Integrating Weather Data into ATC Decision-Support Tools – Human Factors Lessons Learned from the Development of Operational Prototypes

Gabriele Enea

LINCOLN LABORATORY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

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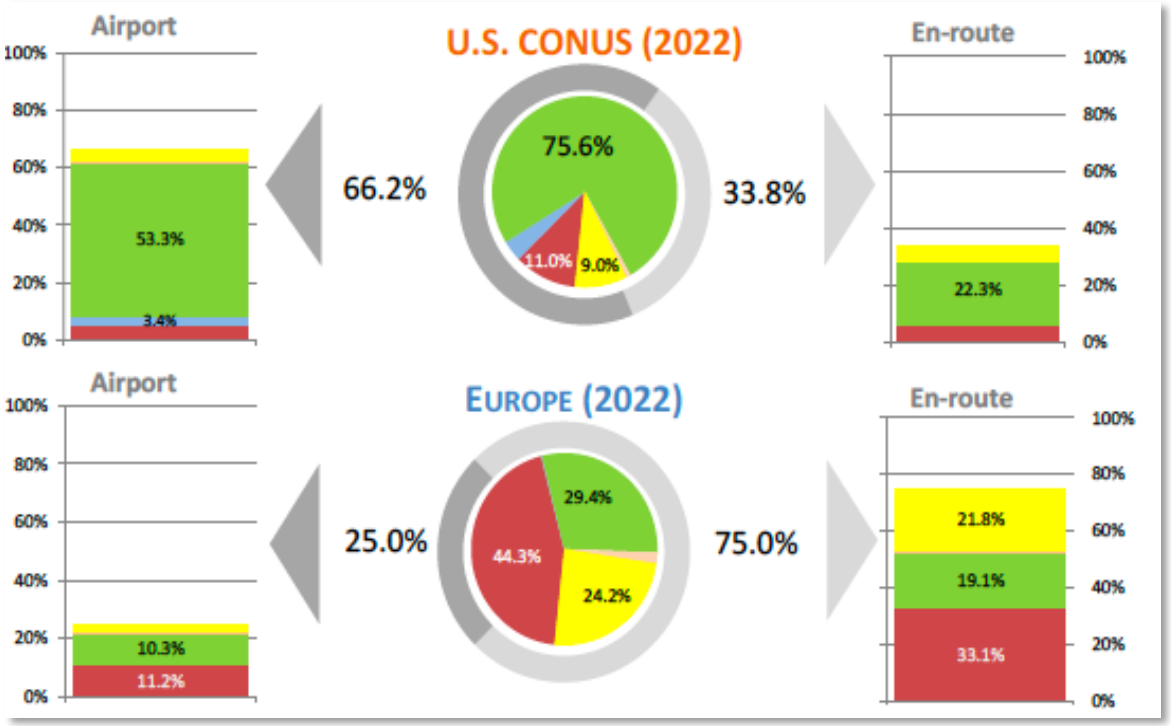
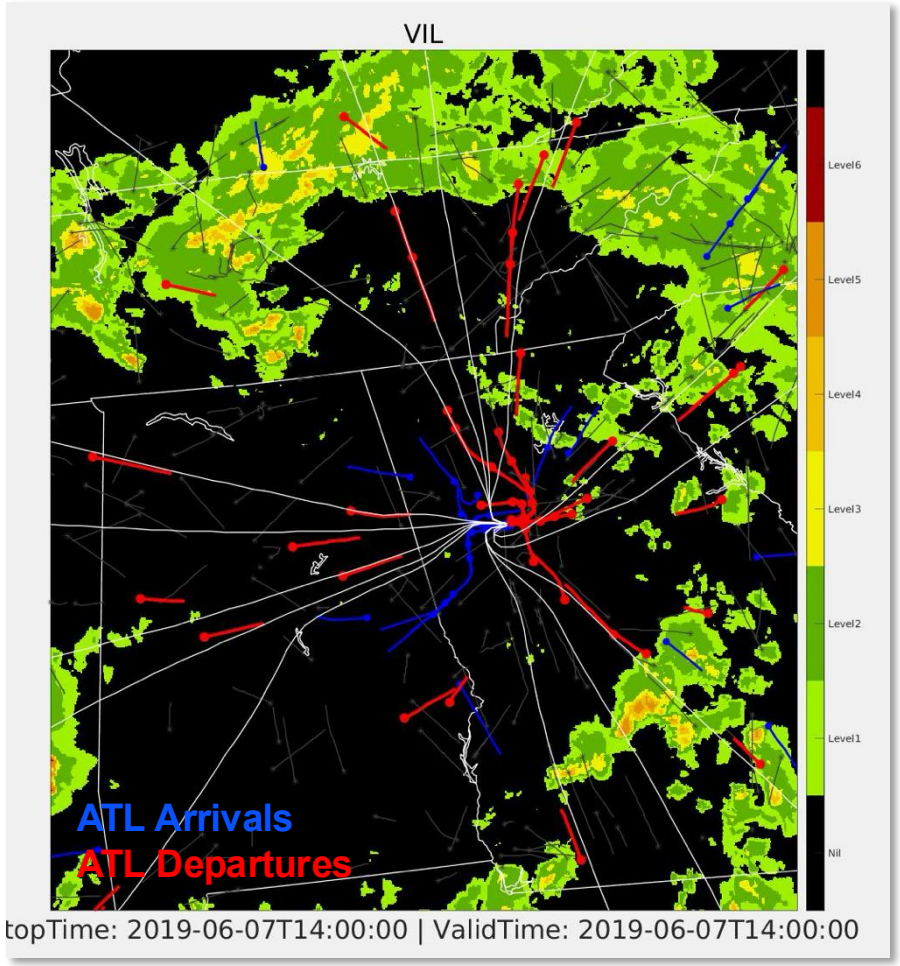
Motivation

- **Weather events disrupt air traffic operations in the United States & Europe, causing significant delays**

- **These regions experience weather & manage it differently**



Weather
Volume
Runway/taxi
Equipment
Other



Aviation weather impacts will likely increase in the future

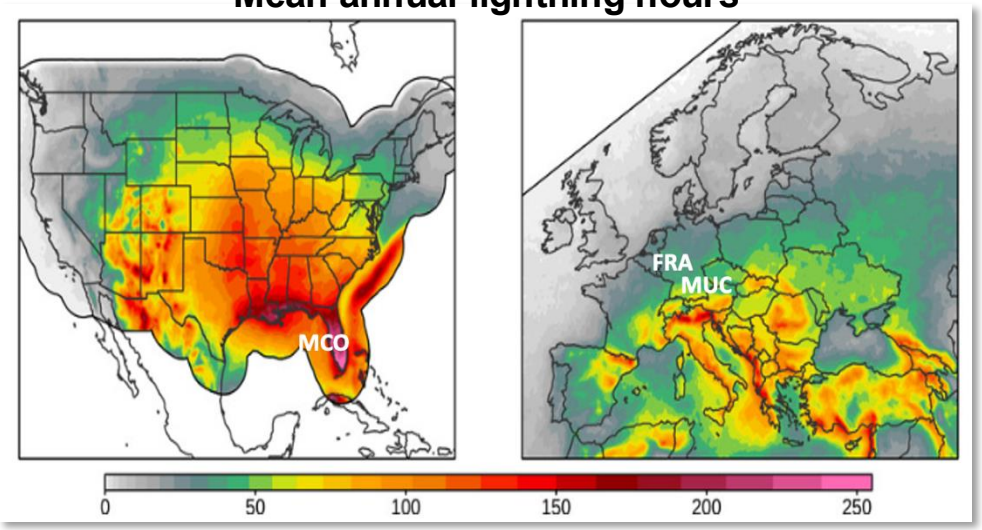
Sources: 06/07/2019 CIWS weather & TFMS tracks
FAA and EUROCONTROL, "Comparison of Air Traffic Management related operational and economic performance: U.S. – Europe", 2024.

Severe Weather in U.S. & Europe

- **Historical observations**
  - **High thunderstorms frequency in south-east of U.S. and northern Italy/south of Germany**
  - **High winds in north-east U.S. and in central and east Europe especially in the summer**
- **Future predictions**
  - **Severe thunderstorms projected to increase in the East Coast and Gulf of Mexico of the U.S.**
  - **Future estimates for the European continent show some increases in the Mediterranean and reductions in parts of northern Europe**

Weather impacts in future climate will vary by area

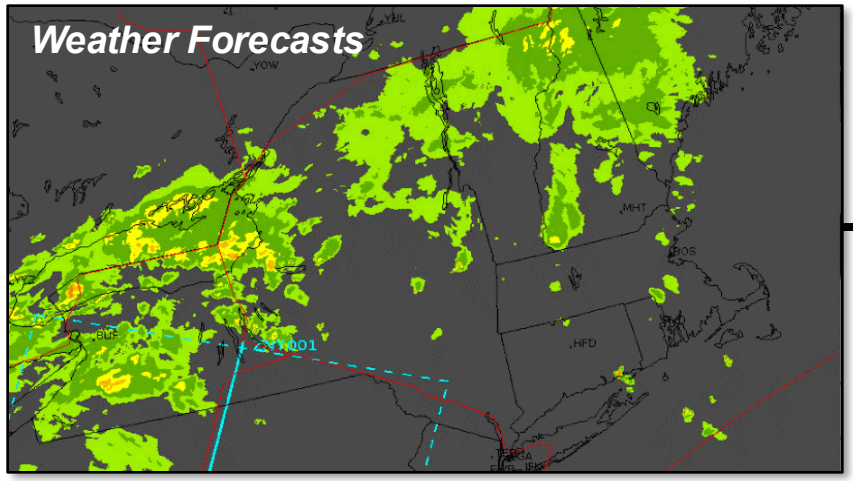
Mean annual lightning hours

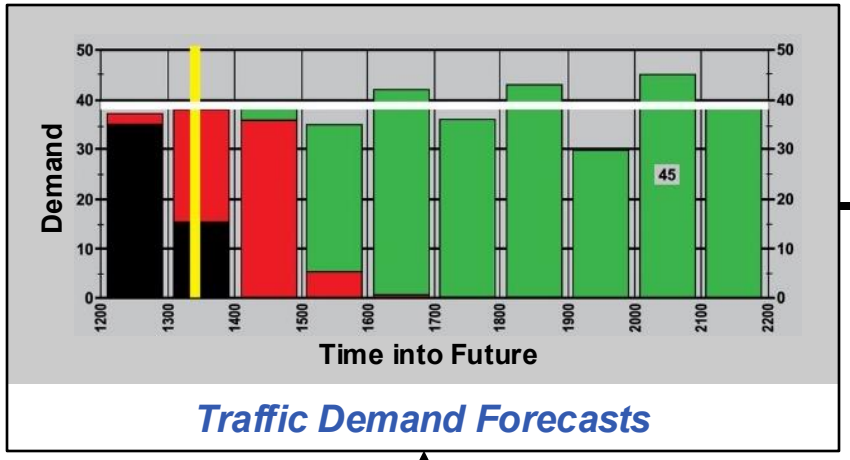


Future severe thunderstorms areas: blue and red represent negative & positive trends respectively

Taszarek, M.,, Kendzierski, S., Pilguj, N., "Hazardous weather affecting European airports: Climatological estimates of situations with limited visibility, thunderstorm, low-level wind shear and snowfall from ERA5", *Weather and Climate Extremes*, 28, 100243, 2024.
EASA, Appendices to EASA *Scientific Committee Annual report 2022*.

Role of Advanced Weather Technology in ATC Decision Making



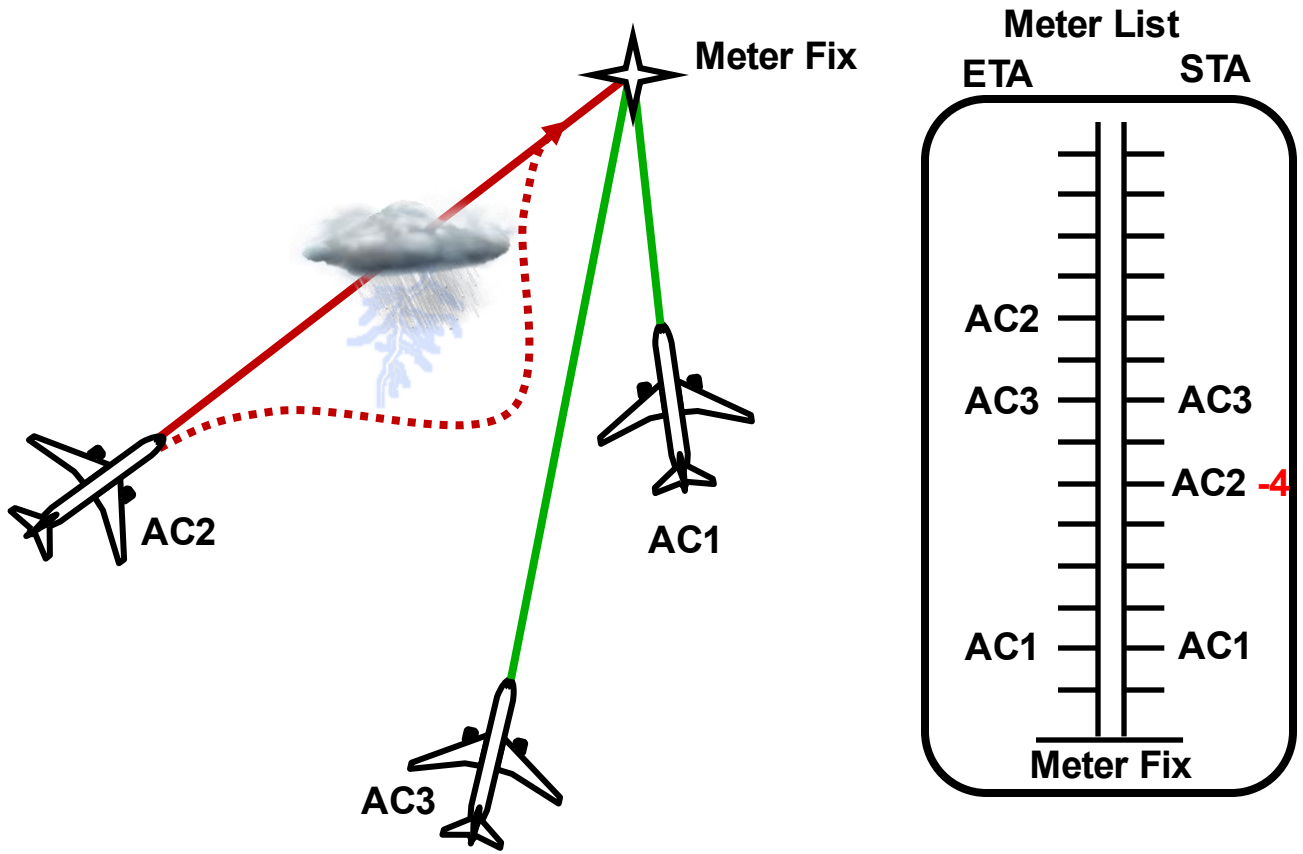


Missing overlay of weather & traffic projections to identify demand/capacity imbalances and develop strategies to mitigate

Delay programs

Weather Impacts on Trajectory-Based Operations

- Time is used to sequence flights to a meter fix
- Automation provides times (STA) and sequence of flights
- Weather can disrupt actual flight trajectories
- If too many flights have large differences between ETA and STA, metering is discontinued



Missing weather information in ATC automation leads to errors in ETA predictions & controllers losing confidence in the automation

STA = Scheduled Time of Arrival
ETA = Estimated Time of Arrival

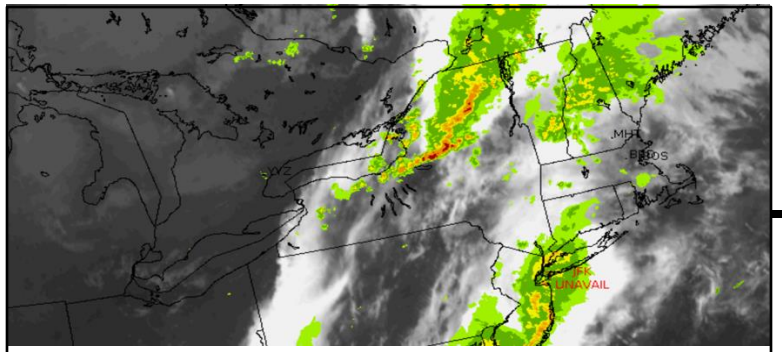
Outline

- Motivation
- NAV CANADA Decision-Support Systems
- Weather TBO HITL & Operational Benefits
- Future Vision & Summary

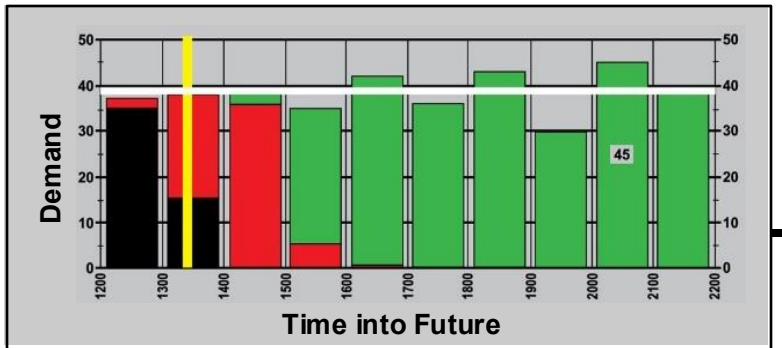
TBO = Trajectory Based Operations
HITL = Human In The Loop

Supporting Strategic Decision Making in Today's ATC System

Advanced weather technologies translate weather forecasts into capacity/demand imbalances across flight domains



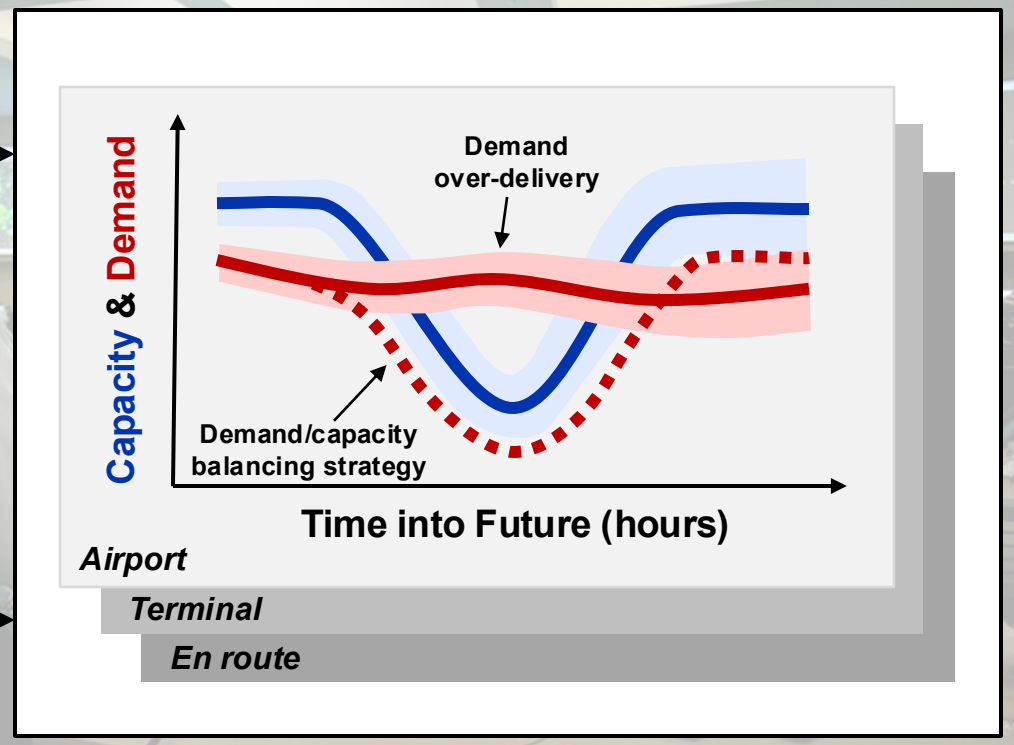
Weather Forecasts



Traffic Demand Forecasts

Translate weather into capacity impact

Demand profiles



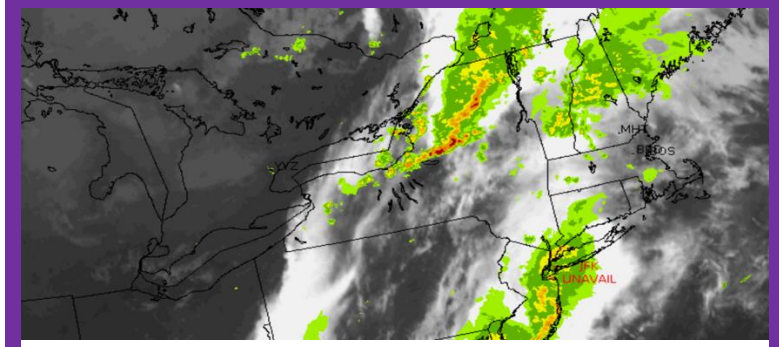
Delay programs

Supporting Strategic Decision Making in Today's ATC System

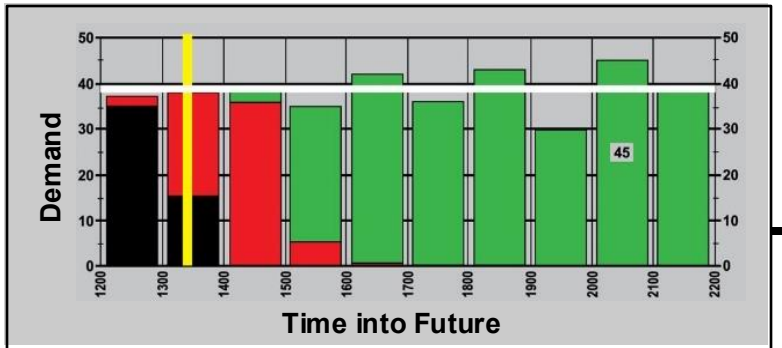
1 Provide common source of weather & impact information

2 Translate weather into capacity impacts

3 Identify operational impact onset, duration, severity



Weather Forecasts



Traffic Demand Forecasts

Translate weather into capacity impact

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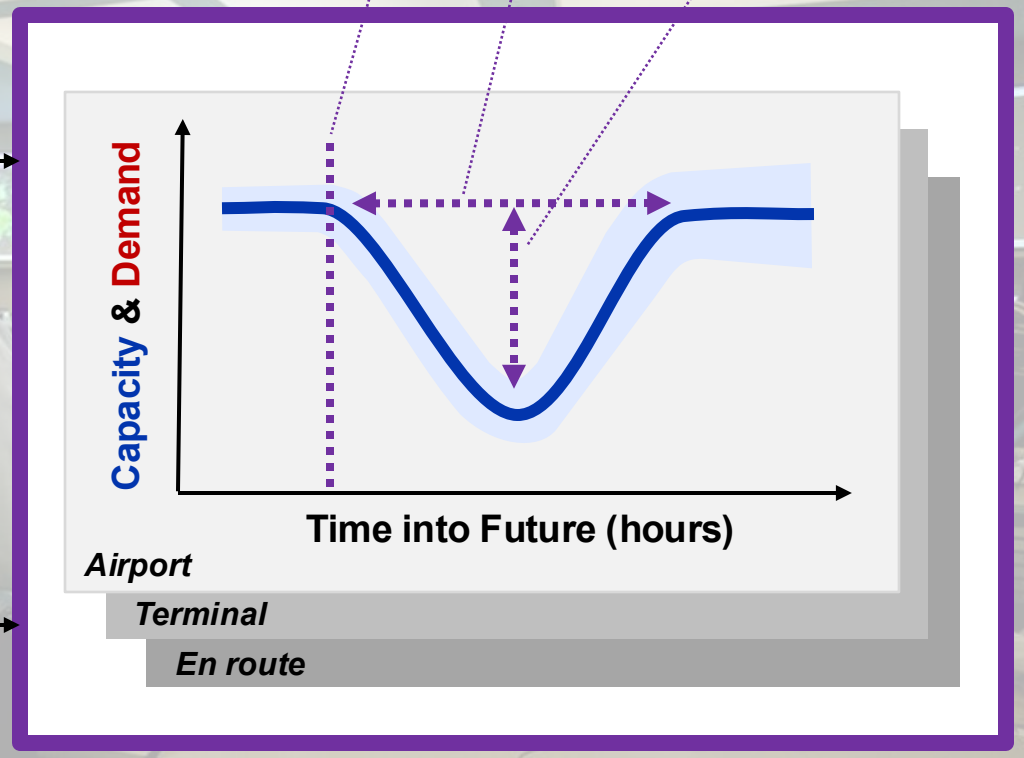
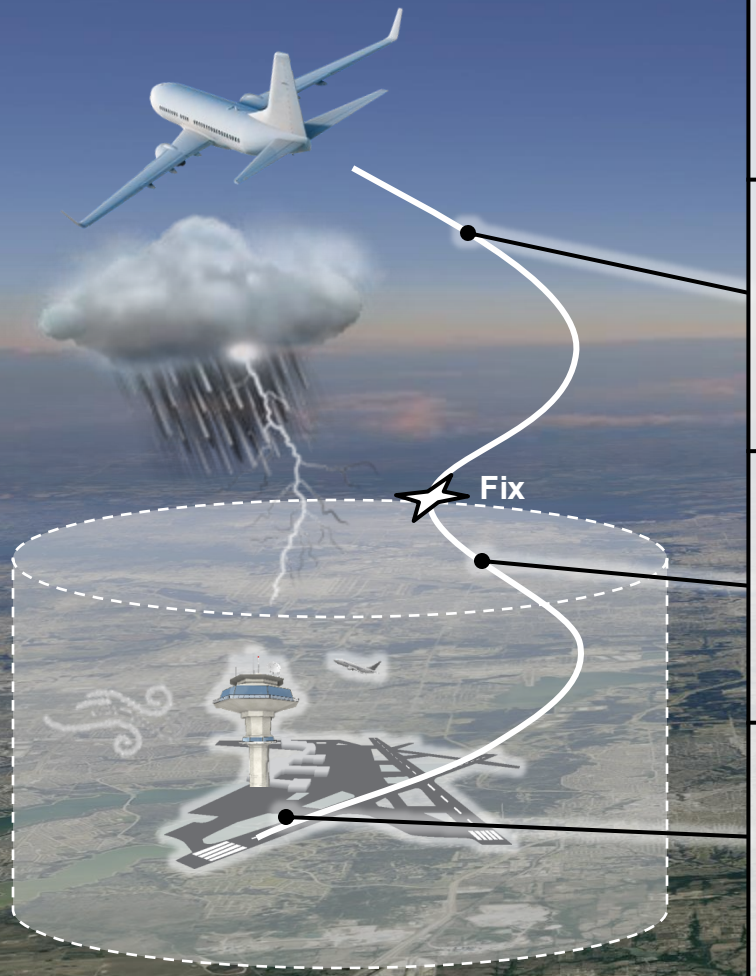


Delay programs

4 Determining appropriate ATM responses

NAV CANADA Weather ATC Systems



ATC Domain	Key Weather Challenges	Technology	
		① Weather Info	② ③ Impact Info
En route	Storm impacts on en route airspace capacity	Canadian Aviation Weather System (CAWS)	Enroute Capacity Evaluation & Prediction Tool (ECEPT)
Terminal	Storm & wind impacts on terminal routes & fix capacity		Terminal Capacity Evaluation & Prediction Tool (TCEPT)
Airport	Wind, C&V and precipitation impacts on airport capacity		Airport Capacity Evaluation & Prediction Tool (ACEPT)

Airport Capacity Evaluation and Prediction Tool (ACEPT)

Weather Forecasts
- Wind speed, direction, gust
- Precipitation
- Temperature
- Humidity
- Ceiling
- Visibility

Operational Constraints
- System Constraints
- Construction
- Equipment

Demand Forecasts

Airport Capacity Prediction Algorithm

Prototype User Display

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NAV CANADA Airport Capacity Evaluation and Prediction Tool (ACEPT) — NOT FOR REAL-TIME OPERATIONAL USE – SOFTWARE UNDER DEVELOPMENT — ? SIGN OUT

CYYZ – TORONTO
Lester B. Pearson Intl

Wind: **230° 10 KTS G25**
Ceiling: **UL**
Visibility: **15+ SM**

MET Category: **VIZ**
Precipitation: **NONE**
2023-02-02 17:15Z

LAST UPDATE: 17:15Z

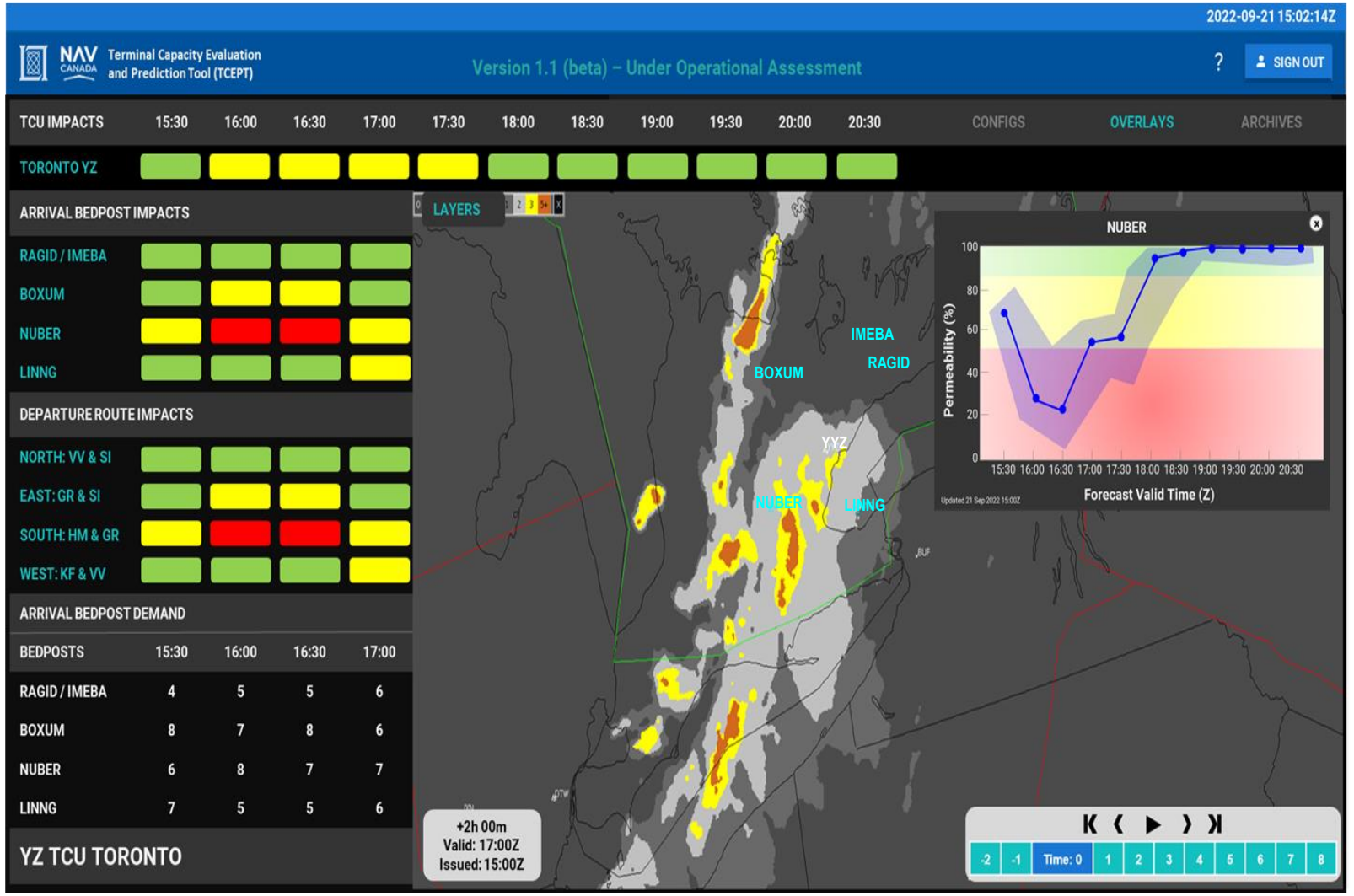
Hours	18Z	19Z	20Z	21Z	22Z	23Z	00Z	01Z
Recommended Arrival Direction	WEST	WEST	WEST	WEST	WEST	WEST	NORTH	NORTH
Probability (%)	100	100	100	100	100	40	80	100
Planned Operation	DUAL	DUAL	DUAL	DUAL	DUAL	DUAL	LODO	LODO
Airport Arrival Rate (AAR)	44	44	44	44	44	44	36	36
Demand	25	28	30	40	26	48	40	32
Imbalance (AAR-Demand)	+19	+16	+14	+4	+18	-4	-4	+4

- Web-based interface for ATC, airlines, and airport users for shared situational awareness

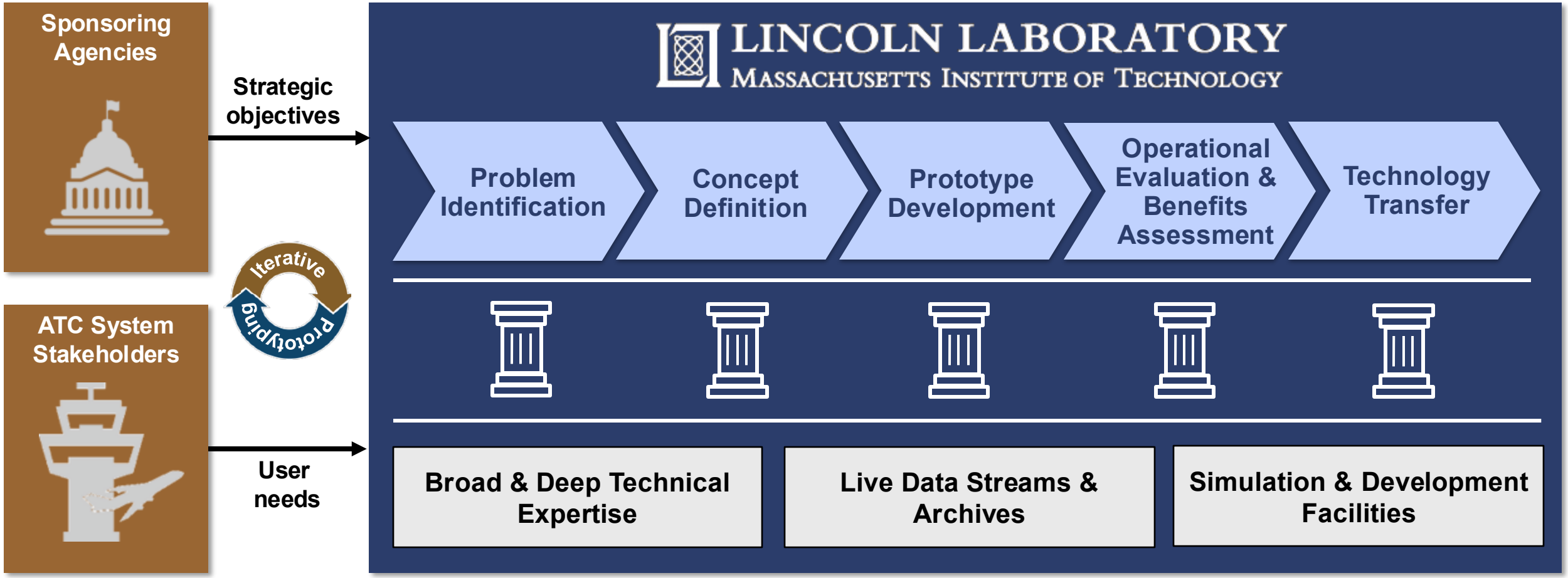
ACEPT predicts airport weather, recommended runway arrival direction, resulting airport capacity, and identifies demand imbalances 8 hours into future to support effective collaborative decision making

Terminal Capacity Evaluation & Prediction Tool (TCEPT) Concept

- Predicts terminal fix availability & capacity to guide strategic / tactical planning in convective weather
  - Proactive re-routing of arrivals to available arrival fixes
  - Conditioning of arrival demand for transition during convective weather
  - Estimating forecast uncertainty bounds
- Complementary to ACEPT
- Builds on en route Traffic Flow Impact (TFI) prototype developed by MIT LL for FAA



ATC Technology Development Approach



Approach to build/deploy high value ATC operational prototypes of advanced technologies & transferring to users

ACEPT Prototype Development

Tabular: colors focus attention, explicit summary of key information, drill-downs for details

YYZ Time: 1542Z AAR: 48 Config: 05,06R|05,06L What-if

Hour	16	17	18	19	20	21	22	23
Configuration	05,06R| 05,06L	05,06R| 05,06L	05,06R| 05,06L	33L|33R	33L|33R	33L|33R	33L|33R	33L|33R
Arrival capacity	58	56	52	32	32	36	36	36
Arrival demand	38	41	43	42	37	32	25	22
GDP rate	…							
Departure capacity	58	56	52	32	32	36	36	36
Departure demand	50	52	48	48	44	35	34	32
Priority	DEP	DEP	ARR	ARR	ARR	ARR	DEP	DEP

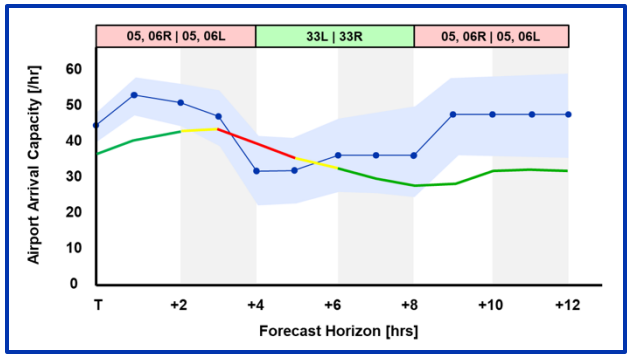
Additional required rows determined from user needs assessment

TAF / METAR | Wind Profile | Fronts | Compression / Fleet Mix | Graphs | Config

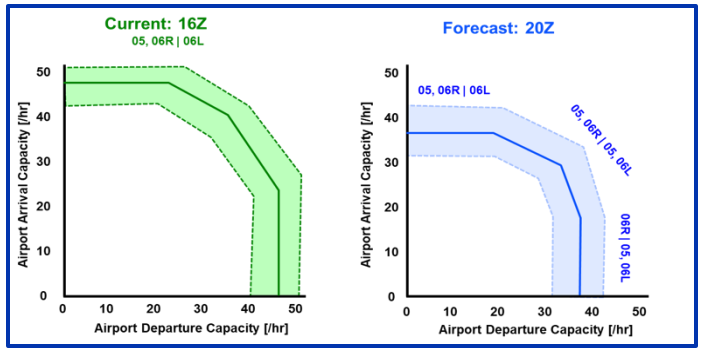
Display drill-down options m… sed on user inputs

Circa 2019

Graphical arrival capacity forecast: arrival planning, uncertainty estimate



Coupled arrival / departure capacity forecast: push management, procedure selection



- **Mockups guide discussion of decision support tool requirements**
- **Assess effectiveness of interface design & information presentation to refine capability needs**

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ACEPT current interface comes from iterative process and extended user feedback

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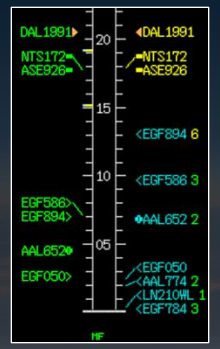
Trajectory-Based Operations (TBO)

TBO automation uses expected route & wind forecasts to calculate efficient flight schedules



Benign wind conditions

No convective activity

Time target at cruise or merge meter fix

Meter Fix

TFMS

TBFM

Time target at arrival meter fix

Meter Fix

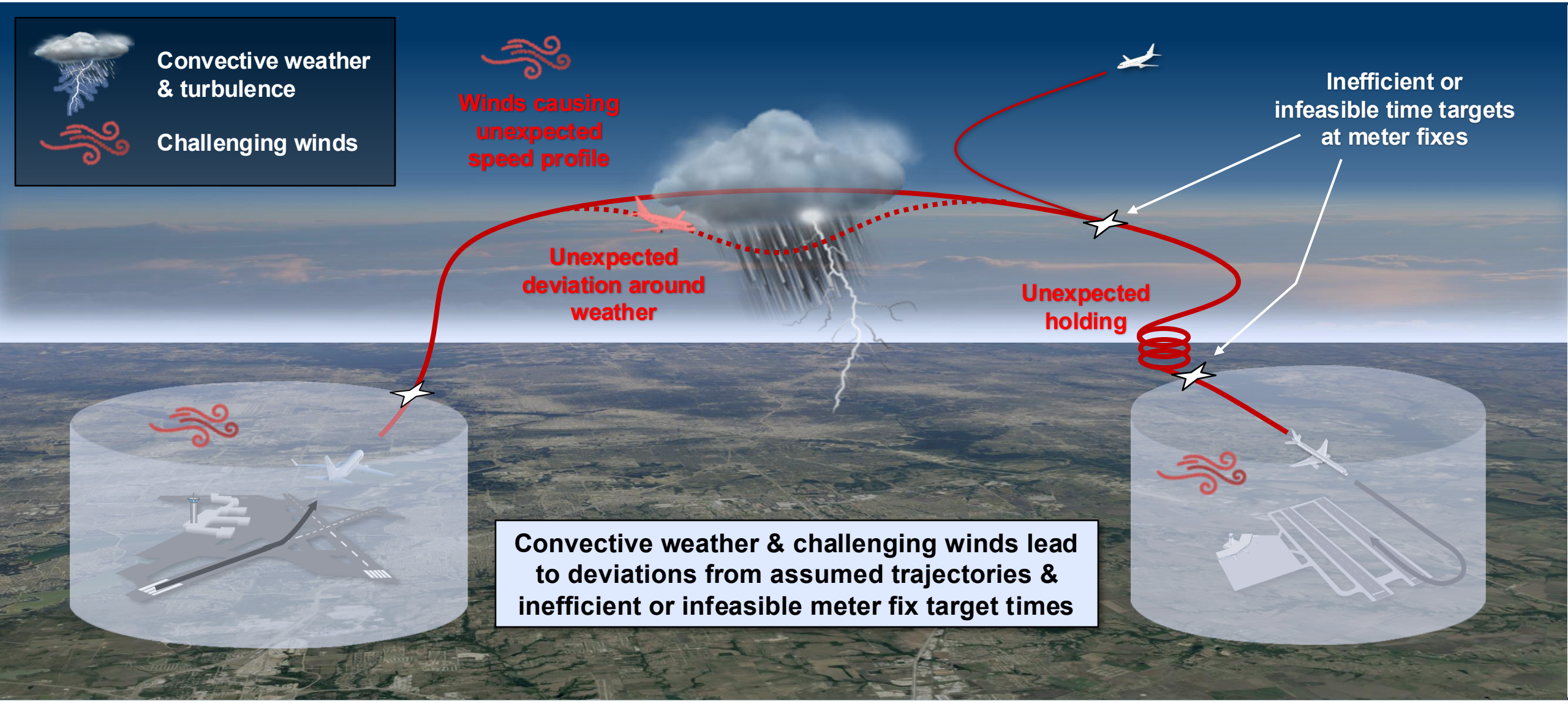
TFDM

Under nominal conditions, TBO automation enables efficient metered flight flows

- Terminal Flight Data Manager (TFDM)
- Traffic Flow Management System (TFMS)
- Time Based Flow Management (TBFM)

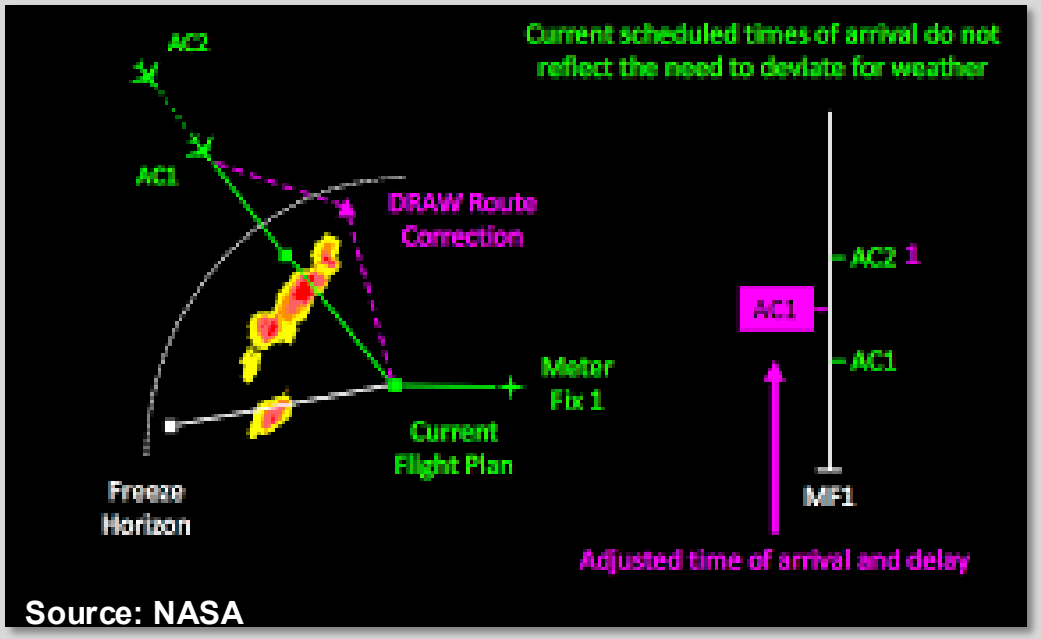
Foundational TBO automation systems

TBO Under Challenging Weather Conditions



TBO Research & Development Prototype

Dynamic Route for Arrivals in Weather (DRAW)



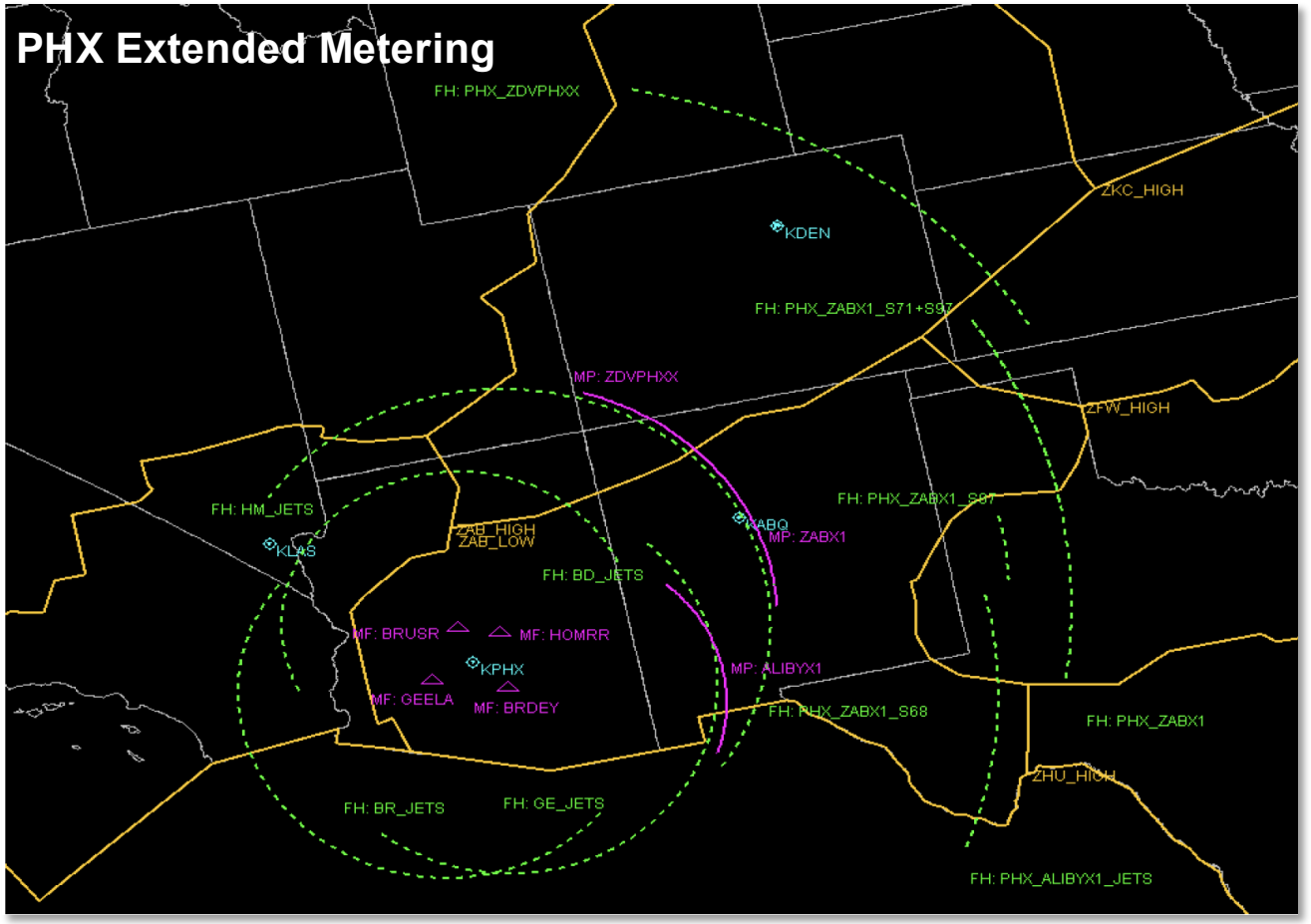
Source: NASA

- Uses models of pilot behavior around convective weather to predict reroutes & impact on TBFM schedule
- Tech-transferred from NASA to FAA in 2019 for evaluation
- Candidate to help TBO weather awareness enhancements in the future

System needs to be assessed in multiple metering configurations

DRAW Human-In-The-Loop (HITL) Experiment

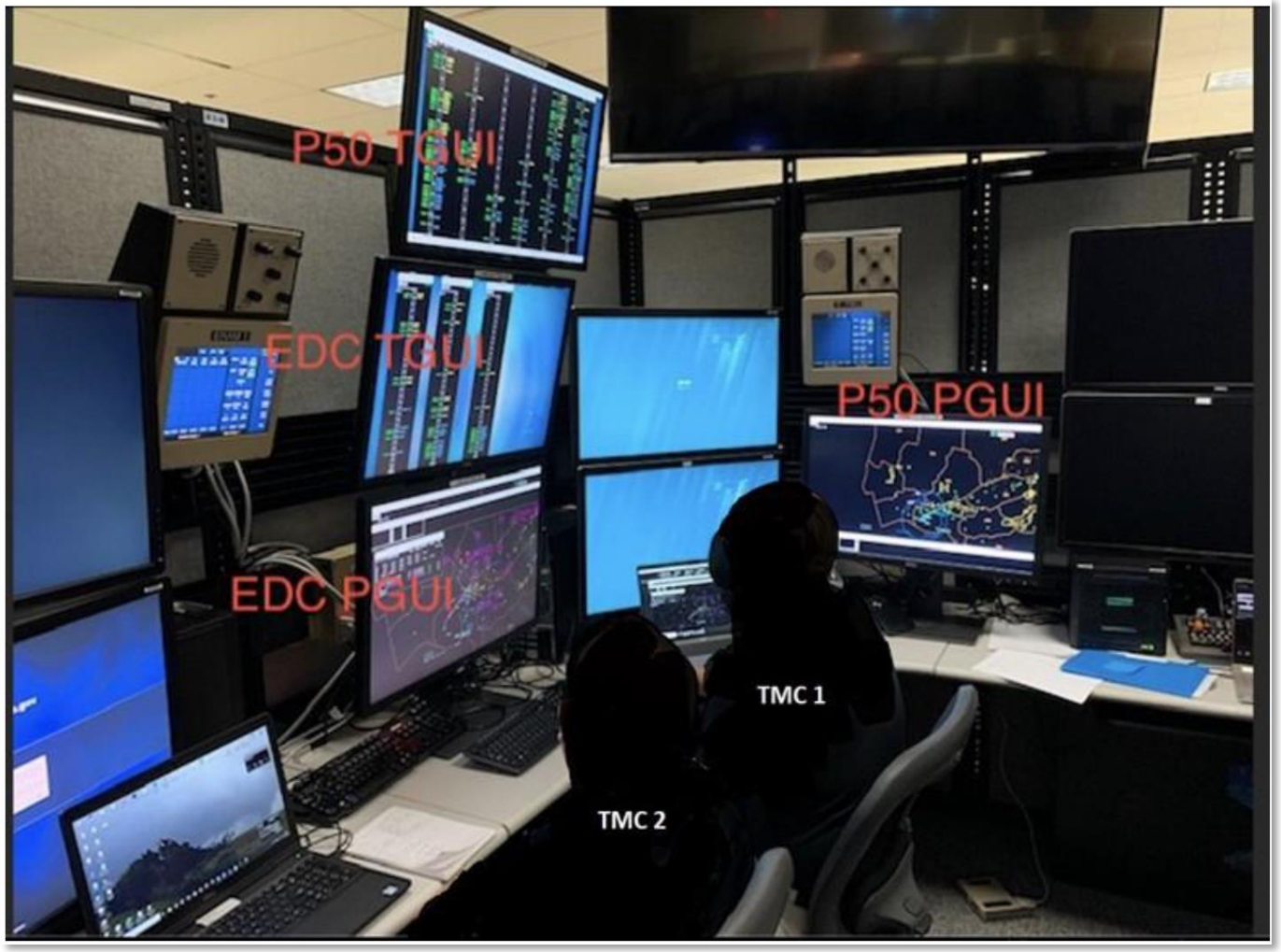
- NASA developed and tested DRAW only in en route metering conditions
- FAA interested in DRAW integration further from airports (Extended Metering (XM))
- In collaboration with the FAA WJHTC, the HITL helped identify usability and potential benefits of DRAW in XM environment
  - DRAW adapted to ZAB and ZLA multi-tier metering environments
  - During two weeks testing in May 2022, 27 runs were completed with 4 retired Traffic Manger Coordinators (TMCs)
  - The software was exercised with multiple weather and traffic scenarios



Concept tested with experienced retired Traffic Managers to identify potential operational benefits

WJHTC = William J Hughes Technical Center
ZAB = Albuquerque Center
ZLA = Los Angeles Center
PHX = Phoenix Sky Harbor Airport

DRAW HITL Configuration

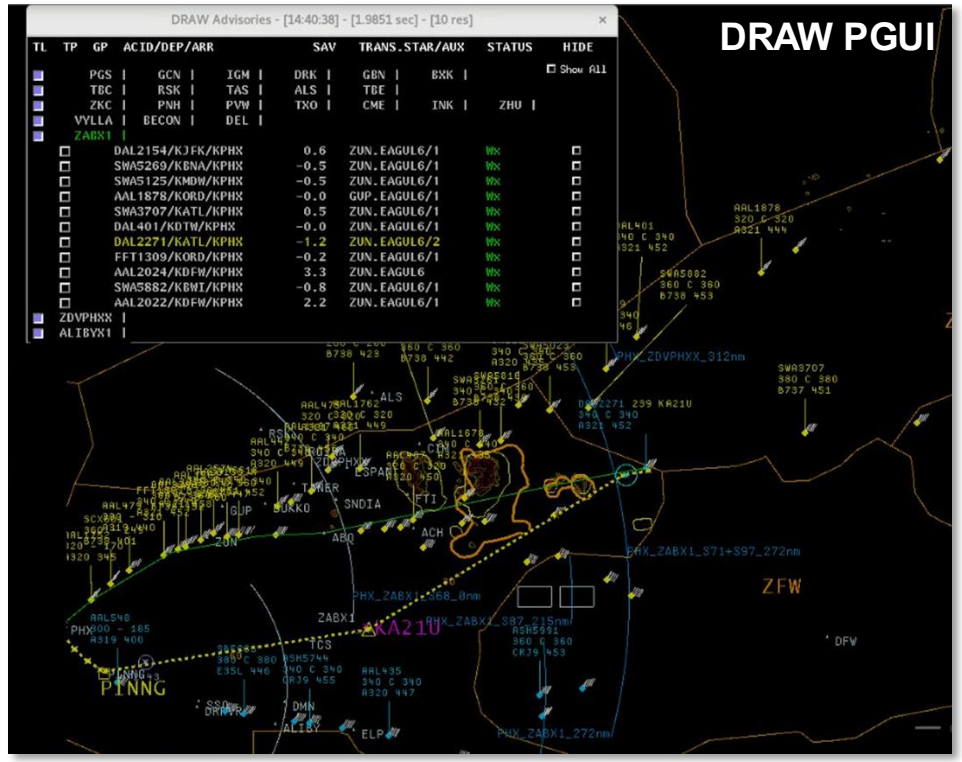


TGUI = Timeline Graphical User Interface
PGUI = Plan-view Graphical User Interface

P50 = Phoenix Terminal Area
EDC = En-Route System

Potential Operational Benefits

- DRAW allows traffic managers to examine and assign reroutes that are outside of the Freeze Horizon (FH), and to identify early conflicts with weather therefore continuing metering operations
- DRAW was effective at identifying appropriate route amendments for both single or multiple aircraft (preferred solution), allowing traffic managers to solve multiple flight weather conflicts at once
- The trial plan capability for multiple aircraft reroutes coupled with the display of delay impact on the TGUI was effective in providing a “script” for TM to approach the weather problem
- Displaying forecast weather on the TBFM PGUI provides the potential to improve TMC situational awareness and early conflict recognition during weather events
- Presenting weather data on the same display with metered aircraft, presents a great improvement compared to today’s operations that are ceased when weather impacts arrival routes



TGUI = Timeline Graphical User Interface
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TBFM = Time-Based Flow Management
TMC = Traffic Manager Coordinator

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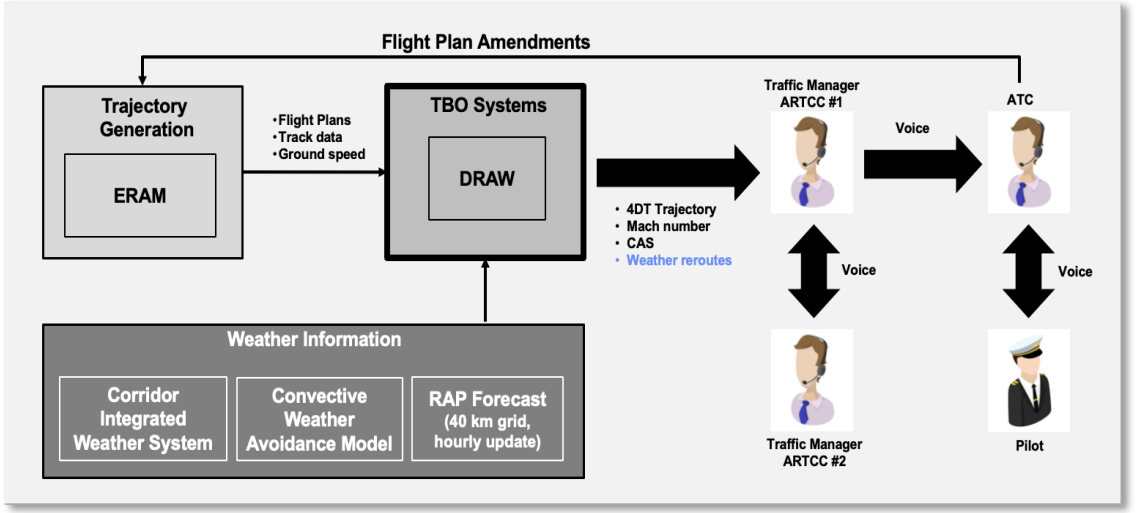
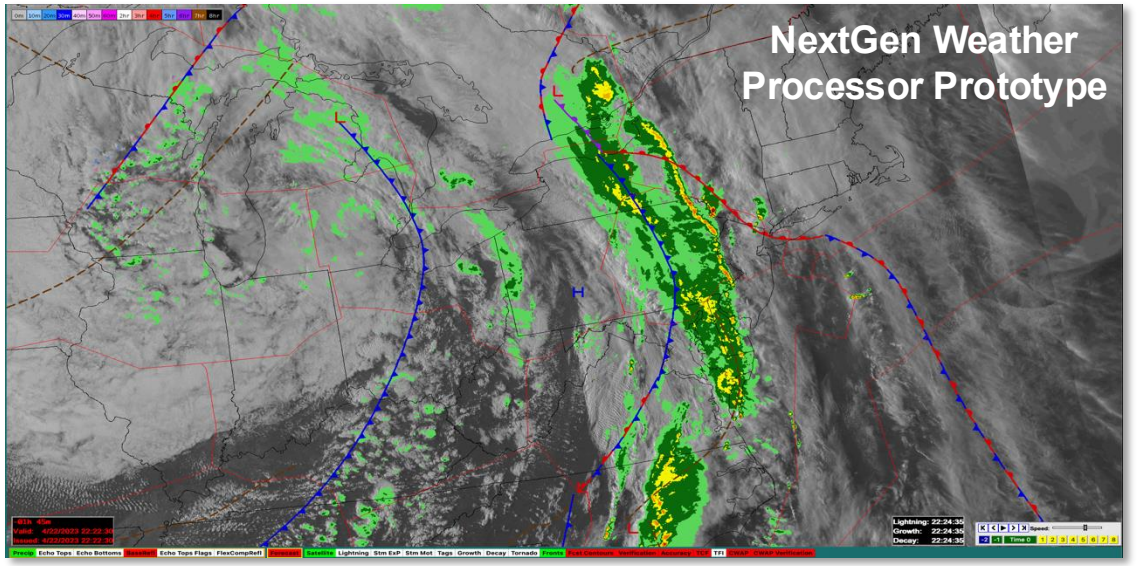
HITL = Human In The Loop

Weather TBO Open Questions

- **Promising results were observed during the HITL but more research is necessary in some key areas**
- **How to achieve smooth inter-facility coordination of the weather re-routes in Extended Metering (XM) operations**
- **How to properly define the weather data to provide to the automation and to show to the users in terms of forecast timeline, granularity and update rate**
- **How to harmonize weather data across multiple TBO automations system is also key to ensure all-weather, departure to arrival, TBO operations**

More work is necessary to define key communication and weather requirements for all-weather TBO operations

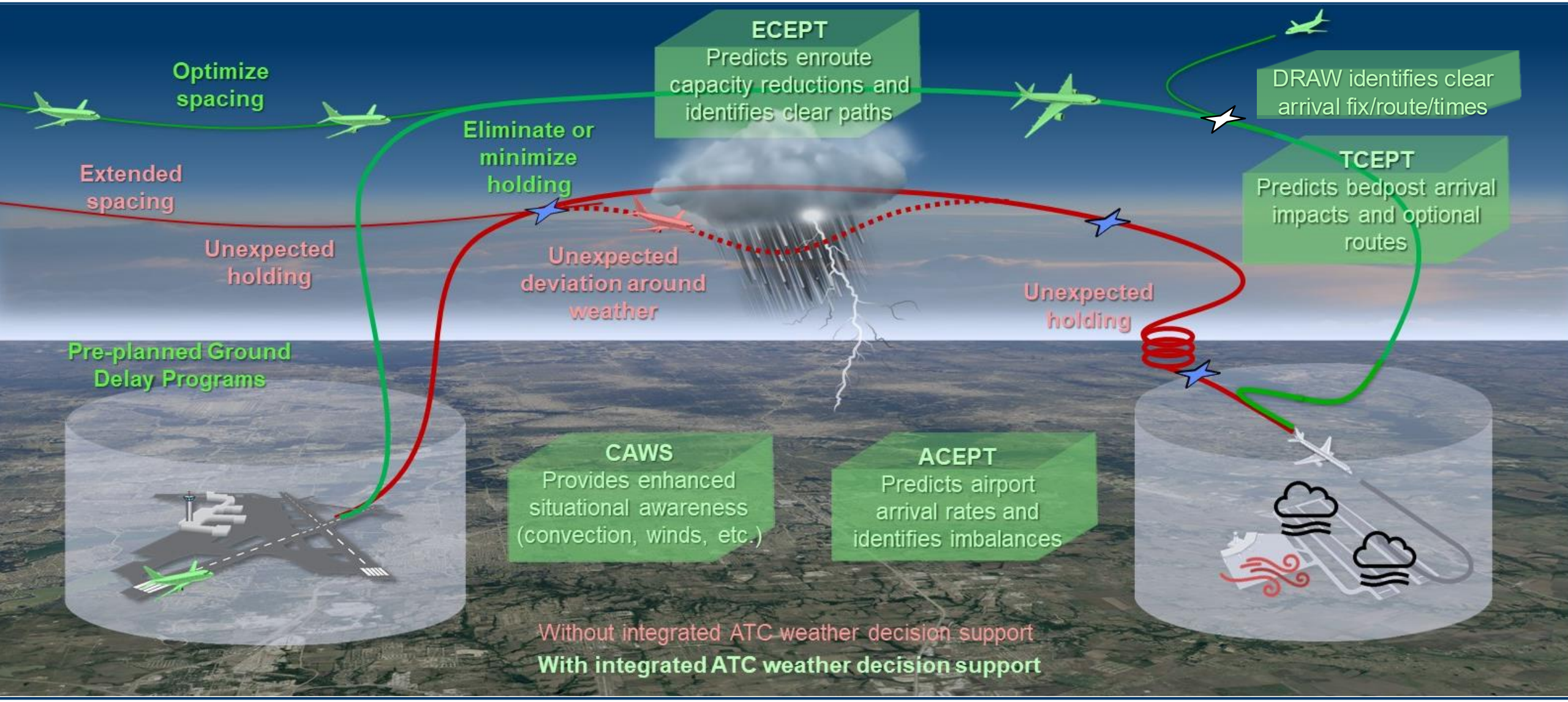




ERAM = En Route Automation Modernization
DRAW = Dynamic Weather for Arrivals during Weather

ARTCC = Air Route Traffic Control Center
RAP = Rapid Refresh

Long-Term Technology Vision



ACEPT = Airport Capacity Evaluation & Prediction Tool
CAWS = Canadian Aviation Weather System
DRAW = Dynamic Weather for Arrivals during Weather
ECEPT = Enroute Capacity Evaluation & Prediction Tool
TCEPT = Terminal Capacity Evaluation & Prediction Tool

Summary

- Automation plays a key role in supporting ATC in managing weather impacts
- Integration of weather data into ATC systems requires understanding how humans make decisions under uncertain conditions
- Developing weather-aware automation is an iterative process that requires prototyping and continuous users' feedback
- HITLs and operational deployments are effective in teasing out human factors insights to achieve mature and effective systems