GNSS RO Water Vapor Histogram Results & Implications

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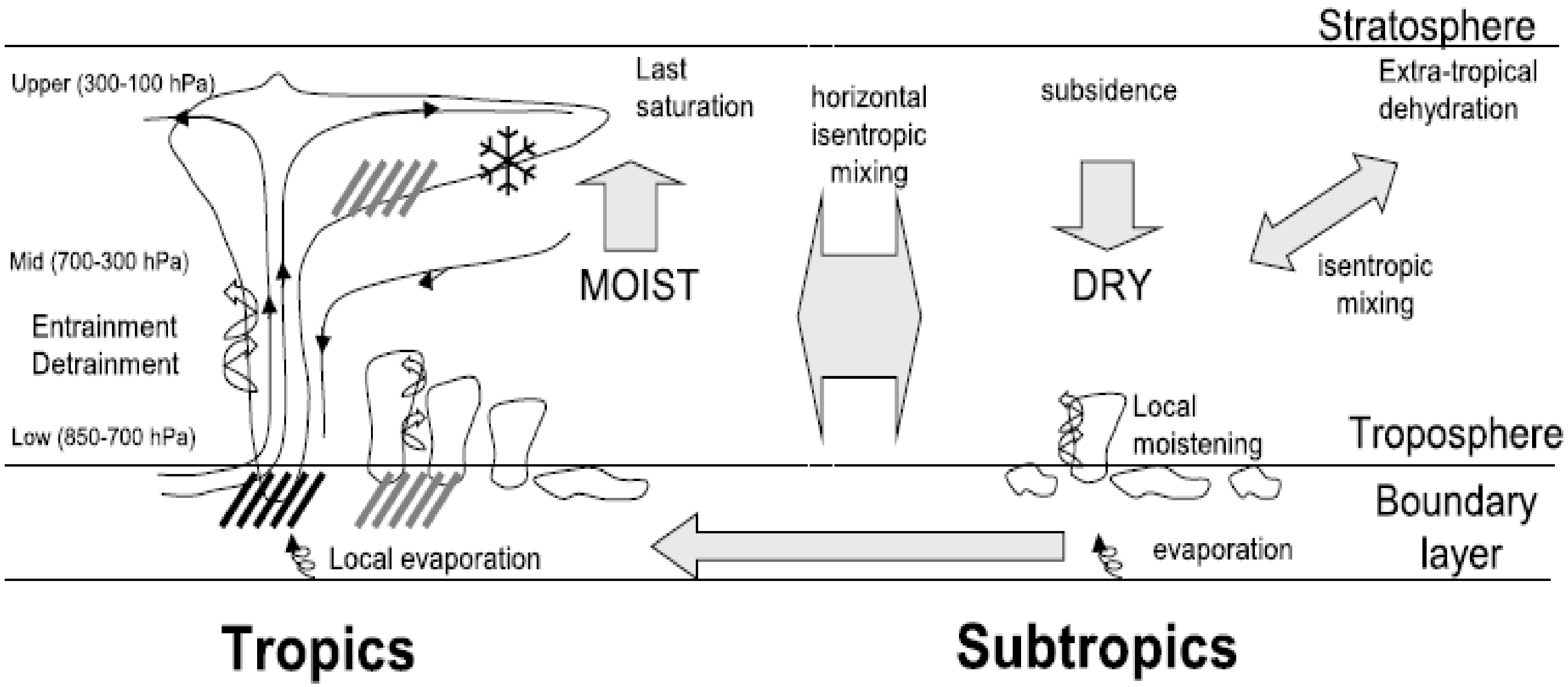
Key results

- 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: $N_{wet} = N_{tot} - N_{dry}$

- Determine dry refractivity (N_{dry}) from analysis temperature profile and hydrostatic equation
- Scale N_{wet} to get water vapor

2. (1D) Variational Method

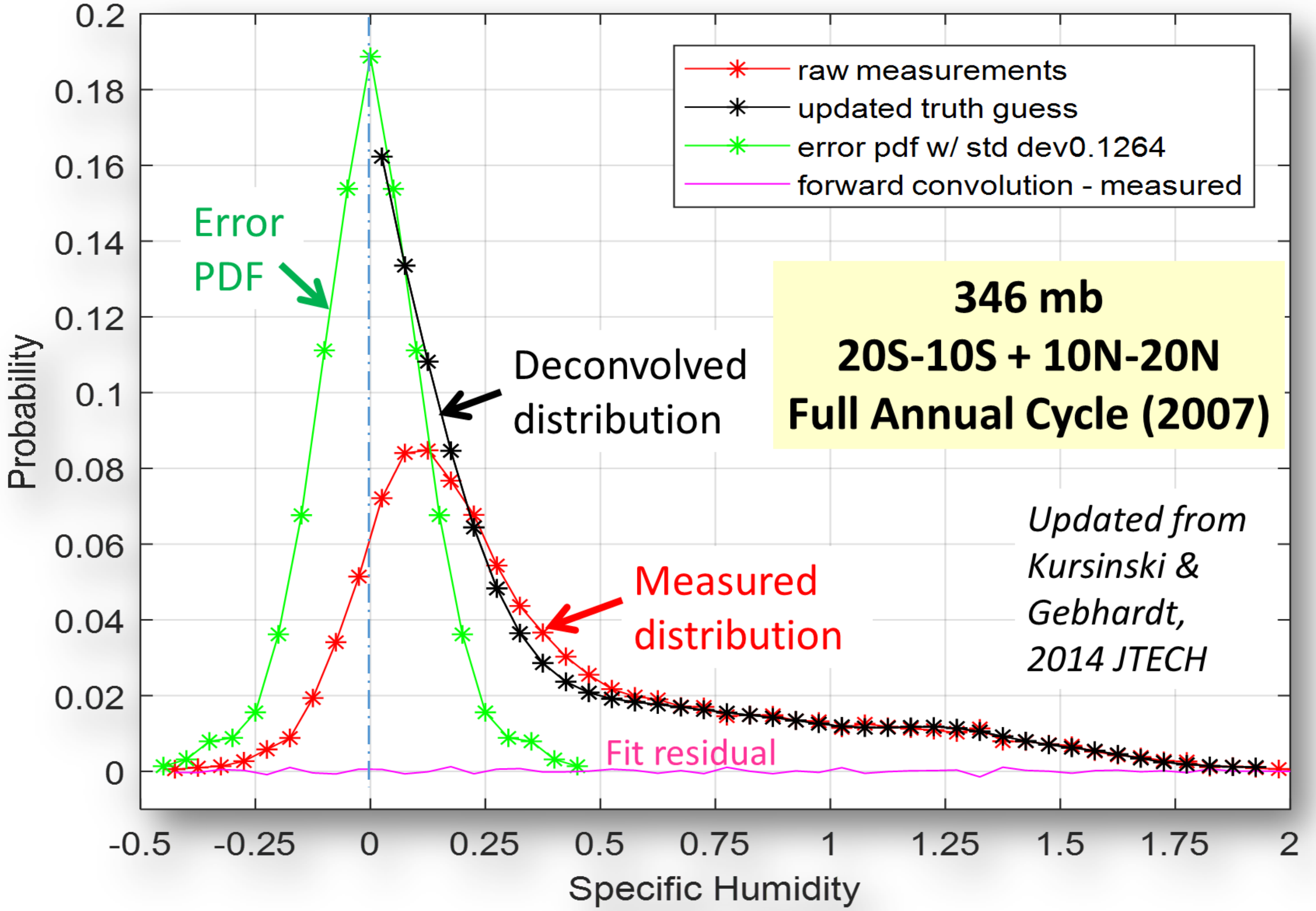
- Combine GPS refractivity or bending angle with
- Analysis temperature & water vapor profiles and surface pressure
- and error covariance estimates

$\Rightarrow$ Over-determined, least squares solution

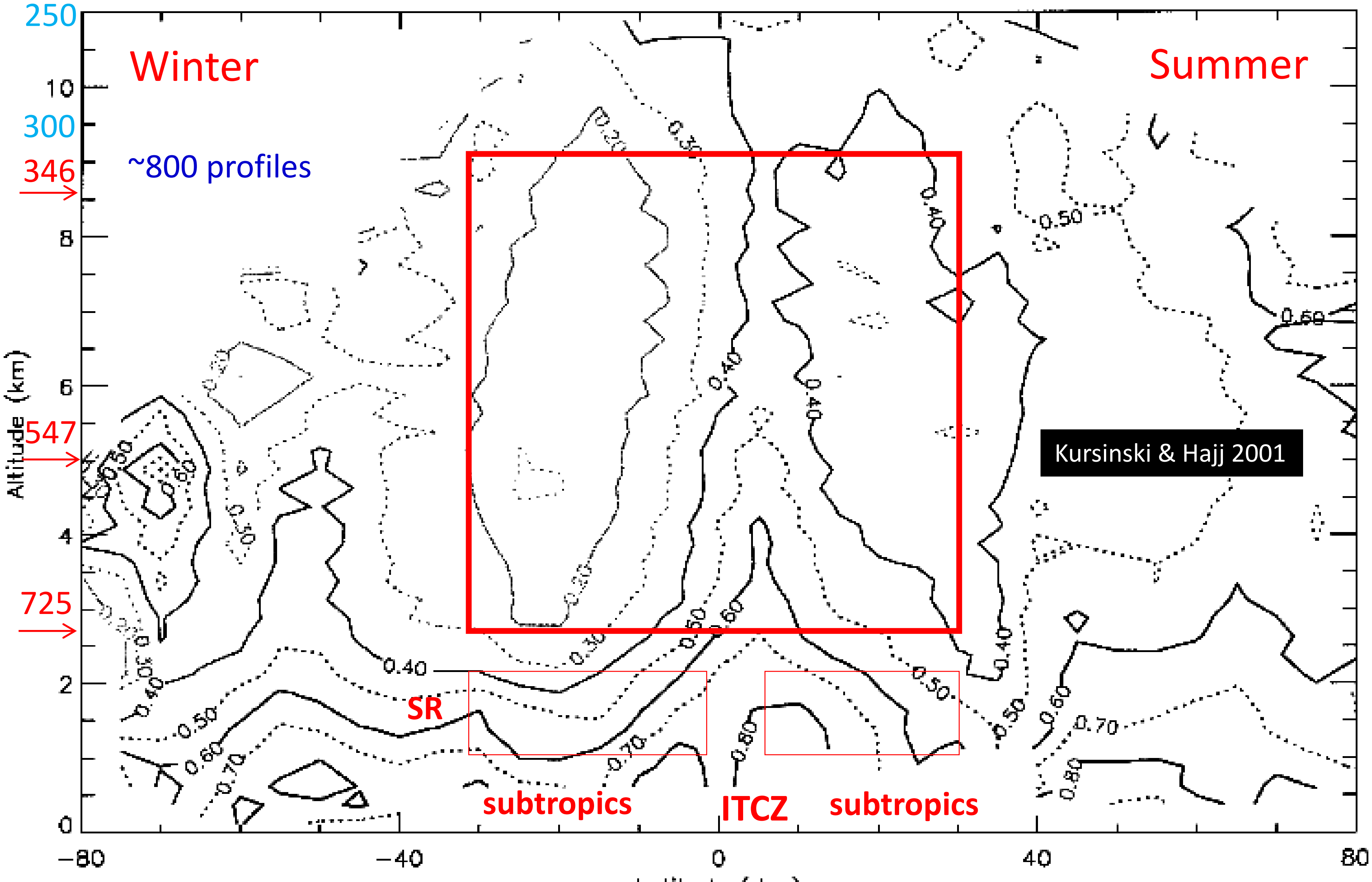
Advantage of Direct Method: Not affected by biases in background water vapor forecast/analysis

Deconvolution of Errors from Histograms

- Technique described in Kursinski & Gebhardt (2014)



Zonal Mean Relative Humidity GPS-MET Jun 21-Jul 4 1995



Uncertainty Estimates Derived from Error Deconvolution

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

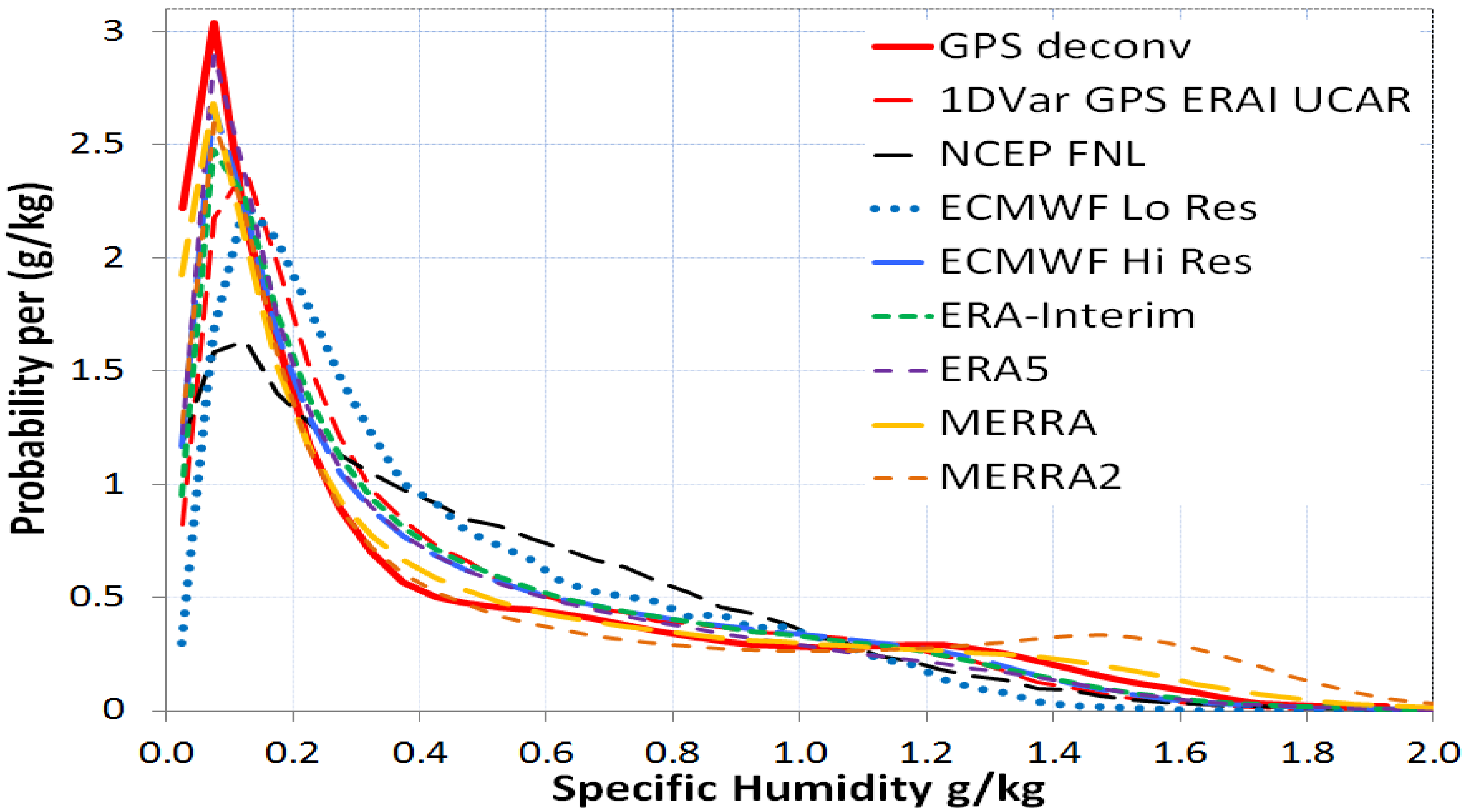
	Specific Humidity σ (g/kg)				Fractional Refractivity σ (%)				Temperature σ (K)				Ref. Pressure σ (%)	
Level (mb)	KH01 global	KG14 30S-30N	**K+19 20S-20N**	**K+19 30-20**	KH01 global	K+04 30S-30N	KG14 30S-30N	**K+19 30S-30N**	KH01 global	KG14 30S-30N	**K+19 20S-20N**	**K+19 30-20**	KH01 global	KG14 30S-30N
346	0.24	0.143	**0.128**	**0.142**	0.2	0.2	0.2	**0.2**	1.5	0.85	**0.7**	**0.8**	0.3	0.19
547	0.31	0.25			0.5	1	0.6	**0.62**	1.5	0.85	**0.7**	**0.8**	0.3	0.19
725	0.47	0.39			0.9	2	1	**1**	1.5	0.85	**0.7**	**0.8**	0.3	0.19

KH01: Kursinski & Hajj (2001) *KG14: Kursinski & Gebhardt (2014)* *K+19: Kursinski & Kursinski (2019)*

Comparison of (re)analyses at 346 mb

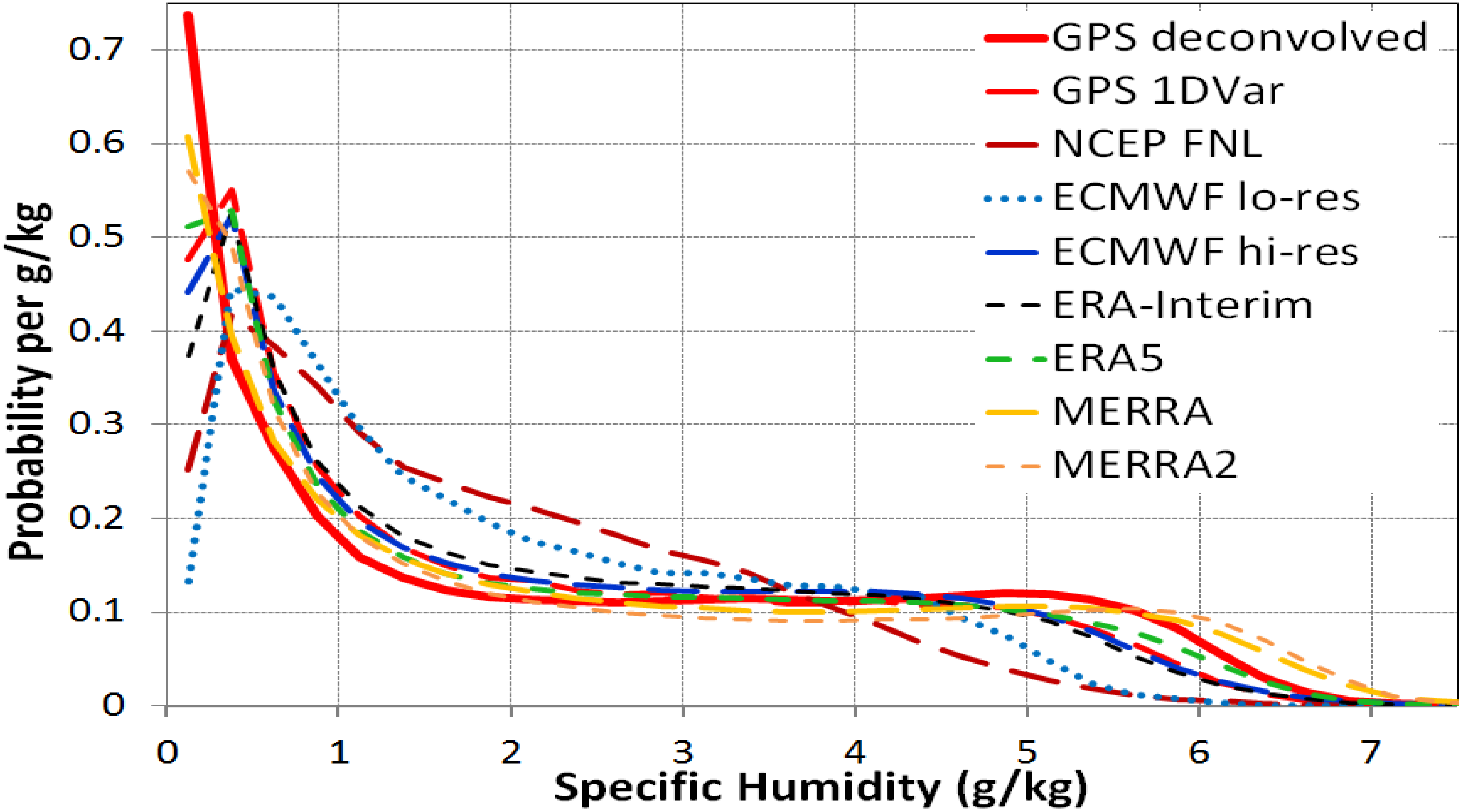
- Two GPS estimates
- 3 operational analyses
- 4 reanalyses

- 30S-30N
- Upper troposphere
- Quite peaked at dry end



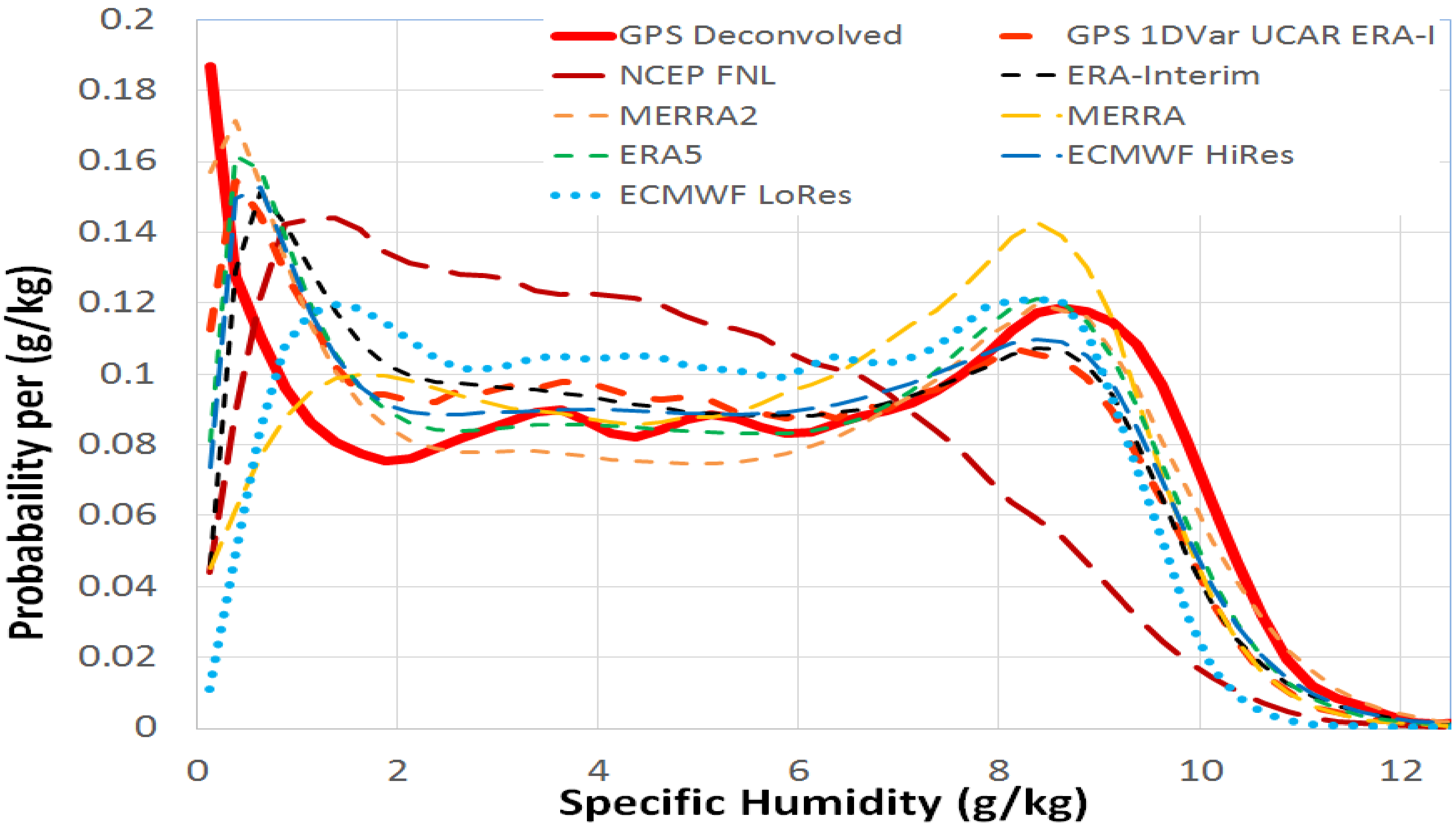
Comparison of (re)analyses at 547 mb

- 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.

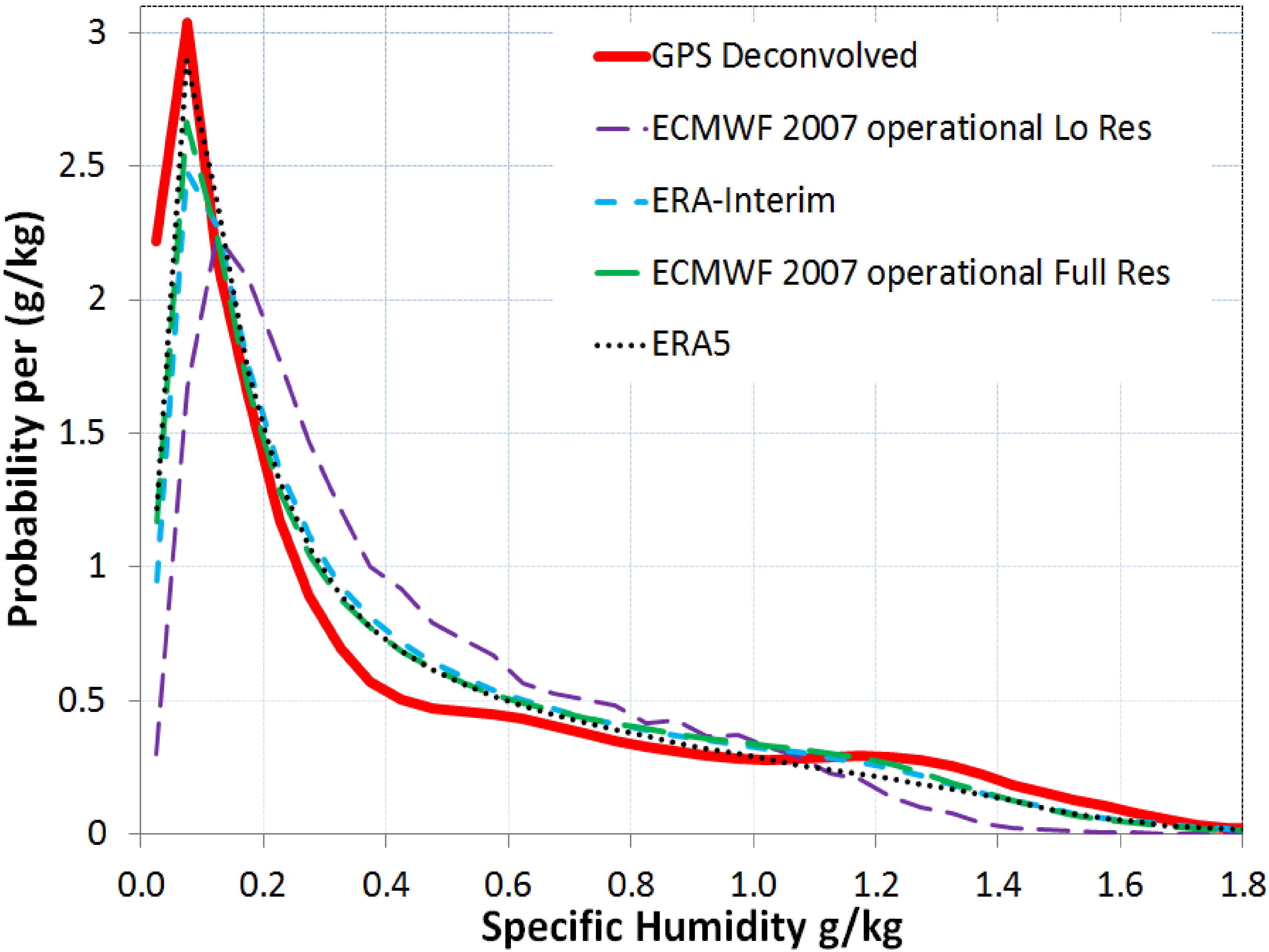
Maximum value of 2 or 200%

TAPDs of (re)analyses relative to GPSD (=$TAPD_G$)

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

ECMWF Products
346 mb

	TAPD$_G$
• 2007 Op low res	48.7%
• ERA Interim	23.7%
• 2007 Op full res	19.5%
• ERA5	19.0%



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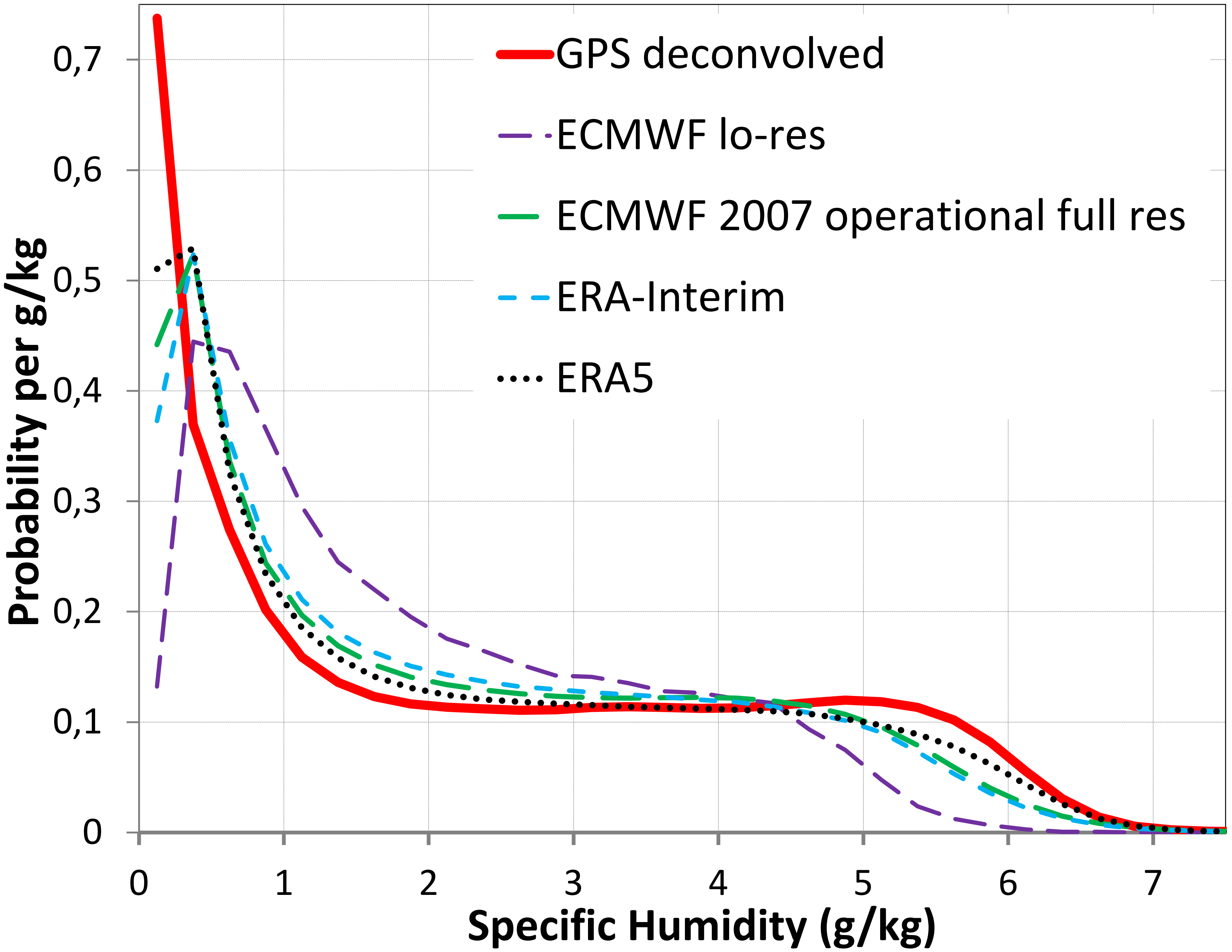
ECMWF Products
547 mb

	TAPD$_G$
• 2007 Op low res	55.1%
• ERA Interim	30.6%
• 2007 Op full res	25.0%
• ERA5	18.2%



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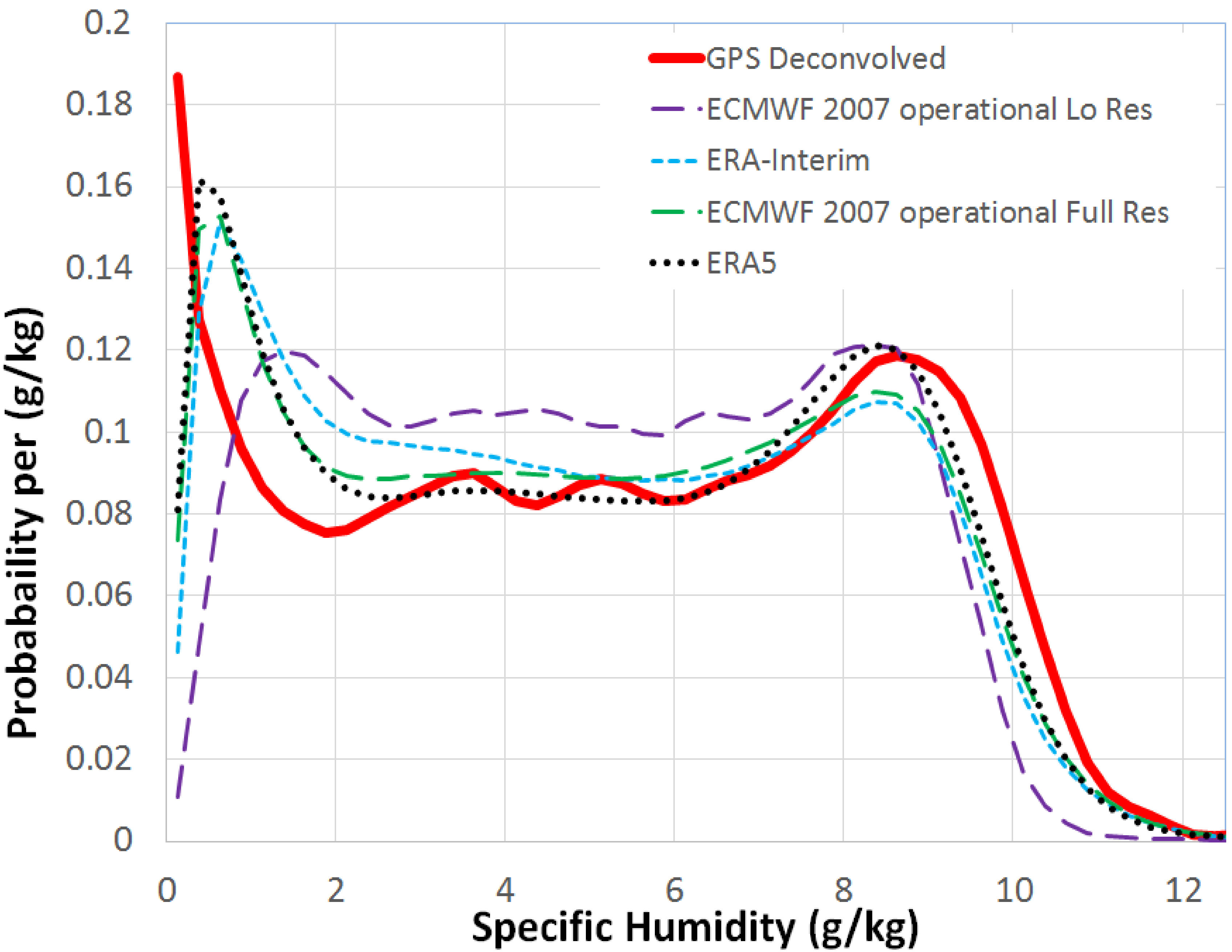
ECMWF Products
725 mb

	TAPD$_G$
• 2007 Op low res	30.3%
• ERA Interim	19.1%
• 2007 Op full res	15.5%
• ERA5	14.0%



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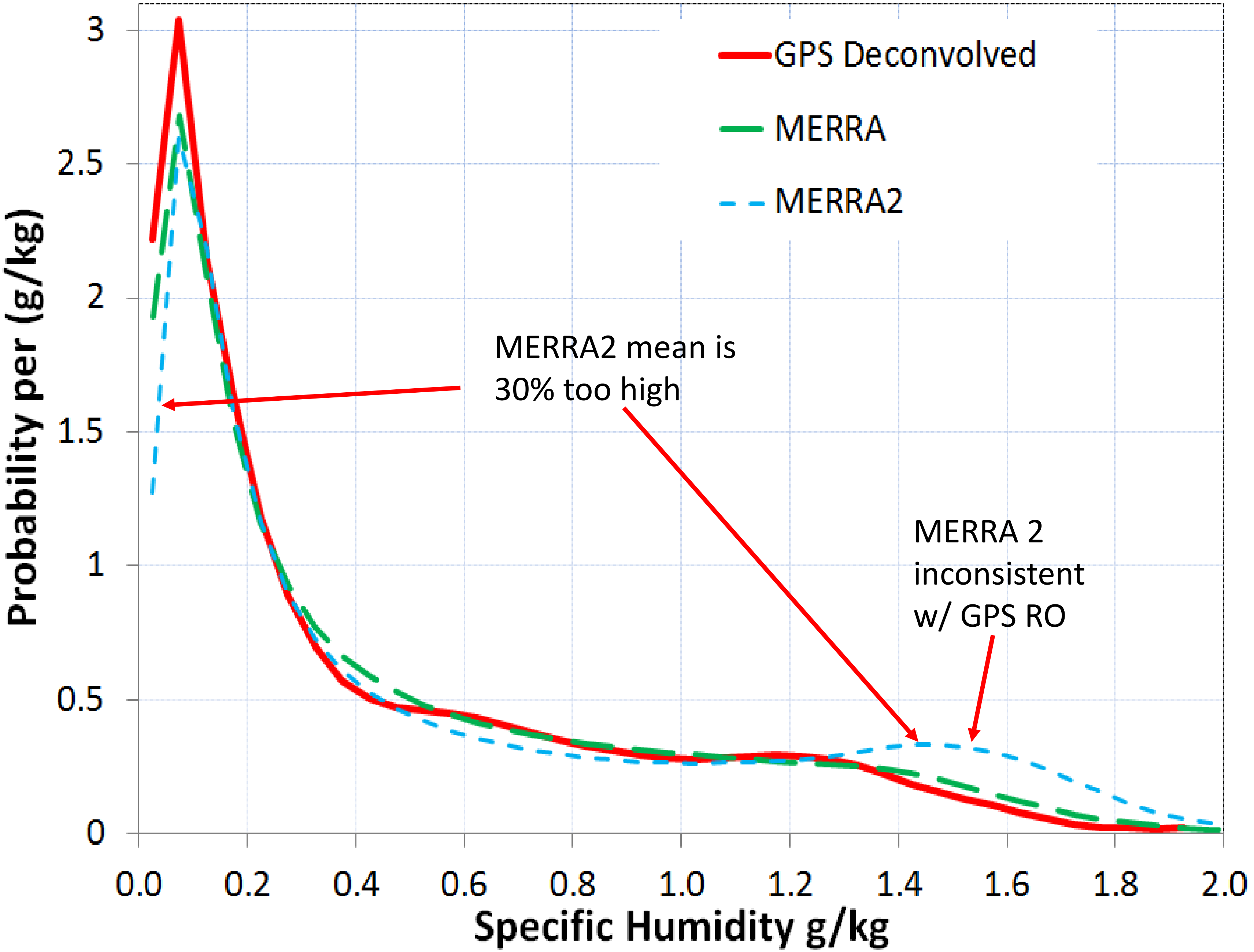
MERRA Products 346 mb

TAPD$_G$

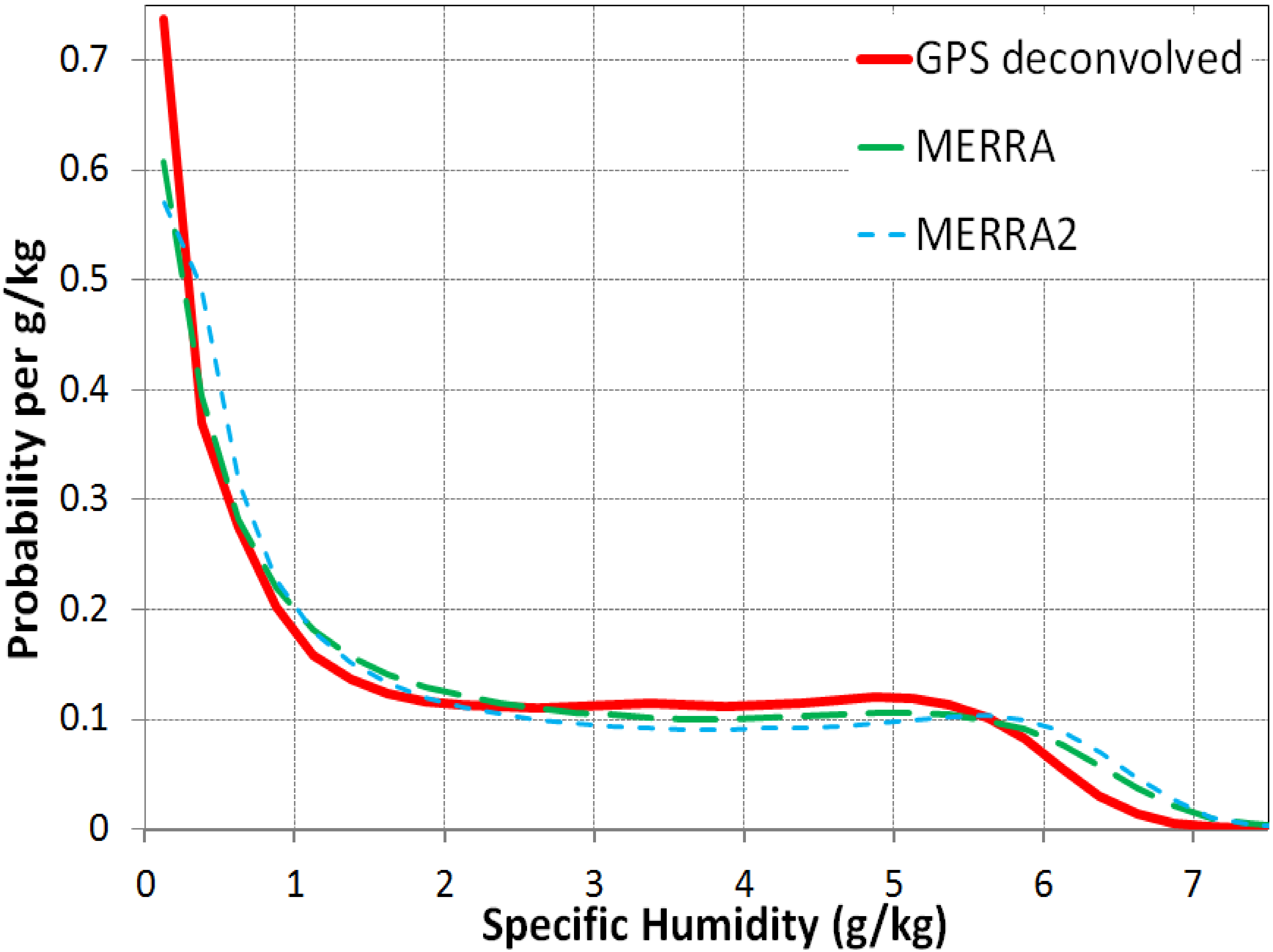
- MERRA 8.9%
- MERRA2 19.5%



MERRA Products
547 mb

TAPD$_G$

- MERRA 12.6%
- MERRA2 20.3%



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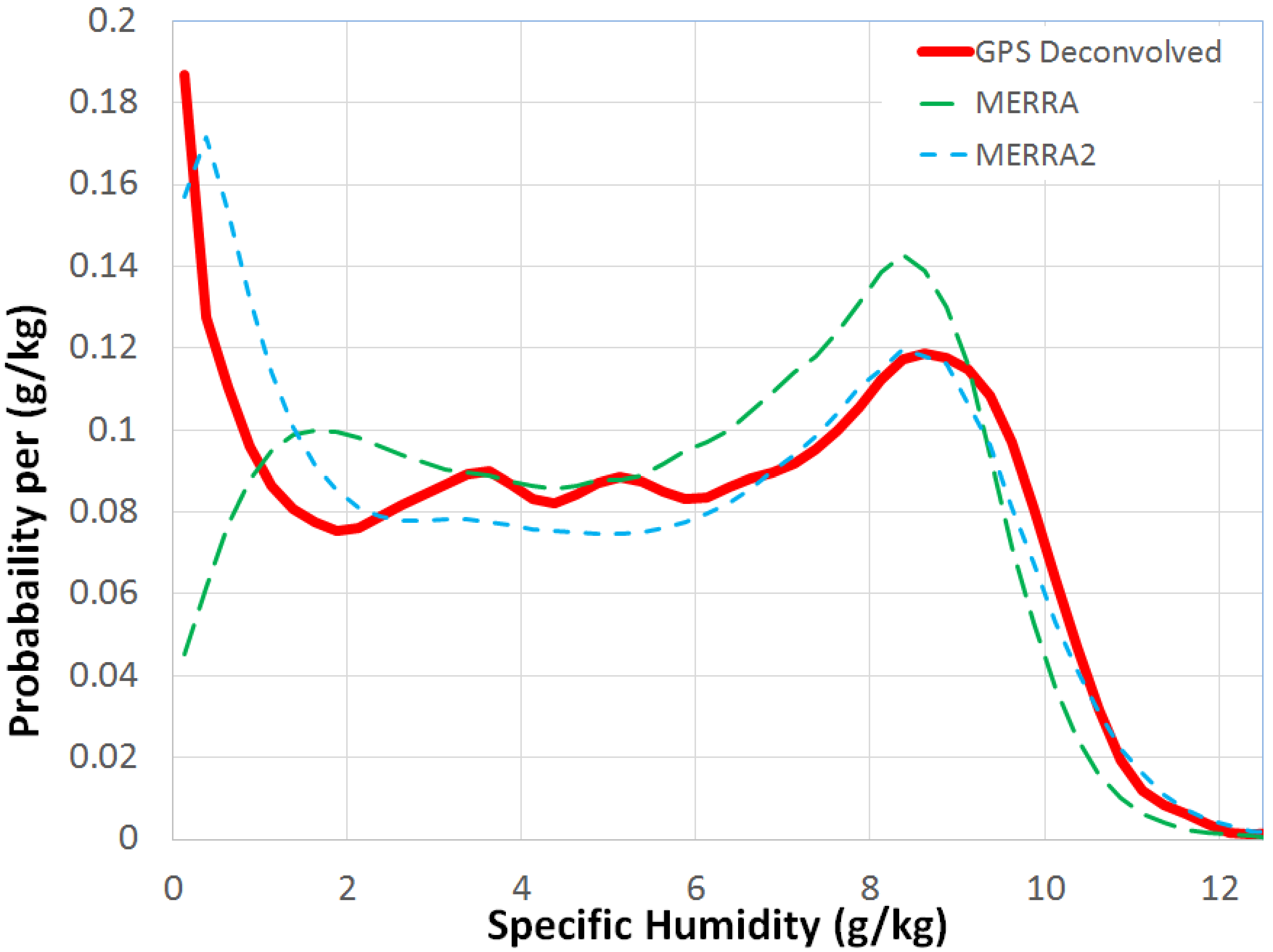
MERRA Products 725 mb

$\underline{TAPD_G}$

- MERRA 20.7%
- MERRA2 12.1%



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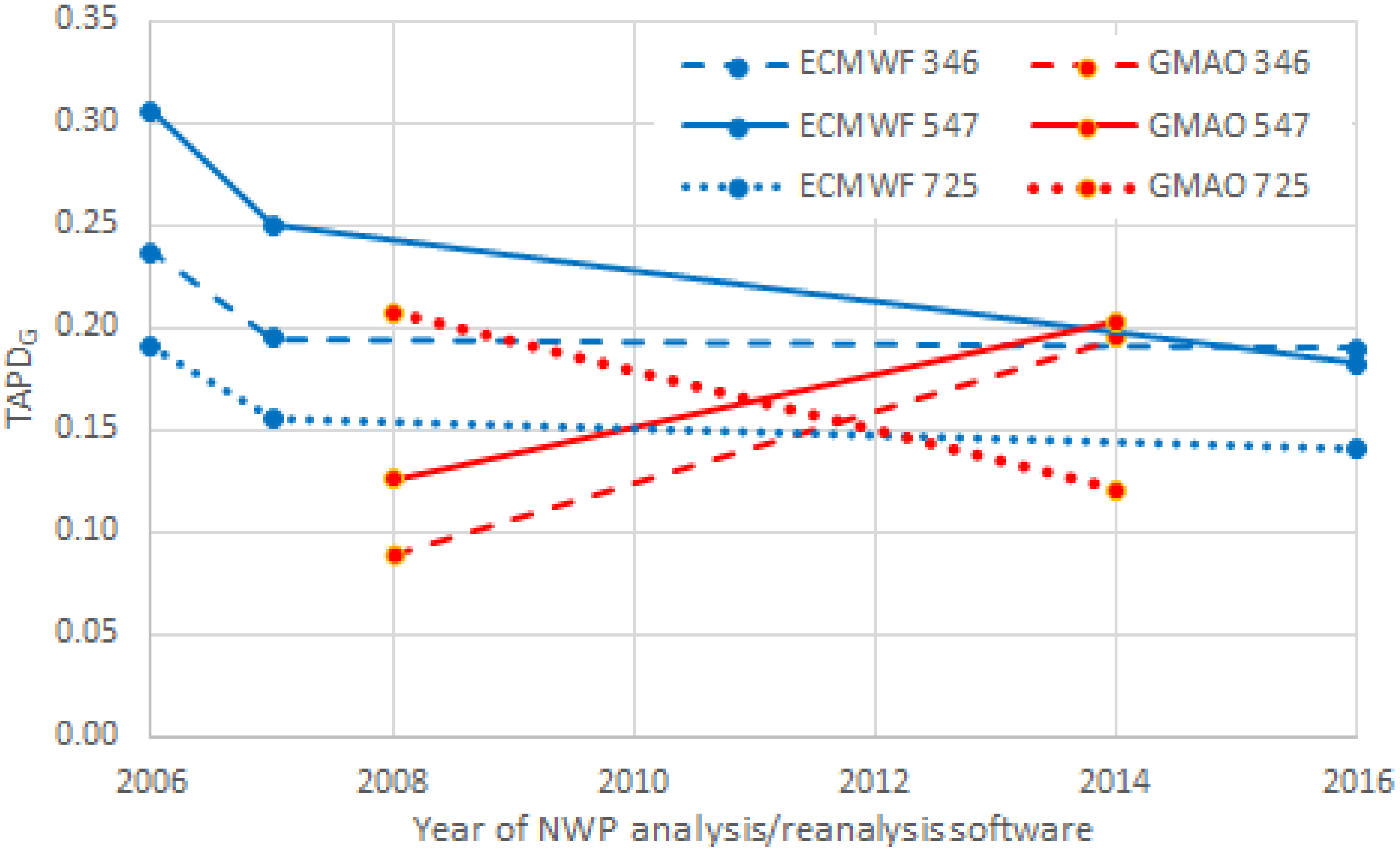
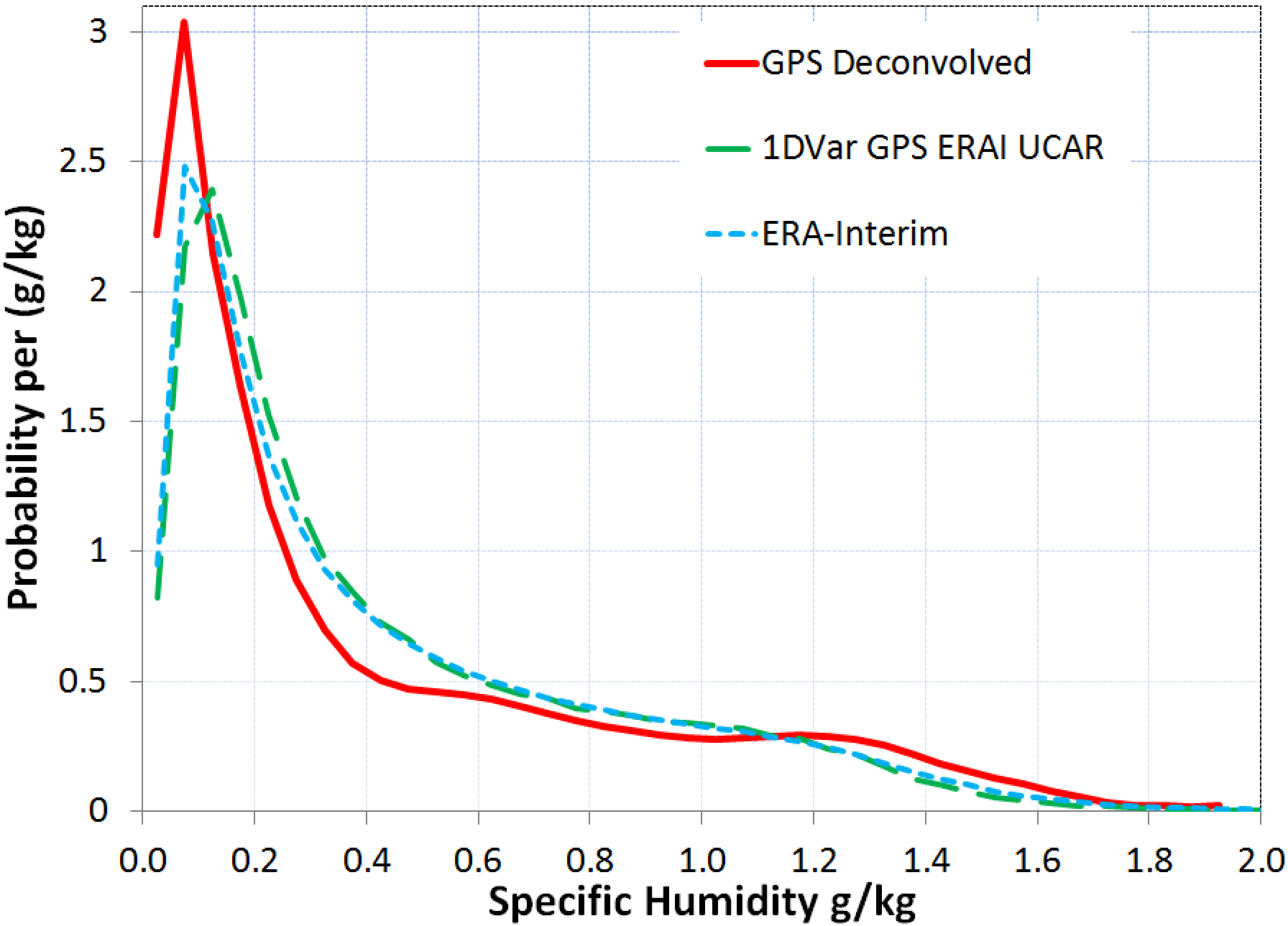
ECMWF and GMAO product performance evolution



1DVar v ERA-I 346 mb

TAPD$_G$

- 1DVar 29.8%
- ERA-I 23.7%



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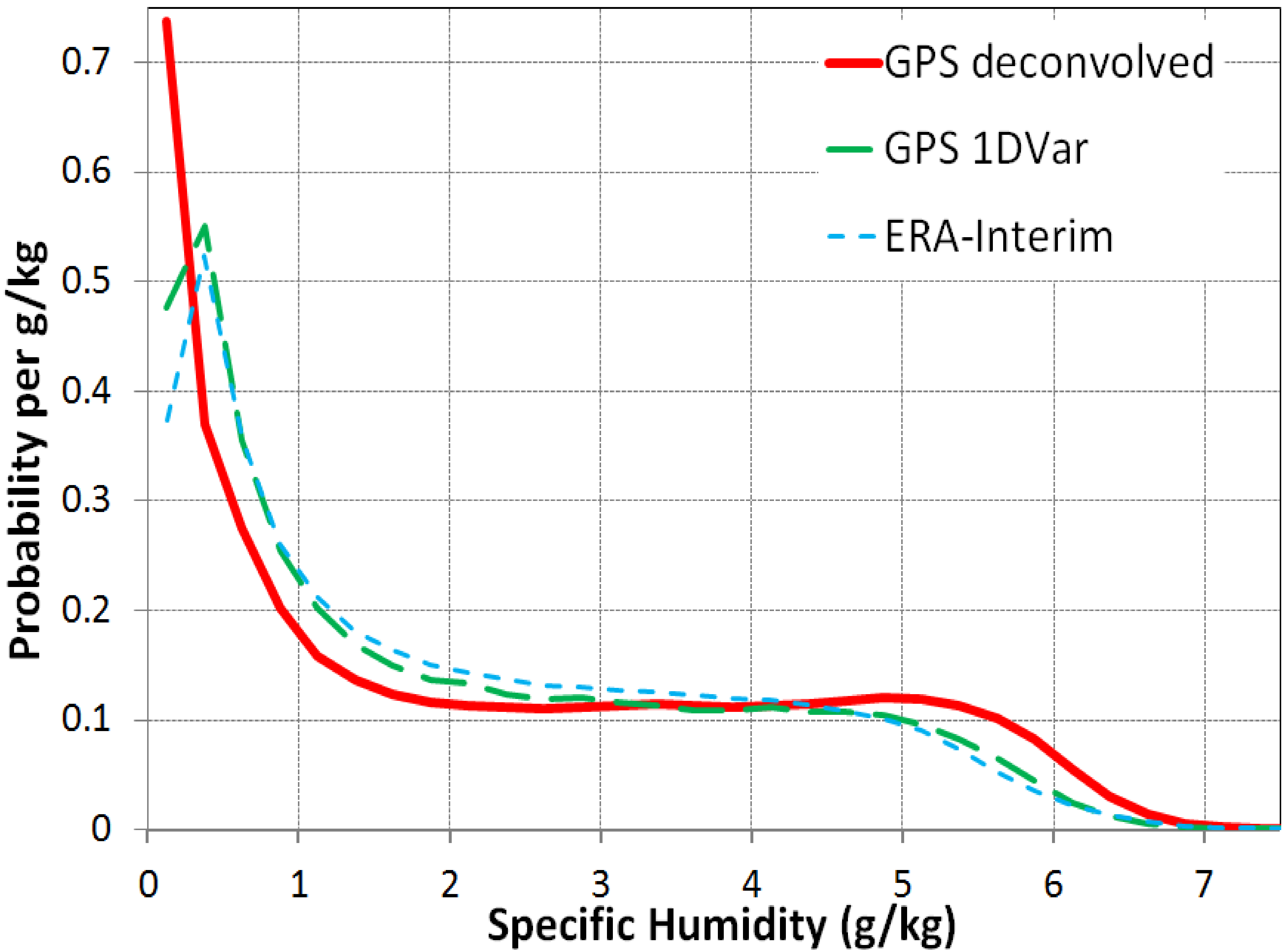
1DVar v. ERA-I 547 mb

<u>TAPD$_G$</u>

- 1DVar 24.5%
- ERA-I 30.6%



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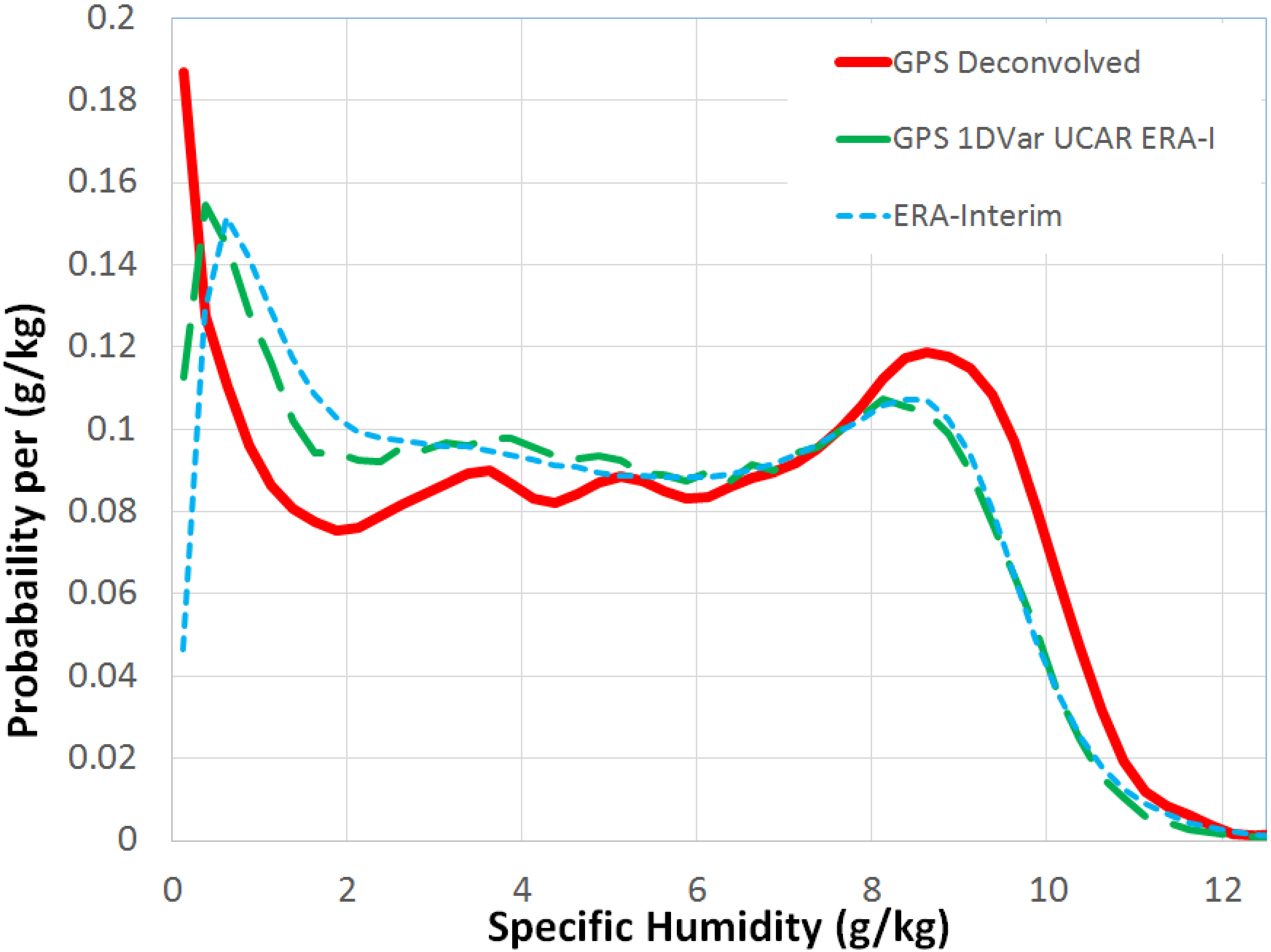
1DVar v ERA-I 725 mb

	$\underline{TAPD_G}$
• 1DVar	17.1%
• ERA-I	19.1%



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Similarity between 1DVar and ERA-Interim

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

Pressure (mb)	TAPD			TAPD Ratio
	GPS 1DVar – GPSD	GPS 1DVar – ERAI	ERAI – GPSD	GPS 1DVar - GPSD / GPS 1DVar - ERA-I
346	0.298	0.072	0.237	4.1
547	0.245	0.085	0.306	2.9
725	0.171	0.063	0.191	2.7

- 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

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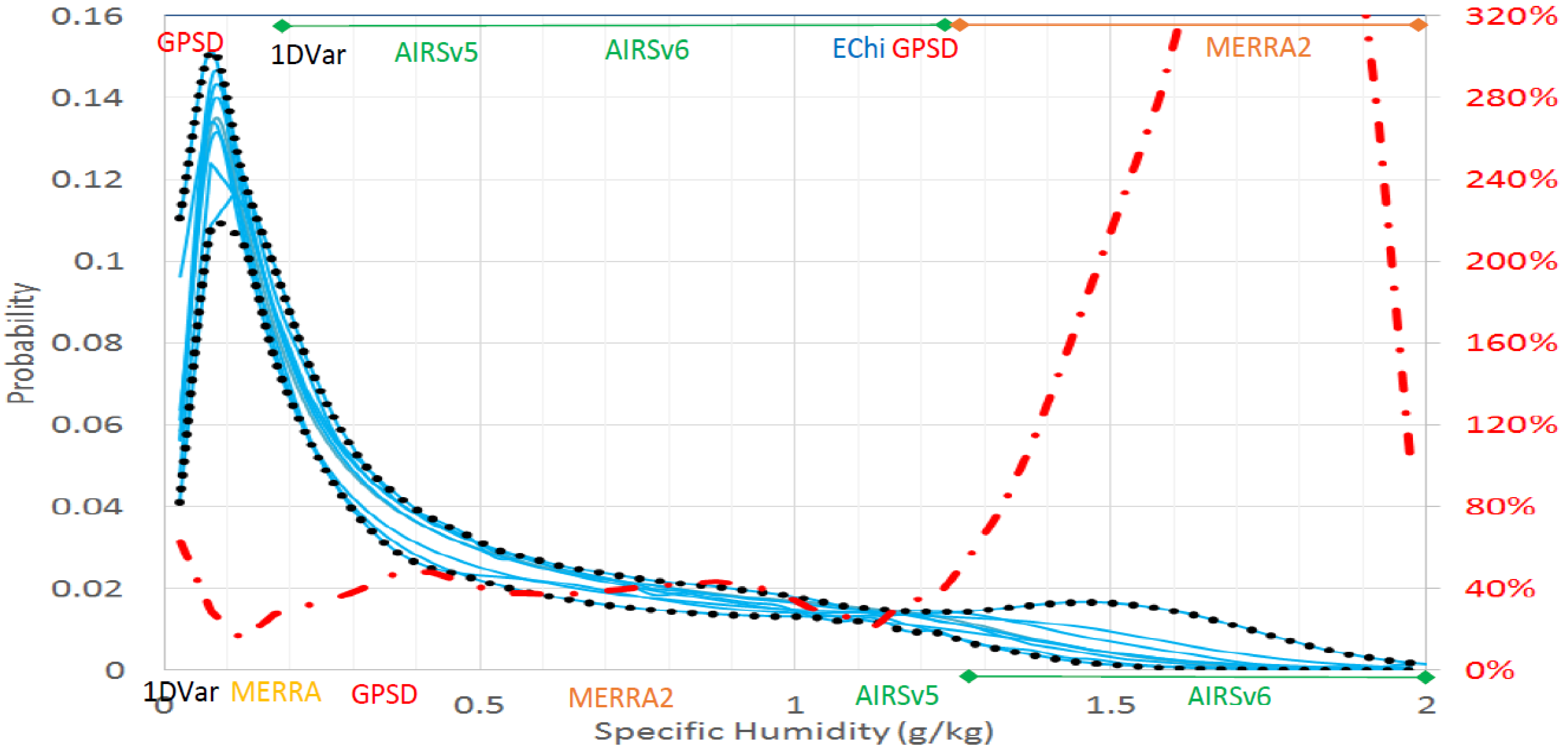
Structural uncertainty of radiance-based estimates of water vapor

- 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.

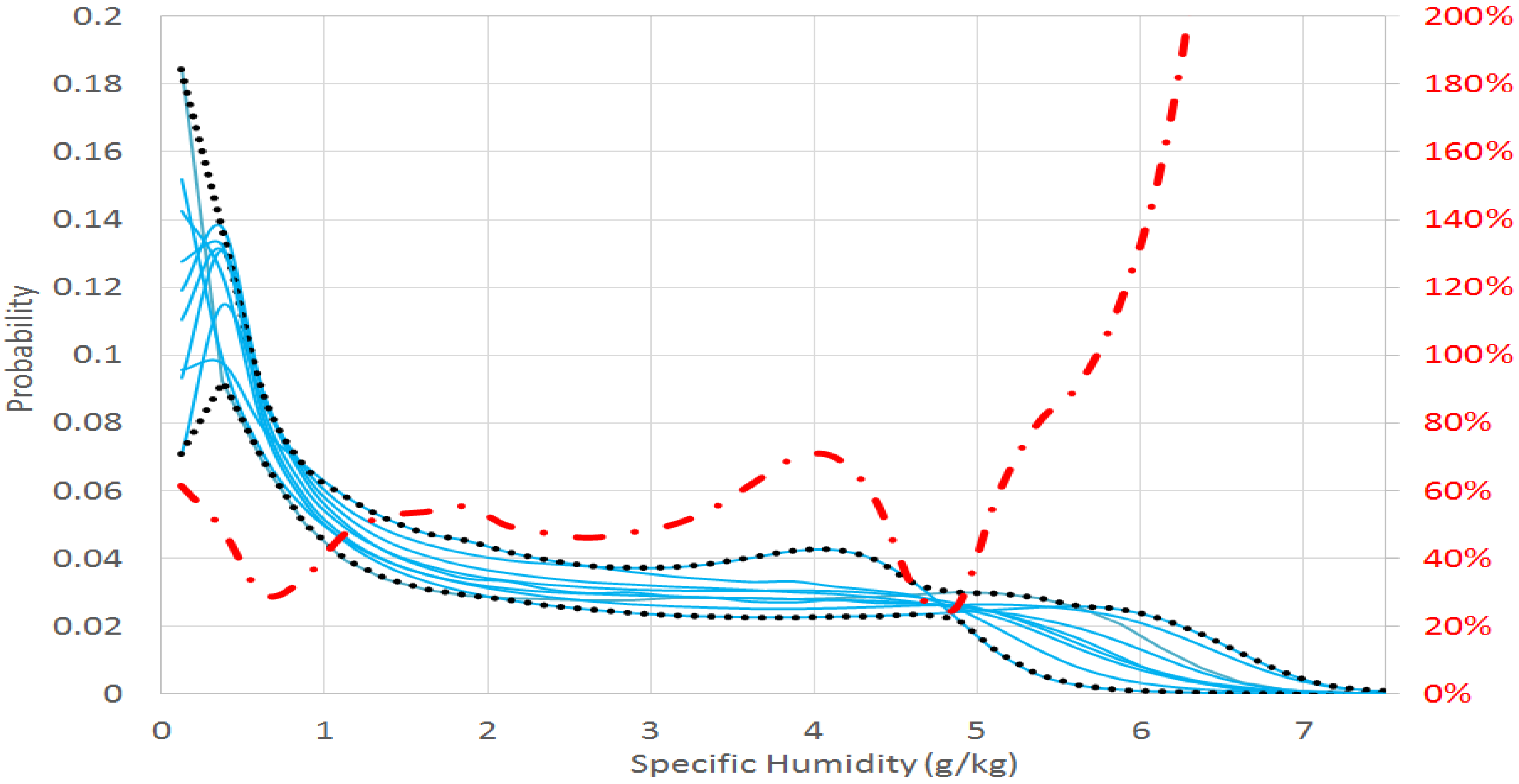
Structural uncertainty of radiance-based estimates of water vapor

- 346 mb



Structural uncertainty of radiance-based estimates of water vapor

- 547 mb



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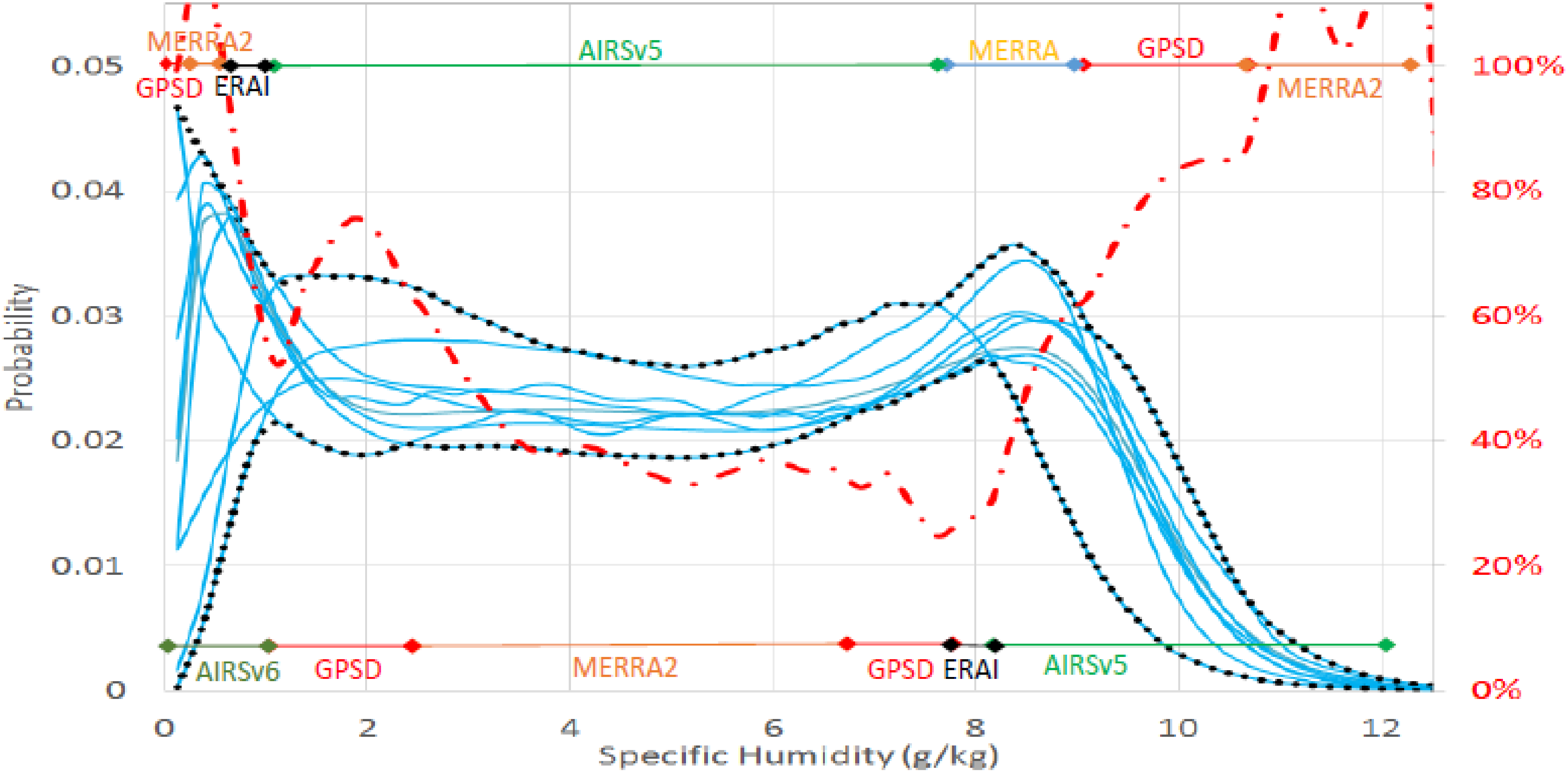
Structural uncertainty of radiance-based estimates of water vapor

- 725 mb



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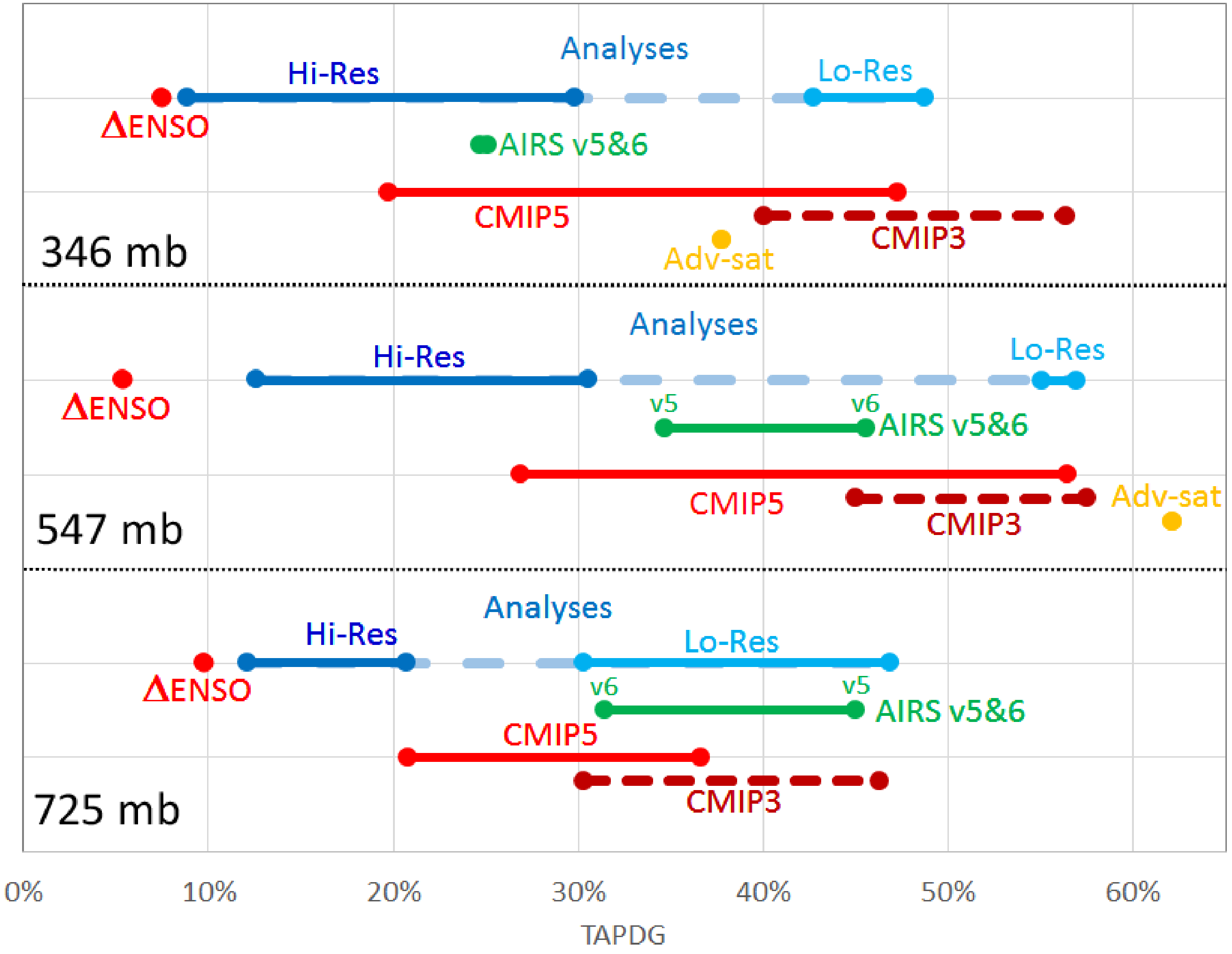
Summary of behavior by measurement type

- 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