American Meteorological Society

AFIT Air Force Institute of Technology

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Weather Cubes and 4D Visualizations of Atmospheric and Radiative Effects

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33rd Environmental Information Processing Technologies

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Overview

- LEEDR Background
- Weather Cubes
  - Hurricane Arthur
  - Non-Significant Weather Case
- Validation
  - Cloud Fields
  - Rain Fields
- Summary

LEEDR Goals

Laser Environmental Effects Definition and Reference

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- Atmospheric characterization and radiative transfer code that calculates line-by-line and spectral band solutions by creating correlated, physically realizable profiles of meteorological and environmental effects (e.g. gaseous and particle extinction, optical turbulence, and cloud free line of sight) data
- Accesses terrestrial and marine atmospheric and particulate climatologies
  - Graphical access to and export of probabilisitc data from the Extreme and Percentile Environmental Reference Tables (ExPERT)

LEEDR
Laser Environmental Effects Definition and Reference

Characterizes effects from 200 nm to 8.6 meters

LEEDR

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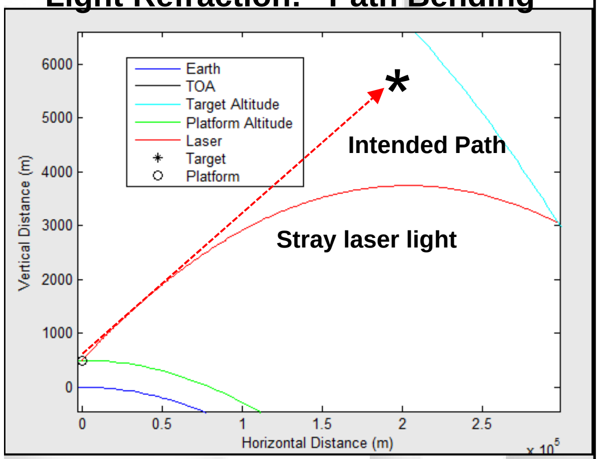
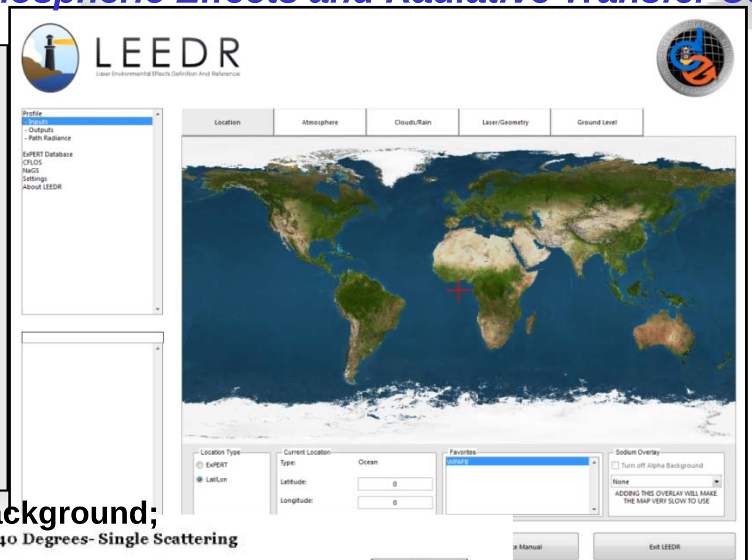
V&V'd Atmospheric Effects and Radiative Transfer Code for HEL

Light Refraction: Path Bending

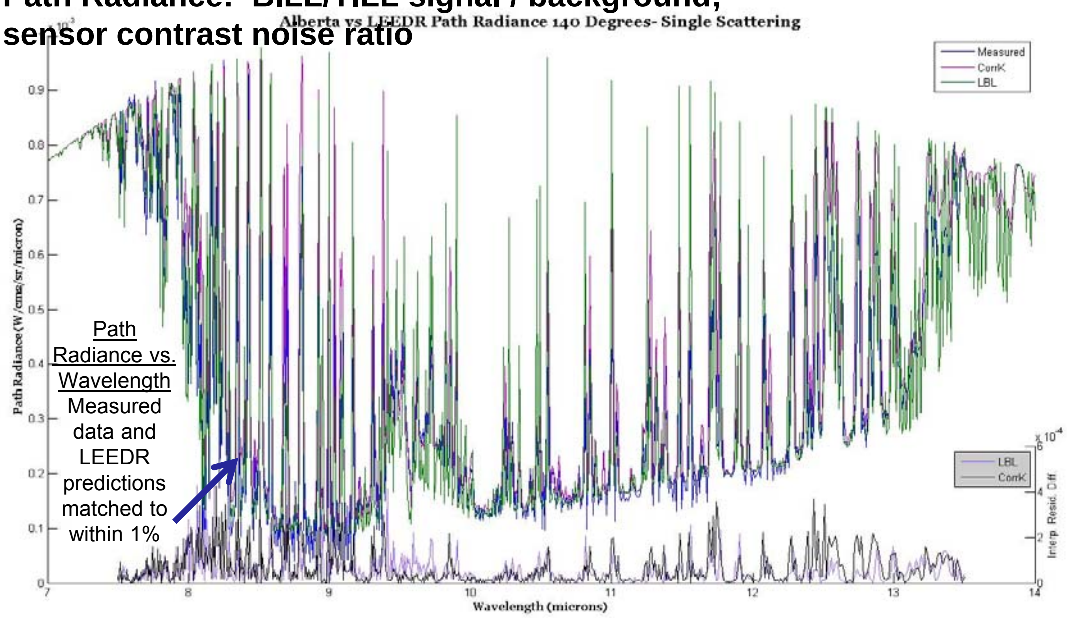




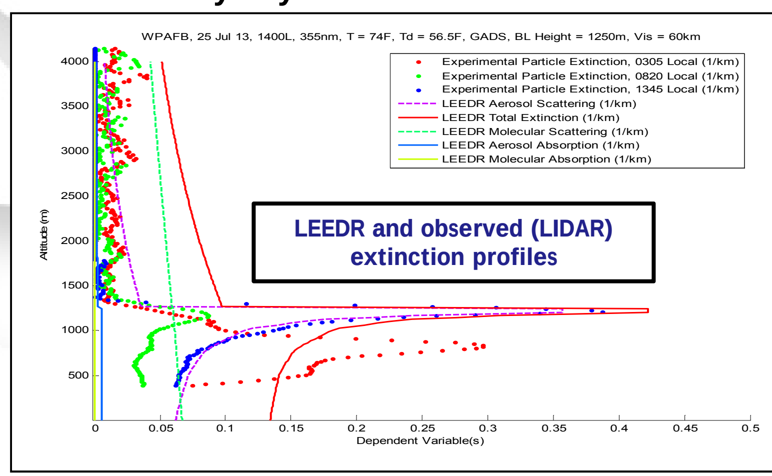
Creates physically realizable horizontal / vertical profiles of meteorological and weather event data and associated radiative effects (e.g. optical extinction, path radiance):

- Aerosol and surface observation (i.e. T, P, RH) climatology at 573 ExPERT and 1° x 1° oceanic grid locations
- Numerical weather forecast, re-analysis data
- Profiles optical turbulence (i.e. C_n^2)
- Accounts for light-refraction and single/multi-scatter
- Includes sun-moon calculator

Path Radiance: BILL/TILL signal / background; sensor contrast noise ratio



Boundary Layer - Extreme Aerosol Extinction



Weather Cubes

4D Wx Effects Visualizations

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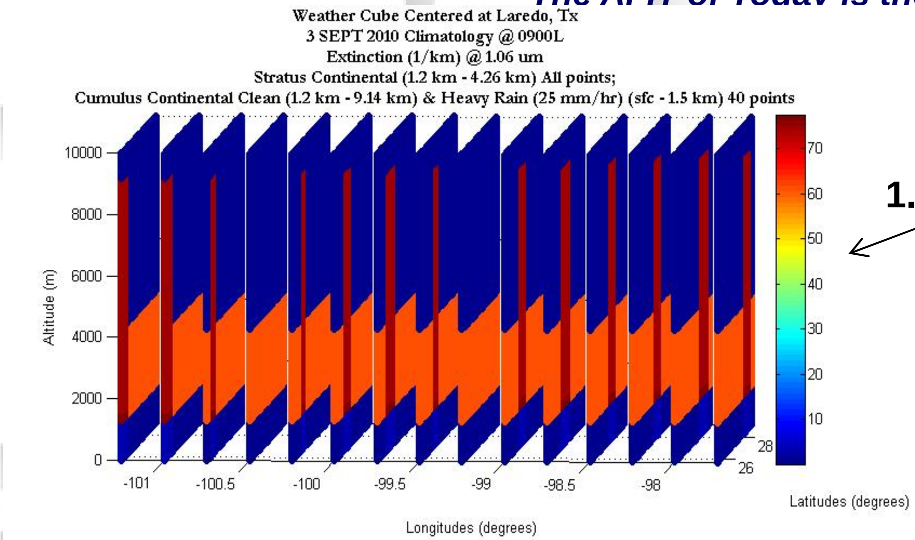
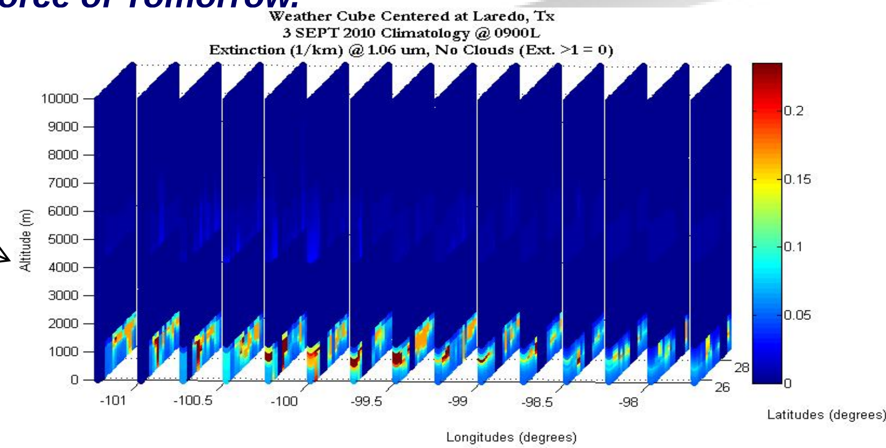
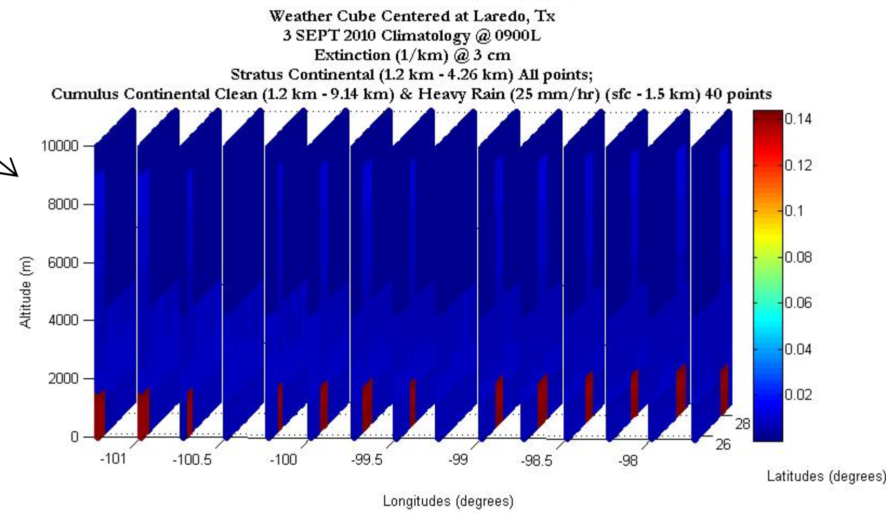


1.06 µm



3 cm



- **Provide visually stunning and realistic-looking visible-spectrum images to accurately translate to propagation and atmospheric effects outside of the visible spectrum**
- **Turbulence and more!**
  - **Extinction: linear / non-linear effects**
  - **Path / target background radiance**
  - **Path Refraction/Bending**
  - **Weather**
    - **Fog / Clouds / Rain / Snow**
    - **Wind/velocity structure function**

Weather Cubes

Hurricane Arthur

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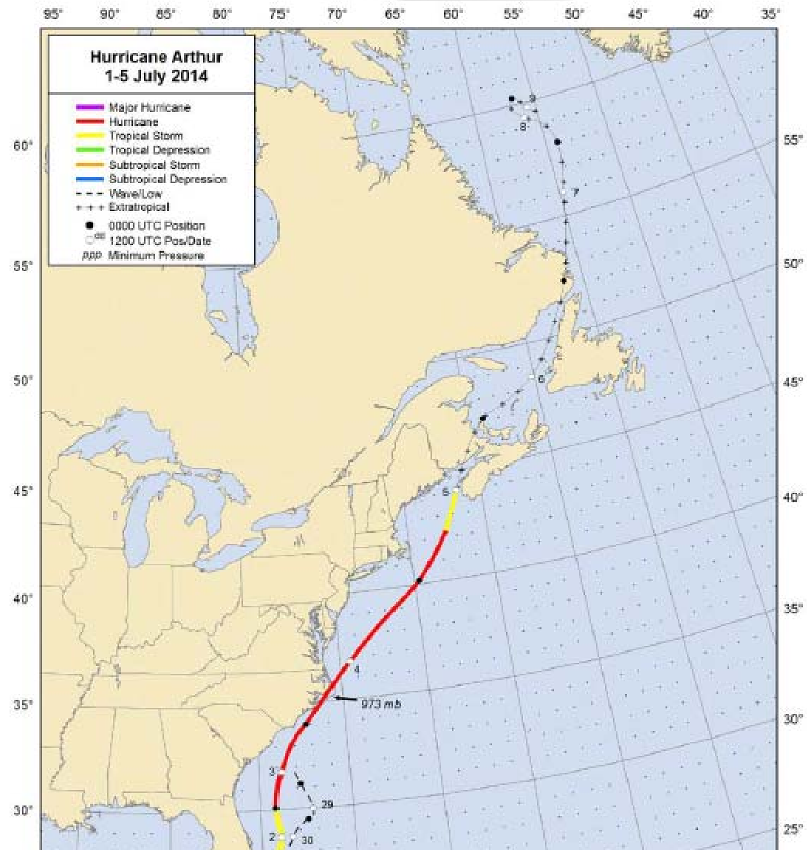
GOES-EAST VISIBLE SATELLITE IMAGE OF HURRICANE ARTHUR AT 1945 UTC 3 JULY 2014 BEFORE ITS LANDFALL ALONG THE NORTH CAROLINA COAST. PHOTO COURTESY OF THE NHC.



Flooding in Downtown Manteo

Hurricane Arthur Statistics

- Earliest hurricane to hit North Carolina in a season since records began in 1851
- Made landfall just west of Cape Lookout as a Category 2 at 0315 UTC on 04 July 2014
- Verification Analysis for 1800 UTC on 03 July 2014

Weather Cubes
Hurricane Arthur

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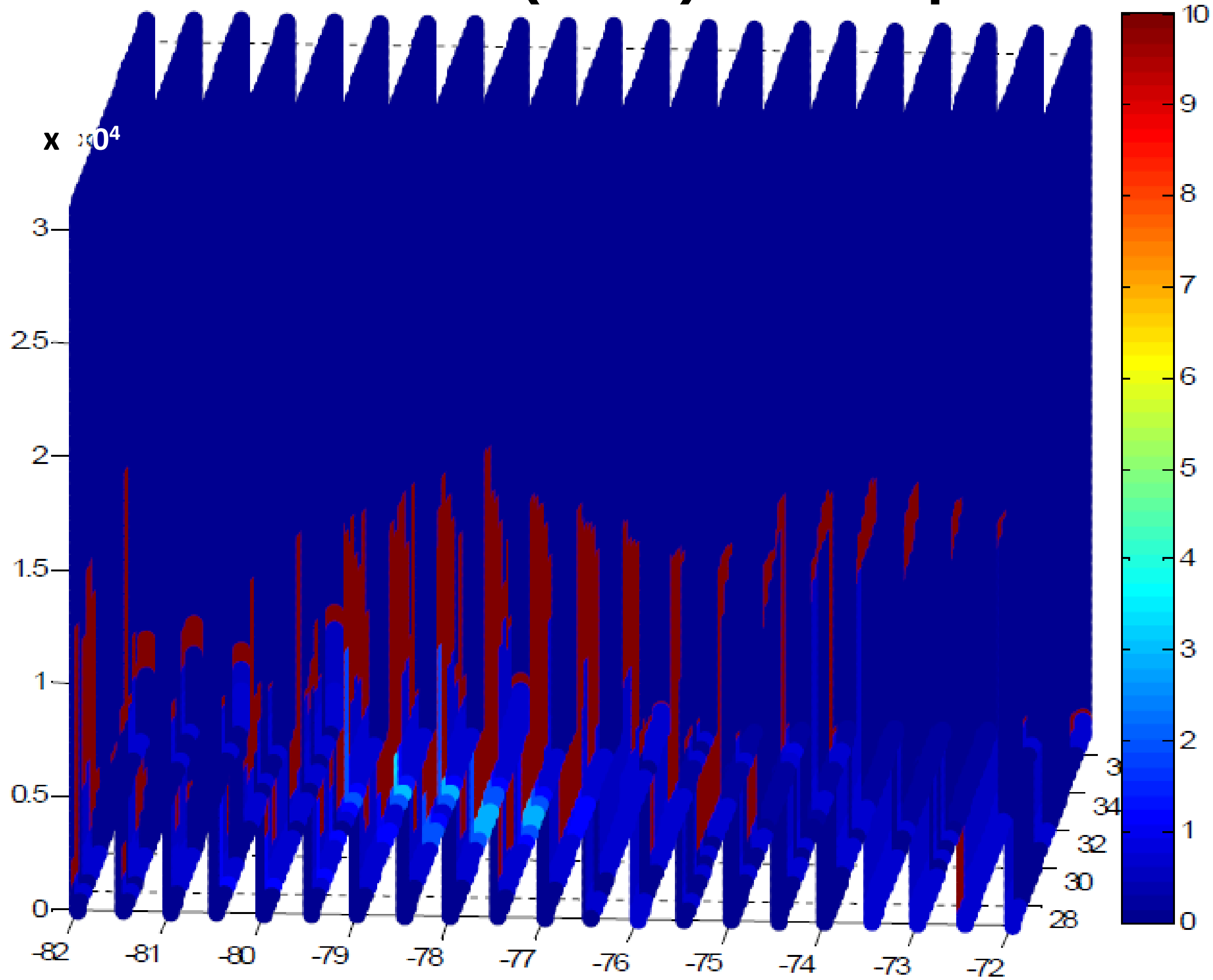
- 10° x 10° x 30km volume data cube
- Created using 0.5-deg Global Forecast System data
- Microphysical & optical properties characterizations for clouds, rain, and aerosols from LEEDR
- Processed at 12 different wavelengths, the following are shown:
  - SWIR
  - MWIR
  - LWIR
  - Radar

Extinction (1/km) at 1.06 µm



Weather Cubes

Hurricane Arthur

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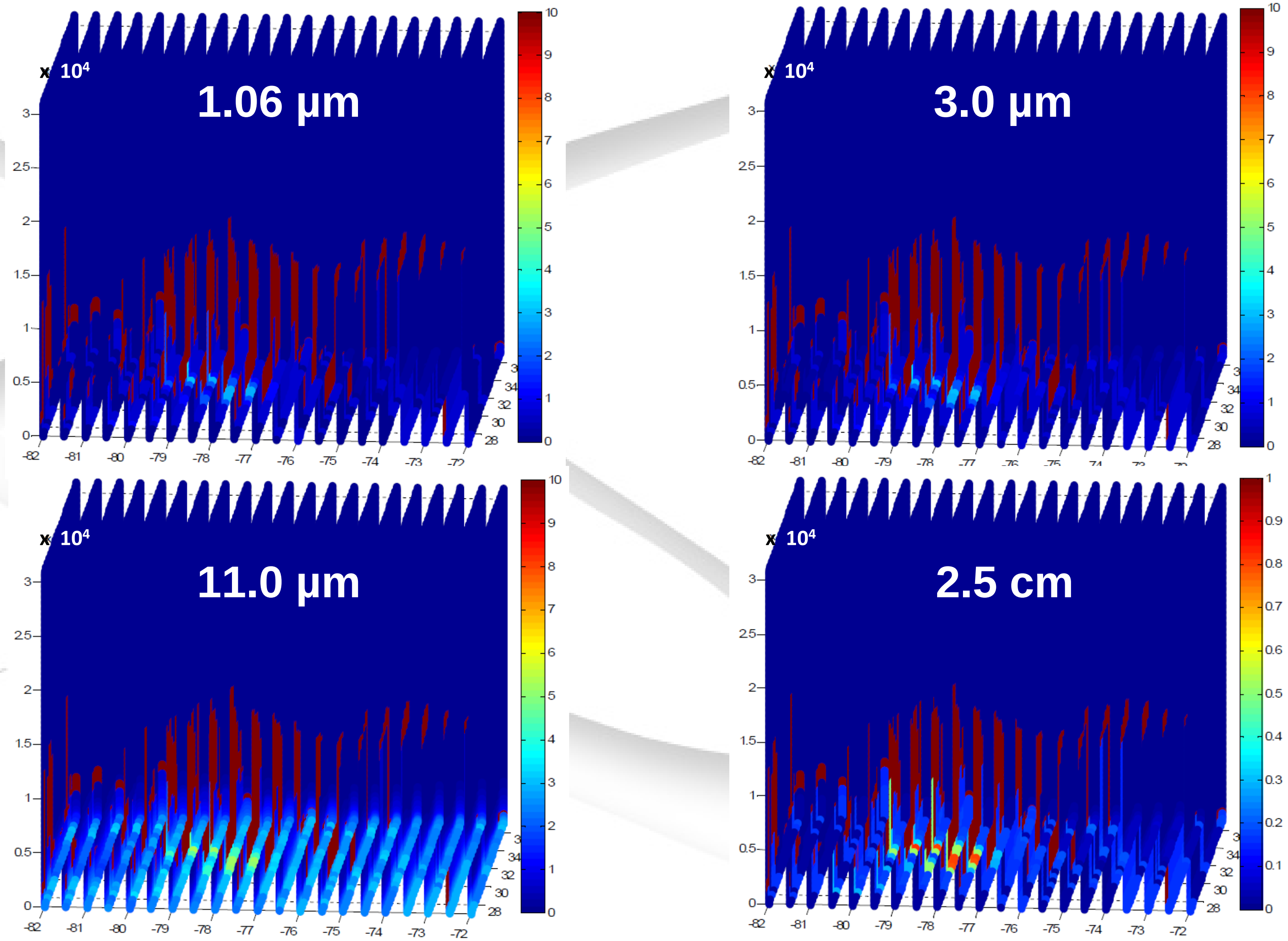

Cloud Field Validation

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Cloud fields are generated from NWP data using the following two GFS parameters outputs:

- Relative Humidity
- Vertical Velocity

Cumulus and Stratus cloud types are considered and determined by Vertical Velocity thresholds

Cloud field verification was performed using:

- NASA's Moderate Resolution Imaging Spectroradiometer (MODIS)
- NOAA's Geostationary (GOES) satellites

Cloud Field Algorithm

	Relative Humidity (RH)	Vertical Velocity (ω)	Cloud Type
Within the Boundary Layer	≥ 100%	Upper Limit: -0.12 Pa/s Lower Limit: -11.99 Pa/s	Stratus
	≥ 100%	Upper Limit: -12.0 Pa/s Lower Limit: - Infinity Pa/s	Cumulus
Above the Boundary Layer	≥ 70%	Upper Limit: -0.12 Pa/s Lower Limit: -11.99 Pa/s	Stratus
	≥ 70%	Upper Limit: -12.0 Pa/s Lower Limit: - Infinity Pa/s	Cumulus

Cloud Field Validation
Results

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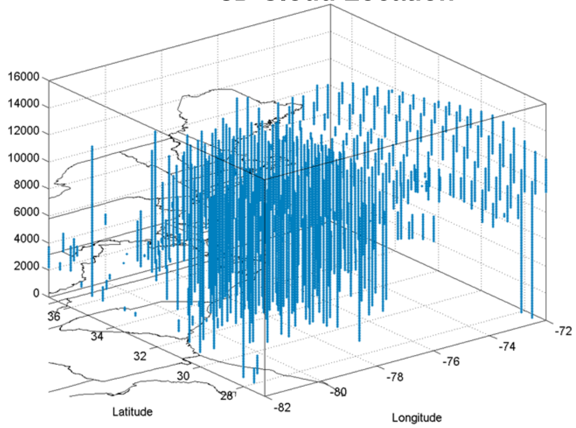
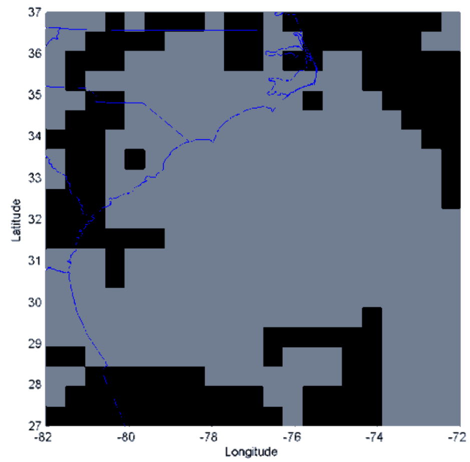
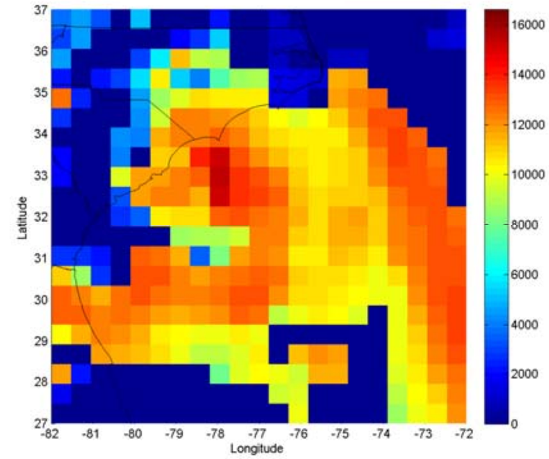
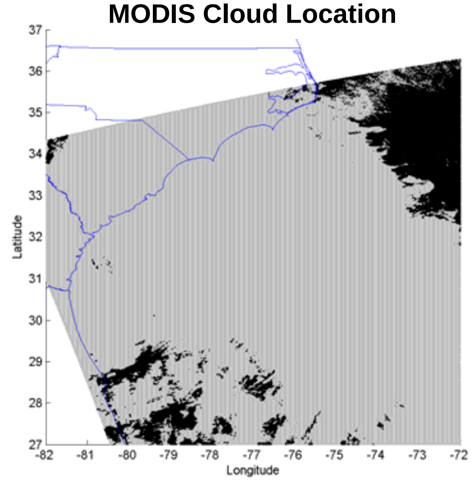
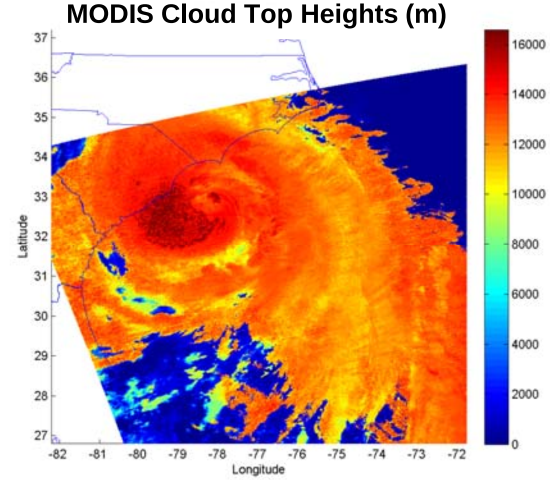
	Cloud Placement	Cloud Coverage	Cloud Top Heights
Wx Cubes	3D Cloud Location 	Cloud Top-Down Location 	Cloud Top Heights (m) 
MODIS		MODIS Cloud Location 	MODIS Cloud Top Heights (m) 

Cloud Field Validation

Optical Depth Results

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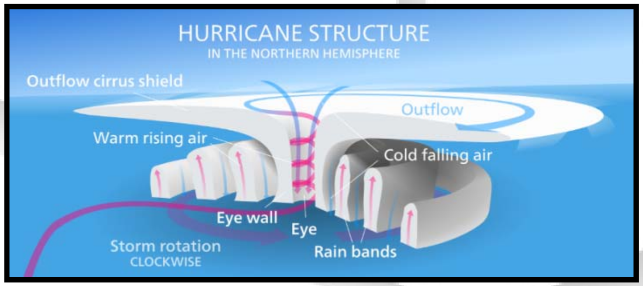
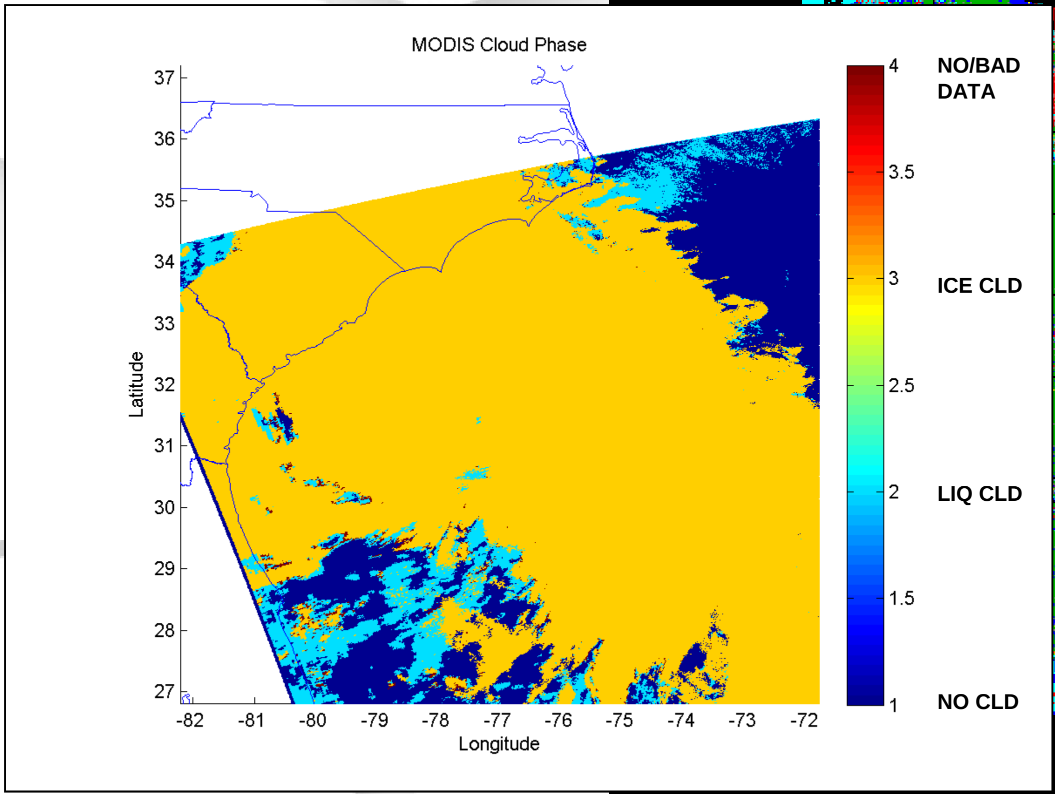
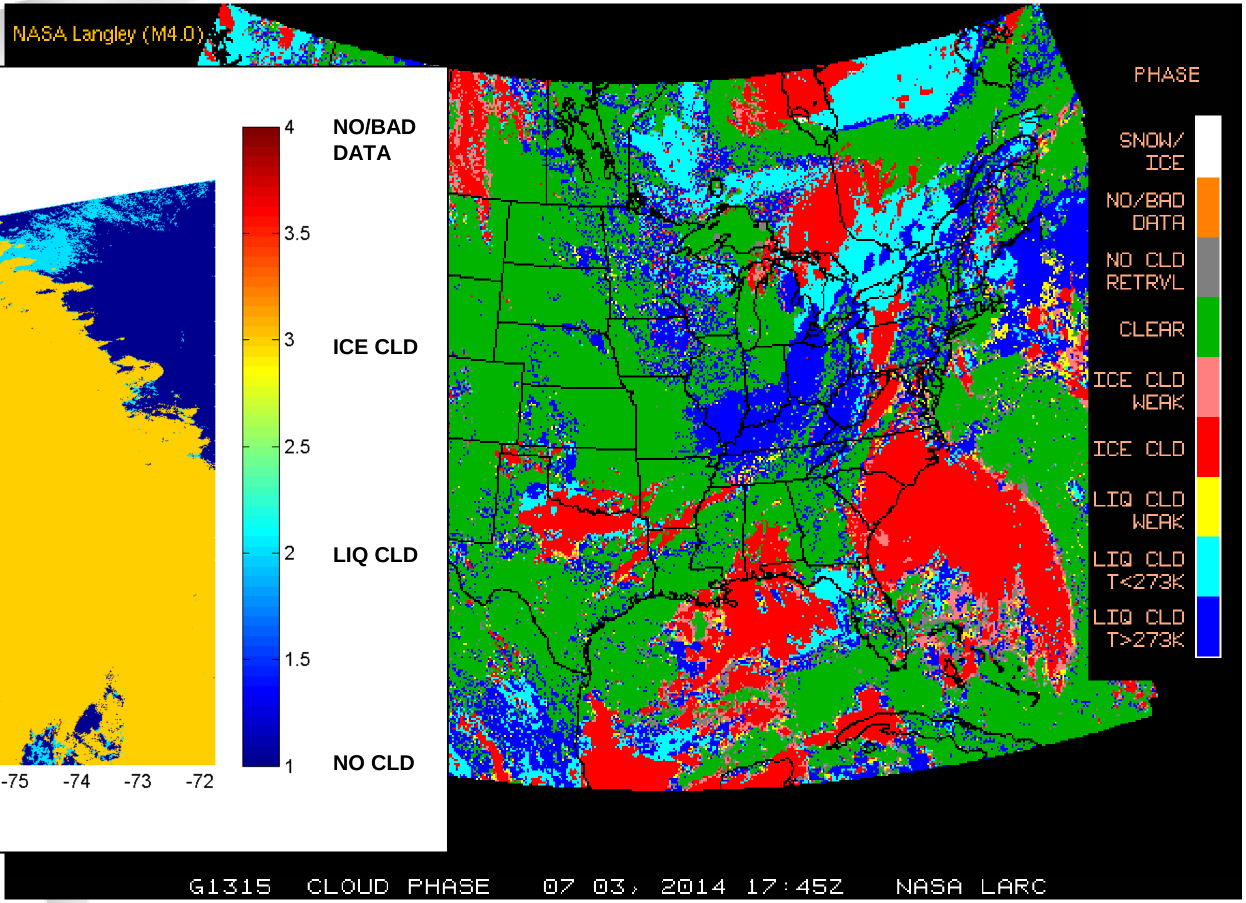


Satellite-derived Cloud Phase





Cloud Field Validation
Optical Depth Results

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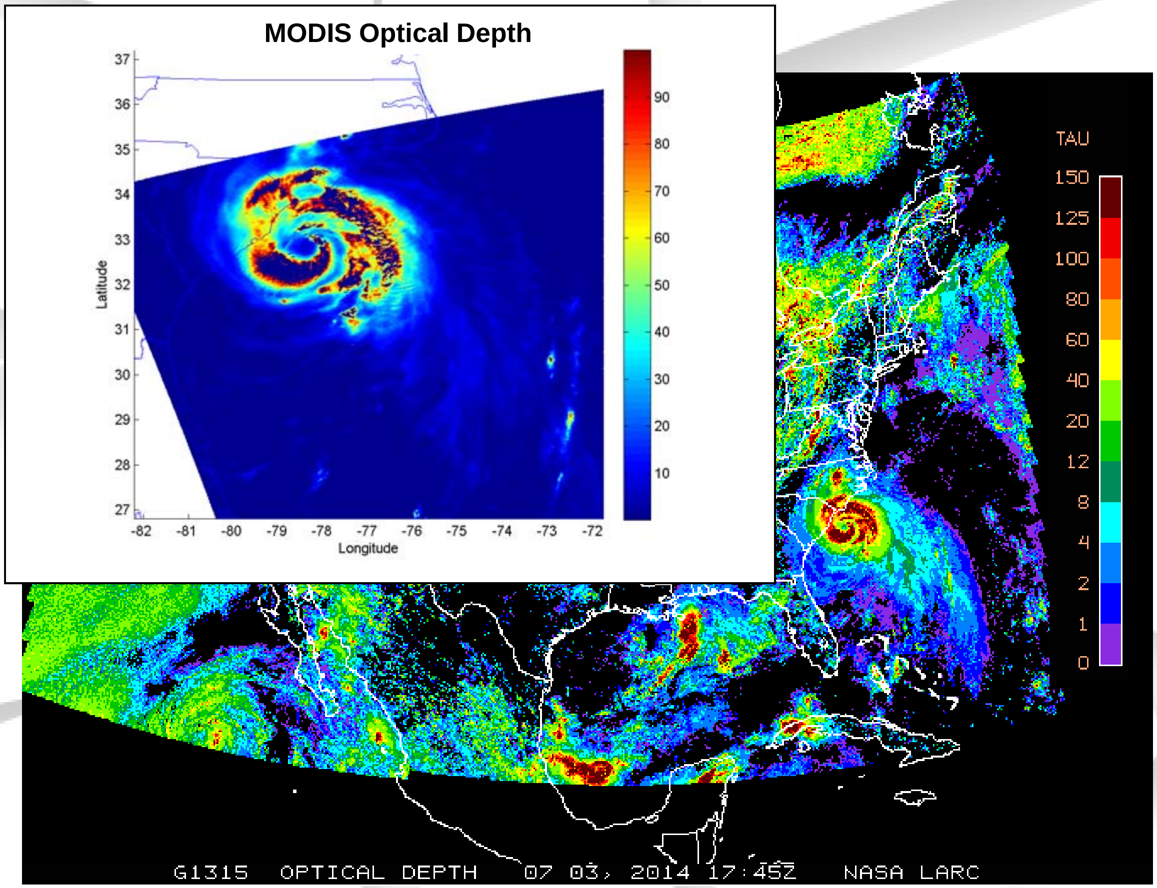
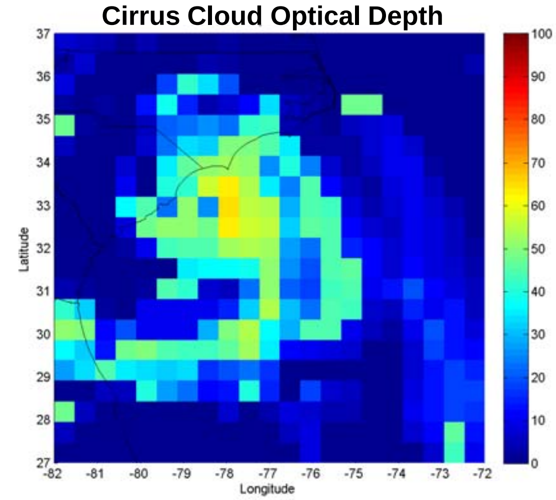
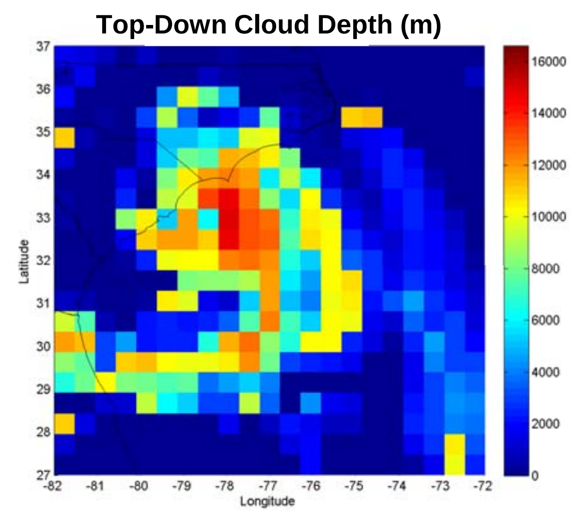
Satellite Analysis



Wx Cube Analysis





Rain Field Validation

Algorithm Methodology

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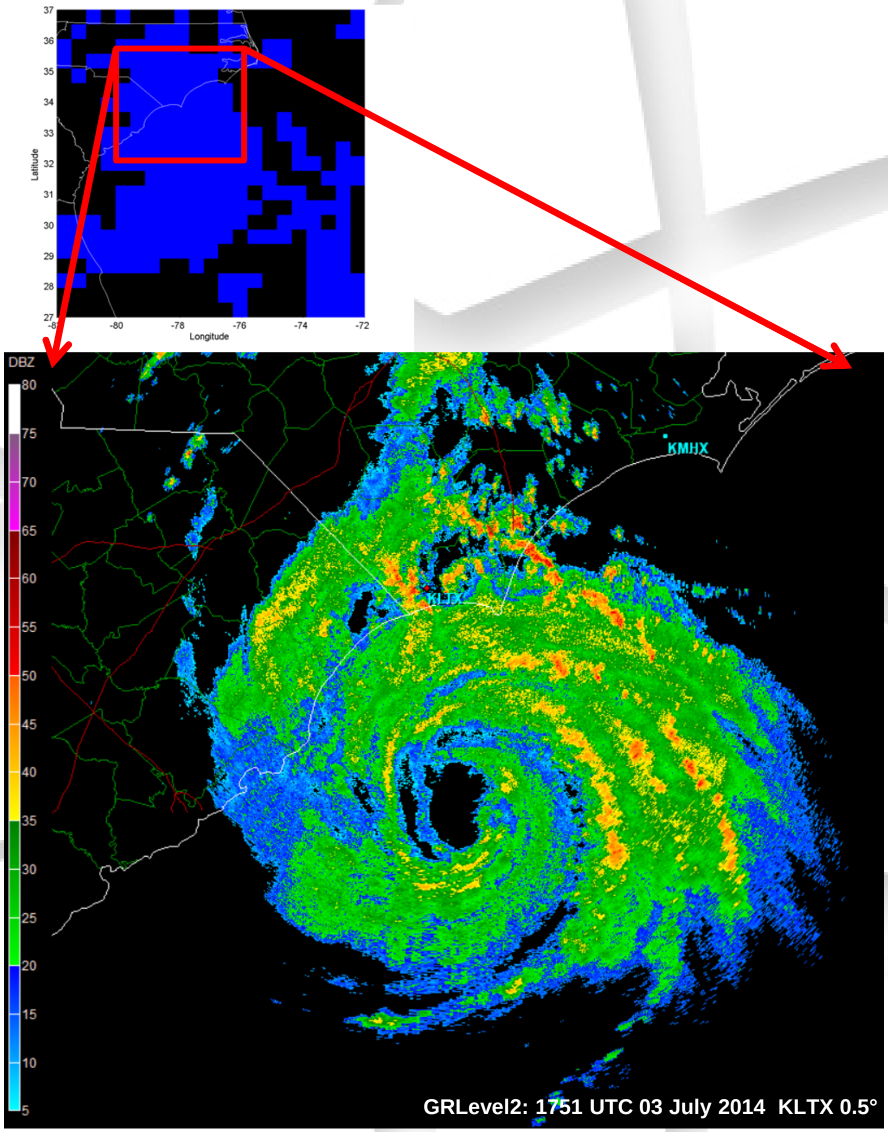

Rain fields are generated from NWP data if the following conditions exist:

- A cloud must be present
- 3-hour precipitation totals available per grid point

Rain Rate determine by an averaged hourly rain rate based on precipitation totals

- Very Light Rain (2mm/hr)
- Light Rain (5 mm/hr)
- Moderate Rain (12.5mm/hr)
- Heavy Rain (25 mm/hr)
- Extremely Heavy Rain (75 mm/hr)

Rain fields are located from the middle of the cloud layer to the surface.

Rain Field Validation

Algorithm Methodology

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Rain Field Algorithm

GFS 3-hr Total Precipitation (kg/m^2) to Rain Rate (mm/hr) Conversion

Density of water: ρ_{water} = 1000kg/m^3

Multiplying GFS 3hr Total Precip by the inverse ρ_{water},

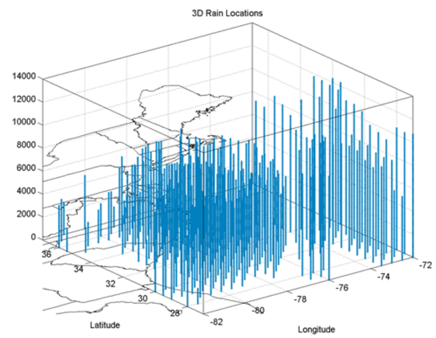
[GFS Total Precip * ρ_{water}^{-1}] / 3hr

$= \left[1\frac{kg}{m^2}\ \left(\frac{1}{1000\,{}^{kg}/_{m^3}}\right)\right]$ / 3hr

= [0.001m] / 3hr

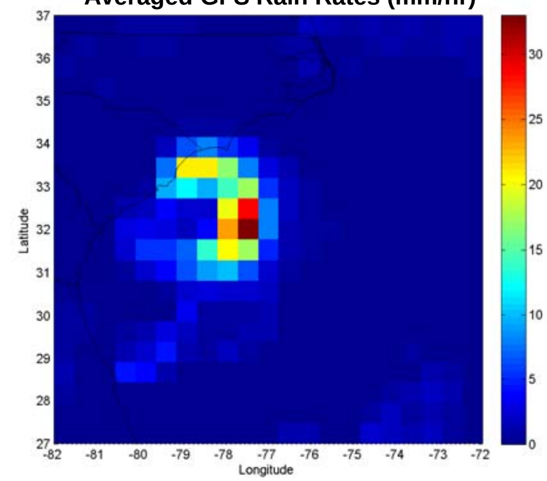
= [1mm] / 3hr

= 0.333 mm/hr

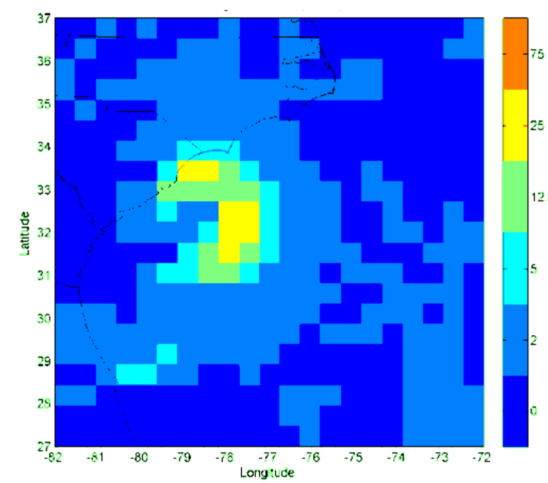


Weather Cube Rain Rate	Averaged GFS Rain Rate Thresholds (mm/hr)
Very Light Rain (2 mm/hr)	0 < RainRate ≤ 3.5
Light Rain (5mm/hr)	3.5 < RainRate ≤ 8.75
Moderate Rain (12.5mm/hr)	8.75 < RainRate ≤ 18.75
Heavy Rain (25mm/hr)	18.75 < RainRate ≤ 50
Extreme Rain (75mm/hr)	50 < RainRate ≤ Infinity

Averaged GFS Rain Rates (mm/hr)



Weather Cube GFS Rain Rates (mm/hr)



Rain Field Validation

Radar-Derived Rain Rates

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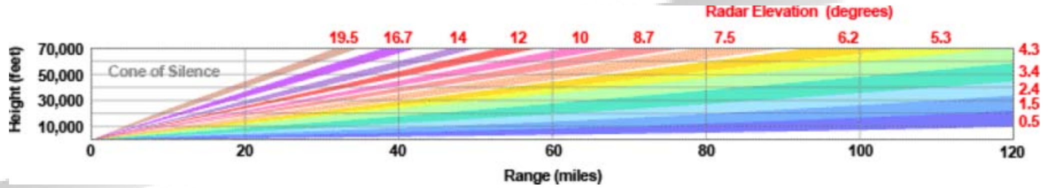
The lowest elevation scan (0.5 degree tilt) of NEXRAD data from the Wilmington, NC site used to validate the rain fields.



- Reflectivity values (Z) were converted to Rain Rate (mm/hr) through Marshall-Palmer distribution relationships:

$$Z = 200(Rain\ Rate)^{1.6}$$

- Due to rain droplet size being on the order of microns, radar reflectivity units are reported as dBZ, a logarithmic method that differentiates between precip size (I.e. drizzle, hail),

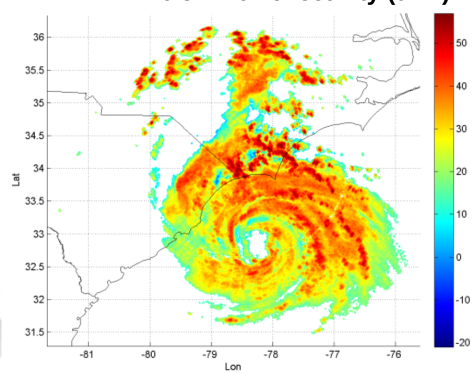
$$dBZ = 10\ log_{10}Z$$

- and thus:

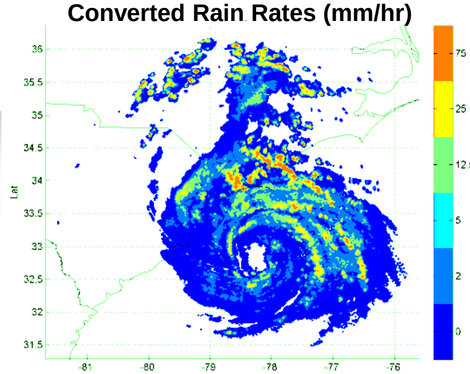
$$RainRate\ (mm/hr) = \left[\frac{\left(10^{\frac{dBZ}{10}}\right)}{200}\right]^{\frac{5}{8}}$$

Rain Rates were averaged per 0.5-degree grid point for a 1-to-1 comparison with Weather Cube Rain Placement and Rates.

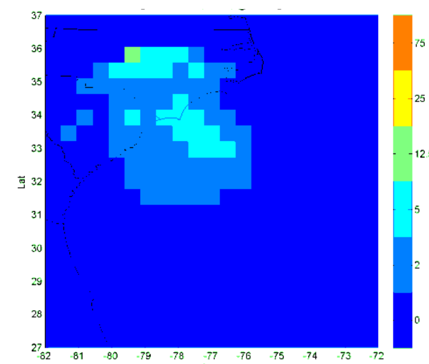
NEXRAD 0.5° Tilt Reflectivity (dBZ)



Converted Rain Rates (mm/hr)



Converted Rain Rates (mm/hr)



Rain Field Validation
Radar-Derived Rain Rates

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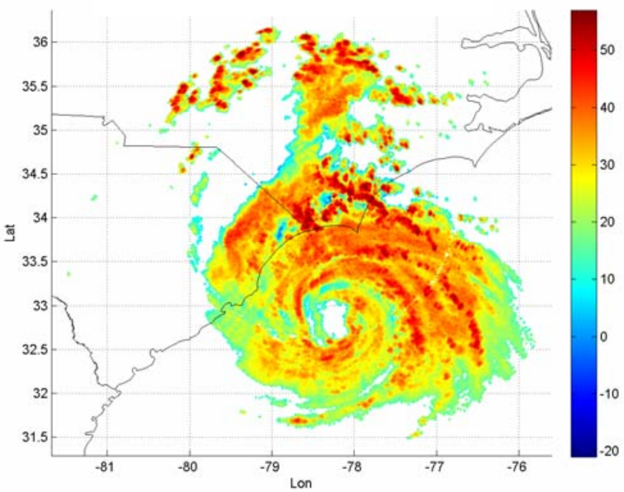
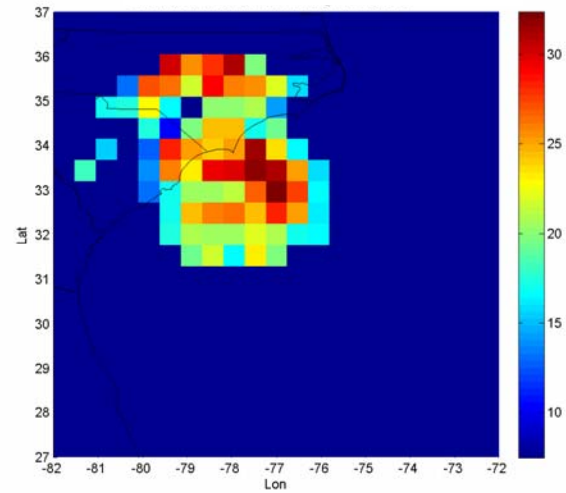
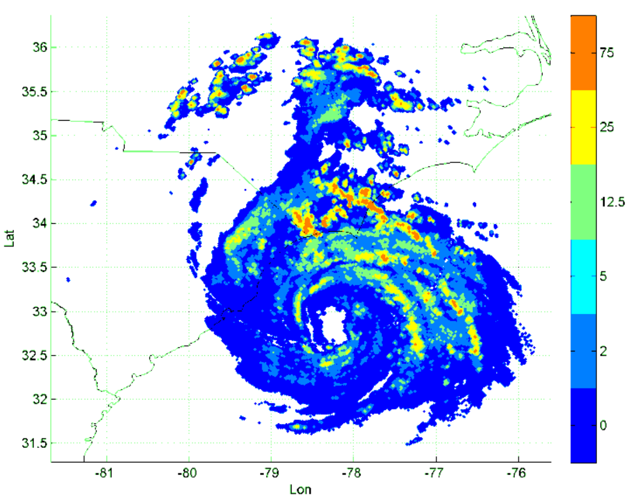
NEXRAD (KLTX) 0.5° Tilt Reflectivity (dBZ)



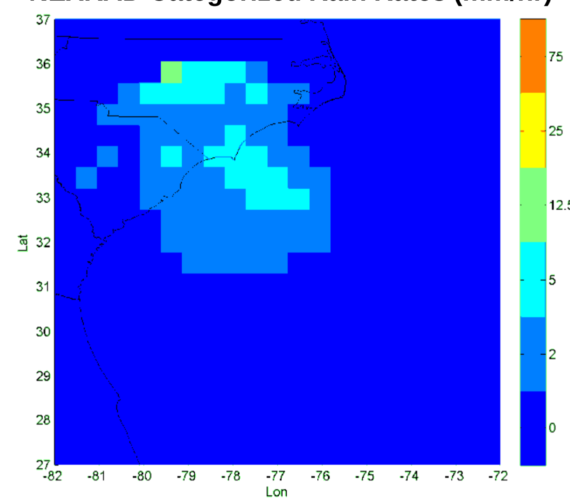
Averaged Reflectivity Grid (dBZ)



NEXRAD-Derived Rain Rate (mm/hr)



NEXRAD Categorized Rain Rates (mm/hr)



Rain Field Validation
Results

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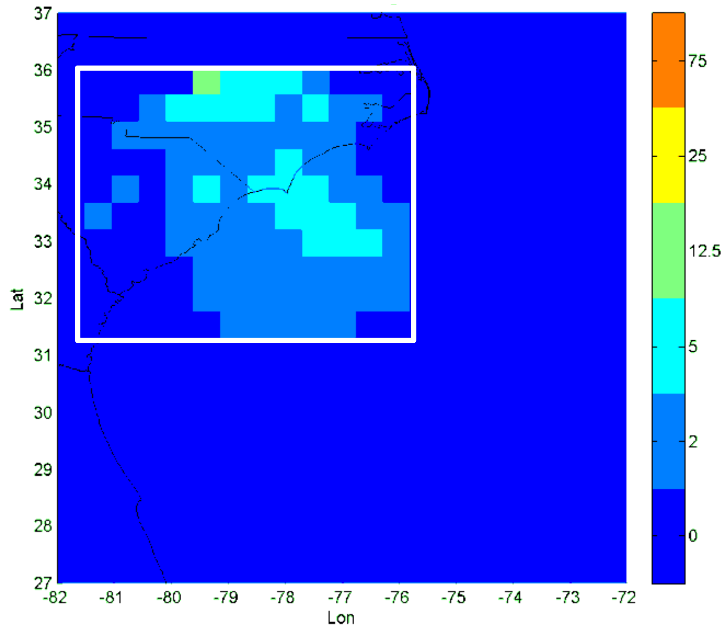
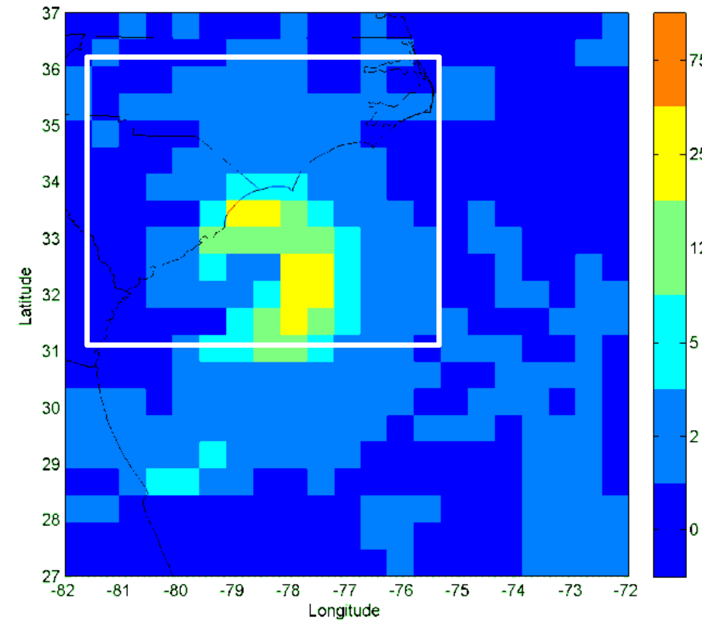
NEXRAD Rain Rates (mm/hr)
03 July 2014 1751 UTC



Weather Cube Rain Rates (mm/hr)
03 July 2014 1800 UTC



Weather Cubes

Non-Significant Weather Case

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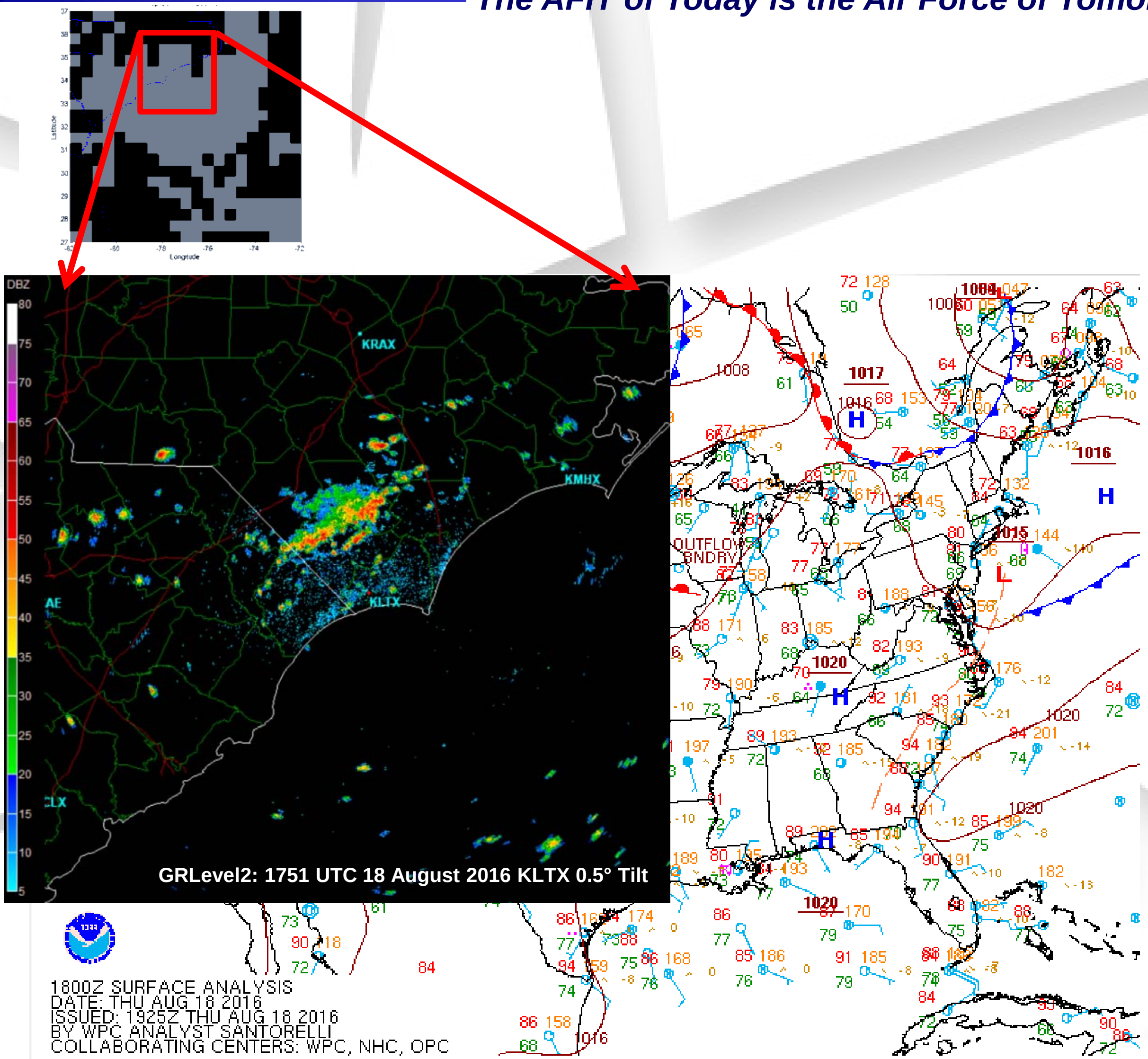

Non-Significant

<u>Weather Case</u>

- A few showers and thunderstorms in the area
- Verification Analysis 18 August 2016 1800 UTC

How will the Cloud and Rain Field algorithms perform in a “more normal” weather event?

Weather Cubes

Non-Significant Weather Case

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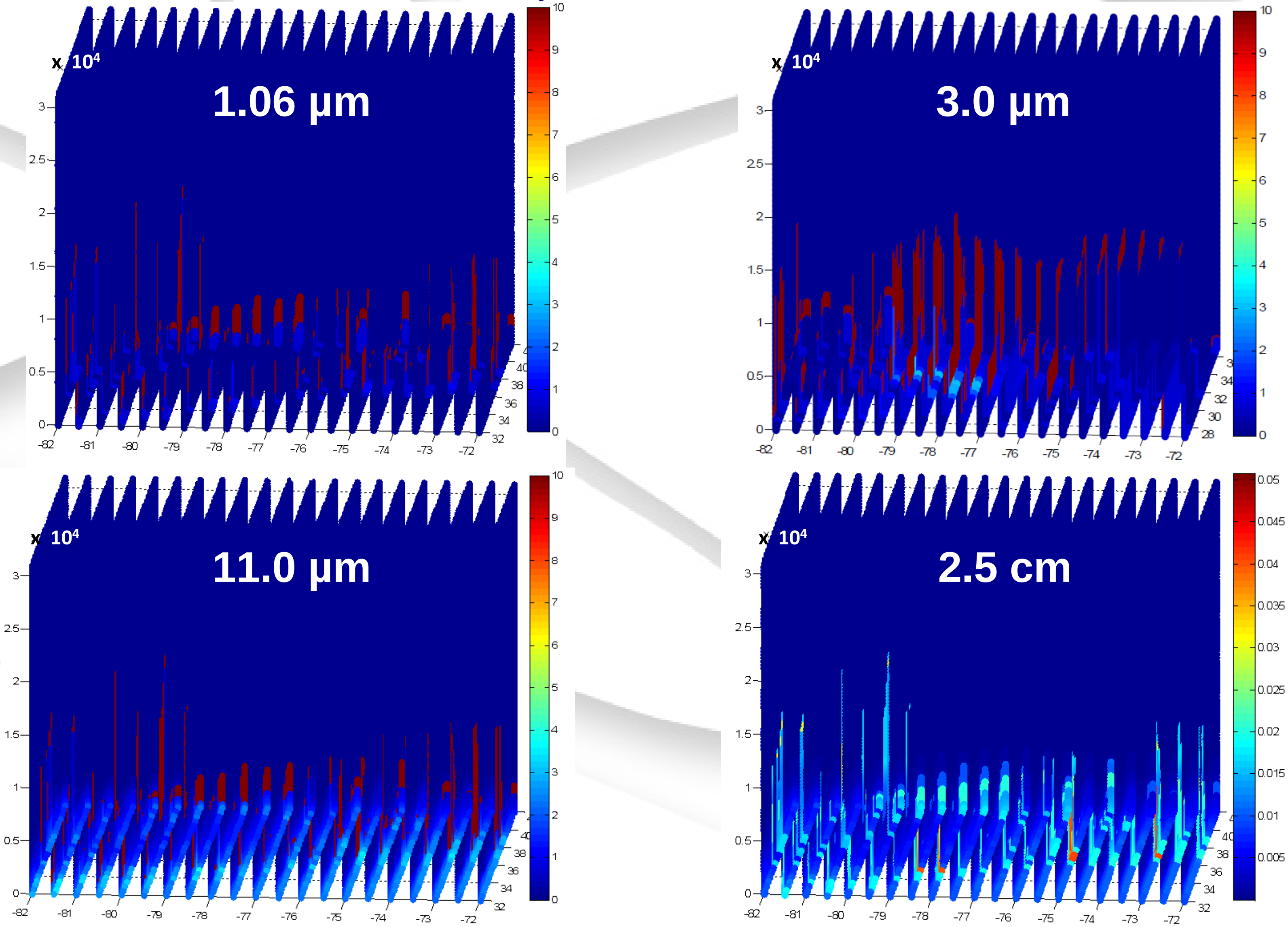

Cloud Field Validation

Results

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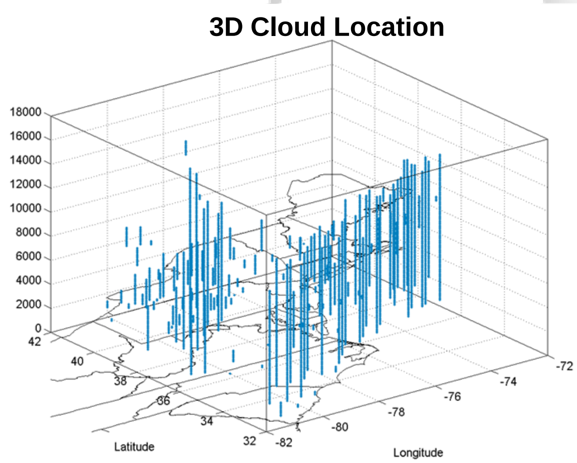
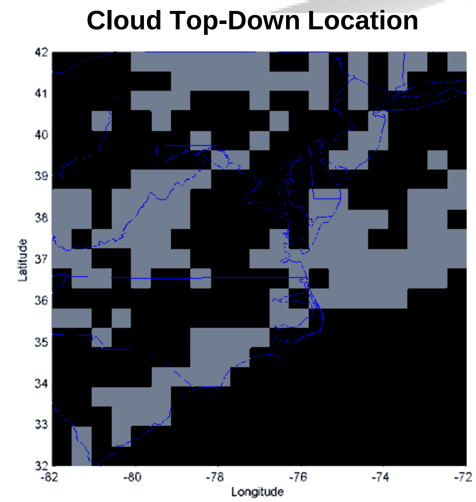
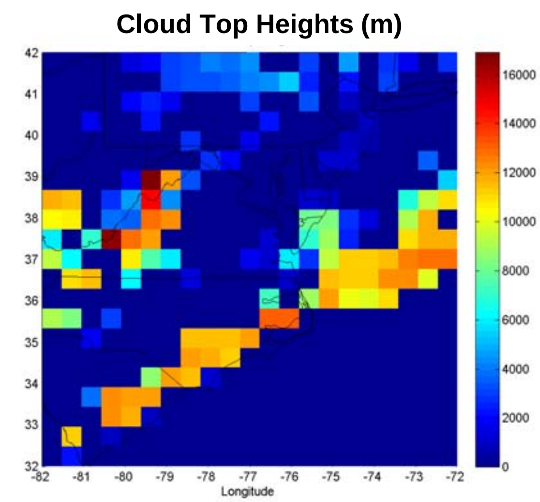
Cloud Placement | **Cloud Coverage** | **Cloud Top Heights**

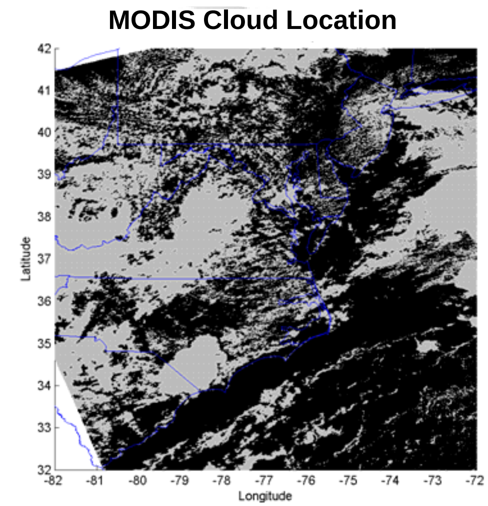
Wx Cubes

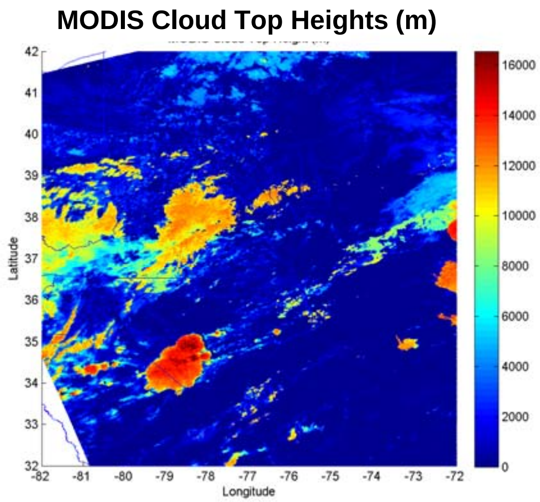






MODIS





Cloud Field Validation
Optical Depth Results

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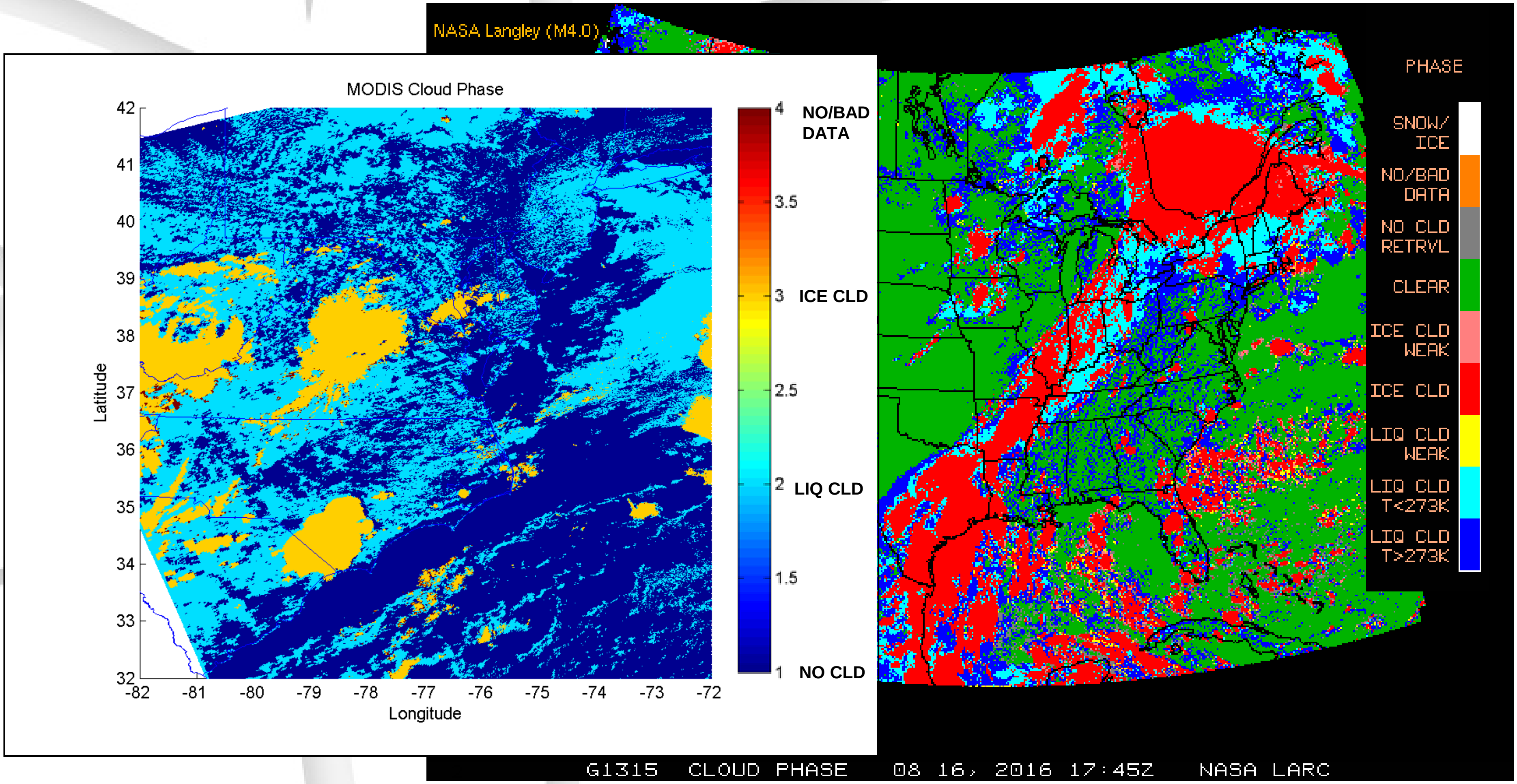
Satellite-derived Cloud Phase



Cloud Field Validation
Optical Depth Results

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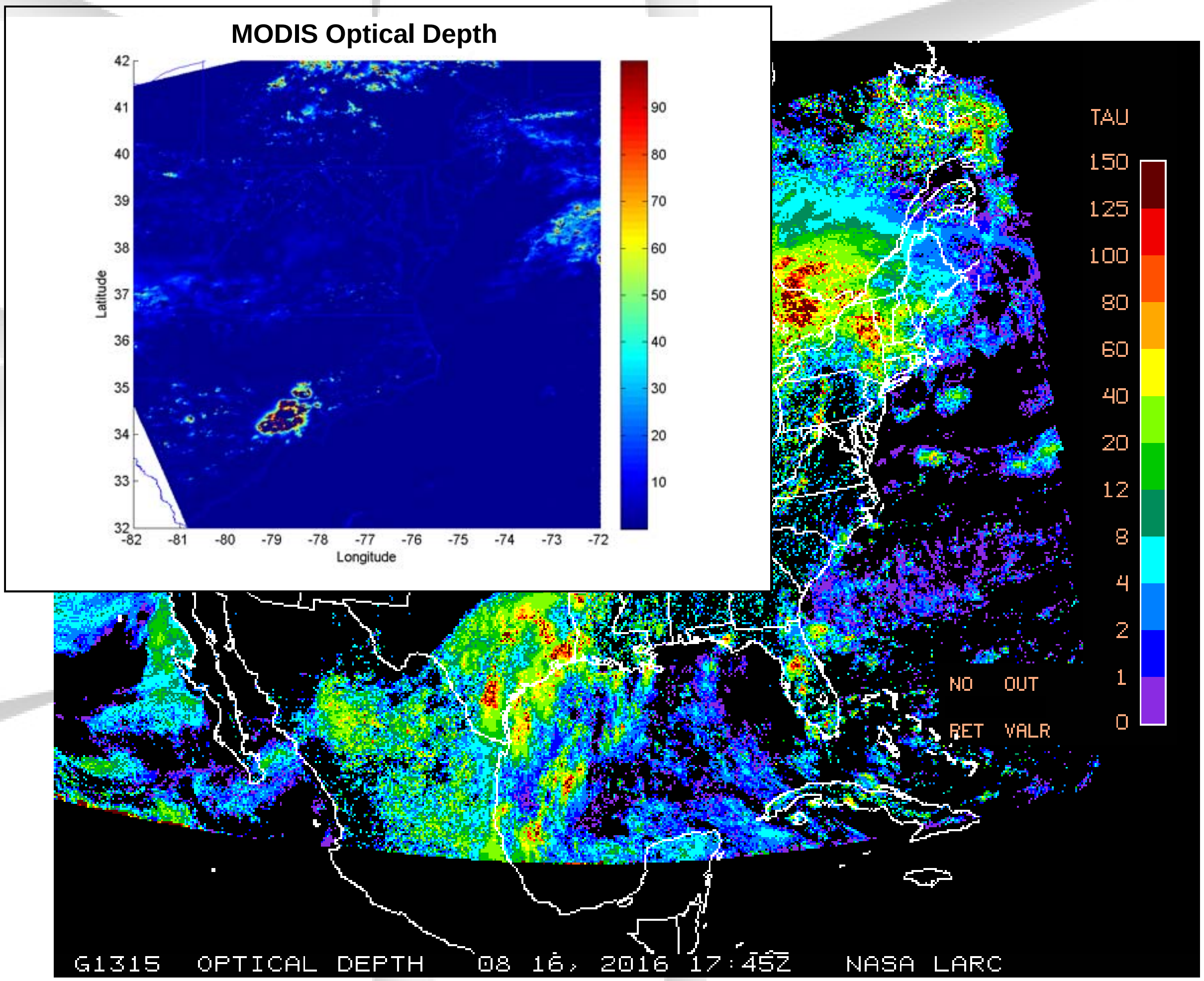
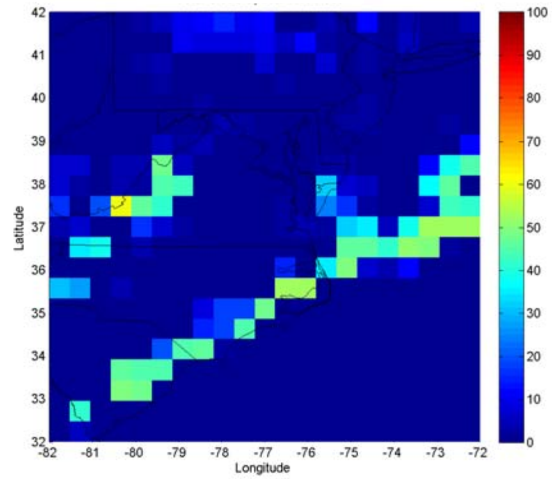
Satellite Analysis

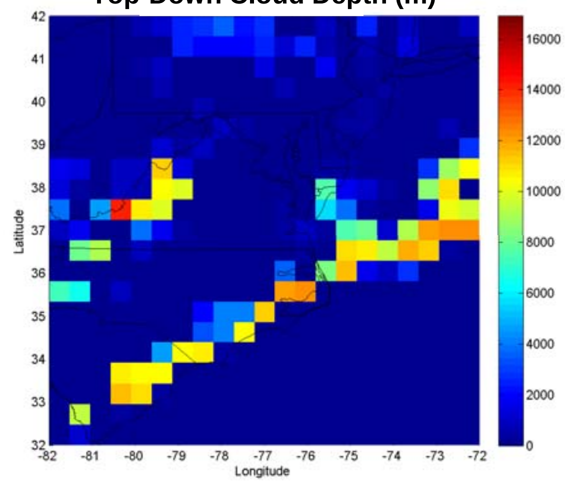


Wx Cube Analysis

Cirrus Cloud Optical Depth



Top-Down Cloud Depth (m)



Rain Field Validation
Radar-Derived Rain Rates

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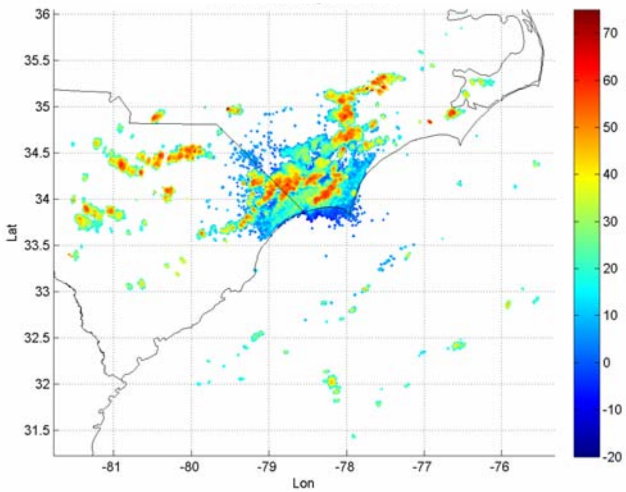
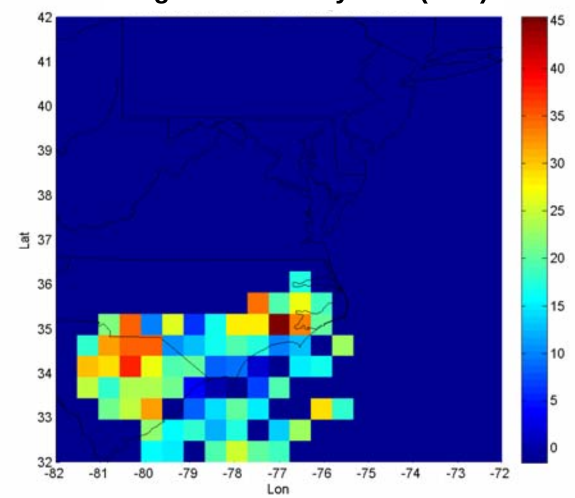
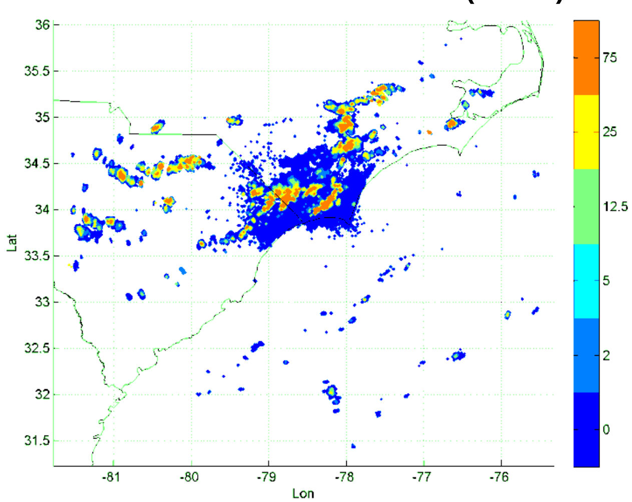
NEXRAD (KLTX) 0.5° Tilt Reflectivity (dBZ)



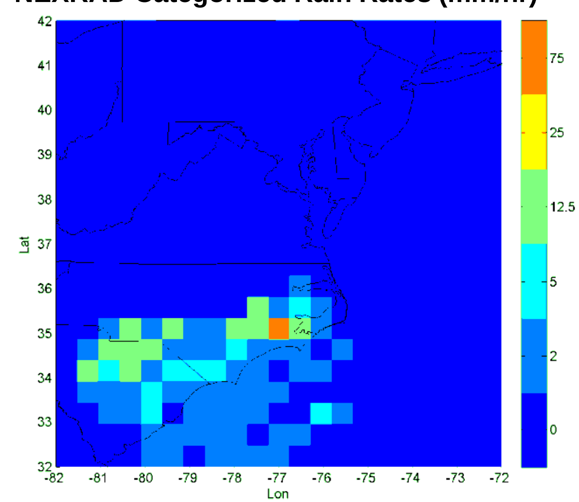
Averaged Reflectivity Grid (dBZ)



NEXRAD-Derived Rain Rate (mm/hr)



NEXRAD Categorized Rain Rates (mm/hr)



Rain Field Validation
Placement & Rain Rate Results

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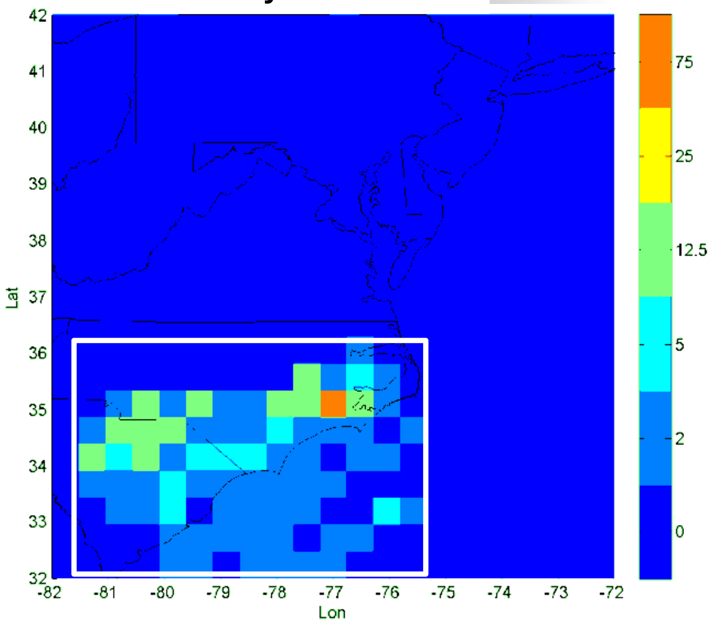
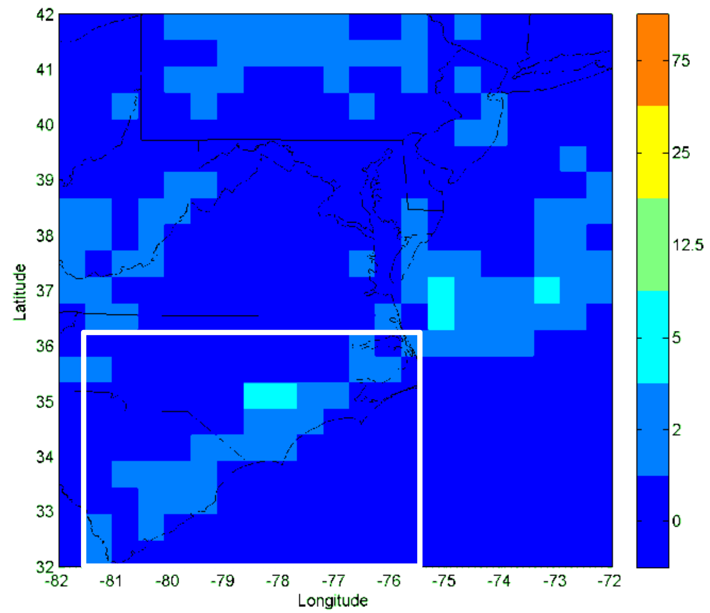
NEXRAD Rain Rates (mm/hr)
03 July 2014 1751 UTC



Weather Cube Rain Rates (mm/hr)
03 July 2014 1800 UTC



Summary

- Weather Cubes, visually stunning and realistic-looking visible-spectrum images accurately translating to propagation and atmospheric effects outside of the visible spectrum, were created using NWP and LEEDR.
- Cloud and Rain Field algorithms were incorporated into Weather Cubes to generate a more realistic atmospheric characterization.
  - Cloud Fields were validated by MODIS and GOES data
  - Rain Fields were validated by NEXRAD data
- This simple approach has the benefit of providing relatively accurate cloud placement and precipitation results with limited data sources.

Importance of Observations

Weather Cubes provide the way forward for quantifying and visually displaying atmospheric effects for any spectral range. But the need still remains for higher quantity and fidelity meteorological observations for input data, as well as validation data.

These meteorological observations would generate higher fidelity Weather Cubes and ultimately aid the war fighter make crucial decisions to protect our nation and its allies.

Future Research

The AFIT of Today is the Air Force of Tomorrow.

- Continue to improve upon Cloud and Rain Field algorithm

- Incorporate satellite and radar resources into Weather Cube data processing

- Radiance Cubes
  - Additional data cubes produced in conjunction with Weather Cube calculations
  - Provide foreground, background, or total path radiance values for any geometry within Weather Cube

AMERICAN METEOROLOGICAL SOCIETY

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Weather Cubes and 4D Visualizations Including Cloud and Rain Field Generated from Numerical Weather Prediction Data

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The need to accurately account for atmospheric and radiative transfer effects when generating visualizations is vital to the modeling and simulations community. The Laser Environmental Effects Definition and Reference (LEEDR) is a verified and validated atmospheric propagation and radiative transfer code which creates physically realizable vertical and horizontal profiles of meteorological data and environmental effects using climatological and Numerical Weather Prediction (NWP) data, allowing for post-event, nowcast, and forecast analysis for atmospheric radiative effects including particle-induced extinction, turbulence profiles, and path refraction (light bending). By itself, LEEDR and its graphical user interface (GUI) has the capability to provide a "2D" picture of localized atmospheric radiative properties and processes. Wrapper classes provide a means to circumvent LEEDR's GUI and easily execute batch runs for efficient, speedy parametric analyses to yield 4D weather cubes specific to a universal time reference, locations of interest (i.e. geo-referenced light source and remote sensor) and a user-provided output parameter such as transmission. Each weather cube depicts the variability of the output parameter, including refractivity and path-averaged index of refraction structure constant (Cn^2), with respect to the source-endpoint geo-referenced location and, most importantly, relative to the ambient atmosphere. Recent enhancements to weather cubes include the implementation of cloud and rain fields generated from the NWP data to produce realistic sky characterizations. Validation analyses of these characterizations using NASA's Moderate Resolution Imaging Spectroradiometer (MODIS) satellite data are also presented.

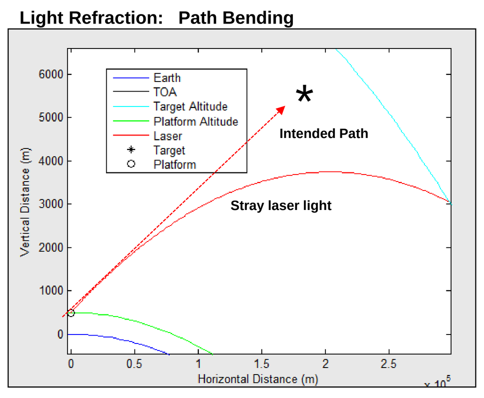
Simulation Tool: LEEDR

LEEDR radiative transfer code augmented by:

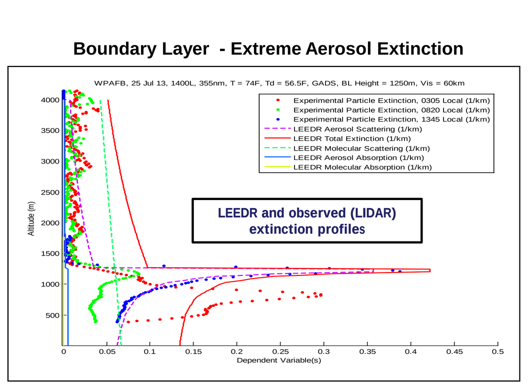
- Probabilistic Extreme and Percentile Environmental Reference Tables (ExPERT) data for 573 land sites; Surface Marine Gridded Climatology
- 4D real-time and/or archived NWP now-cast / forecast and weather satellite data

V&V'd Atmospheric Effects and Radiative Transfer Code for HEL

Light Refraction: Path Bending



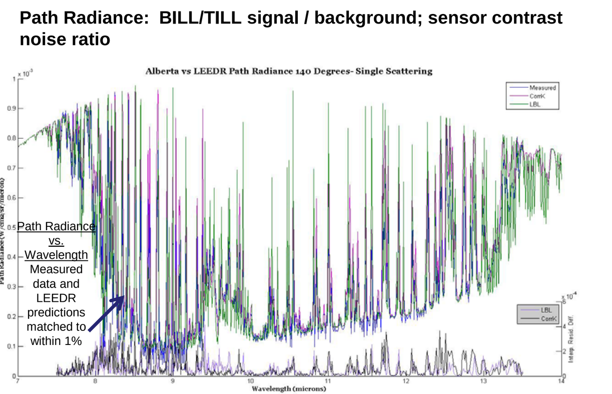
Boundary Layer - Extreme Aerosol Extinction

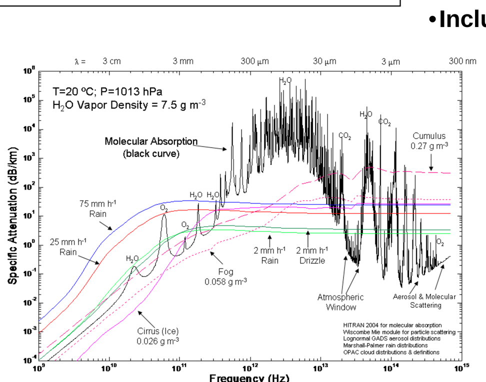


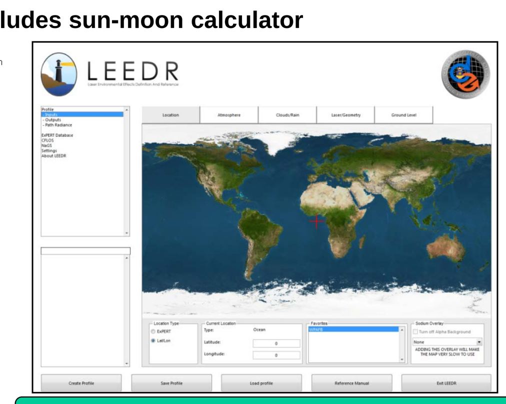
Creates physically realizable horizontal / vertical profiles of meteorological and weather event data and associated radiative effects (e.g. optical extinction, path radiance):

- **Aerosol and surface observation (i.e. T, P, RH) climatology at 573 ExPERT and 1° x 1° oceanic grid locations**
- **Numerical weather forecast, re-analysis data**
- **Profiles optical turbulence (i.e. C_n^2)**
- **Accounts for light-refraction and single/multi-scatter**
- **Includes sun-moon calculator**

Path Radiance: BILL/TILL signal / background; sensor contrast noise ratio





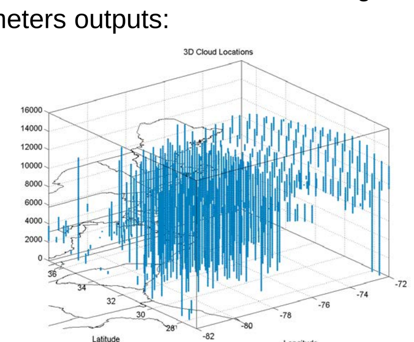


Characterizes effects from 200 nm to 8.6 meters

Cloud Field Algorithm

Cloud fields are generated from NWP data using the following two GFS parameters outputs:

- Relative Humidity
- Vertical Velocity



Cloud types, including Cumulus and Stratus clouds, were determined by Vertical Velocity thresholds.

	Relative Humidity (RH)	Vertical Velocity (ω)	Cloud Type
Within the Boundary Layer	≥ 100%	Upper Limit: -0.12 Pa/s Lower Limit: -11.99 Pa/s	Stratus
	≥ 100%	Upper Limit: -12.0 Pa/s Lower Limit: - Infinity Pa/s	Cumulus
Above the Boundary Layer	≥ 70%	Upper Limit: -0.12 Pa/s Lower Limit: -11.99 Pa/s	Stratus
	≥ 70%	Upper Limit: -12.0 Pa/s Lower Limit: - Infinity Pa/s	Cumulus

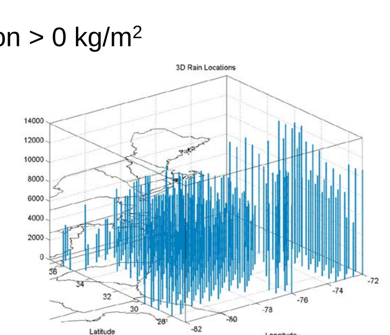
Rain Field Algorithm

Weather Cube Rain Rate	Averaged GFS Rain Rate Thresholds (mm/hr)
Very Light Rain (2 mm/hr)	0 < RainRate ≤ 3.5
Light Rain (5mm/hr)	3.5 < RainRate ≤ 8.75
Moderate Rain (12.5mm/hr)	8.75 < RainRate ≤ 18.75
Heavy Rain (25mm/hr)	18.75 < RainRate ≤ 50
Extreme Rain (75mm/hr)	50 < RainRate ≤ Infinity

In order for Rain Fields to be present, the following requirements need to be met:

- The presence of a cloud
- GFS 3-hour Total Precipitation > 0 kg/m^2

If both requirements are met, the GFS 3-hr Total Precipitation (kg/m^2) is then converted to a Rain Rate (mm/hr).



NEXRAD Reflectivity to Rain Rain (mm/hr) Methodology

The lowest elevation scan (0.5 degree tilt) of NEXRAD data from the Wilmington, NC site used to validate the rain fields.

- Reflectivity values (Z) were converted to Rain Rate (mm/hr) through Marshall-Palmer distribution relationships:

$$Z = 200(Rain\ Rate)^{1.6}$$

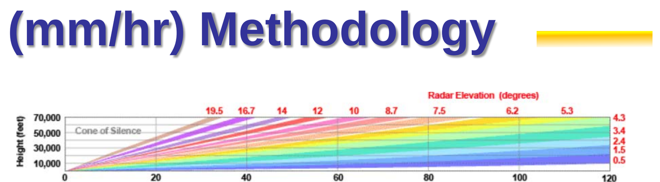
- Due to rain droplet size being on the order of microns, radar reflectivity units are reported as dBZ, a logarithmic method that differentiates between precip size (I.e. drizzle, hail),

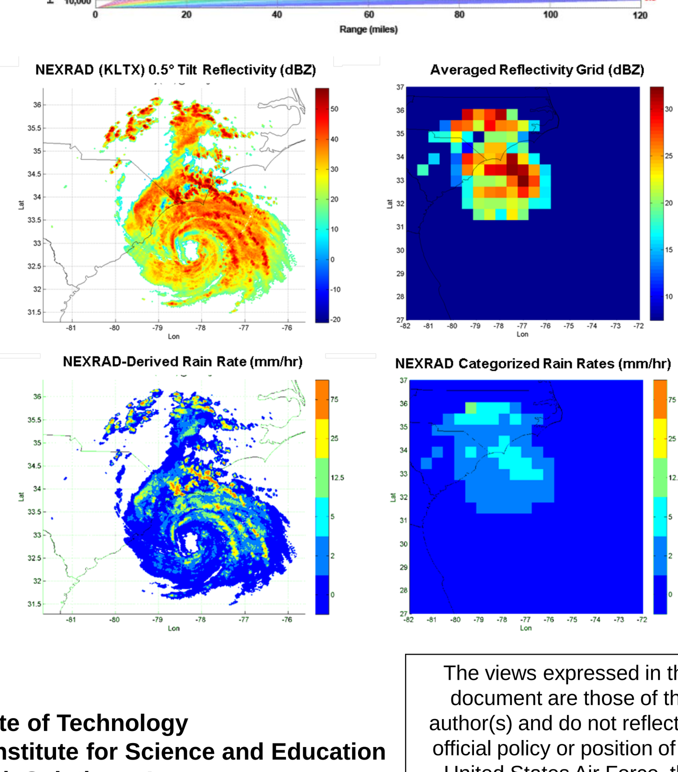
$$dBZ = 10\ log_{10}Z$$

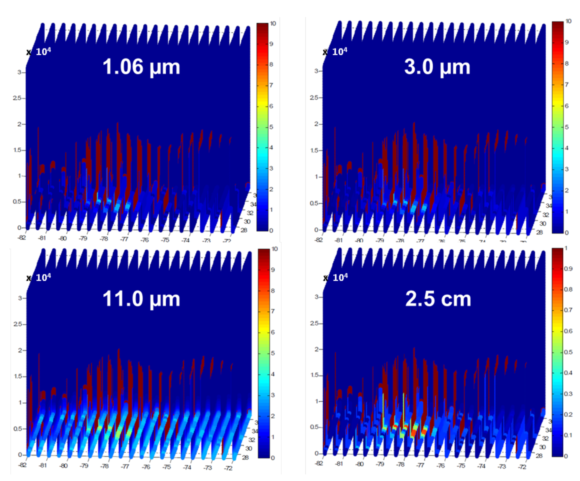
- and thus:

$$RainRate\ (mm/hr) = \left[\frac{\left(10^{\frac{dBZ}{10}}\right)}{200}\right]^{\frac{5}{8}}$$

Rain Rates were averaged per 0.5-degree grid point for a 1-to-1 comparison with Weather Cube Rain Placement and Rates.







4D Weather Cube simulations allow for visually stunning and realistic-looking visible-spectrum images to be accurately translated to propagation and atmospheric effects outside of the visible spectrum via AFIT/CDE's LEEDR physically-based atmospheric characterization model output.

Clouds, precipitation, and aerosol haze effects shown in the visible are also captured at wavelengths for any electro-optical infrared sensor or microwave/radio frequency tracking/illumination system.

Results:

Cloud Fields

Cloud Coverage | Cloud Top Heights | Optical Depth

Rain Fields

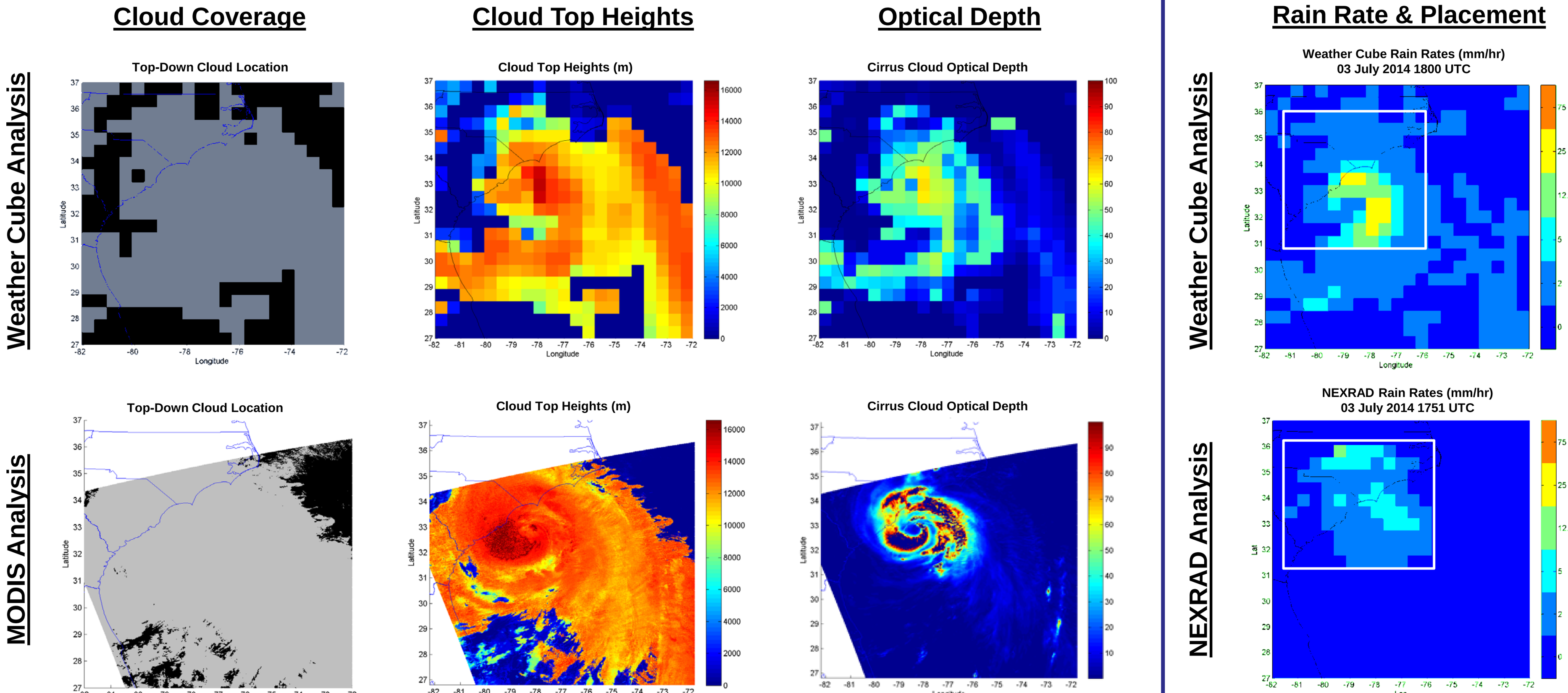
Rain Rate & Placement

Hurricane Arthur

03 July 2014 1800 UTC

Weather Cube Analysis

MODIS Analysis



Weather Cube Analysis

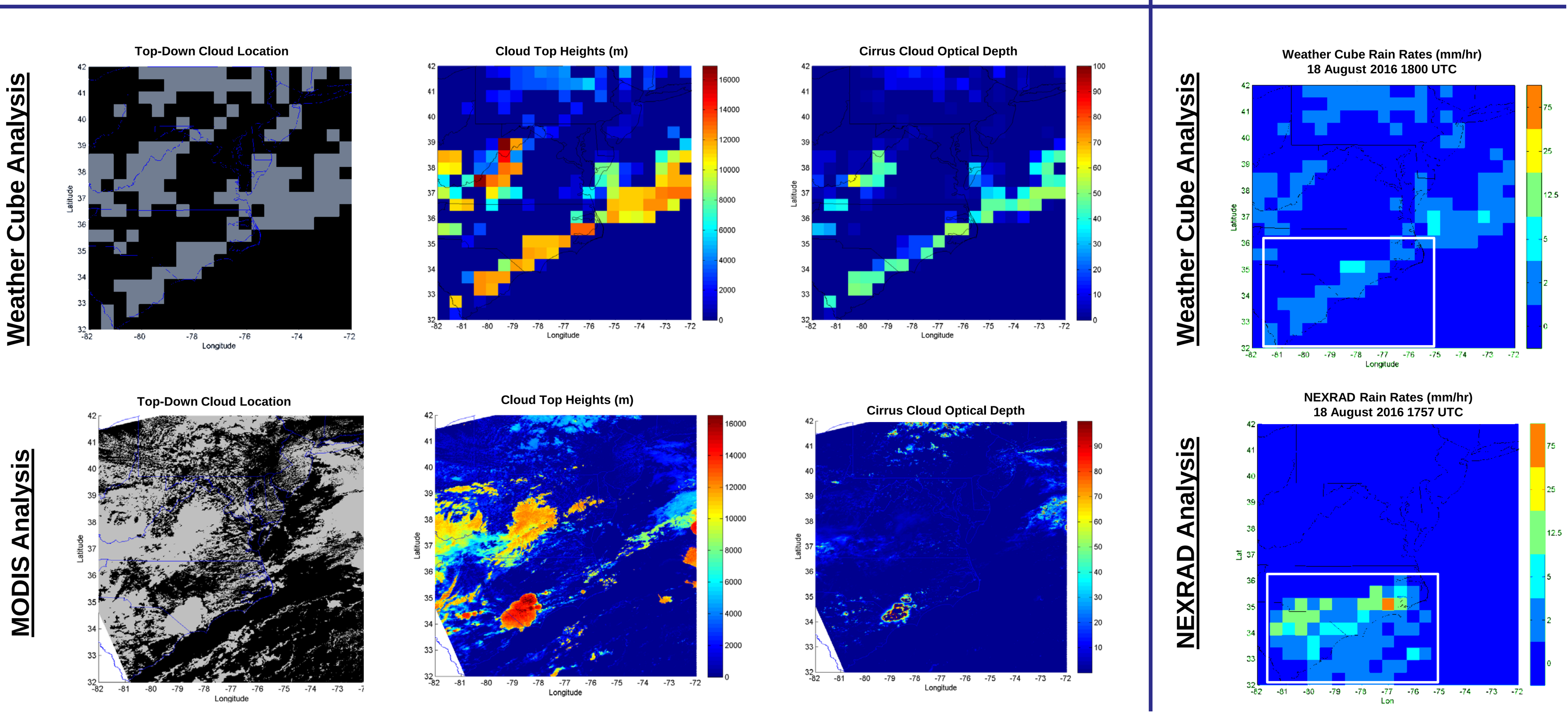
NEXRAD Analysis

Non-Significant Case

18 August 2016 1800 UTC

Weather Cube Analysis

MODIS Analysis



Weather Cube Analysis

NEXRAD Analysis

Conclusions:

- 4D weather cubes provide the user with ready access to radiative effect parameters, as well as the ability to accurately translate realistic-looking images accurately translating to propagation and atmospheric effects outside of the visible spectrum.
- Cloud and Rain Field algorithms were incorporated into Weather Cubes calculations to generate a more realistic sky and weather characterization.
- This simple approach has the benefit of providing relatively accurate cloud placement and precipitation results with limited observations or model data.

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