Weather Cubes and 4D Visualizations of Atmospheric and Radiative Effects

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Overview

The AFIT of Today is the Air Force of Tomorrow.

- 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 probabilistic data from the Extreme and Percentile Environmental Reference Tables (ExPERT)

Characterizes effects from 200 nm to 8.6 meters
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V&V’d Atmospheric Effects and Radiative Transfer Code for HEL

LEEDR

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

Light Refraction: Path Bending

Path Radiance vs. Wavelength Measured data and LEEDR predictions matched to within 1%

Boundary Layer - Extreme Aerosol Extinction

LEEDR and observed (LIDAR) extinction profiles
Weather Cubes
4D Wx Effects Visualizations

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- 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
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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- $10^\circ \times 10^\circ \times 30\text{km}$ 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 \mu m](chart)
Weather Cubes
Hurricane Arthur

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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

<table>
<thead>
<tr>
<th>Relative Humidity (RH)</th>
<th>Vertical Velocity ($\omega$)</th>
<th>Cloud Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Within the Boundary Layer</td>
<td>$\geq 100%$</td>
<td>Upper Limit: -0.12 Pa/s Lower Limit: -11.99 Pa/s</td>
</tr>
<tr>
<td></td>
<td>$\geq 100%$</td>
<td>Upper Limit: -12.0 Pa/s Lower Limit: -Infinity Pa/s</td>
</tr>
<tr>
<td>Above the Boundary Layer</td>
<td>$\geq 70%$</td>
<td>Upper Limit: -0.12 Pa/s Lower Limit: -11.99 Pa/s</td>
</tr>
<tr>
<td></td>
<td>$\geq 70%$</td>
<td>Upper Limit: -12.0 Pa/s Lower Limit: -Infinity Pa/s</td>
</tr>
</tbody>
</table>
Cloud Field Validation Results

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Cloud Placement

Cloud Coverage

Cloud Top Height

MODIS

Wx Cubes

3D Cloud Location

Cloud Top-Down Location

Cloud Top Heights (m)

MODIS Cloud Location

MODIS Cloud Top Heights (m)
Cloud Field Validation
Optical Depth Results

Satellite-derived Cloud Phase

MODIS Cloud Phase

PHASE
SNOW/ICE
NO/BAD
DATA
NO CLD RETRVL
CLEAR
ICE CLD
WEAK
LIQ CLD
WEAK
LIQ CLD T<273K
LIQ CLD T>273K

NASA Langley (M4.0)

G1315 CLOUD PHASE 07 03, 2014 17:45Z NASA LARC
Cloud Field Validation
Optical Depth Results

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Satellite Analysis

Wx Cube Analysis

MODIS Optical Depth

Cirrus Cloud Optical Depth

Top-Down Cloud Depth (m)
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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GFS 3-hr Total Precipitation (kg/m²) to Rain Rate (mm/hr) Conversion

Density of water: \( \rho_{\text{water}} = 1000 \text{kg/m}^3 \)

Multiplying GFS 3hr Total Precip by the inverse \( \rho_{\text{water}} \),

\[
\frac{[\text{GFS Total Precip} \times \rho_{\text{water}}^{-1}]}{3\text{hr}} = \frac{[0.001\text{m}]}{3\text{hr}} = \frac{[1\text{mm}]}{3\text{hr}} = 0.333 \text{ mm/hr}
\]

<table>
<thead>
<tr>
<th>Weather Cube Rain Rate</th>
<th>Averaged GFS Rain Rate Thresholds (mm/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very Light Rain (2 mm/hr)</td>
<td>0 &lt; RainRate ≤ 3.5</td>
</tr>
<tr>
<td>Light Rain (5 mm/hr)</td>
<td>3.5 &lt; RainRate ≤ 8.75</td>
</tr>
<tr>
<td>Moderate Rain (12.5 mm/hr)</td>
<td>8.75 &lt; RainRate ≤ 18.75</td>
</tr>
<tr>
<td>Heavy Rain (25 mm/hr)</td>
<td>18.75 &lt; RainRate ≤ 50</td>
</tr>
<tr>
<td>Extreme Rain (75 mm/hr)</td>
<td>50 &lt; RainRate ≤ Infinity</td>
</tr>
</tbody>
</table>
Rain Field Validation
Radar-Derived Rain Rates

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:

\[ Z = 200 (\text{Rain Rate})^{1.6} \]

• 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:

\[ \text{RainRate (mm/hr)} = \left( \frac{dBZ}{200} \right)^{\frac{5}{3}} \]

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

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 Weather Case

- 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
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

MODIS Cloud Phase

NO CLD
LIQ CLD
ICE CLD
NO/BAD DATA

NASA Langley (M4.0)
Cloud Field Validation
Optical Depth Results
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Satellite Analysis

Wx Cube Analysis

Cirrus Cloud Optical Depth

Top-Down Cloud Depth (m)
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NEXRAD (KLTX) 0.5° Tilt Reflectivity (dBZ)

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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
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.
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

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

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Department of Engineering Physics

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 (Cn²), 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 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

LEEDR Molecular Absorption (1/km)
LEEDR Aerosol Absorption (1/km)
LEEDR Molecular Scattering (1/km)
Experimental Particle Extinction, 1345 Local (1/km)
Experimental Particle Extinction, 0820 Local (1/km)
Experimental Particle Extinction, 0305 Local (1/km)

Results:

Cloud Fields

Weather Cube Rain Rates (mm/hr)

Non-Significant Case

NEXRAD Rain Rates (mm/hr)

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/m2

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.