AI-Enabled Aviation Weather Decision Support Systems

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ATC & Weather Systems Group Overview

Mission: Develop and deploy advanced weather sensing, forecasting and decision support technologies to enable safe, efficient and cyber-secure air transportation

ATC Decision Support

Weather Sensing & Forecasting

Aviation Cybersecurity

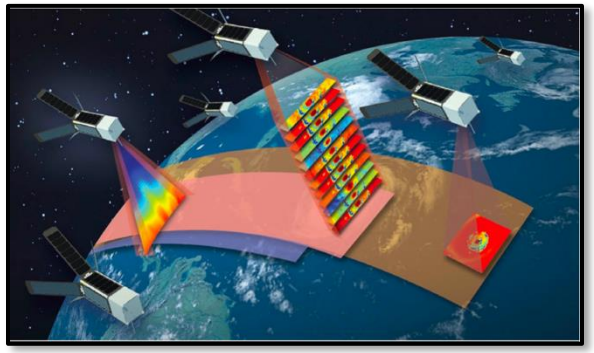
Key Capabilities

- **Multi Modal Sensing and Data Fusion**
- **Systems Analysis**
- **Software Prototyping**
- **Artificial Intelligence and Machine Learning**
- **Deep and Broad Domain Expertise**

ATC = Air Traffic Control

Lincoln Efforts in AI & Weather

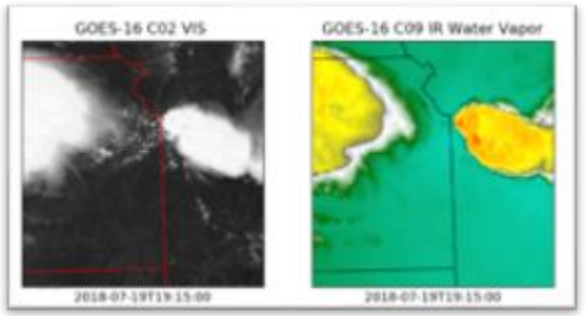
Data → **Modeling** → **Decision Support**



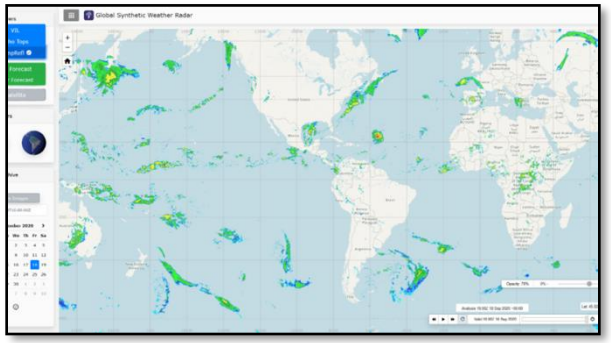
Advanced Sensing

Severe Storm Forecasting

Contrail Prediction



Benchmark Datasets for AI



Synthetic Radar Analyses

Weather Translation

AI = Artificial Intelligence
ML = Machine Learning

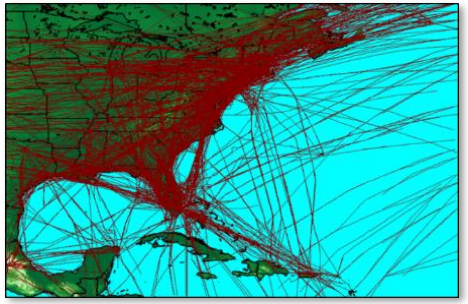
Outline

- Group Overview
- Synthetic Weather Radar
- Traffic Flow Impact
- Summary

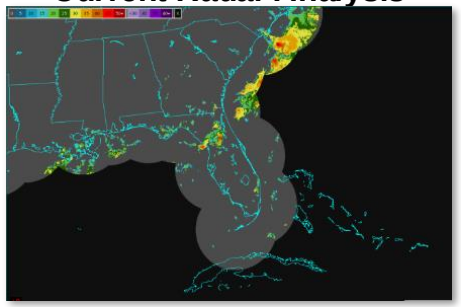
The Need for *Synthetic* Weather Radar

FAA

Domestic Jet Routes

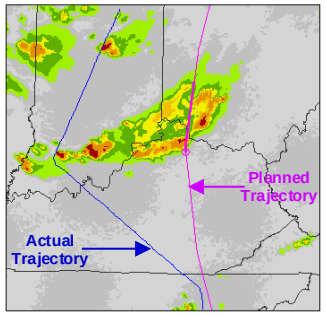


Current Radar Analysis



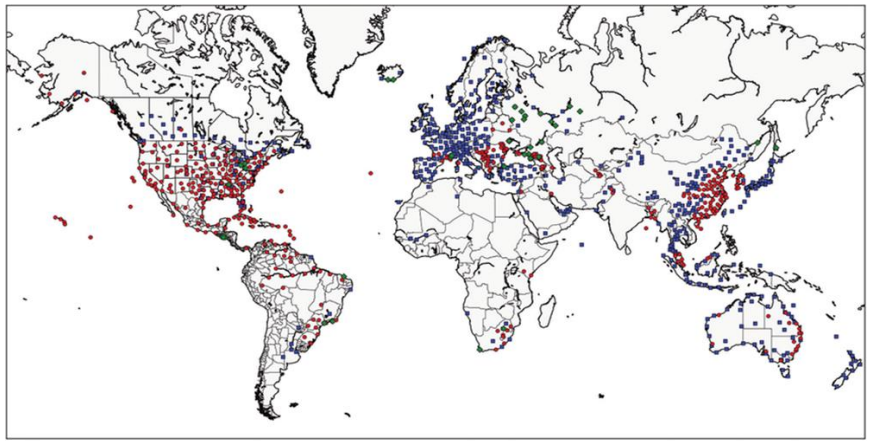
- **Piloted aircraft need to avoid hazardous weather for safety reasons**
- **Air Traffic Controllers lack sufficient weather radar coverage in offshore areas of the National Airspace System**
- **Controllers are unable to provide timely and accurate weather information to pilots in these regions**

Weather Avoidance



MITLL Solution:
Offshore Precipitation Capability (OPC)

DoD



Location of X- (green), C- (blue) and S- (red) band radars[1]

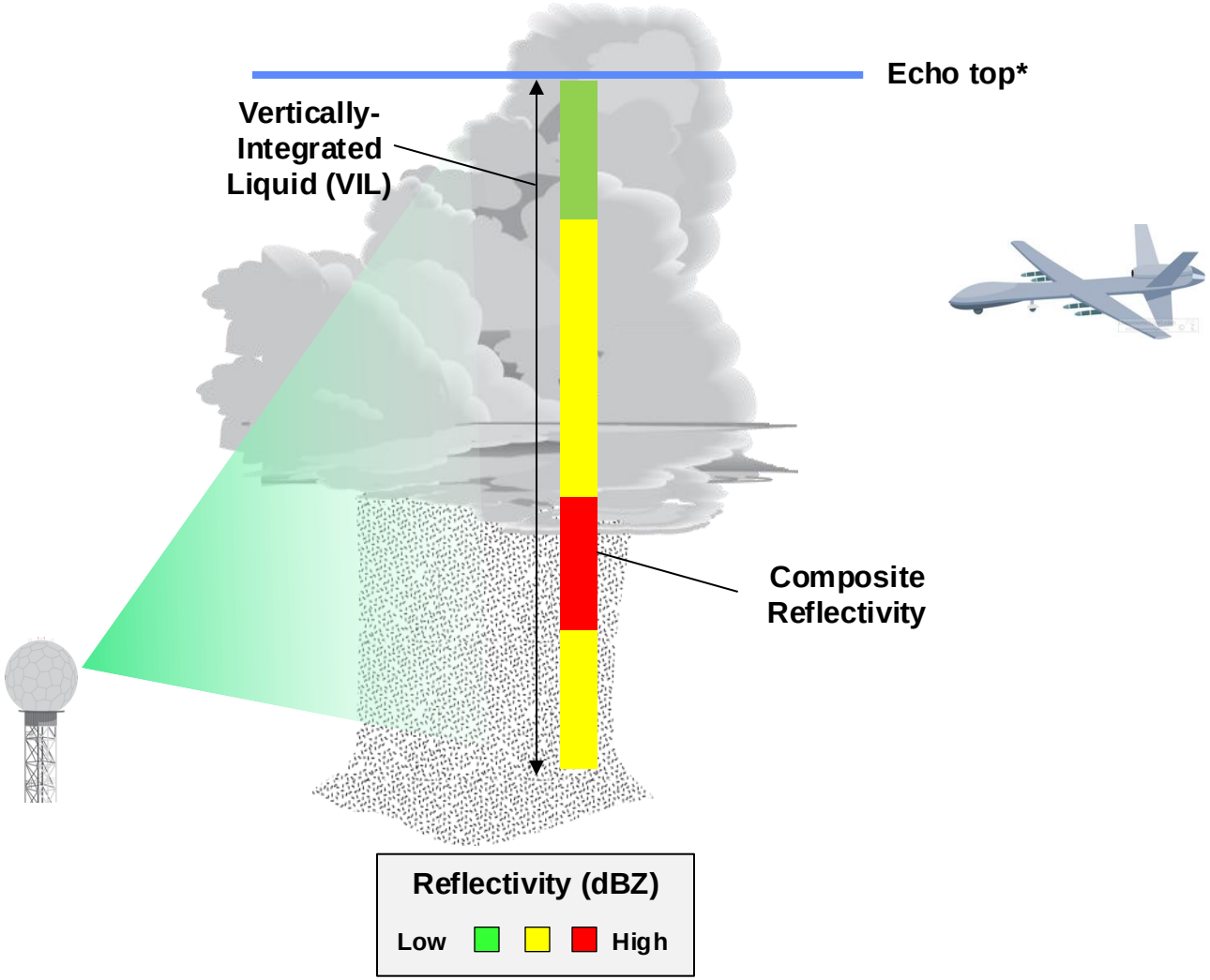
- **Weather radar information is non-existent or not accessible in many high interest areas**
- **Other forms of weather information (e.g., satellite, numerical models) may be insufficient to support operations**

MITLL Solution:
Global Synthetic Weather Radar (GSWR)

[1]Saltikoff, E., et al. "The Threat to Weather Radars by Wireless Technology, Bull. Amer. Meteor. Soc." (2015).

Key Radar Parameters for Aviation Weather Applications

- Global coverage
- 15 minute update rate
- 5 km horizontal resolution
- Three storm properties:
  - Vertically-integrated liquid
  - Composite reflectivity
  - Echo top
- Forecasts out to 12 hours



*Defined by height of 18 dBZ reflectivity

Ways to Fill the Gap

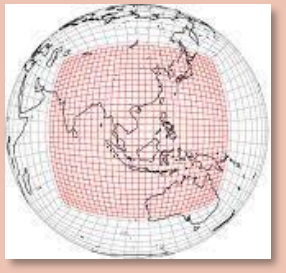
Expand Sensor Network

- Install additional surface-based sensors
- Develop and install additional remote sensors

LEO Sensors

Improve Numerical Models

- Assimilate more data
- Enhance physics and parameterizations
- Run at finer resolution



MPAR = Multi-function Phased Array Radar
LEO = Low Earth Orbit

Ways to Fill the Gap

Expand Sensor Network

- Install additional surface-based sensors
- Develop and install additional remote sensors

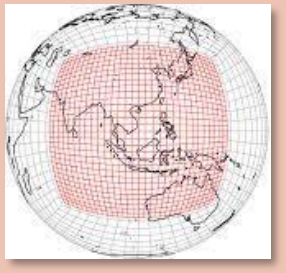
LEO Sensors

Synthetic Weather Radar

- Data fusion
- Feature recognition
- Machine learning

Improve Numerical Models

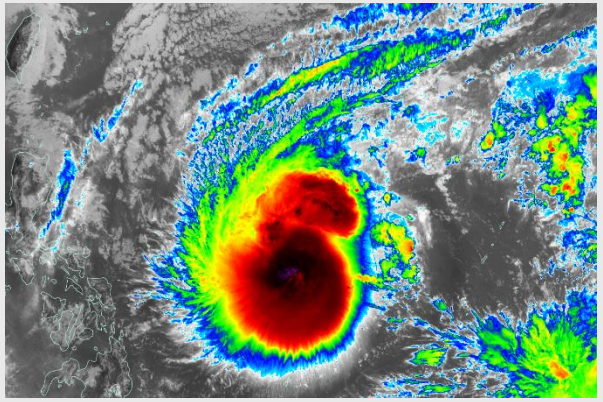
- Assimilate more data
- Enhance physics and parameterizations
- Run at finer resolution



MPAR = Multi-function Phased Array Radar
LEO = Low Earth Orbit

Selected Inputs for Synthetic Weather

Cloud Top Properties



- GOES 16 & 17
- METEOSAT 8 & 11
- Himawari 8

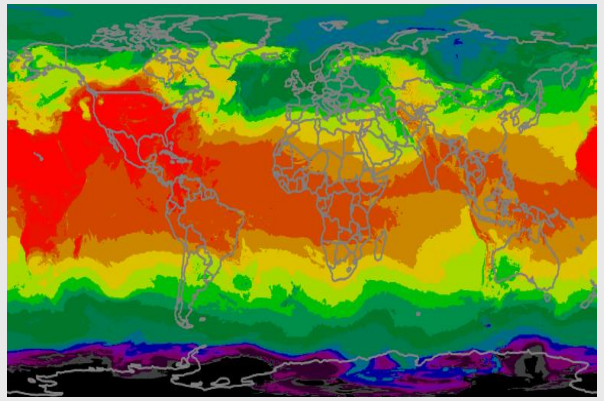
- **Coverage from 65ºN to 65ºS**
- **5-30 min update rate**

Lightning

Vaisala GLD 360
Lightning Network

- **Global strike locations**

Environment



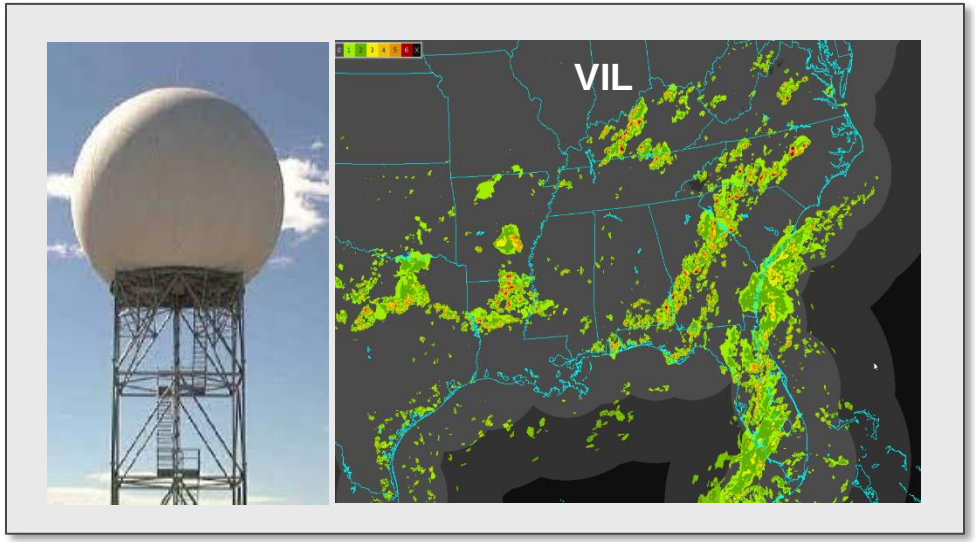
USAF GALWEM
Weather Forecasts

- **Global numerical weather model**
- **Provides temperature, moisture, winds, atmospheric instability**

GLD = Global Lightning Detection
GALWEM = Global Air-Land Weather Exploitation Model

Truth Data Sources for Synthetic Weather Radar

Ground-based Radar



- NEXRAD mosaic over US

Spaceborne Radar

- Vertical profiles of radar reflectivity
- Near-global coverage, ~3 day revisit rate

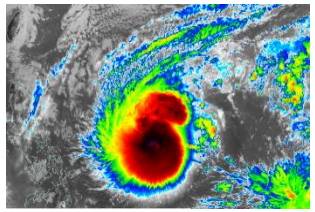
GPM = Global Precipitation Measurement Mission

Machine Learning Model Training

Supervised Learning

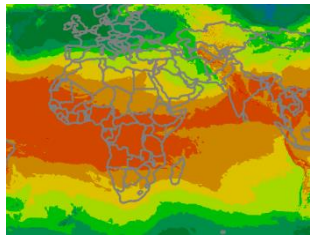
Historical Input Data

Satellite



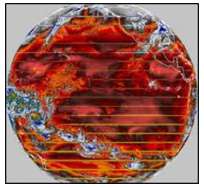
Lightning

Numerical Model

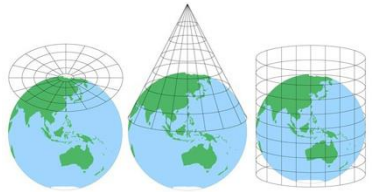


Preprocessing

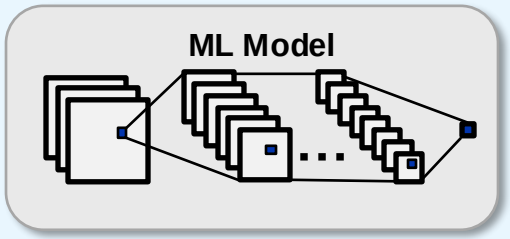
Data Quality



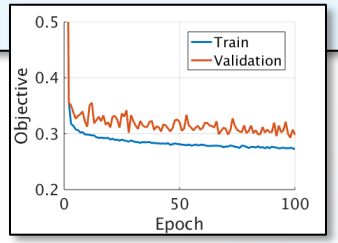
Common Projection



Training



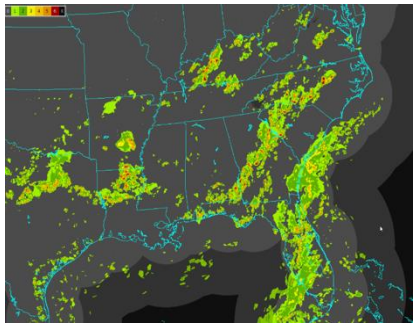
Objective



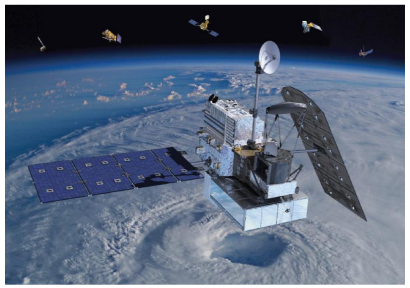
MSE Loss

Truth Data

Ground Radar



Satellite Radar

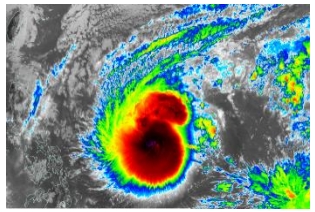


MSE = Mean-squared Error

Machine Learning Model Execution

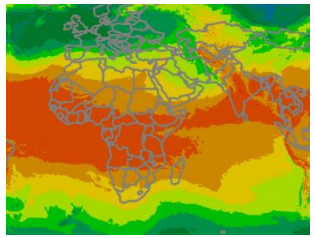
Real-time Input Data

Satellite



Lightning

Numerical Model



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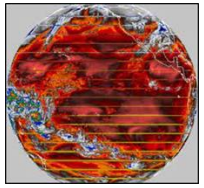

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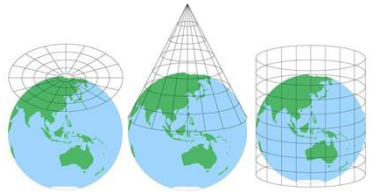
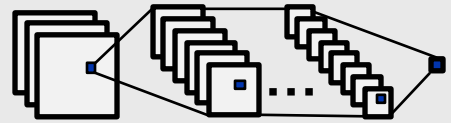


Execution

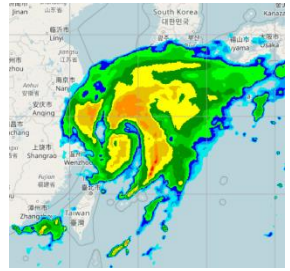
ML Model



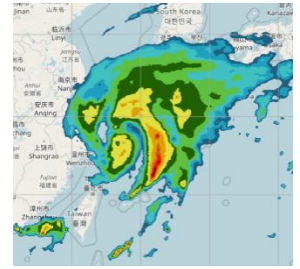
Output

Vertically-Integrated Liquid

Composite Reflectivity

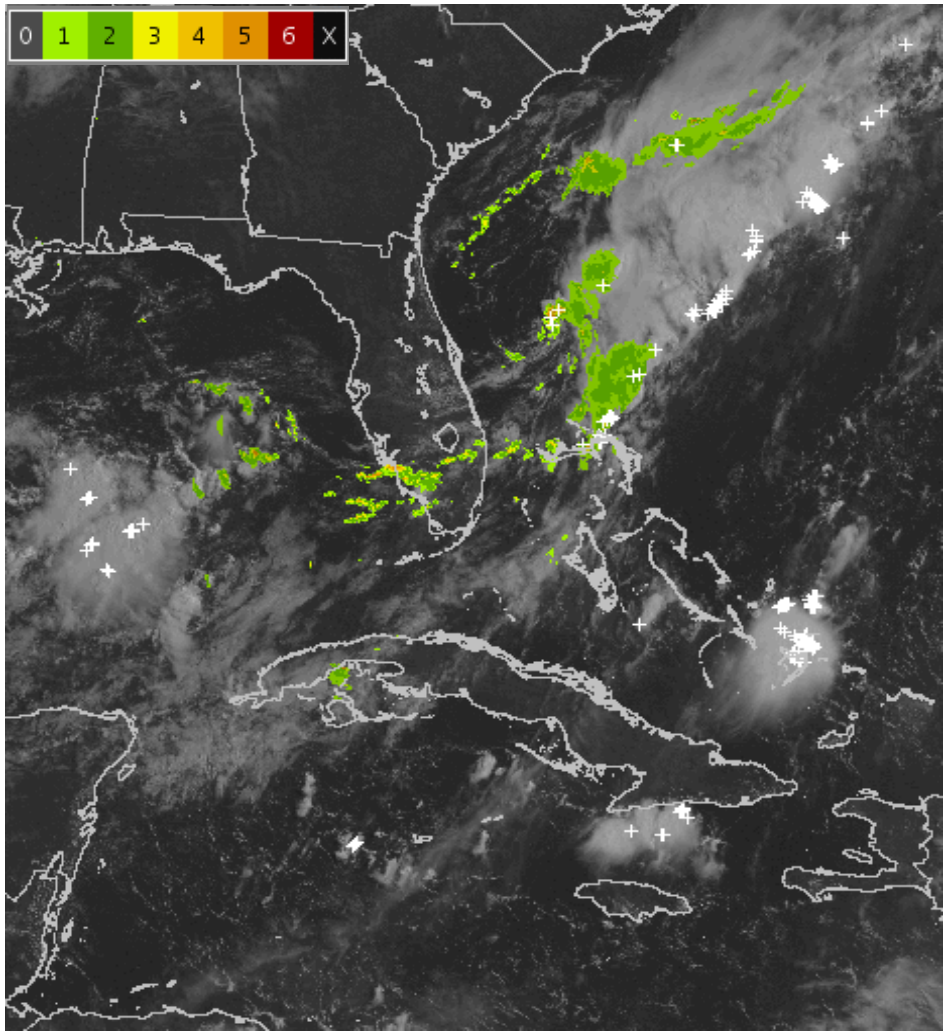


Echo Top

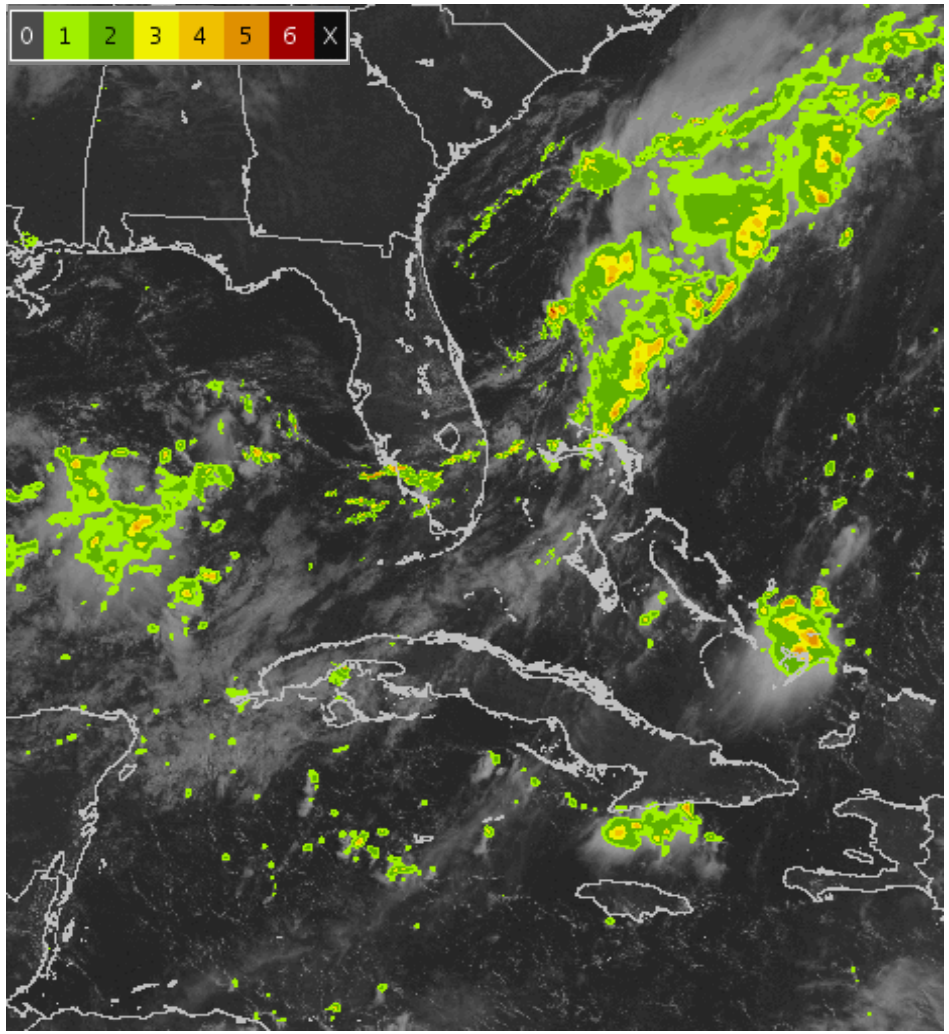


Offshore Precipitation Capability (OPC)

NEXRAD + Satellite + Lightning

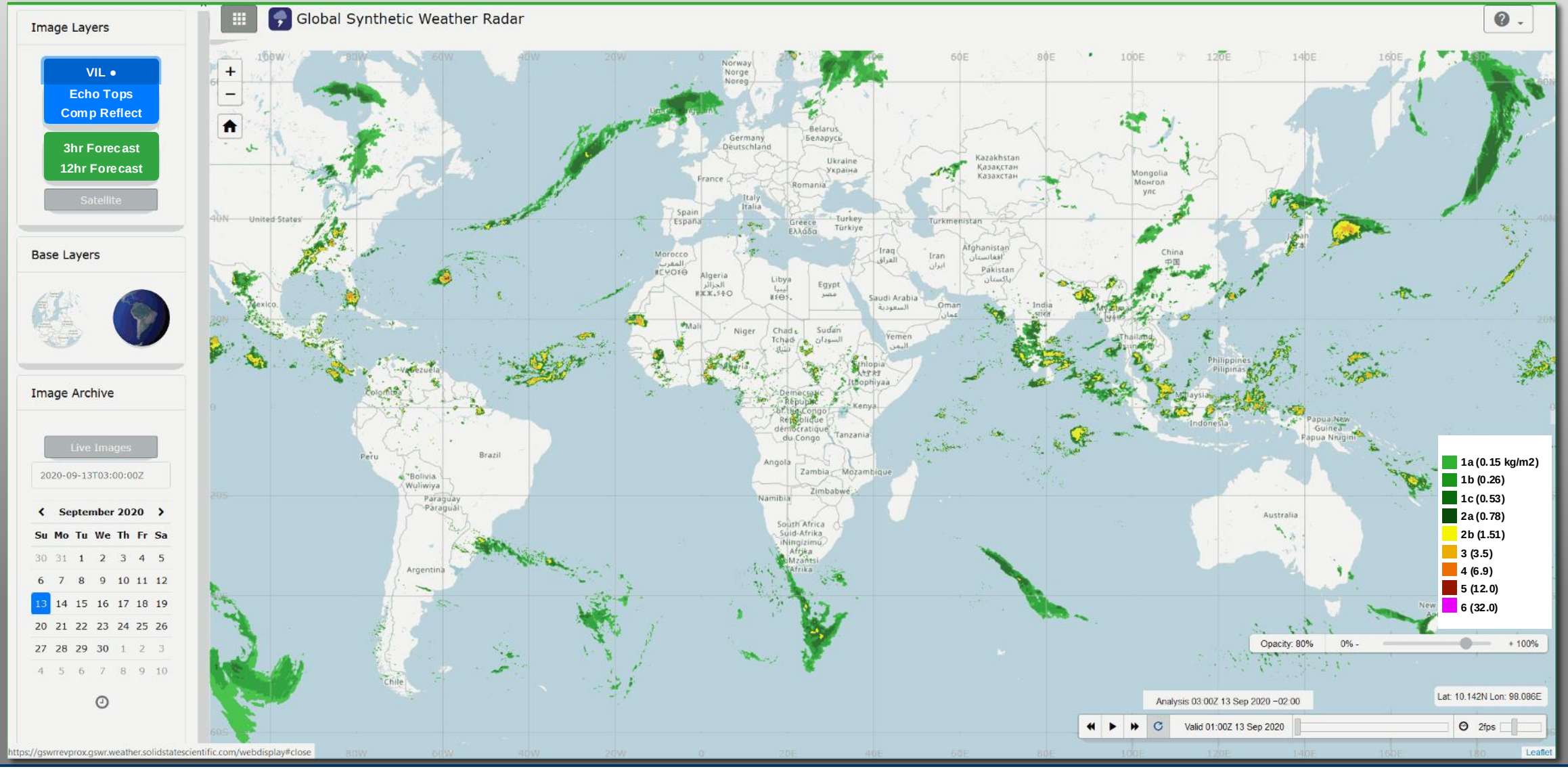


Synthetic + Satellite



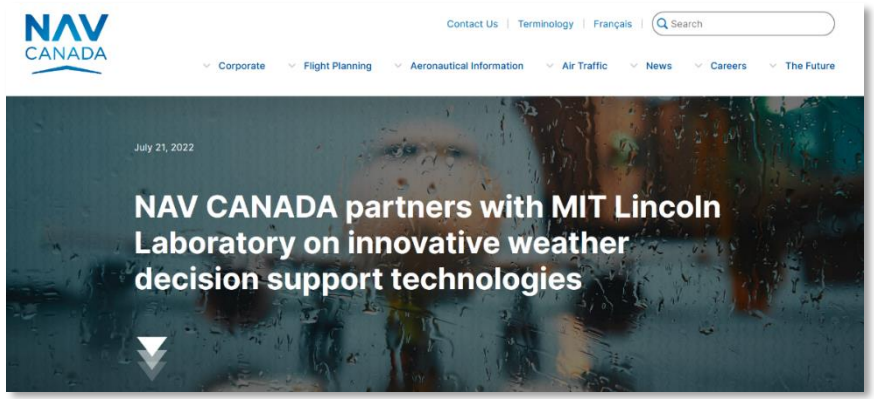
1 August 2017 1400 – 1700 UTC every 5 minutes

Global Synthetic Weather Radar (GSWR)

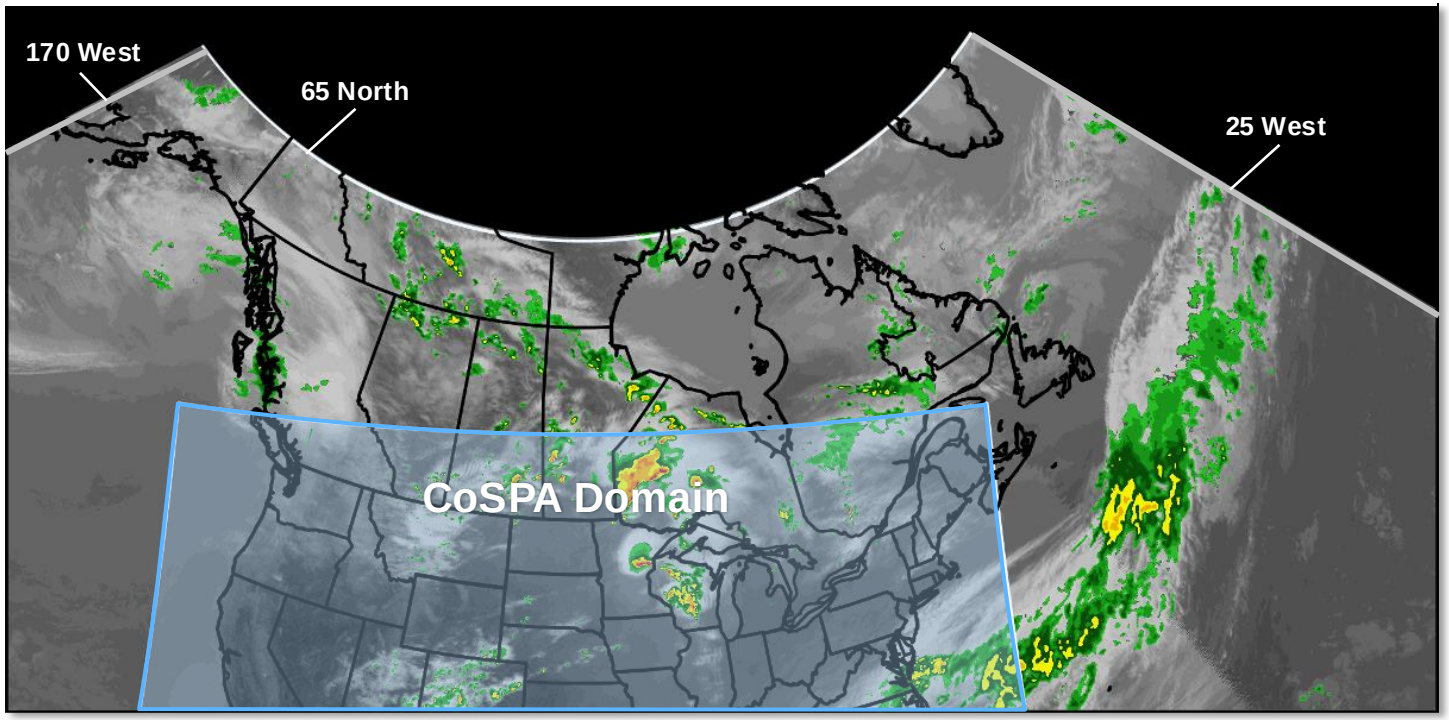


Canadian Aviation Weather System (CAWS)

- **Canadian-optimized aviation weather system providing situational awareness**
- **Builds on CIWS, CoSPA and NWP developed over many years by MIT LL for FAA**
- **Foundation for ECEPT, TCEPT and ACEPT weather impact technologies**
- **Aviation-focused nowcast and forecast products**



CAWS Domain



CIWS = Corridor Integrated Weather System
CoSPA = Consolidated Storm Prediction for Aviation

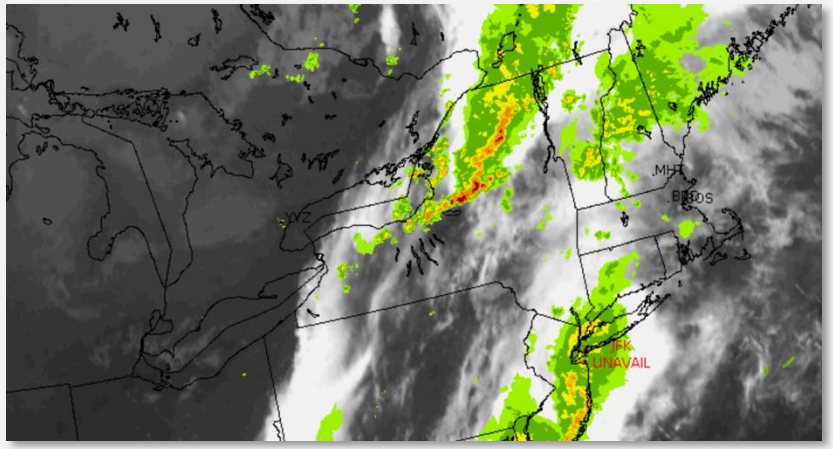
NWP = NextGen Weather Processor

Outline

- **Group Overview**
- **Synthetic Weather Radar**
- **Traffic Flow Impact**
- **Summary**

Translating Weather into Decisions

Weather Forecasting Systems



- Real-time radar mosaics and nowcasts (e.g. NextGen Weather Processor)
- Storm-scale convection-allowing models (e.g. HRRR)
- Probabilistic Forecasts (e.g. LAMP)

ATC Impact Decision Support

- Traffic Flow Impact (TFI)
- Terminal Capacity Estimation and Prediction Tool (TCEPT)
- Airport Capacity Evaluation and Prediction Tool (ACEPT)

ATC Domain

En route/ Oceanic

Terminal

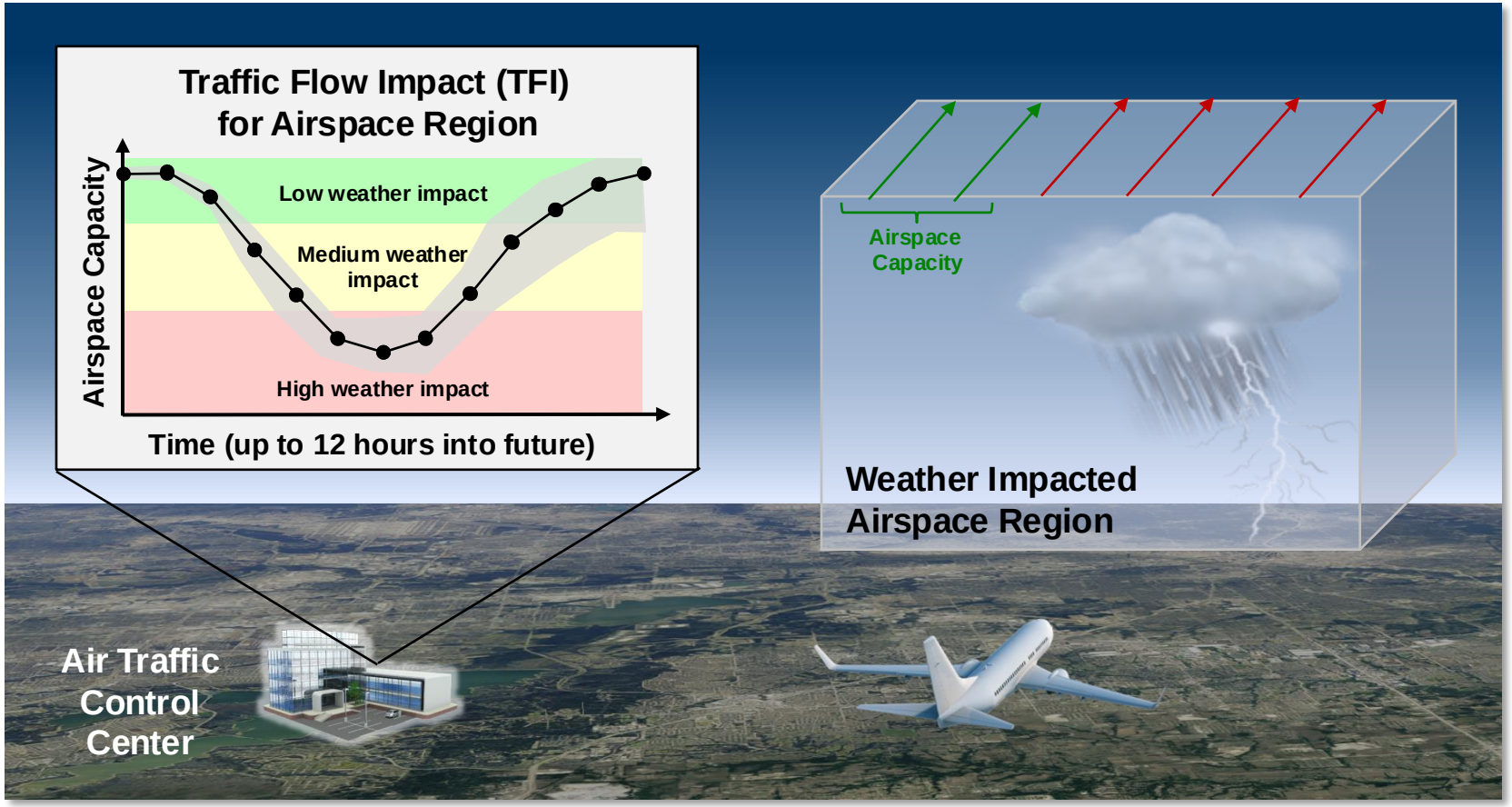
Airport

HRRR = High-Resolution Rapid Refresh
LAMP = Localized Aviation Model Output Statistics Program

Enroute Capacity Prototype: Traffic Flow Impact (TFI)

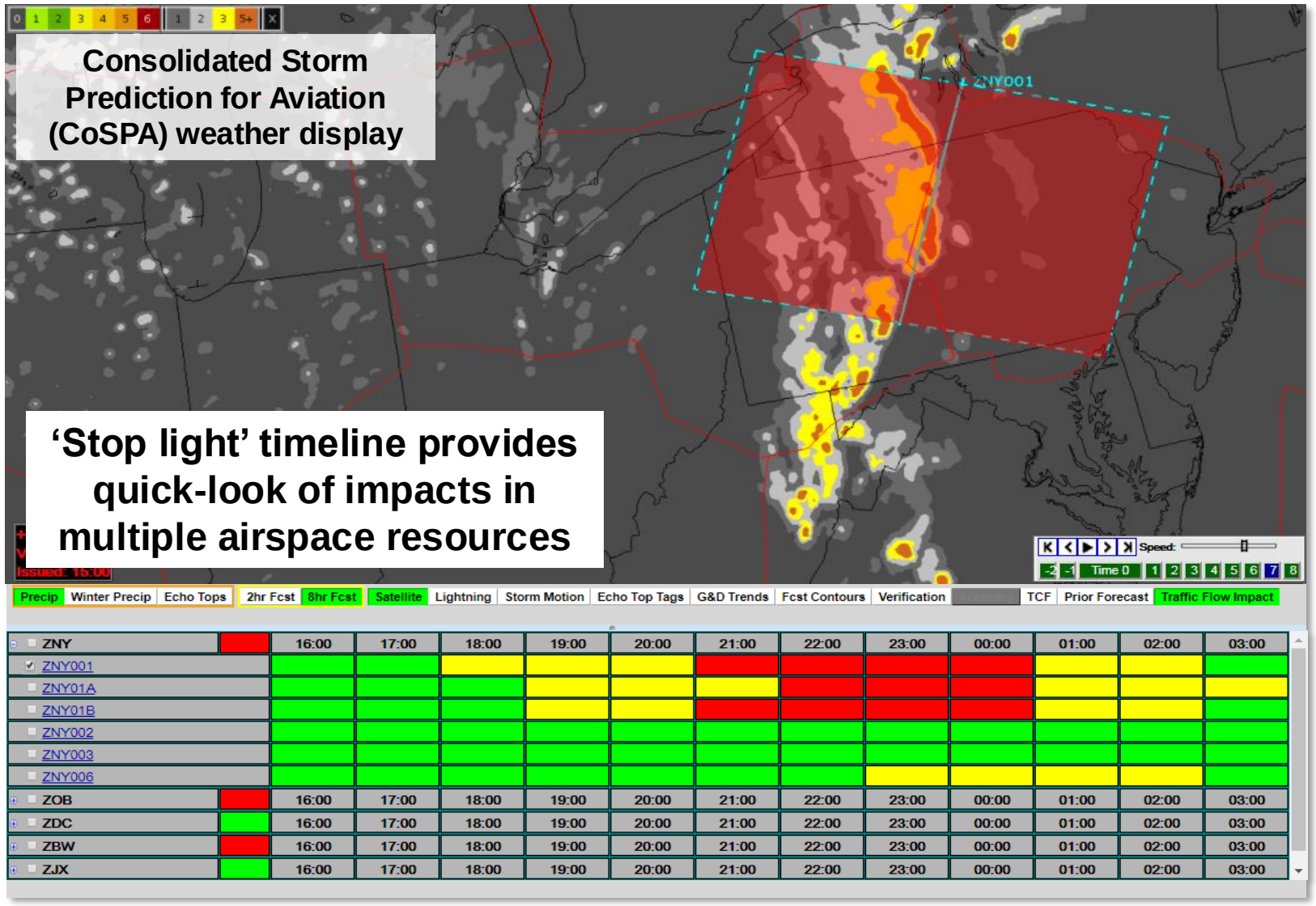
- **Traffic Flow Impact (TFI) explicitly translates weather forecasts into quantitative enroute airspace capacity predictions**

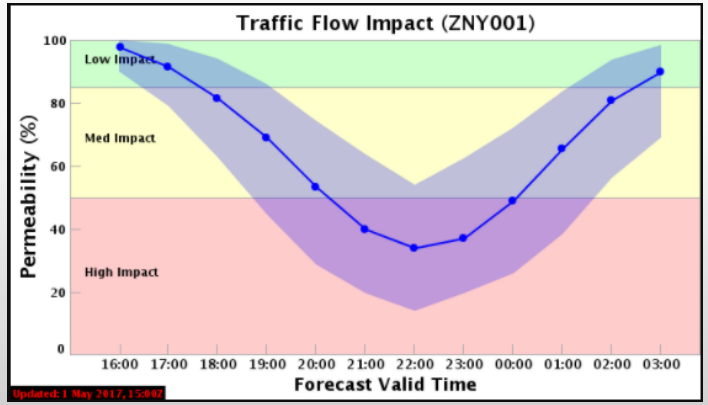
- **Initial prototype deployed in 2014**
  - **Currently available to select ATM & airline users**
  - **Will become operational in FAA's NextGen Weather Processor (NWP)**



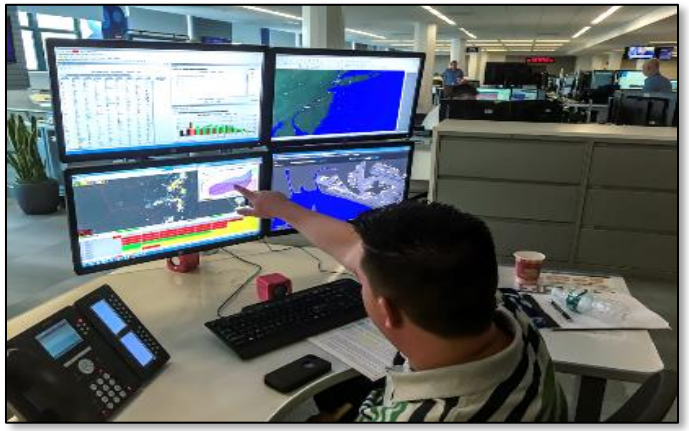
First-of-its kind technology providing forecasts of enroute airspace capacity to facilitate air traffic management responses

Traffic Flow Impact Prototype





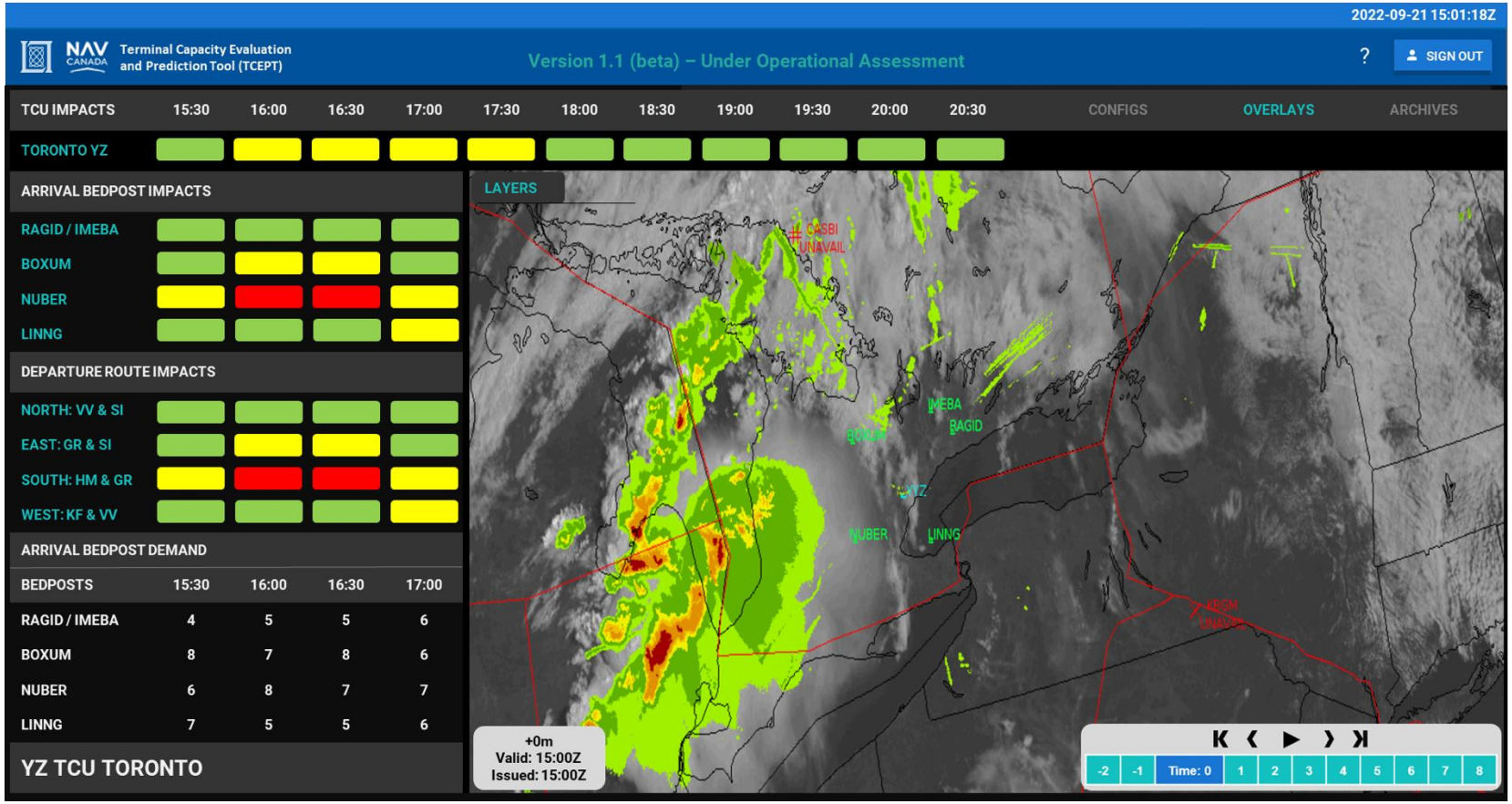
Drill-down provides detail on capacity impact and uncertainty



TFI in use at Airline Operations Center

Terminal Capacity Evaluation & Prediction Tool (TCEPT)

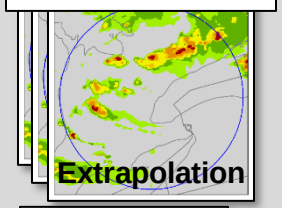
- **TCEPT predicts terminal bedpost availability & capacity to guide planning in convective weather**
  - **Proactive re-routing of arrivals to available bedposts**
  - **Estimating forecast uncertainty bounds**
- **Complementary to ACEPT**
- **Adapts en route Traffic Flow Impact (TFI) prototype for terminal applications**

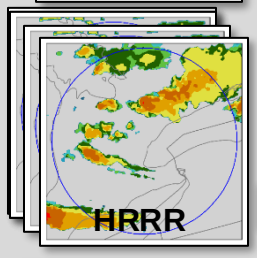


Machine Learning Model 1. Training & 2. Application

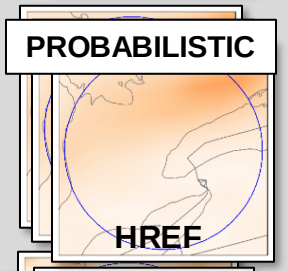
Historic 4-D Weather Forecasts (15mo)

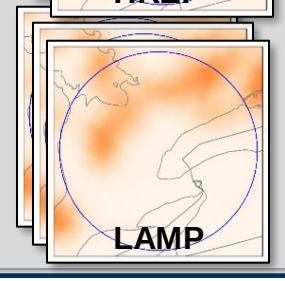
DETERMINISTIC





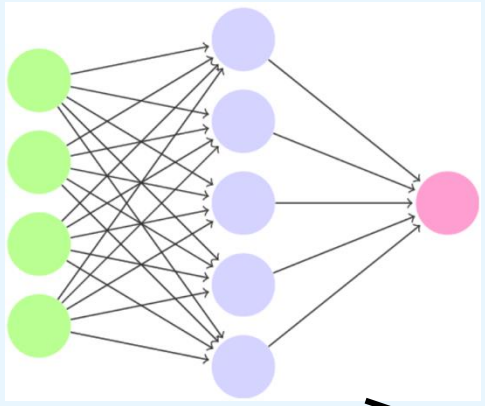
PROBABILISTIC





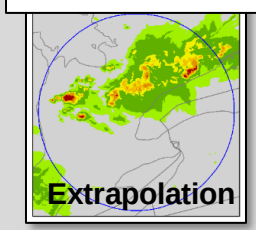
1. Training

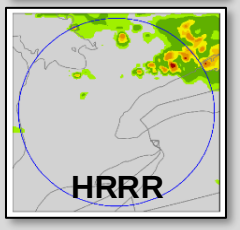
Feed-forward Neural Network



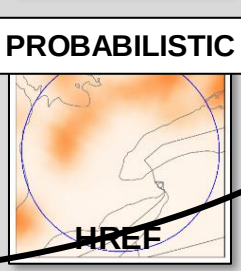
"Day of" 4-D Weather Forecasts

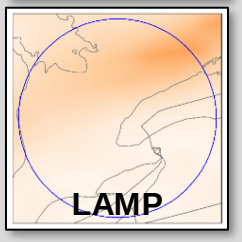
DETERMINISTIC





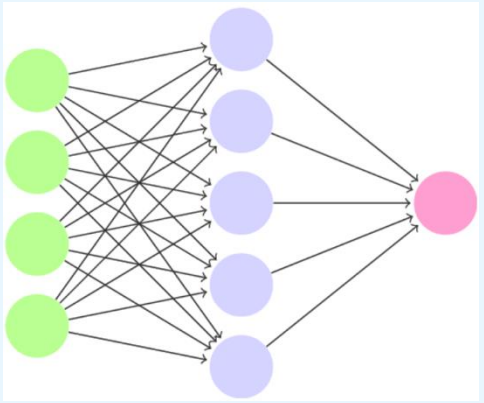
PROBABILISTIC

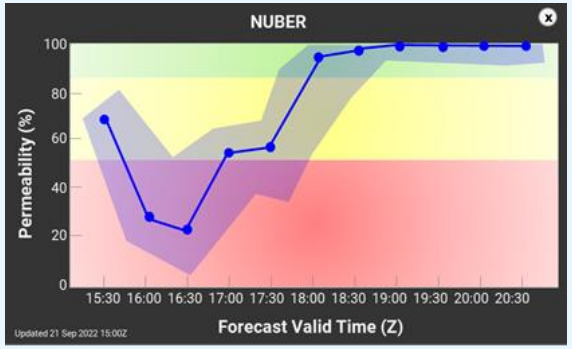




2. Application

Trained Machine Learning Model





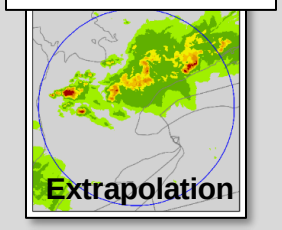
CoSPA = Consolidated Storm Prediction for Aviation
HRRR = High Resolution Rapid Refresh

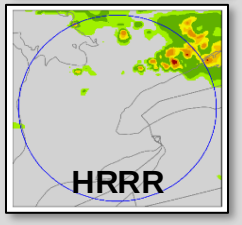
LAMP = Localized Aviation MOS (Model Output Statistics)
HREF = High Resolution Ensemble Forecast

Machine Learning Model 2. Application

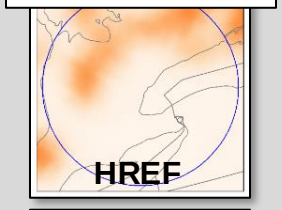
"Day of" 4-D Weather Forecasts

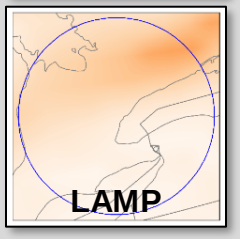
DETERMINISTIC



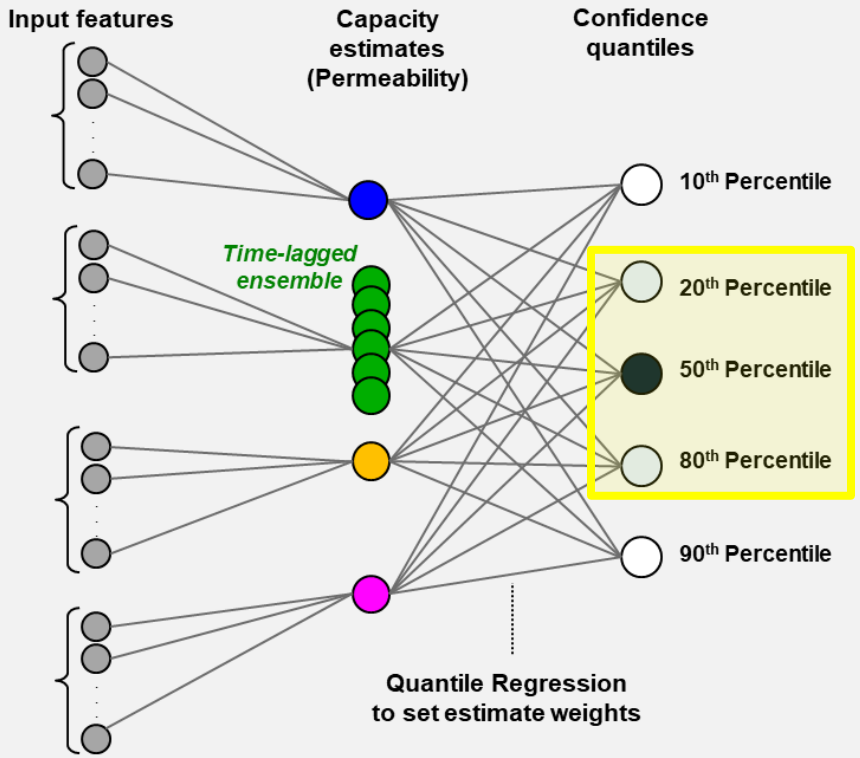


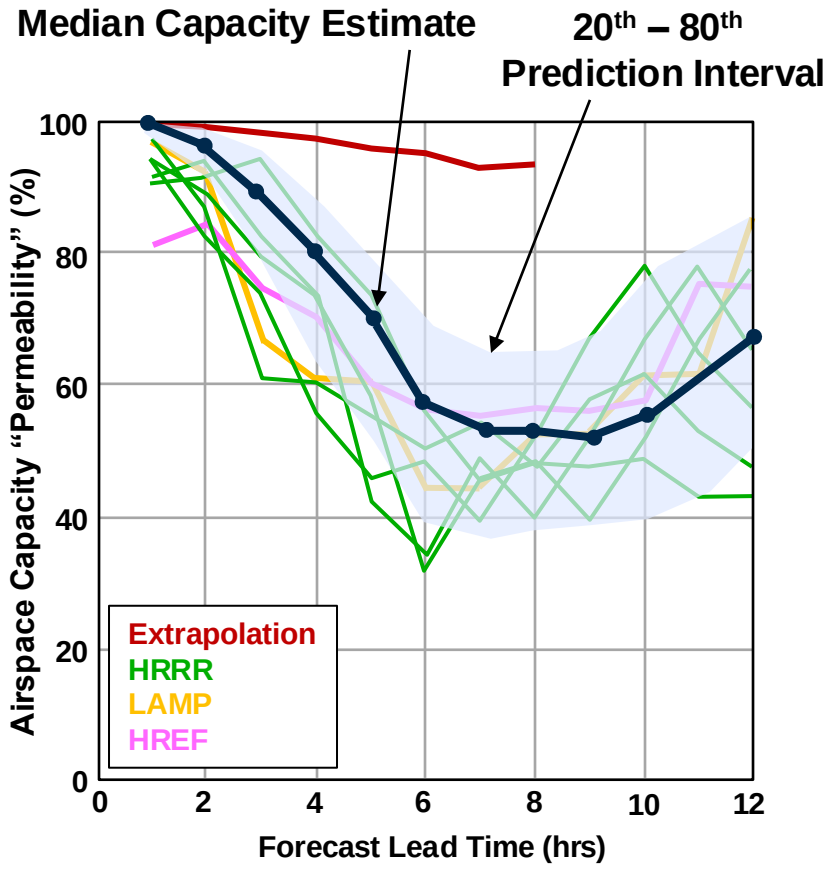
PROBABILISTIC





Machine Learning Algorithm
(Feed Forward Neural Network)





Algorithm combines features from each forecast to provide airspace capacity estimates & prediction interval

CoSPA = Consolidated Storm Prediction for Aviation
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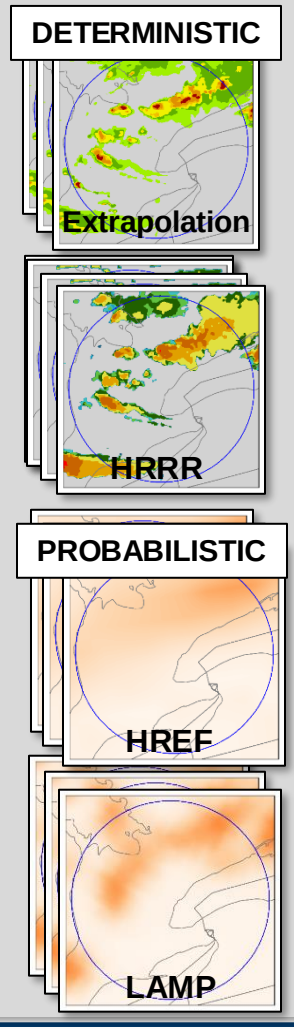
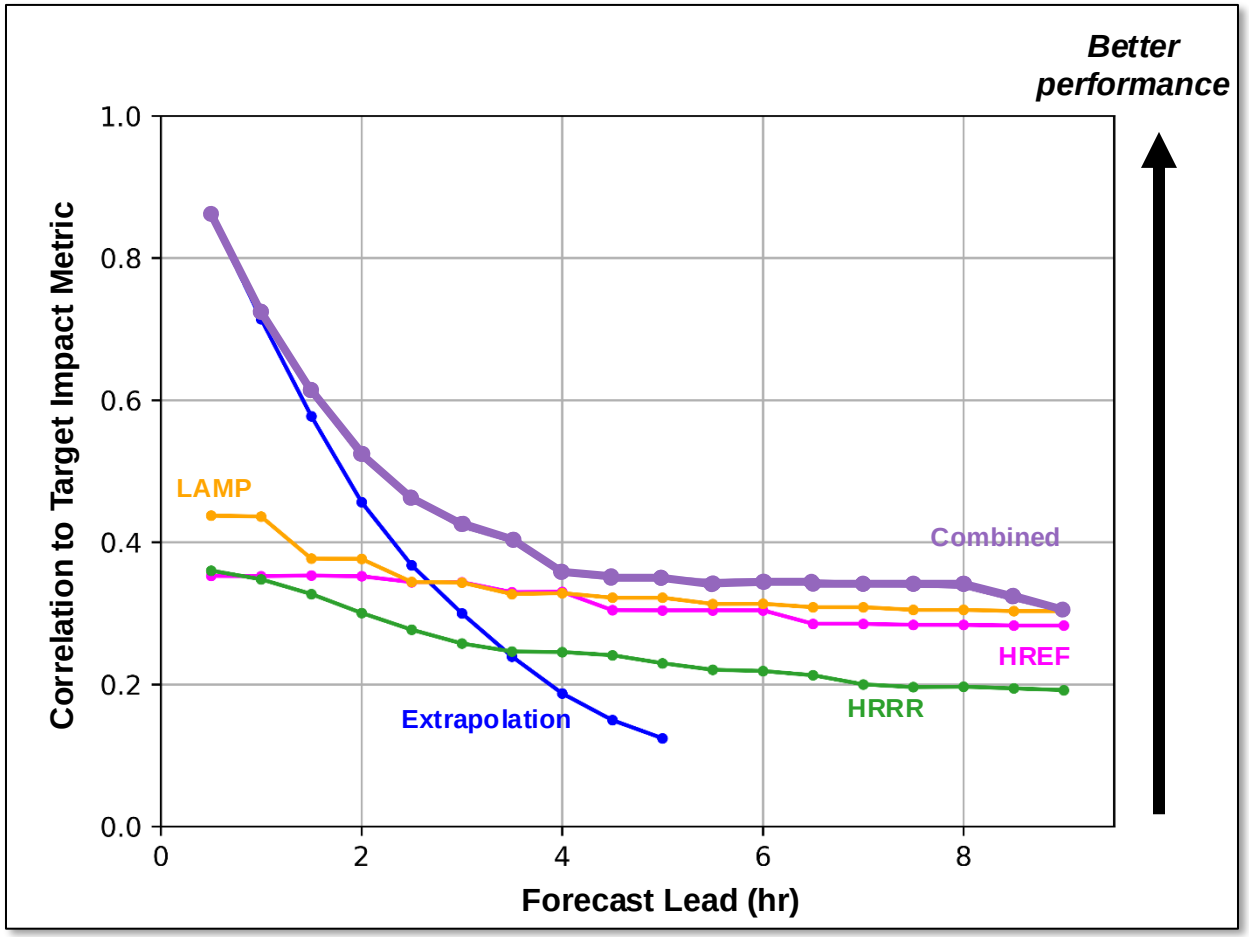
Performance of Current TCEPT Algorithm

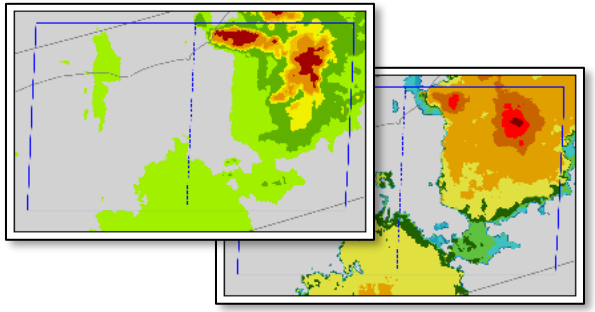
Historic 4-D Weather Forecasts



- 15-month training set
- May 2021-August 2022



Target Precipitation Intensity and Height



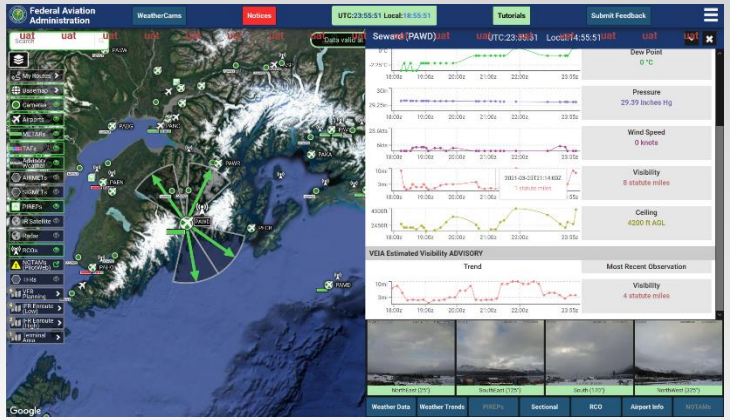
Combined impact model has good correlation for tactical lead times, fair for strategic

Ongoing Prototyping Efforts

Severe Storm Analysis and Forecasting

Climate Impact Mitigation

Cameras for Clouds, Cloud Ceiling, and Visibility



Summary

- The ATC and Weather Systems Group at Lincoln Laboratory specializes in AI-based decision support for aviation weather
- Prototypes developed include graphical weather displays and ATC impact forecasts that have been used throughout the FAA, DoD and industry
- This talk described two enabling technologies that were used in a number of operational prototypes
  - Synthetic Radar Generation fills gaps in weather radar coverage using deep learning-based data fusion
  - Traffic Flow Impact translates multiple forecast types into predictions of airspace capacity