National Aeronautics and Space Administration

Investigation of High Ice Water Content (HIWC) with a Convective Cloud Model

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- **The numerical simulations were conducted using the Pleiades high-performance supercomputer cluster of the NASA Advanced Supercomputing Division**

Outline

- High Ice Water Content (HIWC) modeling objectives
- Brief description of numerical model
- Results from numerical simulation
  - Time evolution
  - Structure of mature system
- Summary

High Ice Water Content (HIWC) Modeling Objective

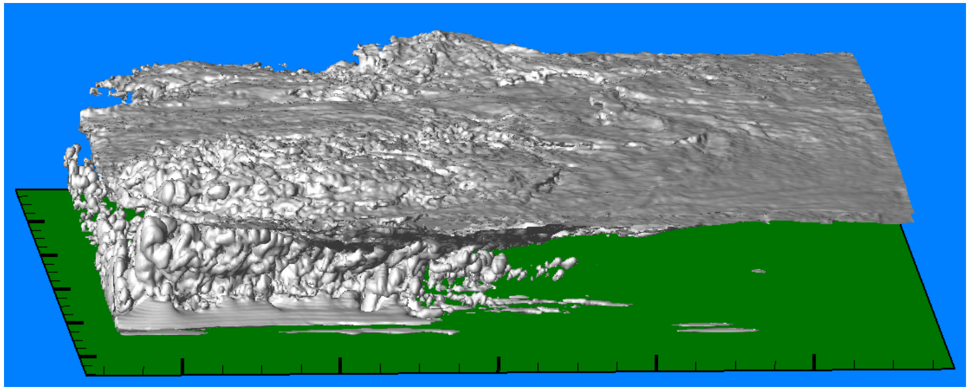
- **Characterize HIWC events through numerical modeling studies**
  - Size, duration, elevations of event
  - Water/ice contents
  - Time evolution of ice water fields
  - Relationship to environment

- **Data for Radar simulation**
  - Generate realistic numerical data sets for Radar detection studies
  - Represent three-dimensional HIWC convective system as it evolves within different environments
  - Extract three-dimensional sub-volumes sequenced in time during the evolution of a HIWC event
  - Provide as input for Radar simulator studies
  - Post-analysis of extracted data provides "truth" for Radar simulation studies

View of Mesoscale Convective System from Space. Satellite image courtesy of Image Science & Analysis Laboratory, NASA Johnson Space Center

TERMINAL AREA SIMULATION SYSTEM (TASS)

- **Time-dependent, 3-D, Large Eddy Simulation (LES) Model**
- **Meteorological Framework**
- **Prognostic Equations for:**
  - **3-Components of Velocity** - **Pressure**
  - **Potential Temperature** - **Rain**
  - **Water Vapor** - **Snow**
  - **Liquid Cloud Droplets** - **Hail / Graupel**
  - **Cloud Ice Crystals** - **Dust / Insects**



- **Subgrid-scale turbulence parameterized with modifications for stratification and flow rotation**
- **Numerics are accurate, highly efficient*, and* essentially free of numerical diffusion**
- **Contains roughly 60 bulk cloud microphysics submodels**
- **Initialization modules for simulation of convective storms, microbursts, atmospheric boundary layers, turbulence, and aircraft wake vortices**
- **Software modifications and re-coding have occurred to take advantage of paradigm shifts in computing platforms**
- **User's guide, version 10.0: NASA TM-2014-218150**

Cloud Ice Variables in TASS

- Important Prognostic Variables:
  - Ice crystal water
    - Represents small ice crystals ~ 200 um diameter and smaller
    - Monodispersed
    - Weak fall speed
    - Hexagonal shape
  - Snow
    - Represents larger precipitating ice crystals
    - Inverse exponential distribution with intercept increasing with colder temperatures (based on Woods et al. JAS 2008)
    - Treated as low density spherical particles
  - Graupel (or hail)
    - Inverse exponential distribution with smaller intercept than snow
    - Higher density and greater fall speed than snow
    - Generated from frozen raindrops and rimed snow

Assumed Particle Size Distributions in TASS

Category	Size Distribution Intercept (m^{-4})	Particle Density ($kg\ m^{-3}$)	Comment
Cloud Water	Monodispersed	1000	Number of drops per volume is an input (=75 cm^{-3})
Rain	$2.25 \times 10^7 M_R^{0.375}$	1000	Intercept increases with rainwater content, M_R ($g\ m^{-3}$)
Cloud Ice	Monodispersed	Particle mass (kg) = $0.1758\ D_{ic}^{\ 2.2}$	Hexagonal plates Diameter mostly < 200 μm
Snow	$10^{(7.02 - 0.0475\ Tc)}$ for $4^oC > Tc > -40^oC$	100 if $Tc < -20^0C$ $100 + 35/20\ (Tc + 20)$ if $Tc > -20\ ^oC$	Intercept increases with decreasing temperature: graupel like snow
Hail/Graupel	N_{oH}	450	N_{oH} intercept used for graupel = $4 \times 10^5\ m^{-4}$)

Diagnostic of Model Radar Reflectivity Factor *(e.g. Smith et al JAM 1975)*

- **Radar Reflectivity Factor from rain based on Rayleigh Scattering:**

$$Z_R = \int_0^\infty N(D_R)\, D_R^6\, dD_R$$

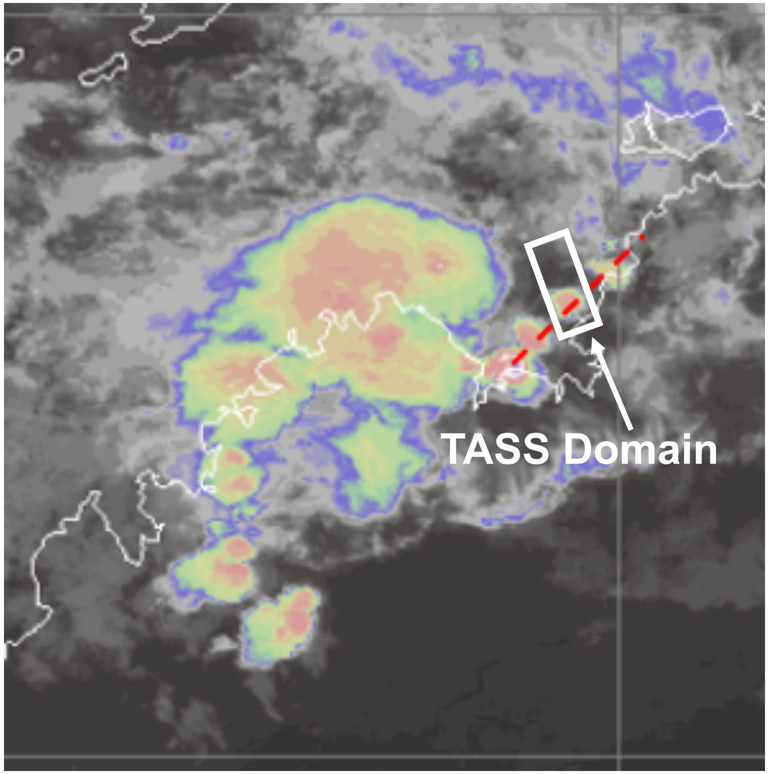
- **Radar Reflectivity Factor from "dry" snow (similarly for ice crystals and dry hail/graupel)**

$$Z_S = |K_I|^2/|K_W|^2 \;\; \delta_S^2/\delta_w^2 \;\; \int_0^\infty N(D_S)\, D_S^6\, dD_S$$

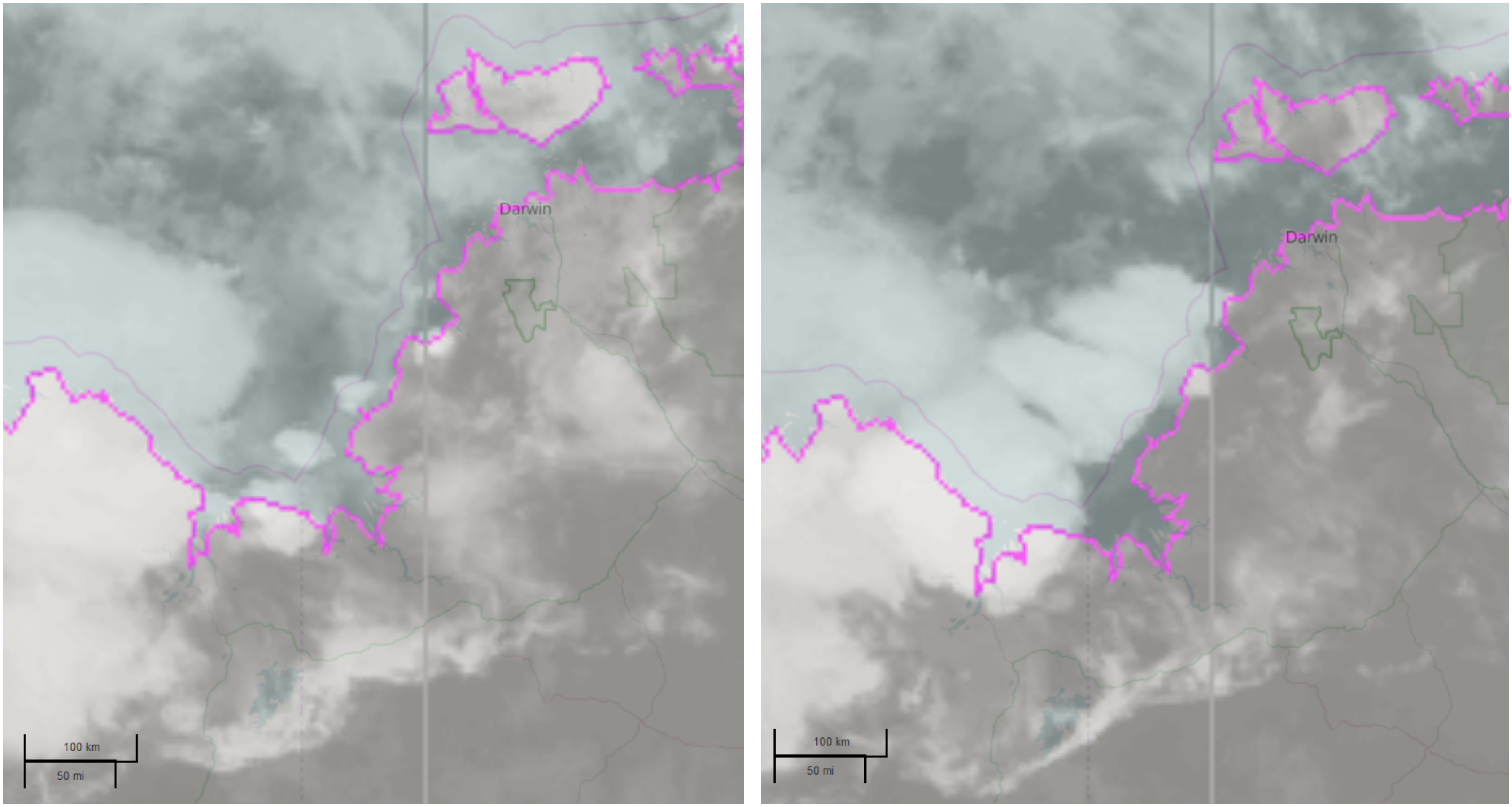
TASS Simulation of Darwin HIWC Event

- **Initialization based on atmospheric sounding launched at Darwin, on 24 January 2014, 0000 UTC**
- **Weakness: the actual system was over 200 *km* from Darwin and formed several hours earlier**
- **Domain configured offshore over the Timor Sea (southwest of Darwin) – within area where convective line is developing**

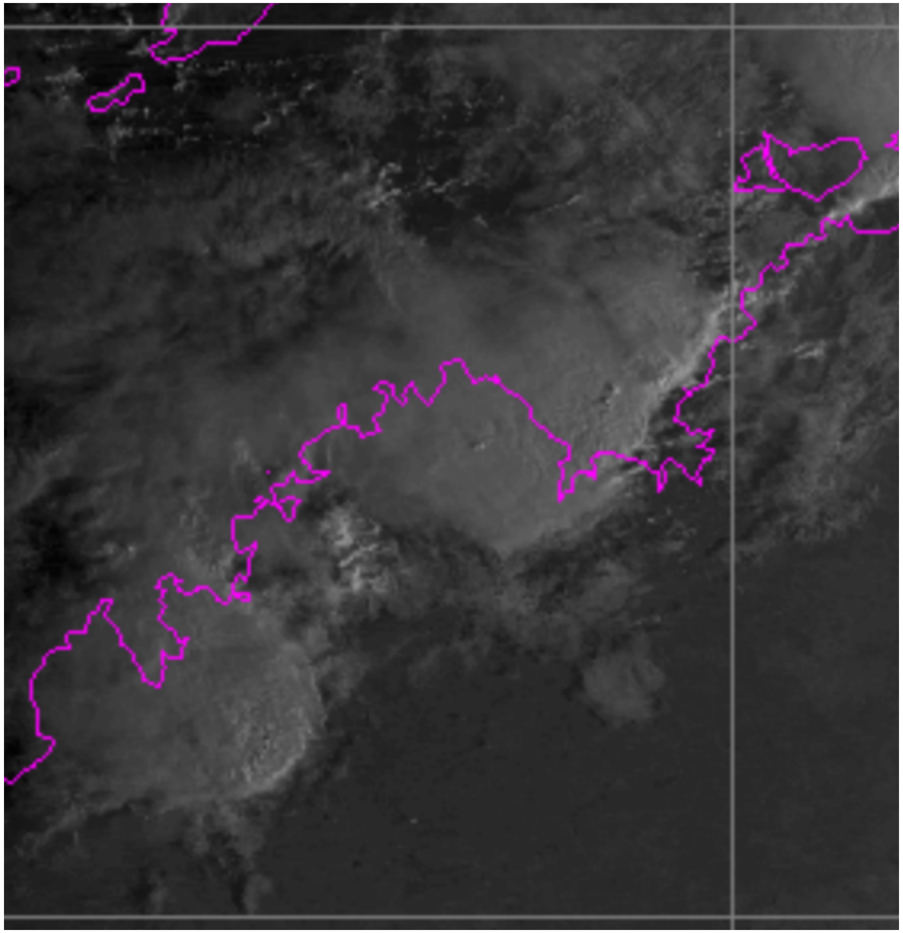
Infrared satellite imagery showing cloud top temperatures of a mesoconvective system offshore of Northern Australia on 23 Jan 2014 (Courtesy NASA Langley Satellite Group)



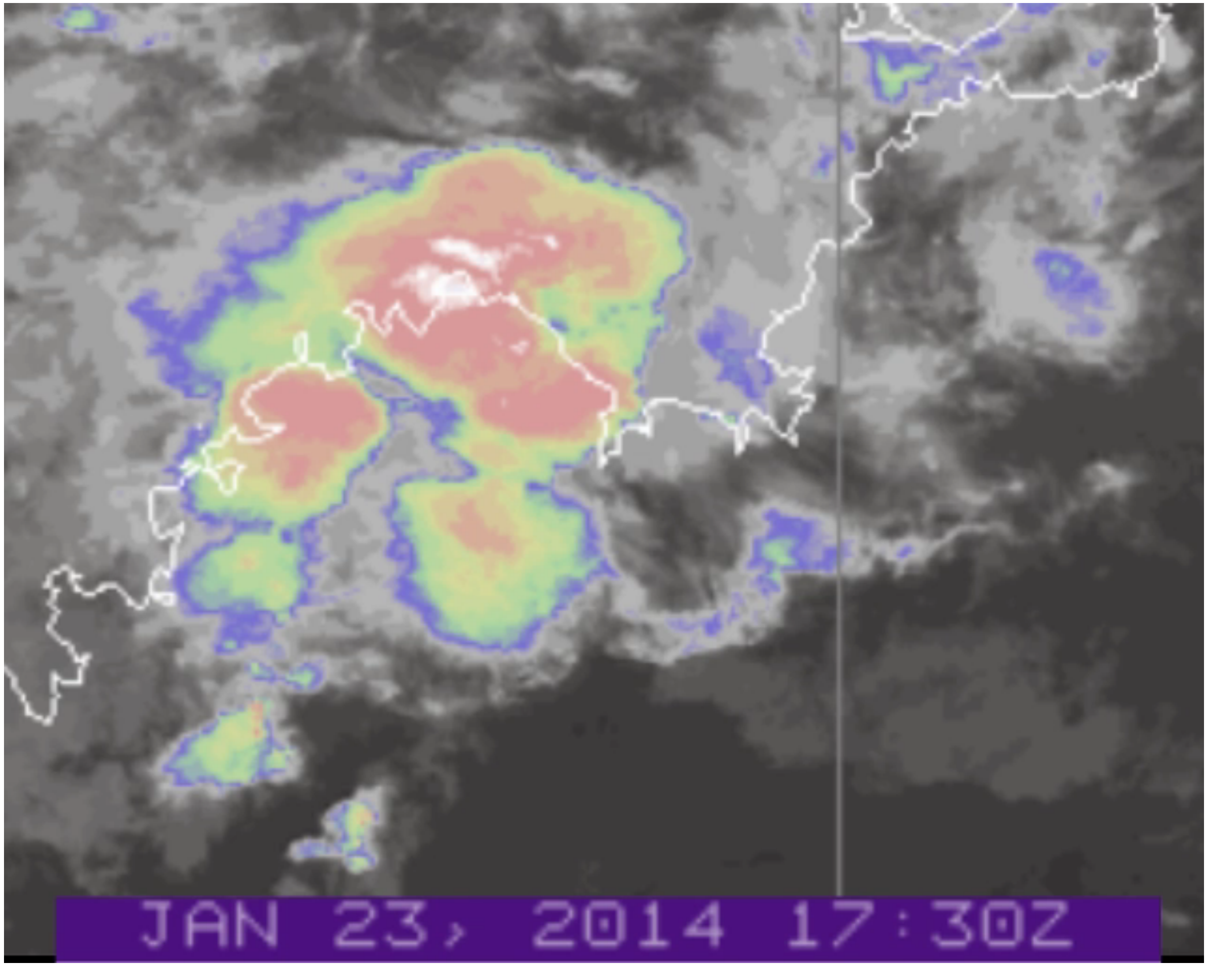
MTSAT-IR, 23 Jan 14, 18:15 & 2000 UTC
Channel 2 *(Courtesy NASA Langley Satellite Group)*



MSAT VISIBLE, 23 Jan 2014, 2201 UTC 122 E -132E, 10S-20S *(Courtesy NASA Langley Satellite Group)*



Animation: IR Satellite (cloud top temperatures) *(Courtesy NASA Langley Satellite Group)*

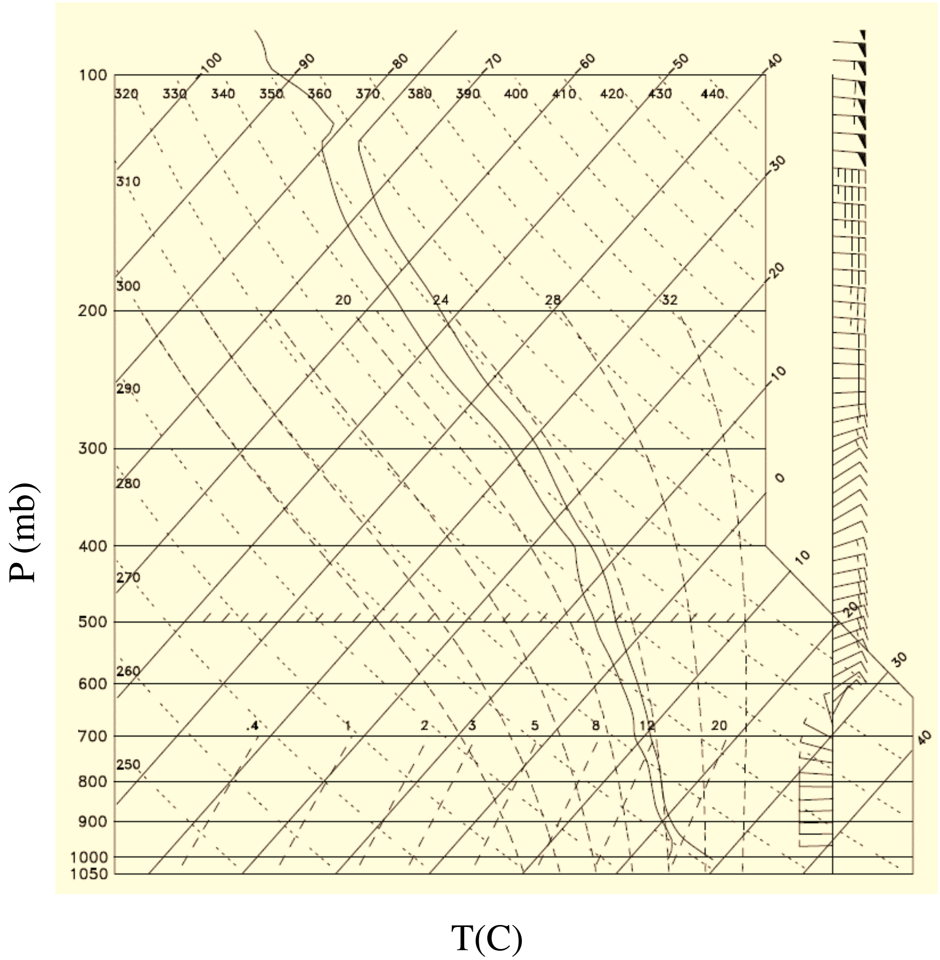


Darwin, 0000 UTC, 24 Jan 2014 – Model Setup

Sounding Parameters:

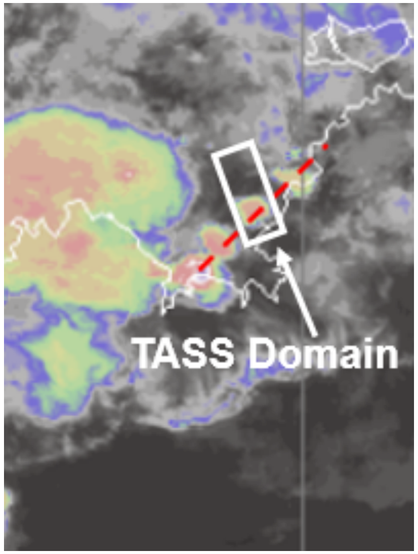
- **Tropopause height: 15.55 *km***
- **Tropopause temperature: - 76.8°C**
- **Melting level: 5.2 *km***
- ***Windshear vector, cloud base to 6 km elevation: from 75⁰***

Convection triggered by Initial Impulse



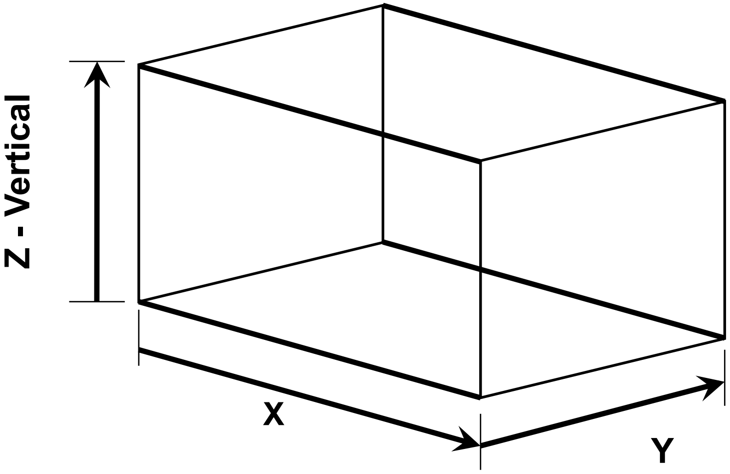
TASS Initialization Sounding

TASS Domain Configuration



Domain Size and Resolution	
Domain Parameter	Physical Dimension
Lateral dimensions	45 *km* x 112.5 *km*
vertical dimension	18.6 *km*
Lateral grid spacing	150 *m*
Vertical grid spacing	150 *m*
Computational grid	~29 x 10^6 points

- **Grid rotated: -15° (y- directed toward 345°). Shear vector aligns orthogonally with cyclic BC**
  - **Periodic BC at x = X^0 and X*,**
  - **Open BC at y= Y^0 and Y***
- **Integrated in time for almost 4 hours**

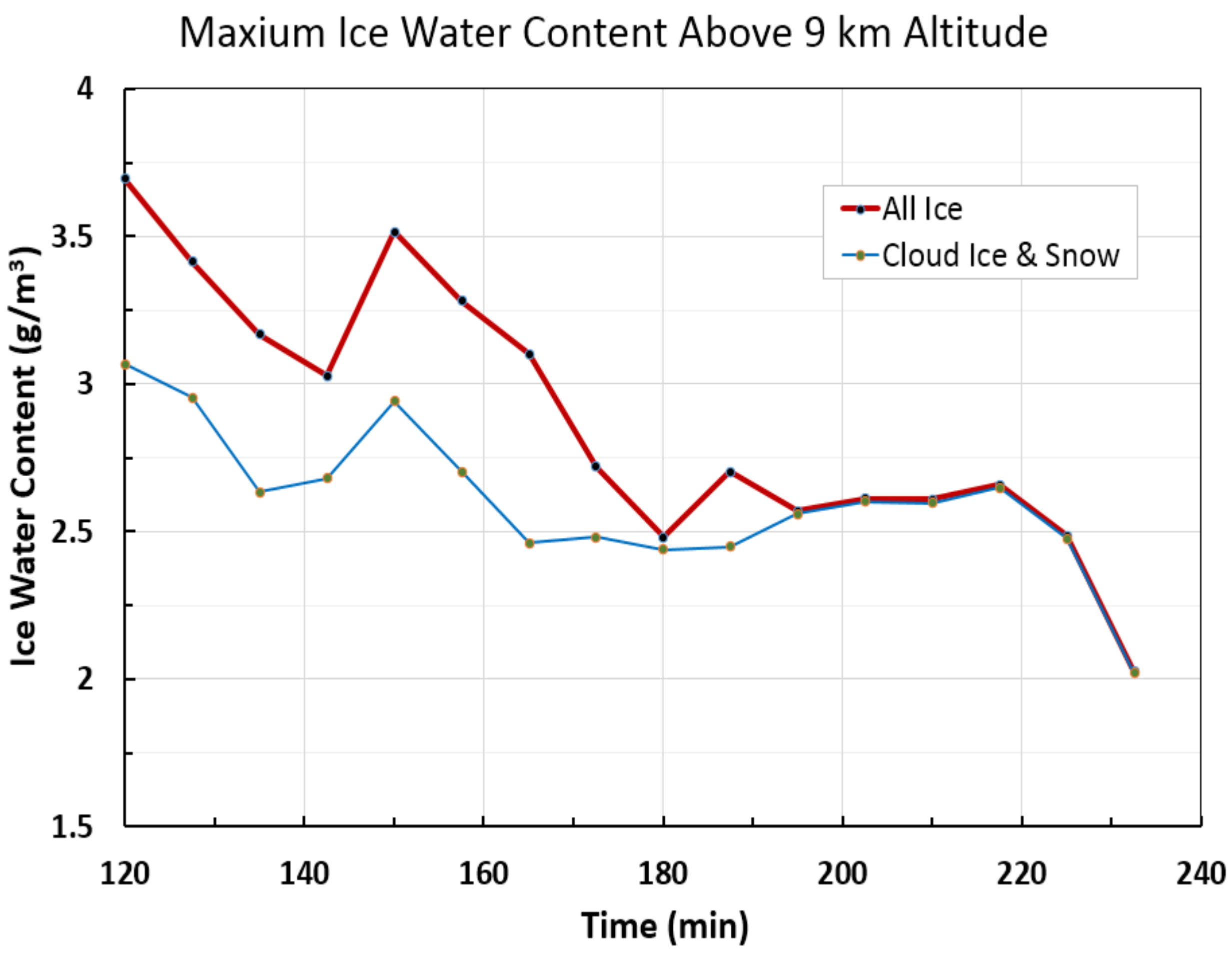


Comparison Between Observed and Simulated Features for Darwin

Parameter	Observed	TASS
Orientation of convective line	SW - NE	WSW - ENE
Lifetime of system	5+ hours	4+ hours
Coldest cloud top temperature	$-87^{o}C$ at 2019 UTC	$-86^{o}C$ at t =165 *min*
Primary direction of canopy expansion	WNW	NW
Line movement	nearly stationary	nearly stationary
Maximum IWC at flight level	3.5 $g\ m^{-3}$	3.5 $g\ m^{-3}$
Maximum scale of IWC greater than 1 $g\ m^{-3}$	65 *km*	40 *km*
Maximum scale of IWC greater than 2 $g\ m^{-3}$	40 *km*	10 *km*

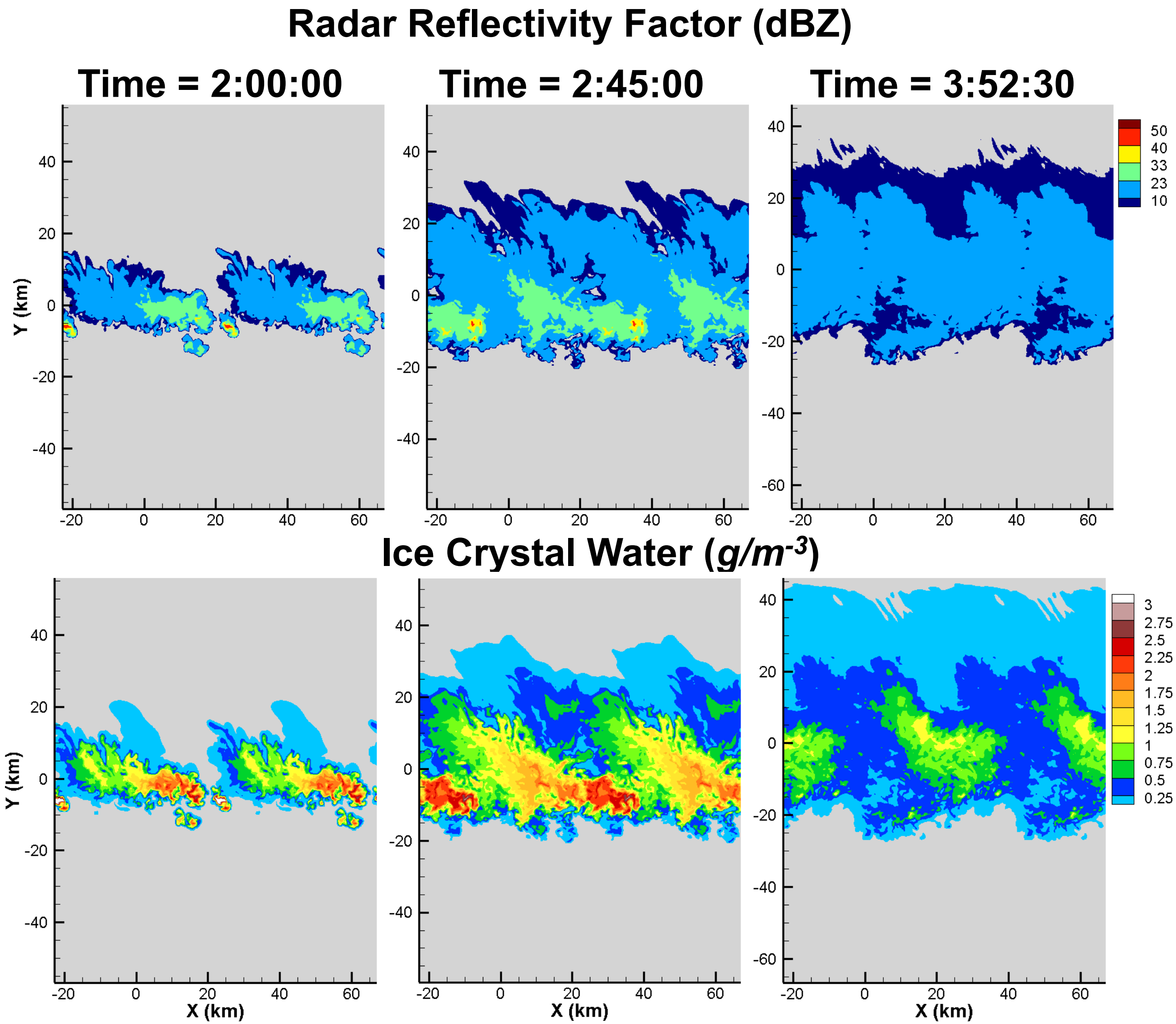
Time Evolution of Simulated Mesoconvective System

Simulated Maximum Ice Water Content above 9 km Elevation



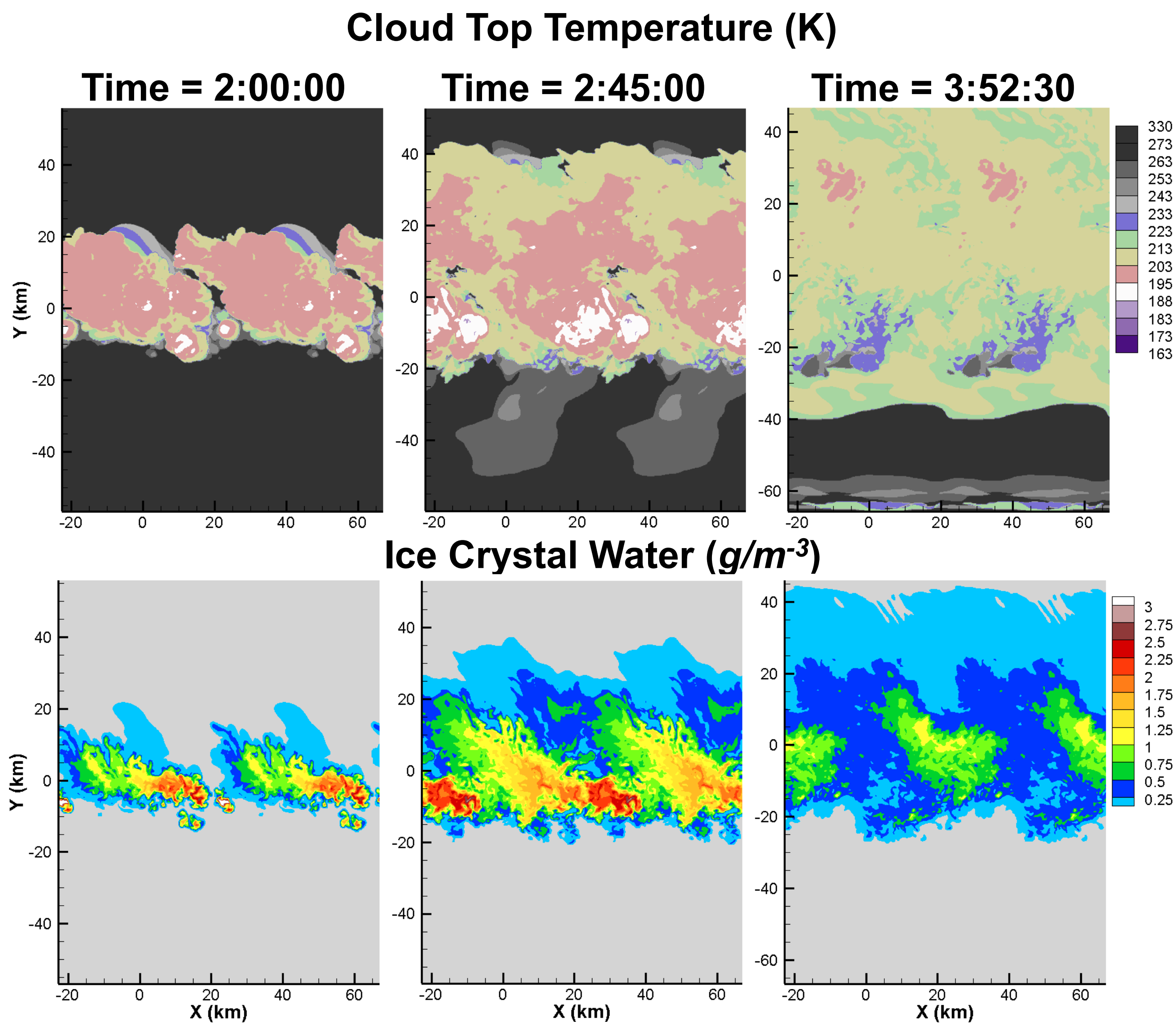
Evolution of Storm: RRF vs IWC

Horizontal Cross Sections at 10 *km* elevation

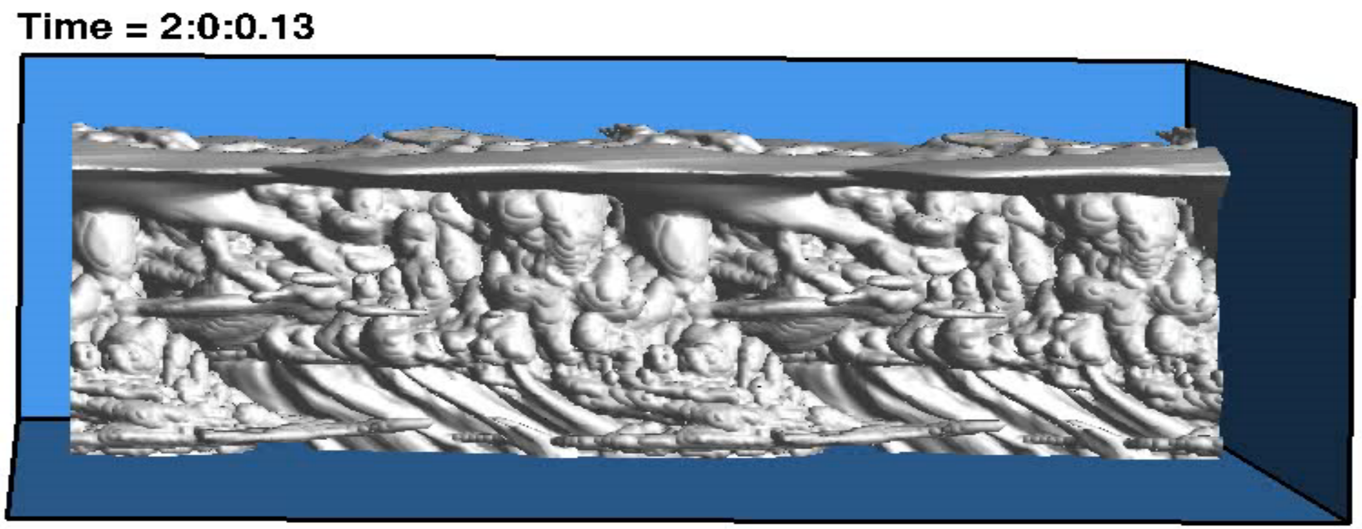


Evolution of Storm: RRF vs IWC

Horizontal Cross Sections at 10 *km* Elevation



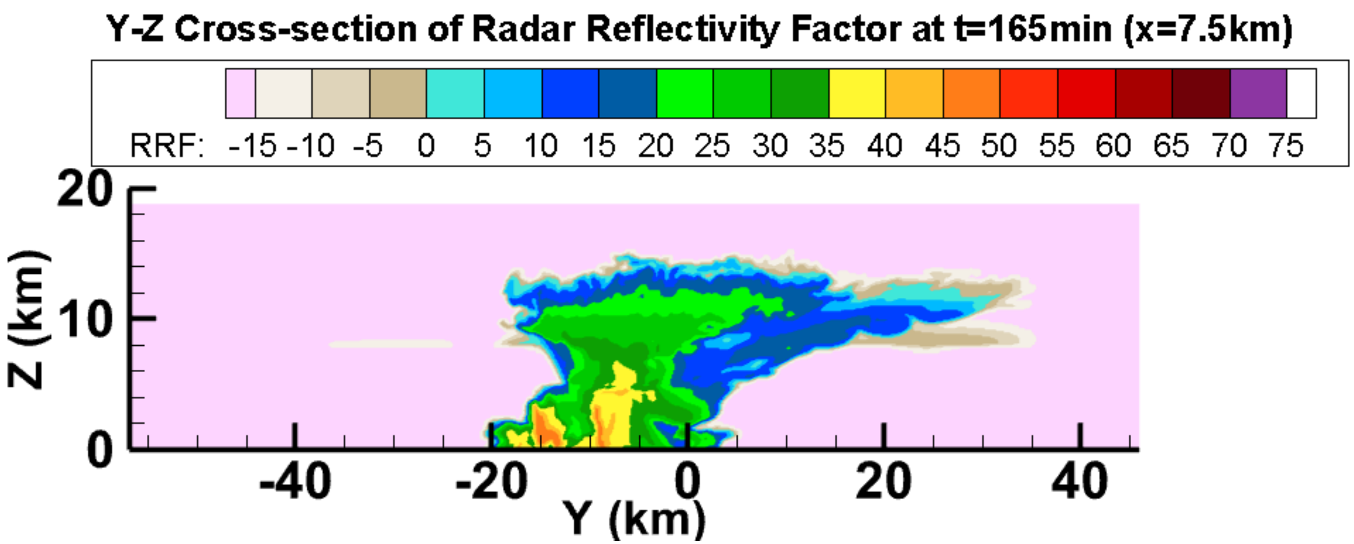
TASS Darwin Simulation: Animation of 3-D Cloud System (2 *hr* – 4.5 *hr*)



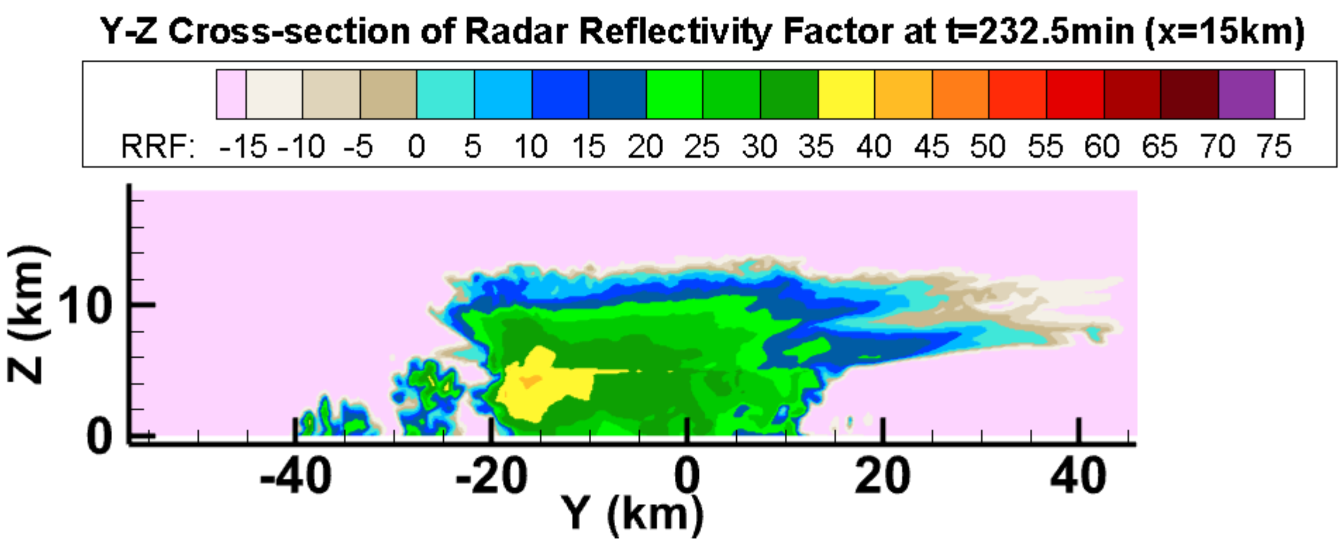
- **Viewed from South**
- **Multiple pulsing convective cells feed canopy overhang**
- **Overhanging cloud canopy much larger than active cells**

Evolution of Storm: RRF Vertical Cross-Sections

Time of Storm Peak Intensity



Decaying Stage

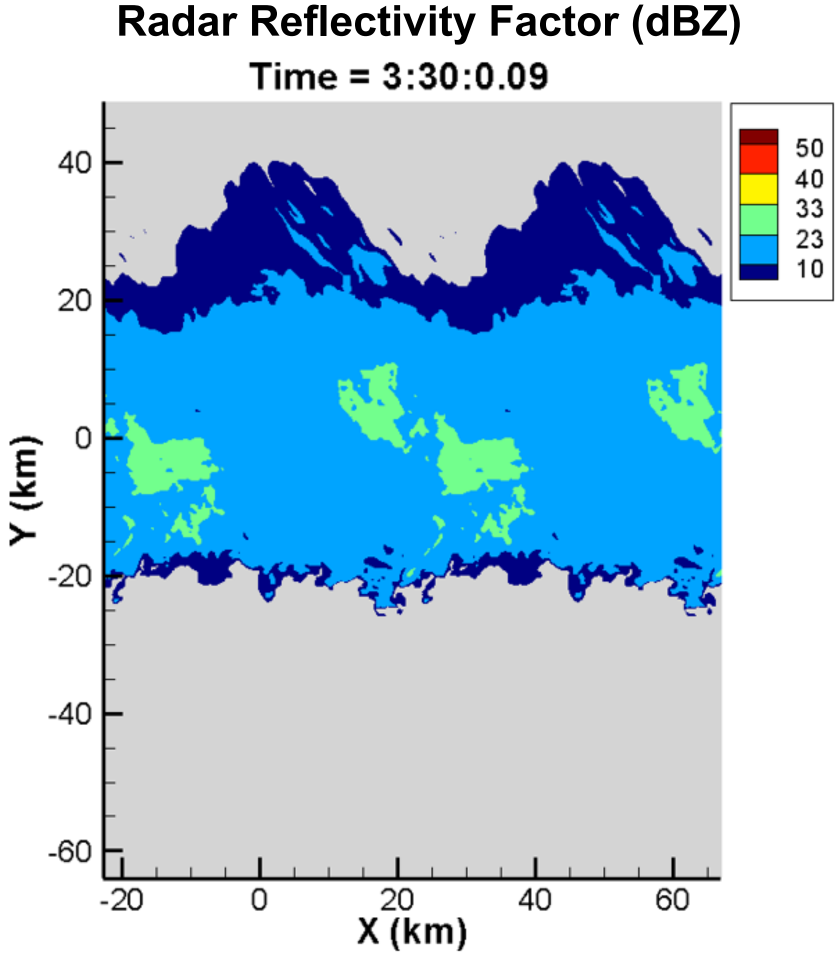


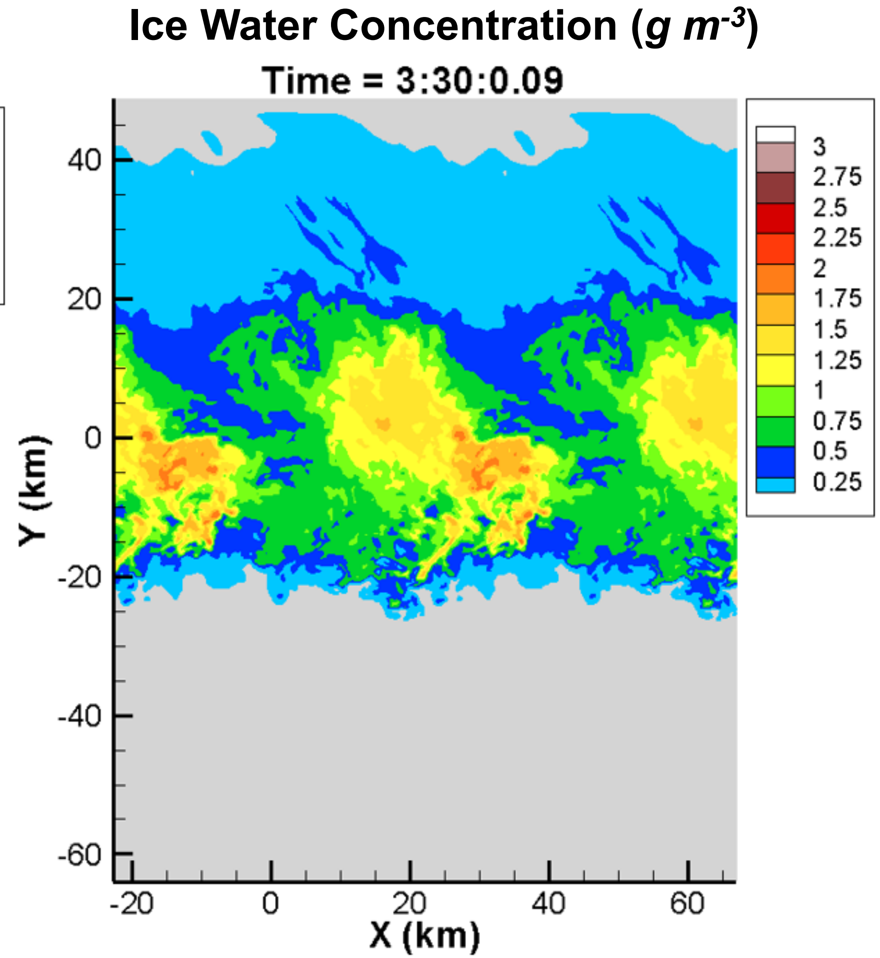
Darwin Simulation

Structure of Mature System

Darwin Simulation: RRF vs IWC

Horizontal Cross Sections at Z = 10 km



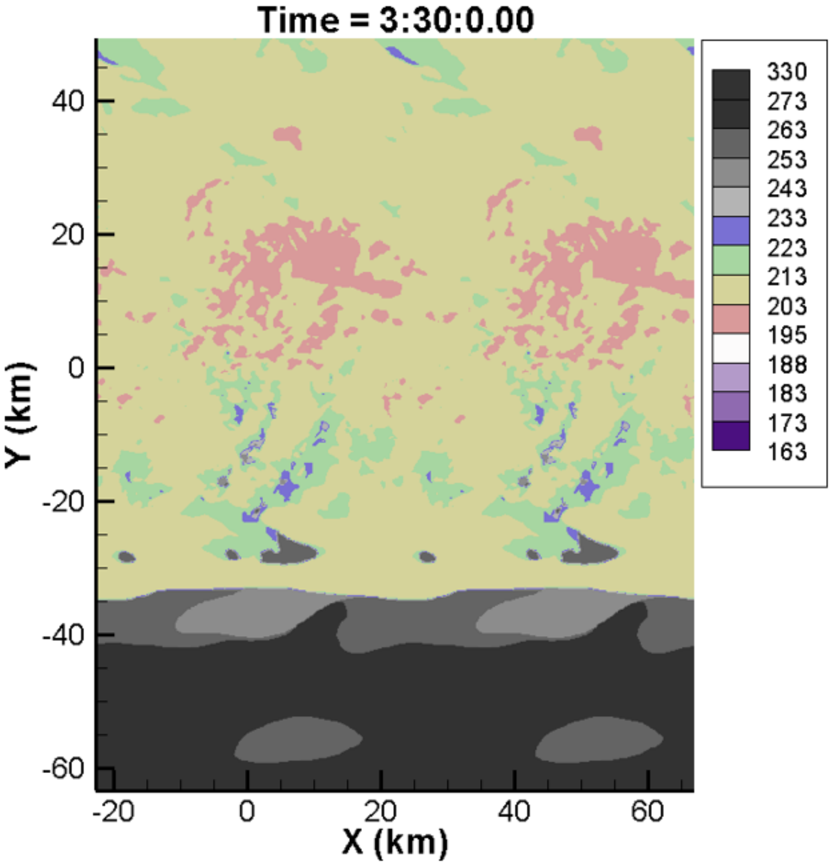


- Large areas of HIWC with RRF less than 33 dBZ (only small areas of green)
- Sustained areas (over 40 *km* wide) of ice water greater than 1.0 *g/m³* and with peak values at 2.6 *g/m³*

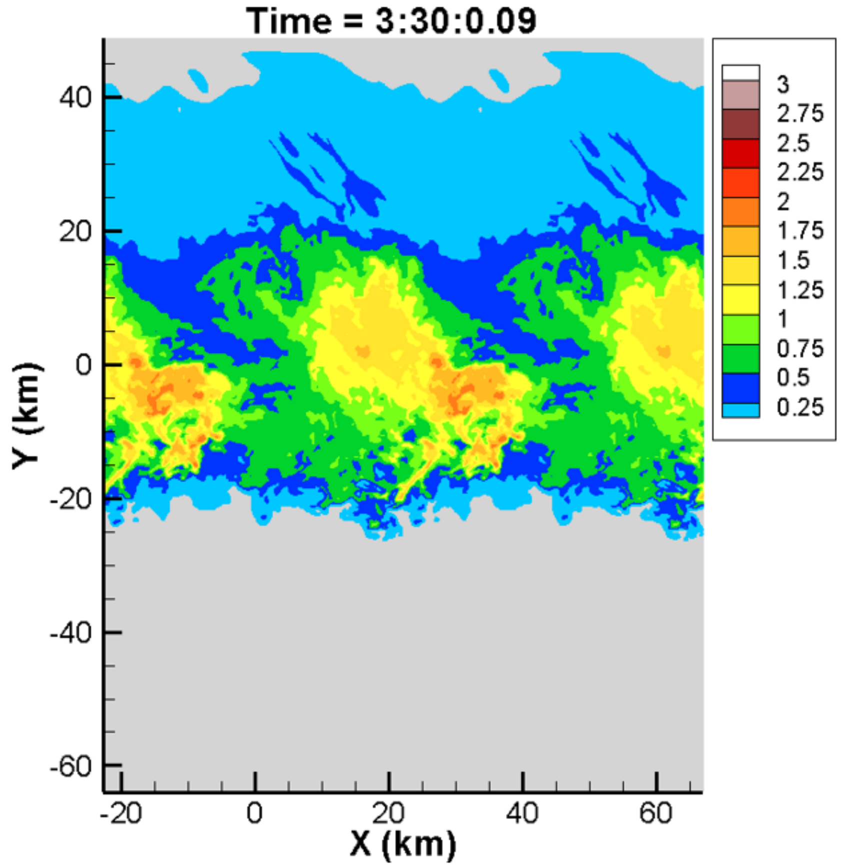
Darwin Simulation: Cloud Top Temperature vs IWC

Horizontal Cross Sections at Z = 10 km

Cloud Top Temperature (K)



Ice Water Concentration (gm^{-3})

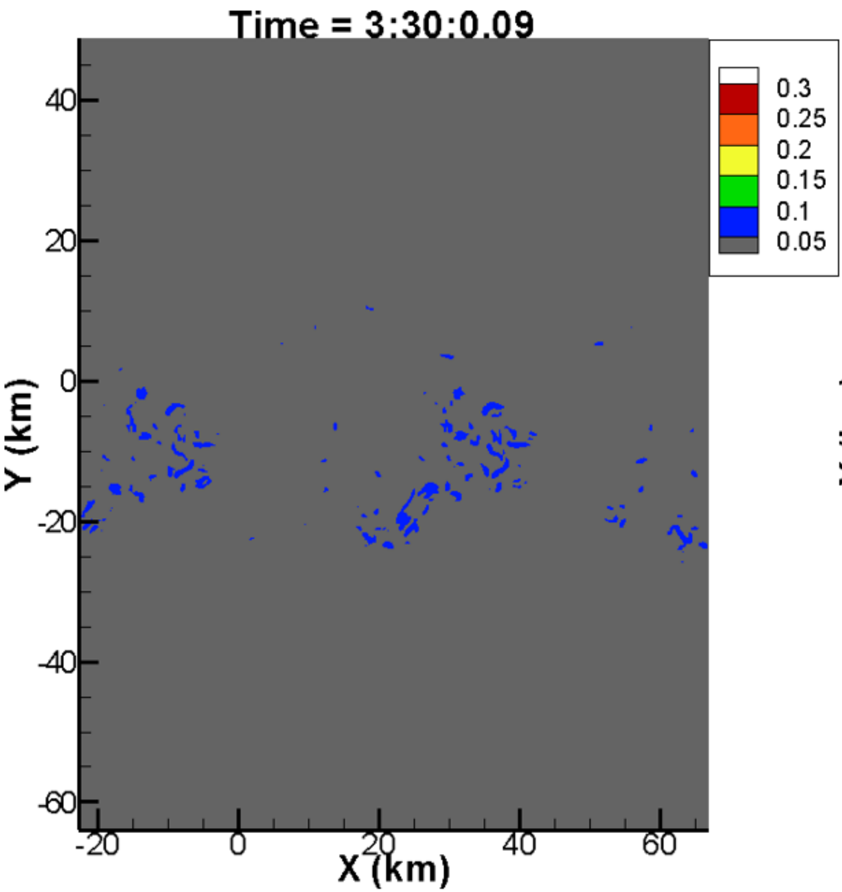


Coldest (highest) cloud tops downshear from peak HIWC values

Darwin Simulation: Turbulence vs IWC

Horizontal Cross Sections at Z = 10 km

RMS-g Acceleration (m/s^2)



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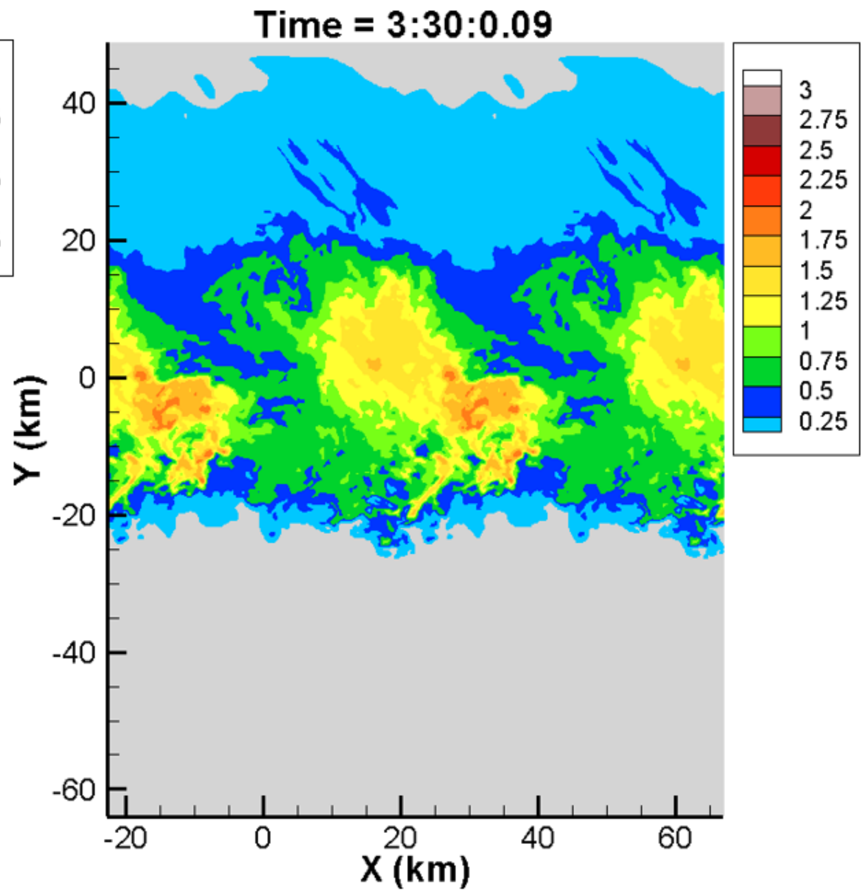
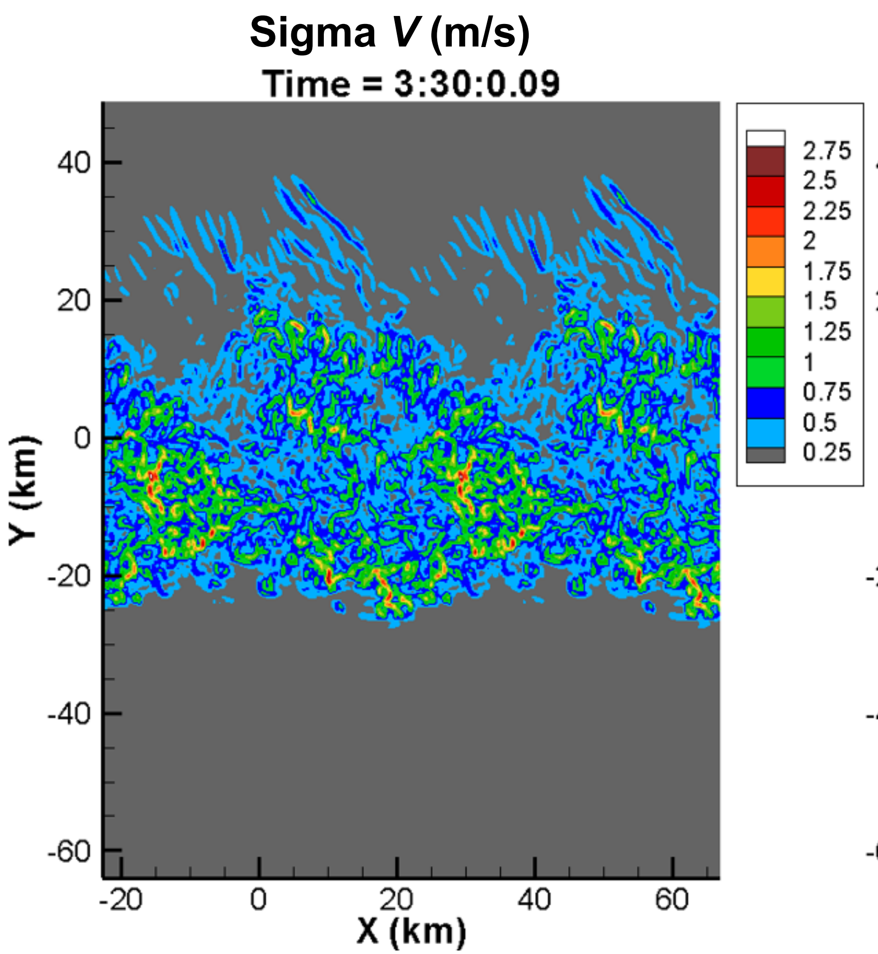
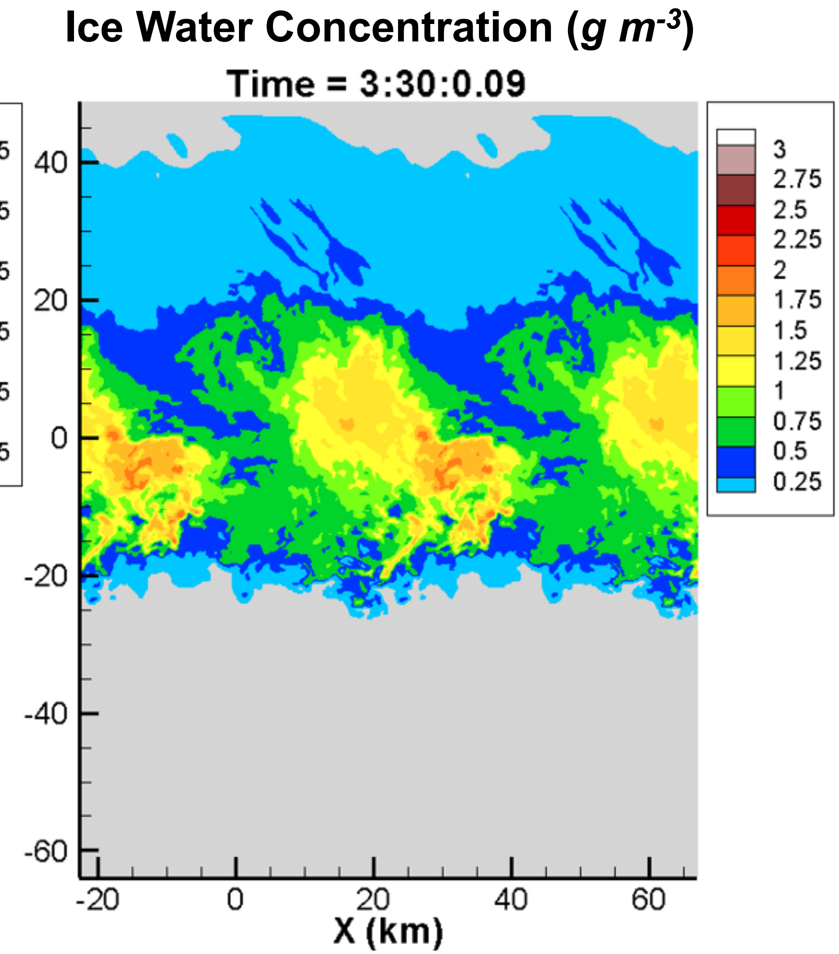


Simulation shows light turbulence at flight level in vicinity of HIWC event

Darwin Simulation: Sigma-*V* vs IWC

Horizontal Cross Sections at Z = 10 km

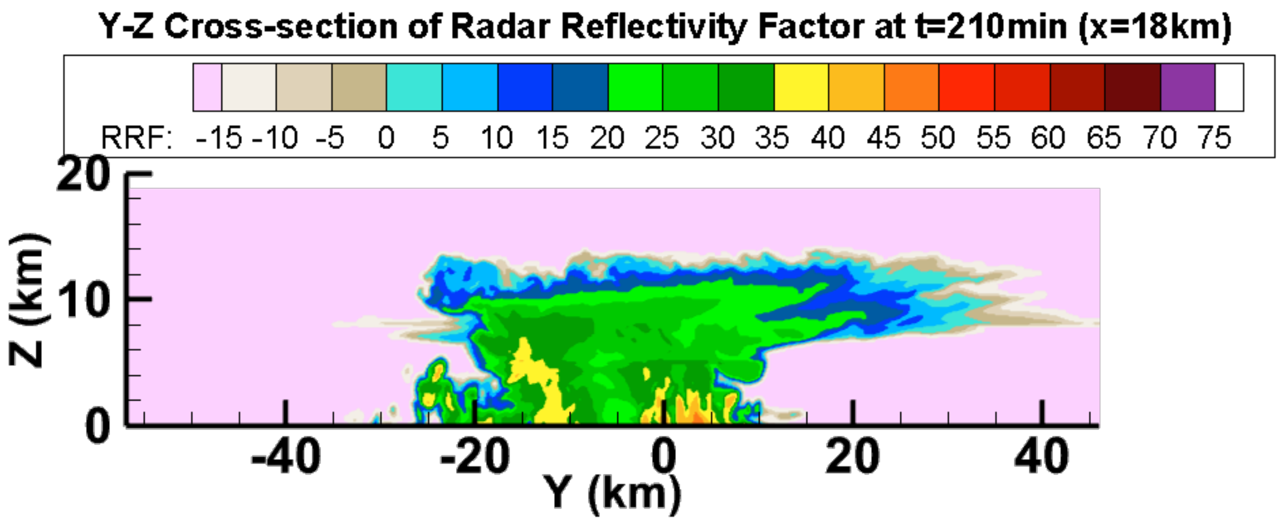


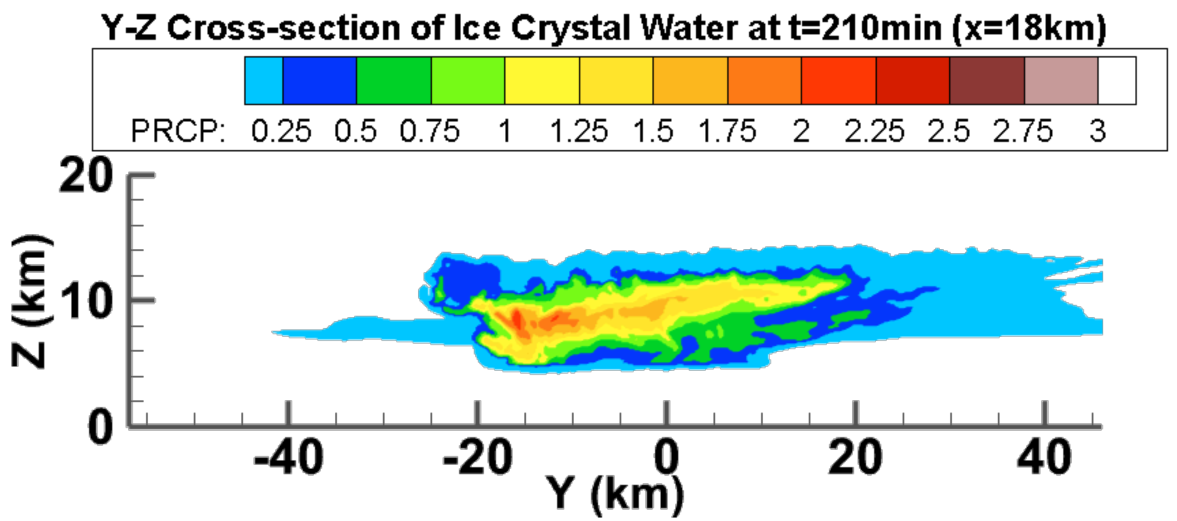


Greater values of standard deviation of velocity (component normal to convective line) in areas of HIWC

TASS Radar Reflectivity Factor vs Ice Water Content: Vertical Cross Section

- Radar reflectivity factor in excess of 40 dBZ mostly confined to lower 6 *km* of storm
- Weak radar reflectivity factor at flight level (~10*km* AGL)
- Peak ice water concentration near 9-10 *km* elevation.
- HIWC extends downshear from peak values





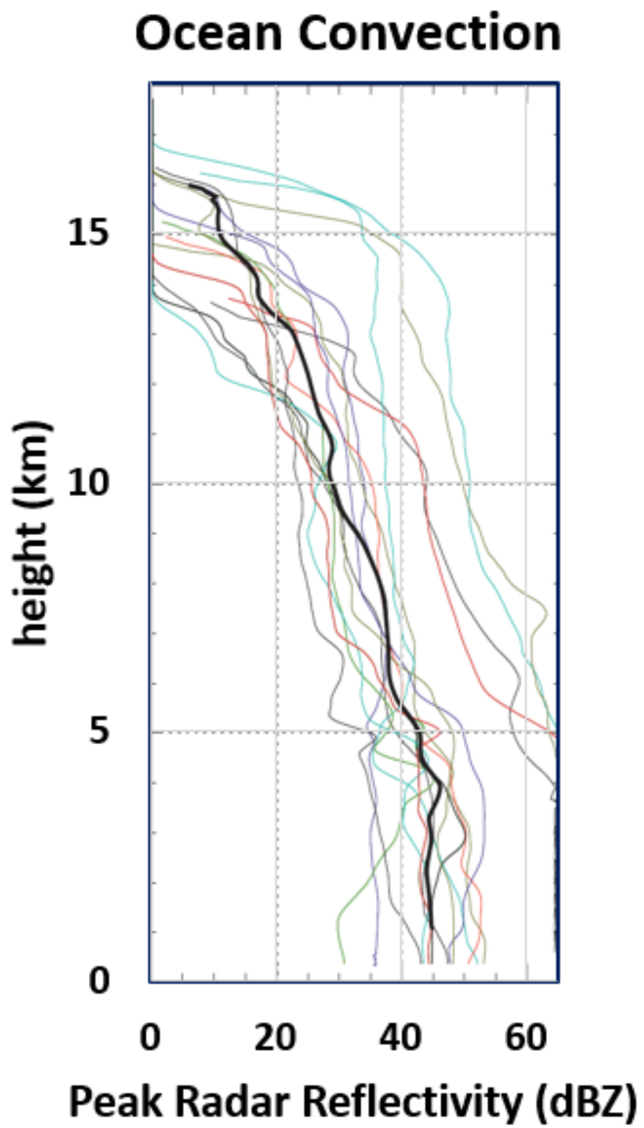
Comparison with Heymsfield's Vertical Profile of Peak RRF for Oceanic Convection

- **Figure from Heymsfield et al, *J. Atmos. Sci*., February 2010;** *©American Meteorological Society. Used with permission*

- **From Nadir viewing high-altitude airborne Radar**
  - **NASA ER-2 Doppler Radar**
  - **X-Band**
  - **Dual 3° beam**

- **Measured vertical profiles of peak radar reflectivity for oceanic mesoconvective systems**

- **Average (heavy dark curve) decreases with elevation, < 40 dBZ above 6 *km* elevation**



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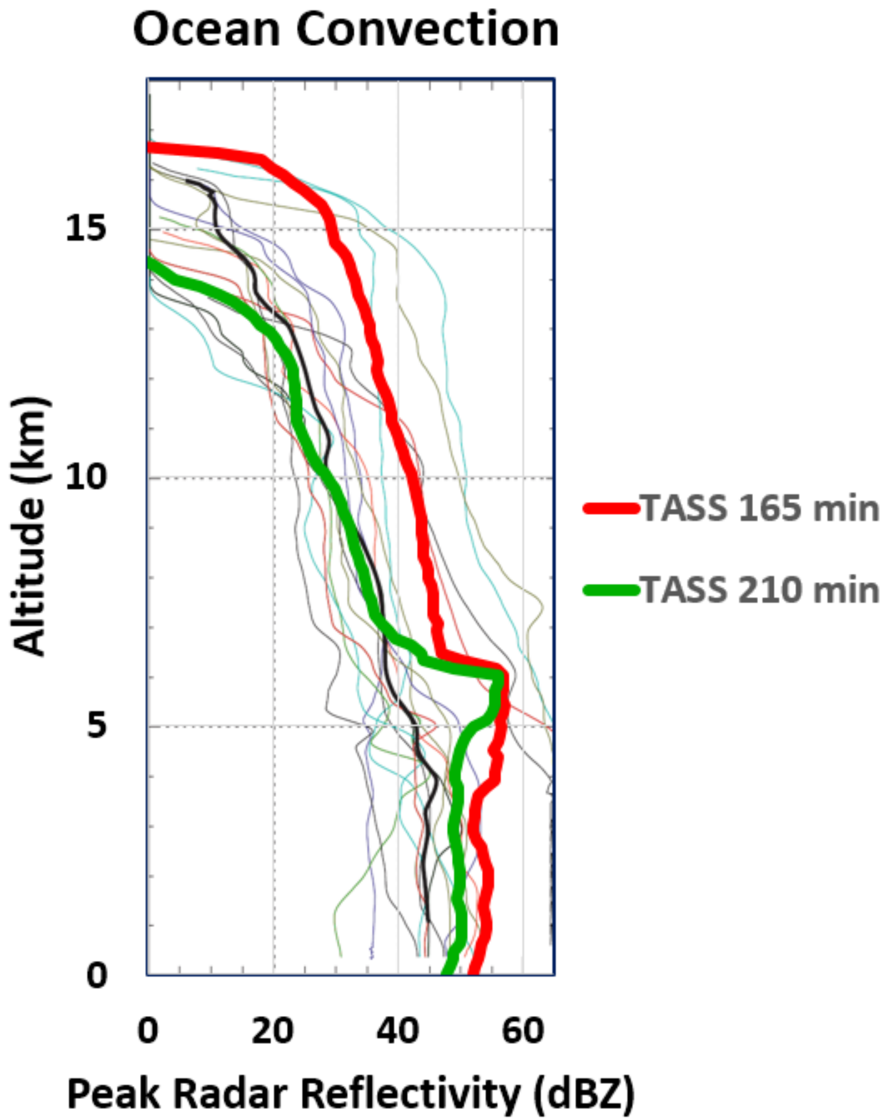
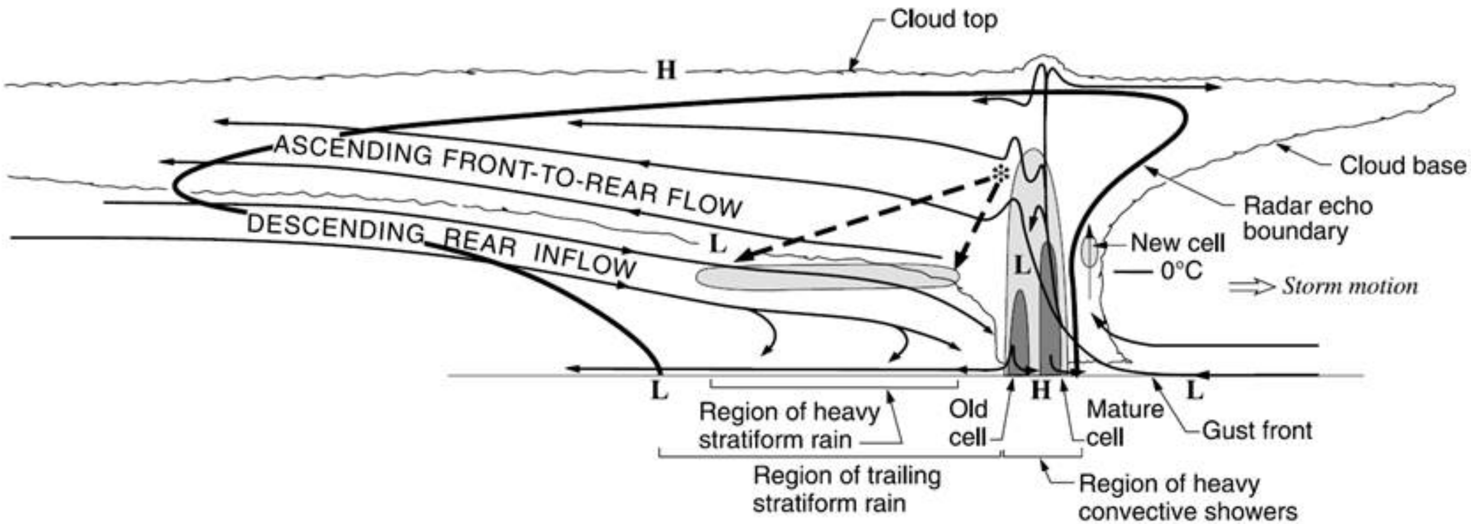
- **With TASS profiles at two times**



Houze et al.'s Conceptual Model with Added Region of Expected HIWC



Conceptual model of a convective line with trailing-stratiform precipitation viewed in a vertical cross section oriented perpendicular to the line. Intermediate and strong radar reflectivity is indicated by medium and dark shading, respectively. Dashed-line arrows indicate fallout trajectories of ice particles passing through the melting layer. HIWC denoted by yellow shading. [Adapted from Houze et al., *Bulletin of the American Meteorological Society*, June, 1989; ©American Meteorological Society. Used with permission.]

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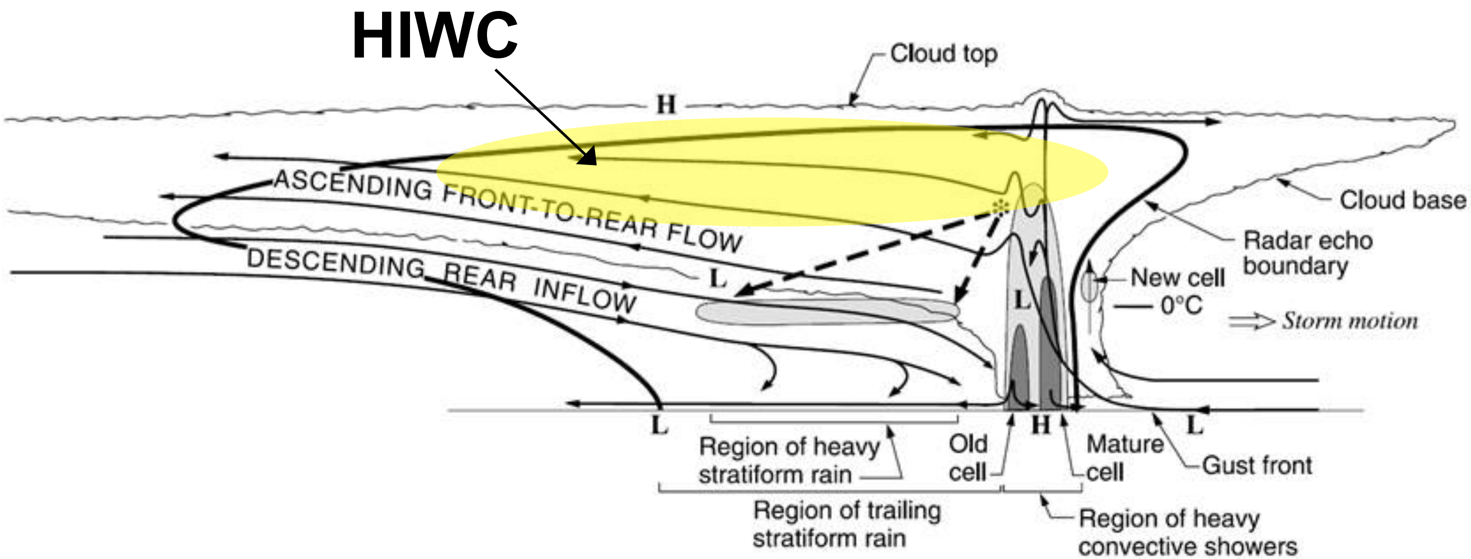

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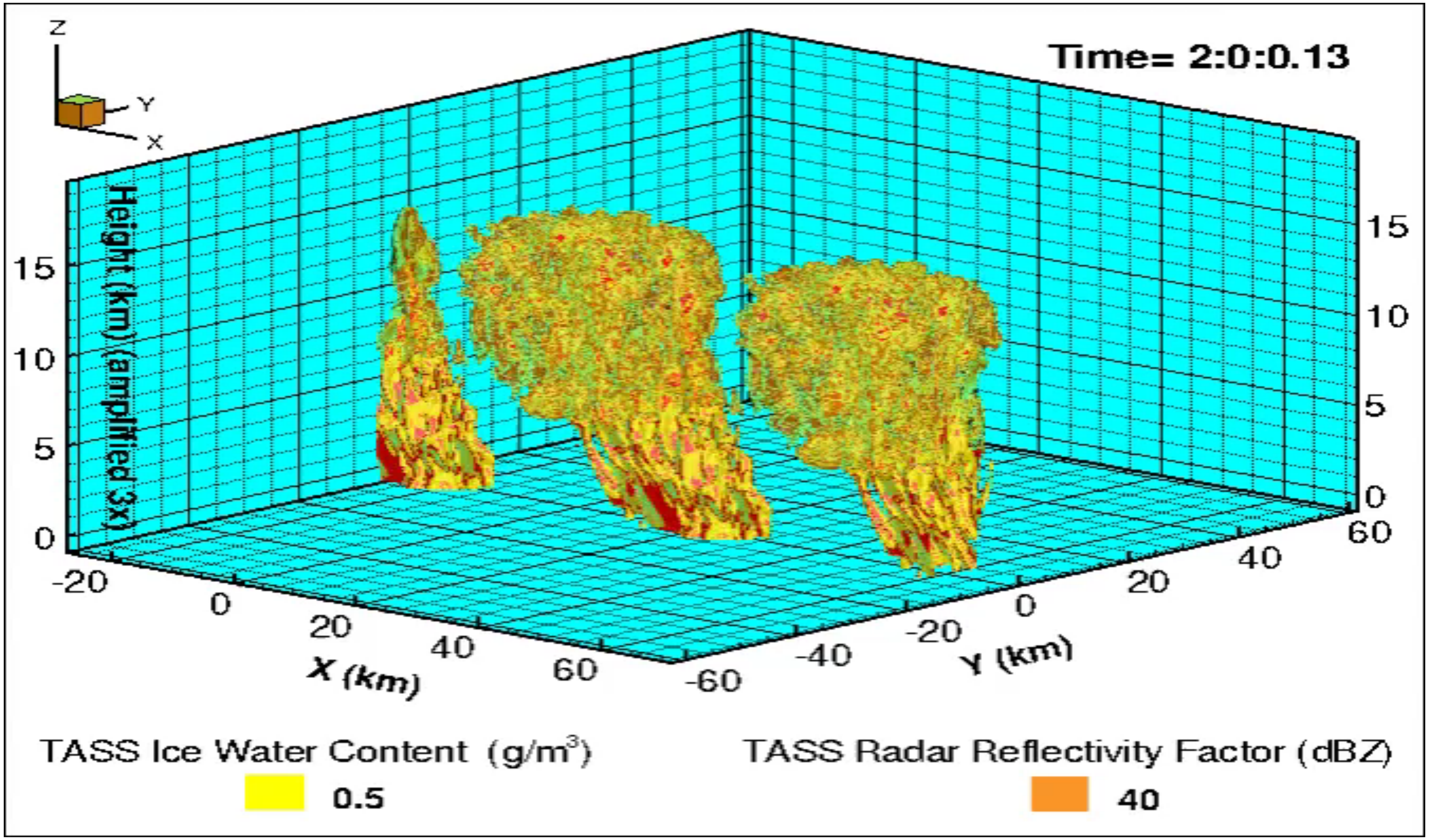
TASS Darwin Simulation: Animation of 3-D Cloud System (2 *hr* – 4.5 *hr*)



- **Viewed from South East**
- **RED - RRF > 40 dBZ**
- **Yellow – IWC > 0.5 *g m*$^{-3}$**

Summary of Findings from Simulation

- **Simulation captures many features of the Darwin storm and demonstrates the feasibility of simulating a HIWC event with a convective cloud model**
- **HIWC conditions were demonstrated to occur in regions with low Radar reflectivity**
- **Peak ice water concentrations in excess of 3.0 $g\ m^{-3}$ were simulated at flight level. Ice water concentrations of at least 1.0 $g\ m^{-3}$ expanded to 40 *km* in scale**
- **During the intense phase of convective system, positions of peak ice concentration were correlated with areas of higher radar reflectivity and cold cloud tops**
- **During mature phase, HIWC expands over larger area, but may not be correlated with coldest cloud tops or have detectable levels of radar reflectivity factor**
- **Darwin was a long-lived mesoconvective system maintained by an ensemble of pulsing convective plumes**
  - **plumes supply high concentrations of ice crystals to a growing cloud canopy**
  - **No evidence of an organized and continuous updraft structure**

References

- **Proctor, F.H. and Switzer, G.F., "Numerical Simulation of HIWC Conditions with the Terminal Area Simulation System," AIAA Paper 2016-xxxx, submitted to the 8th Conference on Atmospheric and Space Environments, June 2016.**

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