On the impact and benefits of AMDAR Water Vapor Observations to operational forecasting – A Tutorial

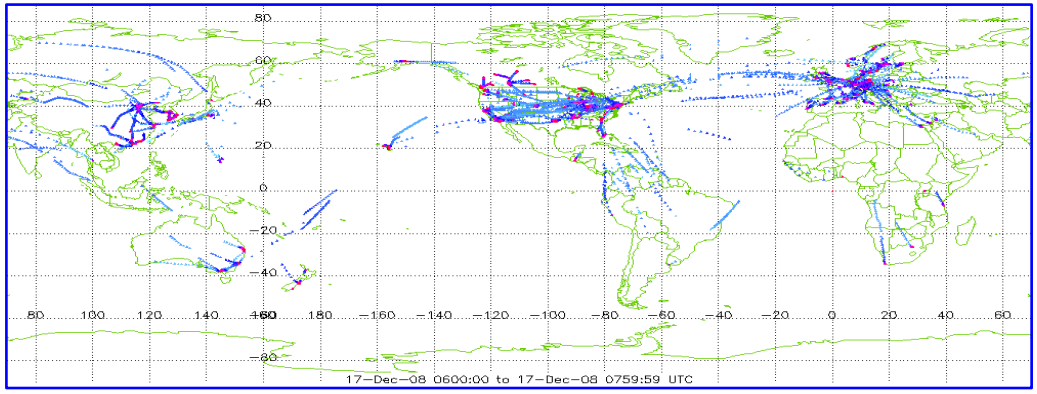
or

Offering A New Opportunity for Validating Satellite Moisture Products

Ralph Petersen[1], Brett Hoover[1], Anthony Mostek[1], Lee Cronce[1], Tim Wagner[1], Skyler Williams[1], Richard Mamrosh[2], Randy Baker[3], Patrick Daley[4], and Nancy Baker[4]

[1] University of Wisconsin-Madison Cooperative Institute for Meteorological Satellite Studies (CIMSS), Madison, WI
[2] National Weather Service (NWS) Forecast Office, Green Bay, WI
[3] United Parcel Service (UPS), Louisville, KY
[4] Marine Meteorology Division, Naval Research Laboratory, Monterey, CA

Global Distribution of AMDAR Temp/Wind Observations



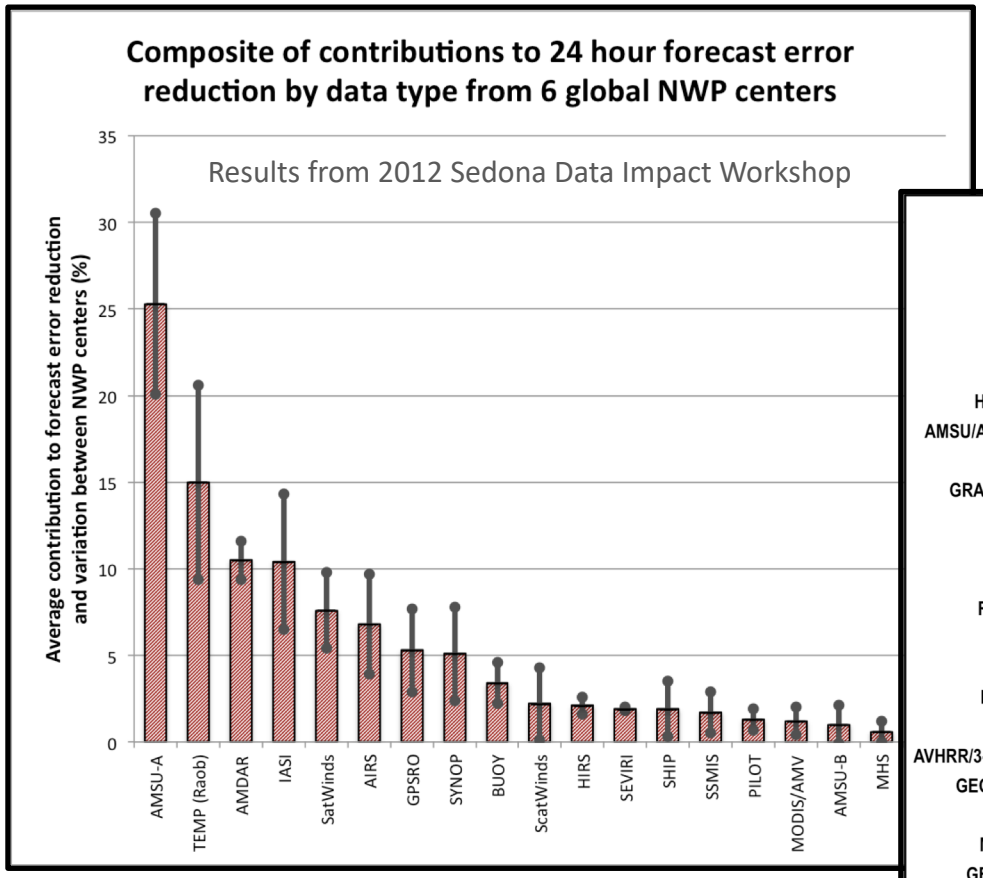
Several Years Old, but still interesting – Credit: Bill Moninger, ESRL

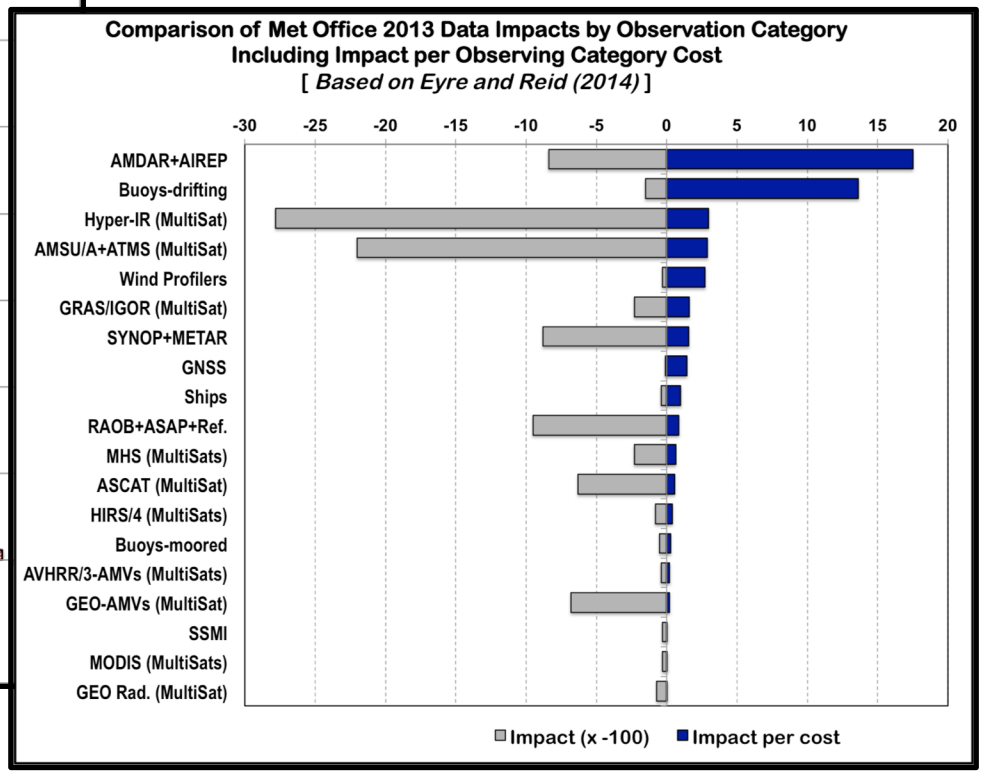
Water Vapor Sensing System - WVSS

Initially UPS, now dominated by SouthWest

Background about AMDAR Impacts

- ***AMDAR Temperature and Wind*** data continue to be among 4-5 most important data sources for global assimilation across multiple NWP centers
  - Extremely Cost Effective (Cost/Impact)
    - Profiles could backfill for lost rawinsondes if moisture is included



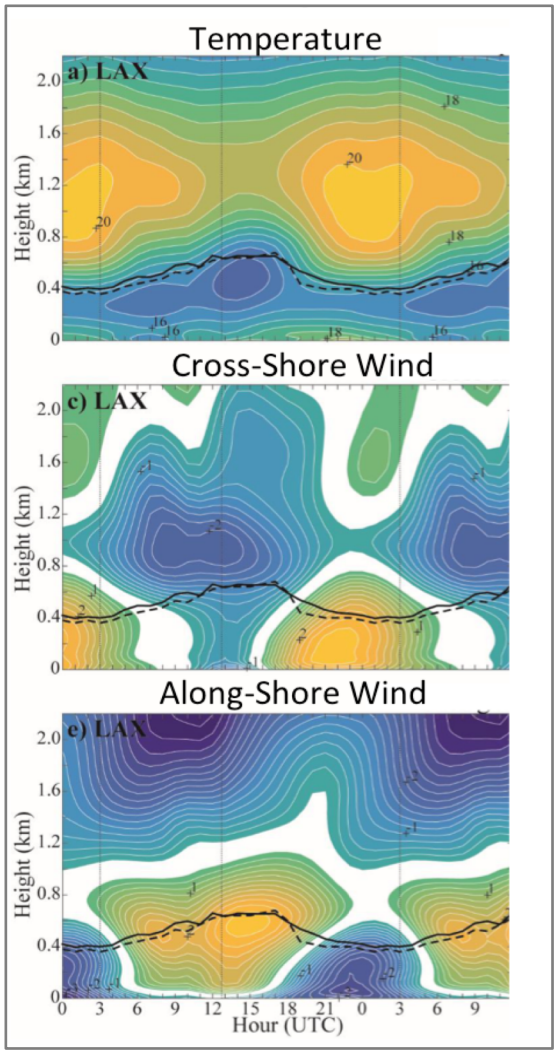


Background about AMDAR Impacts

- ***AMDAR Temperature and Wind*** data continue to be among 4-5 most important data sources for global assimilation across multiple NWP centers
  - Data are finding mesoscale applications outside of 'weather' and NWP
    - Example of an Applied Climate study

From: Rahn, D. A. and C. J. Mitchell, 2016: Diurnal climatology of the boundary layer in southern California using AMDAR Temperature and Wind Profiles. J. Appl. Meteor. Climatol.

- *Used 14 years of AMDAR profiles to develop a climatology diurnal evolution of the lower atmosphere at Los Angeles, San Diego, and Ontario, California*
- *Results reveal the deepening of mixed layers overnight, consistent with cloud-topped boundary layers.*
- *E.g., at Los Angeles, a deeper boundary layer persists about four hours after sunrise and then decreases rapidly as the onshore sea breeze strengthens* ➔



Background about AMDAR Impacts

- ***AMDAR Temperature and Wind*** data continue to be among 4-5 most important data sources for global assimilation across multiple NWP centers
  - Extremely Cost Effective (Cost/Impact)
    - Profiles could backfill for lost rawinsondes if moisture is included
- **Large number of moisture profiles now available over US**
  - Greater impact expected at shorter time ranges and at mesoscale
    - *Used for Nowcasts as well as NWP*

AMDAR Water Vapor Sensing System (*WVSS*) measures Specific Humidity directly

- Uses a laser-diode system to 'count' the number of water vapor molecules passing sensor
- Instruments Tested on UPS 757s
  - Used by UPS for fog forecasting
  - Final tests in 2009-2010
  - Re-engineered electronics
  - Improved mechanics
- Southwest Airlines added

Evaluations of AMDAR Observations using Co-Located Radiosonde and Inter-Aircraft Comparisons made within 50 km and ± 1 hour

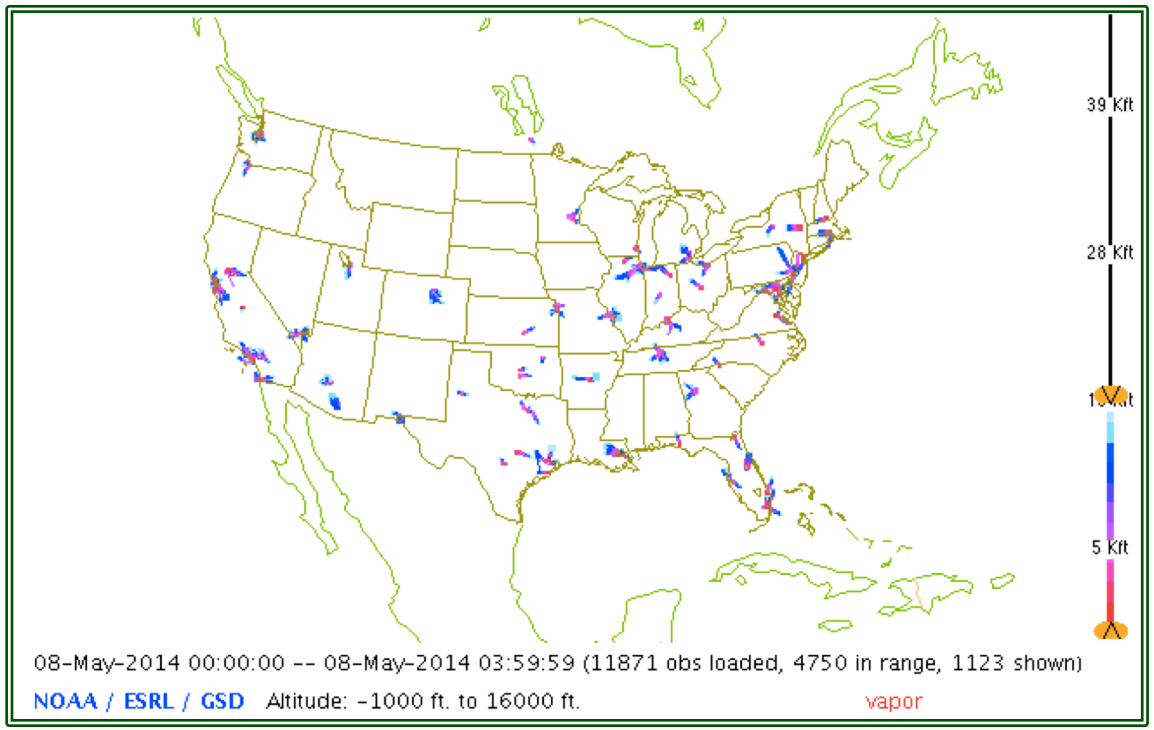
AMDAR WVSS
(Water Vapor Sensing System)
Specific Humidity Profiles

Data reported:

- *Every 100 m from sfc to 1km*
- *Every 300 m to 6km*
- *Every 5-7 min at flight level*
- *Reporting precision better than 0.1 % RH from 0 to 45 g/kg*

Background about AMDAR Impacts

- ***AMDAR Temperature and Wind*** data continue to be among 4-5 most important data sources for global assimilation across multiple NWP centers
  - Extremely Cost Effective (Cost/Impact)
    - Profiles could backfill for lost rawinsondes if moisture is included
- **Large number of moisture profiles now available over US**
  - Greater impact expected at shorter time ranges and at mesoscale
    - *Used for Nowcasts as well as NWP*

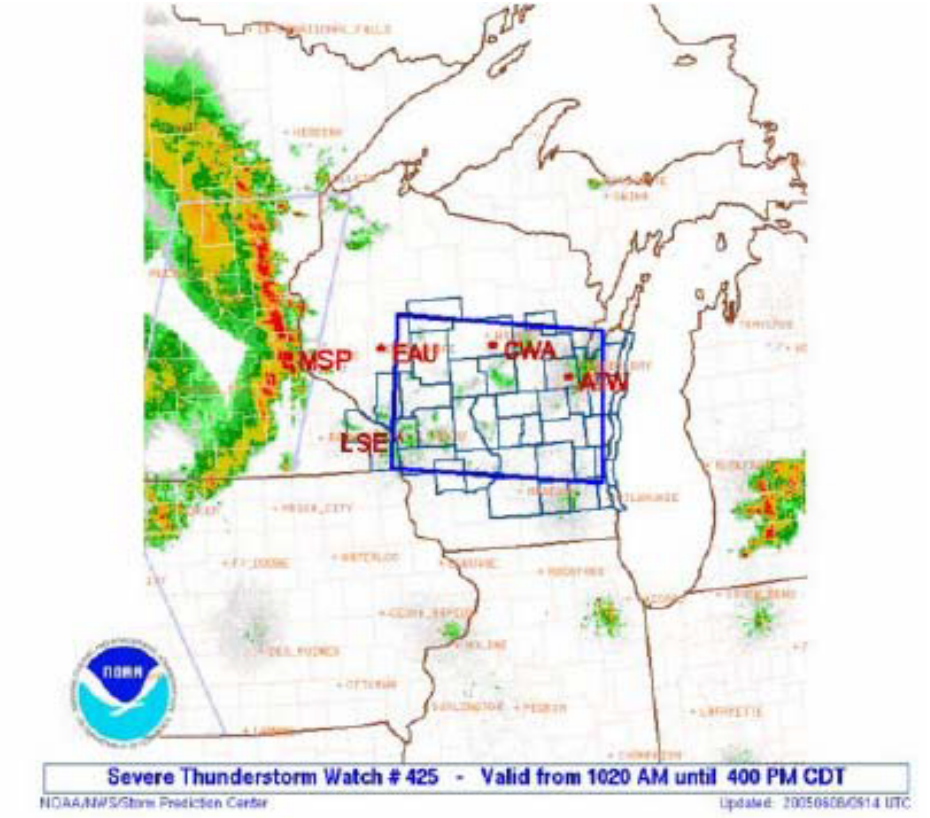


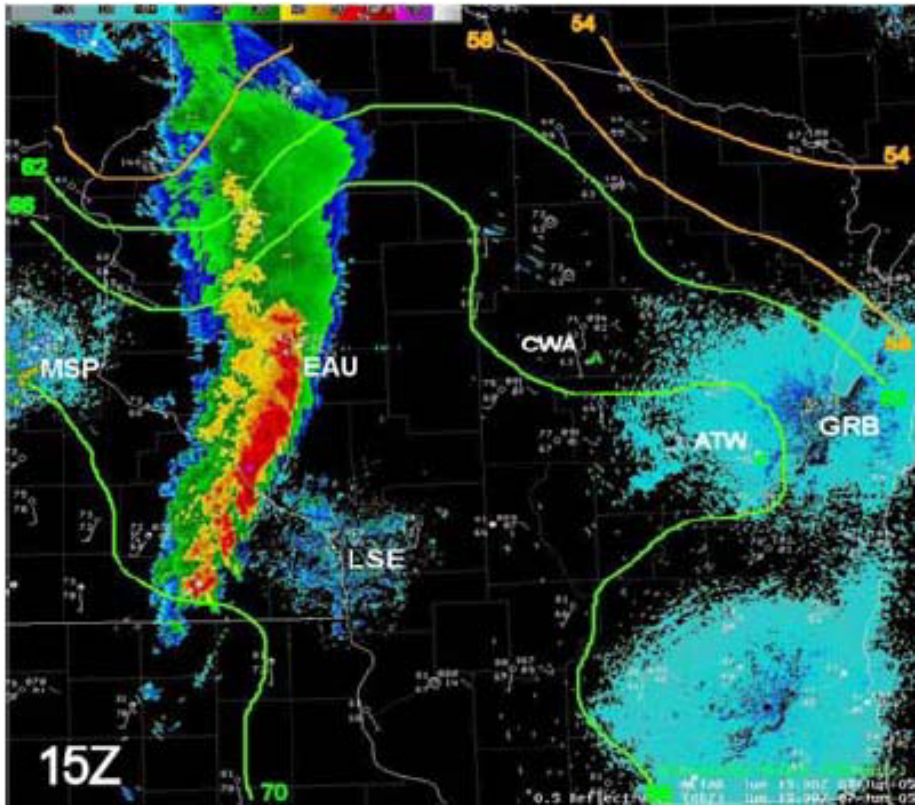
Typical Daily US AMDAR WVSS (Water Vapor Sensing System) Humidity Profiles

- *Currently, 135 WVSS-equipped aircraft in US*
  - *700-800 Profiles/day*
  - *~10 WVSS aircraft in Europe (E-AMDAR)*
    - *Readily Expandable*

Forecaster Impacts: Using real-time aircraft T/Q profiles to in Nowcasting **Convective Storms**

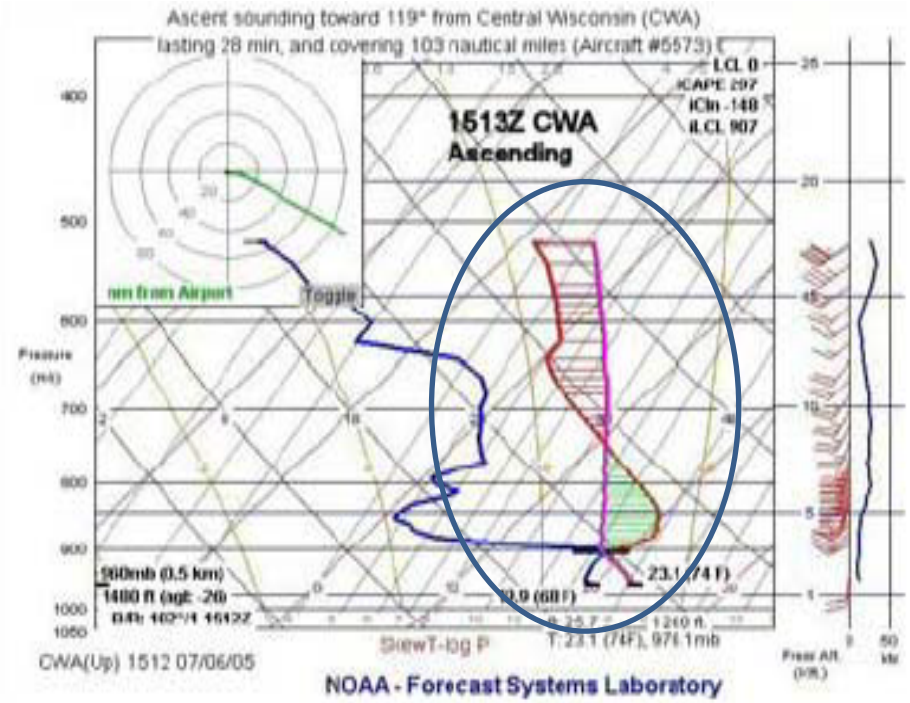
- **Central Wisconsin, 6 July 2005** (Based on TAMDAR Observations)
  - Linear mesoscale convective system expected to persist into Wisconsin
  - Severe thunderstorm watch was initially issued at 1530 UTC for most of Central Wisconsin



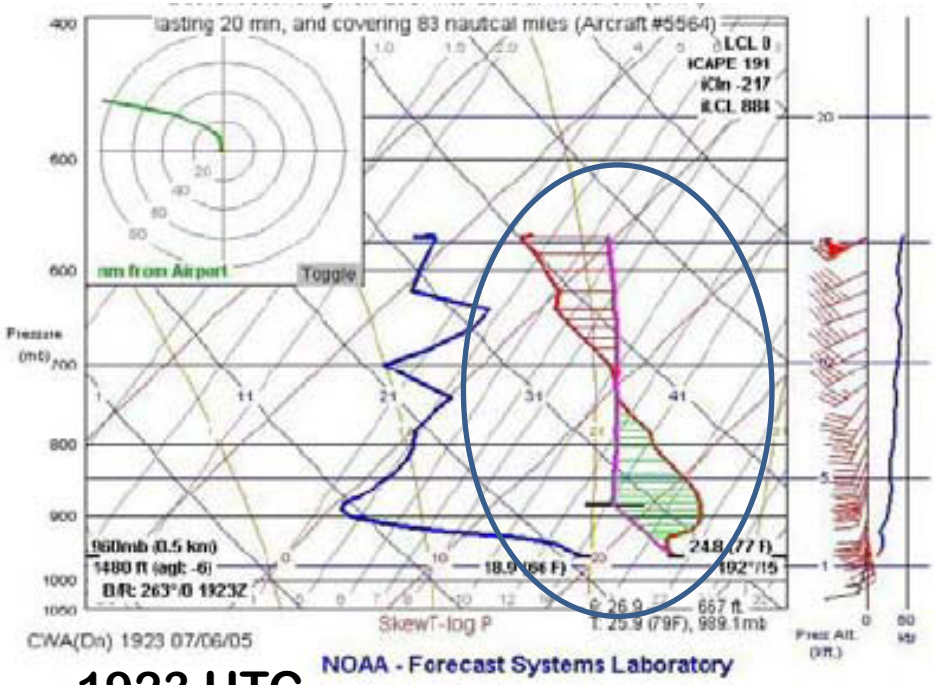


Forecaster Impacts: Using real-time aircraft T/Q profiles to in Nowcasting **Convective Storms**

- Aircraft soundings from watch area showed a persistent strong capping inversion that appeared unlikely to break
- Forecasters lowered the chance for storms and the severe thunderstorm watch was cancelled
- Storms dissipated before reaching central Wisconsin



1513 UTC



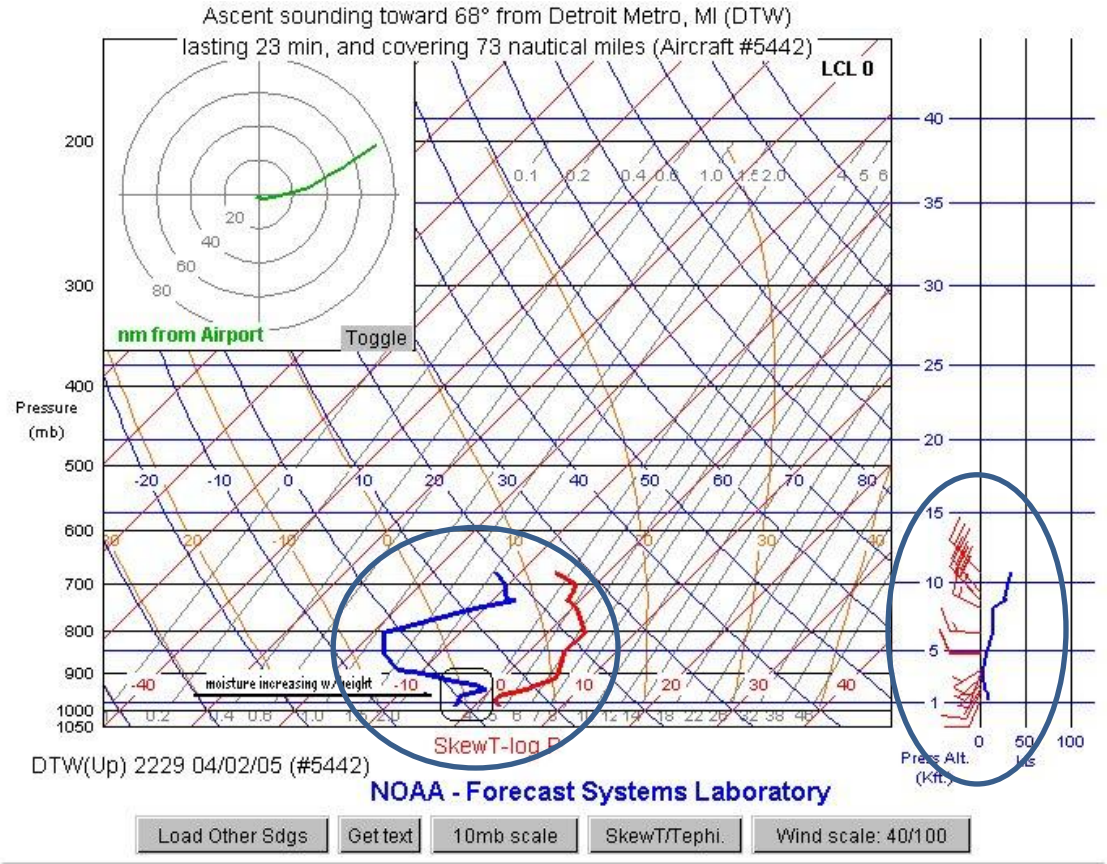
1923 UTC

Forecaster Impacts: Using aircraft T/Q profiles in Nowcasting Low Ceilings, Visibilities and Fog

- Detroit, Michigan, 4 February 2005
  - Soundings near 2230 UTC showed light boundary layer winds, ample near-surface moisture, dryness above
  - *Favorable conditions for fog development (Petterssen, 1940s)*

- Based on the observations, the TAFs for 09 and 12 UTC were amended, reducing visibilities to ½ mile.
- METARS showed that visibilities remained below ¼ mile

KDTW 0532z 00000kt **2sm br clr**
KDTW 0739z 17003kt **1 3/4sm br** r04/1000v3500
KDTW 0936z 17004kt **1/4sm fg** r04/0500v0600
KDTW 1154z 16004kt **1/4sm fg** r04/2800v0600

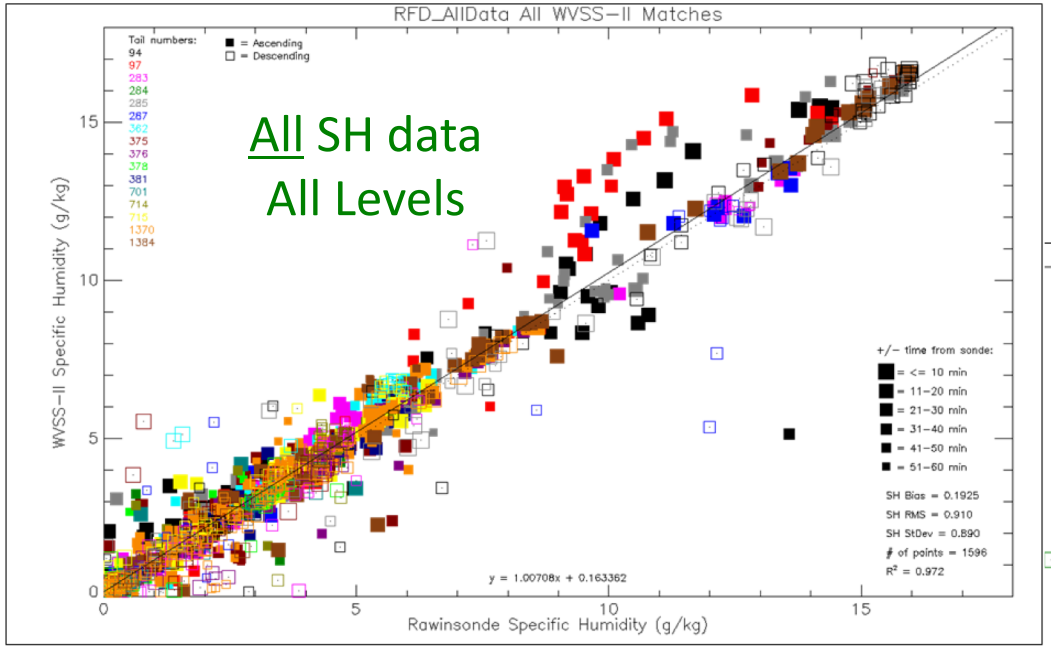


Background about AMDAR Impacts

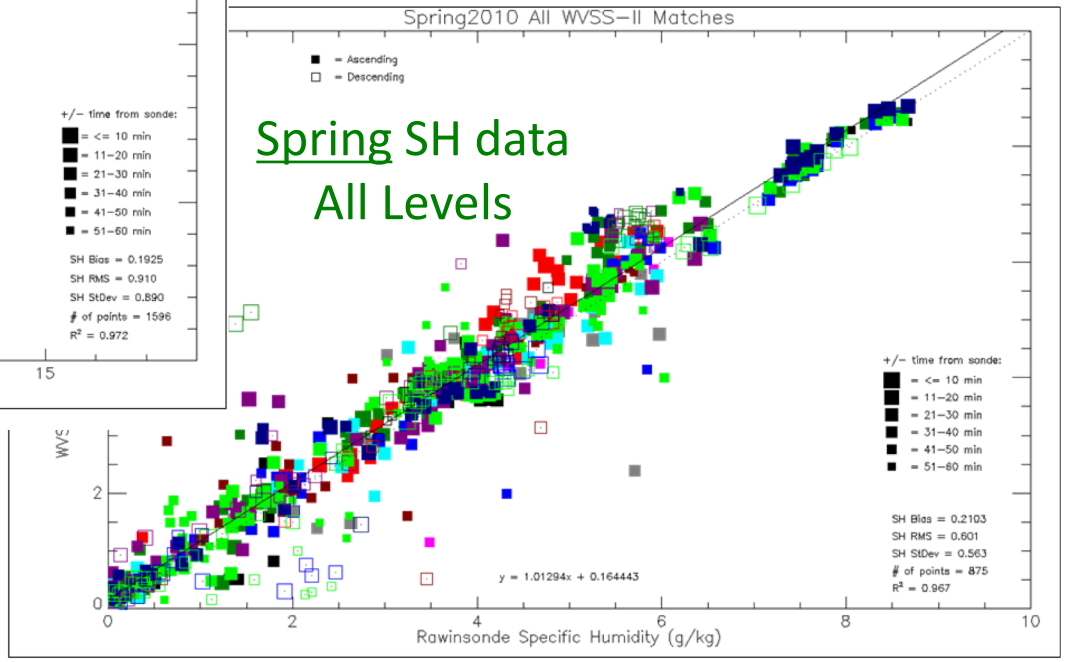
- ***AMDAR Temperature and Wind*** data continue to be among 4-5 most important data sources for global assimilation across multiple NWP centers
  - Extremely Cost Effective (Cost/Impact)
    - Profiles could backfill for lost rawinsondes if moisture is included
- **Large number of moisture profiles now available over US**
  - Greater impact expected at shorter time ranges and at mesoscale
    - *Used for Nowcasts as well as NWP*
- **WVSS Moisture Measurements are high quality (*Bias and Std. Dev. small*)**
  - *Can fill a-synoptic data voids over land*

WVSS-to-RAOB Validation Results

Summary of 3-Season Humidity Inter-comparisons - 2009-2010



- *Single site (RFD) , single airline (UPS)*
- *Special Viasala RAOB launches*
  - *~ 30 minutes from aircraft landing/departures*



Differences showed:

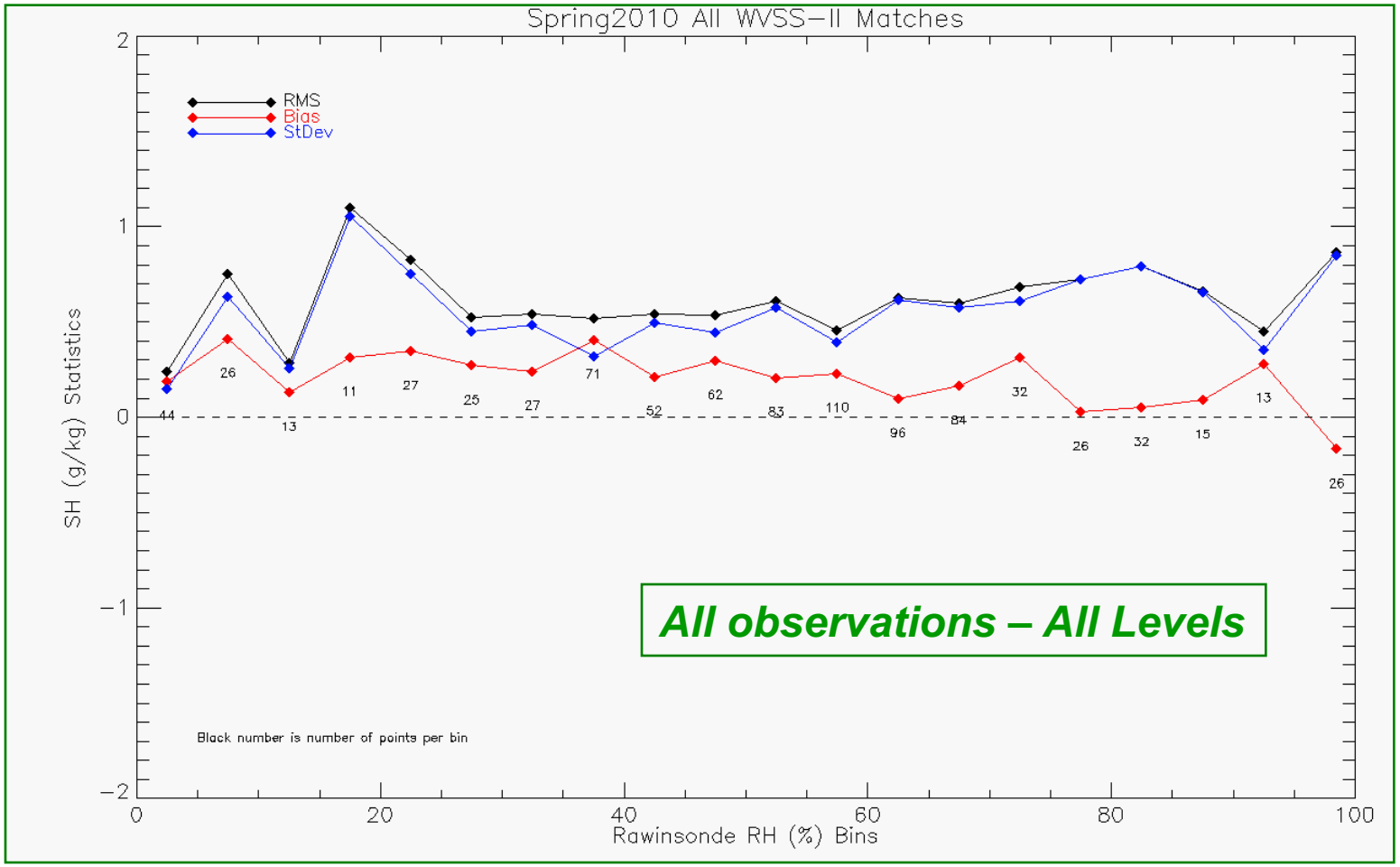
Aircraft data and rawinsonde reports agree well

Overall small positive WVSS bias

Few moist outliers from one case in 10-12 g/kg range – good for moister data

WVSS-to-RAOB Validation Results

Summary of 3-Season Humidity Inter-comparisons - 2009-2010



Differences showed:

Small positive bias across all RH ranges

Random errors average ~0.5-0.7 g/kg

Higher random errors near 20-25% RH and approaching saturation

WVSS-to-RAOB Validation Results

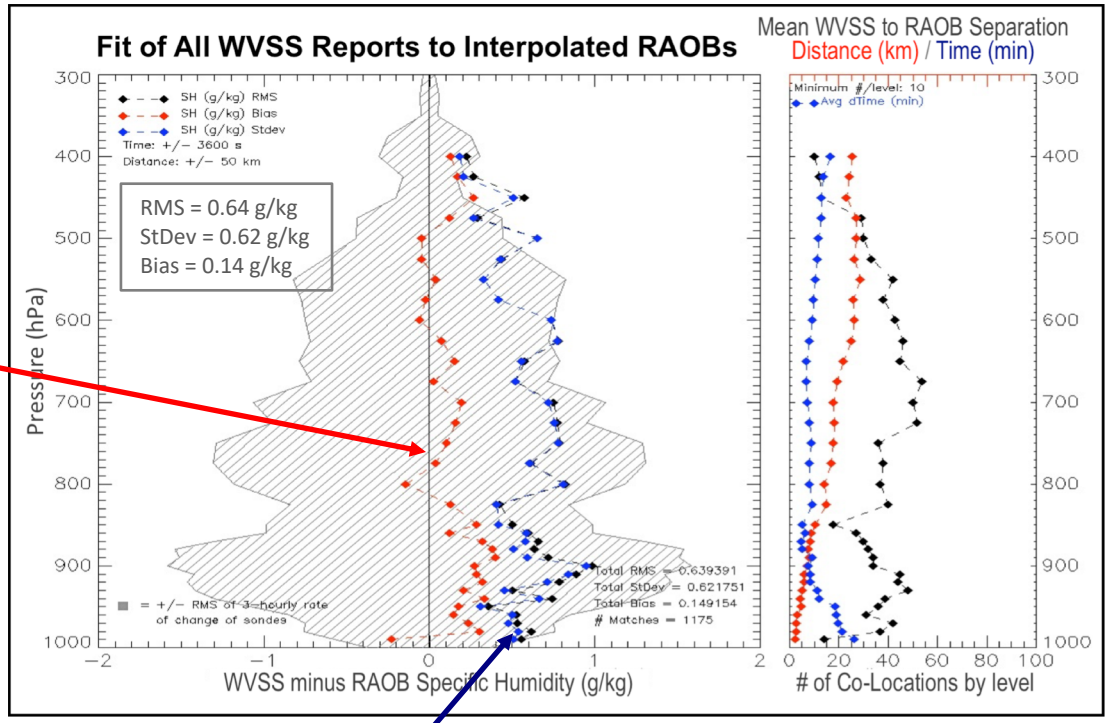
Summary of 3-Season Humidity Inter-comparisons - 2009-2010

Specific Humidity

(Excludes cases with large time and vertical rawinsonde differences)

Systematic Differences:

WVSS Biases at low levels of 0.1 to +0.4 g/kg from surface to 850 hPa. ±0.2 g/kg above



Random Differences *(Including Dry/Moist Environments):*

Differences between aircraft data and rawinsonde reports generally showed variability of 0.3 to 0.8 g/kg from the surface to 600 hPa – decreases aloft.

StDev less than 3-hour variability between bounding rawinsonde reports (gray shading).

Note: Fewer inter-comparisons near 800 hPa and above 700 hPa. Greater time and space separation above 650 hPa.

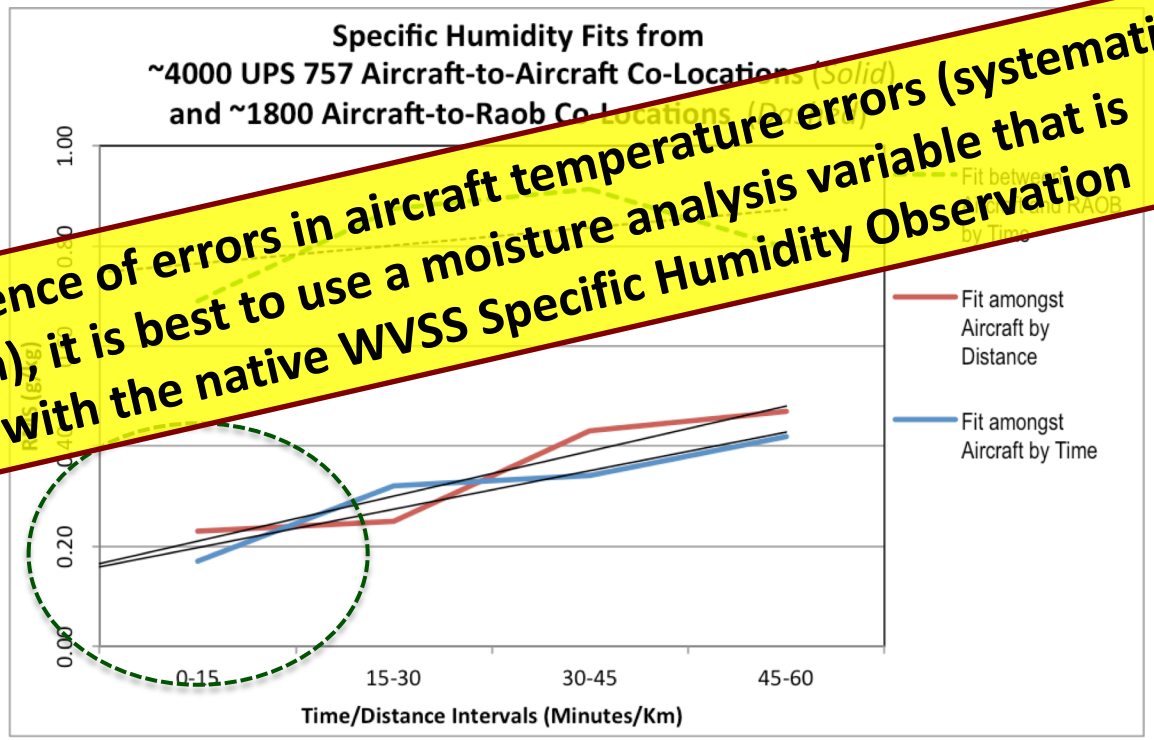
Inter-Comparisons between nearby WVSS Aircraft

Approximating Representativeness Error using WVSS-II SH Observations

RMS calculated for:

Time (and distance) ranges of 0-15, 15-30, 30-45 and 45-60 minutes (km)

To reduce influence of errors in aircraft temperature errors (systematic and random), it is best to use a moisture analysis variable that is consistent with the native WVSS Specific Humidity Observation



RMS Differences show *(ALL reports, All Seasons):*

Moisture Variability more than doubles from 0-15 to 30-45 minute intervals

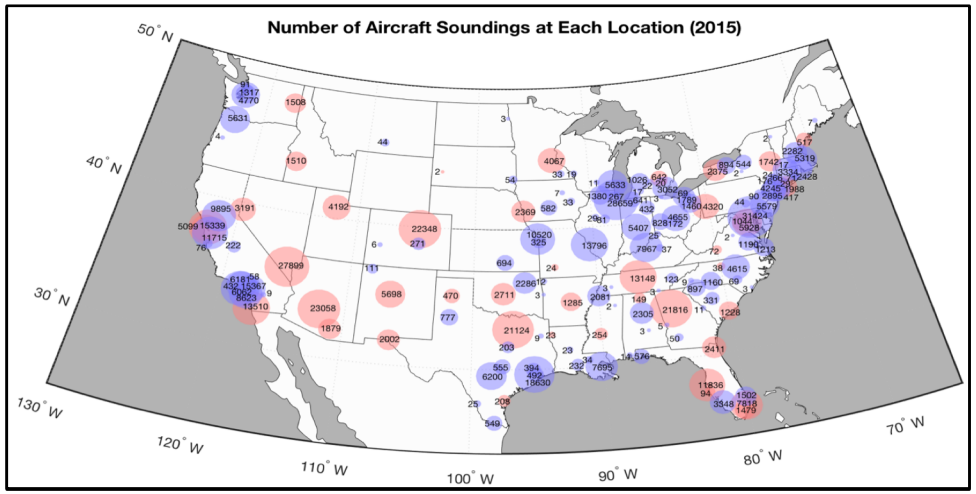
Because the Total Variability is made up of two parts:
1) Instrument Error and 2) Atmospheric Variability

Projecting to exact co-locations ($\Delta T=0$ and $\Delta X=0$) , $\Delta q \sim 0.16$ g/kg

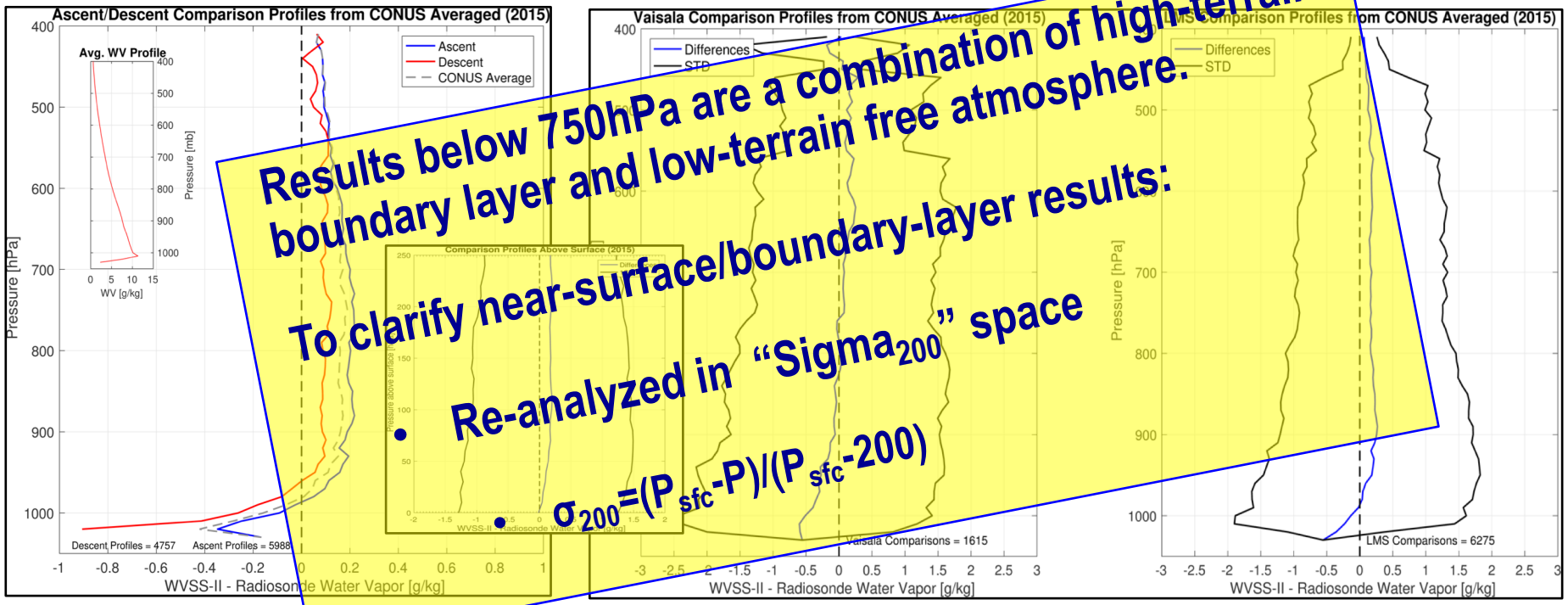
This is substantially better than WVSS-II vs. Rawinsonde Std. Dev.

Expanded Operational WVSS-to-RAOB Validation Results

Summary of year-long Humidity Inter-comparisons - 2015



- *All US Sites, Multiple airlines*
- *Operational RAOBS*
  - *Two manufacturers*
  - *Same Matchup criteria*
    - *Within 30 minutes and 50 km*
- *Results validate special tests*
- *Two US RAOBs provide similar results*



Results below 750hPa are a combination of high-terrain boundary layer and low-terrain free atmosphere.

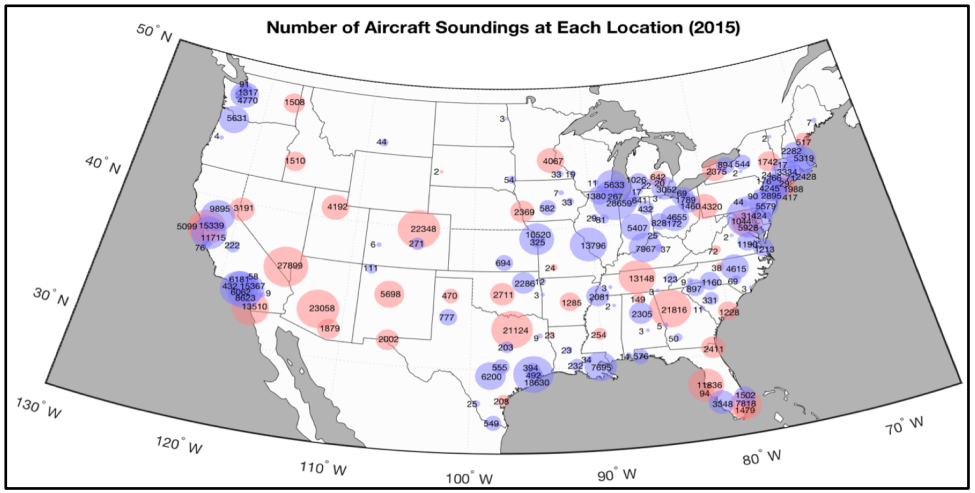
To clarify near-surface/boundary-layer results:

- **Re-analyzed in "$Sigma_{200}$" space**

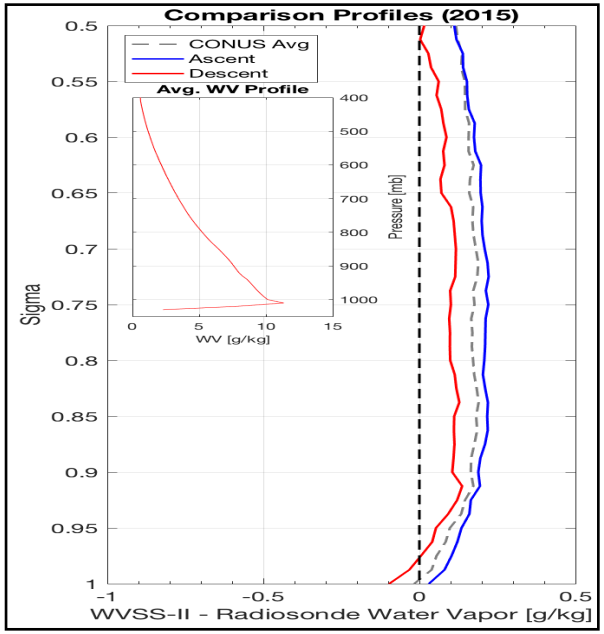
$$\sigma_{200}=(P_{sfc}-P)/(P_{sfc}-200)$$

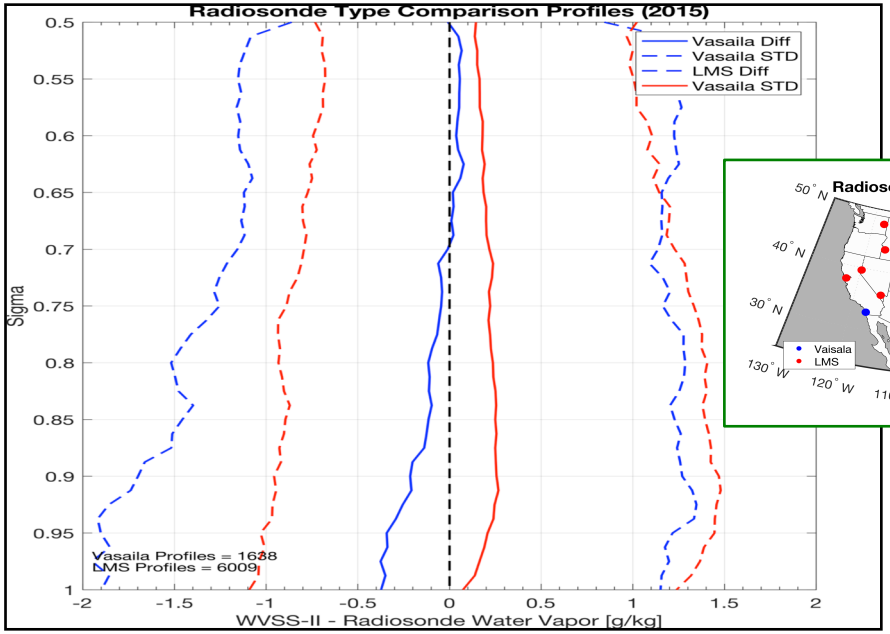
Operational WVSS-to-RAOB Validation Results

Summary of year-long Humidity Inter-comparisons - 2015



- *All US Sites, Multiple airlines*
- *Operational RAOBS*
  - *Two manufacturers*
  - *Same Matchup criteria*
    - *Within 30 minutes and 50 km*
- *Analyzed in "Sigma$_{200}$" space*
  - *$\sigma_{200}=(P_{sfc}-P)/(P_{sfc}-200)$*
  - *Clarifies near-surface results*



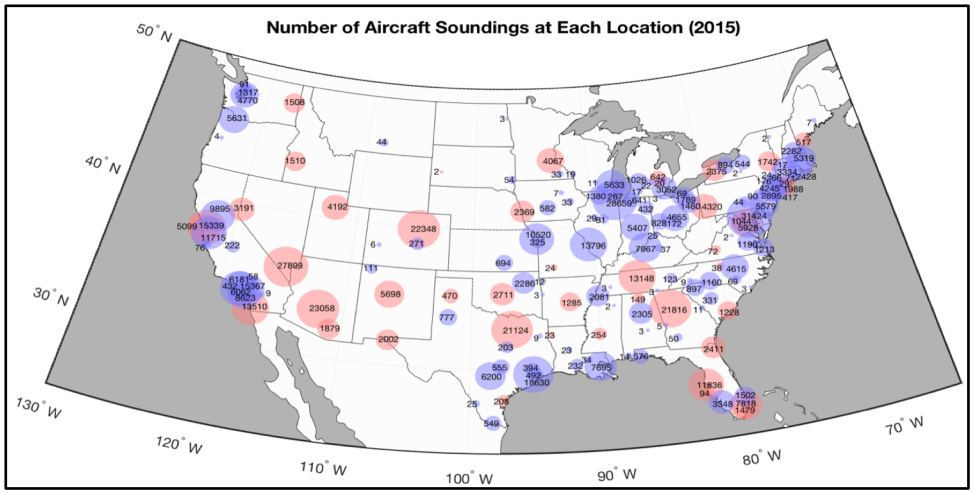


WVSS is systematically 0.1-0.2 g/kg moister than Raobs – with hysteresus

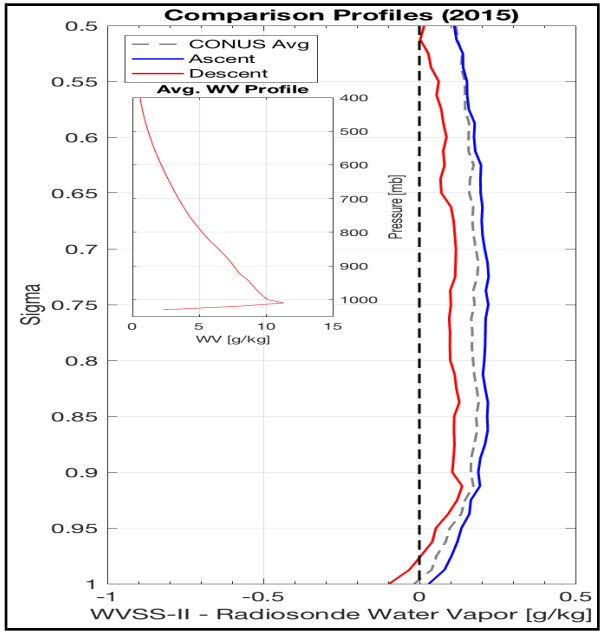
LMS Raobs show slightly larger differences but smaller random error than Vasaila –larger than WVSS

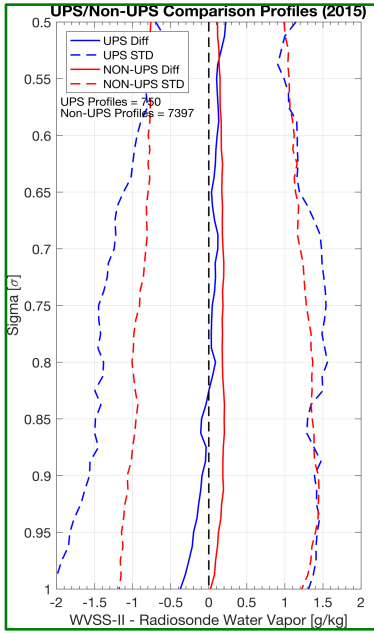
Operational WVSS-to-RAOB Validation Results

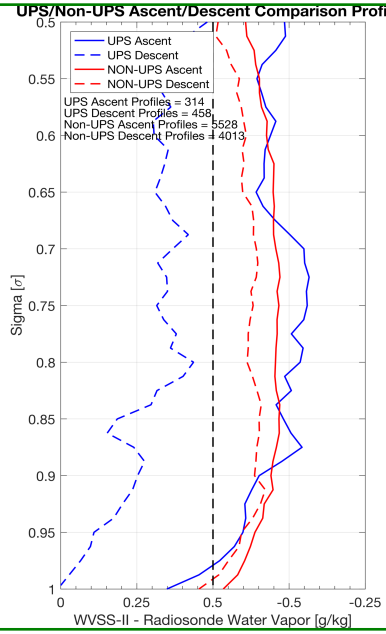
Summary of year-long Humidity Inter-comparisons - 2015

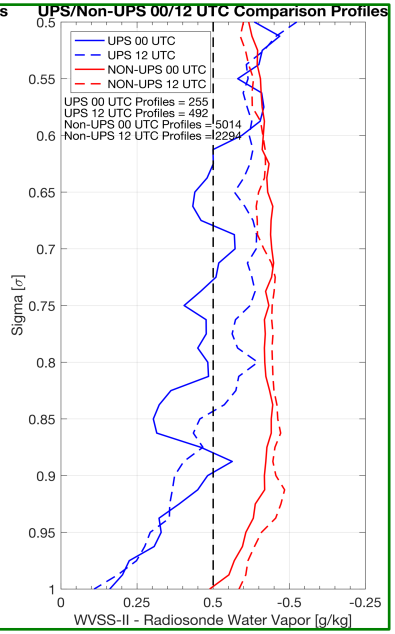


- *All US Sites, Multiple airlines*
- *Operational RAOBS*
  - *Two manufacturers*
  - *Same Matchup criteria*
    - *Within 30 minutes and 50 km*
- *Analyzed in "Sigma$_{200}$" space*
  - $\sigma_{200}=(P_{sfc}-P)/(P_{sfc}-200)$
  - *Clarifies near-surface results*







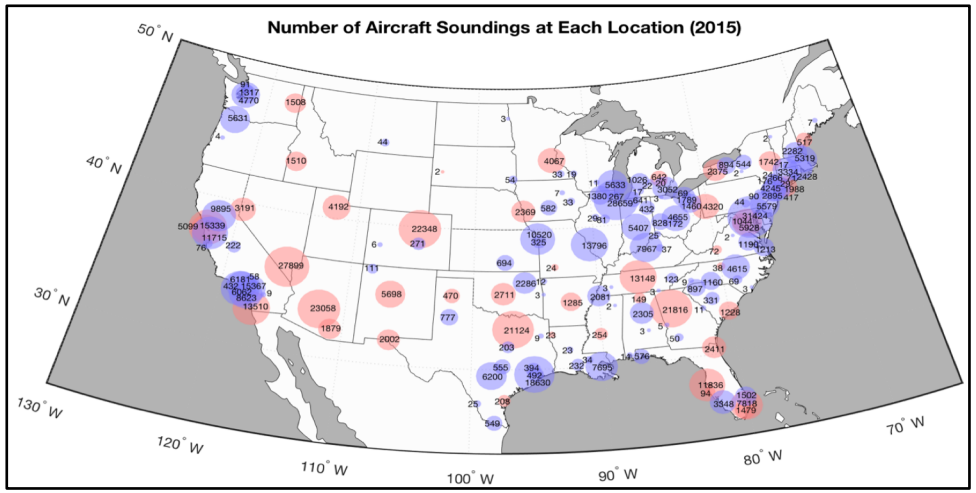


WVSS sensor placement on aircraft may slightly affect reports, but less than Raob type.

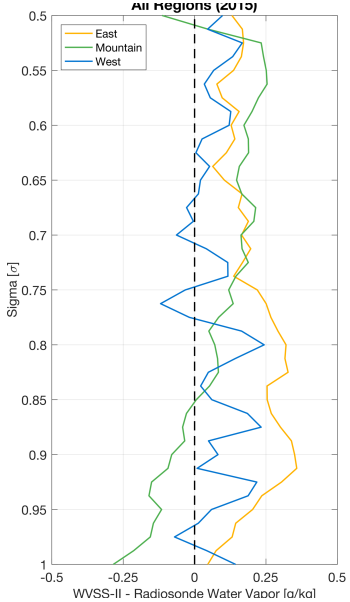
Post-processing can account for both these bias and hysteresis effects.

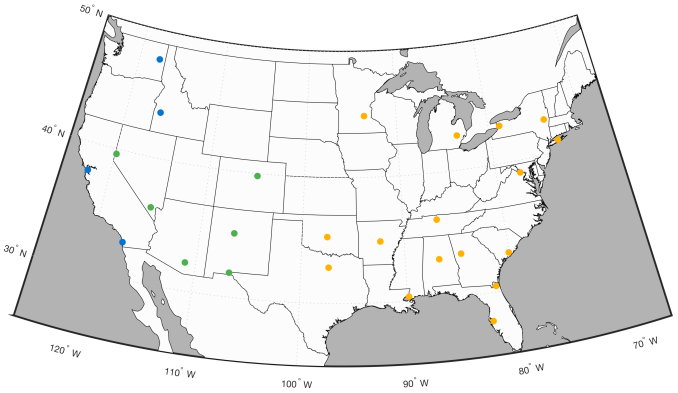
Operational WVSS-to-RAOB Validation Results

Summary of year-long Humidity Inter-comparisons - 2015



- *All US Sites, Multiple airlines*
- *Operational RAOBS*
  - *Two manufacturers*
  - *Same Matchup criteria*
    - *Within 30 minutes and 50 km*
  - *Analyzed in "Sigma$_{200}$" space*
    - $\sigma_{200}=(P_{sfc}-P)/(P_{sfc}-200)$
    - *Clarifies near-surface results*

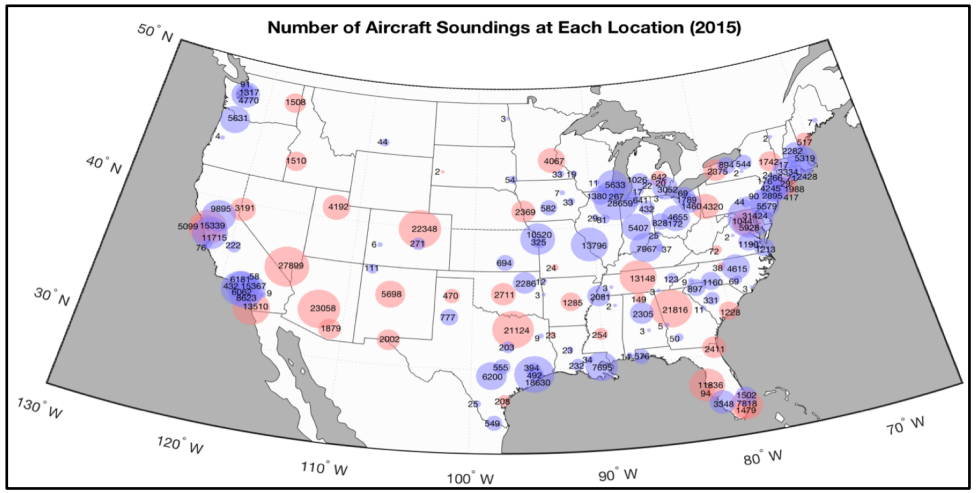




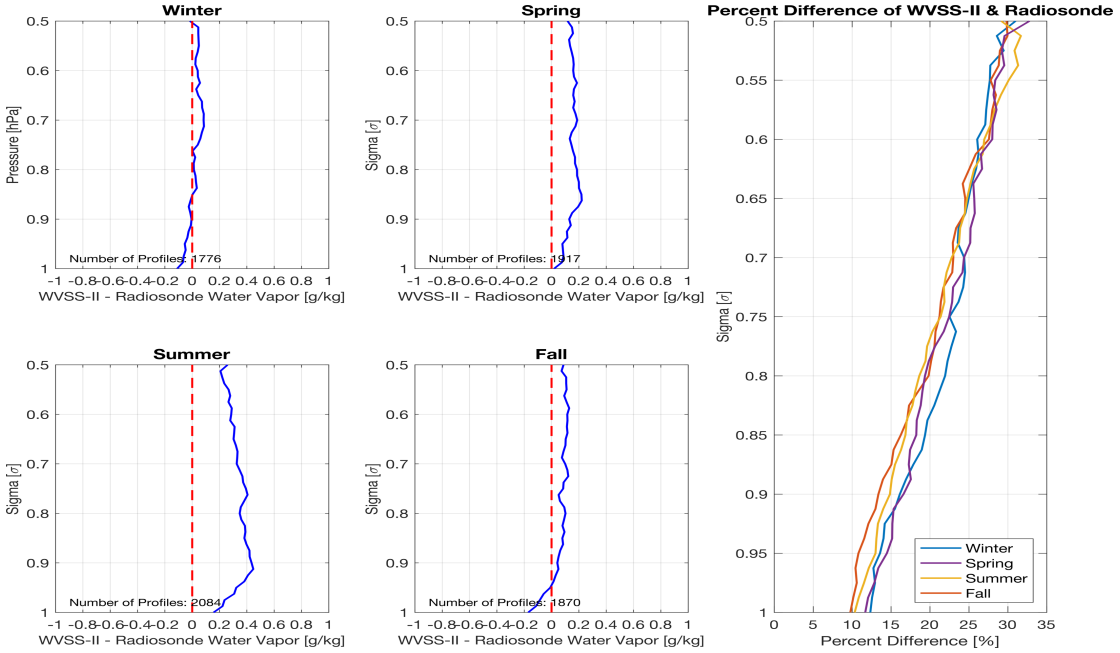
Similar WVSS performance across multiple regions/surface elevations

Operational WVSS-to-RAOB Validation Results

Summary of year-long Humidity Inter-comparisons - 2015



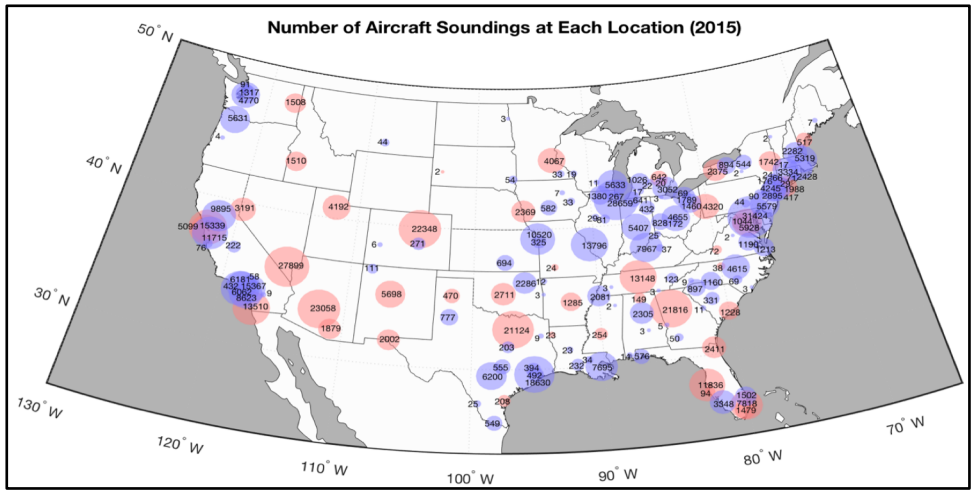
- *All US Sites, Multiple airlines*
- *Operational RAOBS*
  - *Two manufacturers*
  - *Same Matchup criteria*
    - *Within 30 minutes and 50 km*
  - *Analyzed in "Sigma$_{200}$" space*
    - $\sigma_{200}=(P_{sfc}-P)/(P_{sfc}-200)$
    - *Clarifies near-surface results*



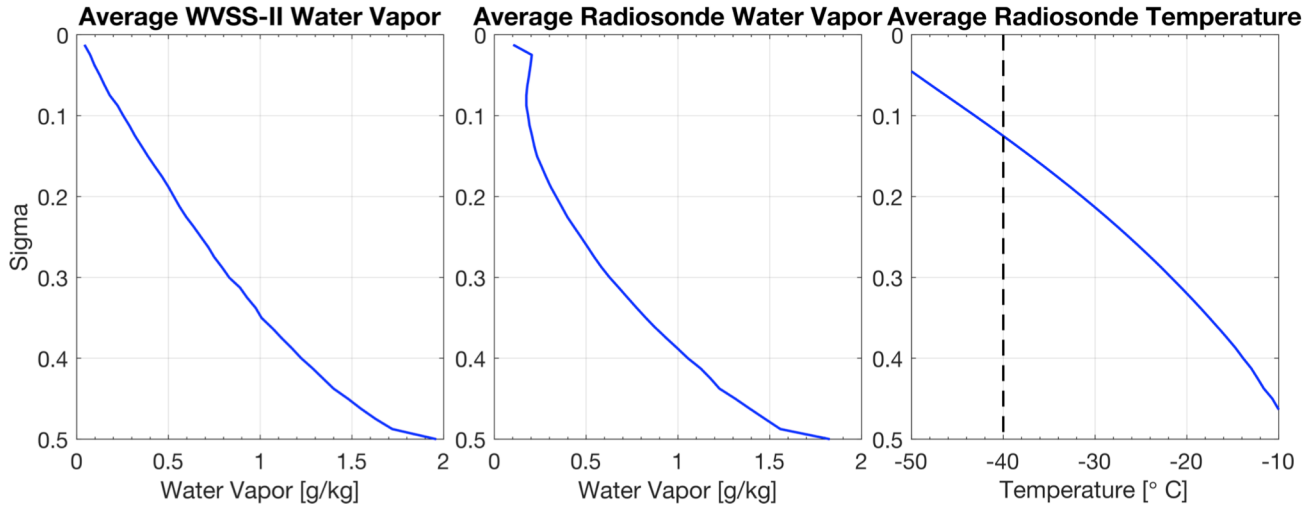
Similar WVSS performance across seasons

Operational WVSS-to-RAOB Validation Results

Summary of year-long Humidity Inter-comparisons - 2015



- *All US Sites, Multiple airlines*
- *Operational RAOBS*
  - *Two manufacturers*
  - *Same Matchup criteria*
    - *Within 30 minutes and 50 km*
  - *Analyzed in "Sigma$_{200}$" space*
    - $\sigma_{200}=(P_{sfc}-P)/(P_{sfc}-200)$
    - *Clarifies near-surface results*



WVSS performance in upper troposphere appears better than RAOBs.

More study is needed

Background about AMDAR Impacts

- ***AMDAR Temperature and Wind data*** continue to be among 4-5 most important data sources for global assimilation across multiple NWP centers
  - Extremely Cost Effective (Cost/Impact)
    - Profiles could backfill for lost rawinsondes if moisture is included
- **Large number of moisture profiles now available over US**
  - Greater impact expected at shorter time ranges and at mesoscale
    - *Used for Nowcasts as well as NWP*
- **Aircraft Water Vapor Measurements are high quality (*Bias and Std. Dev. small*)**
  - *Can fill a-synoptic data voids over land*
- **Aircraft Water Vapor Measurements have positive impacts in NWP systems where available**

Refs:

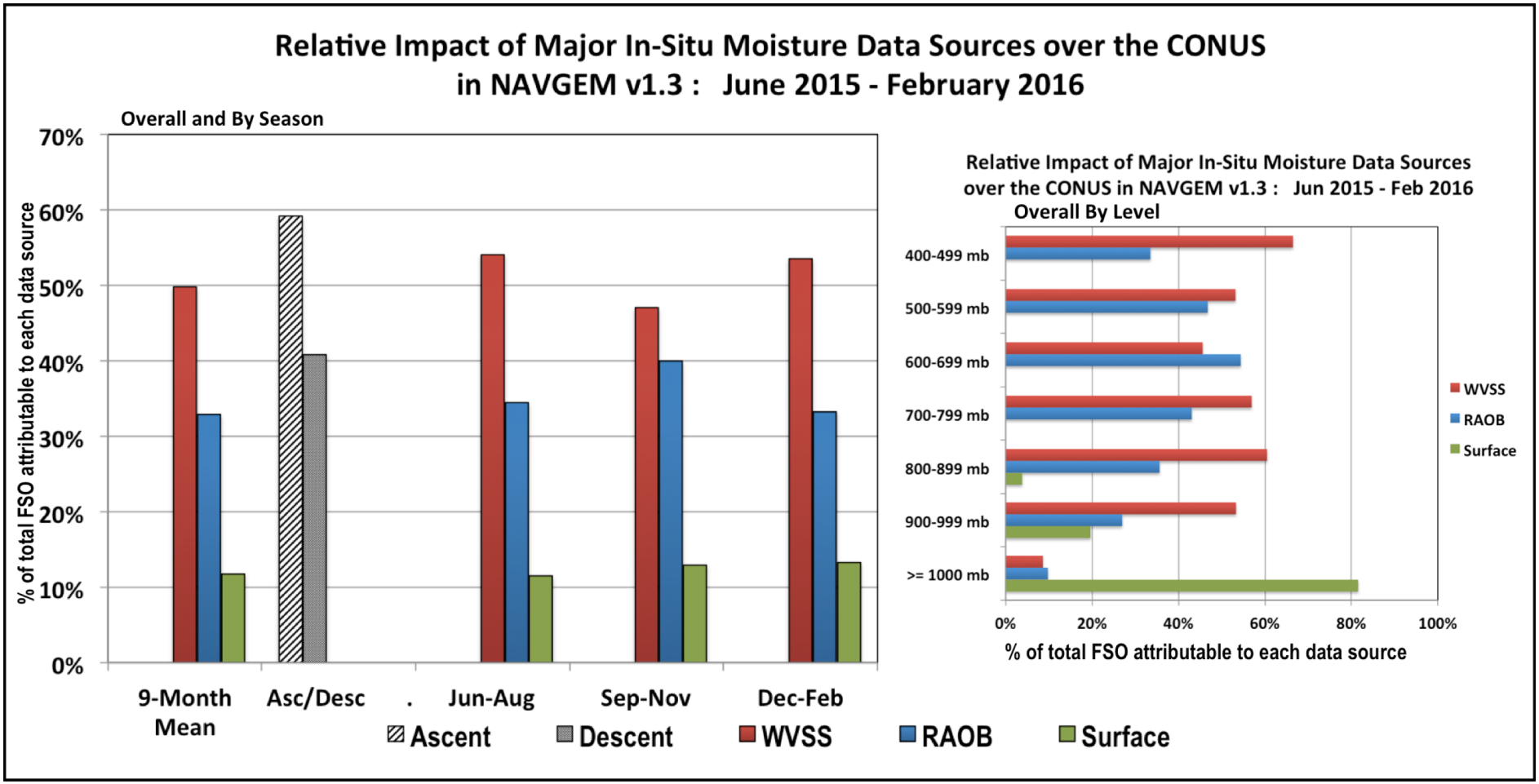
Petersen, Cronce, Mamrosh, Baker and Pauley, 2017: On the impact and future benefits of AMDAR observations in operational forecasting - Part 2: Water Vapor Observations – *Accepted by BAMS*

Hoover, Santek, Daloz, Zhong, Dworak and Ralph A. Petersen, 2016: Forecast Impact of Assimilating Aircraft WVSS-II Water Vapor Mixing Ratio Observations in the Global Data Assimilation System – *Submitted to W&F*

Petersen, R., L. Cronce, R. Mamrosh, and R. Baker, 2015: Impact and benefits of AMDAR temperature, wind, and moisture observations in operational weather forecasting. *WMO Technical Report 2015-01, 93 pp.*

NWP Impacts: Determining the Relative Contribution of In-situ Moisture Observations in the operational NAVGEM v1.3

Data from a 9-month period from June 2015 – February 2016
Impact Calculated as Percentage of Total FSOI attributable to each data source.



- ***WVSS data dominate at all seasons and all levels except surface & 600-700hPa.***
- ***Ascent profiles have more impact than descent, but impact per ob. ~ equal***

Mean profiles of Specific Humidity Ob-Minus-Background (OMB) at rawinsonde sites for multi-season experiments in NCEP's Global Data Assimilation System

Blue - Mean rawinsonde moisture OMB without AMDAR moisture obs

Red - Mean rawinsonde moisture OMB with AMDAR moisture obs

Green - Mean AMDAR moisture OMB

Shading - 5% and 95% confidence limits

Black squares - Levels with statistically significant rawinsonde OMB changes

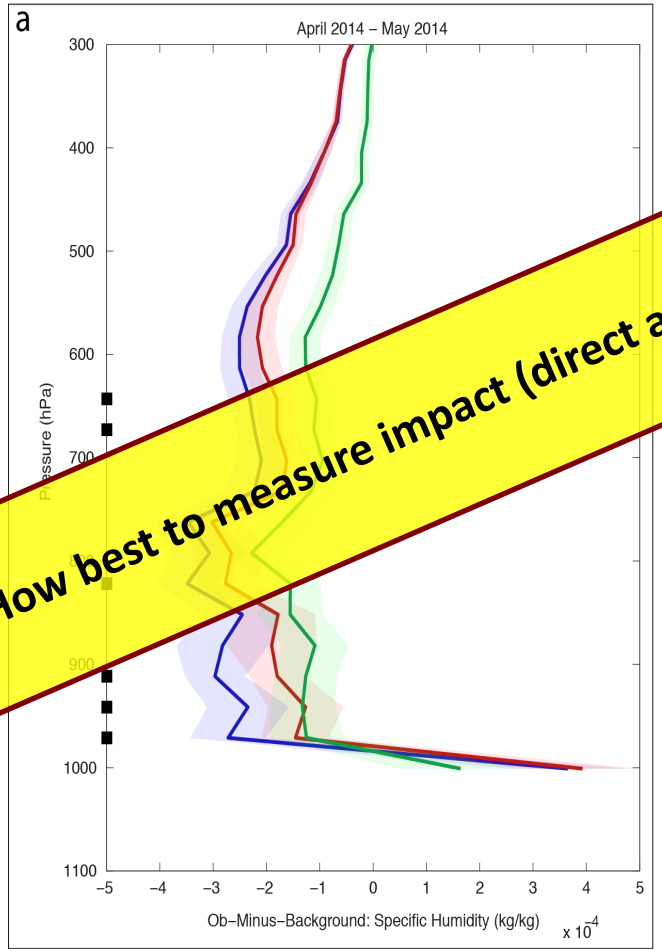
Impacts larger in warm season with greater moisture variability

WVSS obs:

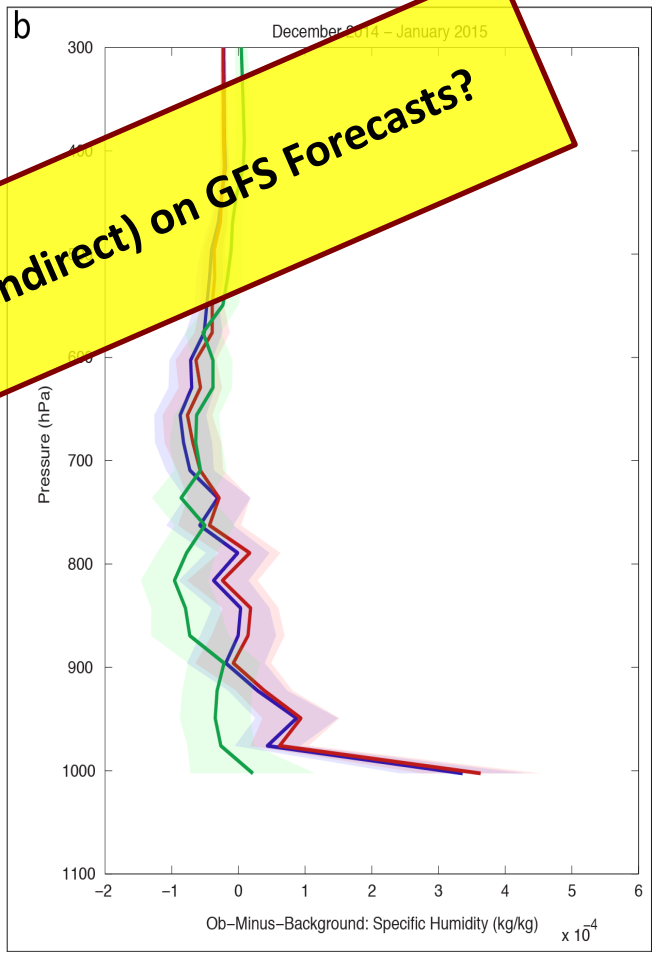
1 - Improve ROAB fits

2 - Fit background better than RAOBs

Warm Season (April 2014 – May 2014)



Cold Season (Dec. 2014 – Jan. 2015)



Question: How best to measure impact (direct and indirect) on GFS Forecasts?

Error in forecast relative to GPS/TPW Observations for Multi-Season Tests

Blue – Control – no WVSS

Red – Experiment with WVSS

5% and 95% confidence limits shaded.

Dots indicate statistically significant differences between the experiment and control

When used in combination with ROABS over CONUS, WVSS observations:

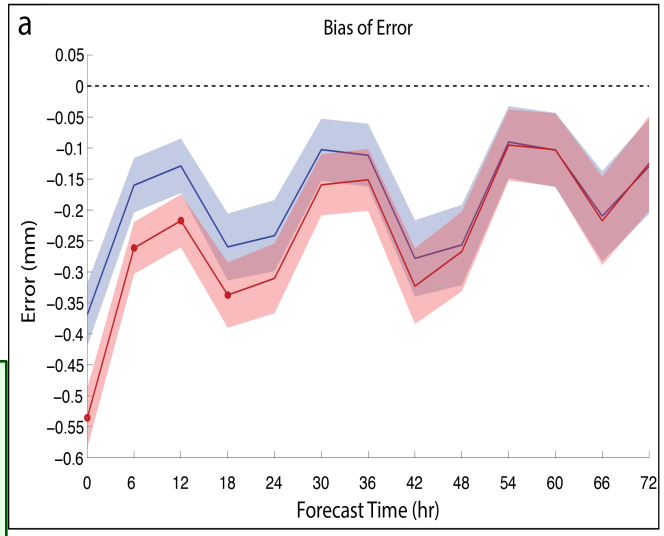
- **Had larger impacts larger in warm season**
- **GFS Random Errors were reduced out to 66hrs (warm season)**
- **GFS integrated dry bias observed during tests increased**

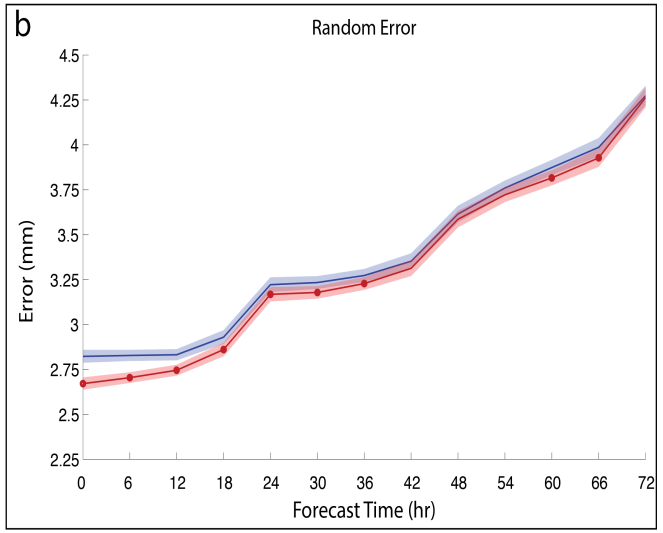
Systematic Error - Bias

Random Error – Std Dev

Warm Season (April 2014 – May 2014)

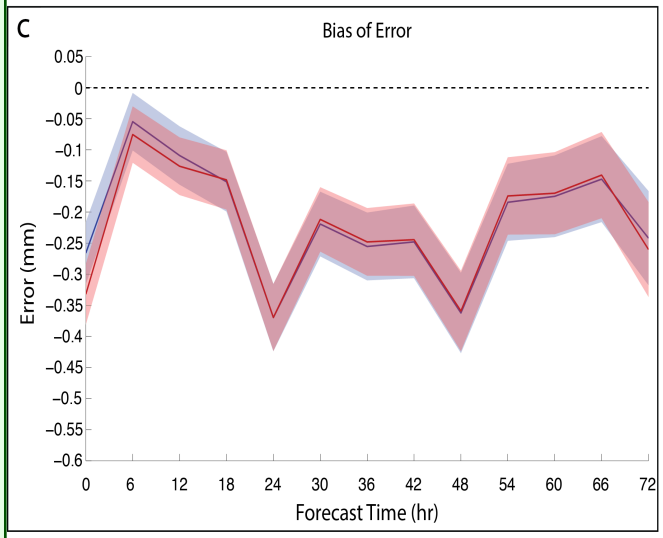
April 2014 - May 2014

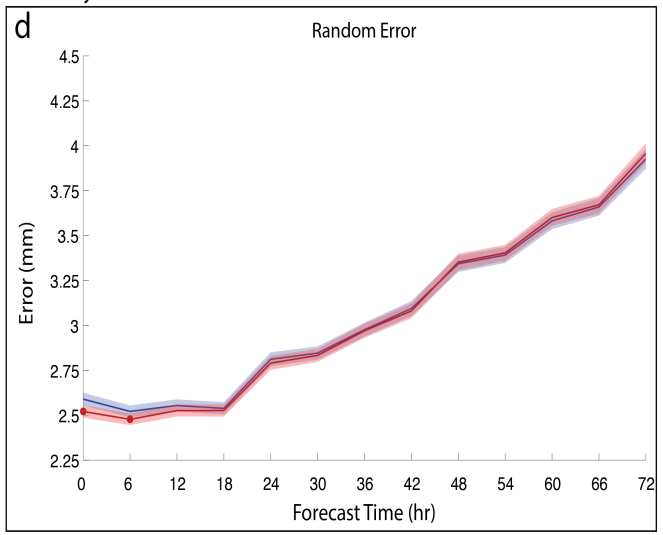




Cold Season (Dec. 2014 – Jan. 2015)

December 2014 - January 2015





WVSS Impact on Random Errors in GFS Analyses for Warm Season Period

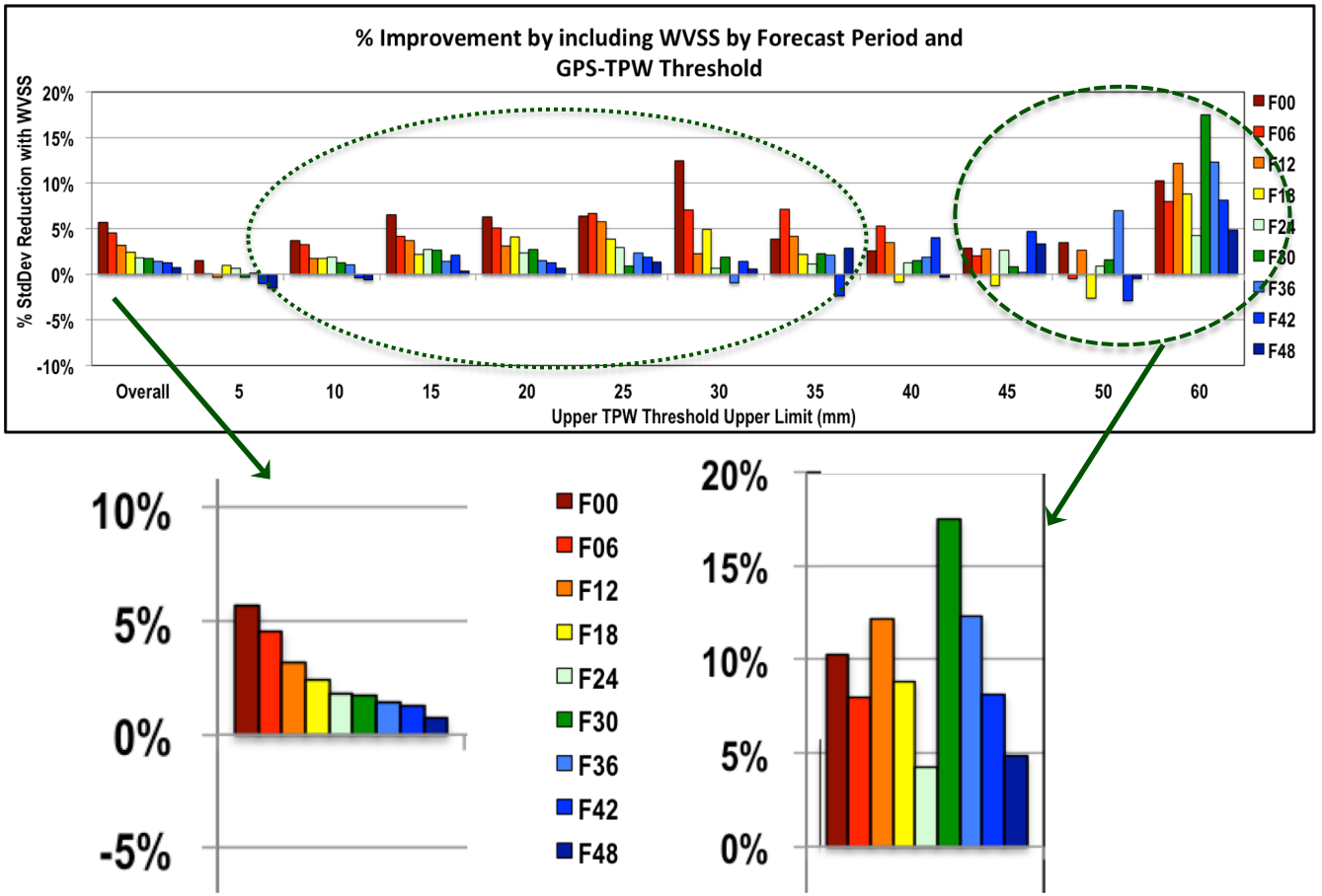
WVSS impacts on GFS random integrated moisture forecast errors were also positive and most apparent:

- *At shortest forecast ranges*
- *>1% Reduction in Random Error out to 42 hours*
- *Majority of GPS sites showed improvements at ALL forecast lengths*

What is the distribution of moisture changes over forecast time?

Throughout the 48 hour forecast period, impacts of the added WVSS observations:

- **Decrease with forecast time**
  - ***Few negative impacts***
- **Positive TPW impacts remain concentrated in 10-30 mm range**
- **Less well organized but larger positive impacts at high TPWs**



Leasons learned about AMDAR WVSS Impacts

Evaluations of the AMDAR-WVSS moisture-observing systems being deployed on US aircraft:

- *Show excellent data quality horizontally and vertically, even across sharp inversions,*
- *Agree with co-located RAOBs to within 0.6 g/kg, with minimal biases (~ 0.15 g/kg), and*
- *Display consistency between observations from different aircraft of at least 0.2 g/kg (RMS)*
  - ***Indicates that WVSS observations perform as well as h… quality RAOBs.***

Forecasters have readily incorporate AWVSS reports av… t the day to improve local, short-range forecasts of a number of high-im… na,

- *Applications range from forecasts of fog and ceili… tion type and improving severe weather outlooks.*

Results using WVSS data in global … de of FSOI *and* Data Denial Tests:

- ***Short-range forecast… other moisture observations***
  - ***Greater im… over CONUS***
  - ***Impa… rm season.***
- *Improvement… ty analyses/forecasts and in the timing and location of precipitation e…*
  - *Examining … R-WVSS and US RAOBs, including 'special off-time' releases.*

So, Why am I here?

Improvements from W… observations are concentrated in areas of highest data availability, **similar advancements are expected in other areas as the spatial/temporal coverage of the reports**

- ***WVSS is available through an enhancements to the existing, cost-effective/high-impact AMDAR data collection program***

On the impact and b… AMDAR Water Vapor Observations to operational forecasting

Offering A New Opportunity for Validating Satellite Moisture Products

Propose using AMDAR WVSS profiles (as well as Temp/Winds) as an Expanded Intercomparison Standard for Satellite Moisture Products

- Eliminates Restrictions of RAOB intercomparisons to 00 and 12 UTC

- Provides a larger geographical distribution throughout the day
  - Provides information on diurnal variability
  - Provides excellent boundary layer resolution
- Expansion into new areas logistically straightforward and inexpensive

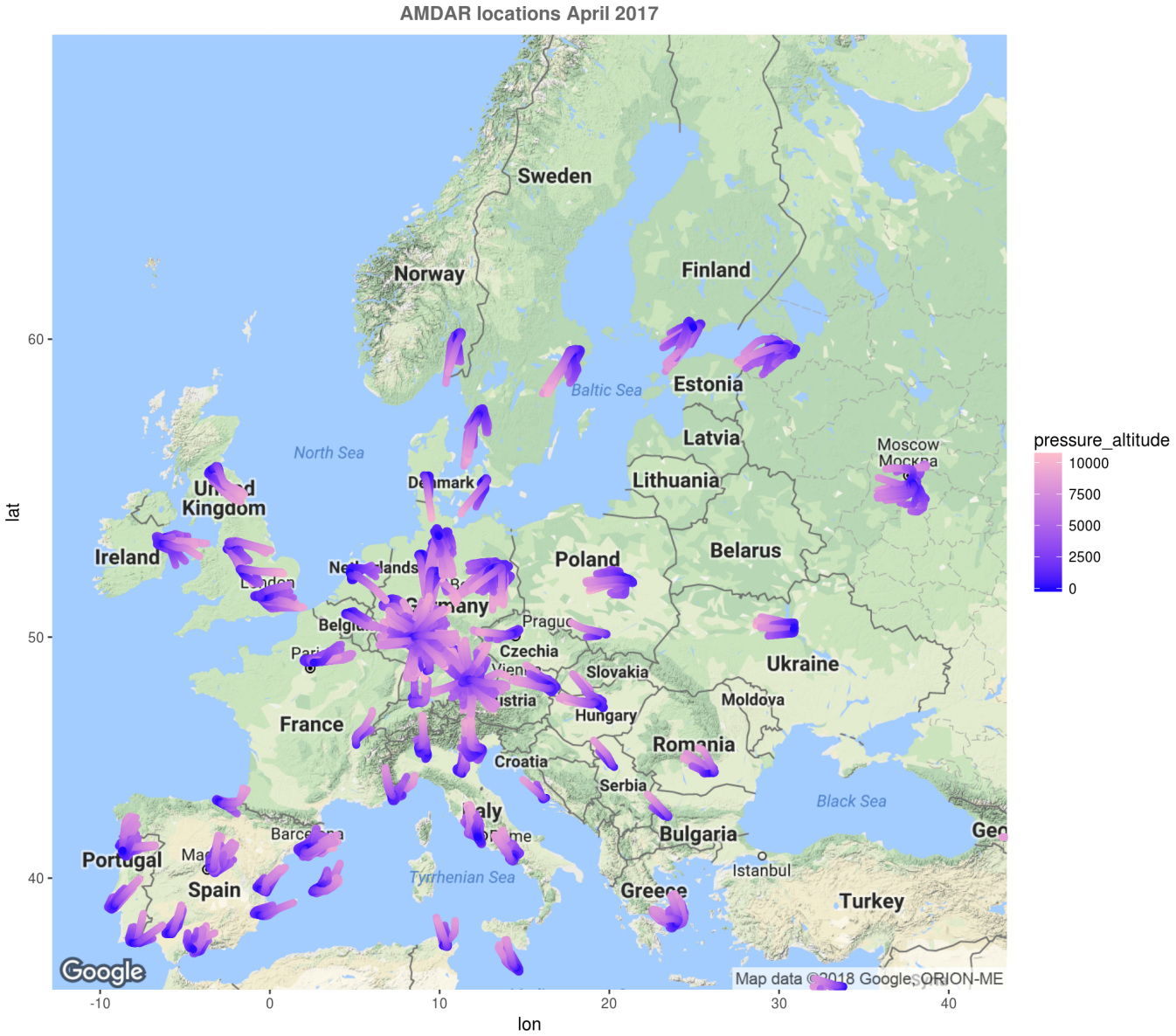
- Much Larger Number of Intercomparisons Improves Statistical Significance

- Expand Prototype currently being developed with EUMETSAT MetOp-A,-B Retrievals
  - *Via EUMETSAT Visiting Scientist Program*
  - *Proof-of-Concept project show benefits*

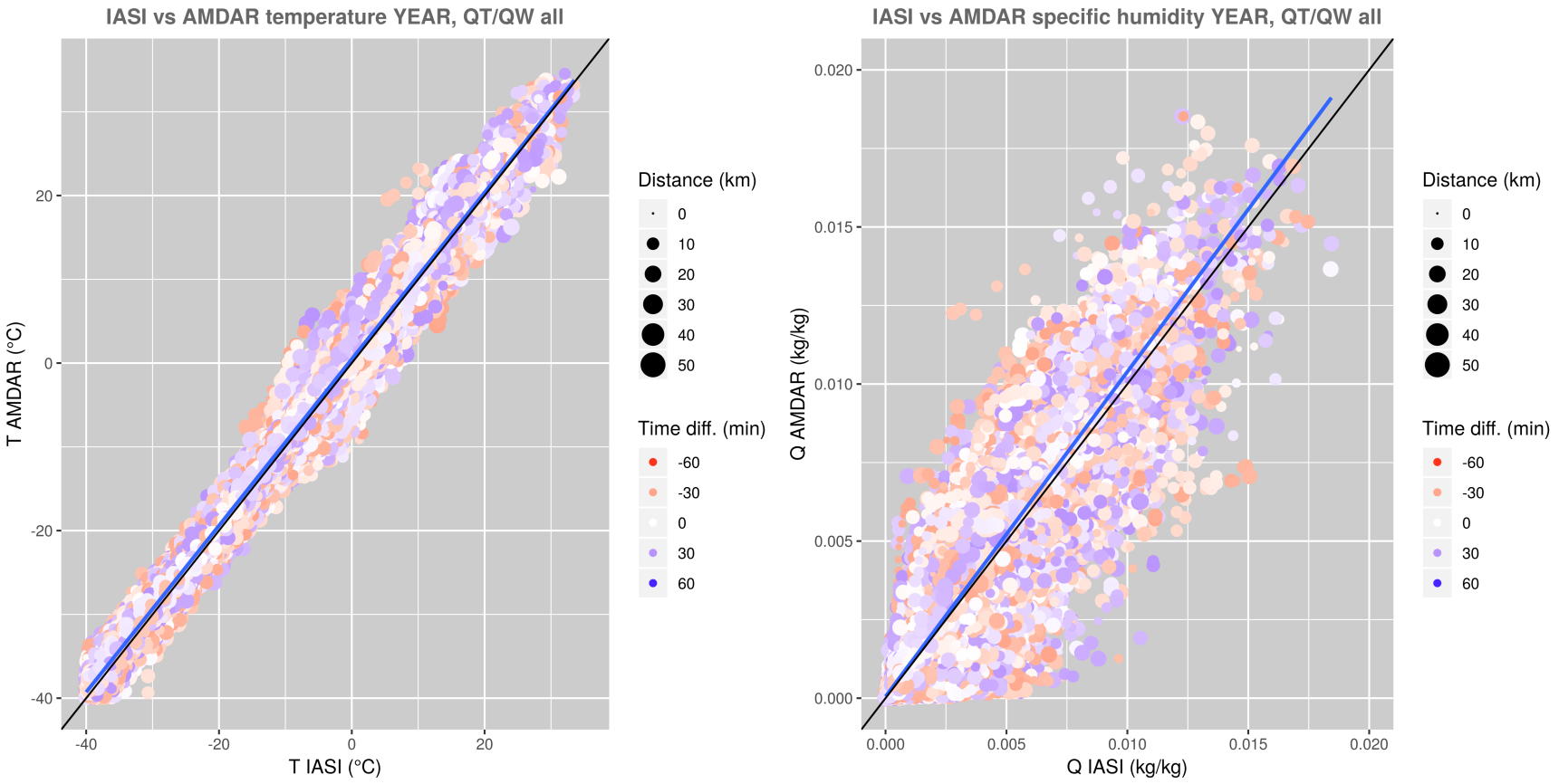
Data - E-AMDAR humidity coverage from < 10 aircraft

April 2017

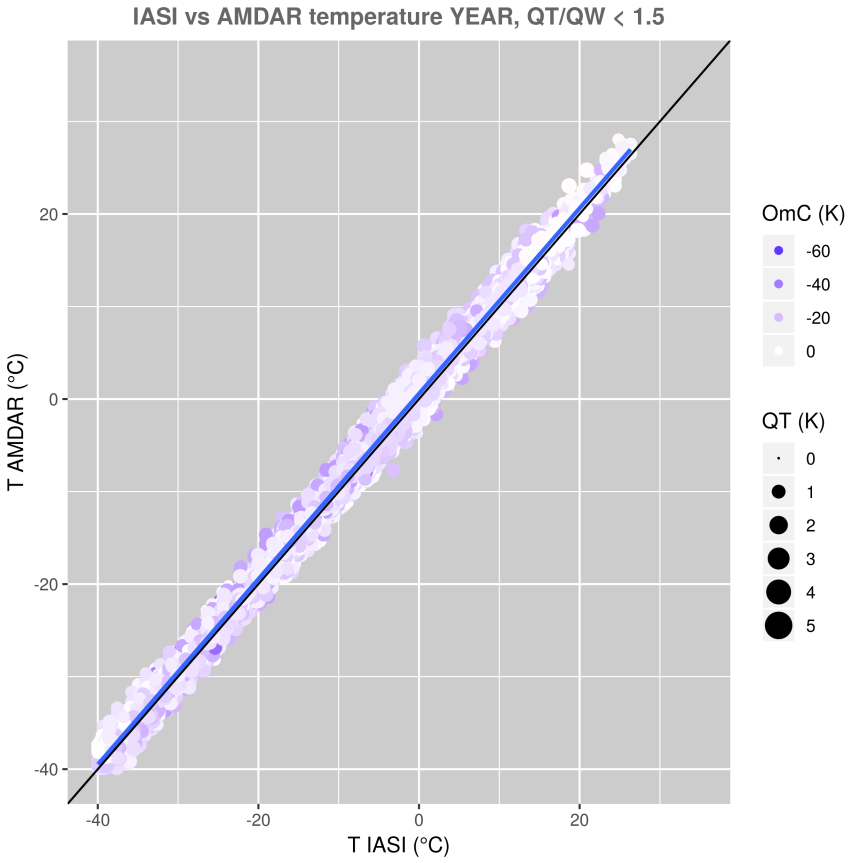
From: Čampa, Strajnar, August, Žibert and Muri

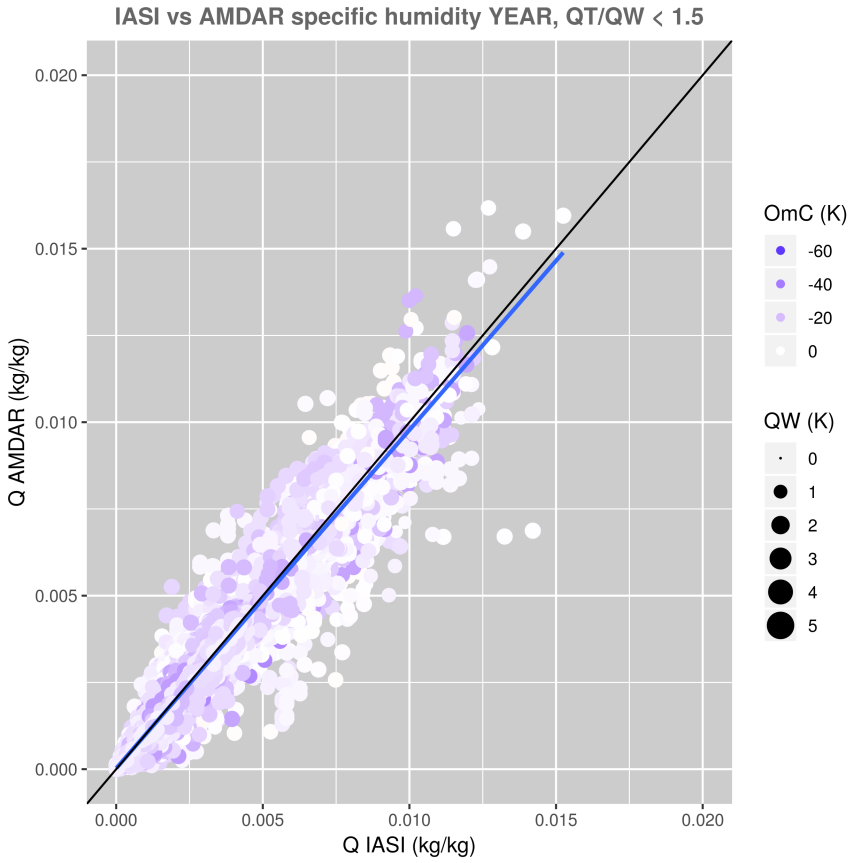


2017 IASI vs AMDAR statistics

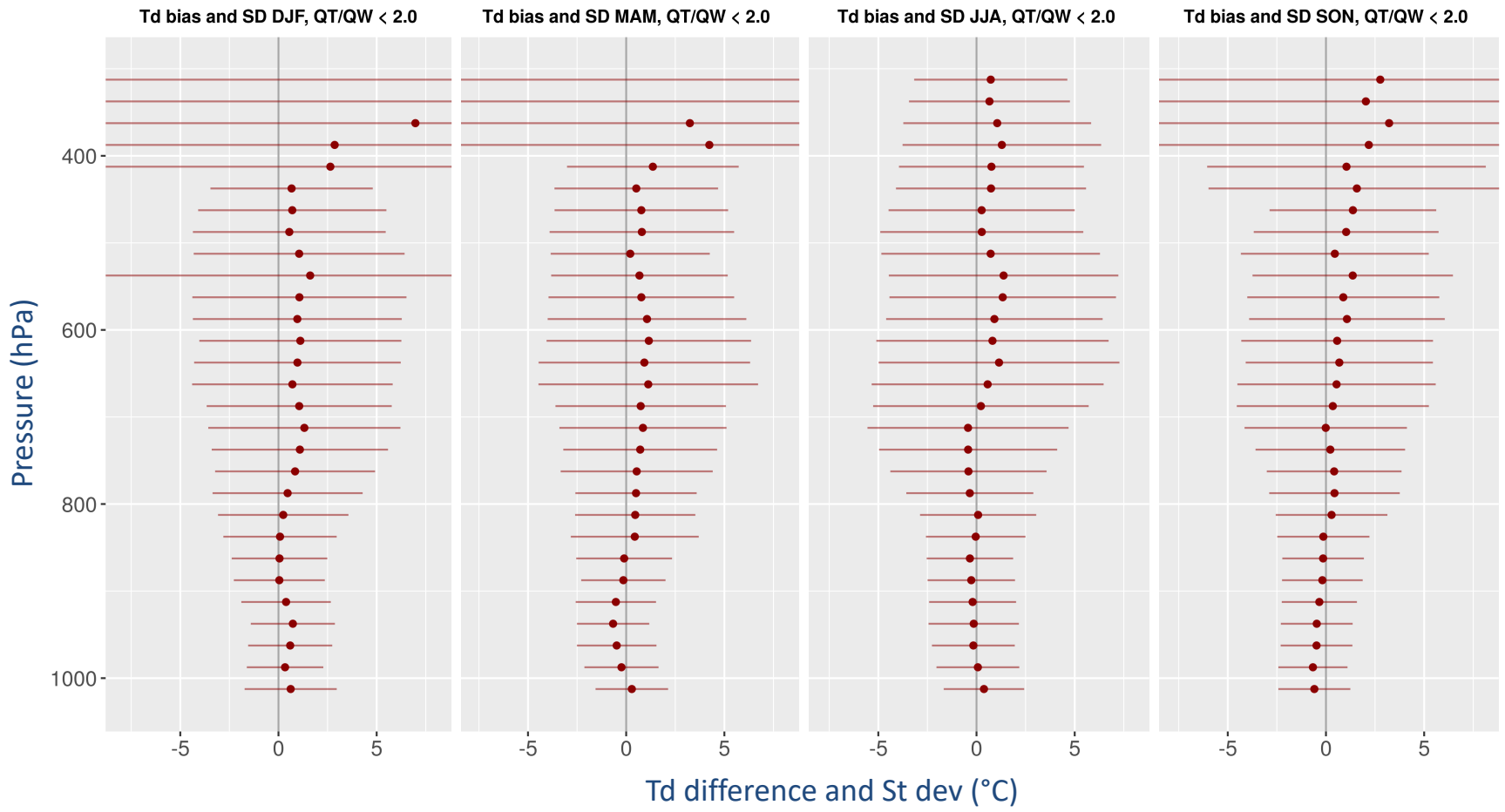


2017 IASI vs AMDAR statistics





IASI vs. AMDAR dew point temperature



On the impact and benefits of AMDAR Water Vapor Observations to operational forecasting

Offering A New Opportunity for Validating Satellite Moisture Products

Propose using WVSS profiles (as well as Temp/Winds) as an Expanded Intercomparison Standard for Satellite Moisture Products

- Eliminates Restrictions of RAOB intercomparisons to 00 and 12 UTC
- Provides a larger geographic … at the day
- Provi… variability
- Provide… boundary layer resolution
- Expansion into new areas logistically straightforward and inexpensive

Questions please ?

- Much Larger Number of Intercomparisons Improves Statistical Significance

- Discriminate by Q/C flags, Distance match, Time match, IR vs. Microwave, Layers vs. levels (to match satellite weighting functions), . . .