University of Wisconsin-Madison Space Science and Engineering Center

Cooperative Institute for Meteorological Satellite Studies

-WVSS-II Moisture Observations – A Tool for Validating and Monitoring Satellite Moisture Data

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A-synoptic Moisture Soundings
Readily Available for
Operational Forecasting
&
High-accuracy Moisture Validations

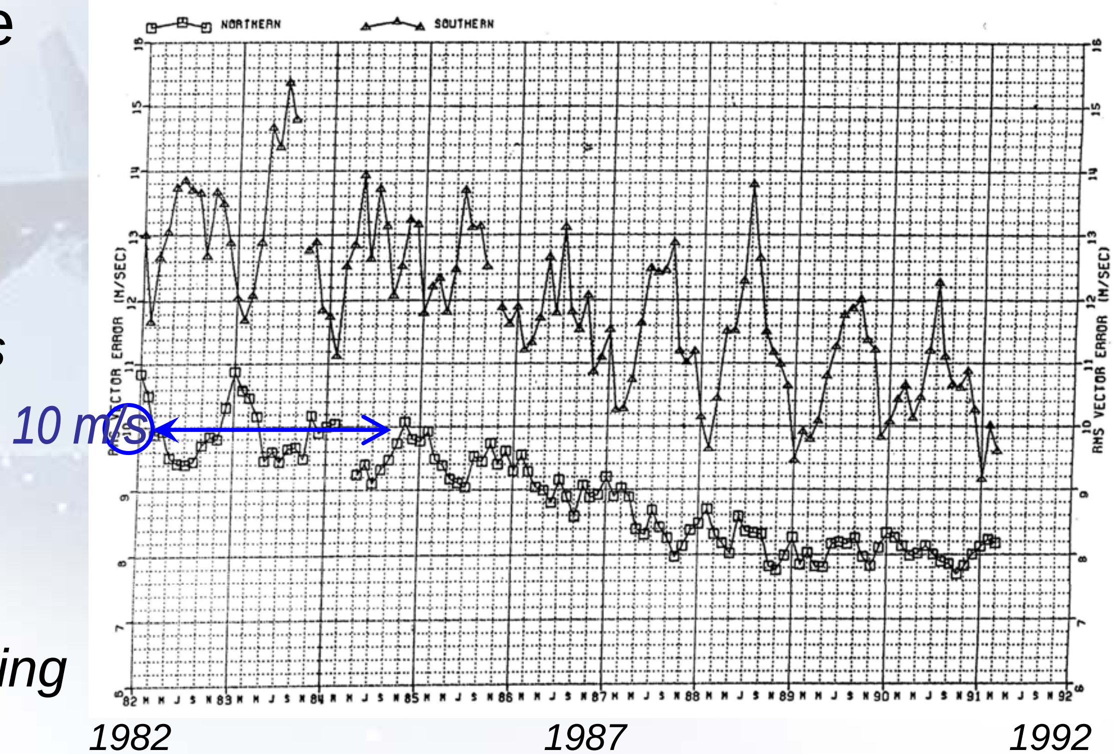
A Brief Historical Perspective

- In the mid-1980s, the FAA formed the “Aviation Weather Forecasting Task Force” led by John McCarthy of NCAR.

- At that time, flight level wind and temperature forecast errors were costing airlines major losses.

  e.g., Trans-oceanic flights often made unscheduled refueling stops in route, requiring overnight lodging for passengers and equipment rescheduling

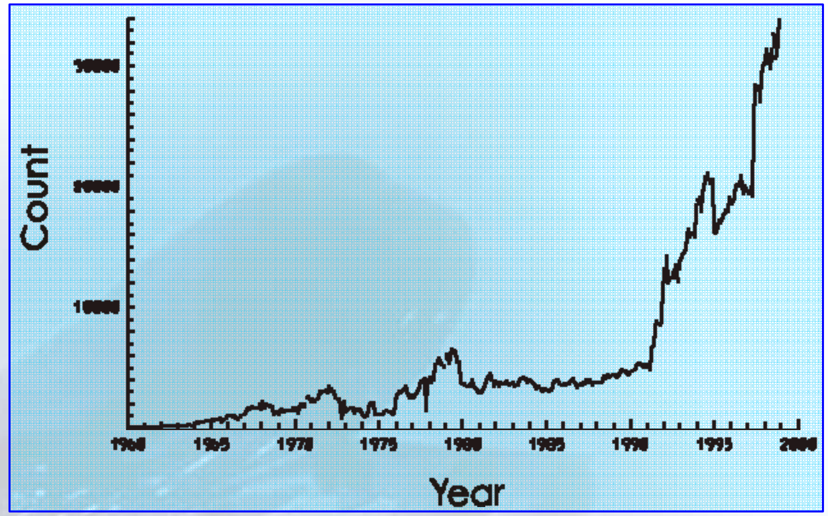
250 hPa 24-hr forecasts vector Wind Error (m/s)



Aircraft Data Collection has been a Joint Industry/Government effort

- Airlines offered to help.
  - Several airlines were already downlinking *automated* temperature and wind data *for their own internal use*
    - At this time, most major airlines had in-house meteorological staffs – and used the aircraft wind/temperature data to update their own systems flight plans
      - Resulted in financial advantage to airlines collecting data
      - Airlines were reluctant to share data with airlines that didn't invest in down-linking costs.
      - Relied upon existing digital air-to-ground communications

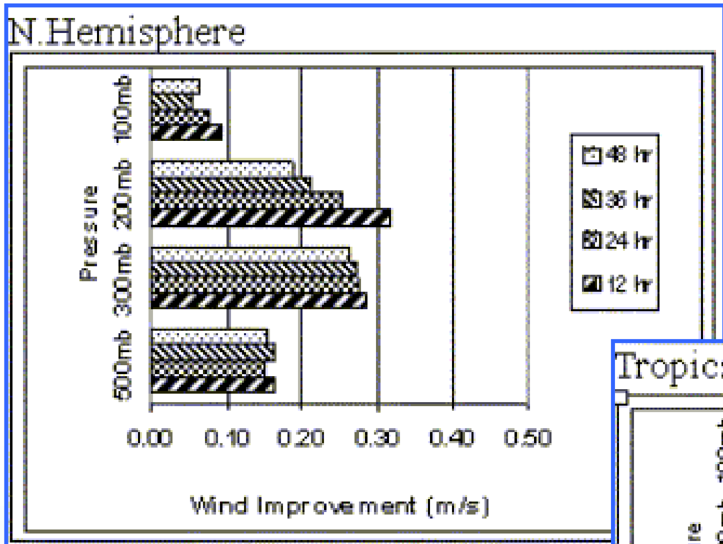
US and European Programs consolidated under WMO AMDAR Program

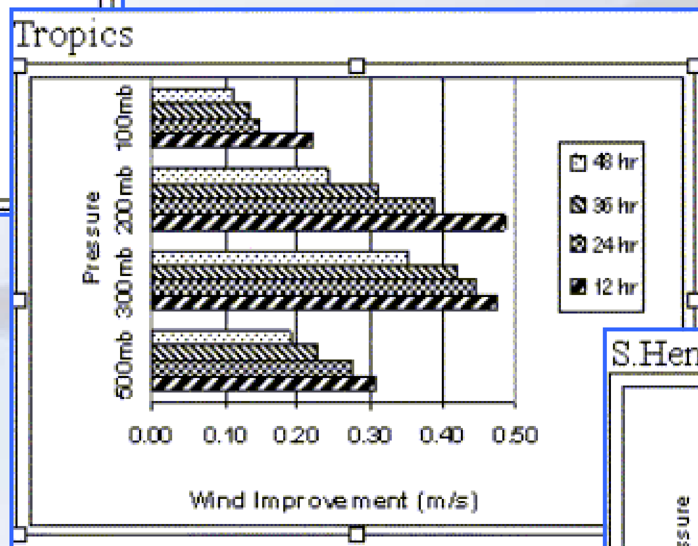


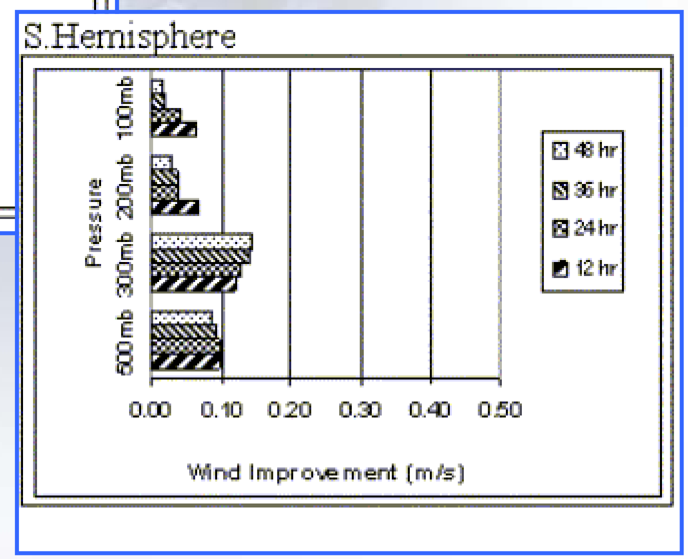
- Airlines offered to help.
  - Basic AMDAR Data (*Flight Level (Pressure), Temperature and Wind*) are copies of observations taken for other purposes
  - Commercial aircraft already had accurate temperature and wind observations for flight efficiency
    - Pressure to determine altitude
    - Jet Engine performance is related to the temperature difference between the engine and the atmosphere
    - Flight efficiency depends on minimizing head winds

The benefits of AMDAR data are global and large for forecasts out to 48 hour.

Results from ECMWF data denial experiments show benefits at all levels, but most in regions where observations are made.



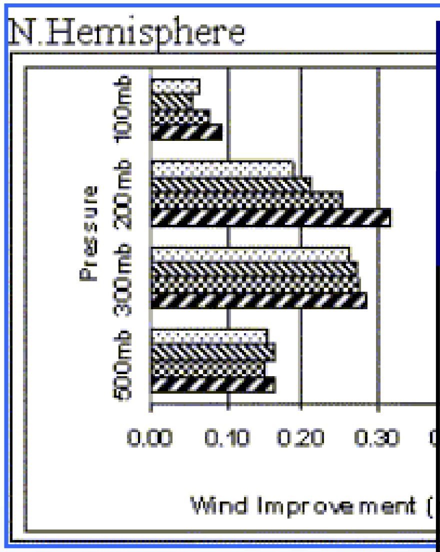




Impact of local detail present in AMDAR Temp / Wind reports is greatest in shorter range forecasts
–
Satellite data dominates longer ranges (>48 hrs)

Impact of AMDAR Temp / Wind data depends on number of reports

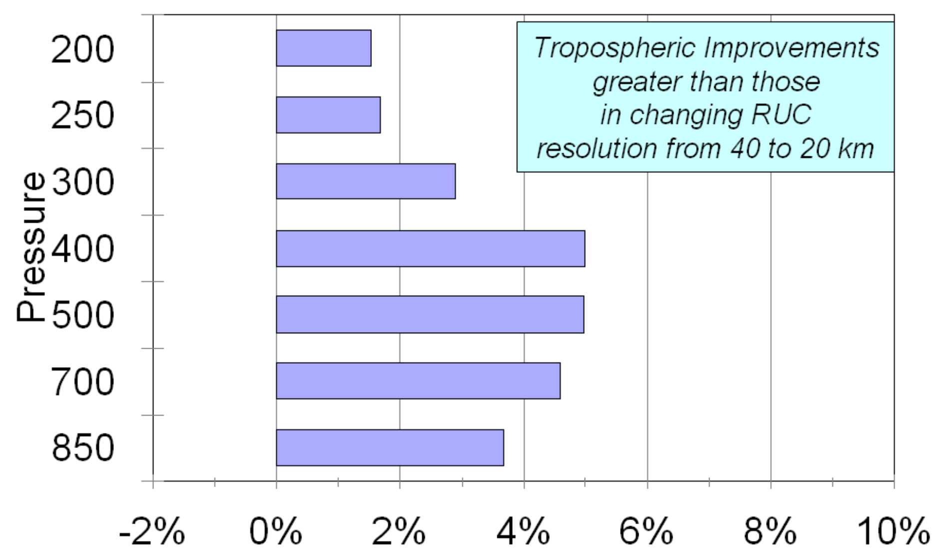
The benefits of AMDAR data are global and large for forecasts out to 48 hour.



Abundance of Wind & Temperature Profiles from aircraft ascent/descent over US further improve forecasts

12 Hr Wind Forecast Difference

Improvement with Ascent/Descent Data



- Significant improvement by including Ascent / Descent data
  - Positive effects at all levels on Winds, Temp and RH
  - Above 25,000', impact comparable to analysis differences
  - Below 25,000', impact slightly smaller, *but still noteworthy*

AMDAR data have help Improve in NWP over past 10 years

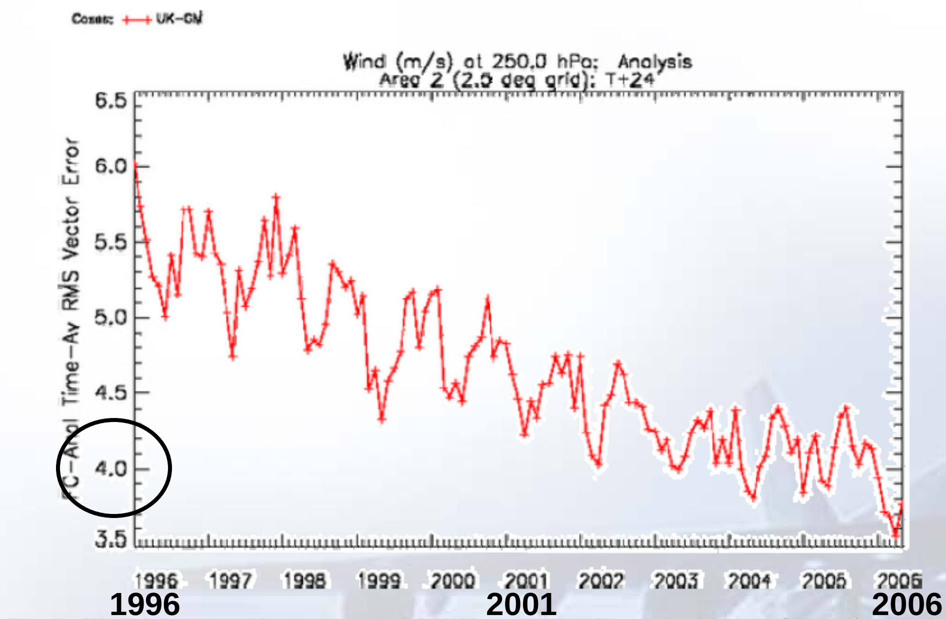
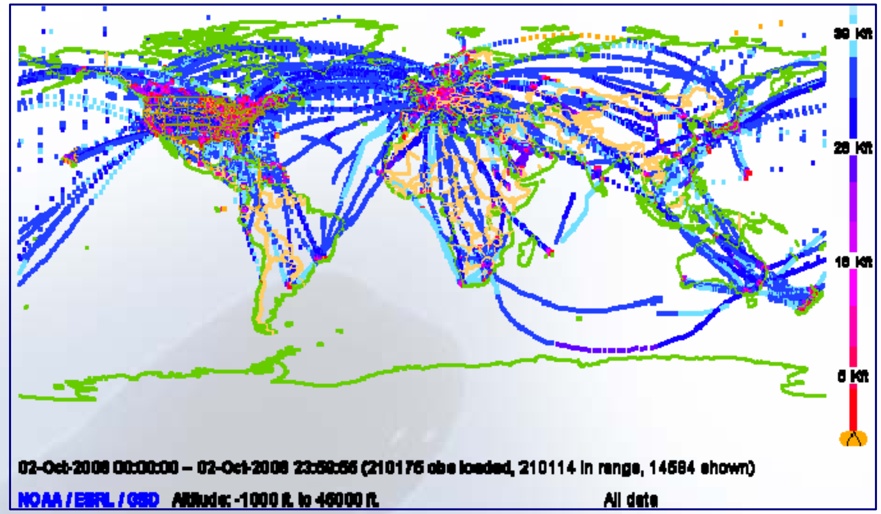
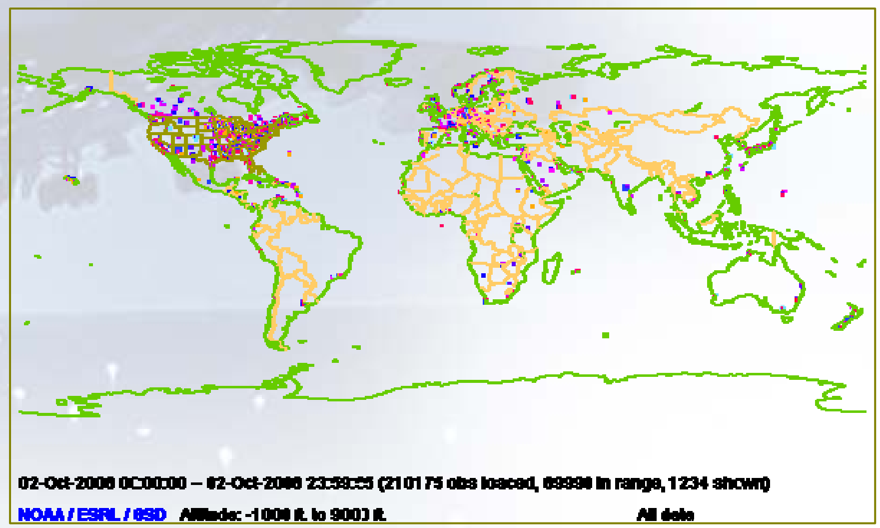


Fig 1. WAFC London North Atlantic RMS Vector Wind Error for 250hpa (FL340) at T+24





SAA pilot said recently that flight times from South Africa to Australia are now typically within 1 minute of predictions

Measuring Moisture from Commercial Aircraft

- Efforts underway for over a decade
  - Research instruments not appropriate for "day-to-day", "real world" application
  - Initial experiments were made using a "stand-alone" Temperature/Relative Humidity sensor called the Water Vapor Sensing System (*WVSS-I*)
    - Used humidity sensors "similar" to those used on radiosondes
      - Test results showed:
        - » Substantial Biases and RMS values that exceeded WMO specification
        - » Systems became contaminated by everyday airport "gunk", e.g. de-icer, dirt on runways, etc.

Measuring Moisture from Commercial Aircraft

- Efforts underway for over a decade
  - Second-generation Water Vapor Sensing System (*WVSS-II*) measures Mixing Ratio directly
    - Uses a laser-diode system to measure number of water molecules passing sensor
    - Testing on UPS 757s
      - Used by UPS for fog forecasting
      - Final tests in 2009-2010
      - Re-engineered electronics
      - Improved mechanics
    - New installation at SouthWest Airlines

EXPERIMENTAL DESIGN

Most recent Independent ground-truth assessments of the WVSS-II systems have been conducted for three periods:

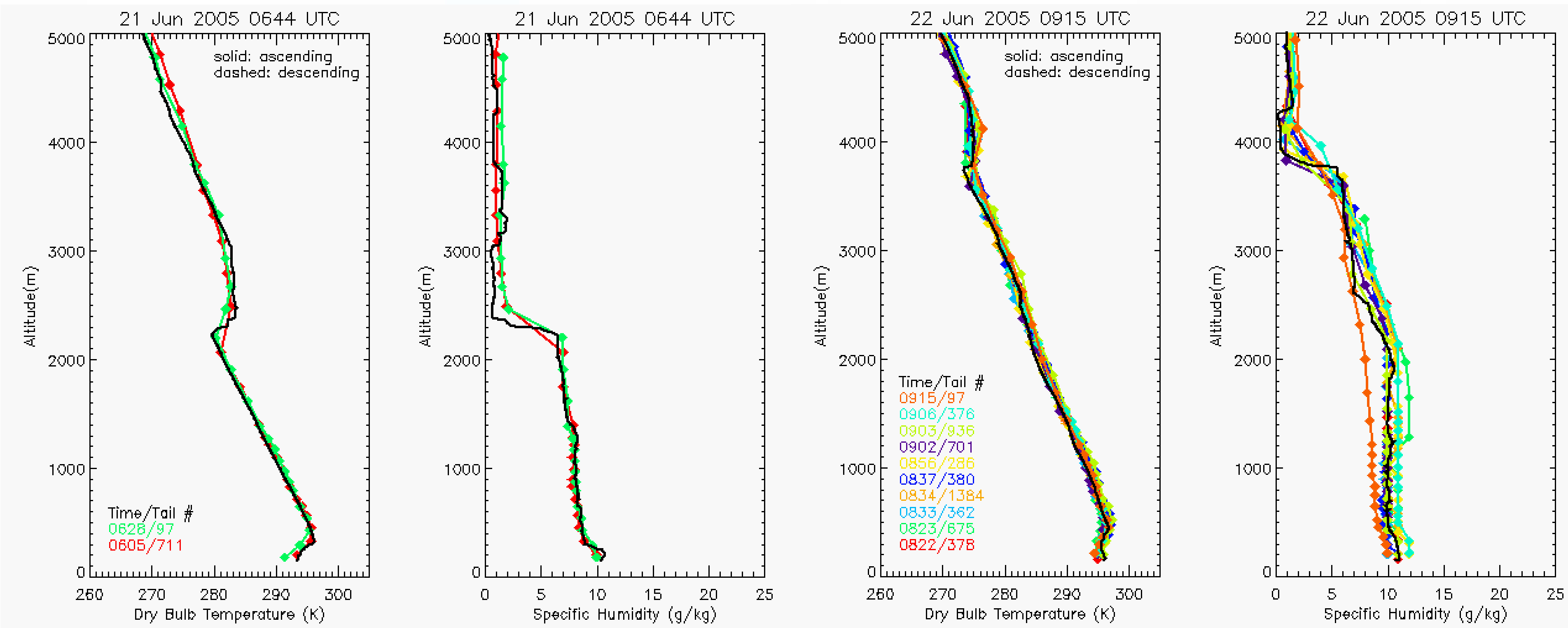
- November 2009,
- May-June 2010, and
- August 2010.

The WVSS-II humidity data were compared with rawinsonde and ground based remote sensing systems.

- Between 15 and 20 different UPS B757 aircraft provided WVSS-II data
  - **--Data available via GTS**

Rawinsondes observations were made at the UPS hub in Rockford, Illinois – where about 20-25% of the WVSS-II equipped planes land / take off daily.

2005 Specific Humidity Profiles Varied



Some WVSS-II profiles matched the rawinsonde profile well.

(Profiles 16 and 39 min before rawinsonde)

Others show much greater spread between individual aircraft and the rawinsonde report.

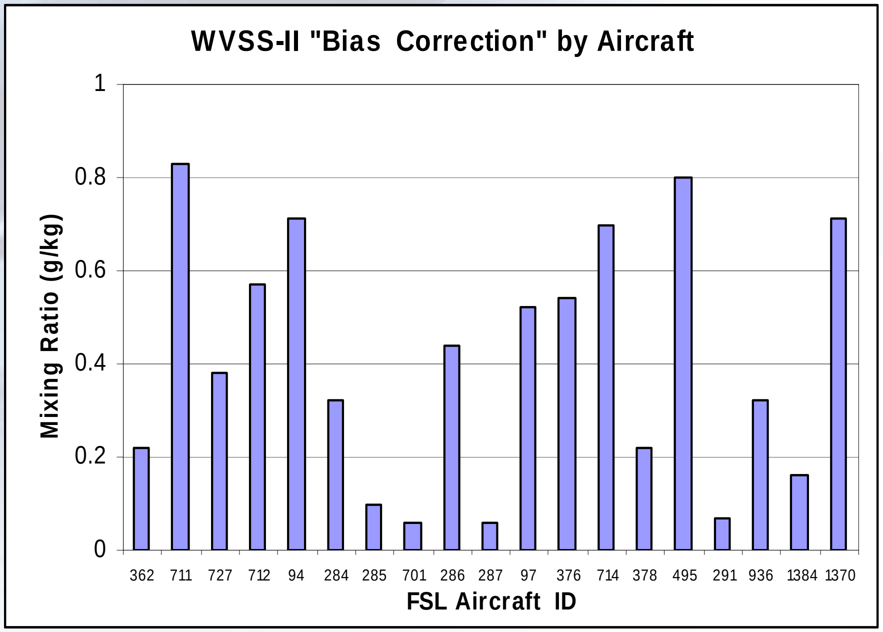
(Of 3 'outlying' reports, one was taken at the exact rawinsonde starting time.)

2005 Test – Conclusions

- **Moisture observations made by WVSS-II equipped commercial (UPS) aircraft show a small, but positive bias in the boundary layer, with slightly larger values above.**
- **Specific humidity RMS and Standard Deviations average around 1 g/kg at all levels.**

<u>But:</u>

- *The <u>accuracy</u> of individual WVSS-II instruments <u>varied greatly</u> from one aircraft to another.*
- *More than 1/3 showed unacceptably <u>large biases</u> and were <u>not included</u> in the evaluation.*
- *<u>Engineering problems contaminated low values</u>*
- *<u>Encoding problems reduced reporting accuracy of high values</u>*

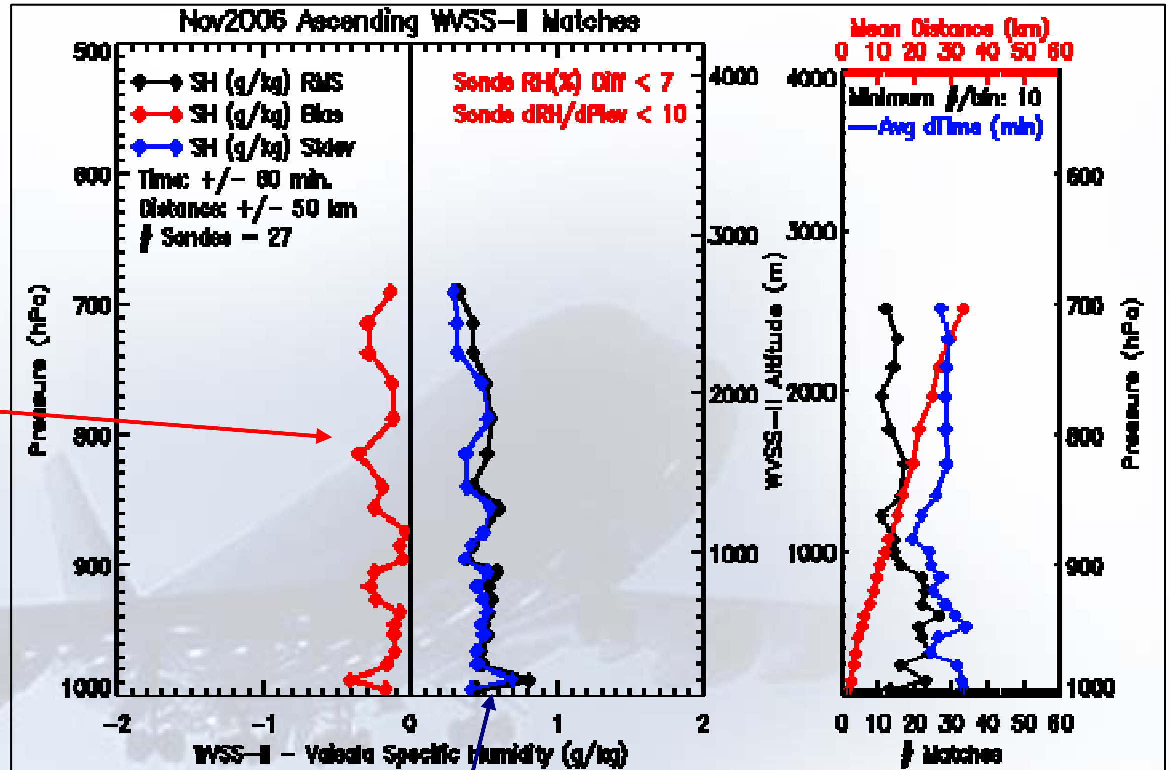


Nov 2006 Validation Results

Specific Humidity

Systematic Differences:

WVSS-II Mixing Ratio Biases were very small, though generally negative (0.0 to -0.25 g/kg) from the surface up to nearly 700 hPa.



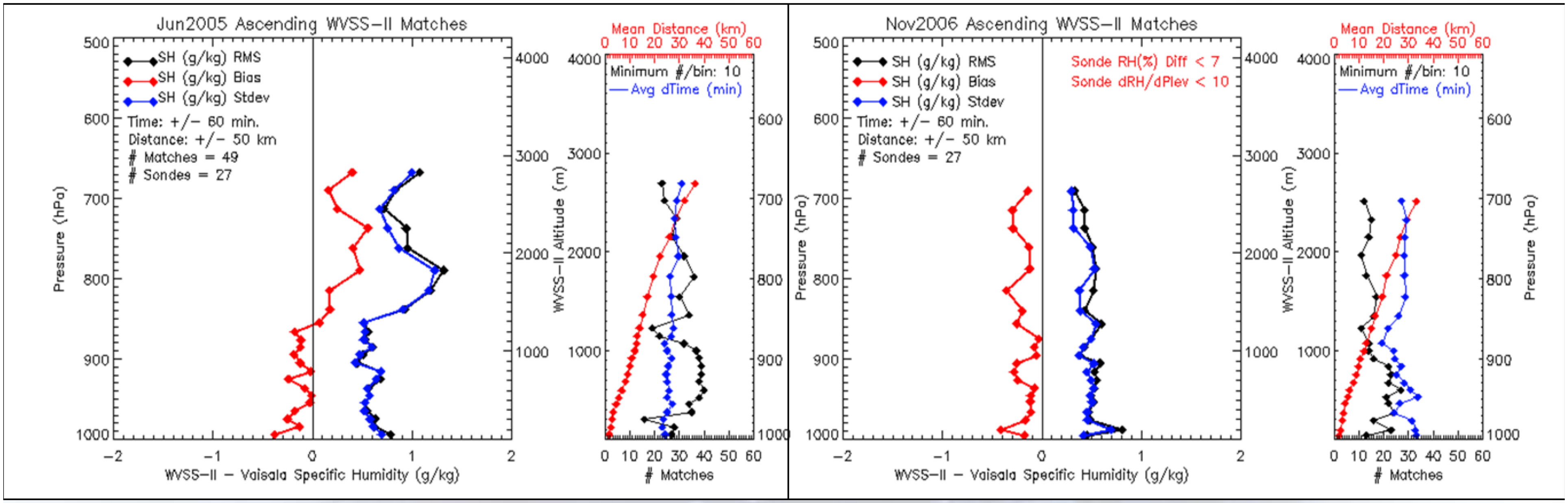
Random Differences:

Differences between aircraft data and rawinsonde reports showed variability of 0.5 to 0.8 g/kg from the surface to 950 hPa. Above 950 hPa, SD values decrease to between 0.3 and 0.5 g/kg

Tests excluded high/low moisture environments

Comparing 2005 & 2006 Validation Results

2005 2006



Engineering changes made after the 2005 test were at least partially successful in improving WVSS-II data taken, but only during ascent.

- **Modified systems produce consistent small negative Biases at all levels.**
- **Random error component improved - ~0.4 g/kg, a 50-65% improvement**

BUT:

Still unacceptably numbers of 'bad' systems and high degradation rate

Only ascending reports > 2 g/kg and <10 g/kg – due to known system deficiencies.

-- Remaining WVSS-II data problems addressed --

Three re-engineered units to NOAA were thoroughly tested before widespread aircraft installation in 2009-2010:

- Data processing hardware replaced with digital systems unaffected by ambient temperature

- Issues regarding water accumulating in intake tubes corrected.

- All moisture was removed from laser chambers.

- Every laser was tested for long-term stability before use.

- Assessed:

- In Chamber at the NOAA's Upper-Air Facility

- In Chamber at Deutscher Wetterdienst

- Versus chilled mirror on P-3

- In long-term laser stability tests

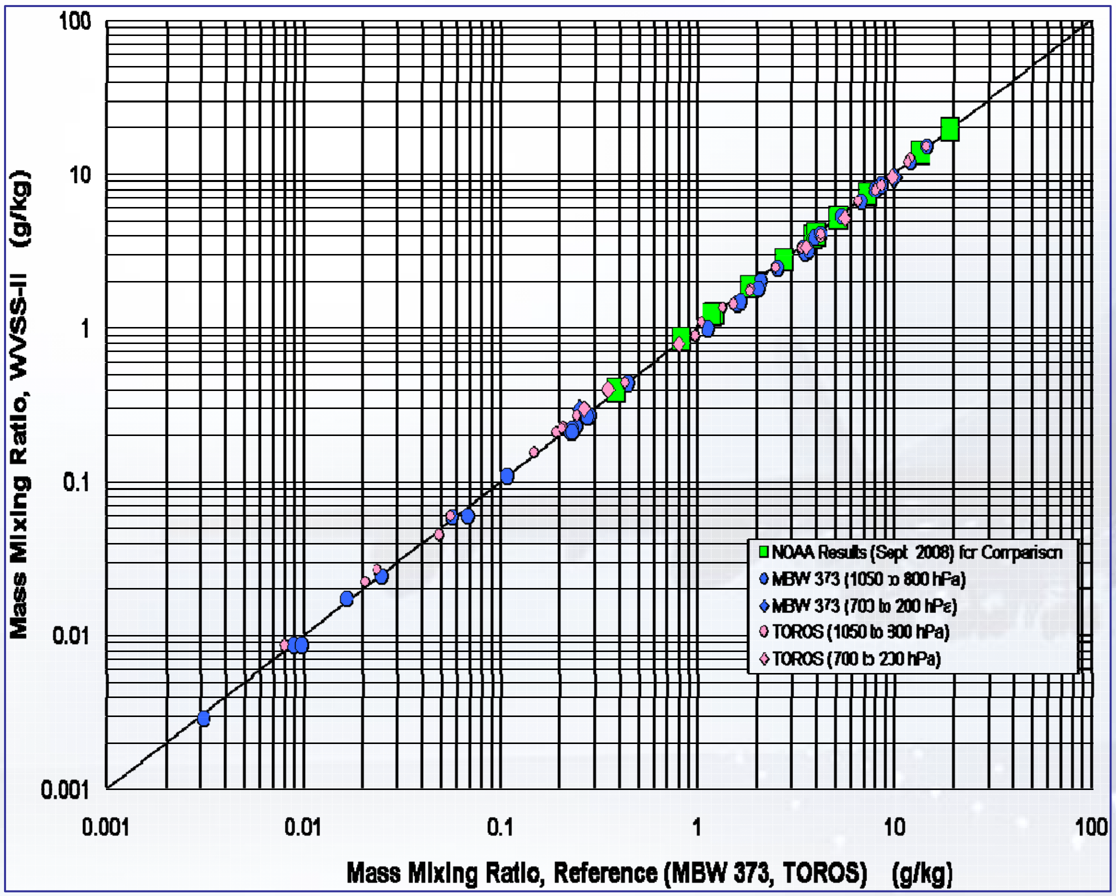
- Reporting Precision issues resolved on all UPS aircraft

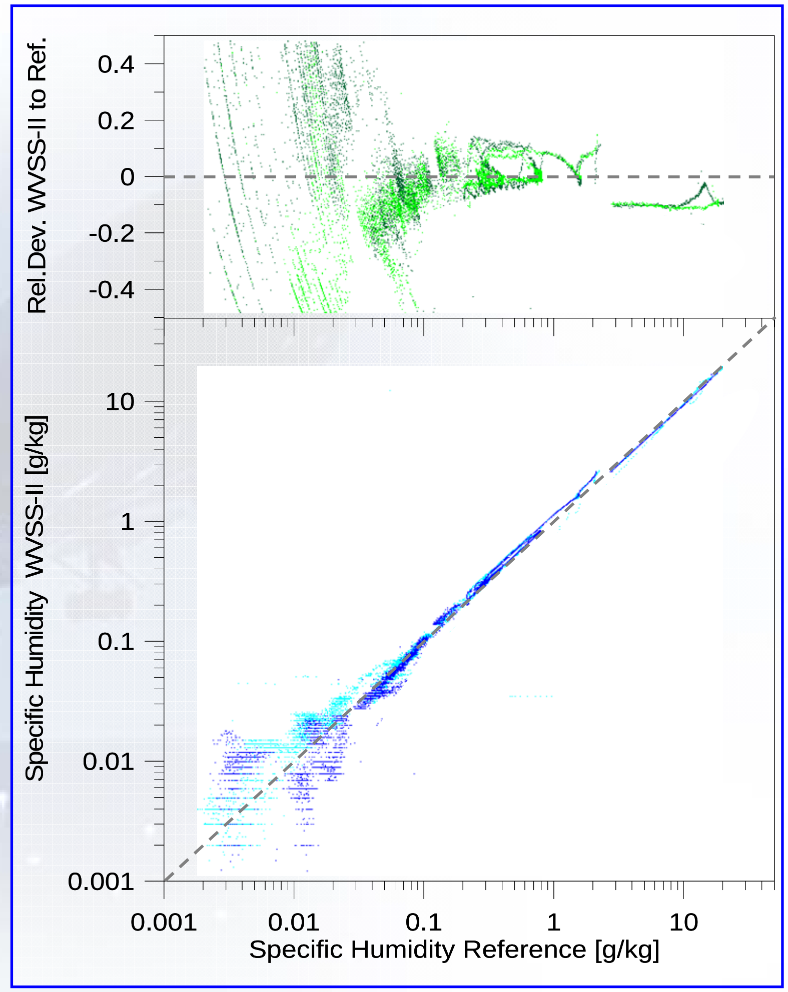
In 2009-2010:

-***Replaced 25 WVSSII units on UPS B-757s***

-***Installing 31 units on Southwest B-737s***

Chamber Experiments by NOAA and DWD were Very Positive



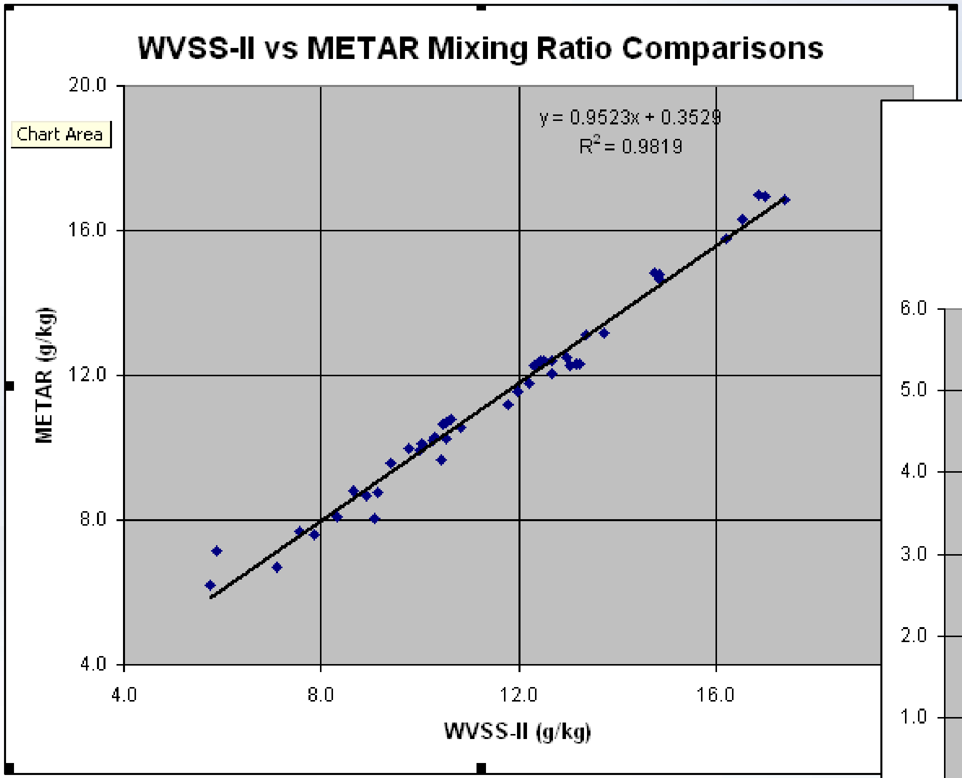


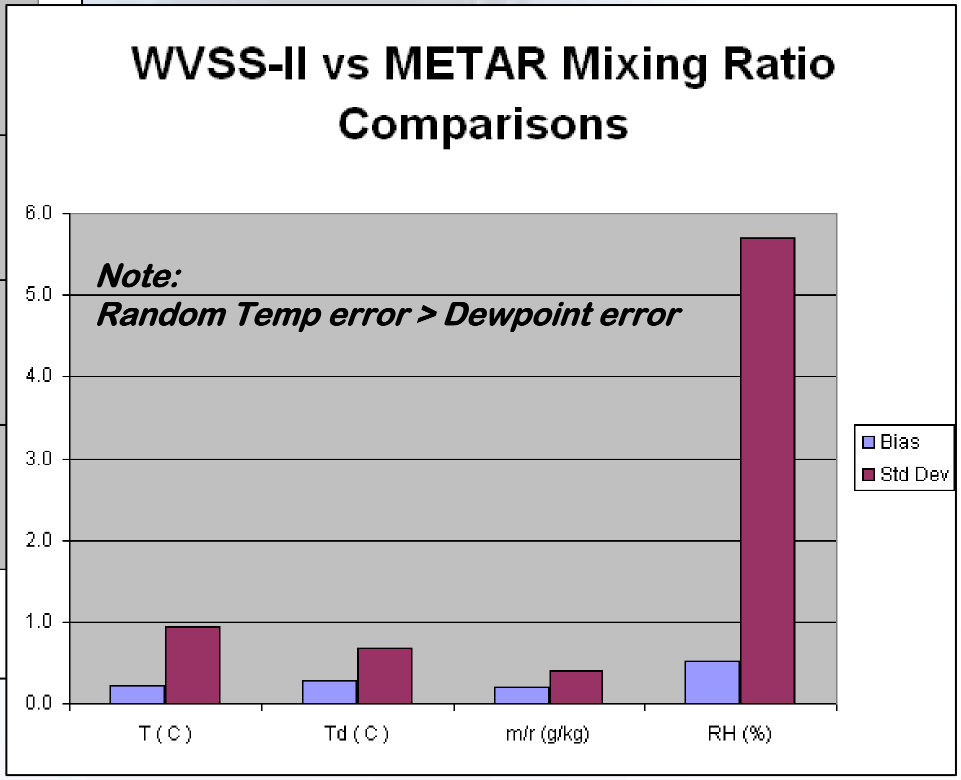
Only substantial differences appear for Specific Humidity below ~0.03 g/kg

Initial Comparisons of re-engineered WVSS-II data with co-located surface (METAR) reports

First new WVSS-II unit on UPS aircraft agrees very closely with time/space co-located night-time surface observations from September 2009:

Mixing Ratio Bias ~ 0.2 g/kg
Mixing Ratio Standard Deviation ~ 0.4 g/kg

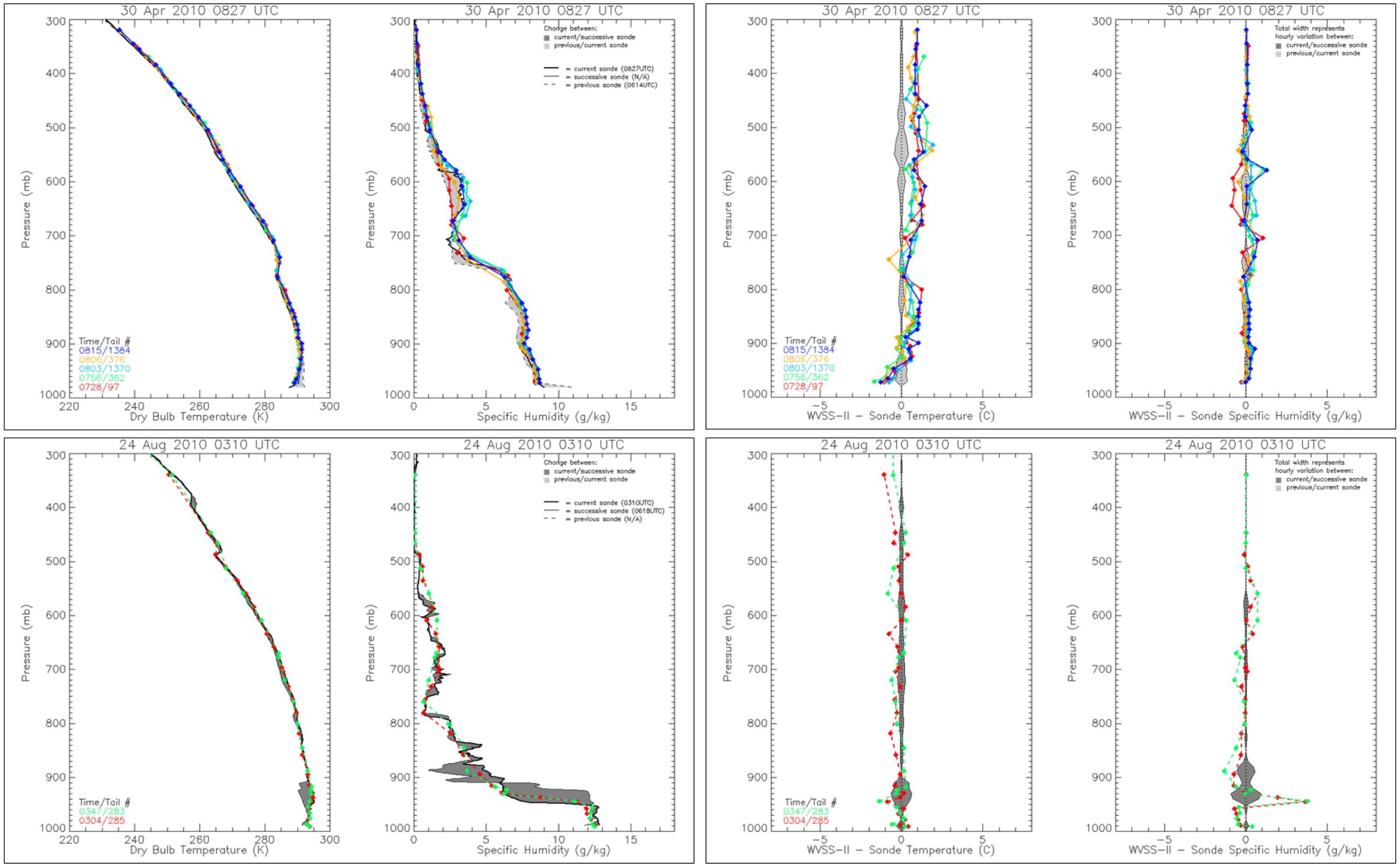




Data provided by Randy Baker, UPS

Nov 2009-2010 Validation Results

Direct Sounding Intercomparisons

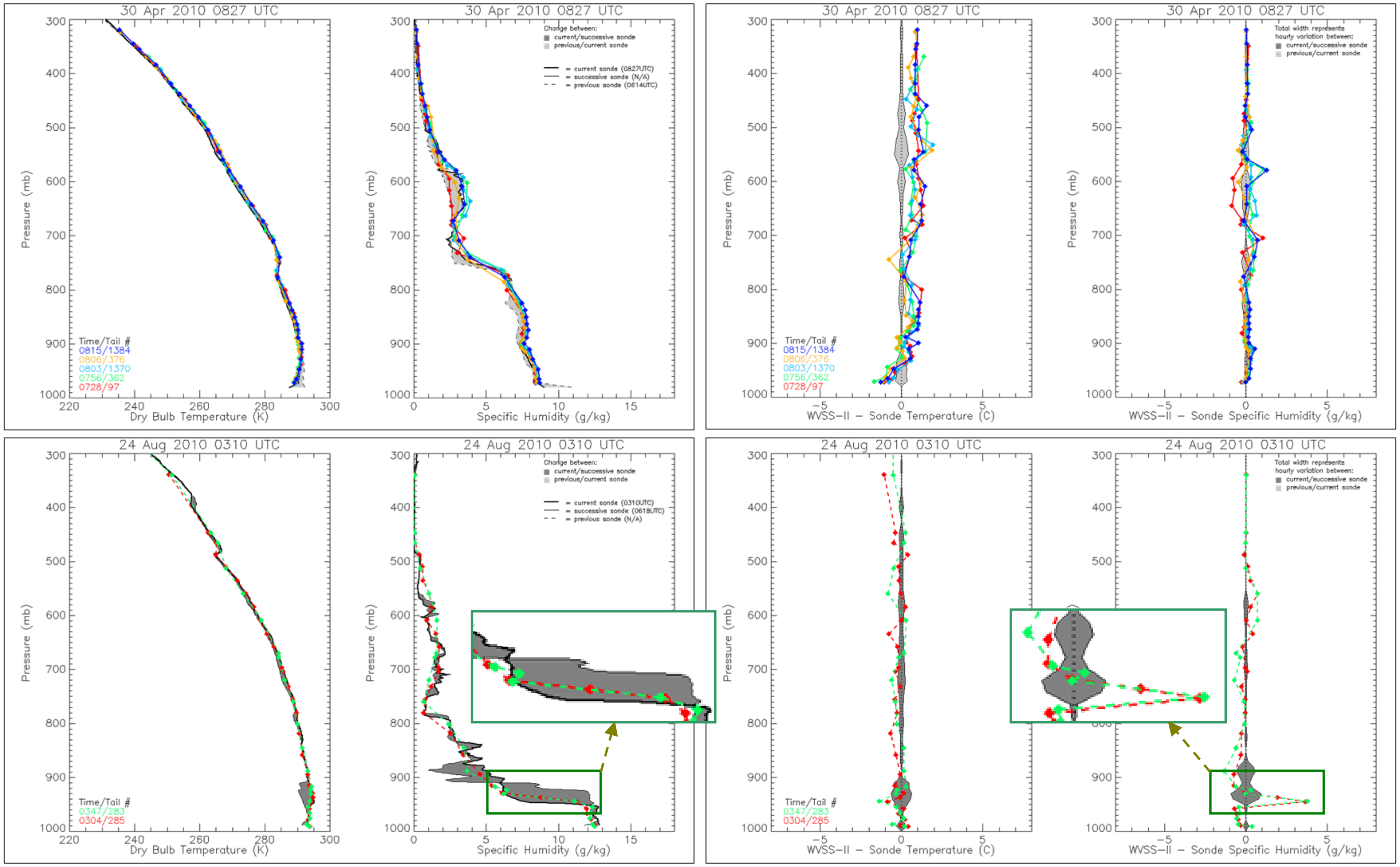


Direct Data Comparison:

Aircraft data generally fell between bounding Rawinsonde reports

Nov 2009-2010 Validation Results

Direct Sounding Intercomparisons



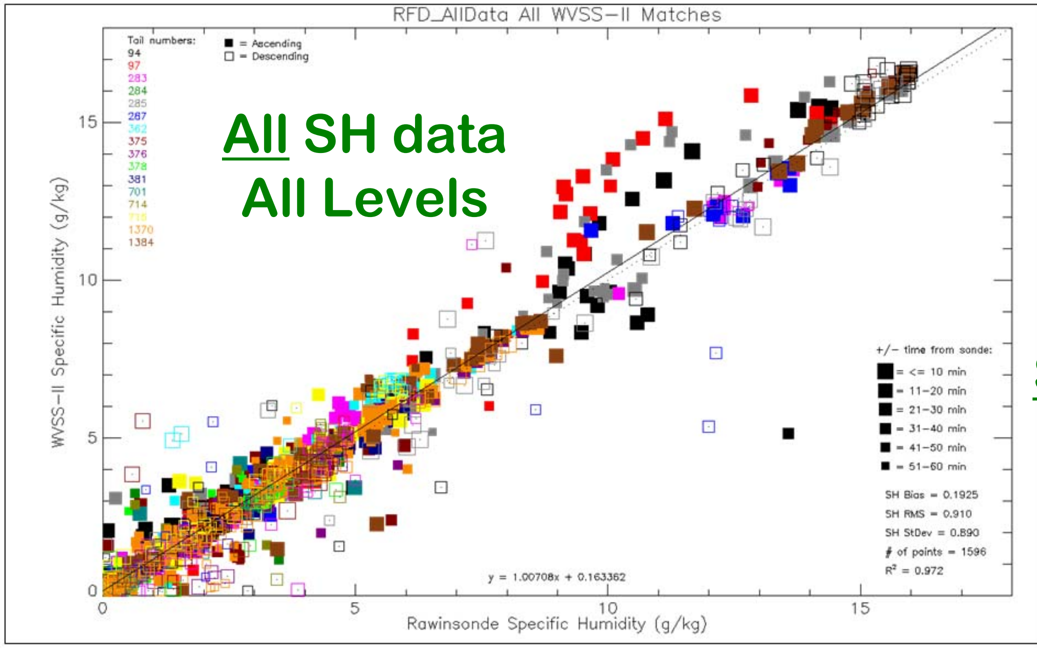
Direct Data Comparison:

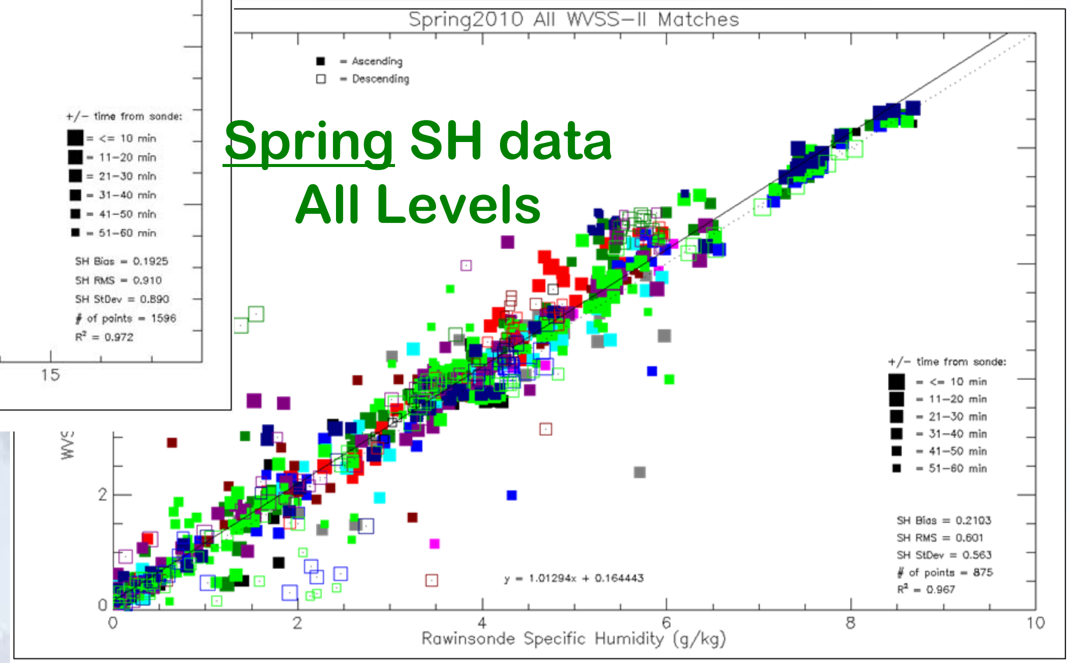
Aircraft data generally fell between bounding Rawinsonde reports

Large variability within Moist regimes led to large Specific Humidity differences

Nov 2009-2010 Validation Results

Summary of Direct Specific Humidity Intercomparisons





Differences showed:

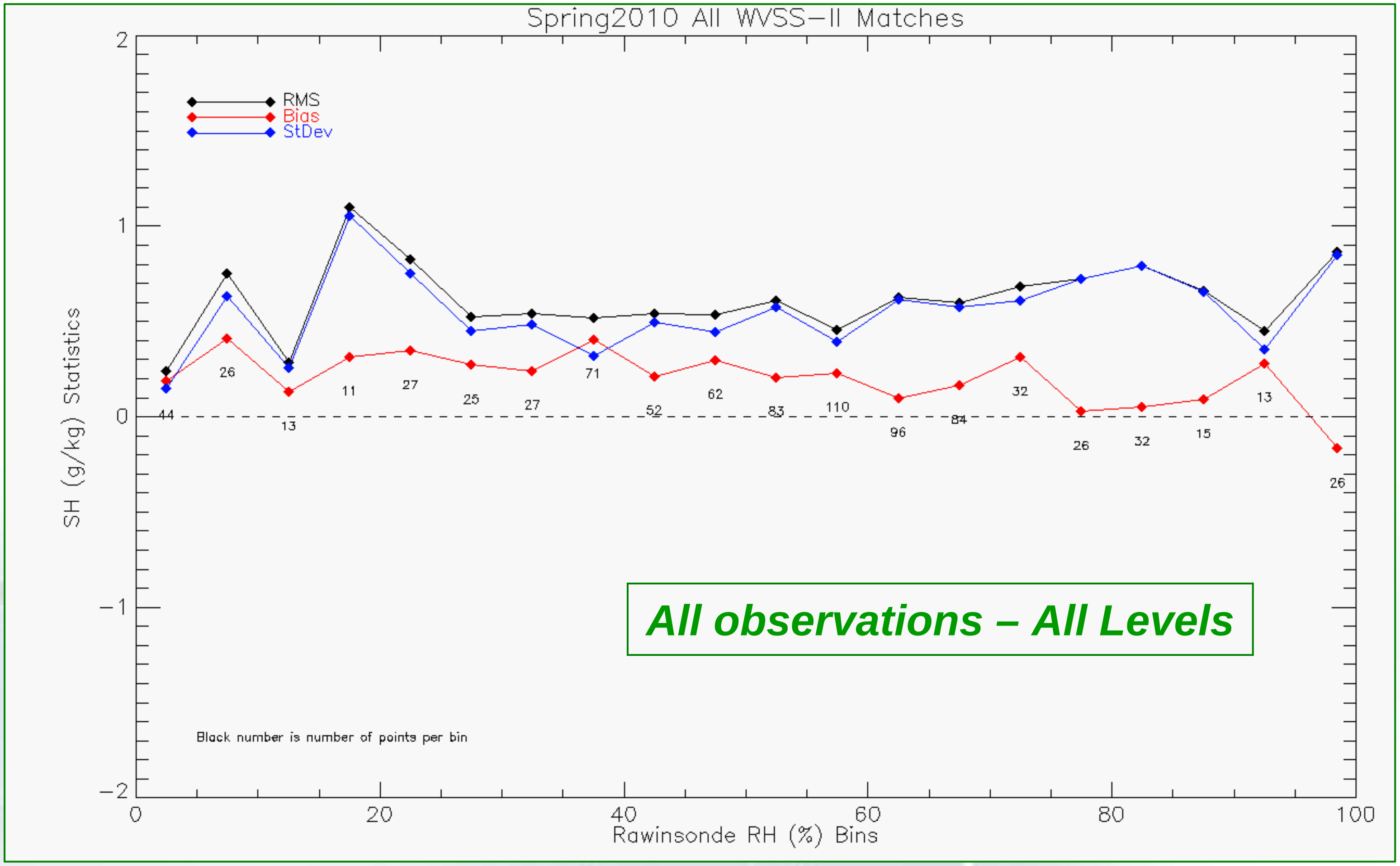
Aircraft data and rawinsonde reports agreed best in middle SH ranges

Positive WVSS-II biases at low rawinsonde values *(low bias improbable)*

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

Nov 2009-2010 Validation Results

Direct Specific Humidity Intercomparisons by Relative Humidity



Differences showed:

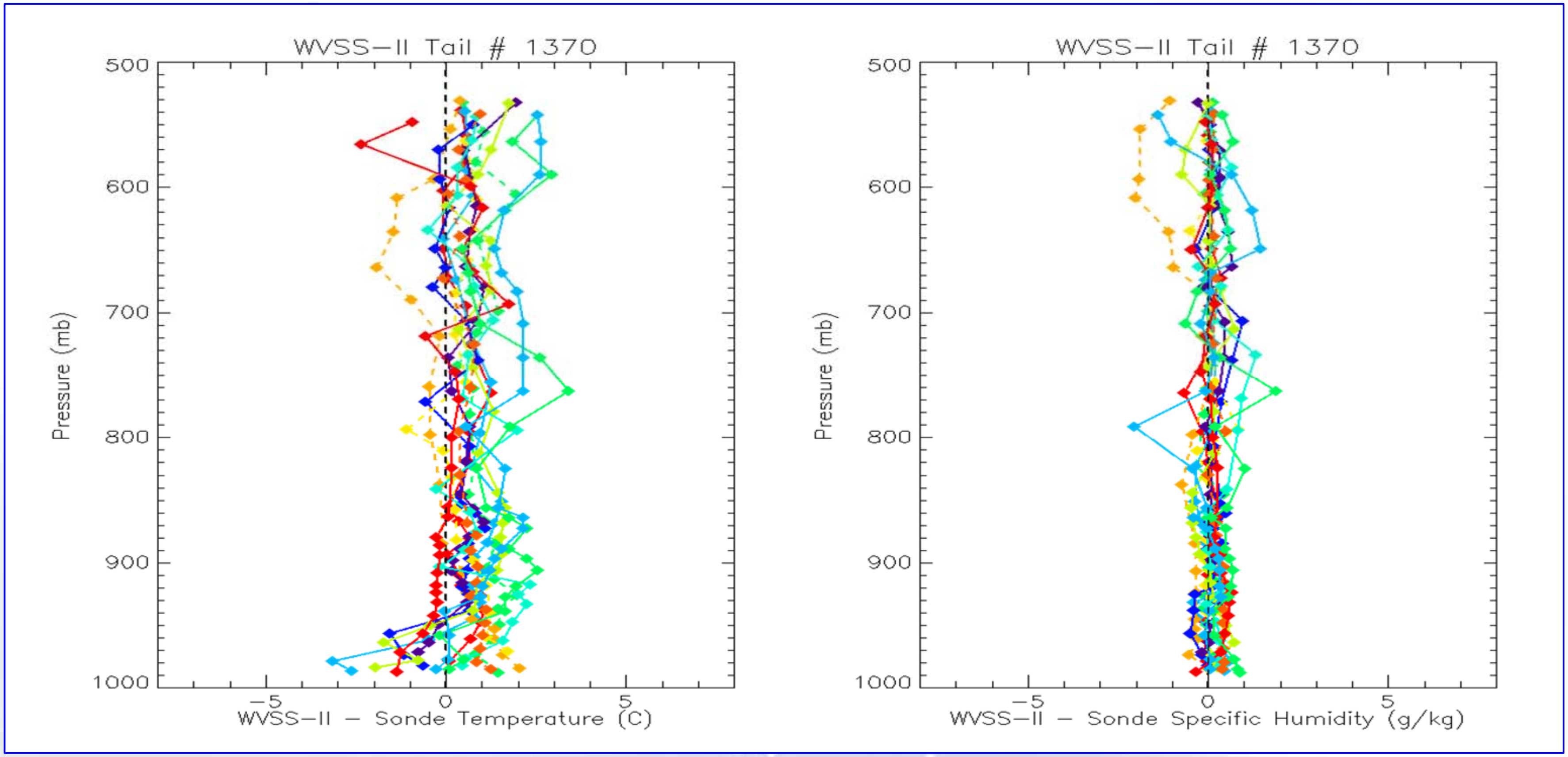
Small positive Bias across all RH ranges

Random Errors average ~0.5-0.7 g/kg *(low bias improbable)*

Higher Random Errors between 20-25% RH and Near Saturation

Spring 2010 Validation Results

Direct Temperature and Specific Humidity Intercomparisons
All Spring Data Only



Differences from Rawinsondes showed:

Warm Temperature Bias at all levels

Large Temperature variability

Random SH Differences average ~ ± 0.5 g/kg

2009-2010 Validation Results

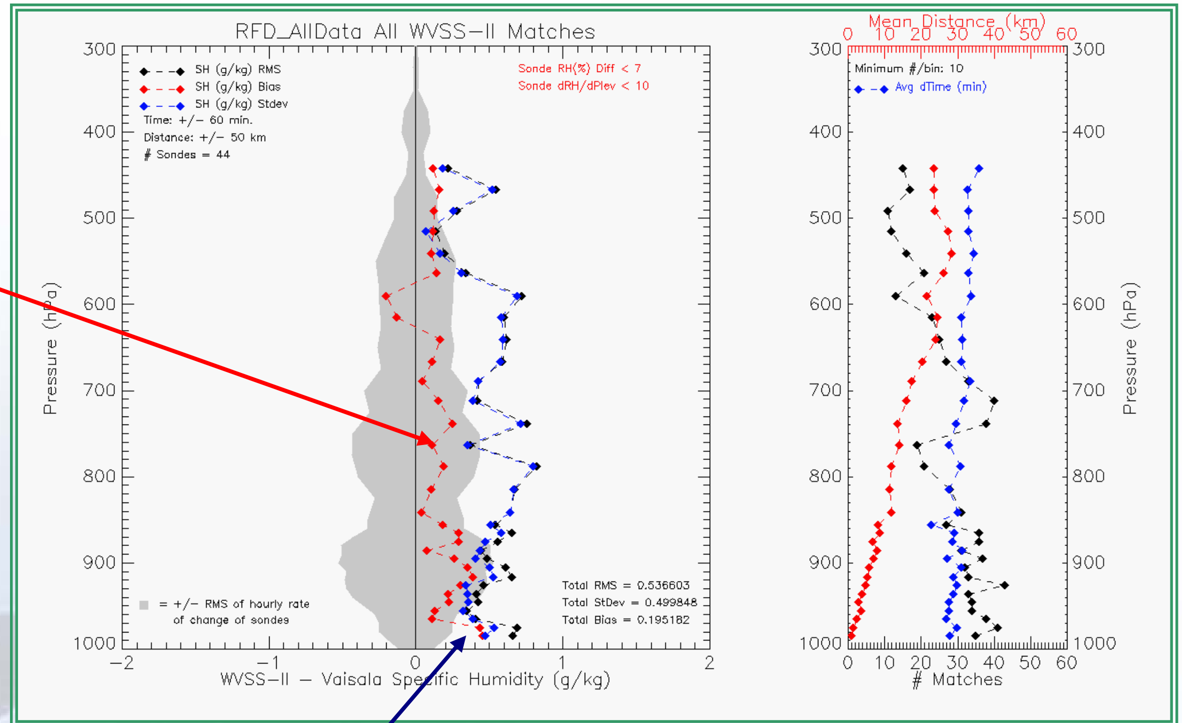
Specific Humidity

(Excludes cases with large time and vertical rawinsonde differences)

Systematic Differences:

WVSS-II 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 0.7 g/kg from the surface to 600 hPa – decreases aloft.

StdDev slightly larger than 1-hour variability between bounding rawinsonde reports (gray shading).

Note: Fewer intercomparisons near 800 hPa and above 700 hPa. Greater time and space separation above 650 hPa.

2009-2010 Validation Results

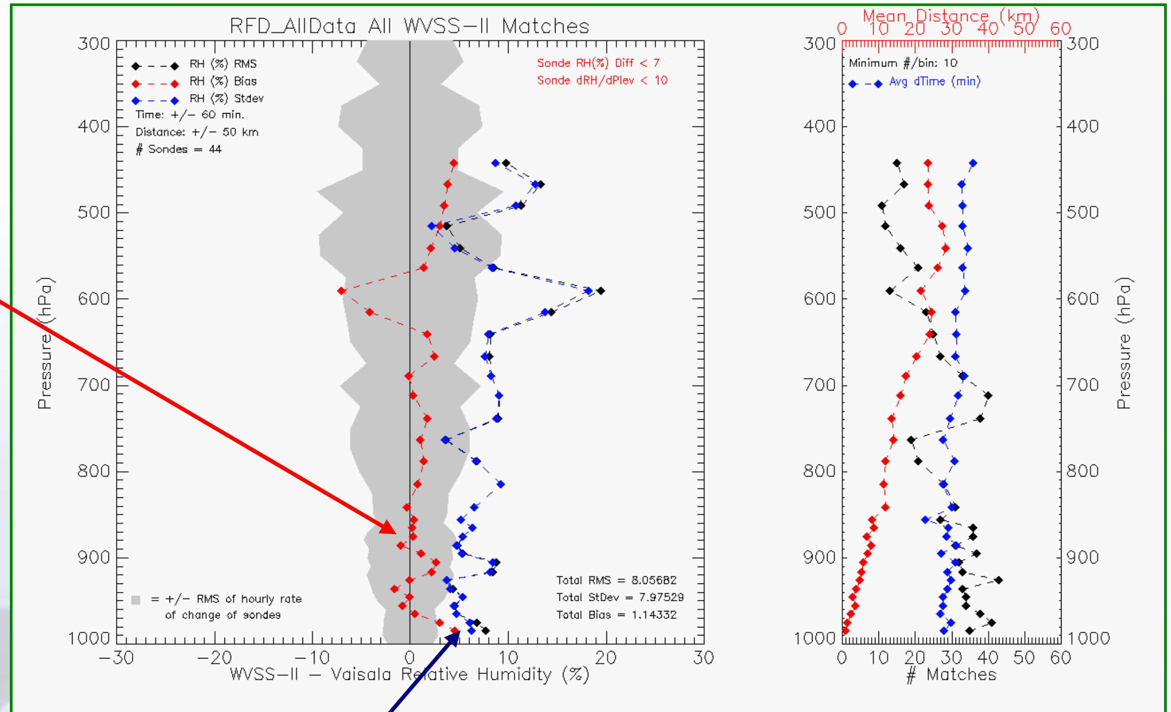
Relative Humidity

(From WVSS-II Humidity & Aircraft Temperature)

Systematic Differences:

WVSS-II RH Biases were very small positive (0 – ±3%) from surface to 650 hPa.

Negative maximum at observation minimum.



Random Differences (Including Dry/Moist Environments):

Differences between aircraft data and rawinsonde reports generally showed variability of 5 to 8% from the surface to 750 hPa.

Above 750 hPa, RH StdDev increases as number of matches decreases and space/time distance increases.

Differences slightly larger than 1-hour variability between bounding rawinsonde reports (gray shading).

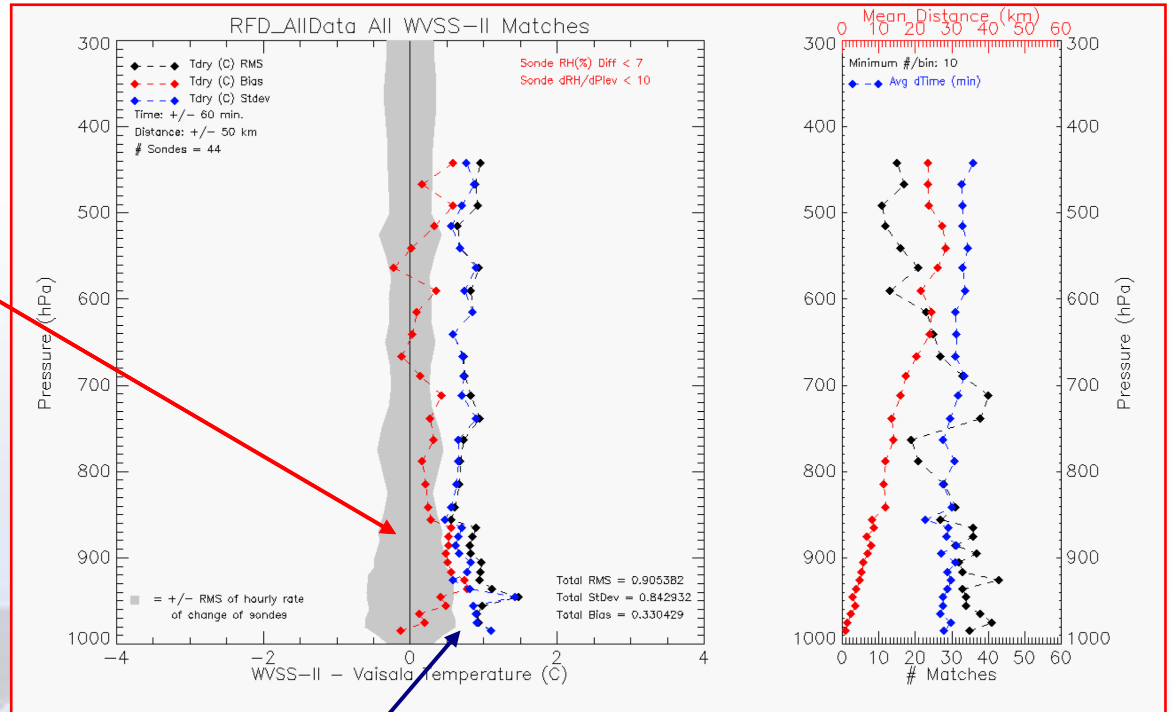
2009-2010 Validation Results

Temperature

Systematic Differences:

Aircraft Temperature Biases at low levels of 0.2 to +0.7°C. from surface to 700 hPa.

Net neutral above that level



Random Differences :

Differences between aircraft data and rawinsonde reports generally showed variability of 0.8 to +1.5°C from the surface to 850 hPa.

Above 850 hPa, T SdtDev stabilizes to about 1.0°C

Differences larger than 1-hour variability between bounding rawinsonde reports (gray shading).

2009-2010 Validation Results

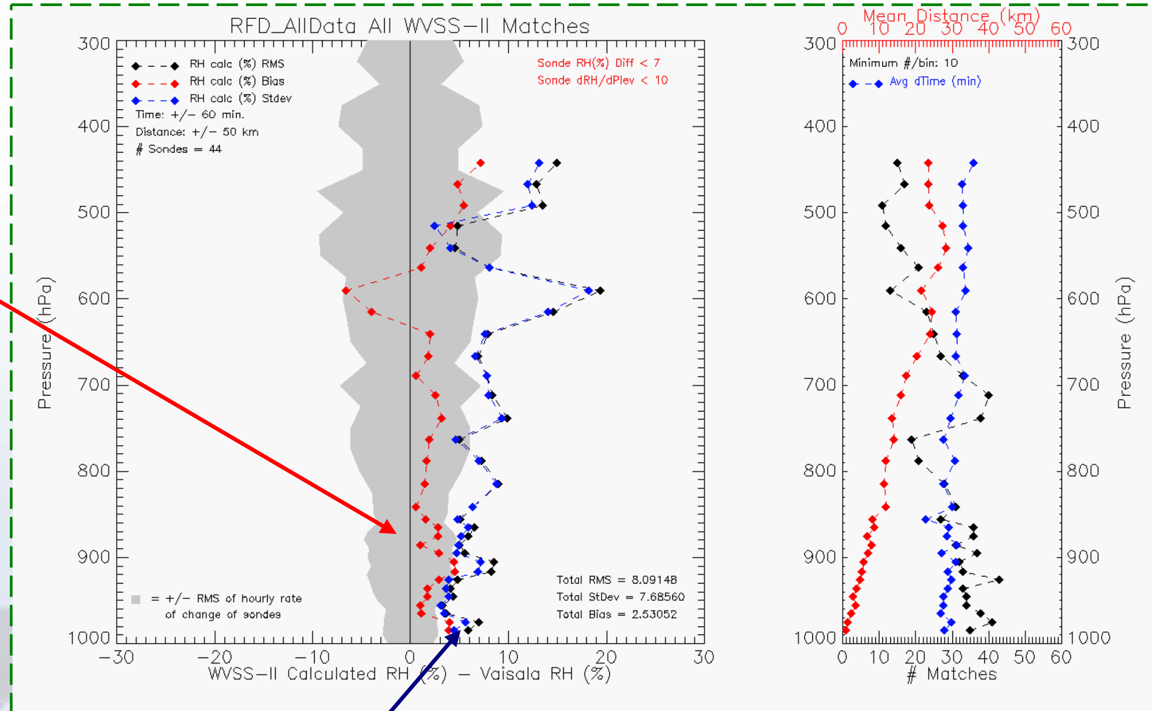
Relative Humidity

(From WVSS-II Humidity & Rawinsonde Temperature)

Systematic Differences:

RH Biases due to WVSS-II were small positive (1 – ±4%) from surface to 650 hPa.

Negative maximum at observation minimum.



Random Differences (Including Dry/Moist Environments):

Differences between aircraft data and rawinsonde reports generally showed variability of 6 to 9% from the surface to 750 hPa.

Above 750 hPa, RH StdDev increases as number of matches decreases and space/time distance increases.

Random Differences slightly larger than 1-hour variability between bounding rawinsonde reports (gray shading).

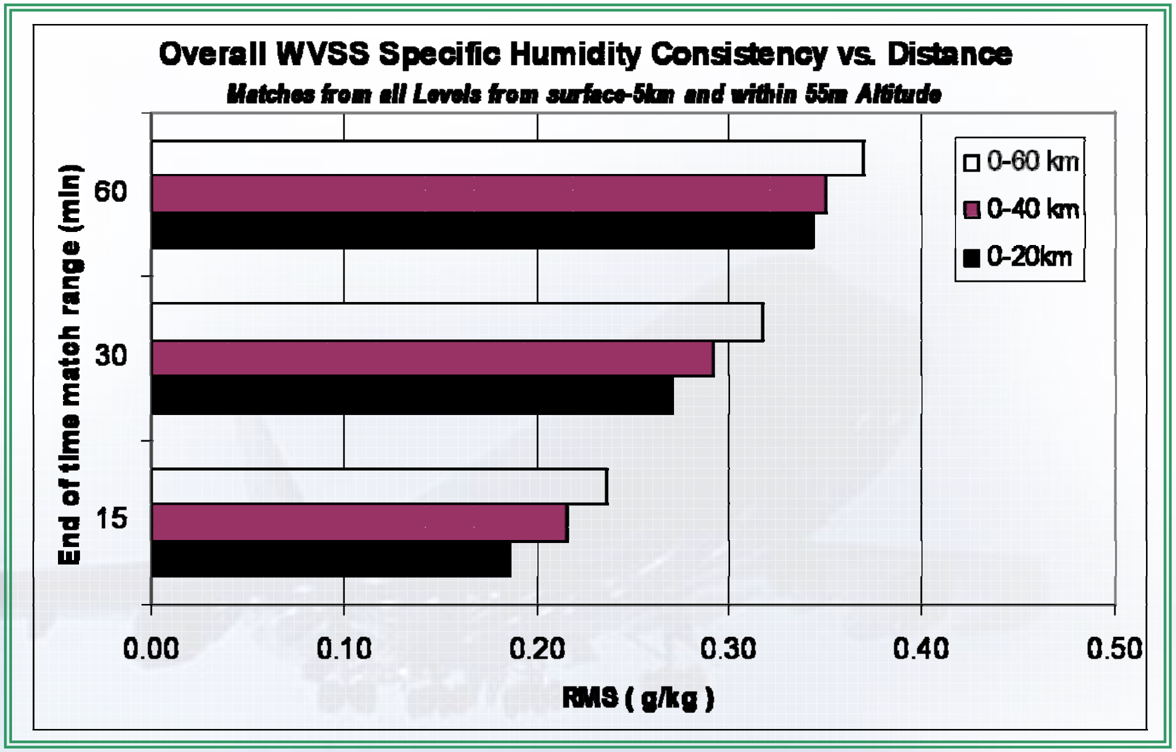
2009-2010 Validation Results

Specific Humidity Variability amongst WVSS-II Observations

RMS calculated for:

Time ranges of 0-15, 0-30 and 0-60 minutes

Distance ranges of 0-20, 0-40 and 0-60 minutes



RMS Differences show (Including Dry/Moist Environments):

0-15 minute / 0-20 km variability of ~0.18 g/kg

Variability nearly doubled for 0-60 time window

Variability increased for larger distance windows:
30% increase for short time windows
10% increase for longer time windows

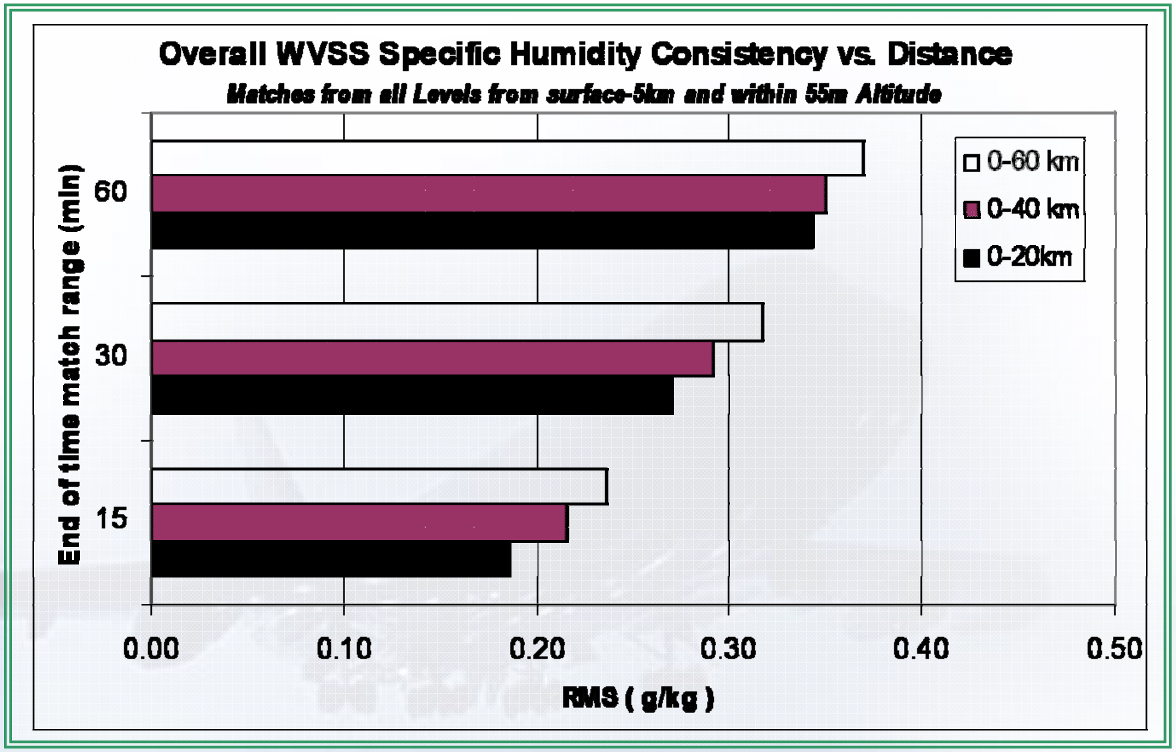
2009-2010 Validation Results

Specific Humidity Variability amongst WVSS-II Observations

RMS calculated for:

Time ranges of 0-15, 0-30 and 0-60 minutes

Distance ranges of 0-20, 0-40 and 0-60 minutes



RMS Differences show (Including Dry/Moist Environments):

WVSS-II observations agree extremely well with one another

Atmospheric Variability:

- More than doubles from 0-15 to 30-60 minute time intervals

- Smaller increases over distance, but larger for short time spacing

For exact co-locations, operational WVSS-II instrument errors should be ~0.1 g/kg

Summary

Engineering/mechanical issues with WVSS-II sensors have been resolved

Tests made over wide range of moisture conditions show:

☑ **Sensors agreed extremely closely with each other**
- Overall Specific Humidity (SH) RMS < 0.2 g/kg

☑ **Sensors agreed well with co-located rawinsonde observations**
Overall SH Bias ~ 0.2 g/kg, SH StDev ~ 0.5 g/kg

☑ **Relative Humidity differences due to WVSS-II were small**
Overall RH Bias ~ 2.5 %, RH StDev ~ 7.5%

☑ ***WVSS-II data Meet WMO requirements for mesoscale observations***

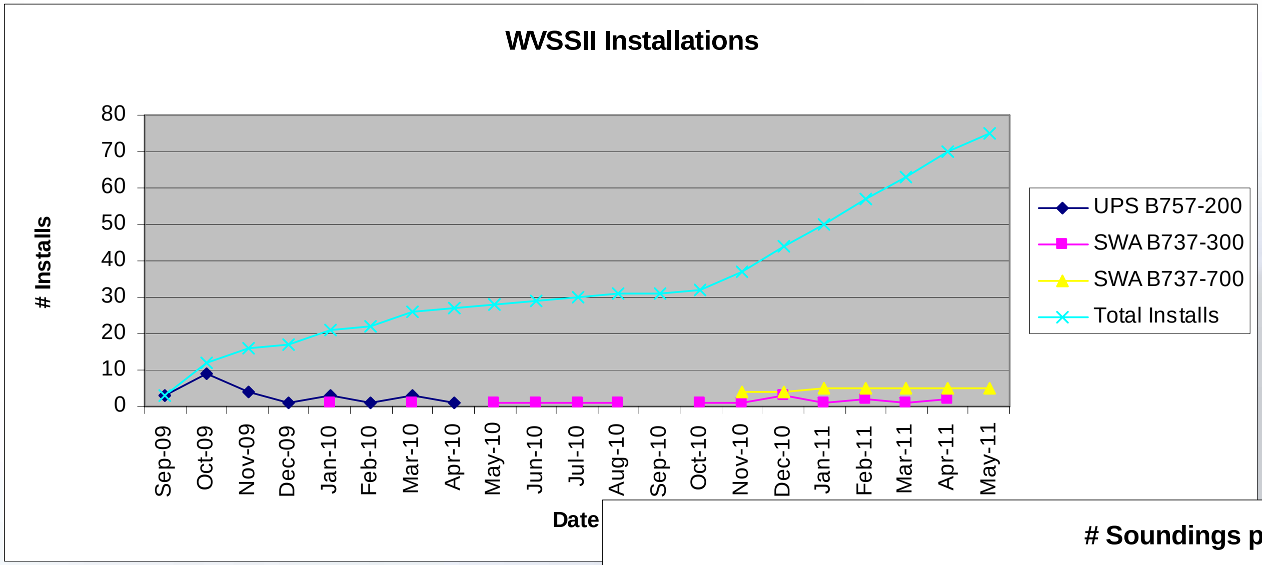
Additional analysis underway to:

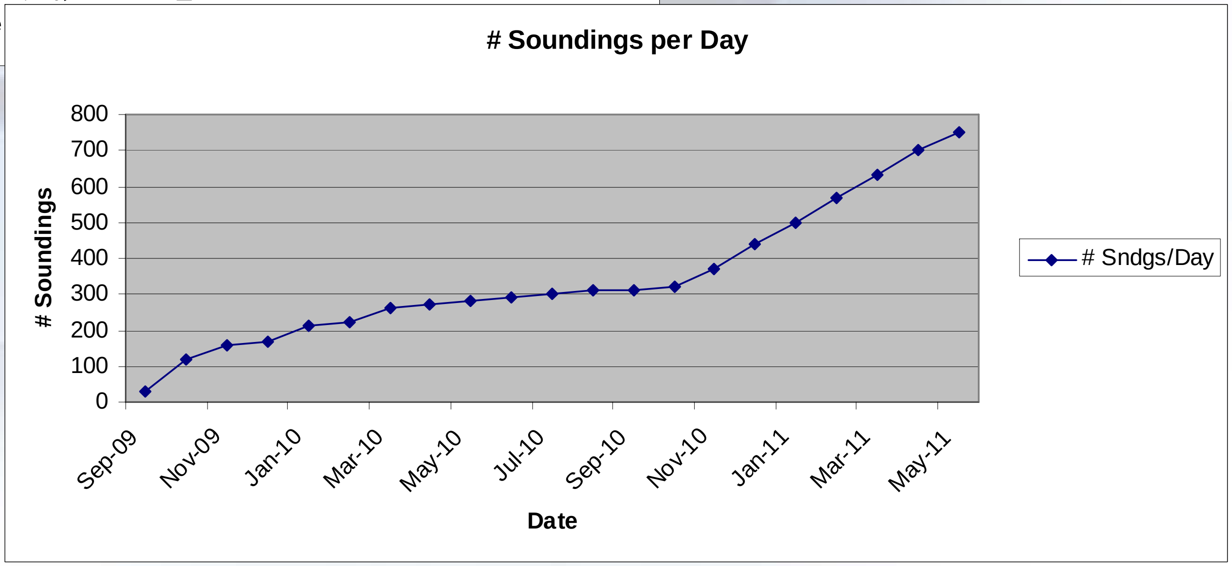
- **Separate atmospheric variability from observation error**
- **Develop error statistics for deeper layers appropriate for satellite validation**

(Past studies comparing WVSS-II total water vapor positive)

The Future

WVSS-II Installations increasing on SouthWest Airlines B-737





WMO and E-AMDAR program working to expand data coverage elsewhere – Including Europe, Asia, Central/South America