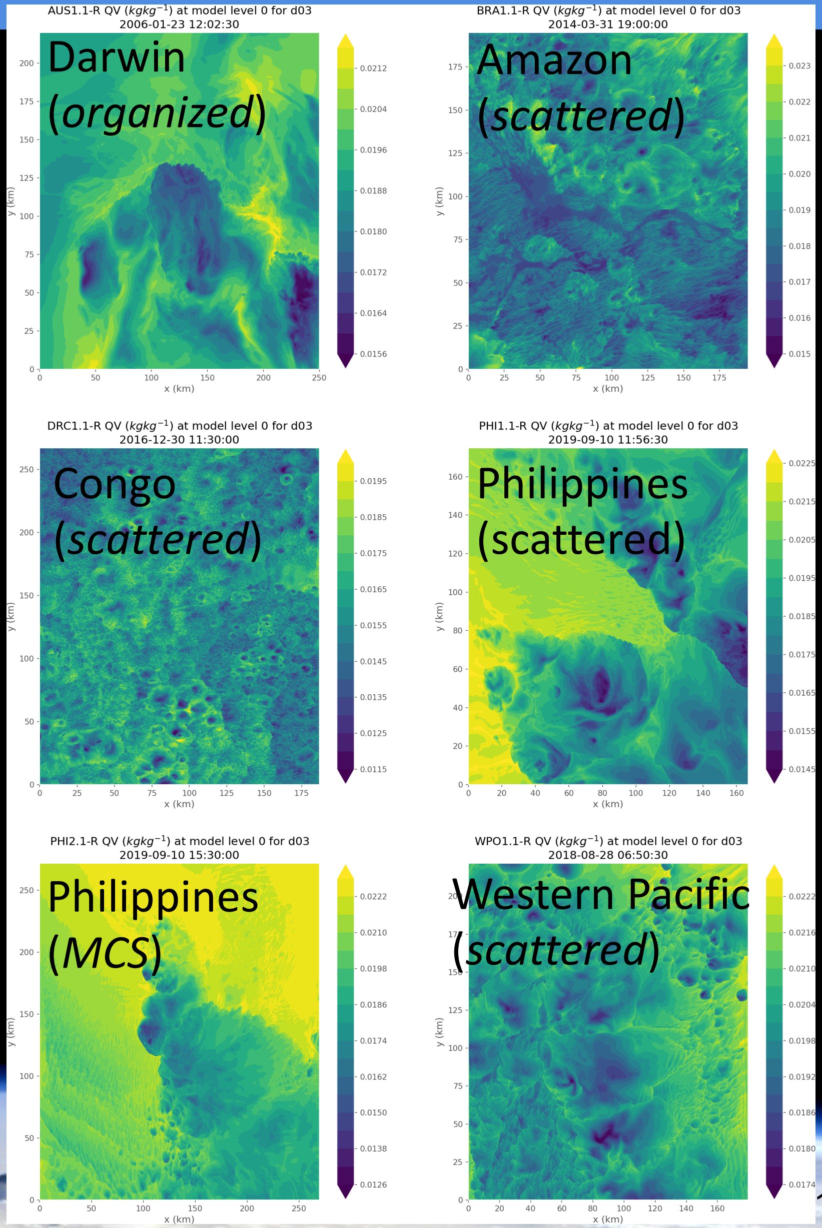
Definition:

- $\gamma(\boldsymbol{h})$ i…
- $N(\boldsymbol{h})$ …
- $Z(\boldsymbol{x}_i)$ …
- $Z(\boldsymbol{x}_i +$ …



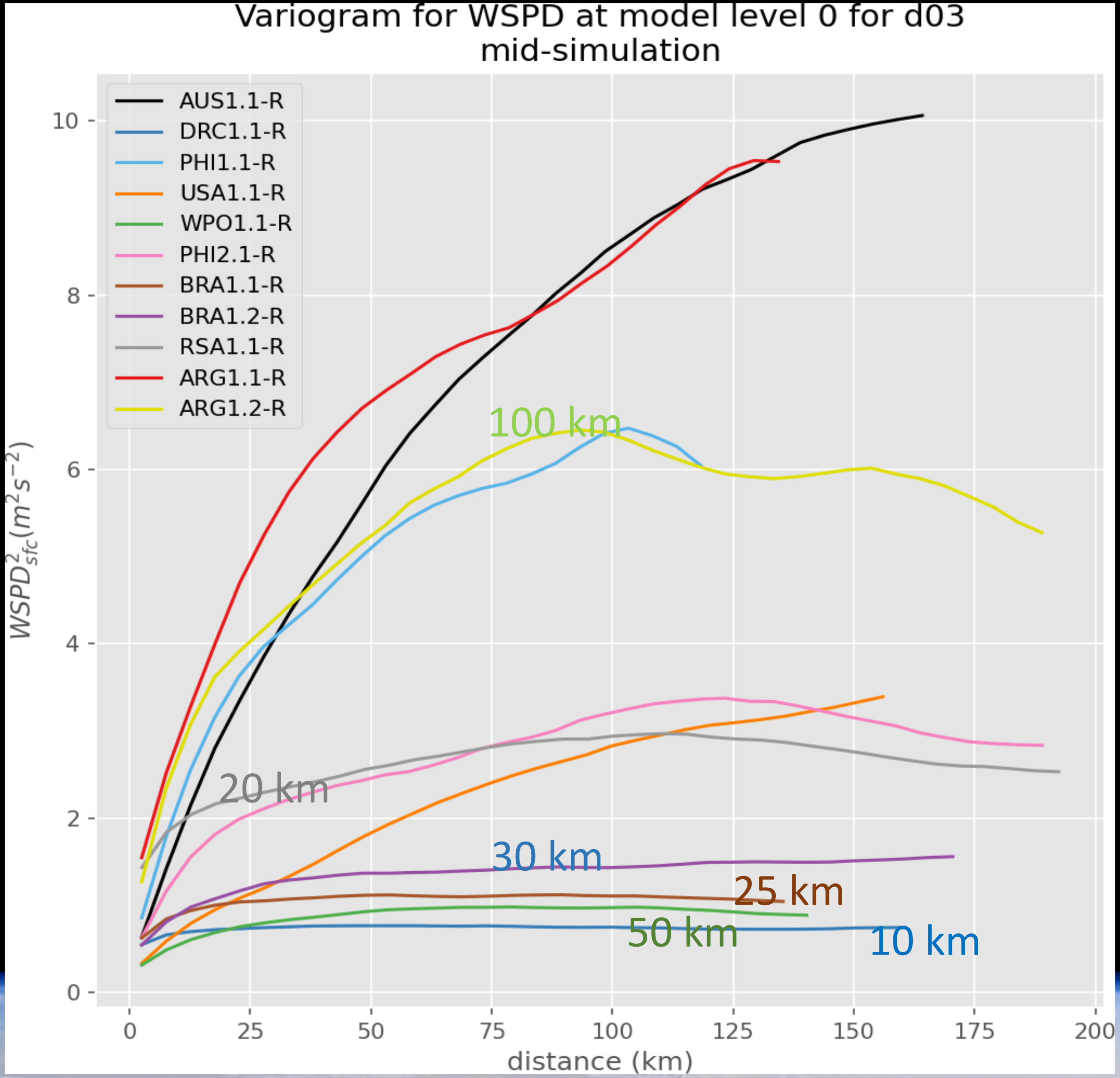


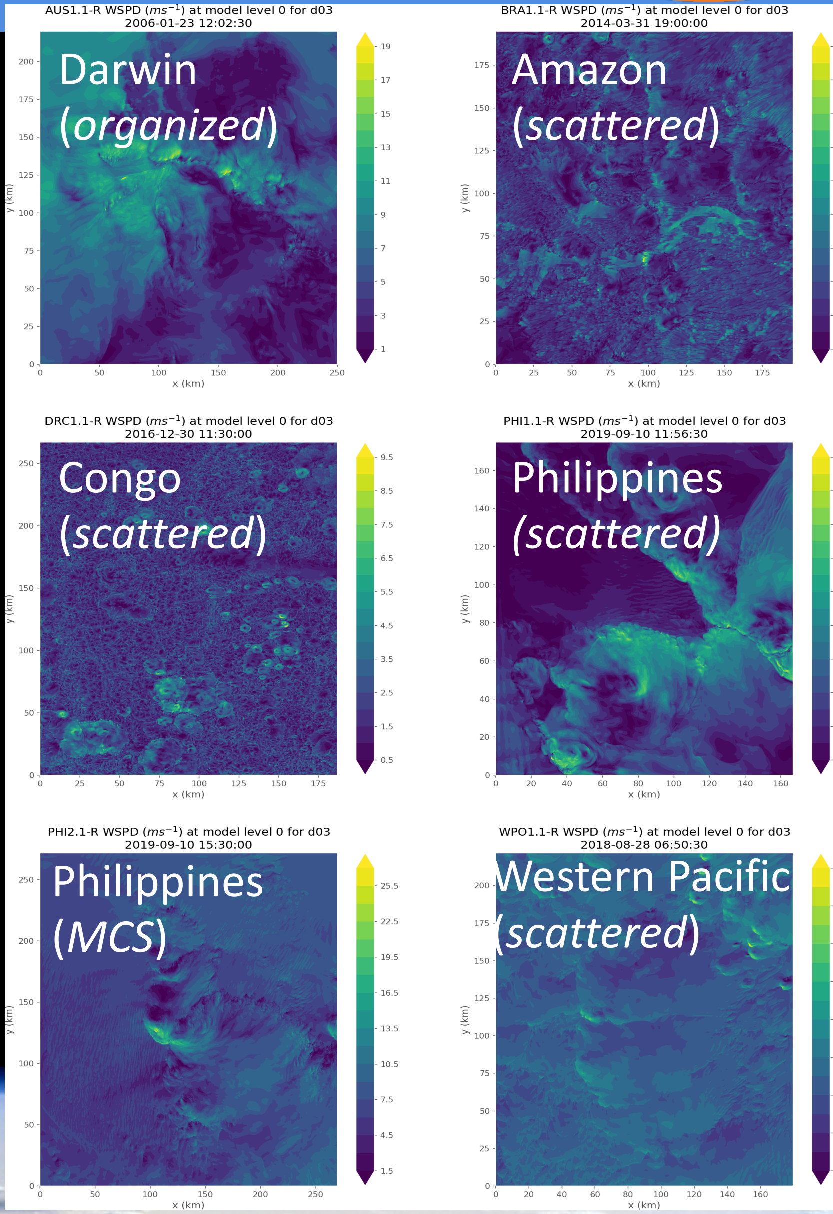




Ongoing Science - Spatial scales of variability

INVESTIGATION OF CONVECTIVE UPDRAFTS





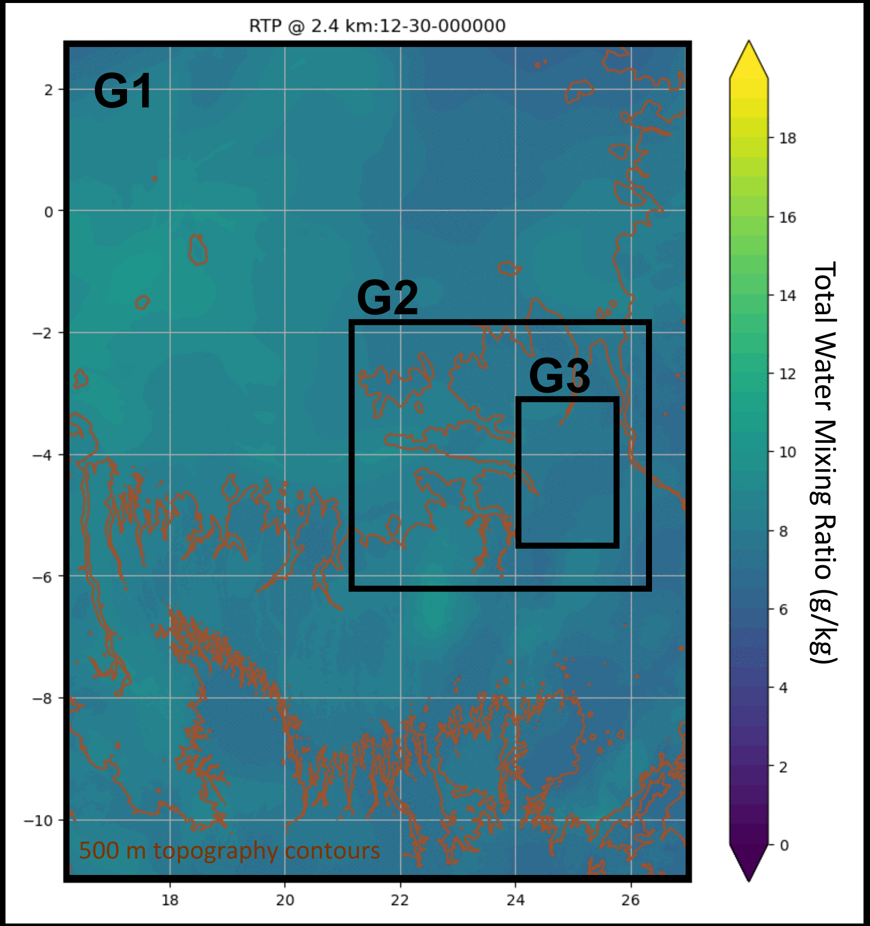
Summary

1. We are producing an extensive database of high-resolution numerical simulations of tropical convection using WRF (Morrison and Thompson) and RAMS models.
   - The goal is to use these simulations as an input into a forward model to then develop the INCUS CMF retrieval algorithm
2. Running simulations at 100 m grid spacing and with large domain sizes (2000x2000x230) poses several challenges:
   - Large memory requirements and high computational costs
   - Issues with (very) large file I/O
3. Comparing model output with available radar data and IR T_b
4. Developing a Python module to analyze output across models
5. Lots of exciting science being done with these simulations!

Extra slides: INCUS LES Physics

Model Details	**RAMS v6.3.02**		**WRF v4.4.2**	
Grids	**#**	**size**	**Δx, Δy**	**output freq.**
	G1	~ 800 km x 800 km	1.6 km	30 min
	G2	~ 300 km x 300 km	400 m	30 min
	G3	**~ 200 km x 200 km**	**100 m**	**30 s**
Vertical	230 levels with max 125 m vertical grid spacing			
I & LBC			ERA5	
Land surface.	LEAF-3		Noah-MP	
PBL/ Turbulence	3D Smagorinsky		G1: YSU PBL Scheme + 2D Smagorinsky G2, 3: No PBL Scheme + 1.5 order TKE	
Radiation	Harrington Two-stream, SW and LW		RRTMG	
Microphysics	2-moment (2M) RAMS		2M Morrison & 2M Thompson Aerosol Aware	

Total Water Mixing Ratio – 2.4 km AGL



[1]Cotton et al., 2003; Saleeby and van den Heever, 2013; [2]Skamarock et al., 2008; [3]Hersbach et al., 2020

Extra slides: WRF namelist


```
cu_physics             =  0,    0,  0,
shcu_physics           =  3,    0,  0,
ra_lw_physics          =  4,    4,  4,
ra_sw_physics          =  4,    4,  4,
bl_pbl_physics         =  1,    0,  0,
topo_wind              =  1,    0,  0,
sf_sfclay_physics      =  1,    1,  1,
sf_surface_physics     =  2,    2,  2,
isfflx                 =  1,
radt                   =  1,    1,  1,
bldt                   =  0,    0,  0,
cudt                   =  0,    0,  0,
icloud                 = 1,
num_land_cat           = 21,
sf_urban_physics       = 0,     0,  0,
fractional_seaice      =  1,
```

```
&dynamics
hybrid_opt             = 2,
w_damping              = 0,
diff_opt               = 2,     2,  2,
km_opt                 = 4,     2,  2,
sfs_opt                = 0,     0,  1,
mix_isotropic          = 0,     0,  1,
diff_6th_opt           = 0,     0,  0,
diff_6th_factor        = 0.12,   0.12,0.12,
base_temp              = 290.
damp_opt               = 3,
zdamp                  = 5000.,  5000.,5000.,
dampcoef               = 0.2,   0.2,  0.2,
khdif                  = 0,     0,    0,
kvdif                  = 0,     0,    0,
non_hydrostatic        = .true., .true.,.true.,
moist_adv_opt          = 4,     4,    4,
scalar_adv_opt         = 3,     3,    3,
momentum_adv_opt       = 1,     1,    1,
gwd_opt                = 0,     0,    0,
mix_full_fields        = .true., .true.,.true.,
time_step_sound        = 0,     0,    0,
/

&bdy_control
spec_bdy_width         = 20,
specified              = .true.
```

Extra slides: INCUS LES Physics