GNSS RO Water Vapor Histogram Results & Implications

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September 23, 2019   IROWG
Key results

• Quick overview of direct retrieval + error deconvolution technique
• Evaluation of ERA5 and MERRA2 reanalyses
• Sensitivity of 1DVar GNSS moisture estimate to the a priori moisture estimate
• Structural uncertainty of radiance information for water vapor
• Value of AIRS Level 3 v5 & v6 results
Value of humidity histograms

• Captures the entire distribution of water vapor statistically, rising air, sinking air, mixing, evaporation, ....
Two Methods for Extracting Water Vapor from GPS RO Refractivity Profiles

1. Direct Method: \( N_{\text{wet}} = N_{\text{tot}} - N_{\text{dry}} \)
   - Determine dry refractivity \( (N_{\text{dry}}) \) from analysis temperature profile and hydrostatic equation
   - Scale \( N_{\text{wet}} \) to get water vapor

2. (1D) Variational Method
   - Combine GPS refractivity or bending angle with analysis temperature & water vapor profiles and surface pressure
   - and error covariance estimates
   \( \Rightarrow \) Over-determined, least squares solution

Advantage of Direct Method: Not affected by biases in background water vapor forecast/analysis
Deconvolution of Errors from Histograms

• Technique described in Kursinski & Gebhardt (2014)
Zonal Mean Relative Humidity GPS-MET Jun 21-Jul 4 1995

- Zonal mean relative humidity from GPS/MET July 1995
- Winter Summer
- ~800 profiles
- SR ITCZ subtropics
- Kursinski & Hajj 2001

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Uncertainty Estimates Derived from Error Deconvolution

- 1-σ specific humidity uncertainty at 346 mb is ~0.13 g/kg across low latitudes.
- Specific humidity $|\text{bias}| < 0.03$ g/kg
- 1-σ ECMWF temperature uncertainty 0.7K at equatorial latitudes

<table>
<thead>
<tr>
<th>Level (mb)</th>
<th>Specific Humidity $\sigma$ (g/kg)</th>
<th>Fractional Refractivity $\sigma$ (%)</th>
<th>Temperature $\sigma$ (K)</th>
<th>Ref. Pressure $\sigma$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>346</td>
<td>0.24 0.143 0.128 0.142</td>
<td>0.2 0.2 0.2 0.2</td>
<td>1.5 0.85 0.7 0.8</td>
<td>0.3 0.19</td>
</tr>
<tr>
<td>547</td>
<td>0.31 0.25</td>
<td>0.5 1 0.6 0.62</td>
<td>1.5 0.85 0.7 0.8</td>
<td>0.3 0.19</td>
</tr>
<tr>
<td>725</td>
<td>0.47 0.39</td>
<td>0.9 2 1 1</td>
<td>1.5 0.85 0.7 0.8</td>
<td>0.3 0.19</td>
</tr>
</tbody>
</table>

Comparison of (re)analyses at 346 mb

- Two GPS estimates
- 3 operational analyses
- 4 reanalyses
- 30S-30N
- Upper troposphere
- Quite peaked at dry end
Comparison of (re)analyses at 547 mb

- Mid troposphere
- Quite peaked at dry end
Comparison of (re)analyses at 725 mb

• Lower free troposphere
• Flatter distribution with peaks at dry & wet
Quantifying Differences Between Histograms

- Simple statistic
  
  TAPD: Total Absolute Probability Difference

  \[ TAPD_{21} = \sum_{i=1}^{N} |PDF_2(i) - PDF_1(i)| \]

  Sum of absolute value of the differences between two histograms, bin by bin.

  Maximum value of 2 or 200%
TAPDs of (re)analyses relative to GPSD (=TAPD<sub>G</sub>)

<table>
<thead>
<tr>
<th>Level (mb)</th>
<th>MERRA</th>
<th>ERA5</th>
<th>MERRA2</th>
<th>ECMWF 2007 op analysis</th>
<th>GPS 1Dvar</th>
<th>ERA-I</th>
<th>ECMWF 2007 op Lo-Res</th>
<th>NCEP FNL</th>
<th>AIRS v6</th>
<th>AIRS v5</th>
</tr>
</thead>
<tbody>
<tr>
<td>346</td>
<td>8.9%</td>
<td>19.0%</td>
<td>19.5%</td>
<td>19.5%</td>
<td>29.8%</td>
<td>23.7%</td>
<td>48.7%</td>
<td>42.7%</td>
<td>26.3%</td>
<td>25.8%</td>
</tr>
<tr>
<td>547</td>
<td>12.6%</td>
<td>18.2%</td>
<td>20.3%</td>
<td>25.0%</td>
<td>24.5%</td>
<td>30.6%</td>
<td>55.1%</td>
<td>56.9%</td>
<td>45.6%</td>
<td>34.7%</td>
</tr>
<tr>
<td>725</td>
<td>20.7%</td>
<td>14.0%</td>
<td>12.1%</td>
<td>15.5%</td>
<td>17.1%</td>
<td>19.1%</td>
<td>30.3%</td>
<td>46.9%</td>
<td>31.4%</td>
<td>45.0%</td>
</tr>
<tr>
<td>avg</td>
<td>14.0%</td>
<td>17.1%</td>
<td>17.3%</td>
<td>20.0%</td>
<td>23.7%</td>
<td>24.5%</td>
<td>44.7%</td>
<td>48.9%</td>
<td>34.5%</td>
<td>35.2%</td>
</tr>
</tbody>
</table>
ECMWF Products
346 mb

\[ \text{TAPD}_G \]

- 2007 Op low res 48.7%
- ERA Interim 23.7%
- 2007 Op full res 19.5%
- ERA5 19.0%
ECMWF Products
547 mb

TAPD_G

- 2007 Op low res 55.1%
- ERA Interim 30.6%
- 2007 Op full res 25.0%
- ERA5 18.2%
ECMWF Products 725 mb

TAPD\textsubscript{G}

- 2007 Op low res 30.3%
- ERA Interim 19.1%
- 2007 Op full res 15.5%
- ERA5 14.0%
MERRA Products
346 mb

\[ TAPD_G \]

- MERRA 8.9%
- MERRA2 19.5%

MERRA2 mean is 30% too high

MERRA 2 inconsistent w/ GPS RO
MERRA Products
547 mb

TAPD_G

- MERRA 12.6%
- MERRA2 20.3%
MERRA Products
725 mb

TAPD_G

- MERRA  20.7%
- MERRA2 12.1%
ECMWF and GMAO product performance evolution
1DVar v ERA-I
346 mb

TAPD_G

- 1DVar 29.8%
- ERA-I 23.7%
1DVar v. ERA-I
547 mb

$TAPD_G$

- 1DVar 24.5%
- ERA-I 30.6%
1DVar v ERA-I
725 mb

TAPD_G

• 1DVar 17.1%
• ERA-I 19.1%
Similarity between 1DVar and ERA-Interim

- Two estimates dominated by GPS: GPSD and 1DVar (UCAR)

<table>
<thead>
<tr>
<th>Pressure (mb)</th>
<th>TAPD</th>
<th>TAPD Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>GPS 1DVar – GPSD</td>
<td>GPS 1DVar – ERAI</td>
</tr>
<tr>
<td>346</td>
<td>0.298</td>
<td>0.072</td>
</tr>
<tr>
<td>547</td>
<td>0.245</td>
<td>0.085</td>
</tr>
<tr>
<td>725</td>
<td>0.171</td>
<td>0.063</td>
</tr>
</tbody>
</table>

- 1DVar moisture is far more similar to ERA-Interim (= a priori) than to GPSD
- A priori has big influence on 1DVar moisture results
- 1DVar moisture is not good for climate applications
Structural uncertainty of radiance-based estimates of water vapor

• Spread in analysis histogram estimates is telling us something

• MERRA, MERRA2, ERA-Interim, and ERA5 reanalyses, ECMWF operational full resolution analysis and AIRS v5 & v6 Level 3 products all make use of satellite IR and microwave radiances.

• The spread in the resulting specific humidity histograms therefore indicates the structural uncertainty of the IR and microwave radiance measurements in terms of determining the humidity histograms.
Structural uncertainty of radiance-based estimates of water vapor

• 346 mb
Structural uncertainty of radiance-based estimates of water vapor

- 547 mb
Structural uncertainty of radiance-based estimates of water vapor

- 725 mb
Summary of behavior by measurement type

• Hi res analyses/reanalyses are closest to GPSD

• But none of the estimates are closer than the difference between 2006-2007 El Nino and 2007-2008 La Nina

• AIRS v5 & v6 are not so useful, less realistic than the best climate models
Conclusions

• GPSD direct retrieval + error deconvolution appears to be most accurate humidity histograms in free troposphere (at low latitudes)
• ERA5 shows improvements relative to ERA-Interim and 2007 operational analyses, slight in UT and lower free troposphere, biggest in mid-troposphere
• MERRA2 is much better than MERRA in lower free troposphere but worse in mid-troposphere and significantly worse in UT.
• AIRS Level3 v5 & v6 do not appear to be very useful
• 1DVar definitely has a memory of the humidity background, not so useful for climate
• GFDL-MC3 model is best overall CMIP5 model in terms of humidity histograms
• Structural uncertainty of radiances for constraining humidity is quite large and not clear how much guidance it can provide to climate model development