Water Vapor, Contrails, and relevance to WMO AMDAR

WMO Workshop on Aircraft-based Water Vapor Measurements for Forecasting and Aviation

Original: December 8, 2023
Update: August 13, 2024 for the National Academies of Sciences, Engineering & Medicine

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Agenda - emphasis on industry development supporting NOAA & WMO

- Background & Motivations
- Current state for aircraft meteorological observations
- Emerging needs/requirements relevant to persistent & temporary contrails (i.e. water vapor)
- Some industry activity towards sensor & reporting needs

Background & Motivations – industry perspective

- Much of our aviation industry shares the views outlined by several CTOs at Farnborough this year: https://www.boeing.com/content/dam/boeing/boeingdotcom/sustainability/pdf/cto-agreement-letter.pdf
- We jointly call for increased research funding to develop the science needed to underpin technology choices, operational changes and policy decisions. We will continue to engage academia, the global climate and weather modeling community, government research organizations and industry partners to advance seven priorities for research:

1. **Improve understanding of contrail formation, persistence, and climate impact**. Progressing the science of contrail physics combined with increasing the fidelity of **upper tropospheric *humidity* data** in global climate and weather modeling will enable more accurate contrail forecasts and analysis data sets for performing impact assessment.
2. **Improve understanding of emissions properties** …
3. **Build research on aerosol cloud interactions …**
4. **Improve understanding of NOX radiative effect and uncertainty …**
5. **Improve understanding of the interdependencies and trade-offs …**
6. **Establish and improve common models for quantifying the effect …**
7. **Research on airspace network impacts of mitigation …**

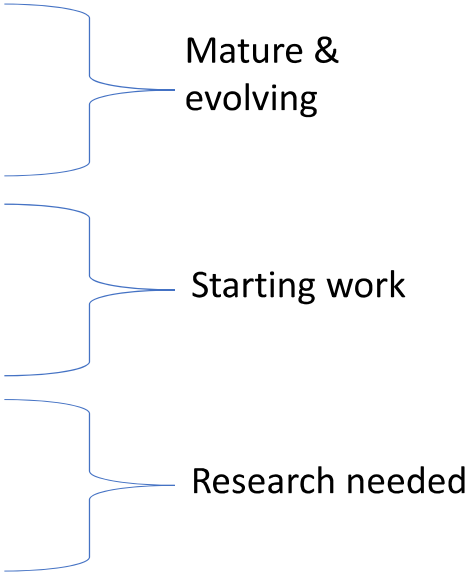
See link above for details

Today's presentation

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

Atmospheric Parameters:

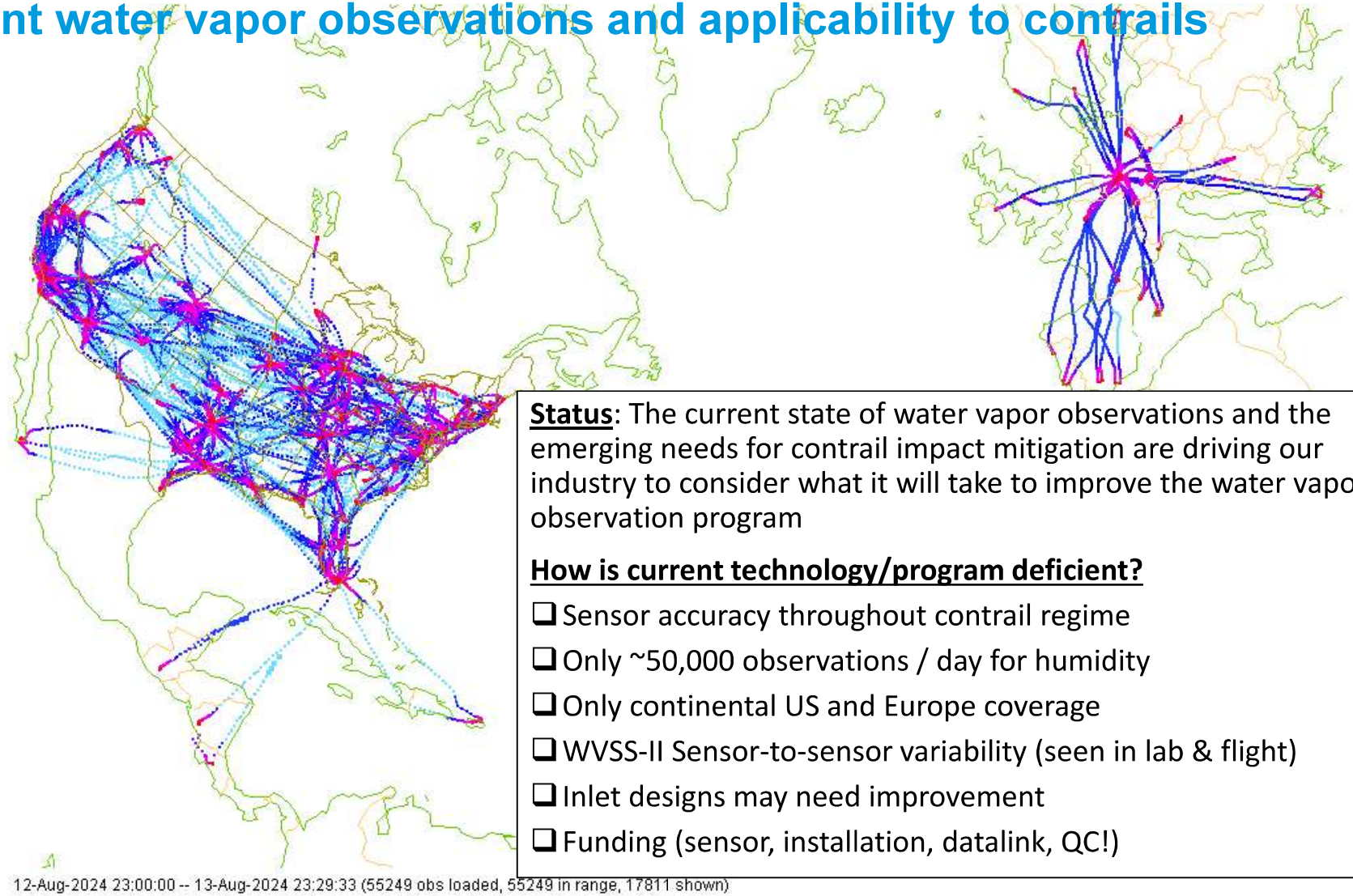
- ☑ Winds
- ☑ Temperature
- ☑ Icing
- ☑ Turbulence
- ❑ Water vapor applicable to contrails[1]
- ❑ Greenhouse Gases
  - ❑ (CO_2, CH_4, N_2O, O_3 ,...)
- ❑ Cloud and Ash
- ❑ Onboard weather radar downlink
- ❑ Other aerosols
- ❑ Space Weather



Notes:

1. Related Needs: WMO Observing System Simulation and Experiment (OSSE)
   - We may need improved models for temporal/vertical/horizontal resolution, assimilation method & microphysics
   - Need accurate forecasts, nowcasts, and reanalysis datasets

AMDAR Current water vapor observations and applicability to contrails

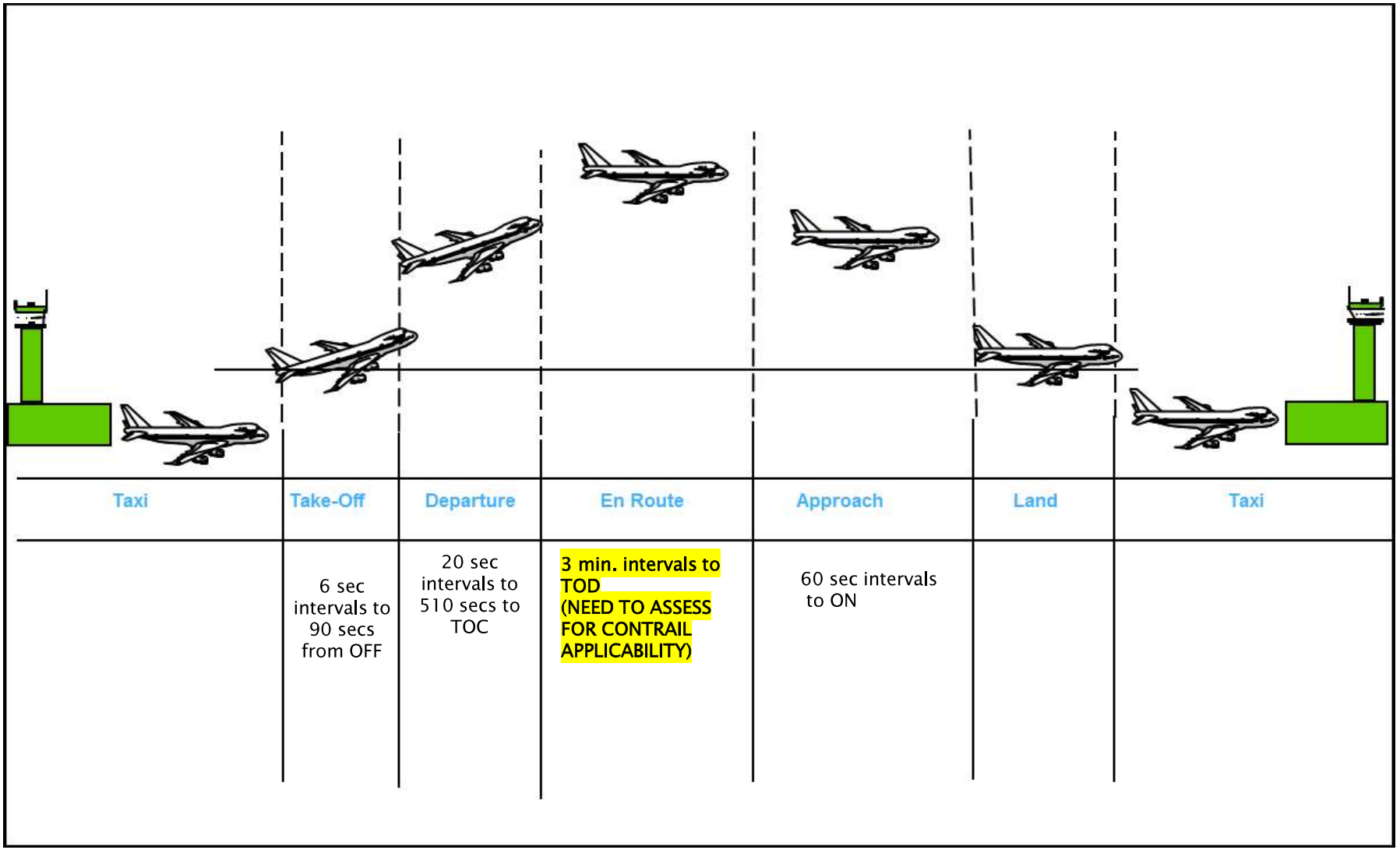


Status: The current state of water vapor observations and the emerging needs for contrail impact mitigation are driving our industry to consider what it will take to improve the water vapor observation program

How is current technology/program deficient?

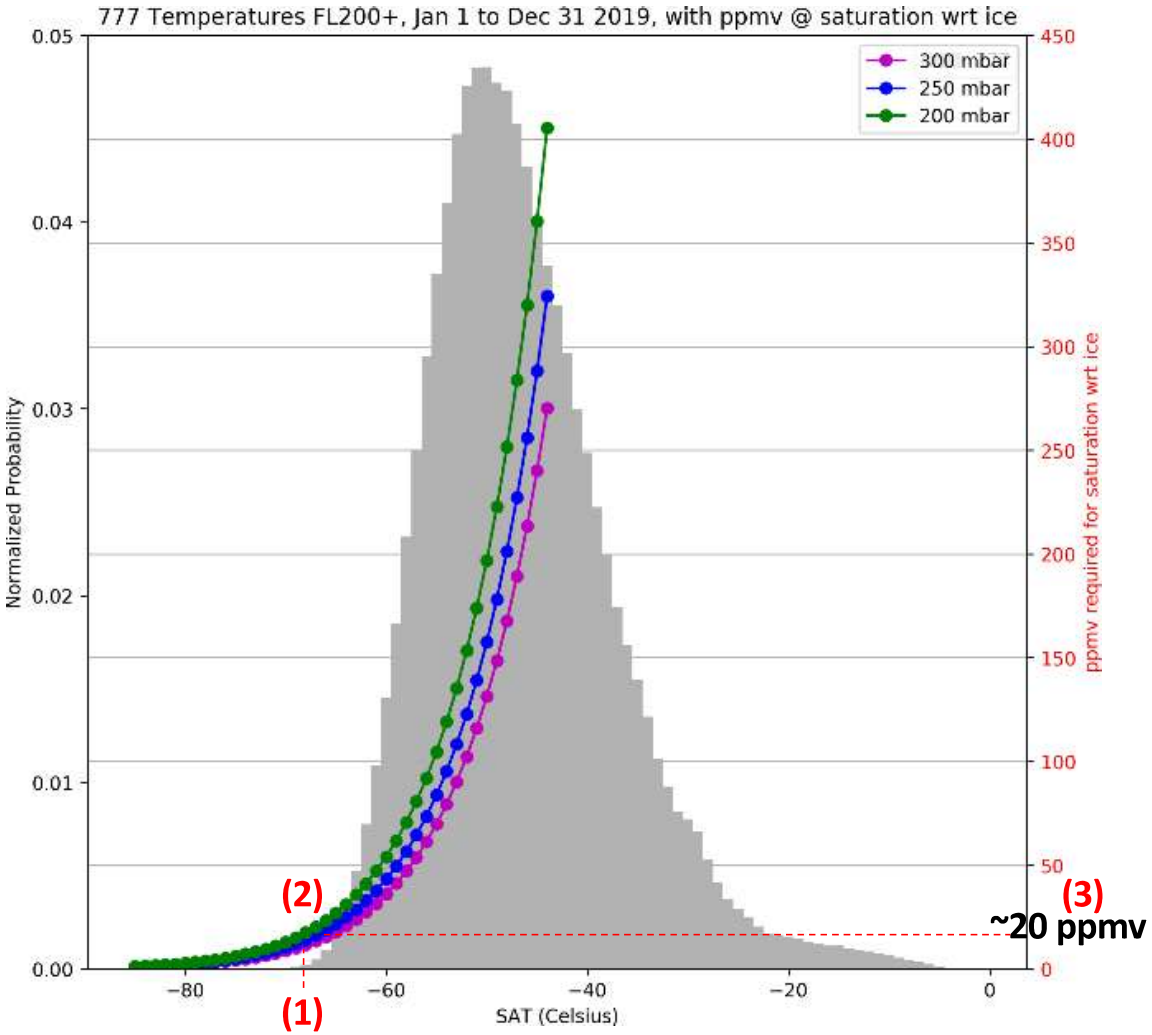
- ❑ Sensor accuracy throughout contrail regime
- ❑ Only ~50,000 observations / day for humidity
- ❑ Only continental US and Europe coverage
- ❑ WVSS-II Sensor-to-sensor variability (seen in lab & flight)
- ❑ Inlet designs may need improvement
- ❑ Funding (sensor, installation, datalink, QC!)

AMDAR Current state and applicability to contrail use case



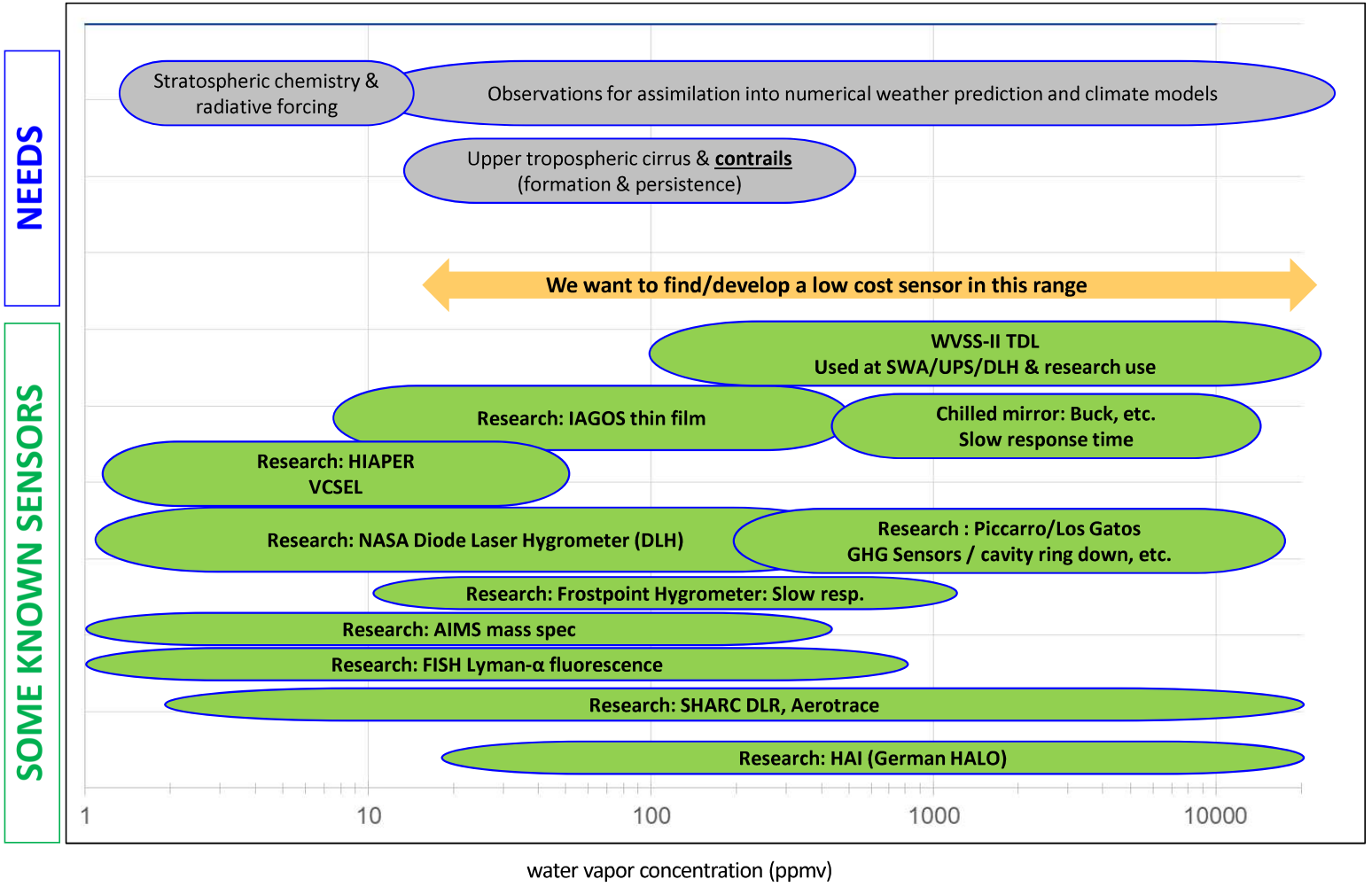
Estimating requirement for lower range of sensor measurement

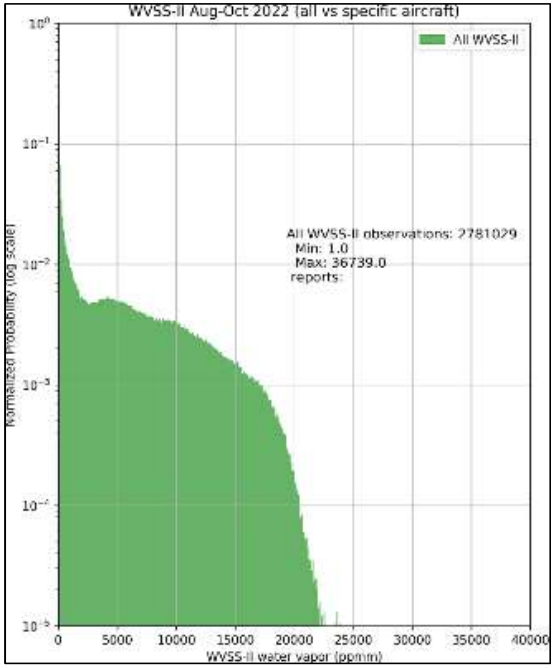
- We know *in situ* temperature ranges fairly well for different aircraft.
- Created statistical analysis of reported temperature using a probability distribution function derived from a histogram, which provides reasonable results
- We should consider the lowest, limiting temperatures **(1)**
- Consider cruise altitudes (300, 250, 200 mbar) **(2)**
- We "back into" the needed performance so that we are accurate near ice supersaturation (100%RHI)
- It's apparent that we desire performance lower than 50ppmv, but don't need 10ppmv **(3)**
- **We estimated 20 ppmv as a reasonable goal for lower sensitivity**
- Other requirements are in development

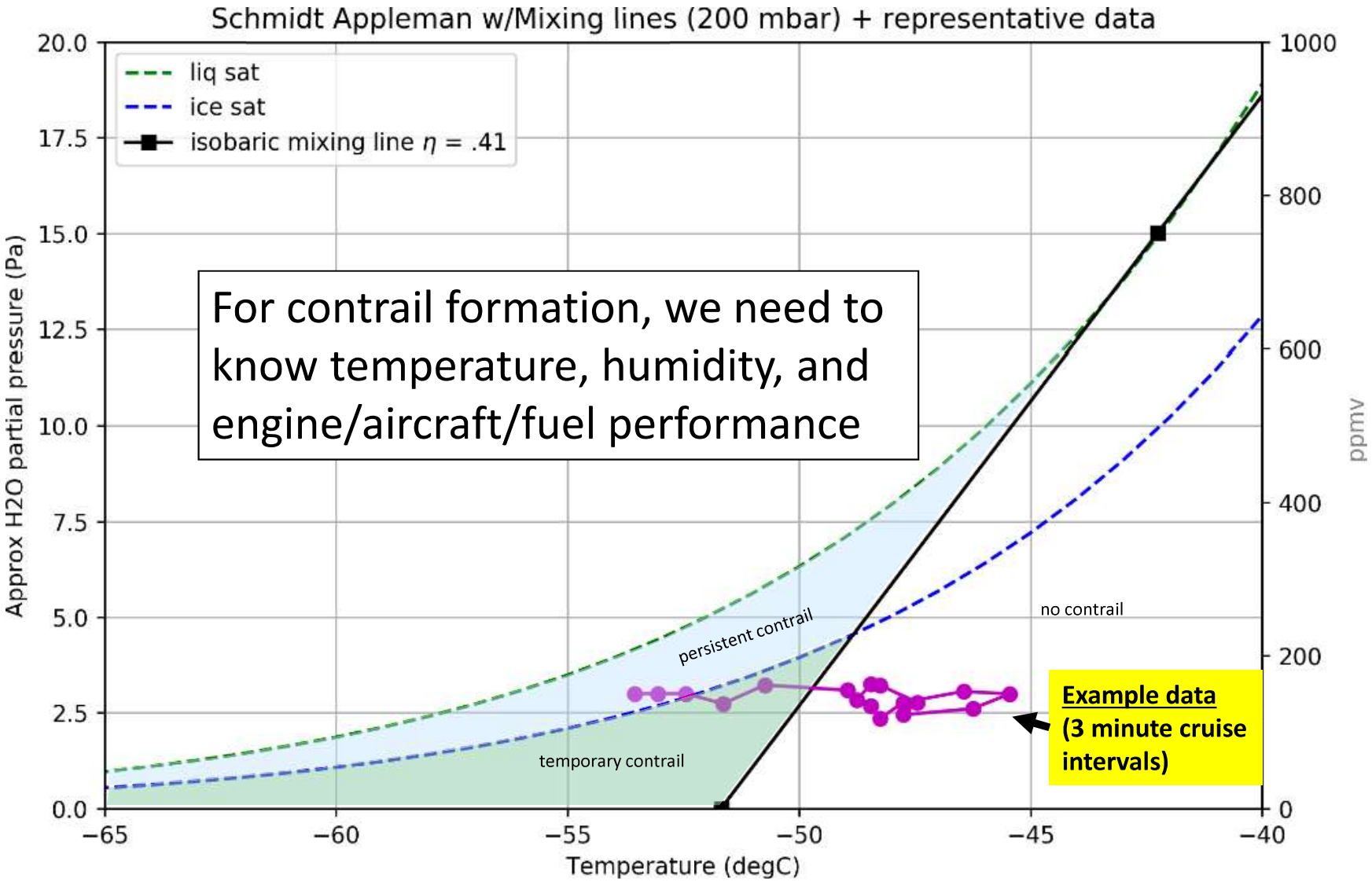


Water vapor spans over 4 orders magnitude in concentration (**ppmv**)

Industry is working to develop a sensor to span range from ~10 to ~25,000+ ppmv






Schmidt Appleman w/Mixing lines (200 mbar) + representative data
liq sat
ice sat
isobaric mixing line η = .41
For contrail formation, we need to know temperature, humidity, and engine/aircraft/fuel performance
persistent contrail
temporary contrail
no contrail
Example data
(3 minute cruise intervals)
Approx H2O partial pressure (Pa)
Temperature (degC)
ppmv
20.0
17.5
15.0
12.5
10.0
7.5
5.0
2.5
0.0
1000
800
600
400
200
0
−65
−60
−55
−50
−45
−40

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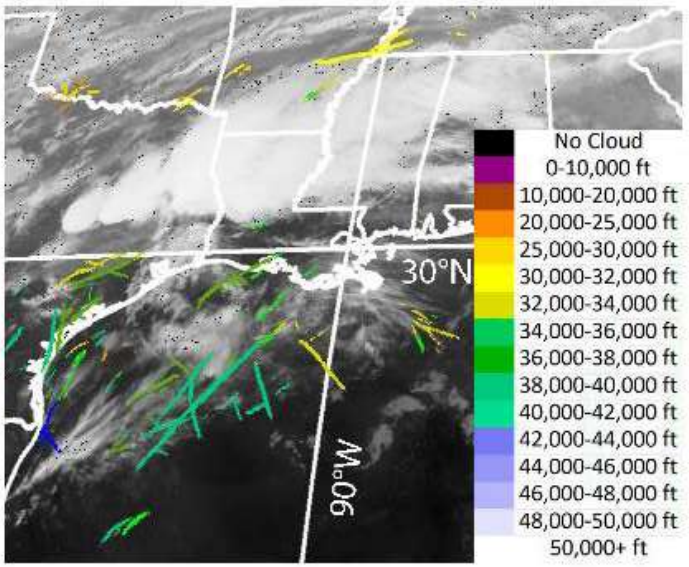
Contrail **IN**formation for **C**ollaborative **O**perations

- **Objective:** Mature technologies for near-term mitigation of persistent contrails that contribute to climate impact
- **Team:** Avionics sensor suppliers, satellite meteorologists, Boeing engineers
- **Approach**
  - Develop water vapor sensors that meet upper tropospheric requirements, remaining cost effective in order to enter the commercial carrier market. Sensors should run unattended in extreme environments.
  - Blend satellite-based observations, deep learning and emerging observations from water vapor sensors
  - Develop a comprehensive approach for operational mitigation of strongly warming persistent contrails

Boeing encourages collaboration with other suppliers as well



Hoffman et al., *Remote Sensing*, 2023, 15, 2854. https://doi.org/10.3390/rs15112854

What deliverables did the WMO workshop recommend?

- Short publication of recommendations: Need for in situ upper air water vapor measurements for contrail prediction and avoidance
- Scientific paper: Need for in situ upper air water vapor measurements for contrail prediction and avoidance
- Define requirements for numerical weather prediction of humidity as a basis for contrail predictions
- Benefits of water vapor measurements for airlines
- Roadmap

The World Meteorological Organization (WMO) organized a workshop on Aircraft-based Water Vapour Measurement for Aviation in December 2023. The workshop was hosted by the Deutscher Wetterdienst (DWD), at their headquarters in Offenbach, Germany.

https://community.wmo.int/en/meetings/wvm-workshop-2023

Final comments

- The aviation industry needs reduced uncertainties in the science of persistent contrail impact to make decisions on mitigation approaches (aircraft/engine, fuel, operational).

- The debate is currently unsettled with insufficient scientific consensus.

- Significant research and flight test campaigns across both Europe and North America have been taking place to help obtain some necessary data.