Global Cloud Free Line of Sight (CFLOS) Characterizations Using Numerical Weather Prediction Data

Jaclyn Schmidt[1,2], Dr Jarred Burley[1], Blaine Fourman[1,2], Dr Steven Fiorino[1]

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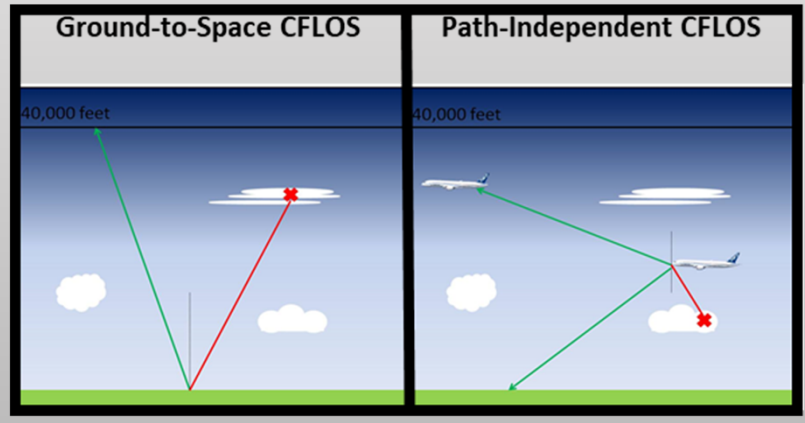
[1]Air Force Institute of Technology
[2]Applied Research Solutions, Inc.

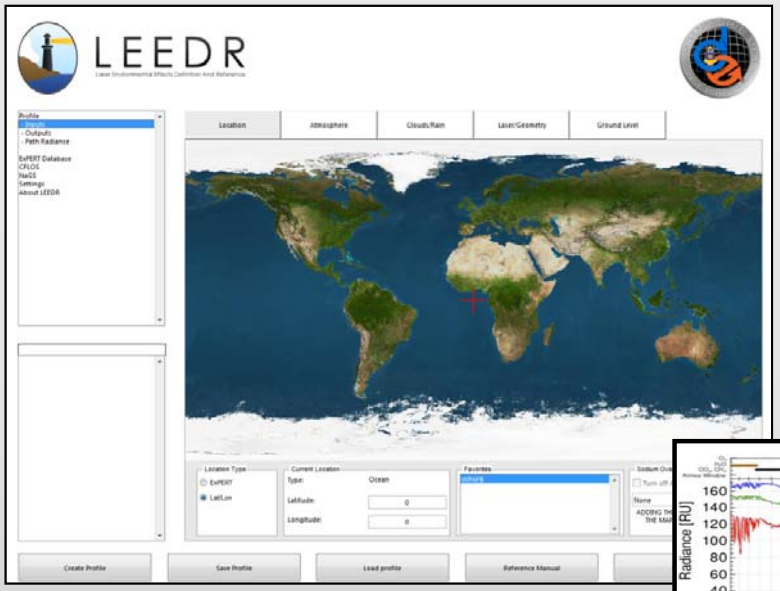
Background & Motivation

- **Cloud free line of sight (CFLOS) is simply a direct line of sight that is not hindered by a cloud.**
  - CFLOS probabilities for path-independent geometries are extremely useful for a variety of applications, including DoD technologies, Military operations, communication, and remote sensing.
- **Ground-to-space CFLOS tables available from the 14th Weather Squadron**
- **Limitations include:**
  - Current CFLOS climatologies only represent ground-to-space probabilities
  - 415 sites worldwide
- **A 2-D Path-Independent algorithm was developed by an AFIT intern in 2006 for creating CFLOS tables with an altitude/zenith dependency-- Approximating intermediate probabilities by using a combination of data sources:**
  - 14WS CFLOS ground-to-space measurements
  - Cloud ceiling tables
  - A CFLOS Monte Carlo simulation
- **Assumes a homogenous distribution of clouds (not azimuthally dependent)**

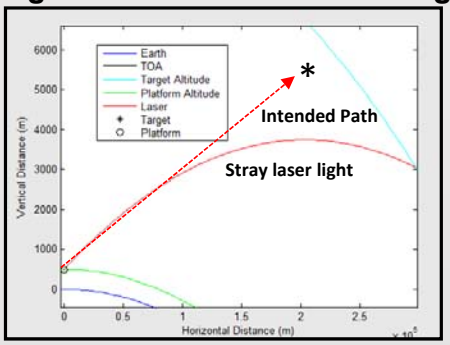


LEEDR

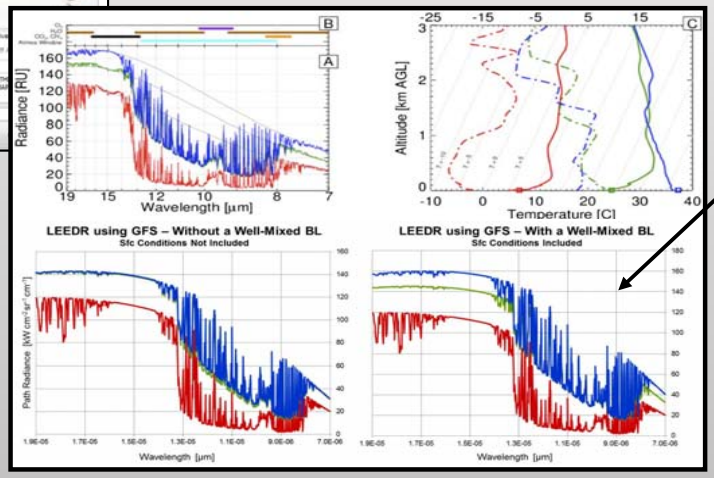
Laser Environmental Effects Definition & Reference



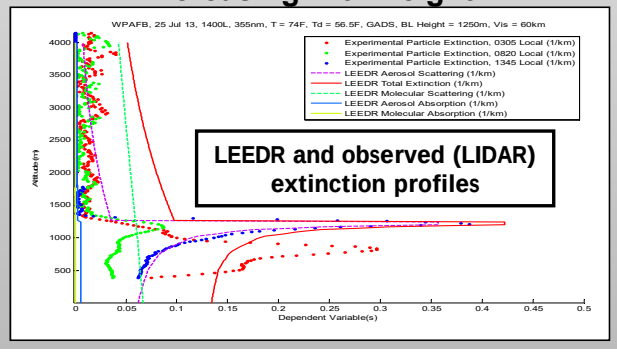
Light Refraction: Path Bending



Path Radiance: Tracker SNR



Boundary Layer - Aerosol Extinction Increasing with Height



Klein, et al, 2015: LABLE: A Multi-Institutional, Student-Led, Atmospheric Boundary Layer Experiment. *Bull. Amer. Meteor. Soc.*, 96, 1743–1764, https://doi.org/10.1175/BAMS-D-13-00267.1

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**
- **Unique boundary layer characterization**
- **Ground observations considered**
- **Profiles optical turbulence (i.e. C_n^2)**
- **Accounts for light-refraction and single/multi-scatter**
- **Includes sun-moon calculator**

V&V'd Atmospheric Effects and Radiative Transfer Code

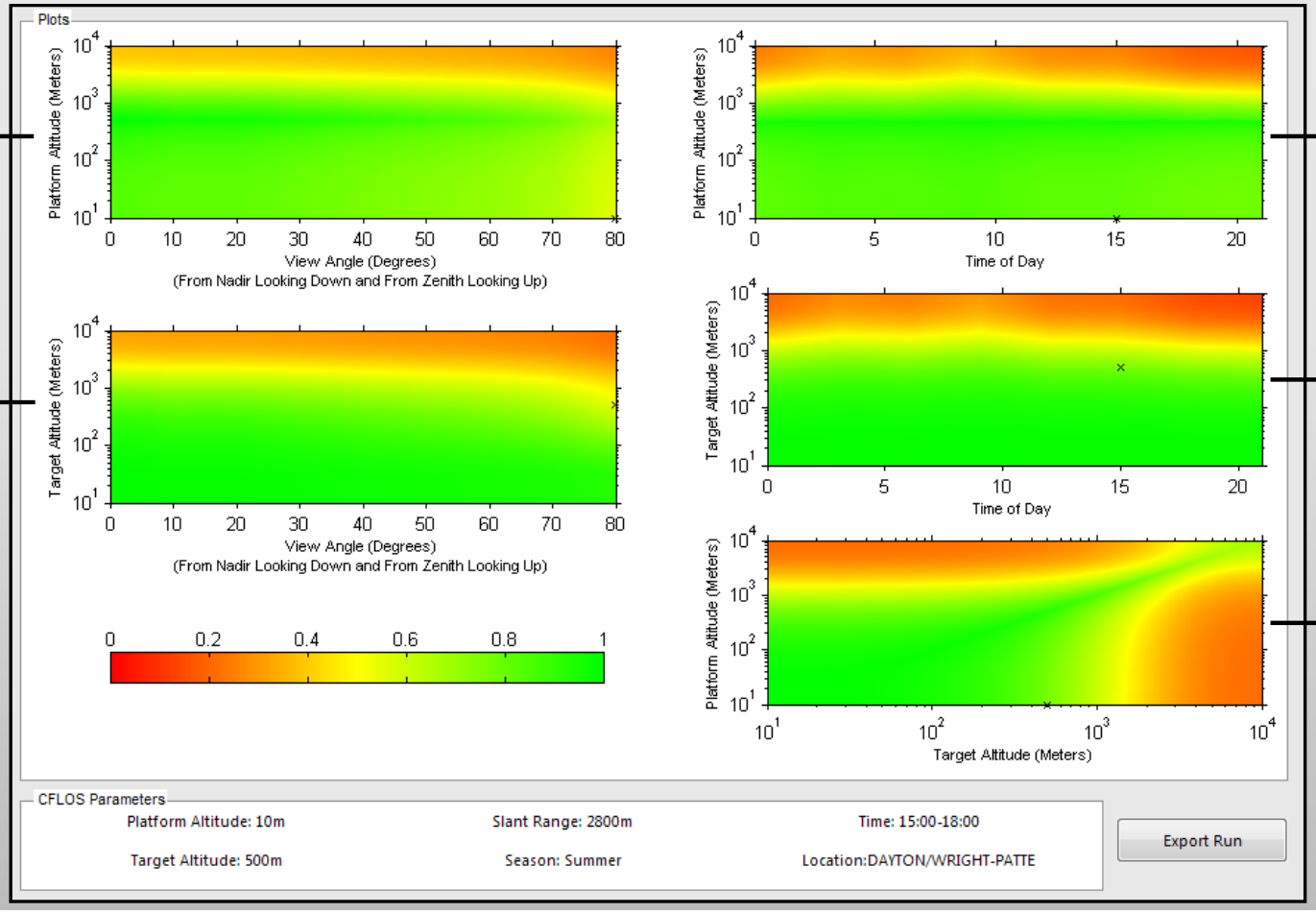
LEEDR CFLOS Output

Based on the USAF 14th Weather Squadron CFLOS Tables

WPAFB at 1500-1800 Local (Summer Season)

Platform vs View Angle

Target vs View Angle



Platform vs Time of Day

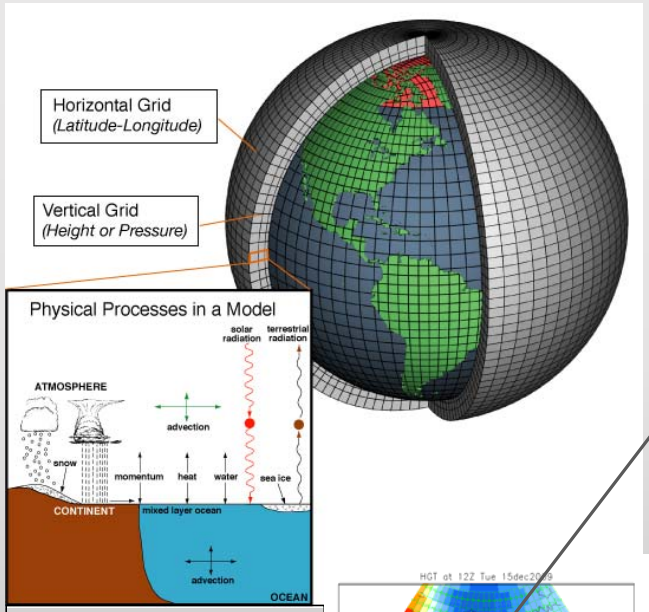
Target vs Time of Day

Platform vs Target

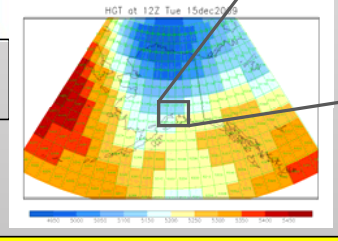
Scenario
Platform = 10m
Target = 500m
Slant Range = 2.8km

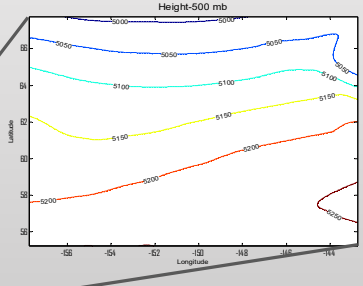
Numerical Weather Prediction (NWP) Models

Gridded Atmospheric Analysis and Forecast



NOAA Website [Online]
http://celebrating200years.noaa.gov
/breakthroughs/climate_model/





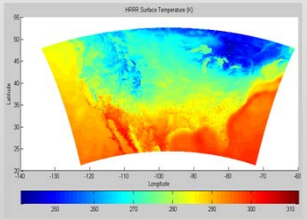
LEEDR primarily ingests Global Forecast System (GFS)

- **Global 3-D gridded data available with 0.50 and 0.25 degree horizontal resolution, 3-hour temporal resolution**
- **Easy data access (e.g. NOMADS)**
- **10+ years of available data**
- **Ops sensitivities negated with global file**

MESOSCALE MODELS

High Resolution Rapid Refresh (HRRR)

Weather Research & Forecasting (WRF)



Global Air-Land Weather Exploitation Model (GALWEM)

Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS)

Historical, Diagnostic and Forecasting Tool
Anywhere, Anytime

Weather Cubes

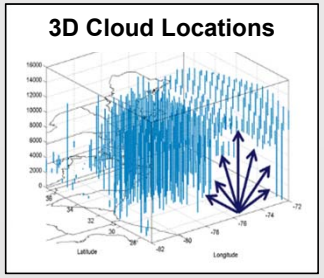
Volumetric, Analytical Weather Tool with Realistic Sky Characterizations

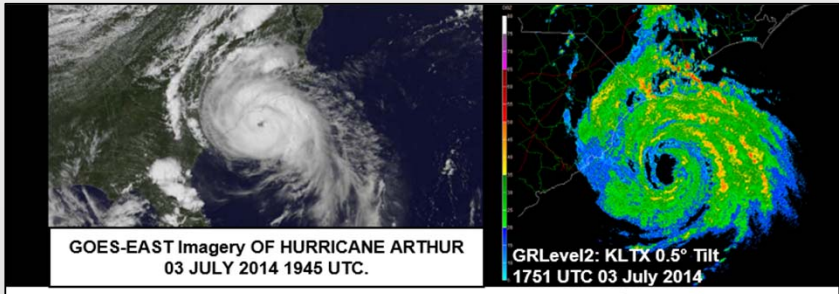
Weather Cubes are analytical, visualization, and decision aid tools which accurately convey multi-spectral (UV through RF) propagation and atmospheric effects.

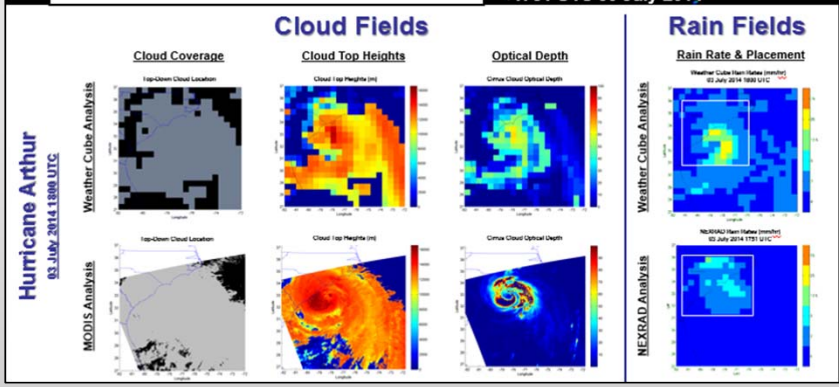
- **Anchor: V&V'd Laser Environmental Effects Definition and Reference (LEEDR) tool**
  - **Incorporates probabilistic climatology and NOAA global-gridded Numerical Weather Prediction (NWP) data for forensic, nowcast and forecast analyses**
- **Blends first principles atmospheric processes and constituent (e.g. droplets, aerosols) microphysical / optical properties to characterize optical turbulence, clouds, rain, and aerosol radiative effects**
- **Realistic sky characterizations – cloud and precipitation layers**

Cloud Types

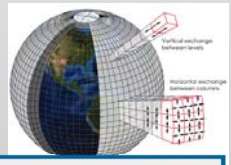
- Fog
- Cumulus
- Stratus
- Mixed-Phase
- Cirrus





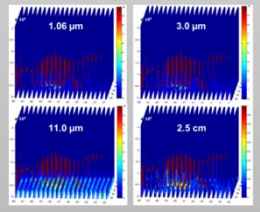


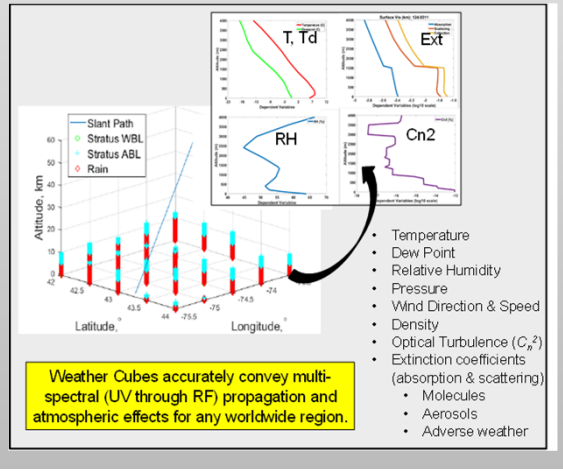
NWP



LEEDR

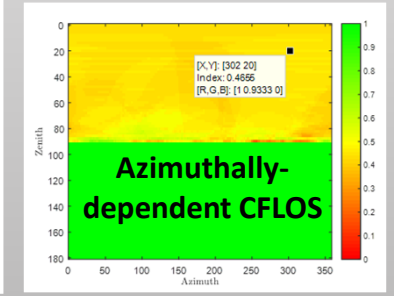
Characterizes effects from 200 nm to 8.6 meters





- Temperature
- Dew Point
- Relative Humidity
- Pressure
- Wind Direction & Speed
- Density
- Optical Turbulence (C_n^2)
- Extinction coefficients (absorption & scattering)
  - Molecules
  - Aerosols
  - Adverse weather

Weather Cubes accurately convey multi-spectral (UV through RF) propagation and atmospheric effects for any worldwide region.



MISSION IMPACT

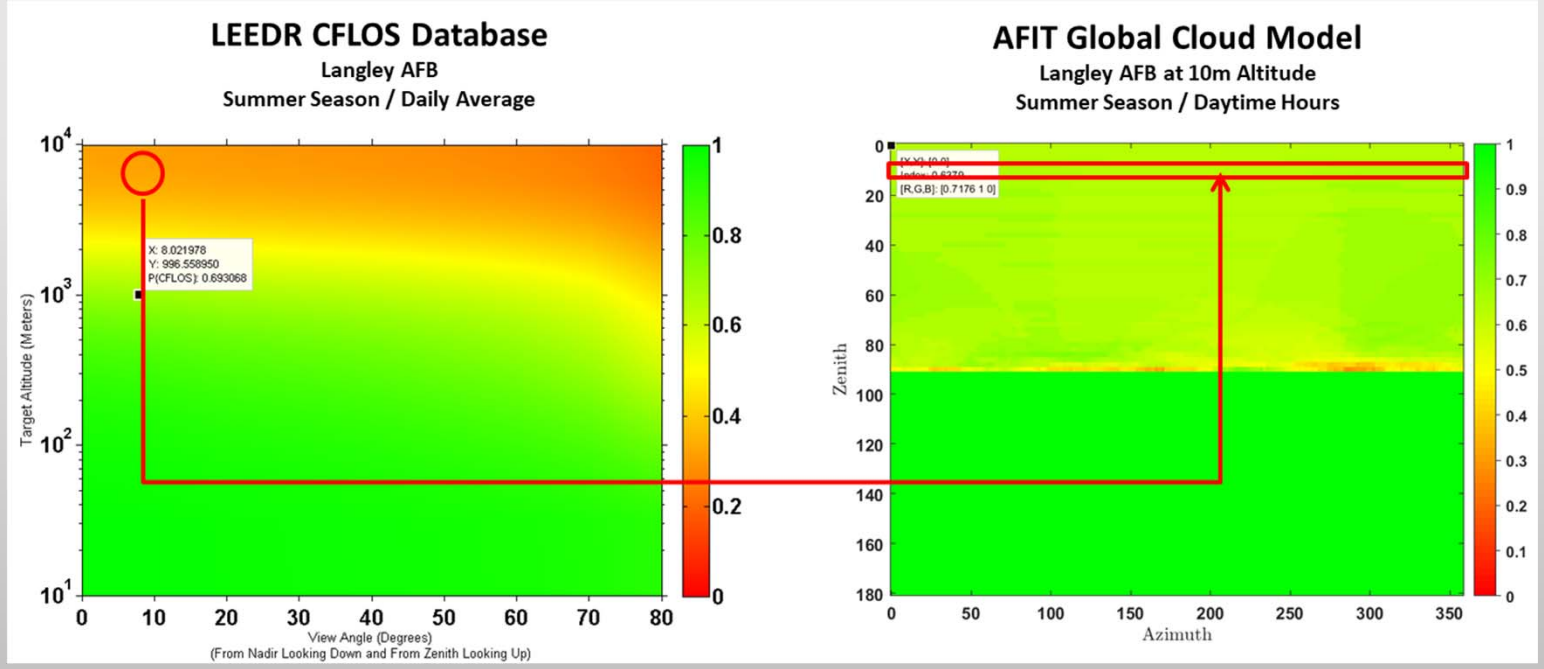
CFLOS climatology can be developed using physics-based cloud placement algorithm for use by remote sensing, Communication, Military and DoD applications.

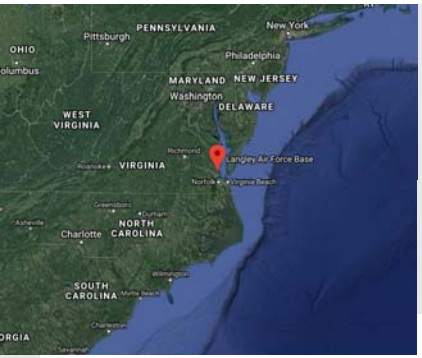
AFIT Global NWP Cloud Model

Utilizing NWP Cloud Model for 10+ years of NWP data can generate new CFLOS climatologies for any location world-wide, any time of day, any view angle, and considering azimuthal variations.

The Global NWP Cloud model fills the limitation gaps of current CFLOS databases:

- **CFLOS for any worldwide site**
- **View angles not limited to 80 zenith**
- **Azimuthally-dependent analysis**
- **Elevation variations captured**
- **Temporal and seasonal variations**



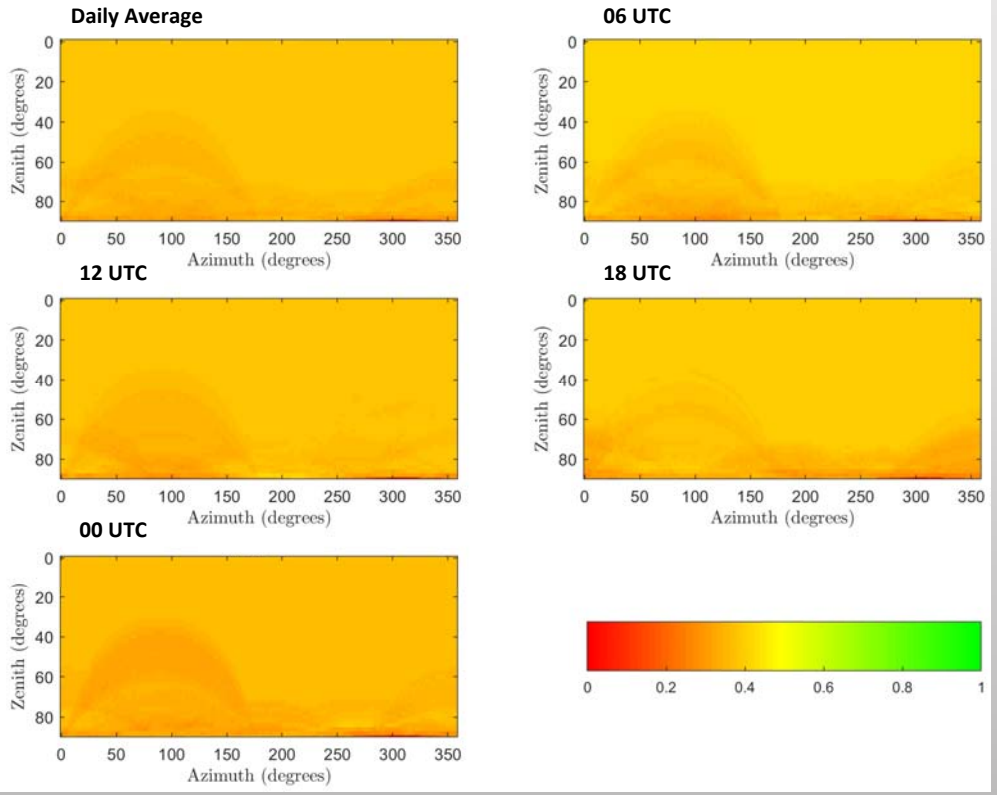


AFIT Global NWP Cloud Model

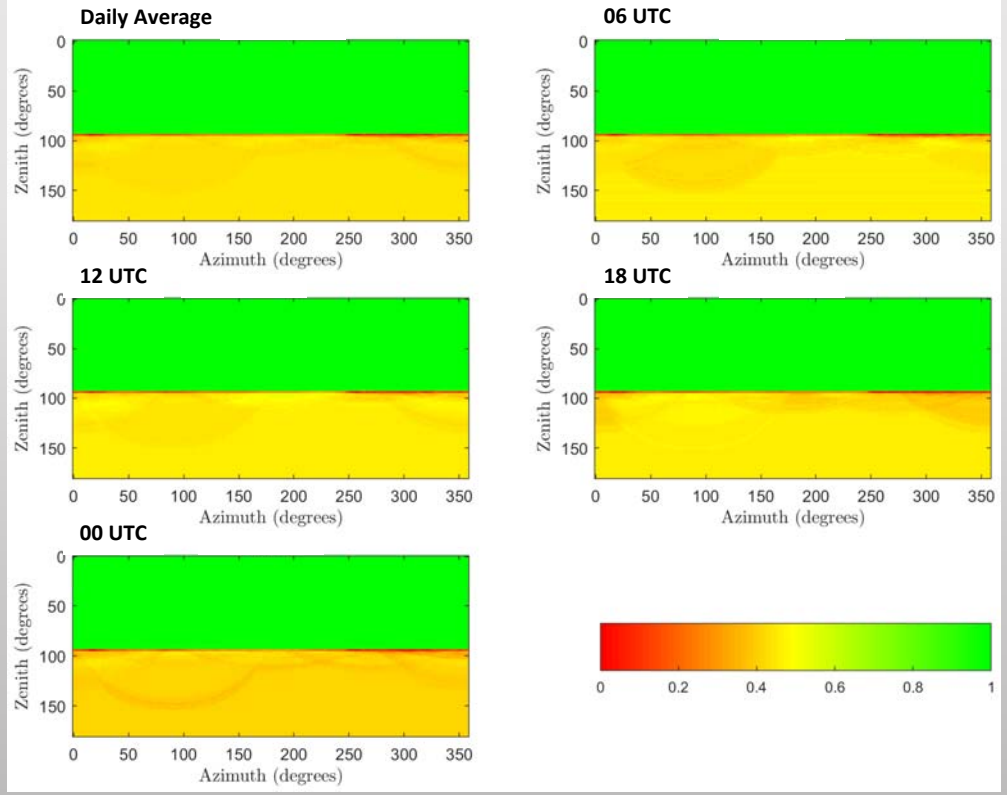
Joint Base Langley-Eustis, VA
2014-2017 GFS

AFIT
AIR FORCE INSTITUTE OF TECHNOLOGY

0m Altitude



20,000m Altitude



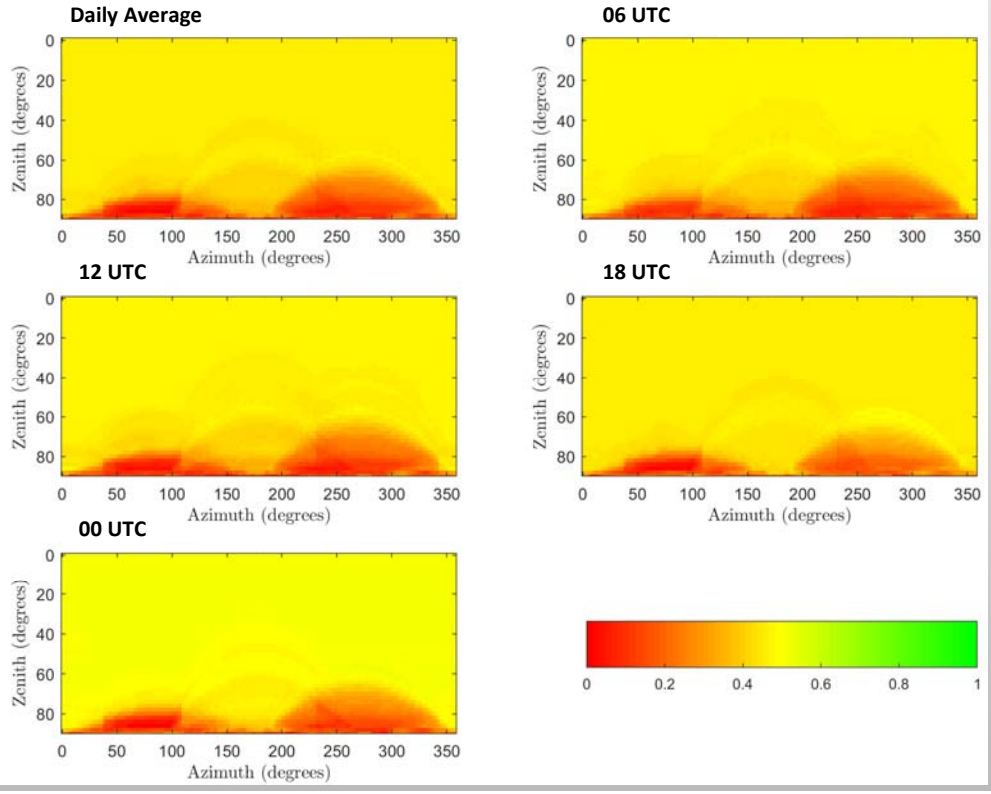
AFIT Global NWP Cloud Model

Holloman Air Force Base, NM

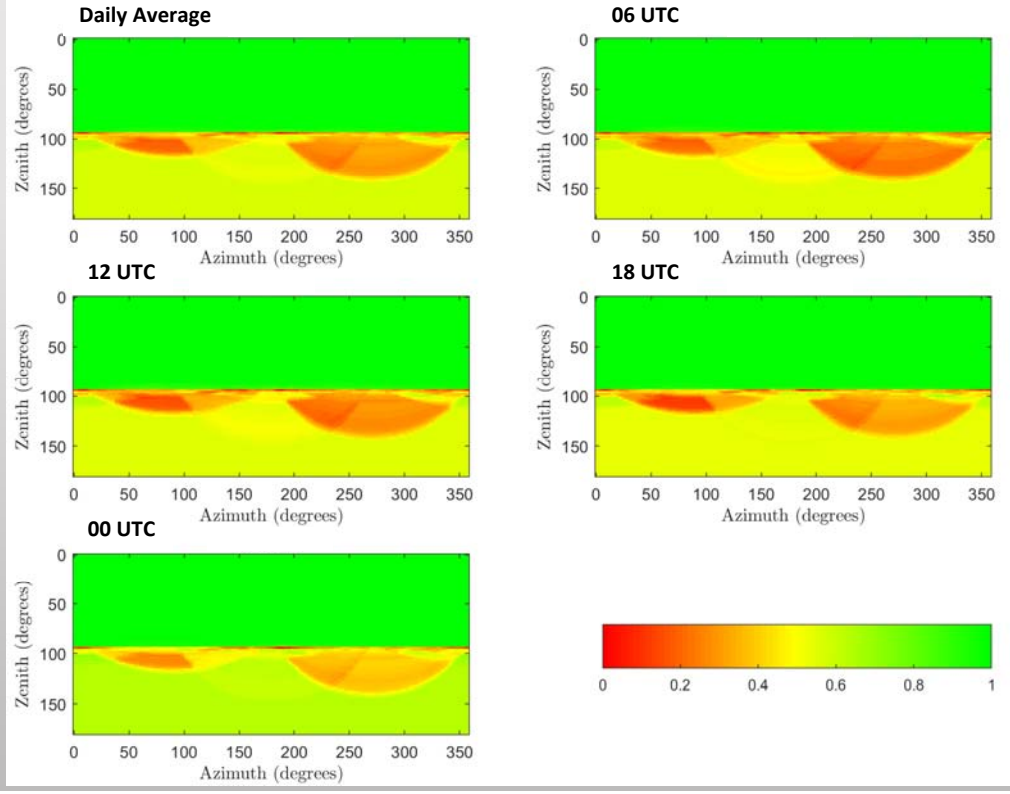
2014-2017 GFS

AFIT
AIR FORCE INSTITUTE OF TECHNOLOGY

0m Altitude



20,000m Altitude

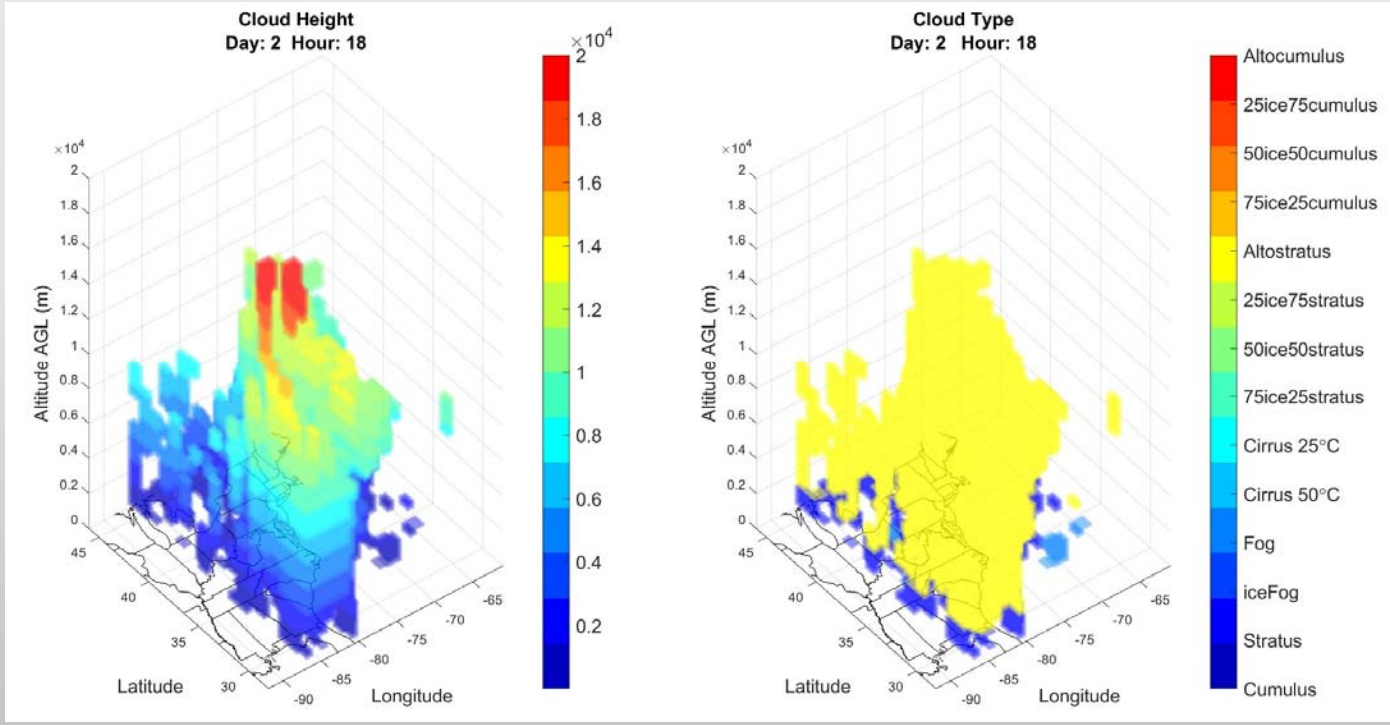


AFIT Global NWP Cloud Model

3D Cloud Analysis for Joint Base Langley-Eustis
2 December 2017 at 1800 UTC (1400 EST)

The Global NWP Cloud model also yields a 3D evaluation of GFS-inferred cloud layers. This analysis displays cloud bases, heights, and types.

- The figures to the right show regional cloud fields for Joint Base Langley-Eustis
- 2 December 2017 at 1800 UTC (1400 EST).



Summary

A Global NWP Cloud Model has been developed by the Air Force Institute of Technology's Center for Directed Energy (AFIT CDE) to generate new CFLOS climatologies for any location world-wide, any time of day, any view angle, and considering azimuthal and elevation variations.

Preliminary CFLOS results are available for 2013-2017 Global Forecast System data

The advantages of the Global NWP Cloud model include:

- CFLOS for any worldwide site
- View angles not limited to 80 zenith
- Azimuthally-dependent analysis
- Includes seasonal, temporal, and geometry variations

Future research includes:

- Expand analysis to include 10+ years of GFS data
- Migrate Global NWP Cloud model to the HPC environment
  - Develop global CFLOS climatology
  - Enhance model to include path-specific CFLOS probabilities
  - Integrate other cloud sources (e.g. AFW's WWMCA) into CFLOS analysis

AMERICAN METEOROLOGICAL SOCIETY
100th Annual Meeting 12 - 16 January 2020
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Air Force Institute of Technology
Center for Directed Energy
Wright-Patterson AFB, Ohio

Global Cloud Free Line of Sight (CFLOS) Characterizations Using Numerical Weather Prediction Data

J. E. Schmidt[1,2], J. L. Burley[1], B. A. Fourman[1,2], and S. T. Fiorino[1]
AFIT Department of Engineering Physics
Jaclyn.Schmidt.ctr@afit.edu Jarred.L.Burley.mil@mail.mil
Fourman.21@buckeyemail@osu.edu Steven.Fiorino@afit.edu

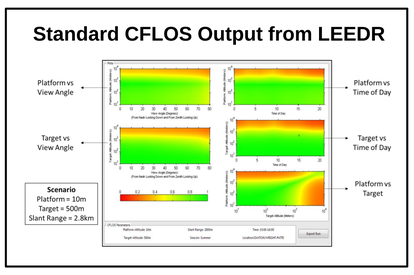
The ability to predict cloud-free line-of-sight (CFLOS) continues to be a critically important parameter for Department of Defense operations and remote sensing applications. Current CFLOS climatologies are available for a limited number of worldwide sites, providing ground-to-space probabilities that do not account for elevation and azimuthal variations. The Air Force Institute of Technology's Center for Directed Energy (AFIT/CDE) has developed a robust simulation technique leveraging years' worth of numerical weather prediction (NWP) model data and AFIT/CDE's realistic sky characterization algorithms to define NWP-inferred cloud and precipitation layers of various types. The resulting analysis yields CFLOS probabilities for any worldwide location, including littoral and over-ocean sites. Recent optimizations can quickly evaluate 10 years of NWP data and generate new CFLOS climatologies for various worldwide locations, times of day, and view angles considering azimuthal variations.

Motivation:

- **Cloud Free Line of Sight (CFLOS) is a direct line of sight that is not hindered by clouds.**
- **Current CFLOS databases are based on ground-to-space CFLOS & cloud ceiling tables available from the 14th Weather Squadron**
- **CFLOS climatologies are accessible in AFIT's atmospheric characterization and radiative transfer code, called the Laser Environmental Effects Definition and Reference (LEEDR)**
- **Limitations with the CFLOS climatologies include:**
  - **CFLOS only represent ground-to-space probabilities**
  - **Available data for 415 sites worldwide**
  - **Assumes a homogenous distribution of clouds (not azimuthally dependent)**

LEEDR Laser Environmental Effects Definition And Reference
V&V'd Atmospheric Effects and Radiative Transfer Code – UV to RF (200nm to 8.6m)

Standard CFLOS Output from LEEDR



Methodology

Leverage years' worth of NWP data and Weather Cube cloud characterization algorithms to develop new CFLOS climatologies for any location world-wide, any time of day, any view angle, and considering azimuthal variations.

Global Forecast System (GFS) data is used for this study. Cloud fields are generated using up to 10 years' worth of GFS data, analyzed 4 times/day (00, 06, 12, 18 UTC) → yielding thousands of sky characterizations.

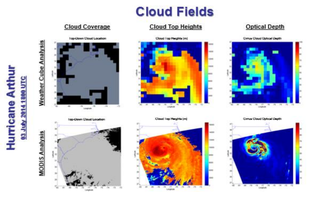
Atmospheric Layer	Relative Humidity	Vertical Velocity (ω)	Wind Speed	Cloud Base	Temperature	Cloud Type	Phase	LEEDR Characterization (% of ORNC # Concentrations, α)
Within Boundary Layer	≥ 100%	Upper Limit: 0 Pa/s Lower Limit: -0.12 Pa/s	< 2.5 m/s (<5 kts)	= 0 m AGL	T ≤ 0 C	Ice Fog	Ice	Ice Fog
					T > 0 C	Fog	Liquid	Fog
	≥ 90%	Upper Limit: -0.12 Pa/s Lower Limit: -5.99 Pa/s	-	> 0 m AGL	T > 0 C	Stratus	Liquid	Stratus
	≥ 90%	Upper Limit: -6.0 Pa/s Lower Limit: - Infinity Pa/s	-	> 0 m AGL	-	Cumulus	Liquid	Cumulus
Above Boundary Layer	≥ 70%	Upper Limit: -0.12 Pa/s Lower Limit: -5.99 Pa/s	-	> 6000 m	T < -40 C	Cirrus	Ice	Cirrus (-25C) when T > -50C Cirrus (-50C) when T ≤ -50C
	≥ 70%	Upper Limit: -0.12 Pa/s Lower Limit: -5.99 Pa/s	-	-	-30 ≥ T > -40 C	Stratus	Mixed Phase	75% Ice Fog 25% Stratus
					-20 ≥ T > -30 C	Stratus	Mixed Phase	50% Ice Fog 50% Stratus
					-10 ≥ T > -20 C	Stratus	Mixed Phase	25% Ice Fog 75% Stratus
					T > -10 C	Stratus	Liquid	Stratus
	≥ 70%	Upper Limit: -6.0 Pa/s Lower Limit: - Infinity Pa/s	-	-	-30 ≥ T > -40 C	Cumulus	Mixed Phase	75% Ice Fog 25% Cumulus
					-20 ≥ T > -30 C	Cumulus	Mixed Phase	50% Ice Fog 50% Cumulus
					-10 ≥ T > -20 C	Cumulus	Mixed Phase	25% Ice Fog 75% Cumulus
					T > -10 C	Cumulus	Liquid	Cumulus

Table 1. Weather Cube Cloud Algorithm

GFS does not explicitly model cloud layers, but rather infers them. Weather Cube cloud algorithms produce random cloud fields to generate more realistic atmospheric characterizations. These NWP-inferred cloud are based on the following NWP outputs: (1) Relative Humidity, (2) Vertical Velocity, and (3) Temperature.

The following clouds are considered:
- Cumulus
- Stratus
- Mixed-phase clouds
- Cirrus


GOES-EAST Imagery OF HURRICANE ARTHUR 03 JULY 2014 1945 UTC.

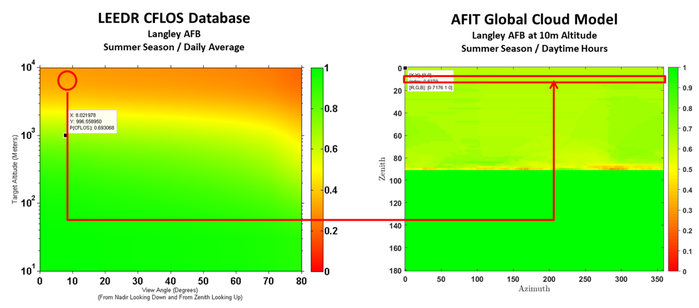


Monte Carlo simulations are used to generate CFLOS statistics, considering every possible line of sight for zenith (1-degree resolution) and azimuth (2-degree resolution) combination. A vertical resolution of 100 meters along these lines is used, and elevation and azimuthal variations are included in the model output. CFLOS probabilities are determined by whether or not a cloud has been encountered along the line of sight for as far as the eye can see (i.e. no regional boundaries implemented).

Interrogating up to 10 years of GFS data requires code optimizations. The CFLOS scripts are parallelized to reduce calculation runtimes down significantly. Additionally, cluster computing is utilized. Calculations are divided between three cluster machines, runtimes are approximately 3 wall-clock hours per year.

Model Advancements

The Global NWP Cloud model fills the limitation gaps of current CFLOS databases:
- CFLOS for any worldwide site
- View angles not limited to 80 zenith
- Azimuthally-dependent analysis
- Includes seasonal, temporal, and geometry variations



MISSION IMPACT
CFLOS climatology can be developed using physics-based cloud placement algorithm for any location world-wide, any time of day, any view angle, and considering azimuthal variations. This model directly benefits the Remote Sensing community, Free Space Optical (FSO) communications, Military and DoD applications.

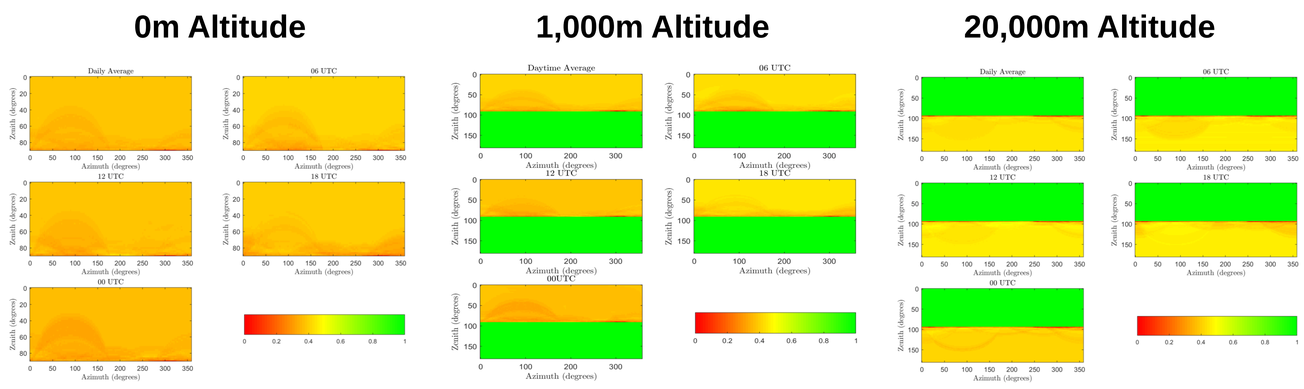
A special thanks to the DoD Directed Energy Joint Transition Office for funding support

[1]Air Force Institute of Technology
[2]Applied Research Solutions, Inc.

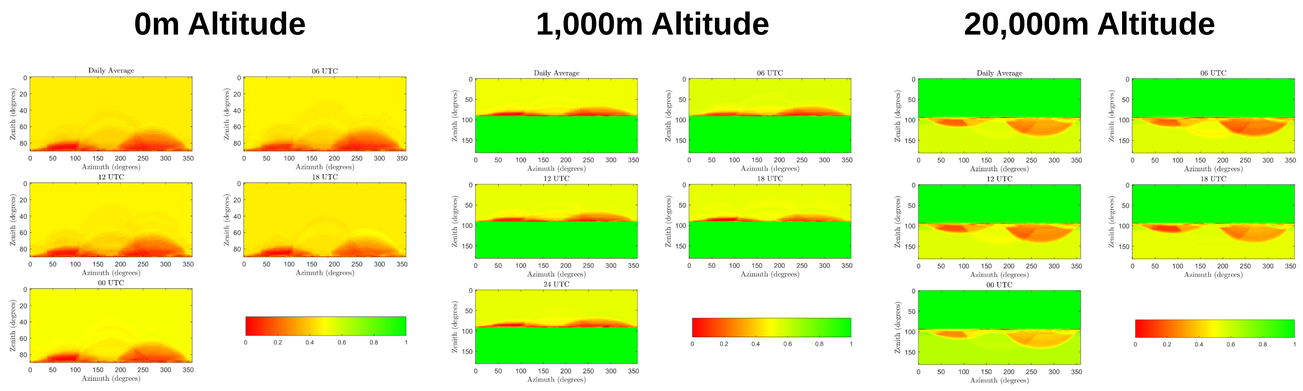
Global NWP Cloud Model

Two-dimensional analysis using 2014-2017 GFS data is shown for two different locations and thus climates: Joint Base Langley-Eustis, VA and Holloman Air Force Base, NM. CFLOS probability data is displayed for surface (0m), 1km, and 20km altitudes and for five times of day (daily average; 00, 06, 12, and 18 UTC). Temporal and azimuthal variations in clouds are evident.

Joint Base Langley-Eustis, VA



Holloman Air Force Base, NM

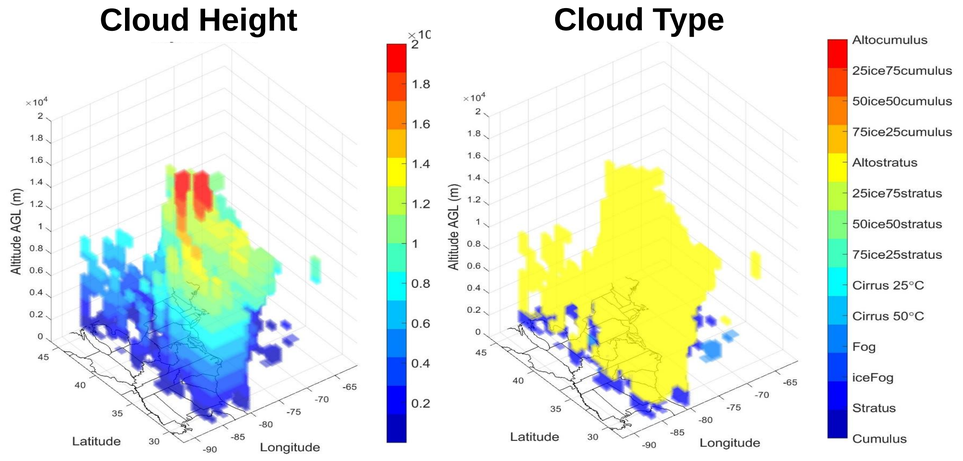


3D Analysis: Cloud Heights & Types

2 December 2017 1800 UTC

The Global NWP Cloud model also yields a 3D evaluation of GFS-inferred cloud layers. This analysis displays cloud bases, heights, and types.

The figures to the right show regional cloud fields for Joint Base Langley-Eustis on 2 December 2017 at 1800 UTC (1400 EST).



Future Research:

- Expand analysis to include 10+ years of GFS data and other worldwide sites
- Migrate Global NWP Cloud model to the HPC environment
  - Develop global CFLOS climatology
  - Enhance model to include path-specific CFLOS probabilities