Signatures of water vapor and precipitation, ENSO and accuracy revealed in GNSS RO

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IROWG-8

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Outline

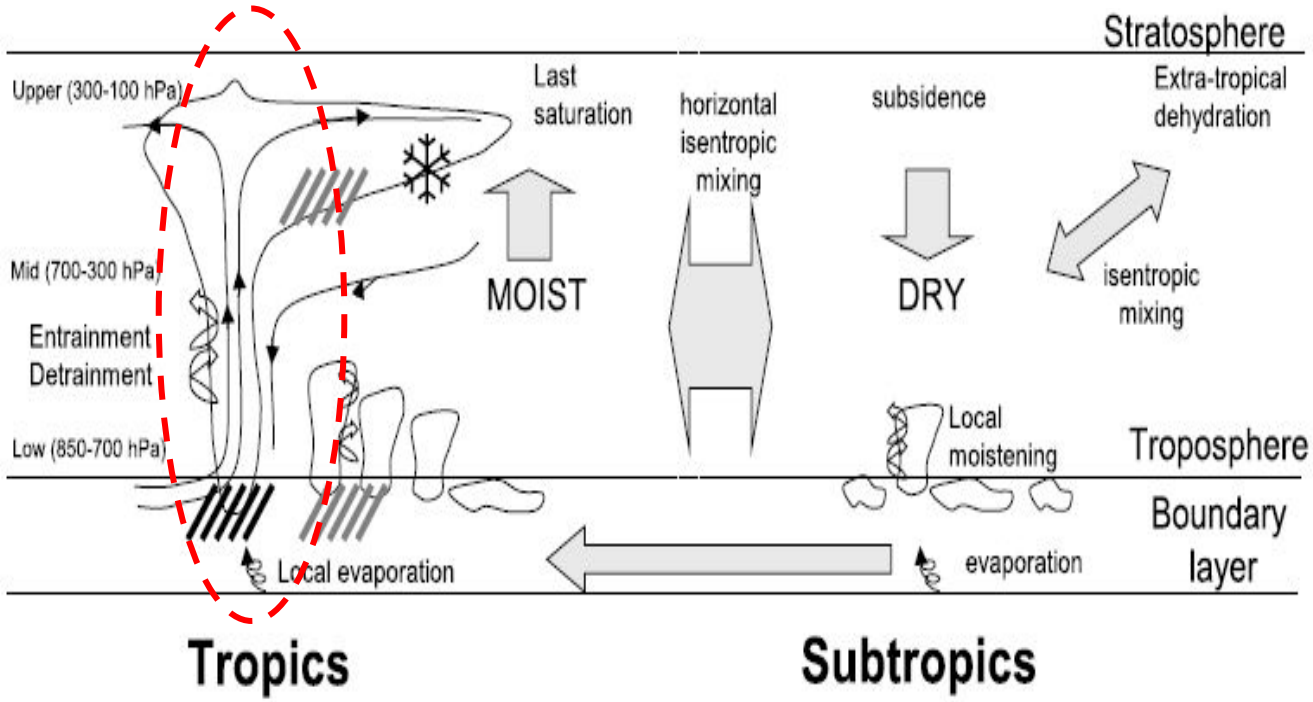
1. Quick update on PlanetiQ Status
2. WV precipitation correlation
3. GNSS RO water vapor based ENSO Index
4. Sonde-Direct RO humidity comparisons
5. Histogram bias revealed and fixed => climate quality RO water vapor?
6. Remarkable HadGEM3 climate model performance

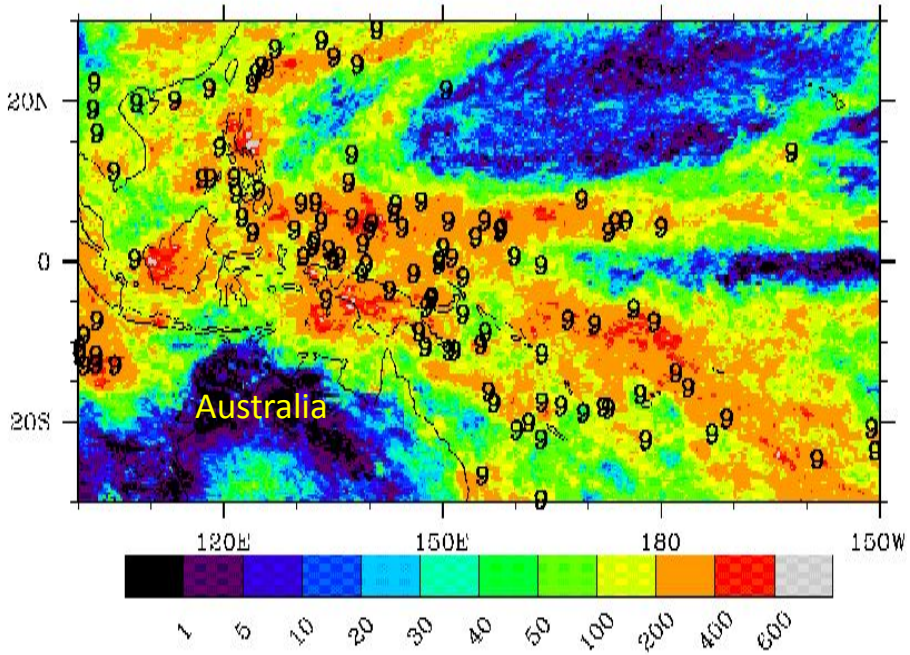
- Quick PlanetiQ update:
  - First PlanetiQ spacecraft launched August 2020 and failed
  - Problems identified and fixed
  - 2nd spacecraft scheduled to launch June 24, 2021
  - 3rd spacecraft scheduled to launch Dec 2021
  - Each spacecraft to provide ~2500 occ/day with SNRs ≥ COSMIC-2

- Humidity results presented here
  - Water vapor derived via **Direct method** using NWP (ECMWF and GFS) temperature but not NWP water vapor
    - **not 1DVar**
  - RO data from COSMIC-2, COSMIC and CHAMP
  - Much of PlanetiQ research is funded by USAF

Wet free troposphere profiles correlated with precipitation

- Convergence and updraft associated with convective rainfall creates very high column water vapor, particularly apparent in free troposphere
- GNSS RO very good at measuring free troposphere water vapor

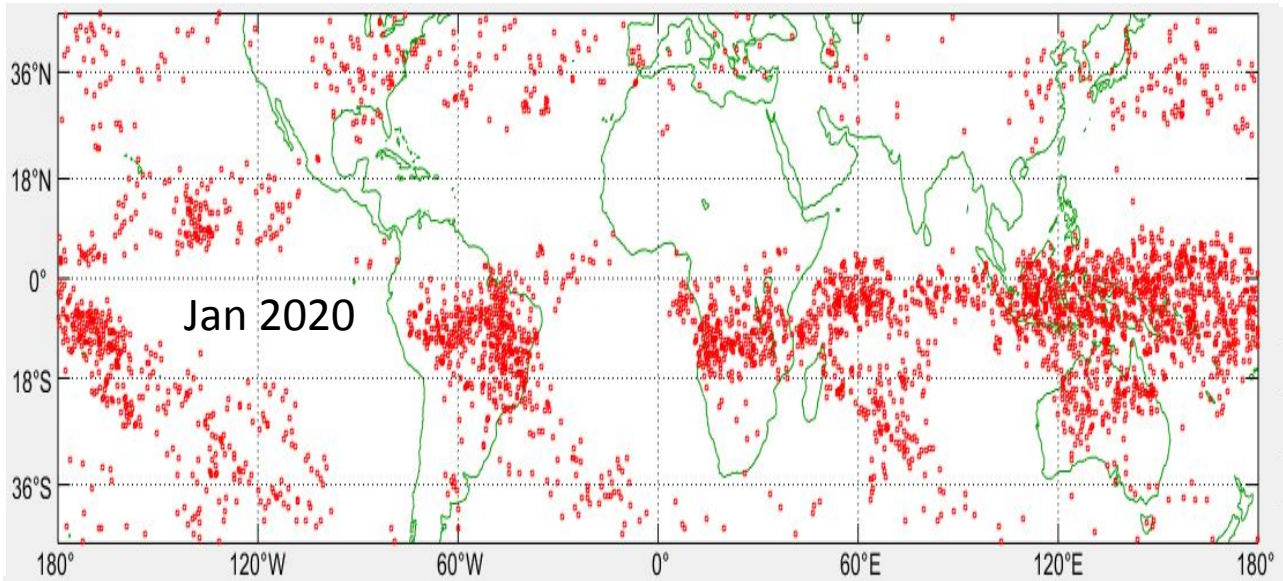


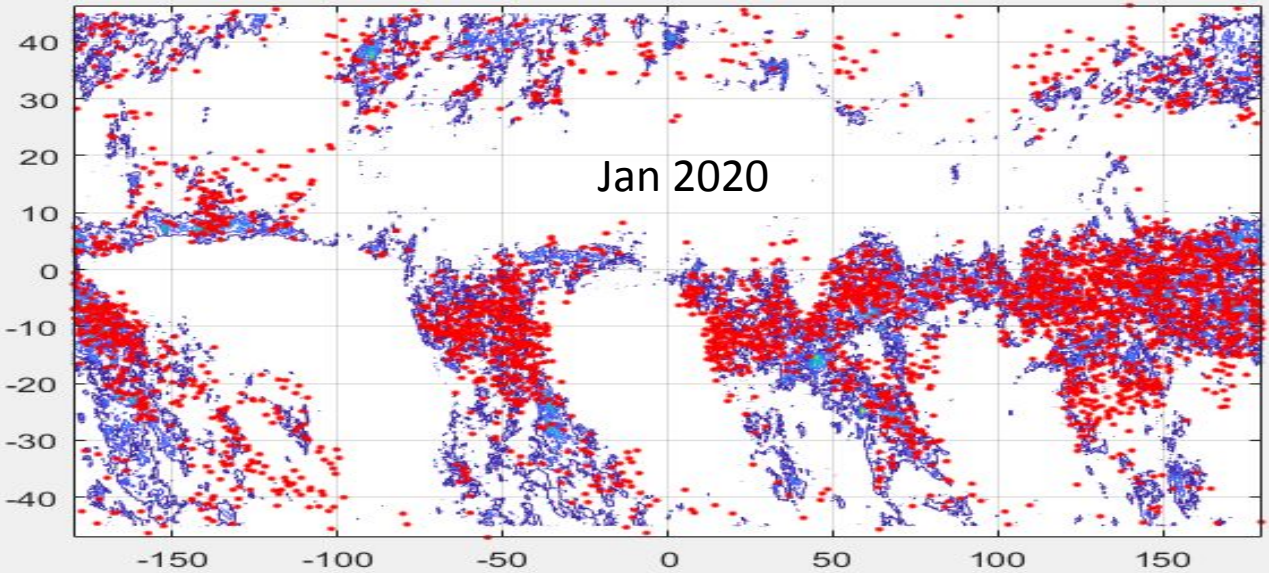


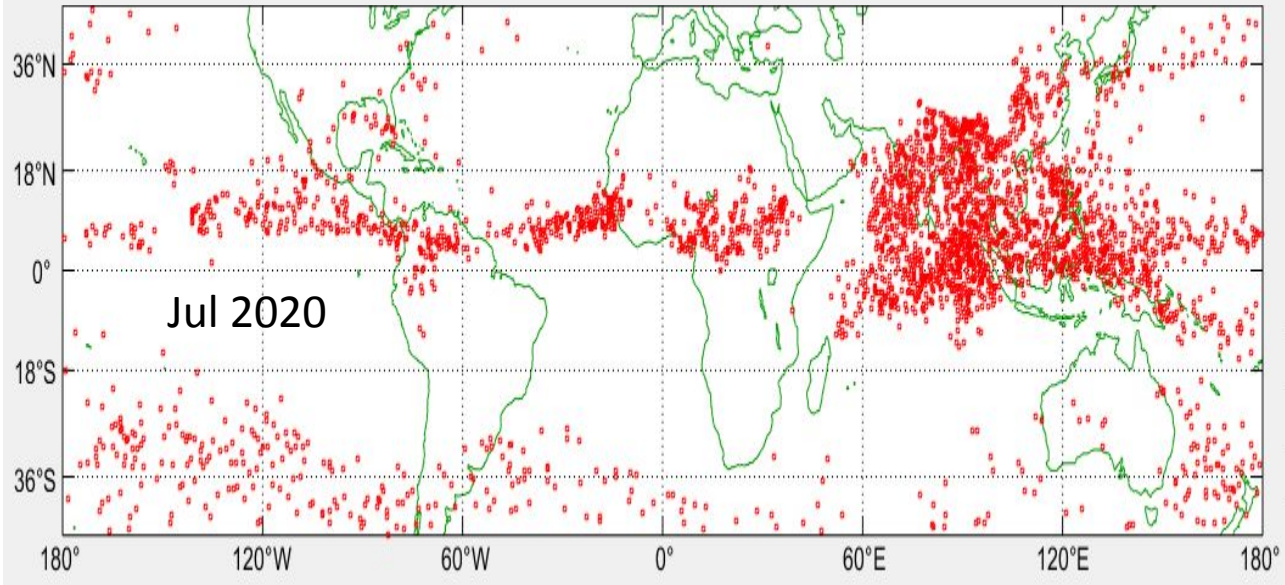
TRMM 1 month rainfall

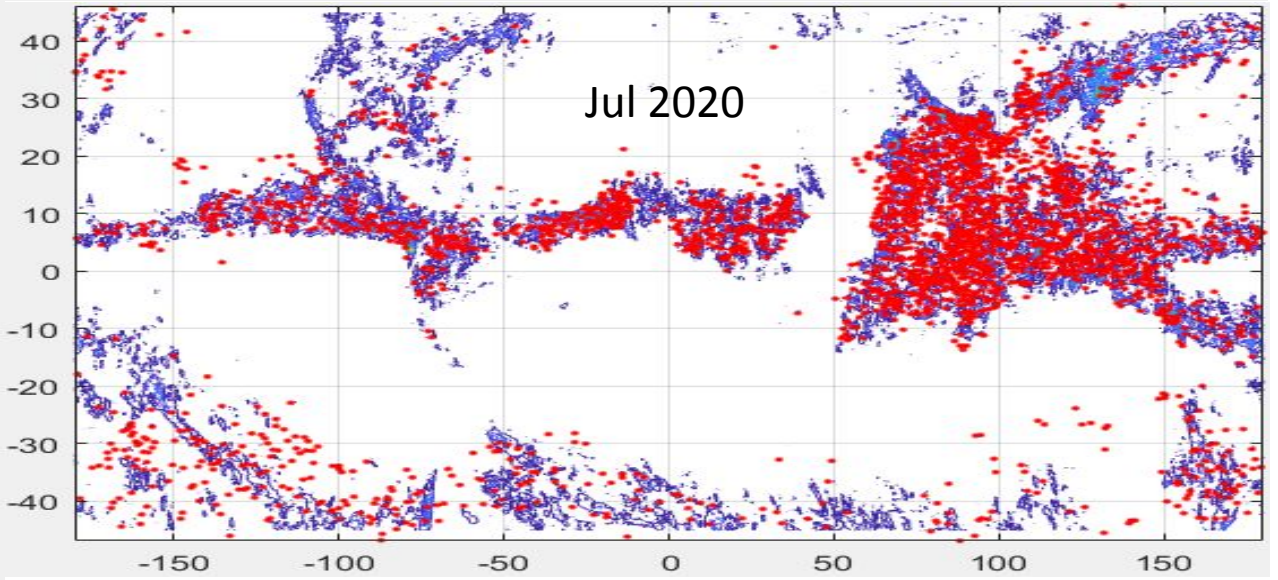
Wet profiles correlated with IMERG precipitation maps

Two Monthly comparisons: Jan 2020 & July 2020 Red: C2 profiles Purple: IMERG contours









PLANETiQ

ENSO Index based on RO water vapor

- ENSO MEI index shown to right
- MEI.v2 uses 5 variables
  - Sea level pressure (SLP),
  - Sea surface temperature (SST),
  - Surface zonal winds (U),
  - Surface meridional winds (V),
  - Outgoing Longwave Radiation (OLR))
- Water vapor and precipitation follow the warmest SSTs
- Can see the water vapor migration with GNSS RO
- Use that migration to create new ENSO index or add it to a multivariable index like MEI

CHAMP

COSMIC

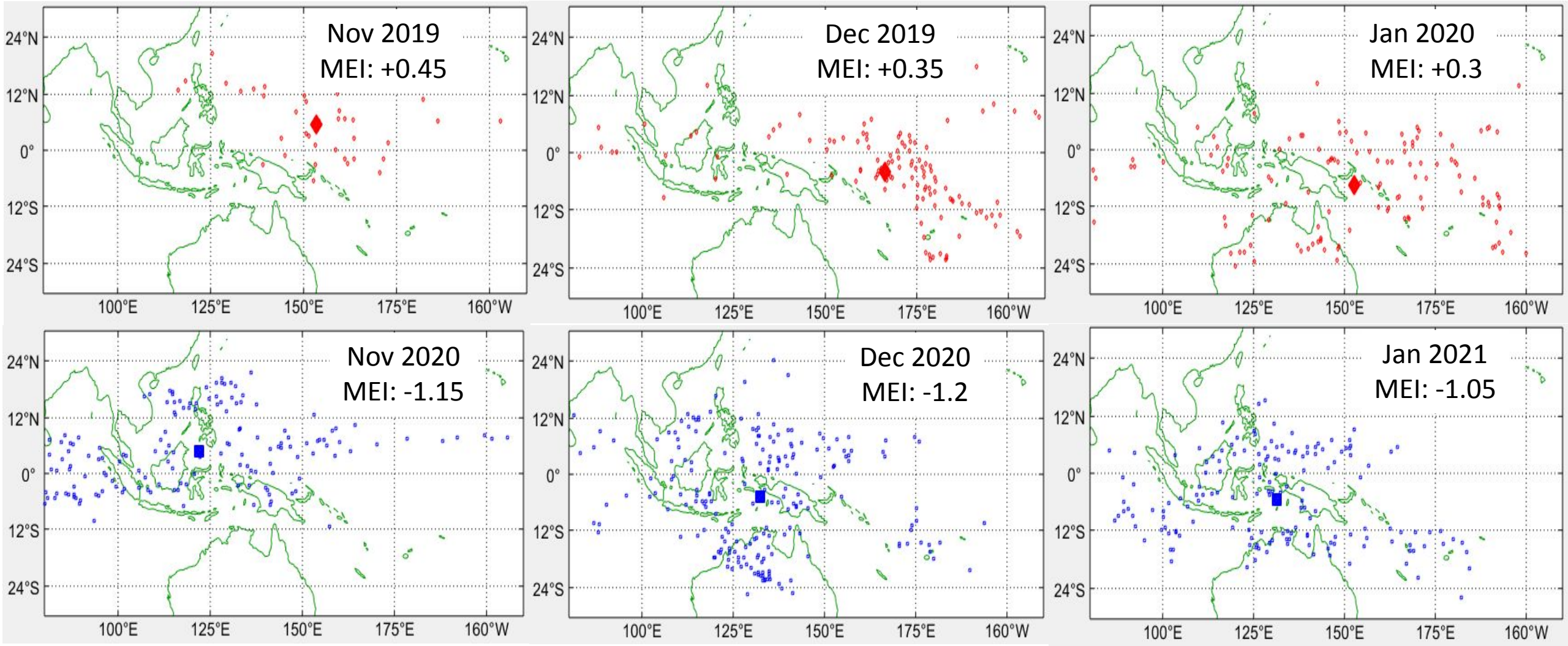
COSMIC-2

YEAR	DJ	JF	FM	MA	AM	MJ	JJ	JA	AS	SO	ON	ND
2000	-1.3	-1.3	-1.4	-0.9	-1	-1.1	-0.6	-0.1	-0.4	-0.6	-(	
2001	-0.8	-0.9	-0.8	-0.6	-0.6	-0.7	0	0.3	-0.1	-0.2	-(	
2002	0.1	-0.3	-0.2	-0.4	-0.1	0.4	0.4	1	0.8	0.8	0.8	0.9
2003	0.8	0.6	0.5	-0.1	-0.6	-0.1	0	0	0.1	0.3	0.3	0.1
2004	0.2	0	-0.4	-0.2	-0.4	-0.3	0.4	0.7	0.5	0.3	0.5	0.5
2005	0.1	0.6	0.8	0.1	0.2	0.2	0	0	0	-0.7	-0.7	-0.7
2006	-0.7	-0.5	-0.6	-0.8	-0.4	-0.2	0.1	0.6	0.6	0.7	0.9	0.6
2007	0.6	0.4	-0.2	-0.4	-0.4	-0.9	-0.8	-0.9	-1.1	-1.1	-1.1	-1.2
2008	-1.1	-1.3	-1.5	-1.1	-1	-0.9	-0.9	-1.1	-1.1	-1.1	-1	-1
2009	-1	-0.8	-0.9	-0.8	-0.7	-0.1	0.5	0.5	0.4	0.6	1.1	1
YEAR	DJ	JF	FM	MA	AM	MJ	JJ	JA	AS	SO	ON	ND
2010	0.9	1.3	1.3	0.5	-0.2	-1.3	-2.4	-2.4	-2.3	-2.2	-2	-1.9
2011	-1.8	-1.6	-1.8	-1.7	-1.3	-1.1	-0.9	-0.9	-1.2	-1.4	-1.2	-1.2
2012	-1.1	-0.7	-0.6	-0.4	-0.3	-0.3	0.3	-0.1	-0.3	-0.2	-0.1	-0.1
2013	0	-0.1	-0.1	-0.4	-0.7	-1.2	-0.8	-0.5	-0.4	-0.2	-0.2	-0.3
2014	-0.5	-0.4	-0.1	-0.2	-0.2	0	0.3	0.2	-0.1	0.1	0.3	0.3
2015	0.2	0.1	0.1	0.4	1	1.9	1.7	1.9	2.2	2.1	1.9	1.9
2016	1.9	1.8	1.3	1.3	1.3	0.4	-0.5	-0.3	-0.3	-0.6	-0.5	-0.3
2017	-0.4	-0.4	-0.6	-0.2	0.2	-0.3	-0.7	-0.8	-0.8	-0.6	-0.6	-0.7
2018	-0.8	-0.7	-0.8	-1.3	-0.9	-0.5	-0.2	0.4	0.5	0.4	0.3	0.1
2019	0.1	0.5	0.8	0.3	0.3	0.4	0.2	0.3	0.2	0.3	0.5	0.4
YEAR	DJ	JF	FM	MA	AM	MJ	JJ	JA	AS	SO	ON	ND
2020	0.3	0.3	0.2	-0.1	-0.2	-0.7	-1	-1	-1.2	-1.2	-1.1	-1.2
2021	-1.2	-0.9	-0.8									

La Nina El Nino

COSMIC-2: Two years of Nov-Dec-Jan

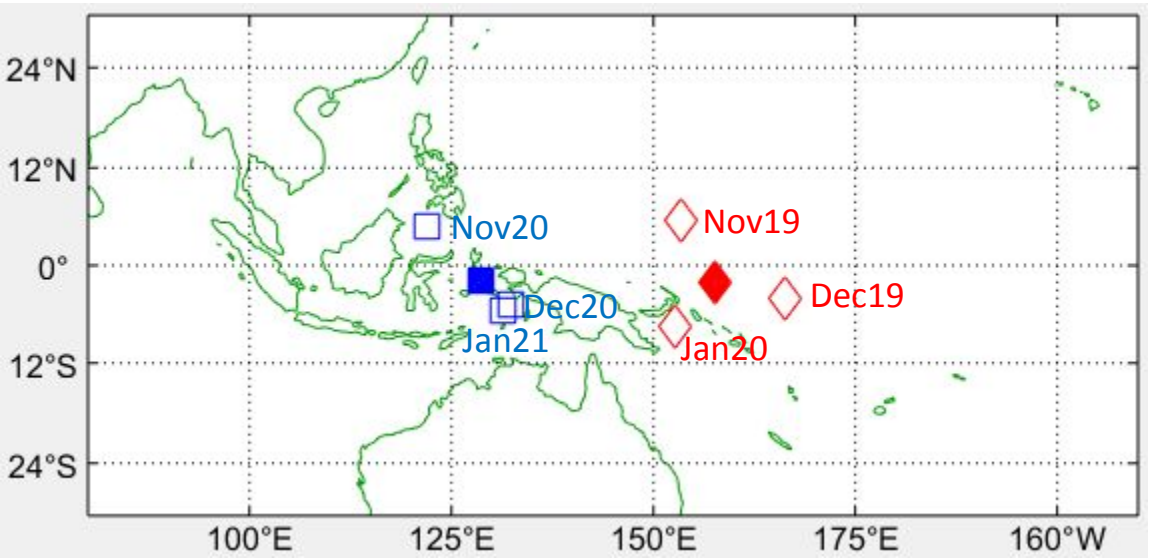
- Centroid of high free troposphere water vapor shifts west during La Nina and east as ENSO index becomes increasingly positive



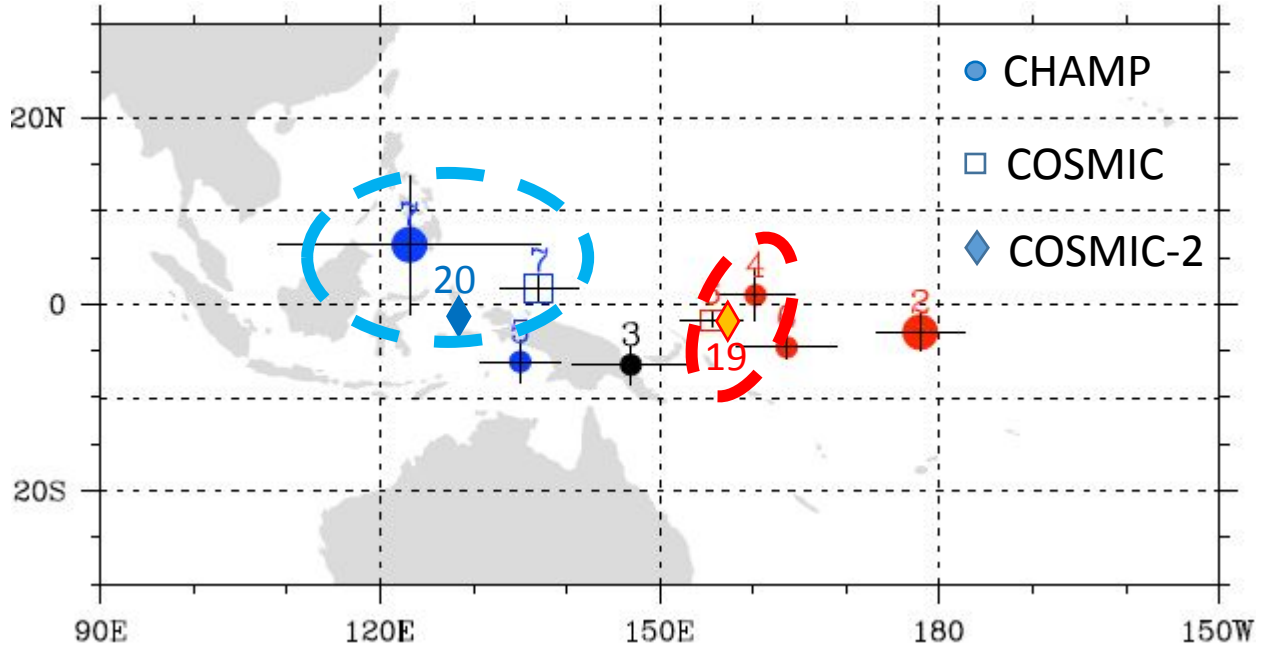
ENSO index from RO

- Closest MEI analogues to COSMIC-2 period

	Nov	Dec	Jan
2004-2005	+0.5	+0.3	+0.35
2019-2020	**+0.45**	**+0.35**	**+0.3**
2020-2021	**-1.15**	**-1.2**	**-1.05**
2007-2008	-1.15	-1.15	-1.2



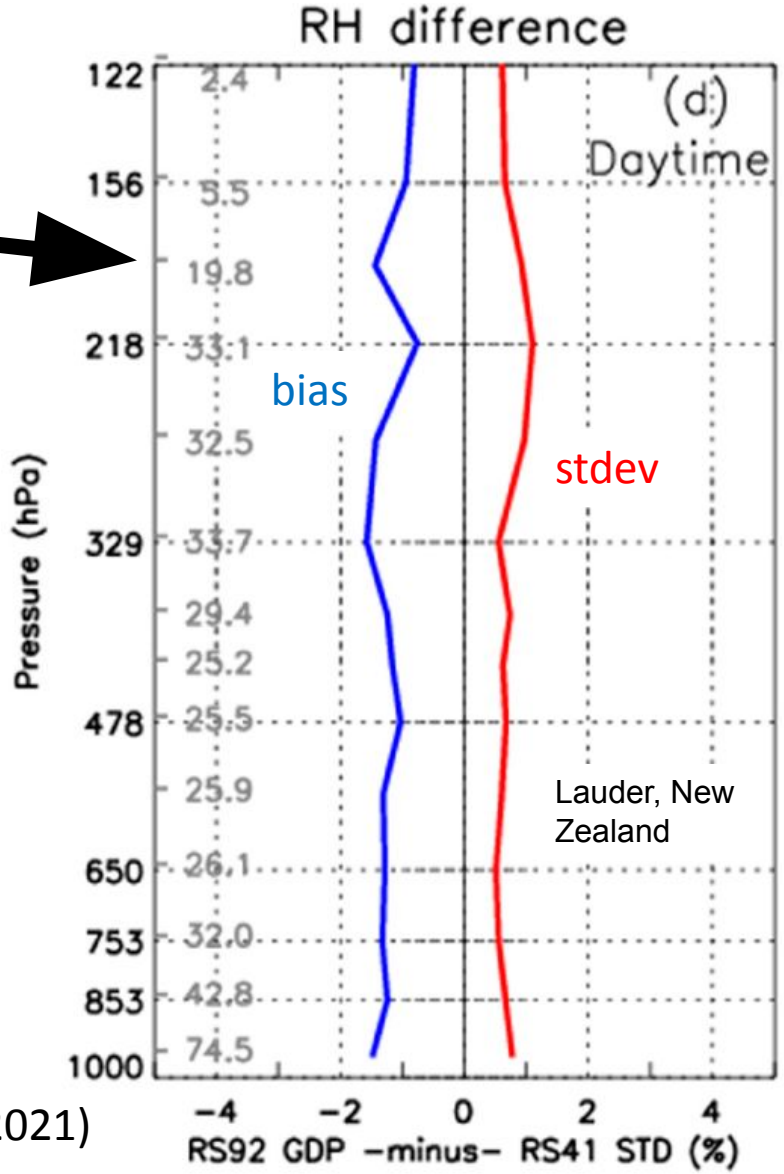
NDJ 2020 ~ NDJ 2007 NDJ 2019 ~ NDJ 2004



- Based on centroid of high free troposphere PWV in East Indian and Pacific Oceans
- Refining unique criteria for ENSO definition

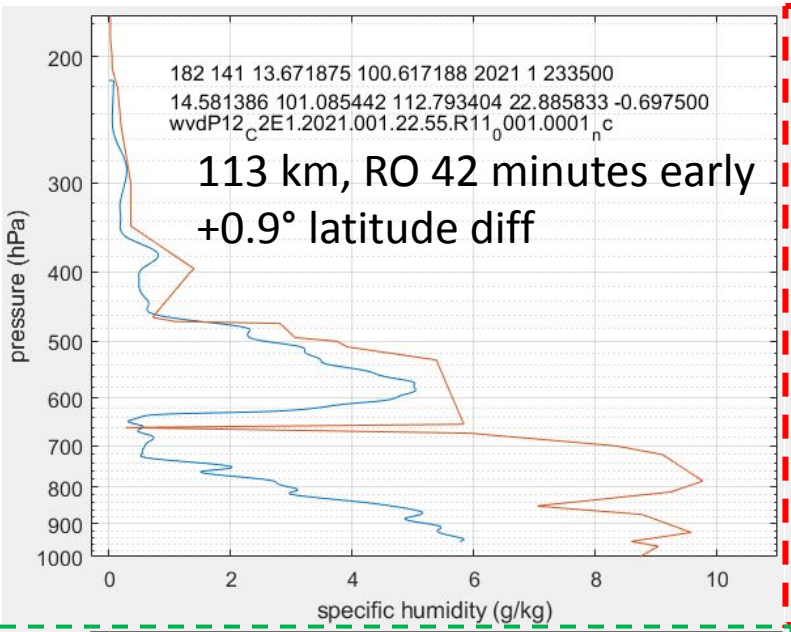
Comparing Humidity: COSMIC-2 Direct-retrieval & Sondes

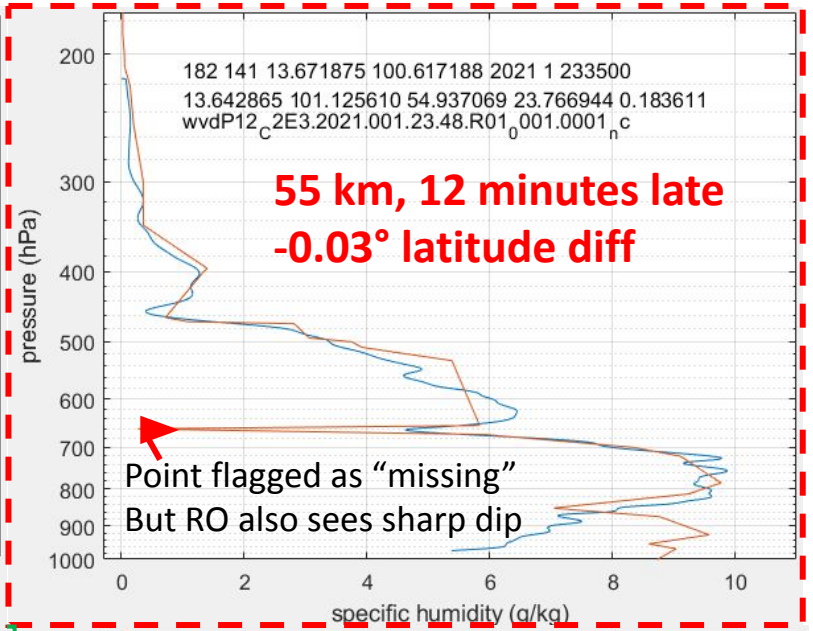
- RS-41 sondes measure humidity quite accurately as demonstrated by comparisons with GRUAN-processed RS92 sondes
- Using NPROVS to identify and compare collocated RS41 sondes with COSMIC-2 profiles
- Comparing RO specific humidity (Direct retrievals) with the collocated sondes
- Early results presented here
  - 4200 collocation over 20 days
  - Need more collocations to reduce sampling noise

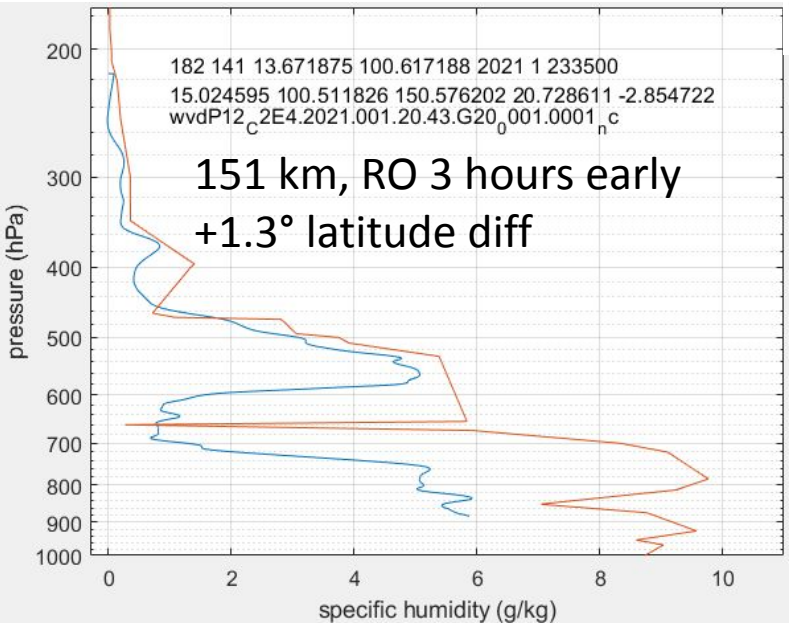


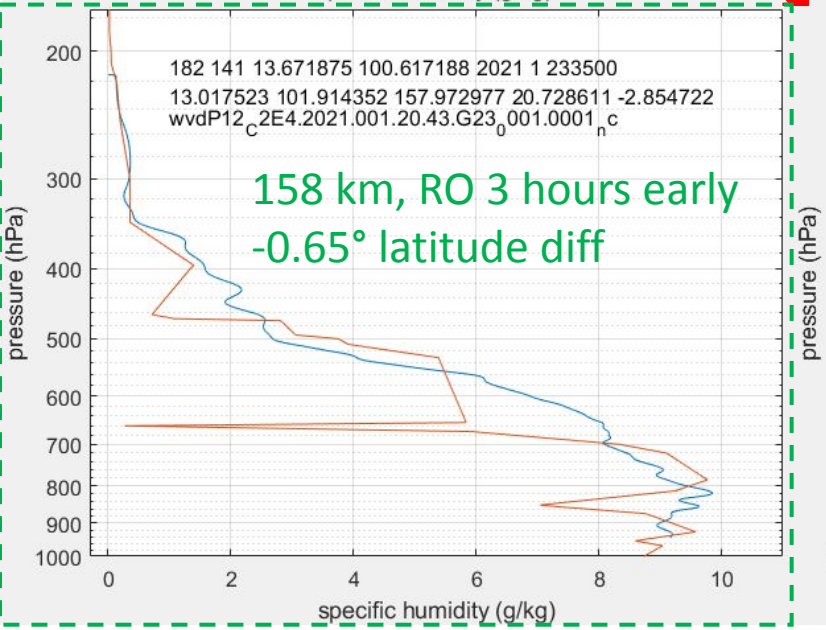
Sun et al. *Remote Sens.* (2021)

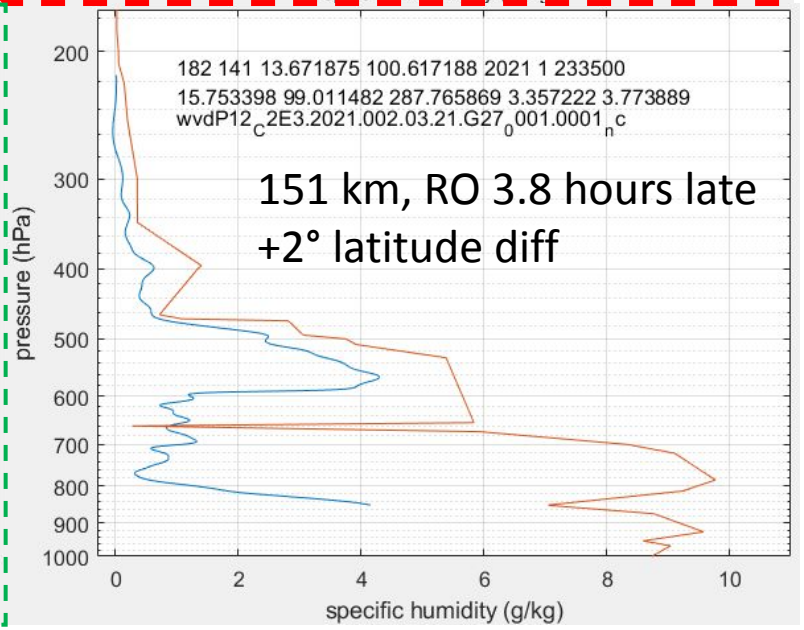
5 RO Collocations with one sonde from Jan 1, 2021







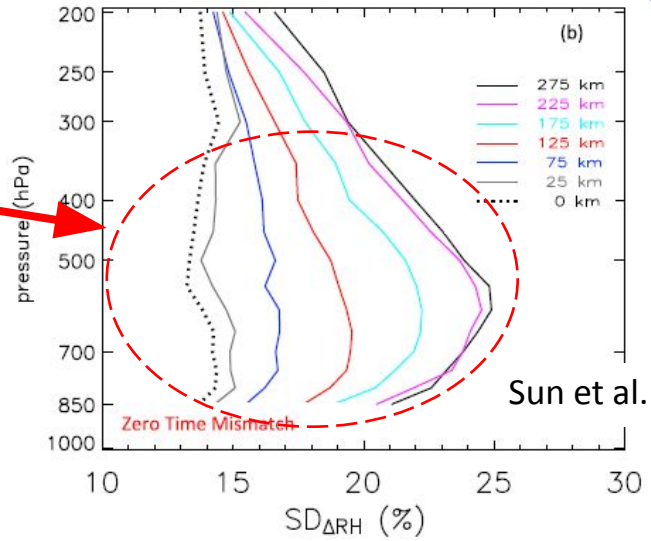




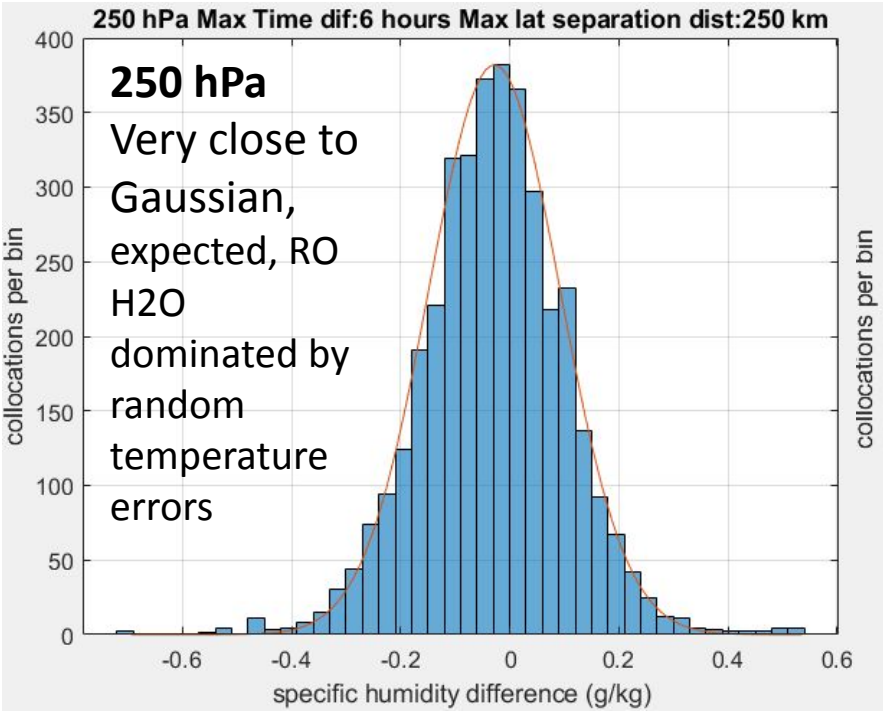
- The very close RO profile matches sonde very closely down to 875 hPa
- There is a strong latitudinal gradient
- RO profile 80 km south and 3 hours earlier is similar to the sonde profile
- RO profiles north of the sonde see much drier air in the lower troposphere
- RO-sonde difference depends more strongly on latitude separation than total distance or time separation

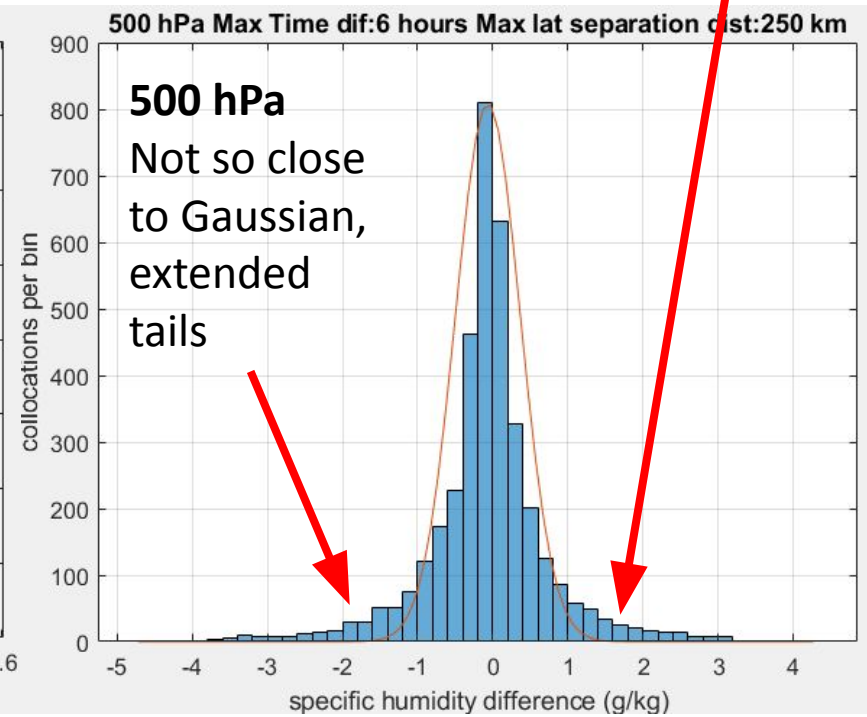
Histograms of specific humidity differences

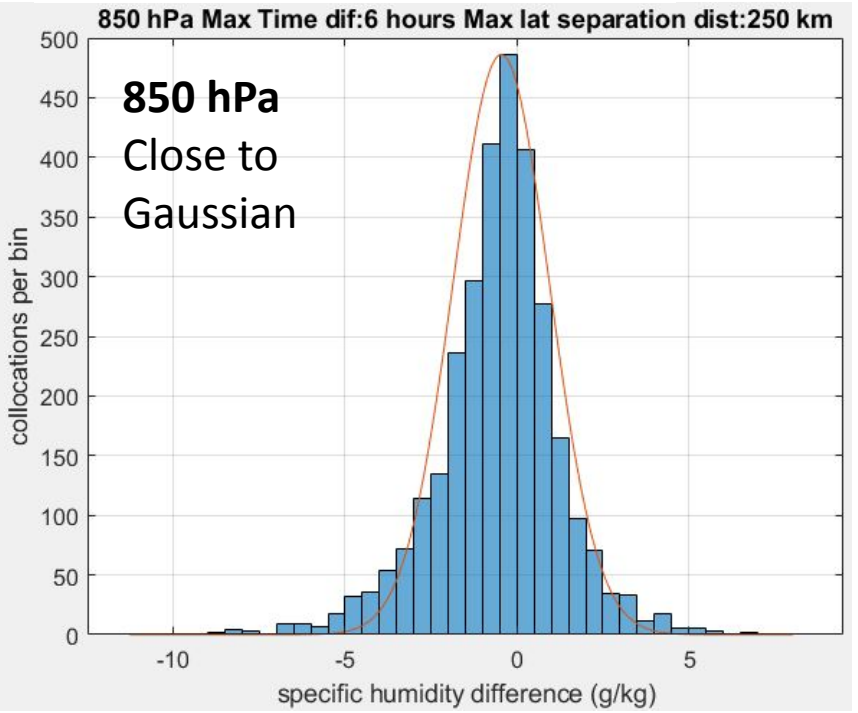
- Stdev's larger than stdev's estimated from quartiles => **outliers** vs Gaussian
  - More horizontal humidity structure between 300 and 800 hPa
  - At 500 hPa, variance is 3x the variance based on quartiles, due to 6% "outliers" relative to a Gaussian
- Develop more sophisticated collocation criteria including horizontal gradients?



Sun et al. (2010)



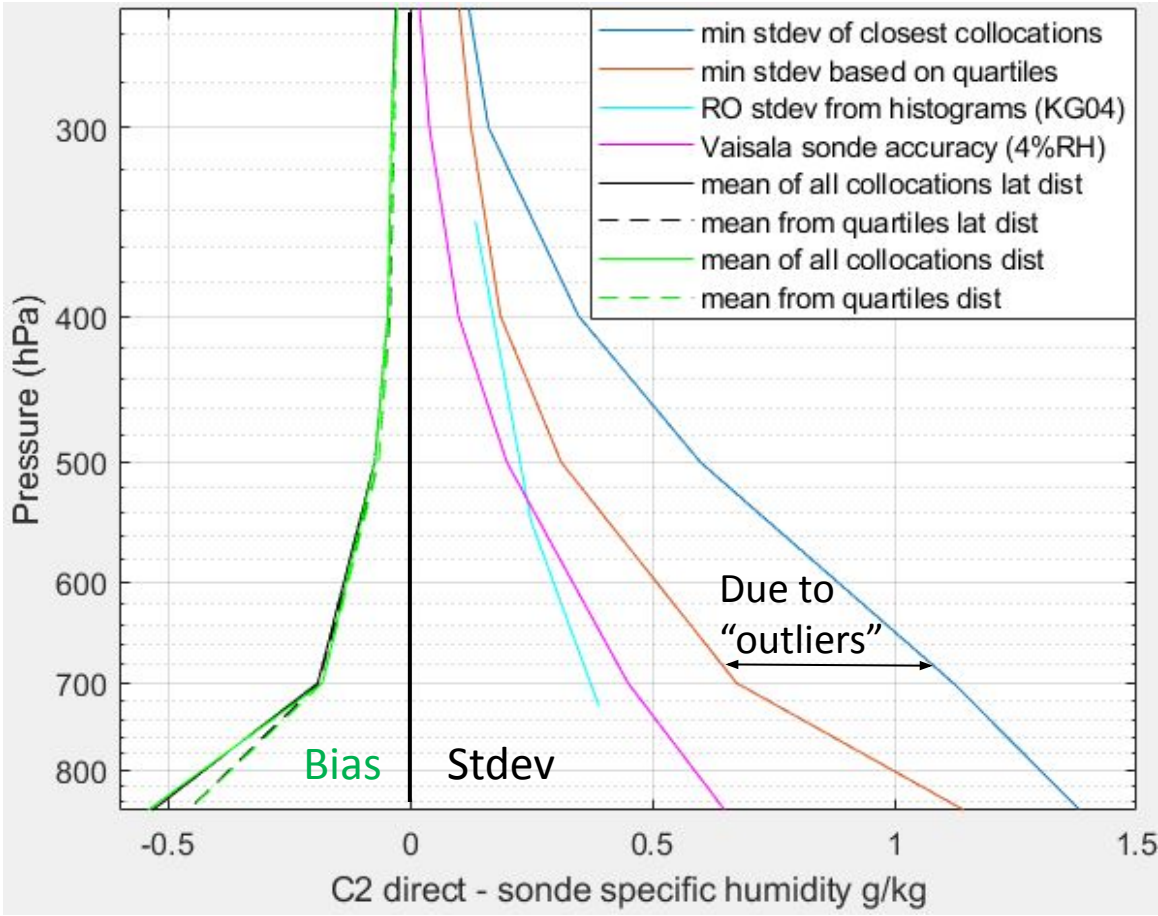




Preliminary Summary

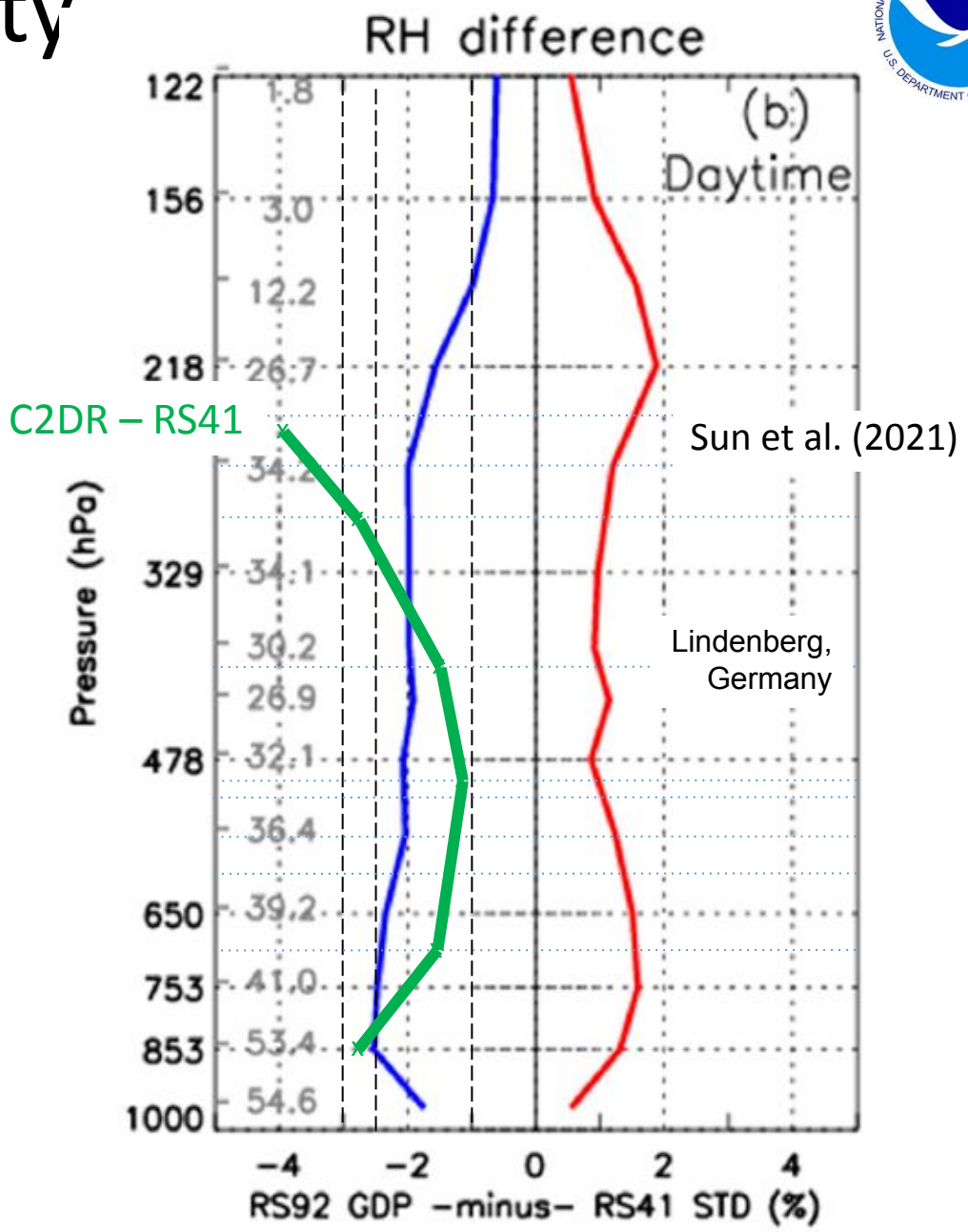
- Differences from RO errors, RS41 errors, and collocation separations, as well as horizontal averaging of the RO vs. sonde point measurements.
- Cyan curve is estimated stdev of RO Direct profiles from Kursinski & Gebhardt 2014
- Pink curve is Vaisala's accuracy spec = 4%RH
- Red stdev curve is ~RSS of σ_{sonde} & σ_{RO} (good)
- $\sigma_{RO} \leq \sigma_{sonde}$ from 500 hPa to 850 hPa?

- Small negative bias:
  - Kursinski/Gebhardt (2014) est. bias < 0.03 g/kg @346 hPa
  - Bias vs RS41 is about -0.03 g/kg at 250 & 300 hPa
  - Bias magnitude increases at higher pressure
    - Slight RO error due to non-ideal gas behavior?
  - At 850 hPa, super refraction causes negative RO bias?



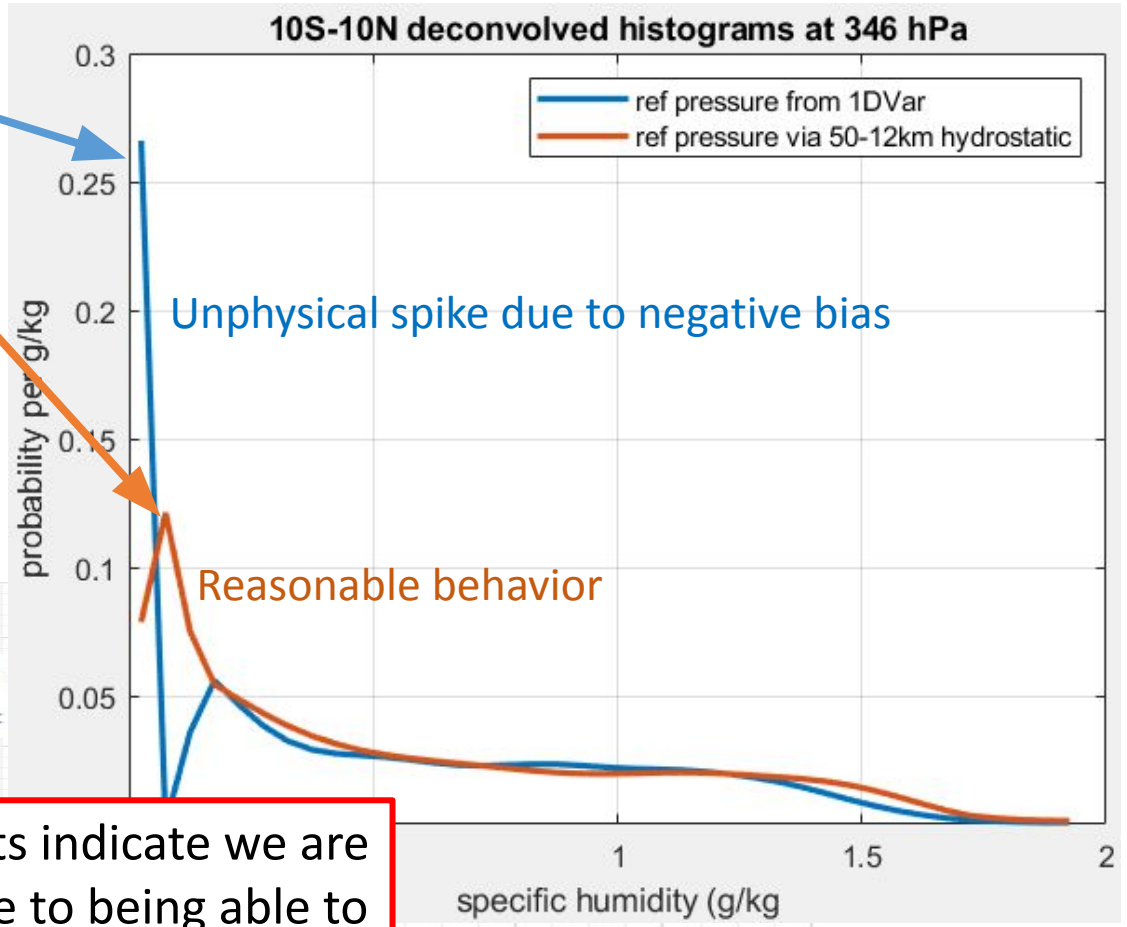
Bias in Relative Humidity

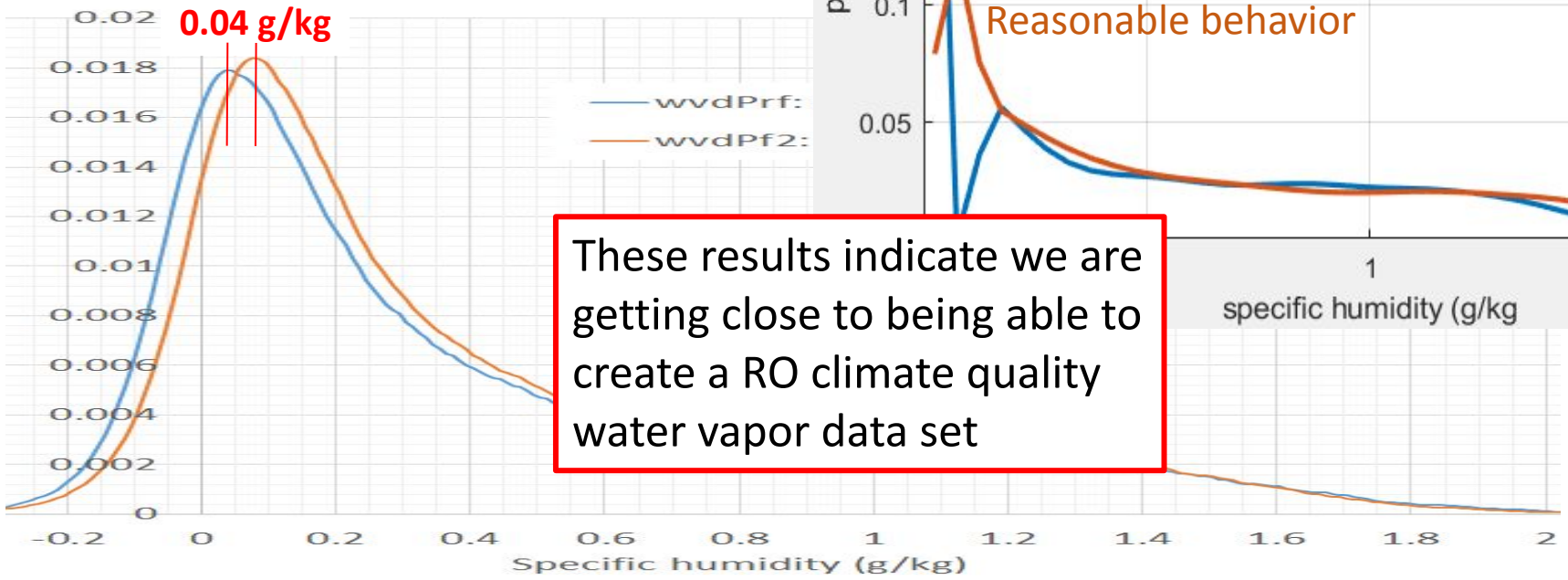
- Similar magnitude of bias between RS41 v. GRUAN-processed RS92 sondes
  - Magnitude and sign of estimated sonde-to-sonde bias varies a bit with location
    - Lauder, New Zealand v. Lindenberg, Germany v. Payerne, Switzerland v. Graciosa, Azores
- Green line is measured **RH** bias (RO-RS41) between Direct retrieved RO water vapor profiles and RS41
- Negative RS92 GDP-RS41 and C2DR – RS41 biases could be explained by RS41 being biased a bit high
- Will add 1DVar



PLANETiQ Toward Climate-Quality RO Water Vapor

- Error deconvolution revealed a negative bias in Direct water vapor retrieved using reference pressure from 1DVar
- By deriving reference pressure using RO refractivity in hydrostatic integral from 50 to 12 km altitude the bias problem disappeared
- Also, freeze drying air to 0.04 g/kg requires temperatures so cold (~212K) that that air is then warmed radiatively causing it to rise into the stratosphere



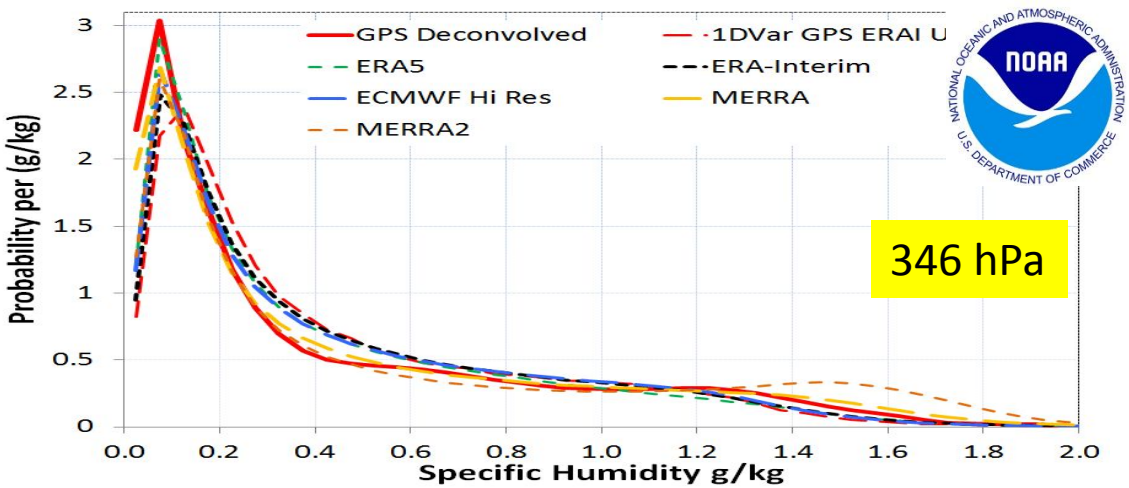


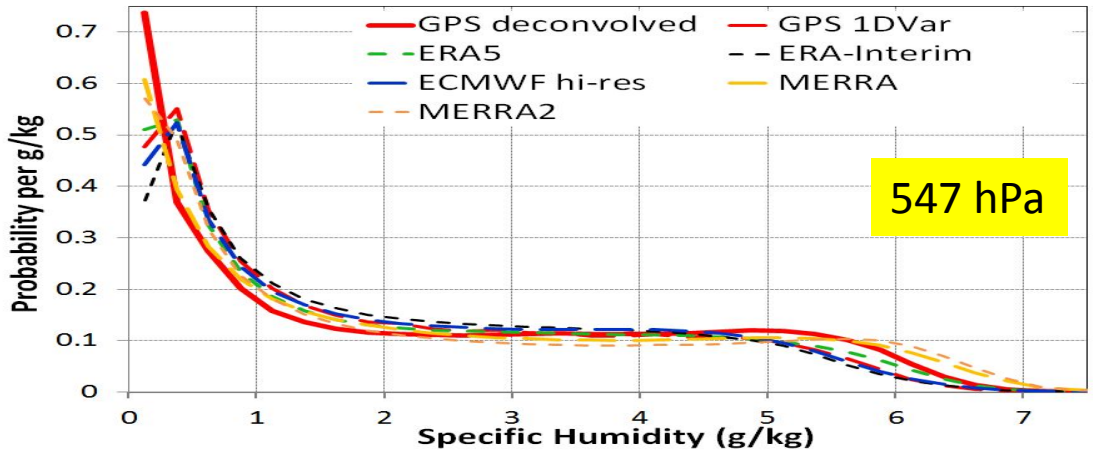
These results indicate we are getting close to being able to create a RO climate quality water vapor data set

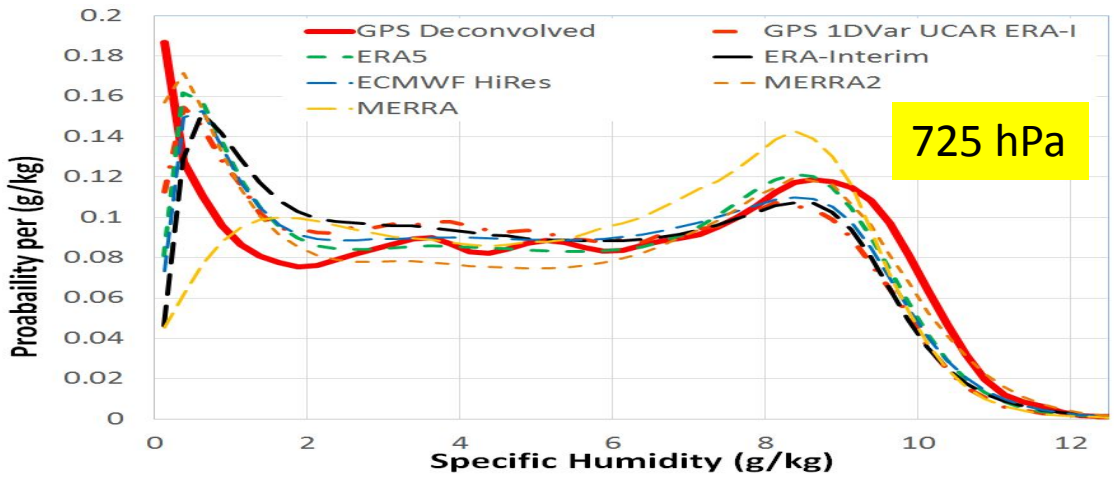
Quick humidity histogram comparison update

Comparisons between error-deconvolved GNSS RO specific humidity histograms and those from

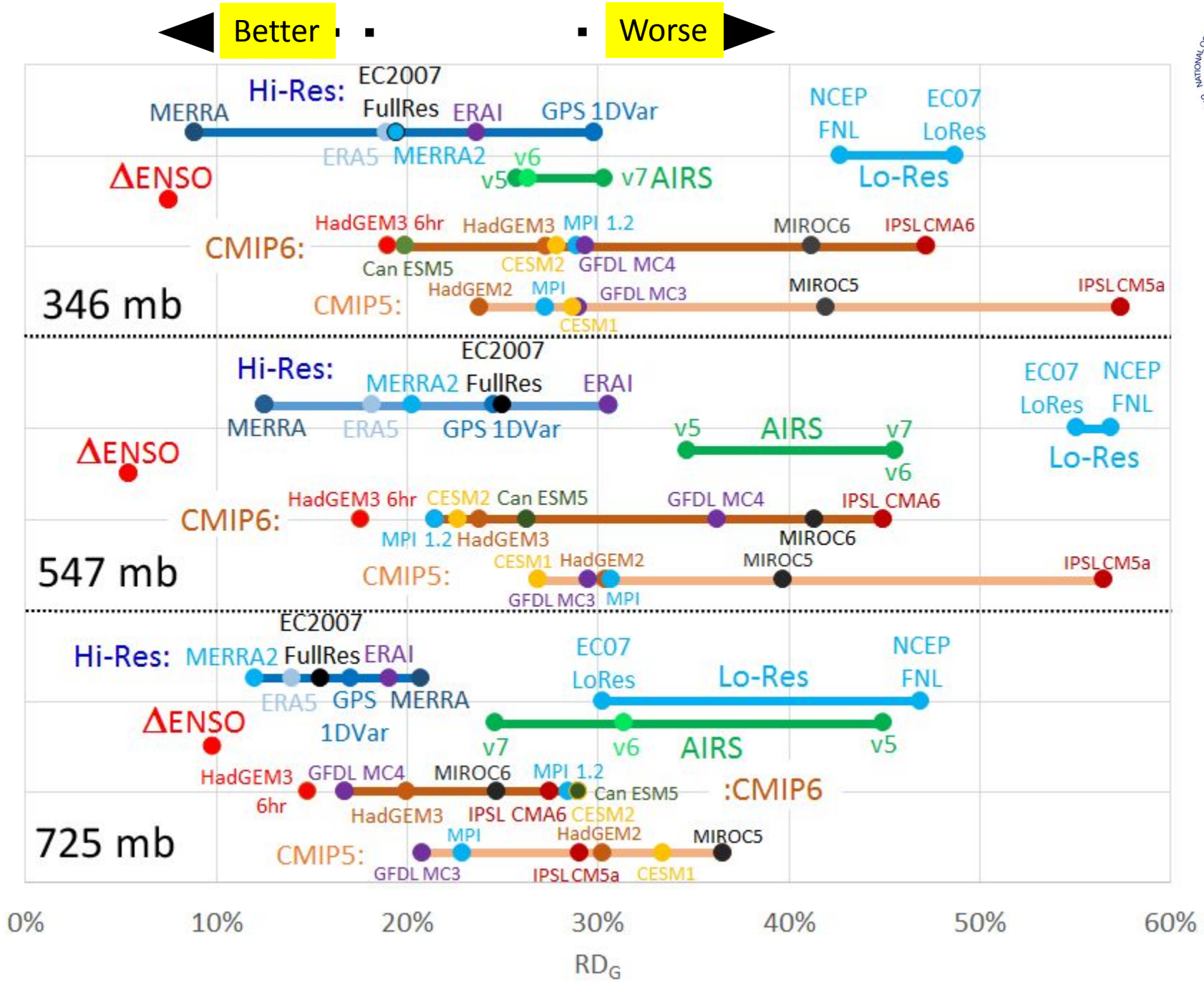
- (Re)analyses
- AIRS
- Climate models





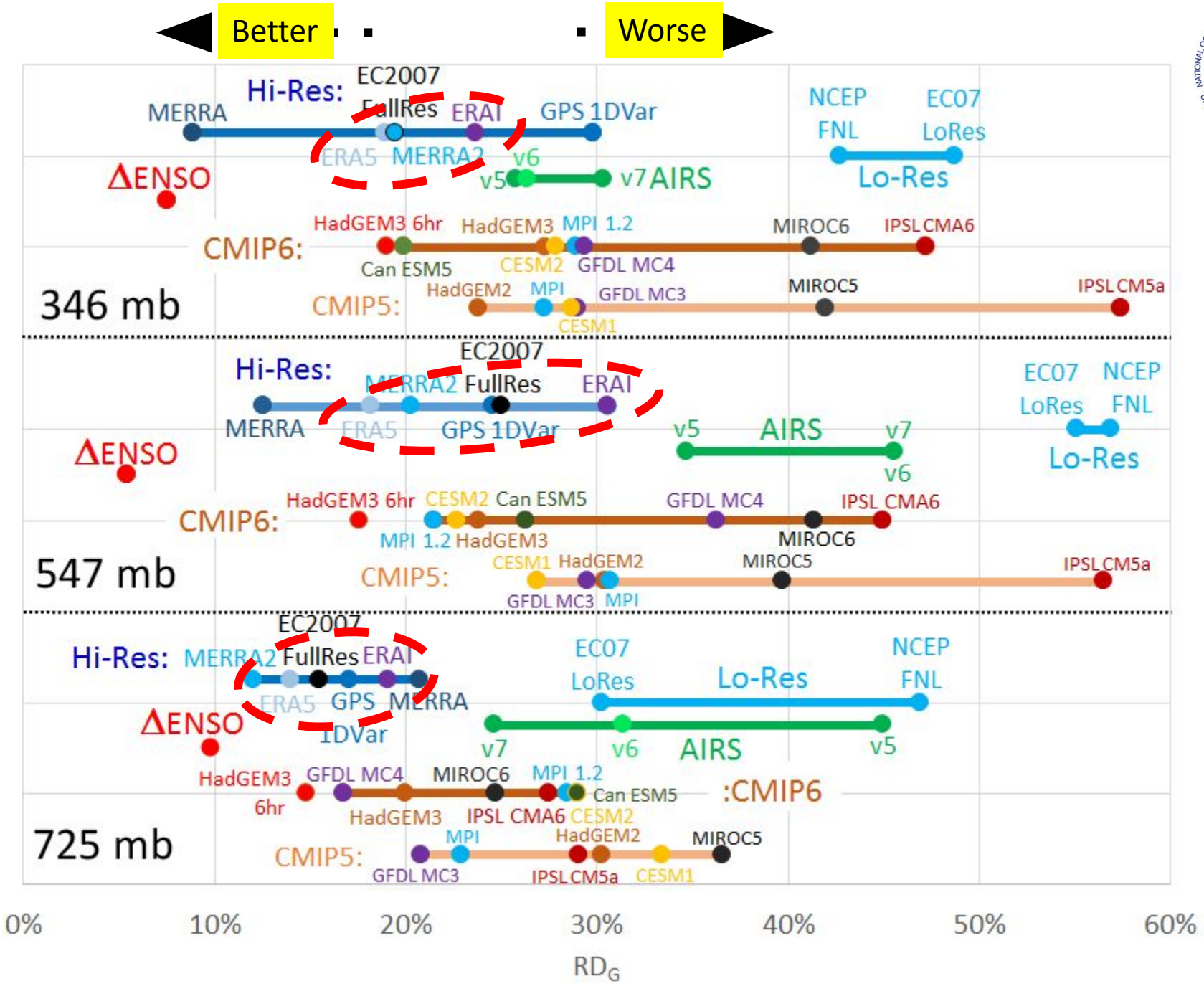


(Re)analysis and climate model comparison



(Re)analysis and climate model comparison

- ERA5 better than ERAI at all 3 levels



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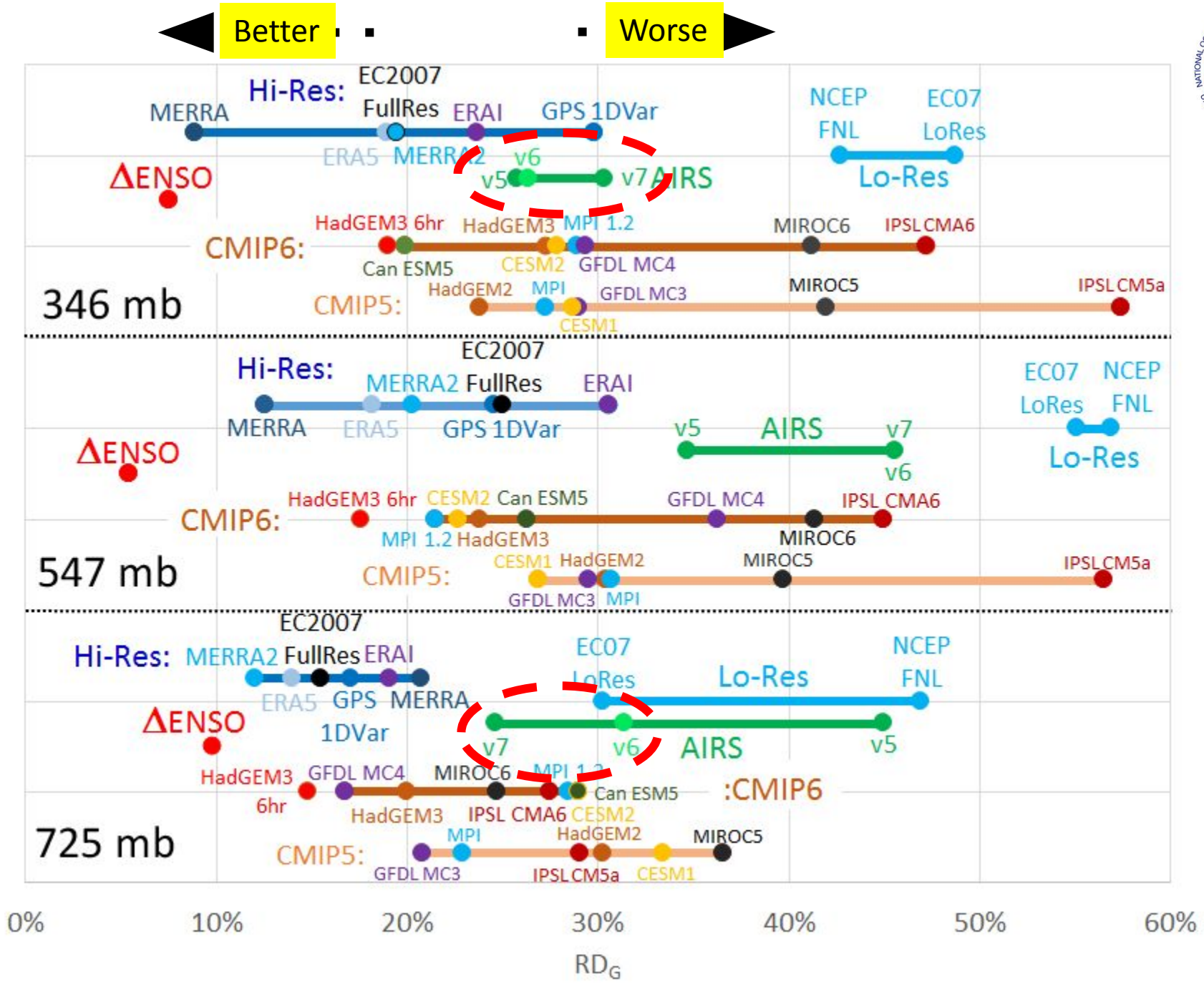

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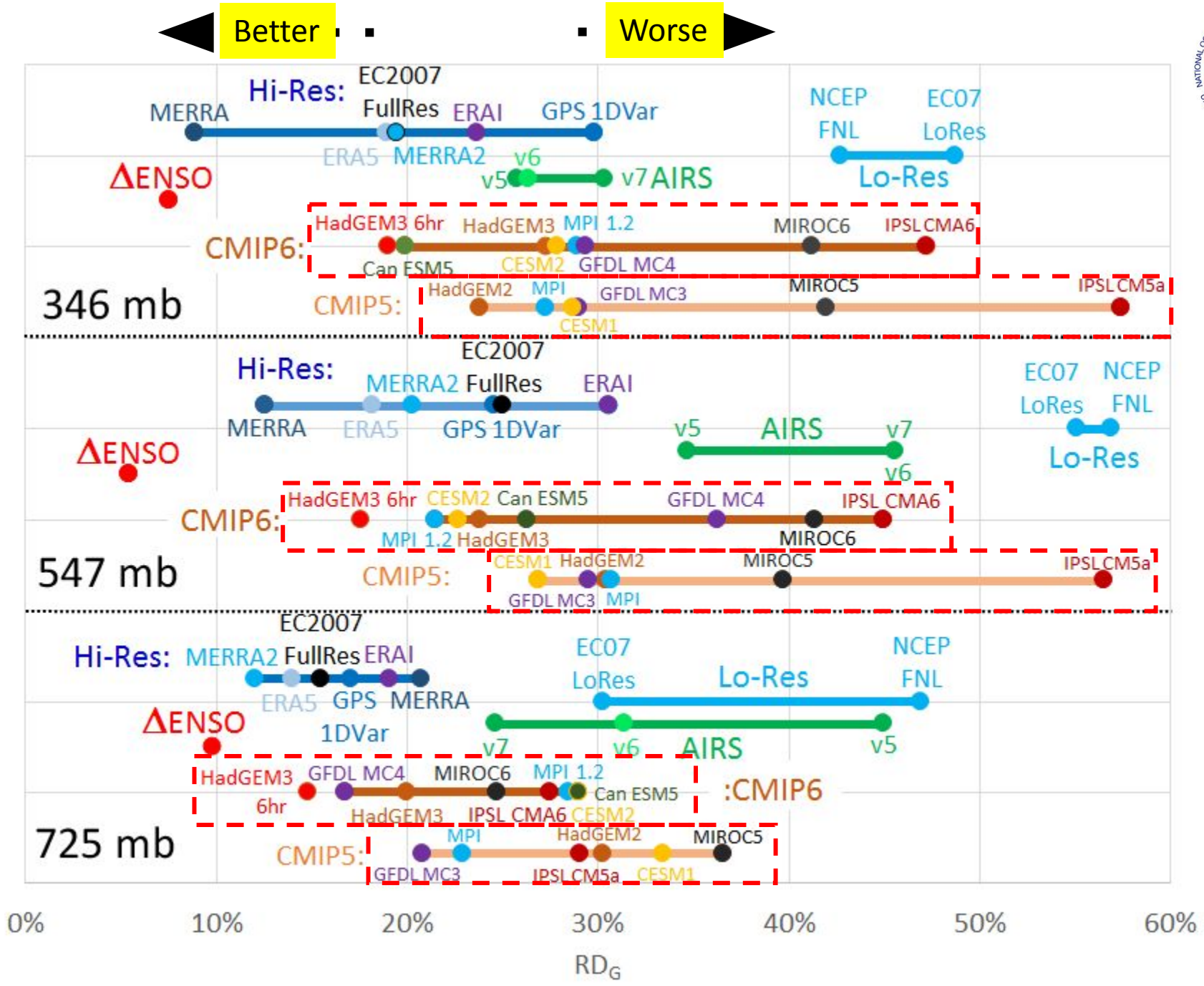
- CMIP6 are generally better than CMIP5
- Challenging to improve at all 3 levels



(Re)analysis and climate model comparison

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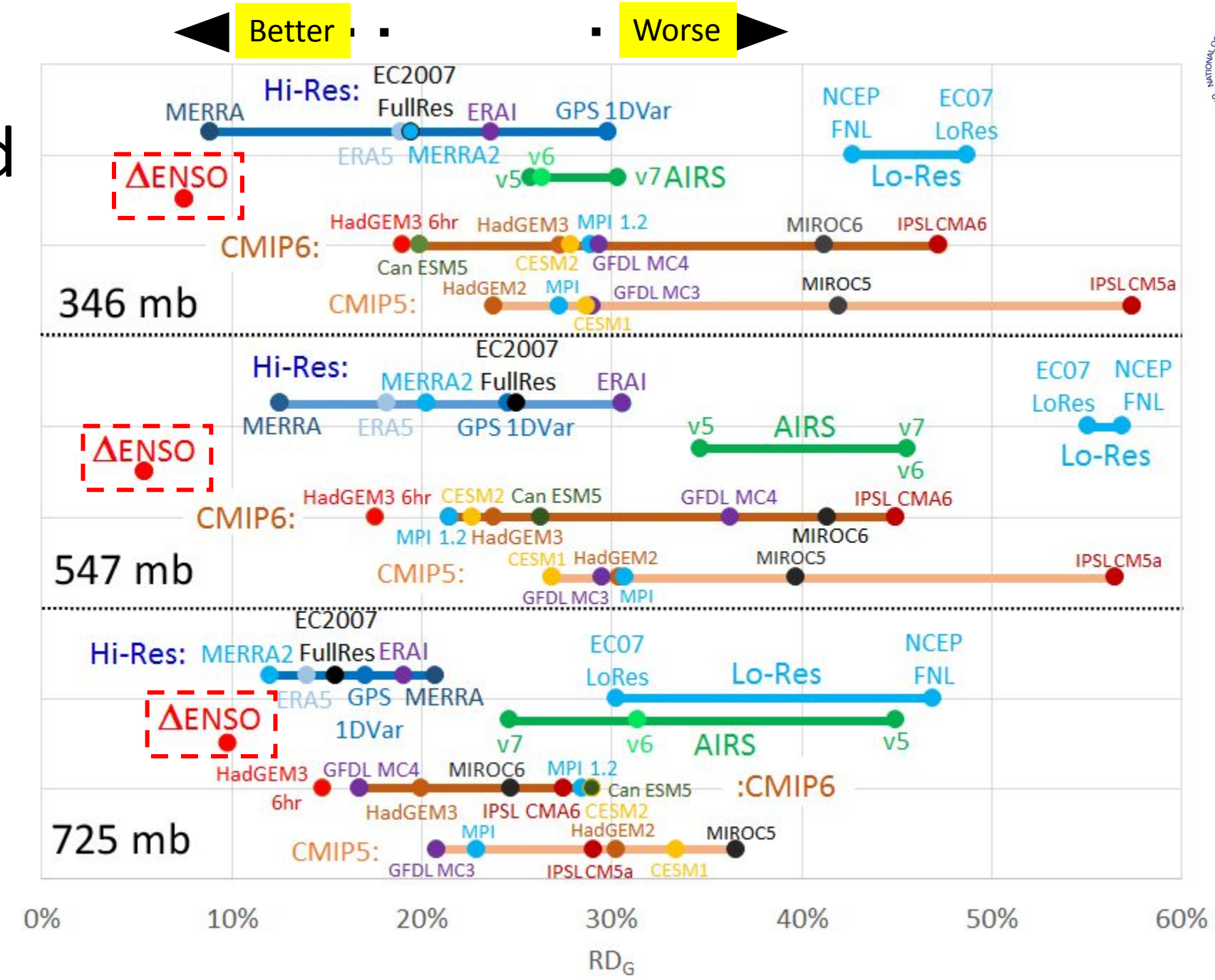
- Challenging to improve at all 3 levels
- None get within ΔENSO

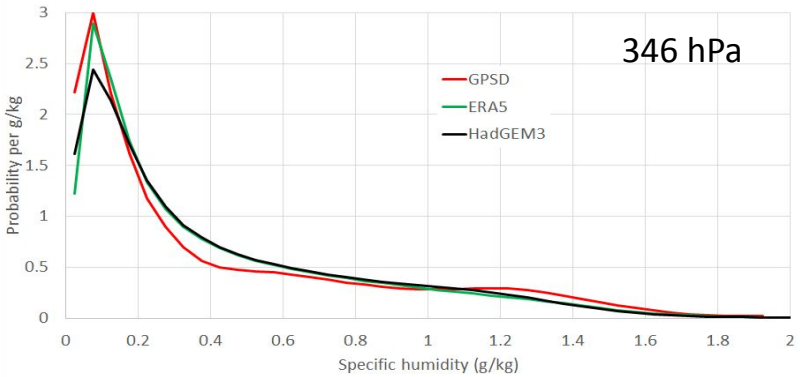


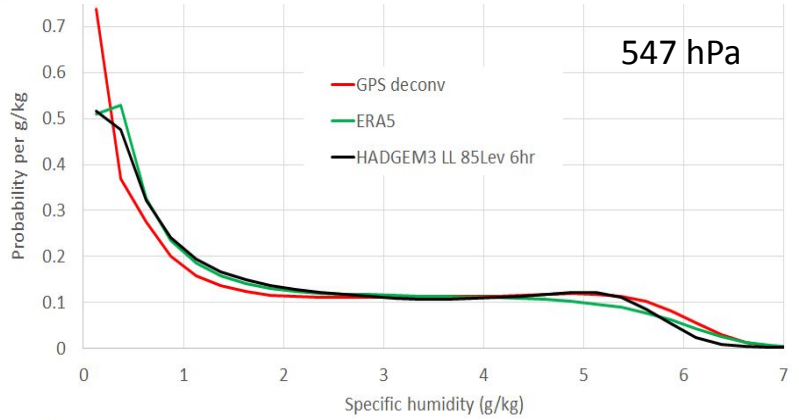
HadGEM3's remarkable performance

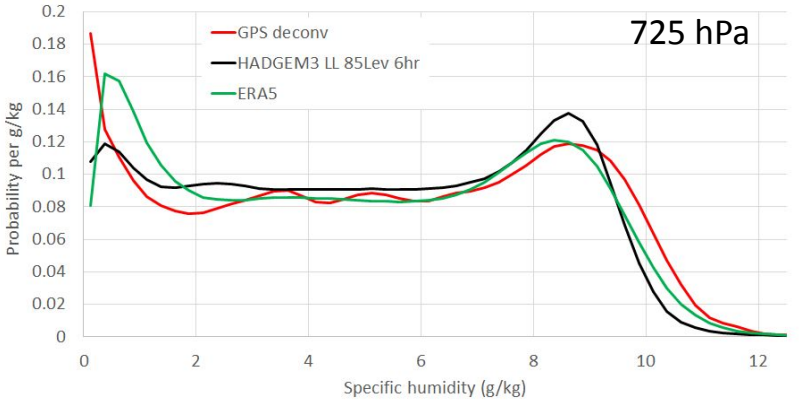
HadGEM3 scores as well as ERA5!

- Surprise: 6 hour HadGEM3 AMIP 2007 specific humidity histograms score as close to GPS RO deconvolved histograms as do the 1 hour ERA5 reanalyses for 2007.

P (mb)	HadGEM3 LL 85Lev 6hr	ERA5 37 lev 1hr
346	**19.0%**	19.0%
547	**17.6%**	18.2%
725	**14.8%**	14.0%
Avg	**17.1%**	17.1%







- ERA5 has assimilated an enormous number of observations,
- HadGEM3 is a free running climate model using specified SSTs

Questions:

- How can HadGEM3 match ERA5 performance without having assimilated any atmospheric observations?
- Is the MOHC model really that good?
- Are present water vapor observations not providing much constraints?