Boeing Commercial Airplanes

Progress in Aircraft-Based Meteorological Observations

Turbulence Mitigation

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Outline

- Background & Motivations
- Progress updates for weather & EDR turbulence observations
    - How it works?
    - Trends in adoption
- Recent examples & ongoing research
- World Meteorological Organization (WMO) support
- Summary & Discussion

Abstract

One of the most promising solutions to address the evolving challenges of hazardous weather events is through sharing of real-time airborne meteorological observation information. The Boeing Company provides airline customers with a baseline airplane capability for cross-model (777, 787, 737 MAX, 777X) real-time weather and turbulence observations. Customers benefit from such information in areas of cabin management, better flight routing decisions, reduced fuel burn and emissions, improved passenger and crew comfort, and reduced crew fatigue. Use of data in scientific research and emerging meteorological services and climate trends will also be discussed.

Weather Hazards & Changes

Aviation Technologies & Procedures

Convergence & Deformation of Wind Field

Extreme Wind

Icing Conditions

Orographic (i.e. mountain wave)

Convection (i.e. thunderstorms)

Lightning

Tropospheric wave breaking near tropopause

Transverse waves (e.g. from large mesoscale systems)

Wake turbulence

Fog and Smoke Visibility Constraints

Presence of Hail

Tropopause height changes

Climate Change Impact

Forecast & Nowcast Models

Heads up Display (HUD)

Flight Deck Design

Aircraft observations

AI/Satellite

LiDAR

Onboard WXR

Flight Crew Training

Gust Alleviation

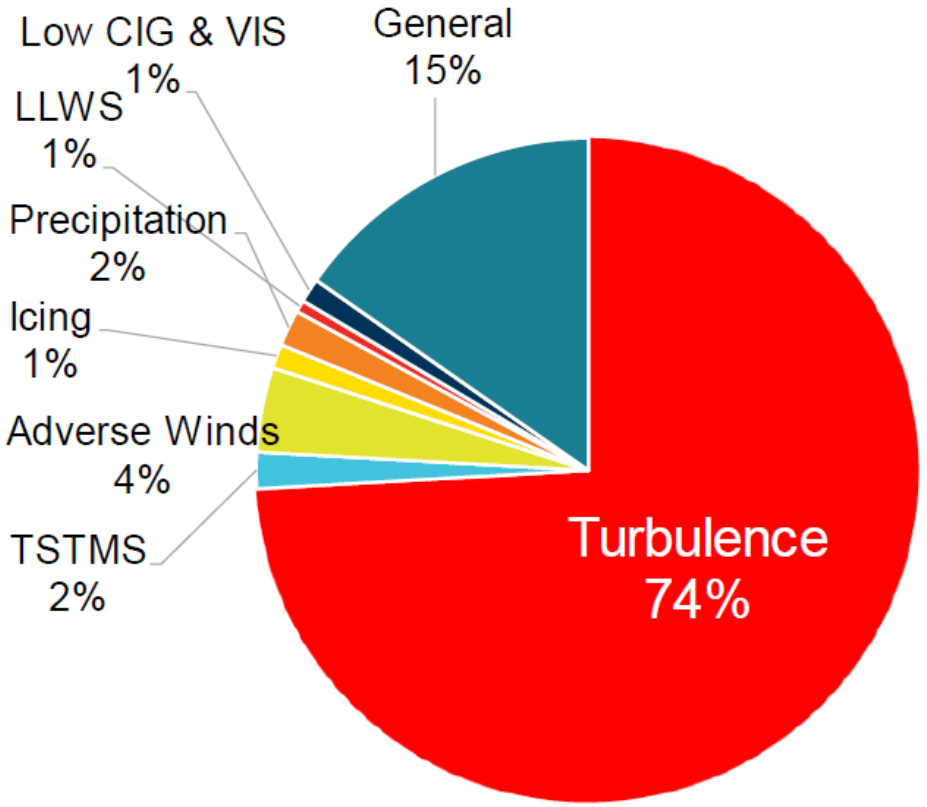
Improved Data Sharing

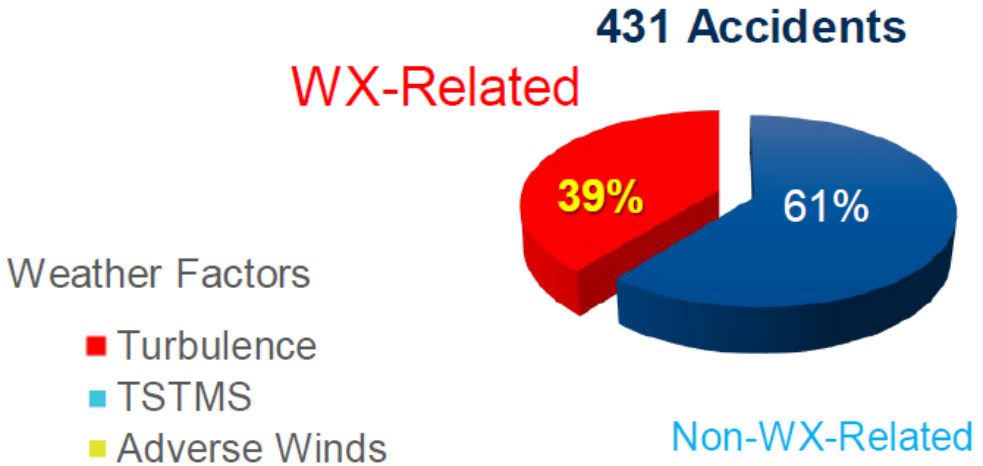
Atmospheric events drive continued solution development for new technologies and procedures to ensure safe airplane operations

As an industry, where do we begin?

Motivations – Turbulence a leading cause of air carrier incidents

Part 121 Air Carrier Weather-Related Accidents: 2008-2022





NTSB

Content courtesy of Don Eick (US NTSB)

Continued direction: Use of airplane as a comprehensive atmospheric sensing platform

Atmospheric Parameters:

- ☑Winds
- ☑Temperature
- ☑Icing
- ☑**Turbulence (EDR)**
- ❑Water vapor (restarting!)
- ❑Cloud and Ash
- ❑Space weather
- ❑Onboard weather radar downlink
- ❑Greenhouse Gases
  - ❑(CO_2, CH_4, N_2O, O_3 ,...)
- ❑Other aerosols

Mature & evolving

Starting work

Research needed

Causes of atmospheric turbulence & their detection/mitigation

Cause
Convergence & Deformation of Wind Field
Convection (i.e. thunderstorms)
Orographic (i.e. mountain wave)
Tropospheric wave breaking near tropopause
Transverse waves (e.g. from large mesoscale systems)
Wake turbulence

The ongoing turbulence events and the many different sources of atmospheric turbulence drive us to continue to **find new technology mitigation approaches**

Today's focus

Technology
Forecast & Nowcast Models
Aircraft observations
AI/Satellite
Onboard WXR
LiDAR
Gust Alleviation

EFB

How does it work?

Generate meteorological data to support airline world-wide operations

Meteorological Observations

Airline & Industry Sharing (e.g. IATA)

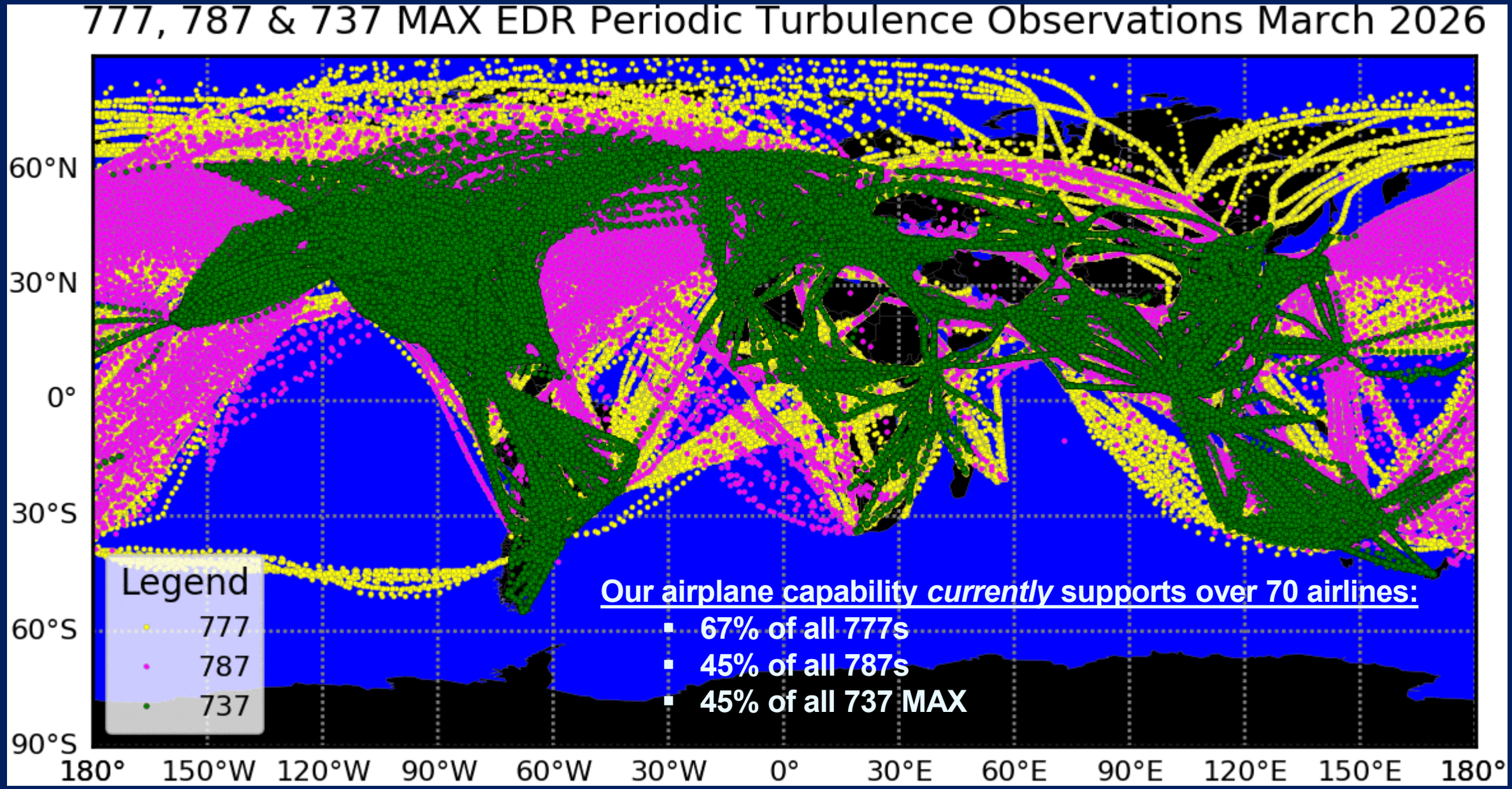
- Aggregate observations
- Parse
- Format
- API to deliver needed information

Better information of weather & turbulence

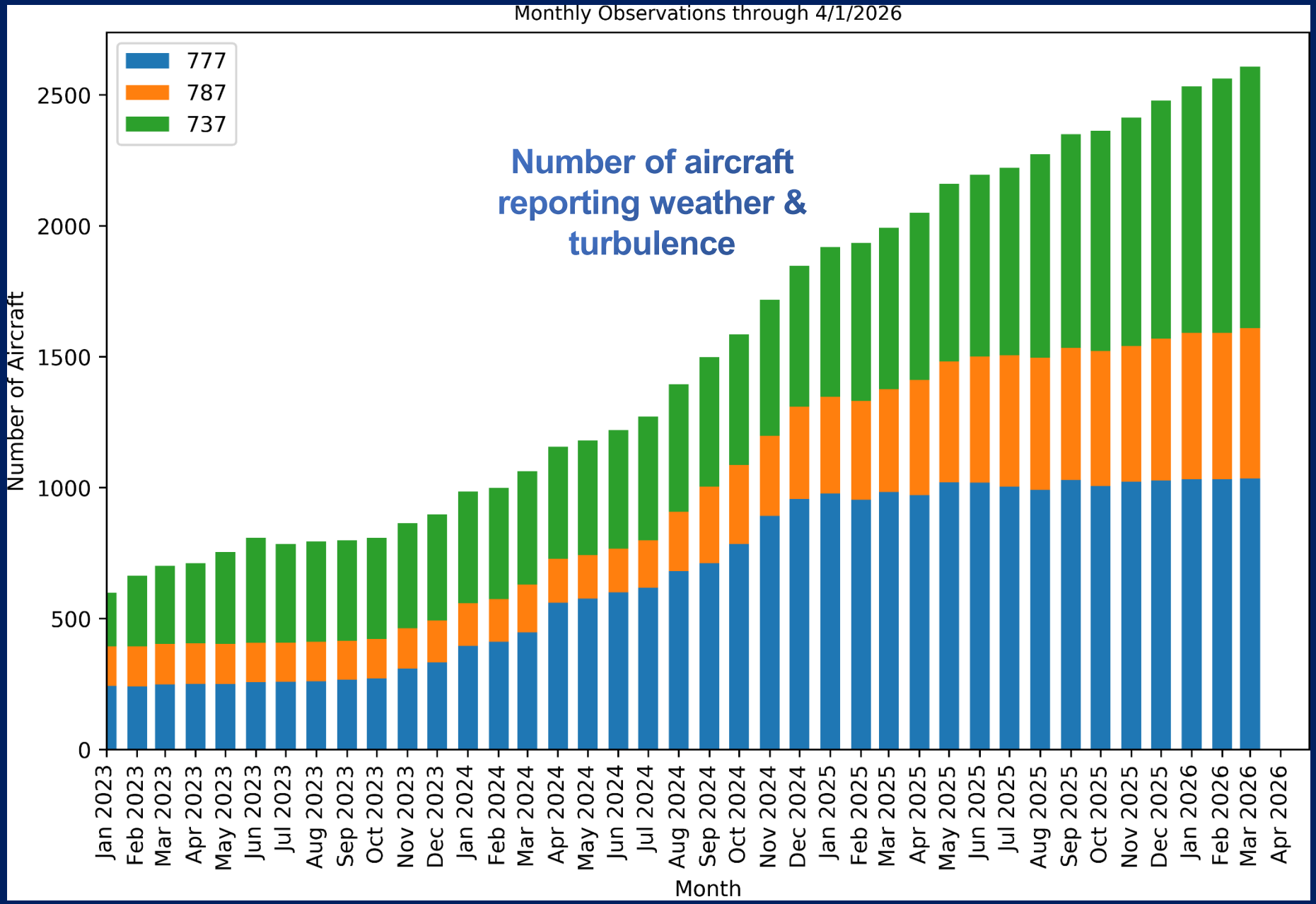
Dispatch & Flight Planning Applications

Other Users

- **Weather Services**
- **Researchers**
- **Regulators/ANSPs**
- **Other service providers**

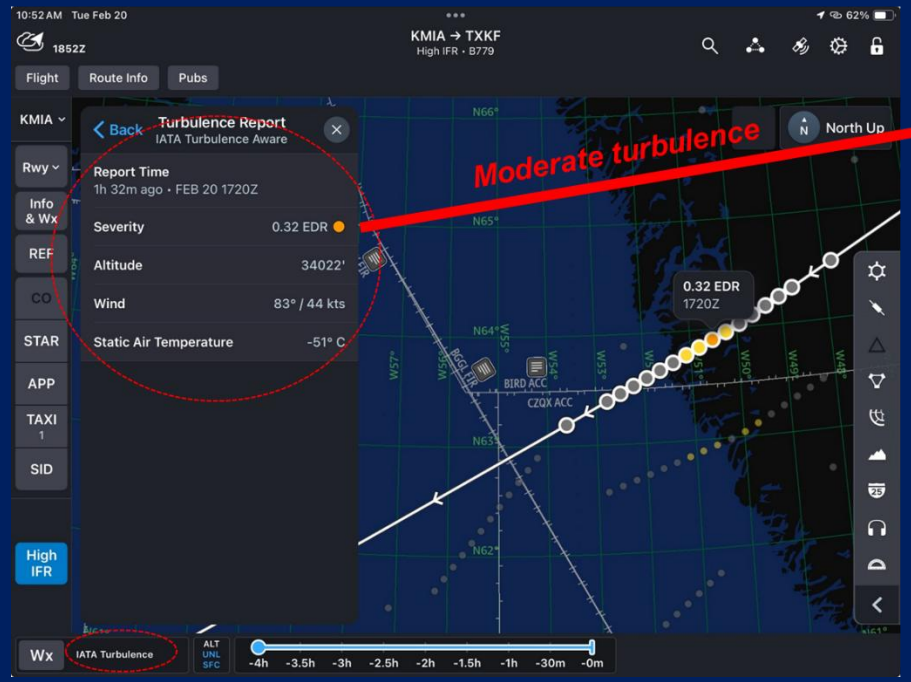

777, 787 & 737 MAX EDR Periodic Turbulence Observations March 2026
60°N
30°N
0°
30°S
60°S
90°S
180°
150°W
120°W
90°W
60°W
30°W
0°
30°E
60°E
90°E
120°E
150°E
180°
Legend
777
787
737
Our airplane capability *currently* supports over 70 airlines:
67% of all 777s
45% of all 787s
45% of all 737 MAX

Monthly 777, 787, and 737 MAX Weather & Turbulence Observations

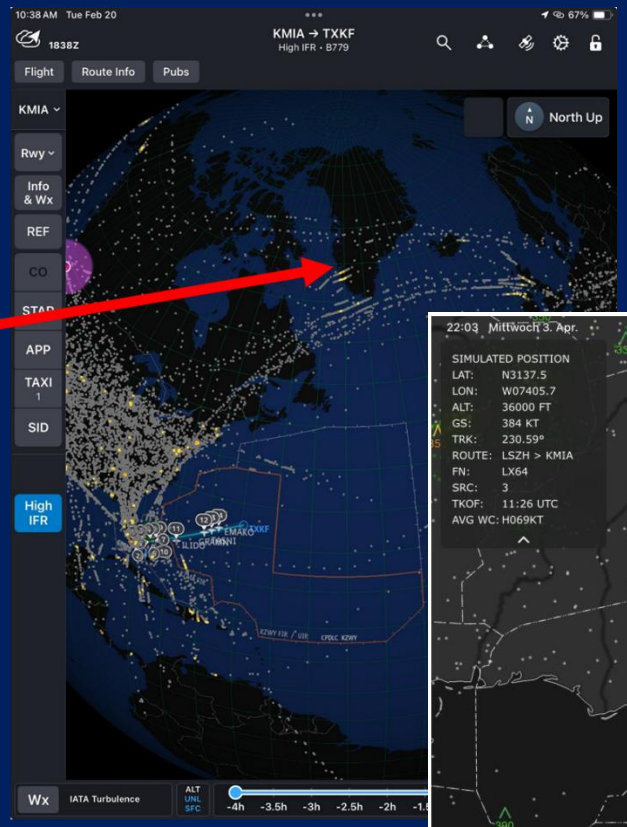


Availability in applications & services

- ❑ Jeppesen FliteDeck Pro
- ❑ SITA eWAS
- ❑ Many others: We are happy to assist as necessary!



Jeppesen FliteDeck Pro



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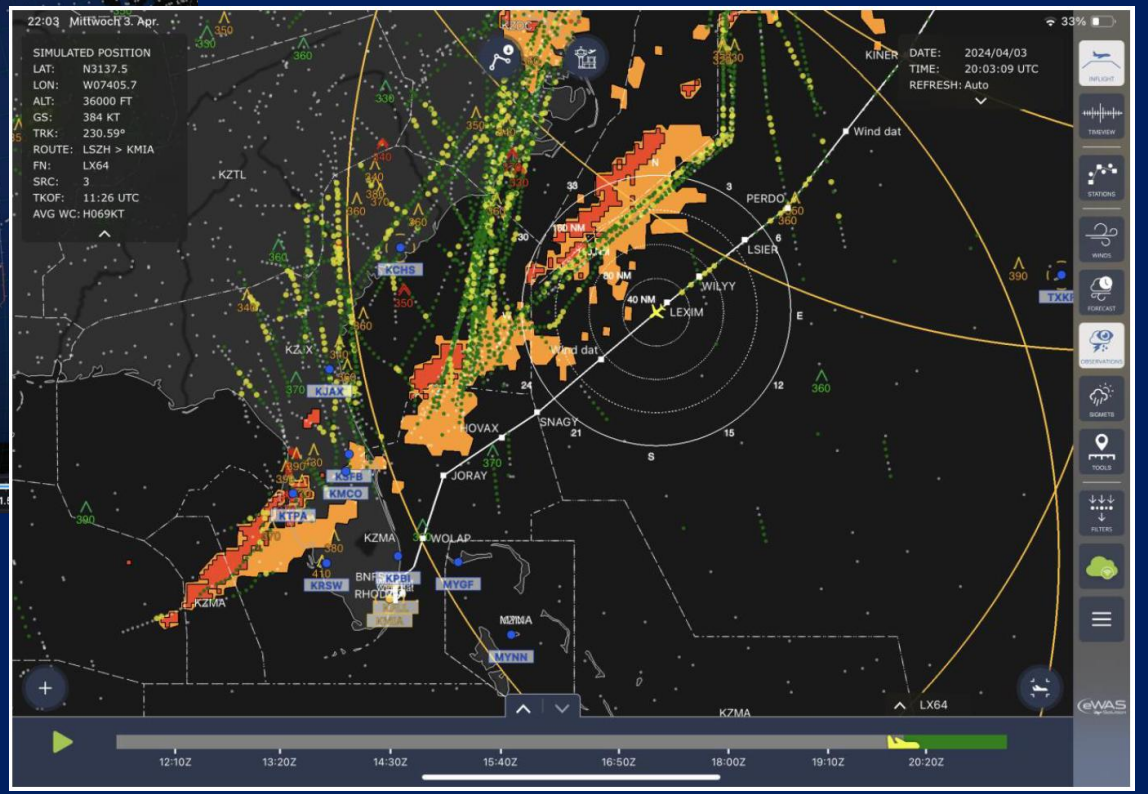
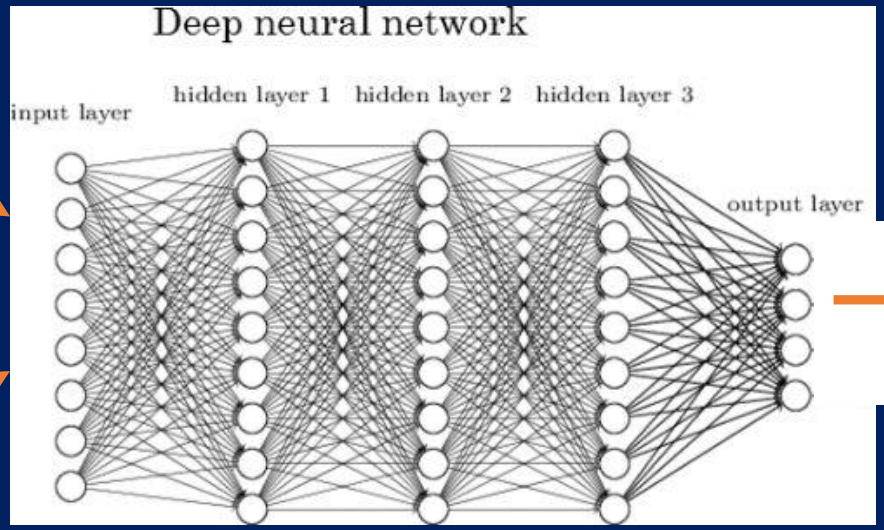


AI: UW-CIMSS Turbulence Model

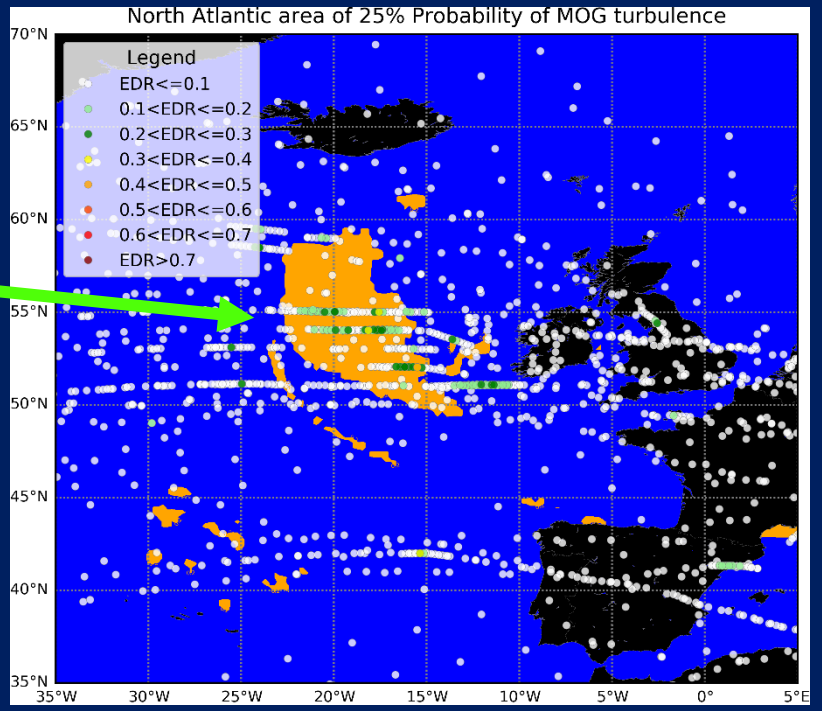
Use satellites to predict moderate-or-greater (MOG) turbulence

64 x 64 image pixels
1. WV (ch 8)
2. IR (ch 13)
3. Surface elevation

Context from the NWP model



Good Results!



- **Prob. of MOG @ 40-41 kft**
- **Prob. of MOG @ 38-39 kft**
- **Prob. of MOG @ 36-37 kft**
- **Prob. of MOG @ 34-35 kft**
- **Prob. of MOG @ 32-33 kft**
- **Prob. of MOG @ 30-31 kft**

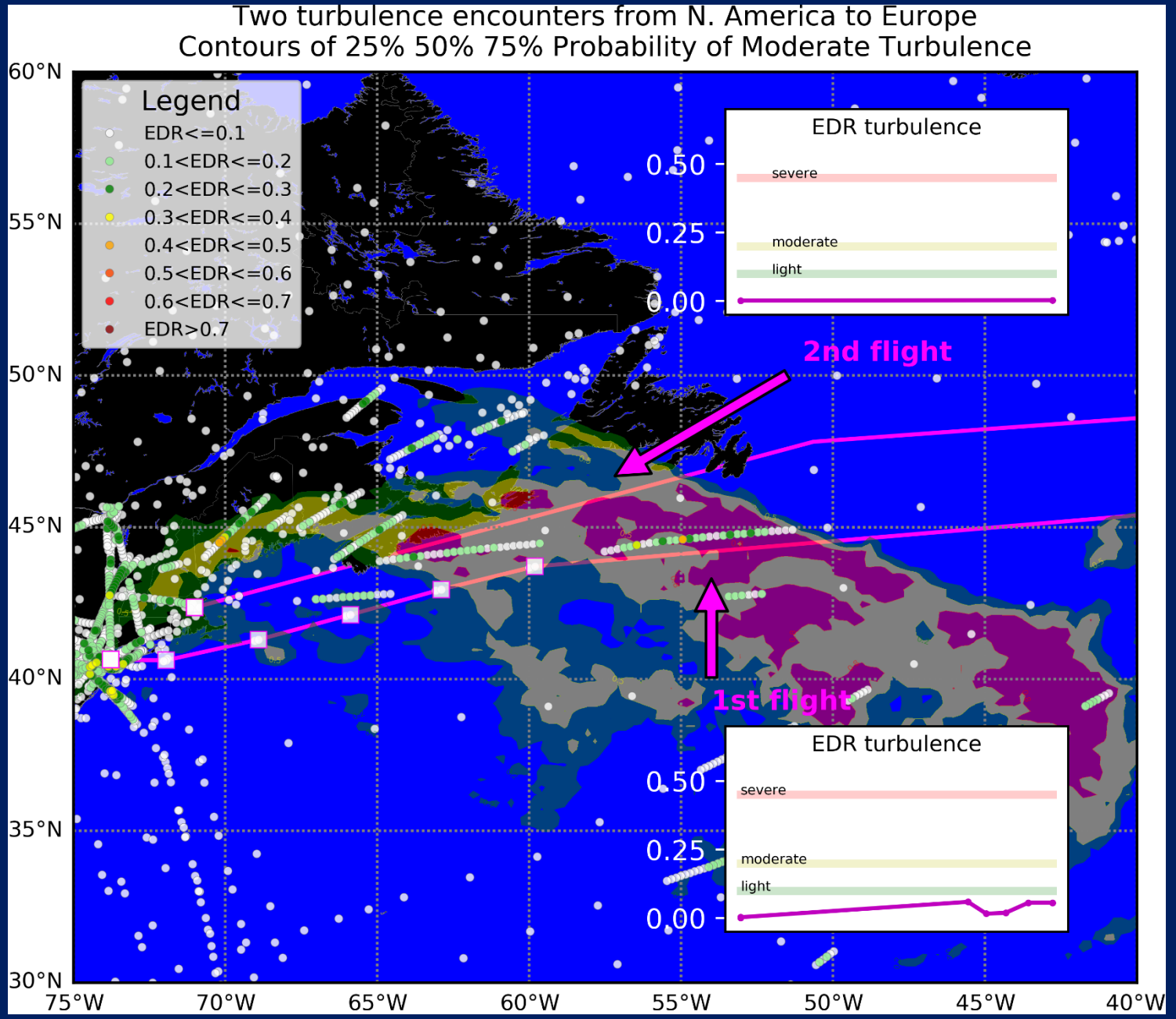
- **AI model is trained using aircraft EDR observations**
- For every 4x4 pixel spot on the satellite image
- Generates probability of MOG *over a 10-minute segment*
- Takes 34 seconds to calculate a full-disk product

Content courtesy of Dr. Tony Wimmers (U. Wisconsin)

Advantage: Satellites are always observing & cover large regions!

Feature detection is improving

- Merging forecast/nowcast with aircraft observations gives valuable guidance
- AI satellite-derived turbulence probability is gaining skill in detecting turbulence hazards



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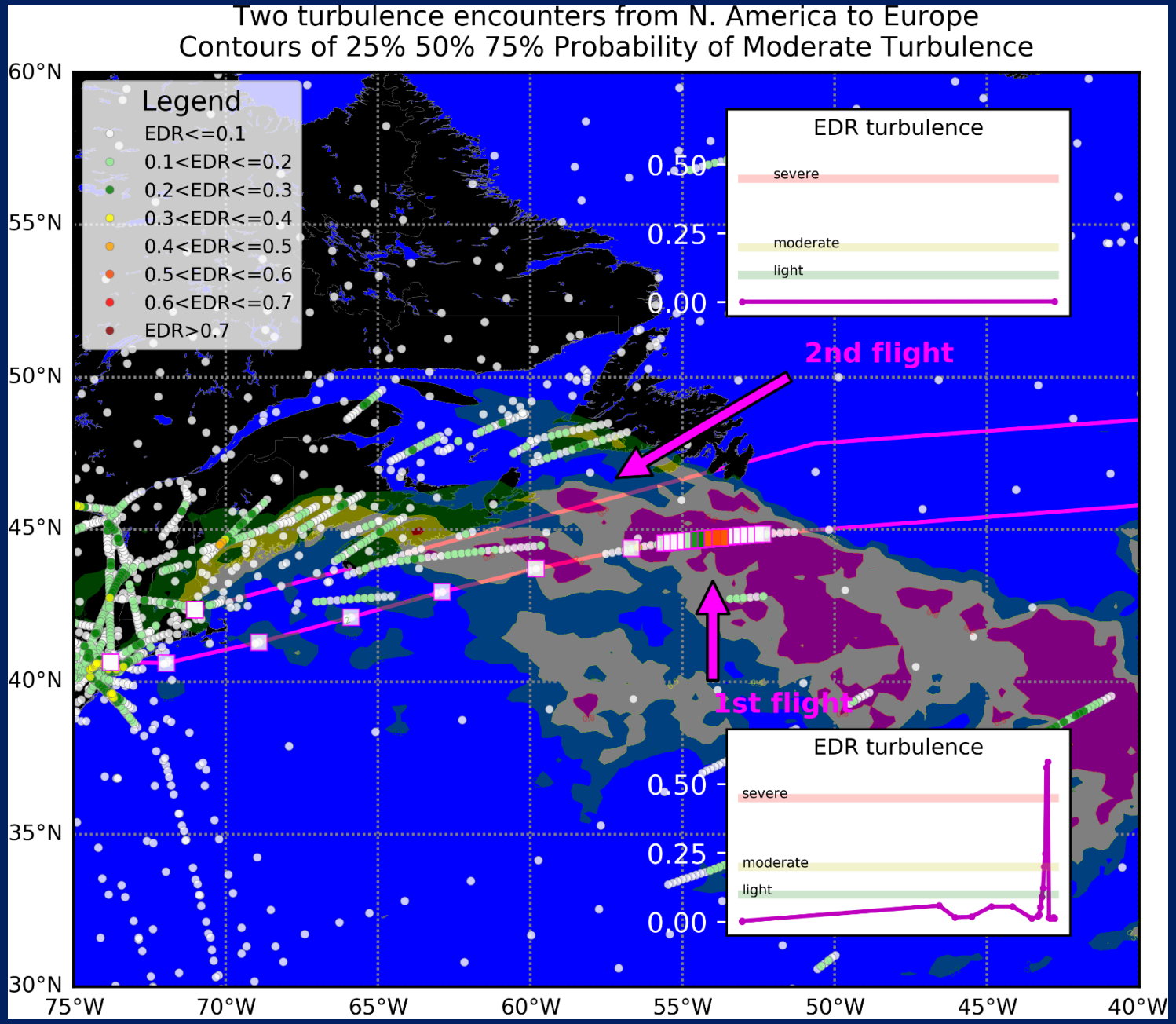

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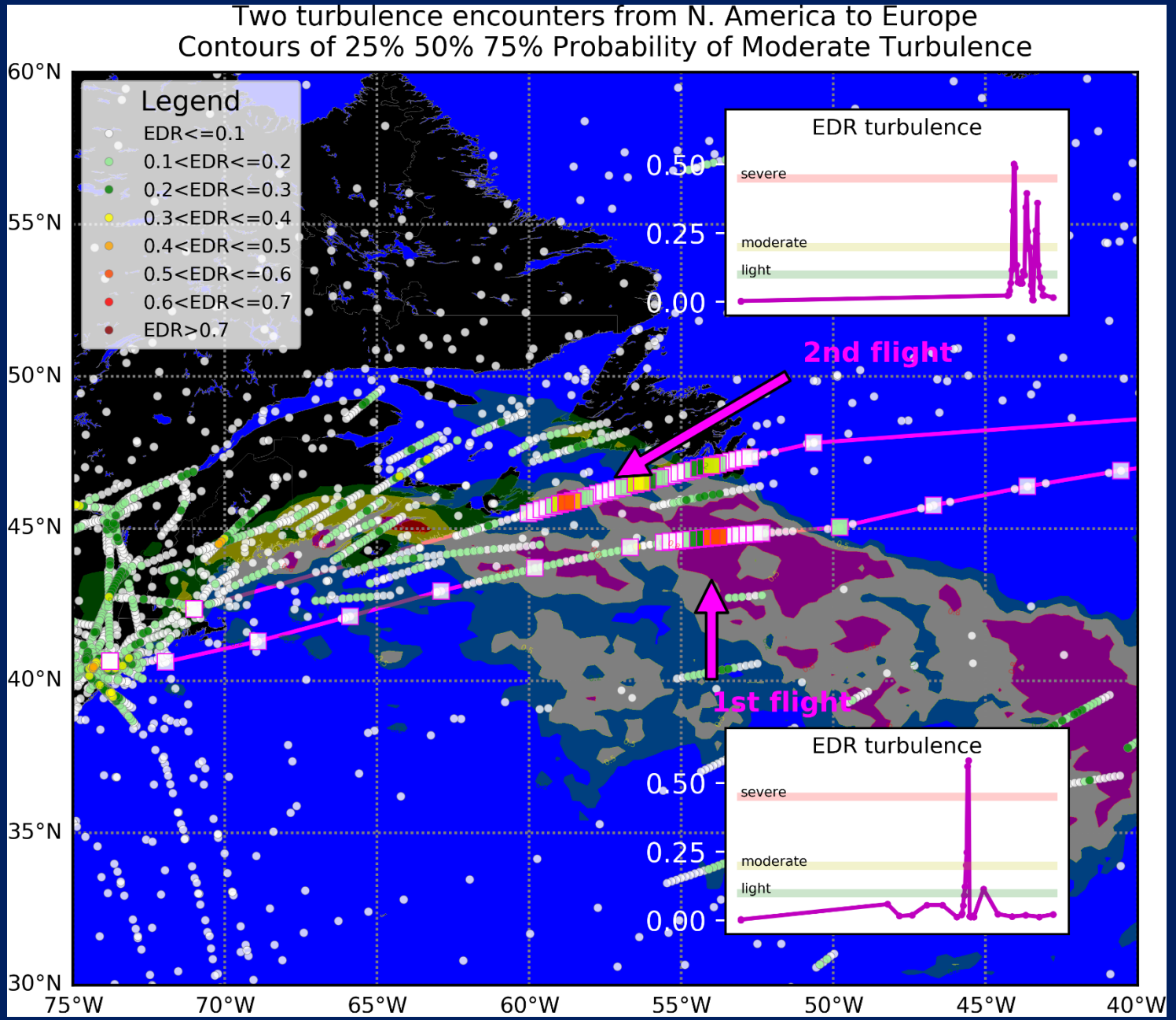
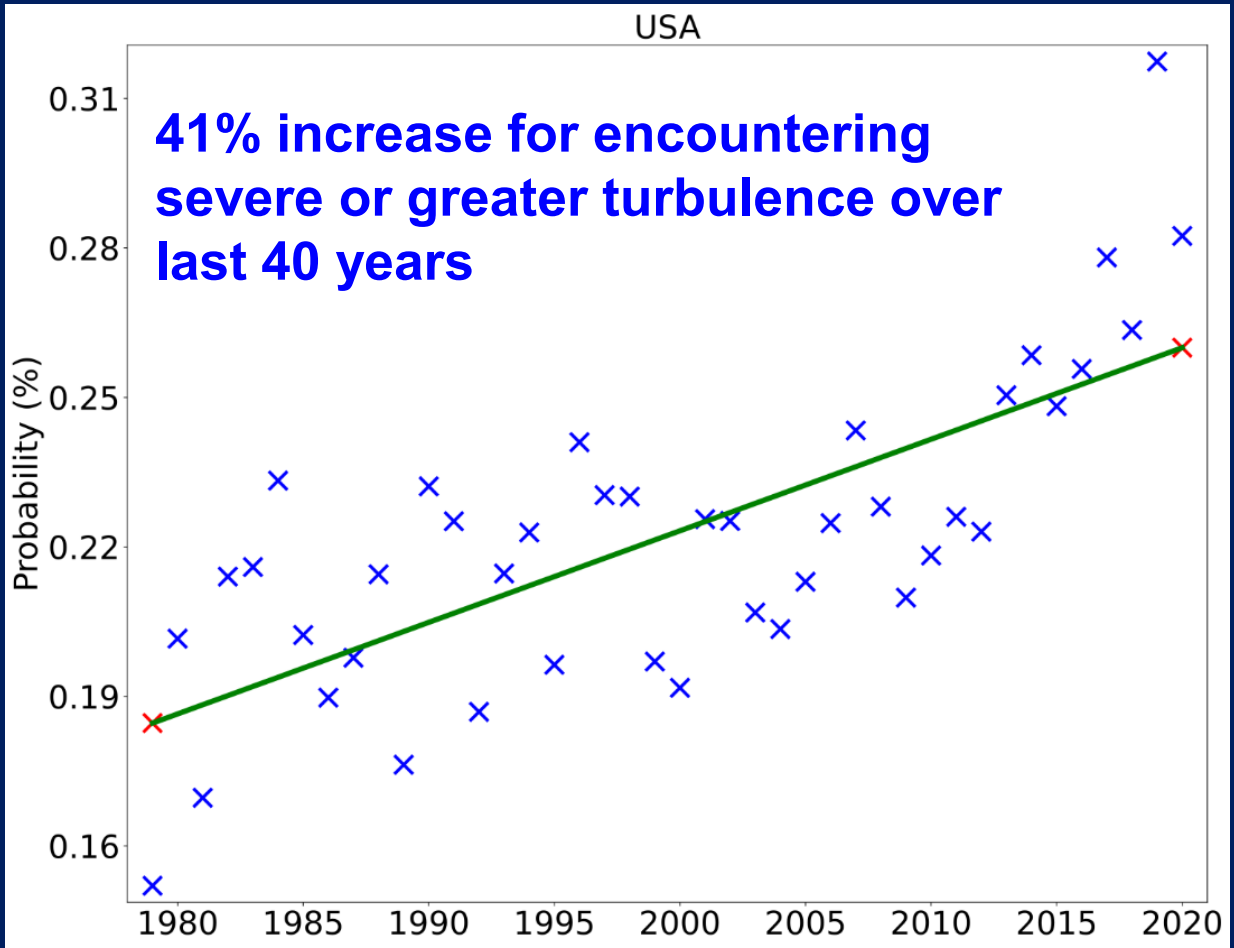
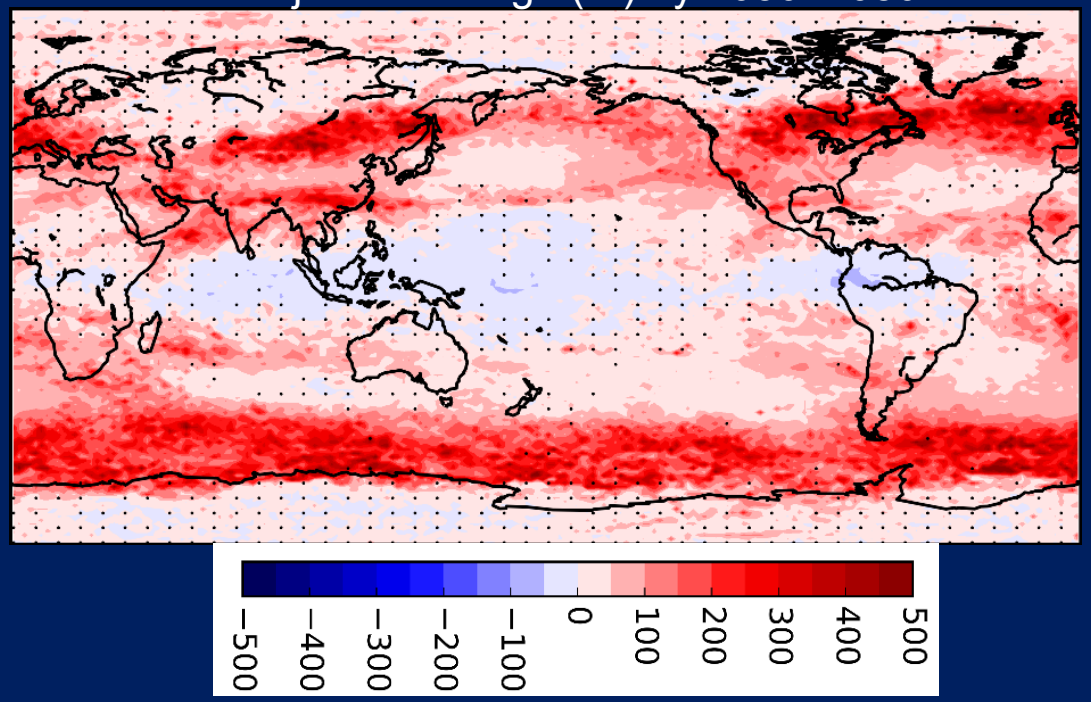


Modeled Past & Future Trends in Turbulence



From 2050-2080, a study shows continued changes in moderate or greater turbulence



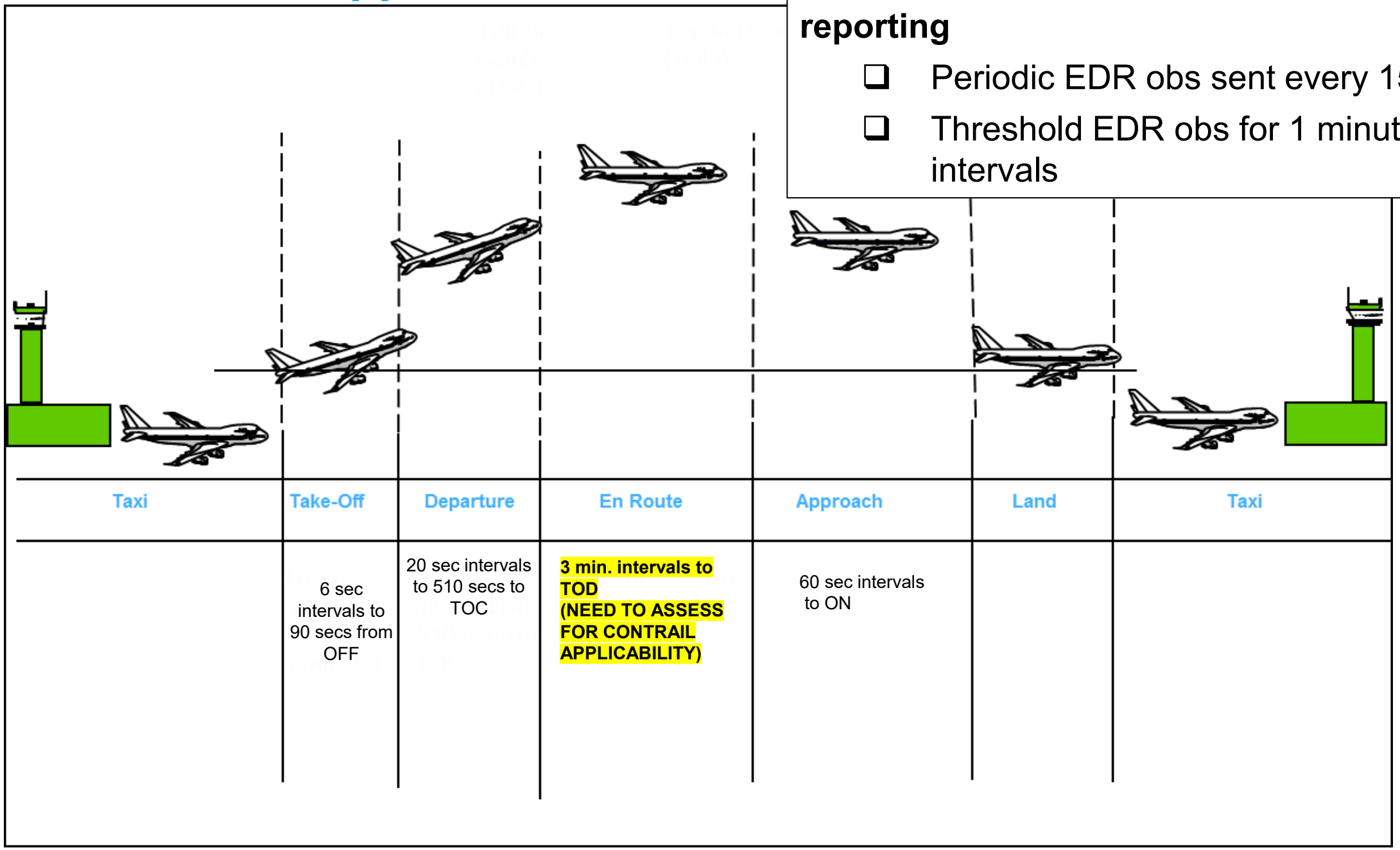
Content courtesy of Dr. Paul Williams (U. Reading)

Scientific studies continue to refine past & future estimates

WMO AMDAR support

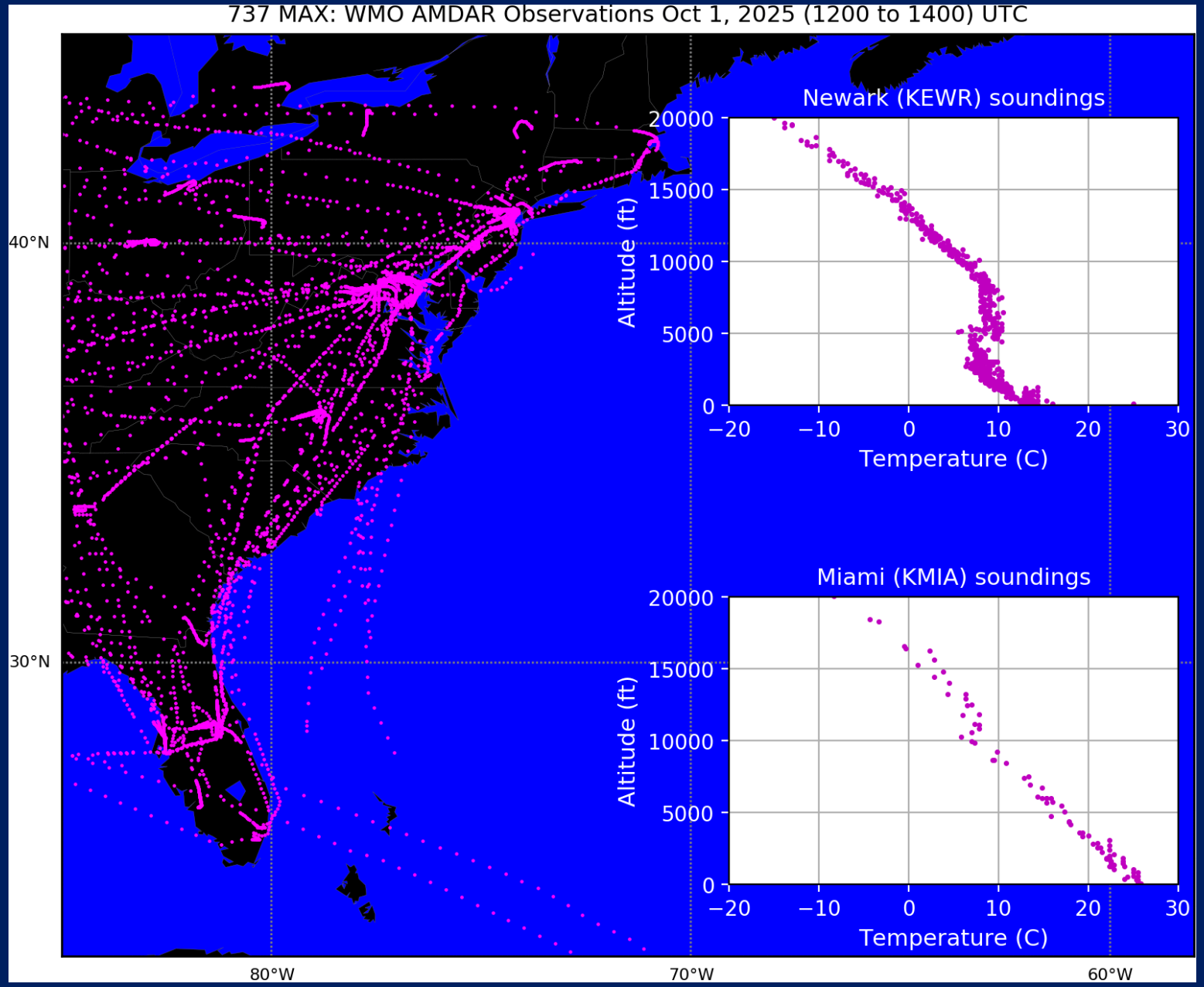
Contrast AMDAR/MDCRS with "EDR" reporting

- ❑ Periodic EDR obs sent every 15 minutes
- ❑ Threshold EDR obs for 1 minute intervals



Boeing support for WMO AMDAR format (ARINC 620-10)

- Boeing supports the AMDAR program
- 3 US airlines already have hundreds of aircraft reporting
- WMO is encouraging other regions (e.g. South America & Africa)
- **Aircraft observations are cited as being the most important to improve weather models**



Boeing's recent support for Meteorological Reporting

1. Aircraft Weather & EDR Turbulence Reports

- 777-200/-200LR/-300/-300ER/Freighter/-8/-9
- 787-8/-9/-10
- 737-7, 737-8, 737-8200, 737-9, 737-10

The downlinked information content includes:

- observation date and time
- aircraft identification
- flight number
- departure
- destination
- latitude
- longitude
- altitude
- static air temperature
- wind direction
- wind speed
- icing
- **mean/peak EDR turbulence**
- software provisions for humidity & cloud properties on certain models

2. WMO AMDAR – Available for interested customers

- **The WVSS-II water vapor software provision is already included on 737 MAX and 777X aircraft**

This capability is available at aircraft delivery or for existing fleet

Summary

- Airlines typically mitigate elevated turbulence by changing altitudes and recommending seatbelts
- Boeing's meteorological reporting continues to increase the amount of data for aviation & meteorological communities
- As an industry, we need more aircraft types and from other segments to contribute to aircraft observations
- Technologies & Standards are being worked in parallel
- For the emerging technologies that involve sensors, we need a "pull" with viable business model(s)
- **While atmospheric turbulence is likely increasing with climate change, our industry's ability to mitigate it continues to improve.**
  - **Aircraft observations have proven to be valuable, but we also desire unbiased observations (e.g. satellite data)**

Above: Boeing 737-10 ecoDemonstrator flight test program in conjunction with **NASA** DC-8 testing various sensors (Oct 2023).