Machine learning for detection of climate extremes: New approaches to uncertainty quantification

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Climate & Ecosystem Sciences

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CASCADE

Atmospheric Rivers: Water resource vs Impacts

Lake Oroville Emergency Spillway: February 2017

image source: William Croyle, CA Dept. of Water Resources

Northern CA ‘8-station index’

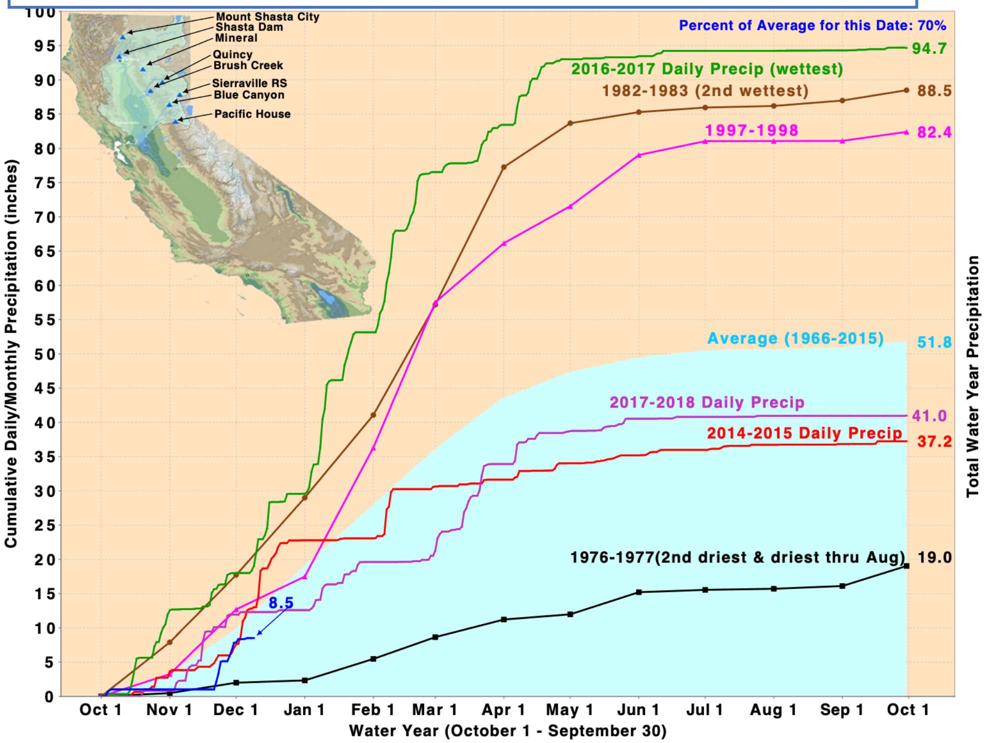
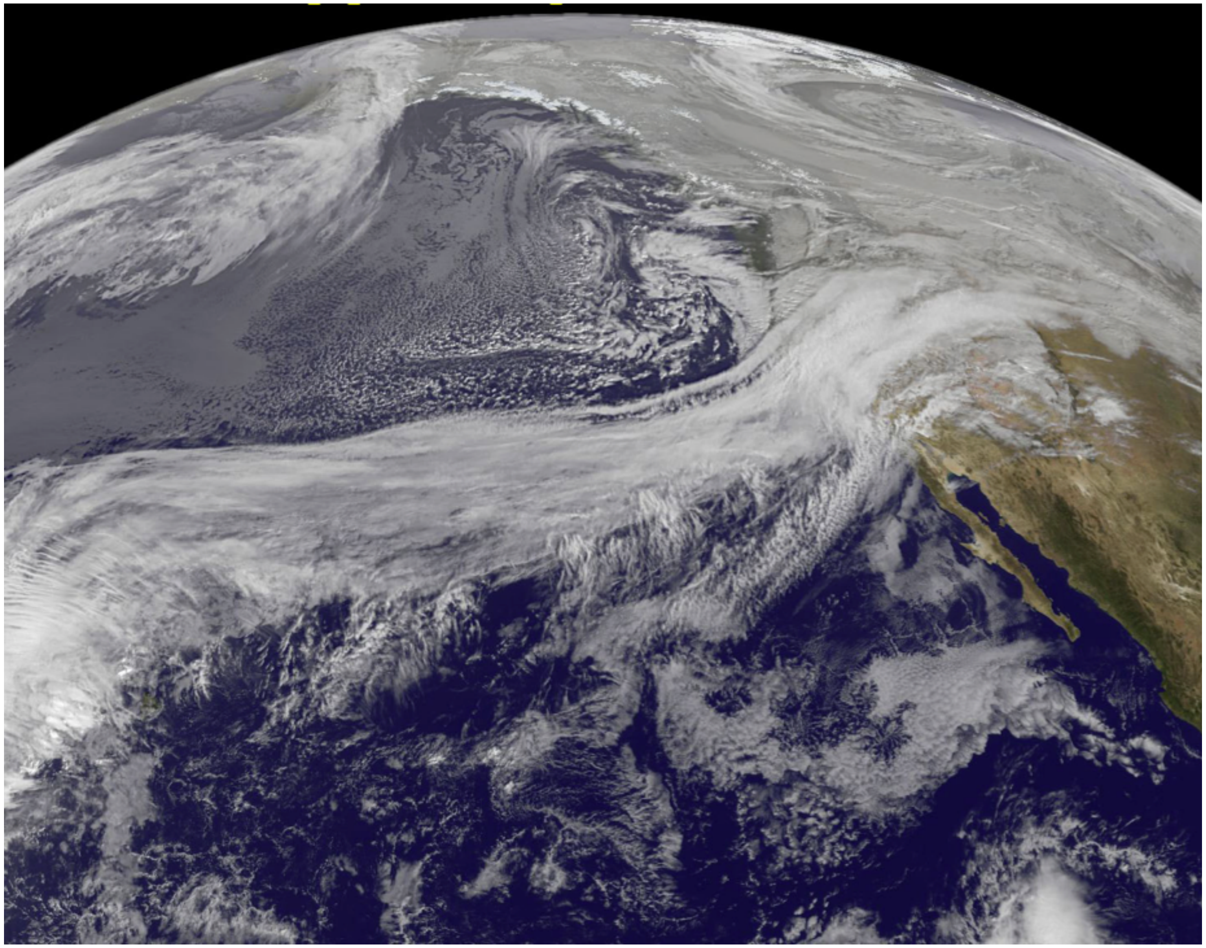


figure source: CA DWR, cedc.ca.water.gov

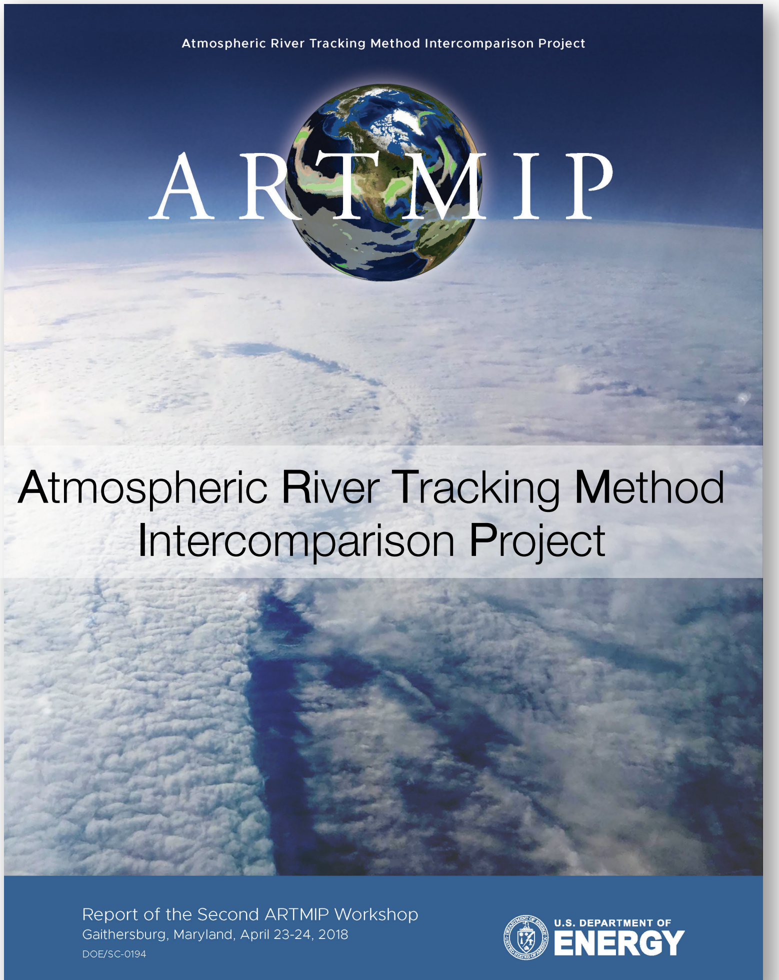


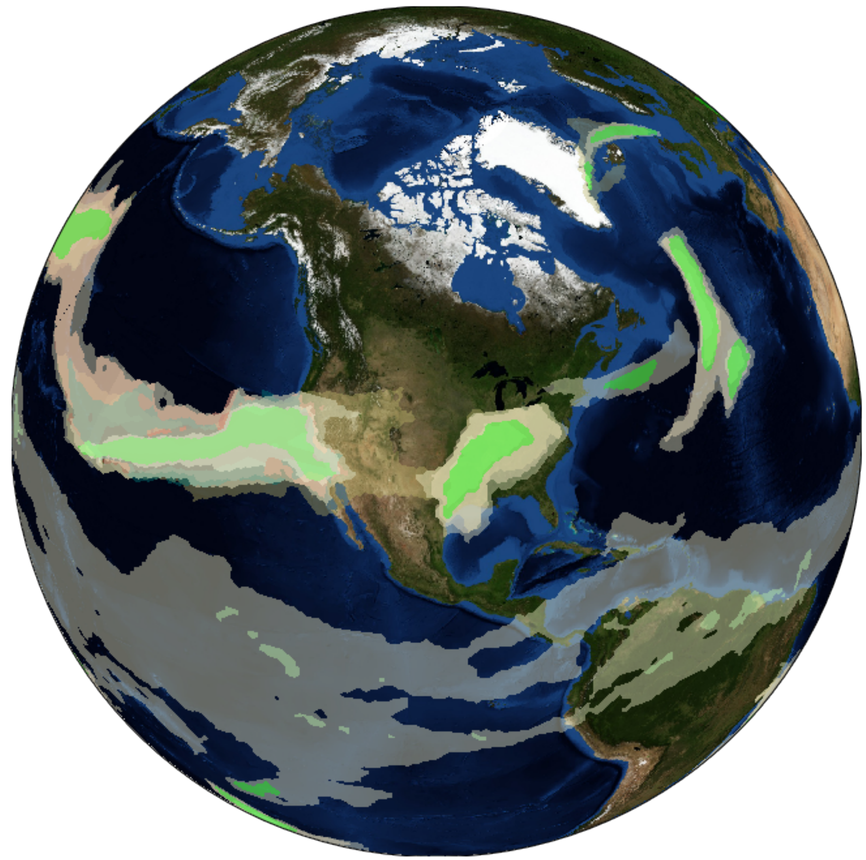
Atmospheric Rivers

- **Atmospheric Rivers (ARs):** "long, narrow, and transient corridors of strong horizontal water vapor transport…" *(AMS Glossary)*
- **Numerous quantitative definitions** but no theoretical or community-accepted definitions.

image source: NASA

How to identify ARs?

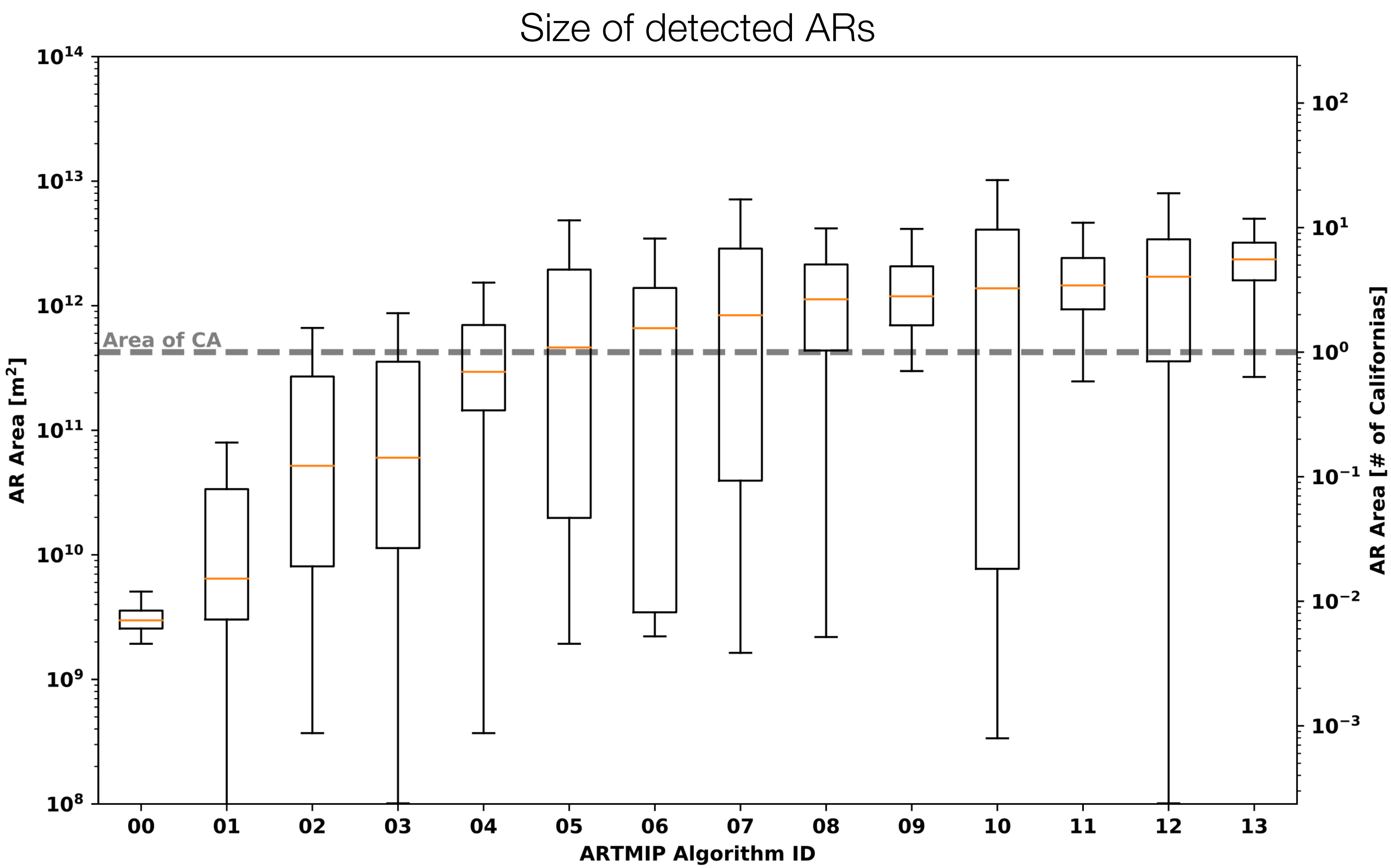




Agreement among AR detections, Feb. 7, 2017, 2019

figure source: Shields, Rutz, Leung, Ralph, Wehner, O'Brien, and Pierce (2019), Bull. Am. Met. Soc. *In Press*

A huge diversity among AR identification methods

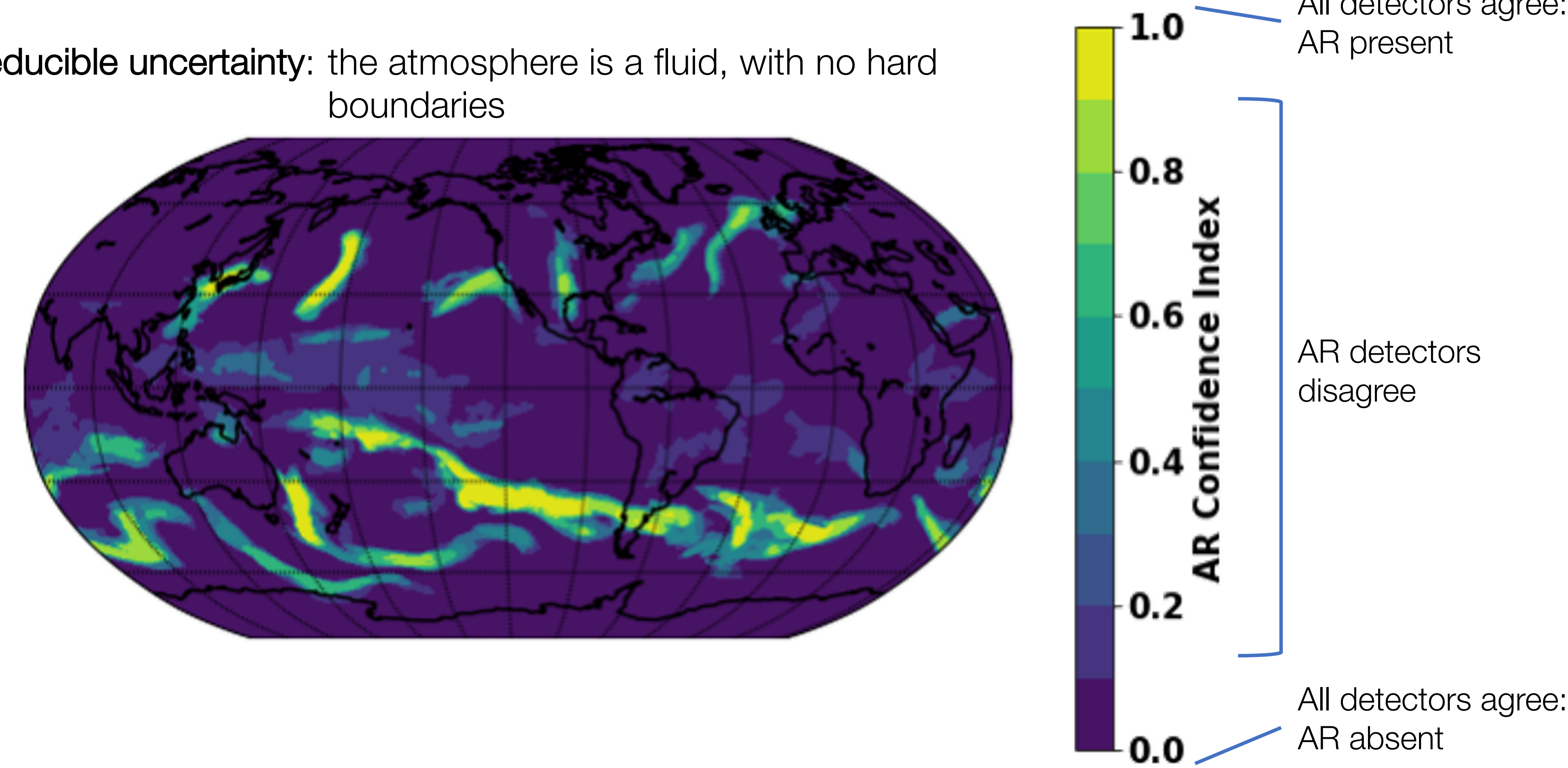


data source: Shields et al. (2018), Geosci. Mod. Dev., doi: 10.5194/gmd-11-2455-2018

Reducible vs irreducible uncertainty in weather event detection

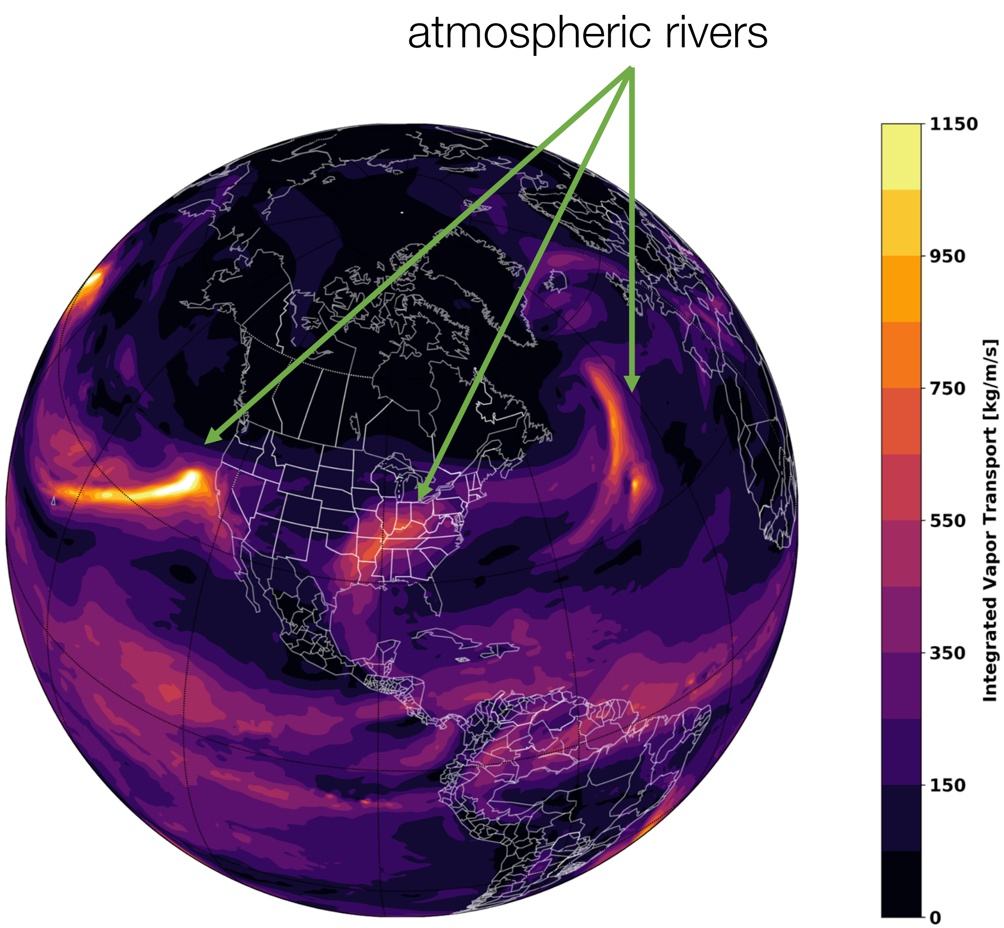
Reducible uncertainty: improving detection based on theory

Irreducible uncertainty: the atmosphere is a fluid, with no hard boundaries



data source: Shields et al. (2018), Geosci. Mod. Dev., doi: 10.5194/gmd-11-2455-2018

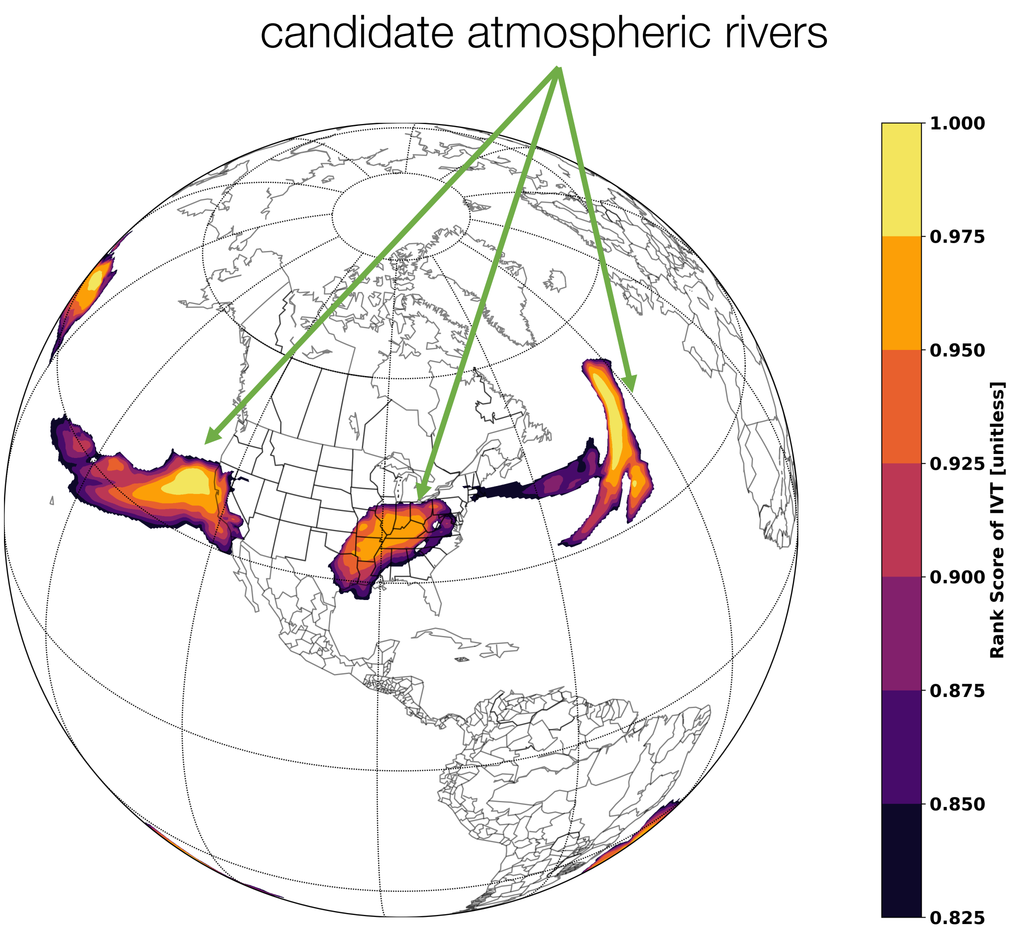
Quantifying and reducing uncertainty in an AR detector



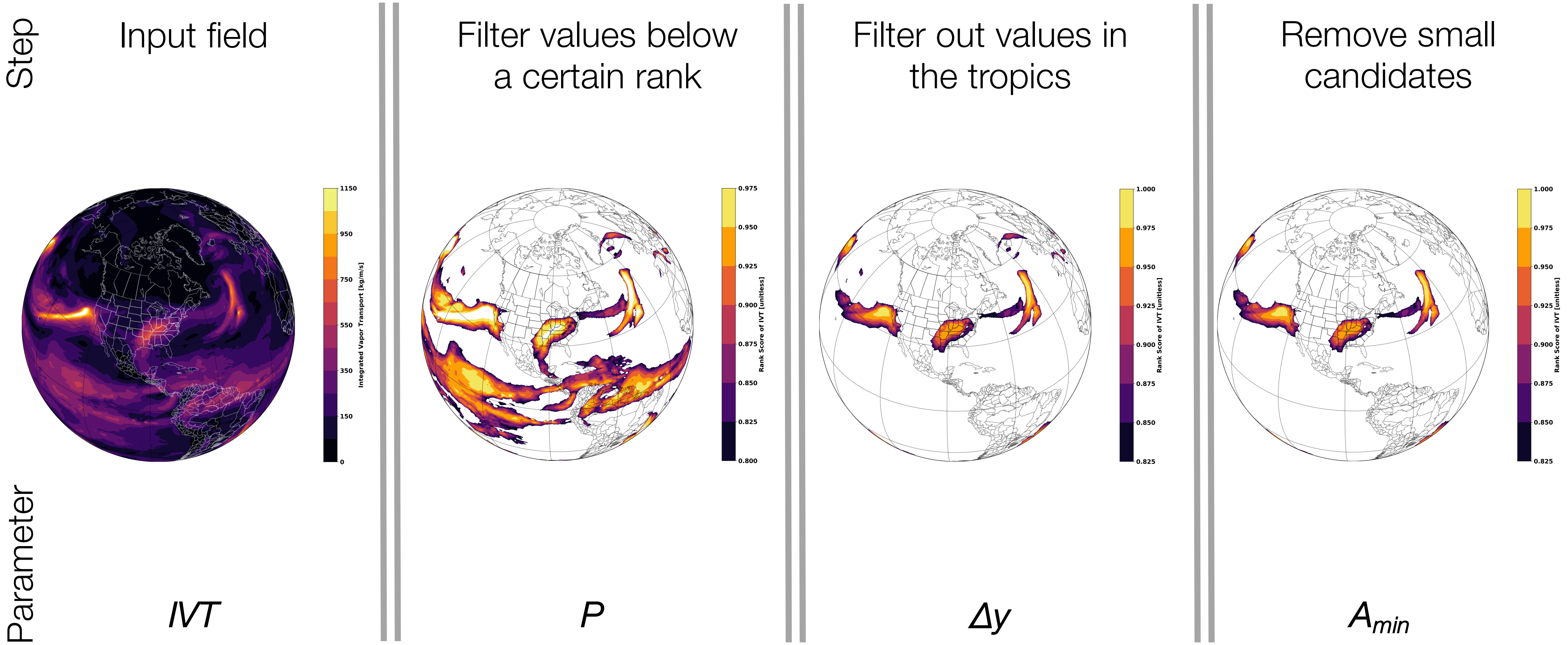
- Integrated **V**apor **T**ransport (**IVT**): the total transport of water in the atmosphere due to wind
- Atmospheric rivers are prominent in IVT fields.

data source: ERA5 Reanalysis

Quantifying and reducing uncertainty in an AR detector



- Pick out highest ranked values of IVT
- Filter out values w/in about 15° of equator
- Remove candidates that are too small



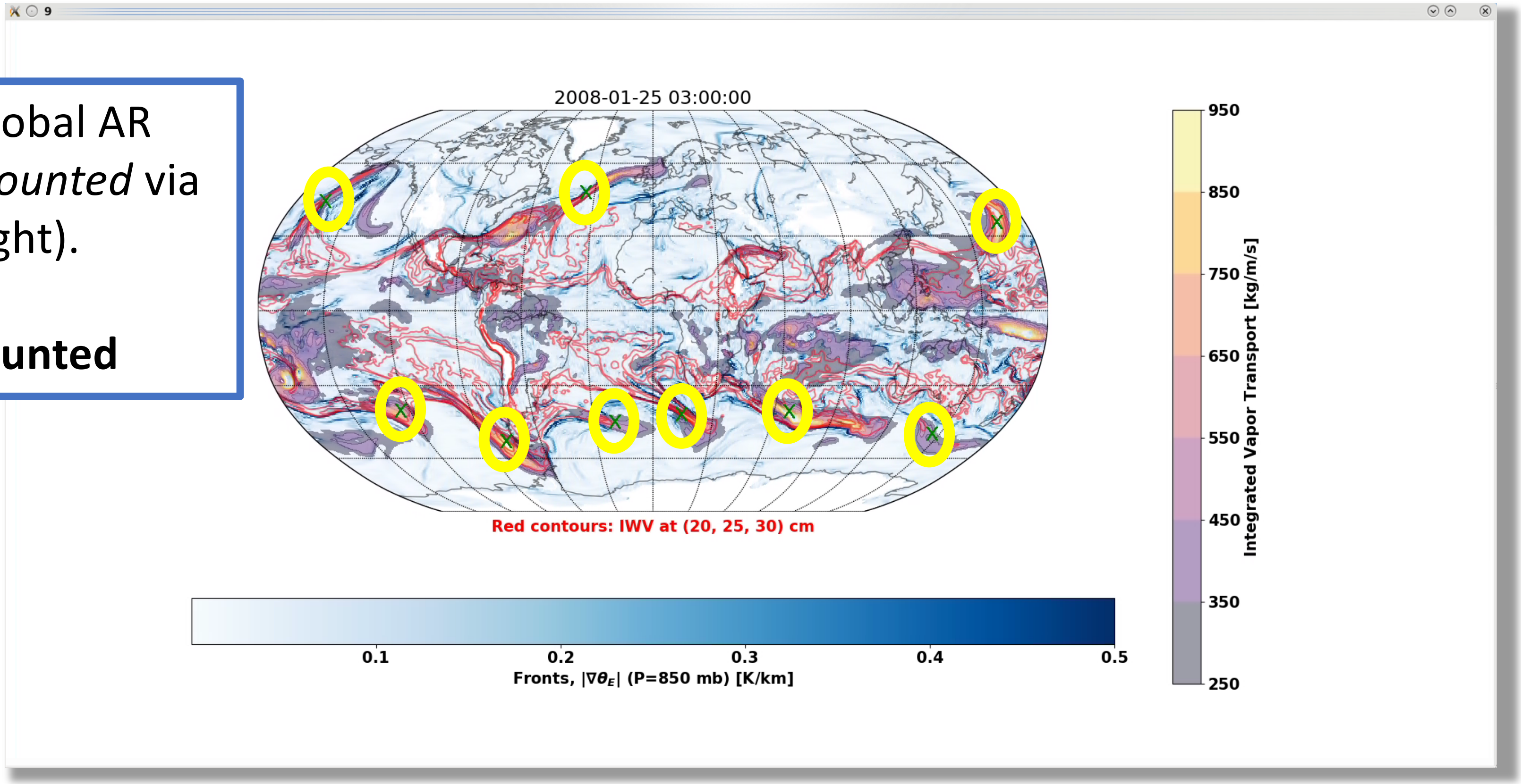
For a given AR detector that operates on an input field $\vec{\mathbf{Q}}$ (e.g., IVT), what are plausible settings for the AR parameters $\vec{\theta}$

Parameter	Description	Range	Candidate Prior(s)
P	Percentile threshold for IVT'	(0.8,0.999)	β, $\mathcal{U}$
A	Minimum area of contiguous region	$(1 \cdot 10^{11},\ 5 \cdot 10^{12})$ m^2	Lognormal, $\mathcal{U}$
Δy	Zonal width of tropical filter	(5, 25) °N	$\mathcal{U}$, Γ

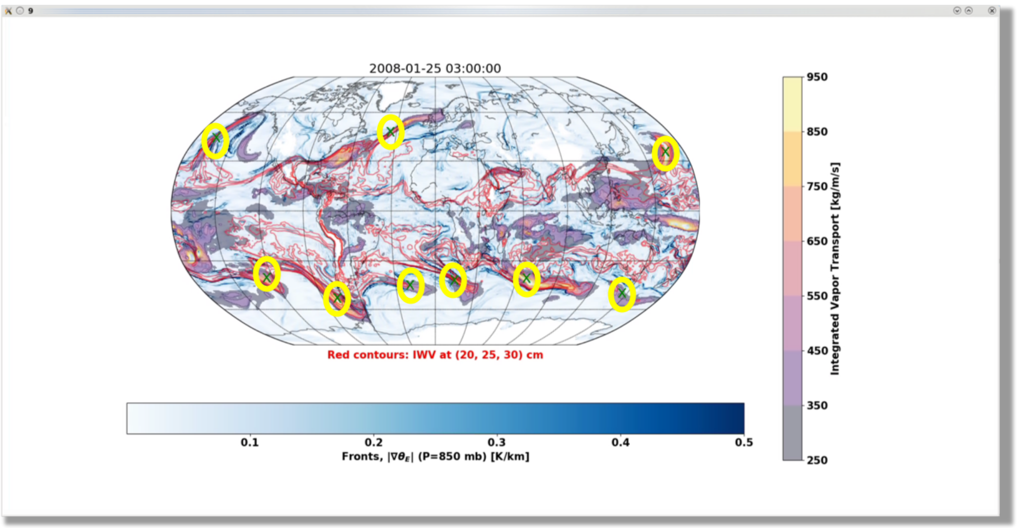
A database of global AR counts for objectively constraining AR detectors

A database of global AR counts – *hand counted* via a simple GUI (right).

> 10,000 ARs counted



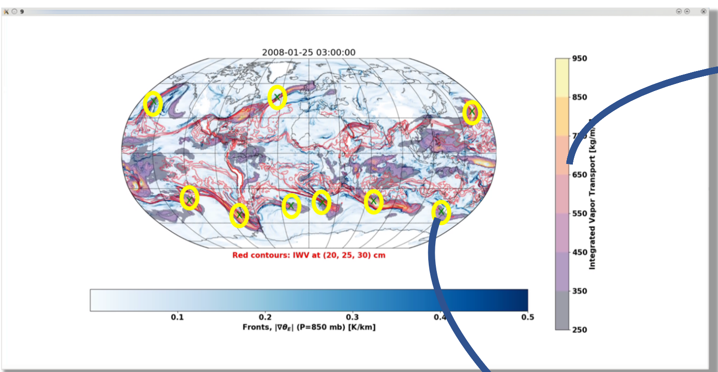
AR detector parameters: a Bayesian optimization problem



- What are plausible AR detector parameters, *given* the global AR counts?

- Given this plausible set of parameters, what is the probability of AR detection?

Formulation of the Bayesian AR detector



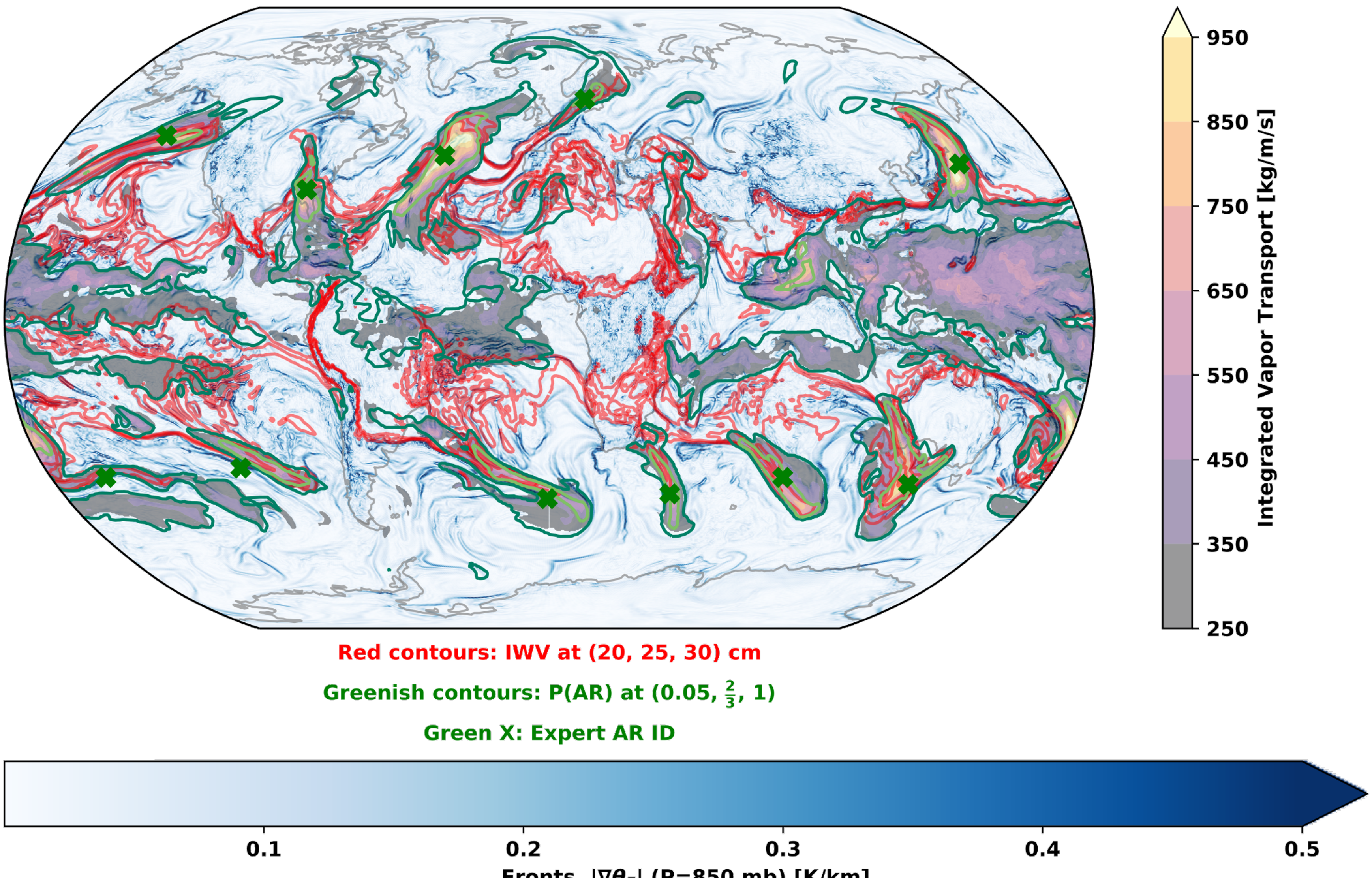
$$p(\vec{\theta} \mid \vec{N}, \vec{\boldsymbol{Q}}) \propto \frac{\left(\prod_{i=1}^{M} \mathcal{L}(N_i \mid \vec{\theta}, \boldsymbol{Q}_i) \right) \cdot p_\theta(\vec{\theta})}{p_N(\vec{N})}$$

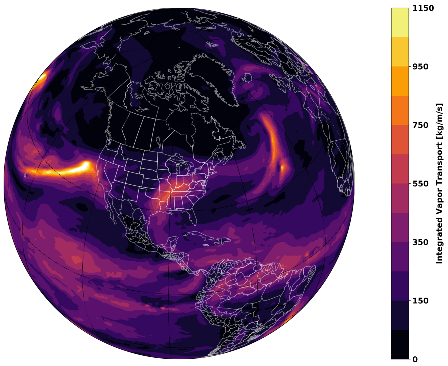
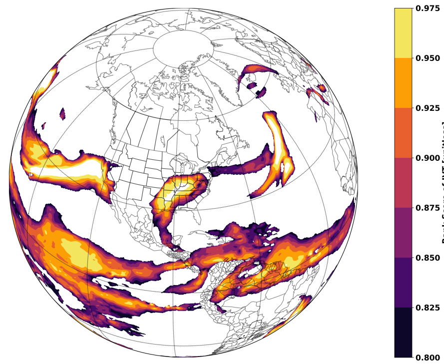
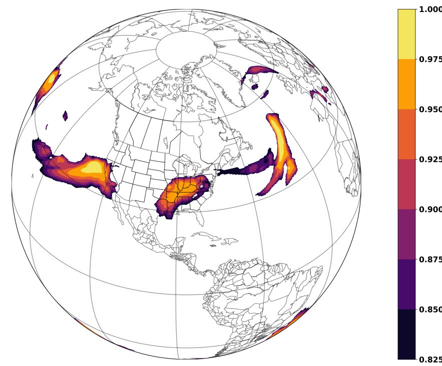
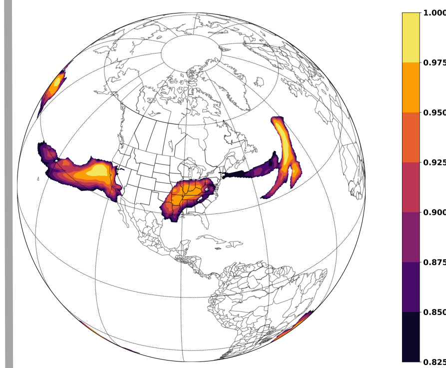
$$\mathcal{L}(N_i \mid \vec{\theta}, \boldsymbol{Q}_i) = \mathcal{N}(N_i \mid N_i', \sigma)$$

$$N_i' = f(\vec{\theta}, \boldsymbol{Q}_i)$$ *(f : the AR detector)*

$$p(\vec{\theta} \mid \vec{N}, \vec{\boldsymbol{Q}}) \propto \left(\prod_{i=1}^{M} \mathcal{N}\left(N_i \mid f(\vec{\theta}, \boldsymbol{Q}_i), \sigma \right) \right) \cdot p_\theta(\vec{\theta}) \cdot p_\sigma(\sigma)$$

A probabilistic AR detector

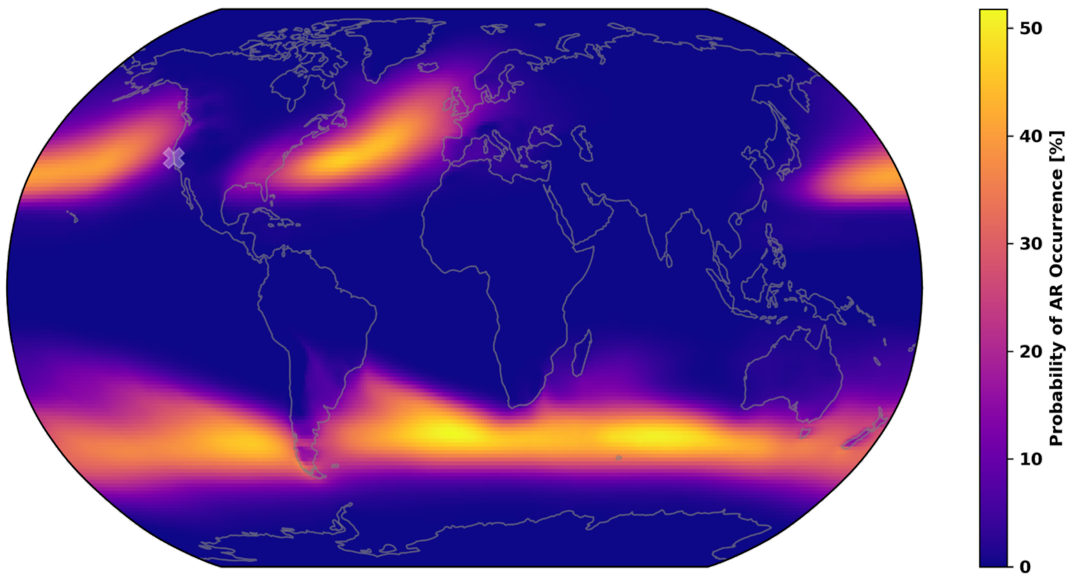


Step	Input field	Filter values below a certain rank	Filter out values in the tropics	Remove small candidates
				
Parameter	*IVT*	P	Δy	A_{min}

For a plausible set of AR detector parameters $\vec{\theta}$,
does uncertainty in $\vec{\theta}$ matter for uncertainty in trends?

Observed trends in ARs

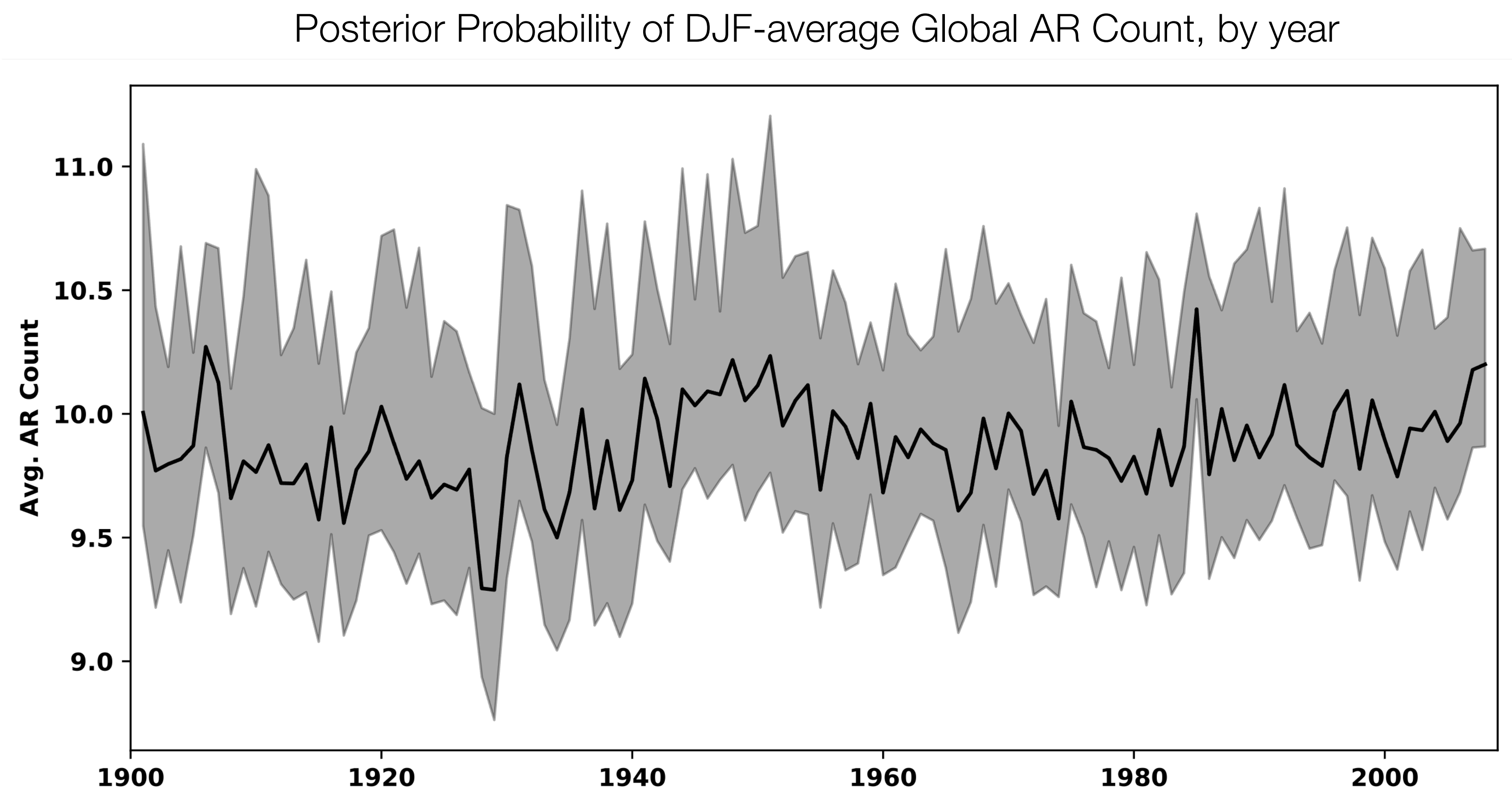
DJF-average Probability of AR Occurrence



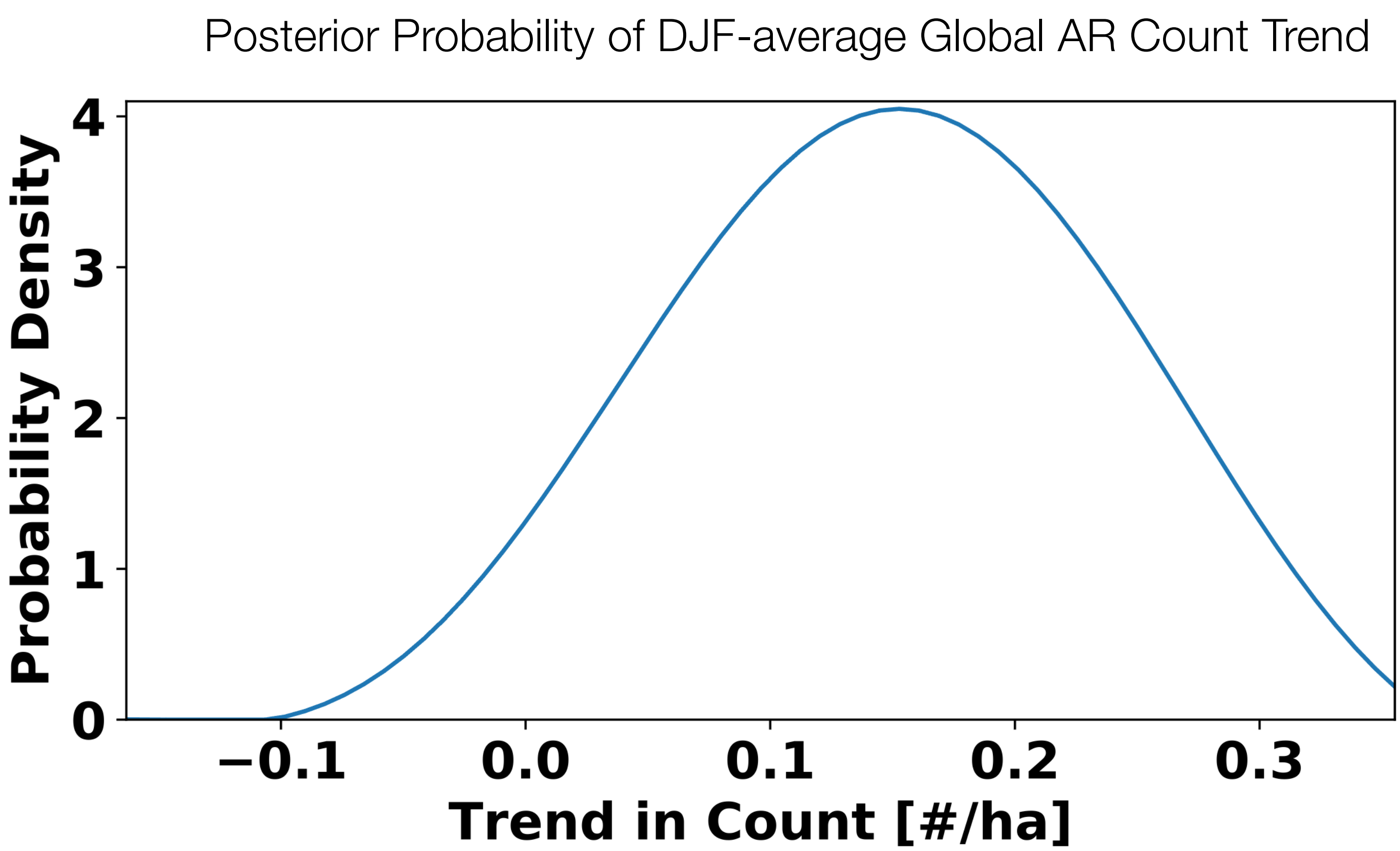
- Applied to 110 years of output:
  - ERA-20C Reanalysis
- Detected global AR counts for multiple AR parameter combinations

† European Centre for Medium-Range Weather Forecasts (2014), ERA-20C Project (ECMWF Atmospheric Reanalysis of the 20th Century), https://doi.org/10.5065/D6VQ30QG, Research Data Archive at the National Center for Atmospheric Research, Computational and Information Systems Laboratory, Boulder, Colo. (Updated daily.) Accessed 13 Jun 2018.

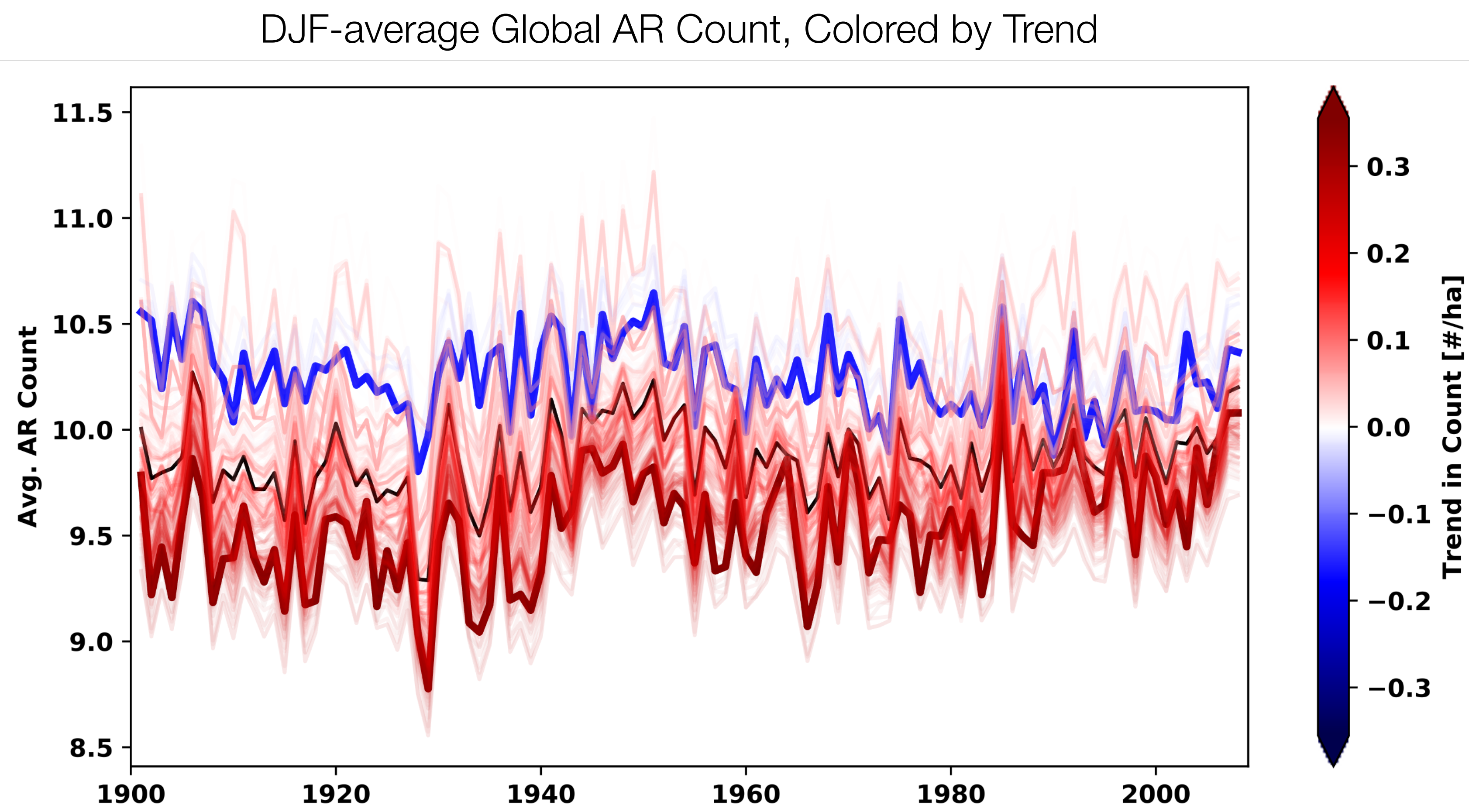
Global AR counts: 20th century



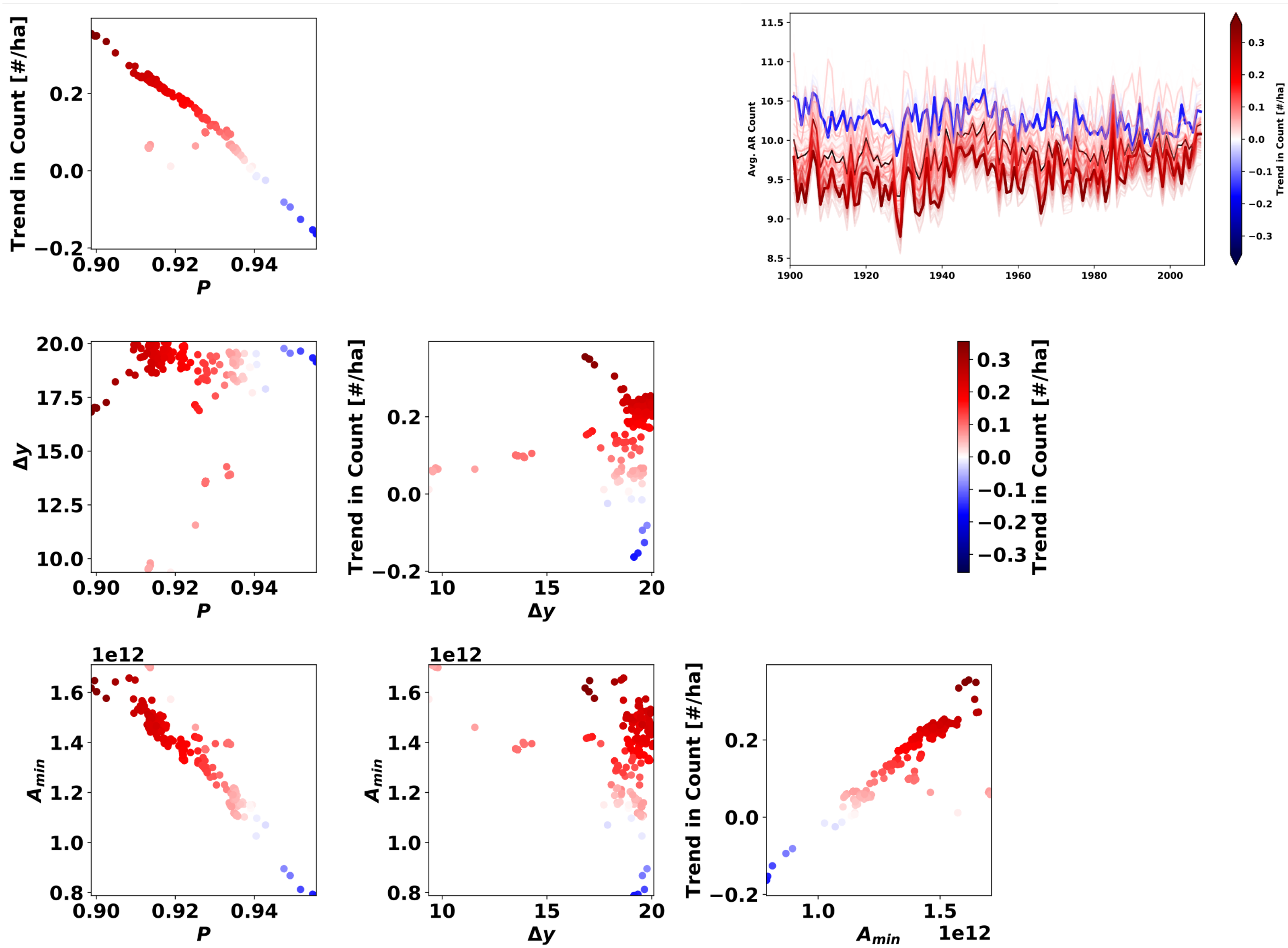
Positive and negative trends



Trends from MCMC samples



Trends Depend on Parameter



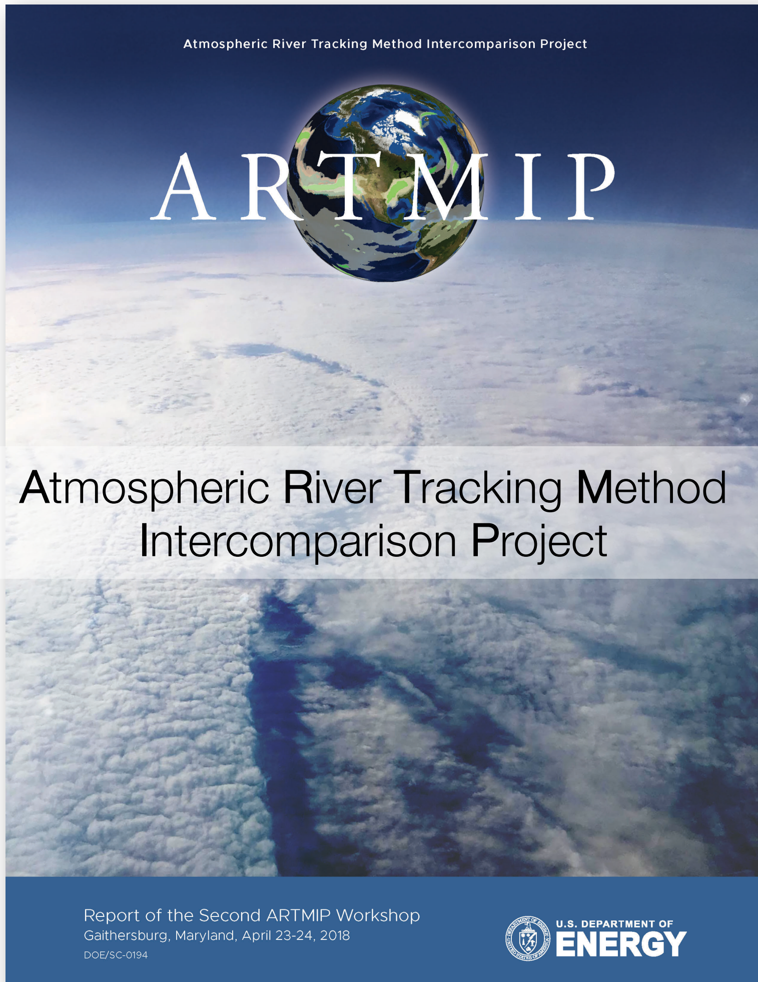
Does this affect how we interpret trends in the literature?

- *"increase in heavy and extreme precipitation…almost entirely due to ARs*"
  Gershunov, A. *et al.* Precipitation regime change in Western North America: The role of Atmospheric Rivers. *Sci. Rep.* **9**, 9944 (2019).

- *"there will be ~10% fewer ARs in the future, the ARs will be ~25% longer, ~25% wider"*
  Espinoza, V., Waliser, D. E., Guan, B., Lavers, D. A. & Ralph, F. M. Global Analysis of Climate Change Projection Effects on Atmospheric Rivers. *Geophys. Res. Lett.* **45**, 4299–4308 (2018).

- "*AR frequency broadens equatorward of peak historical frequency"*
  Payne, A. E. & Magnusdottir, G. An evaluation of atmospheric rivers over the North Pacific in CMIP5 and their response to warming under RCP 8.5. *J. Geophys. Res.* **120**, 11,173-11,190 (2015).

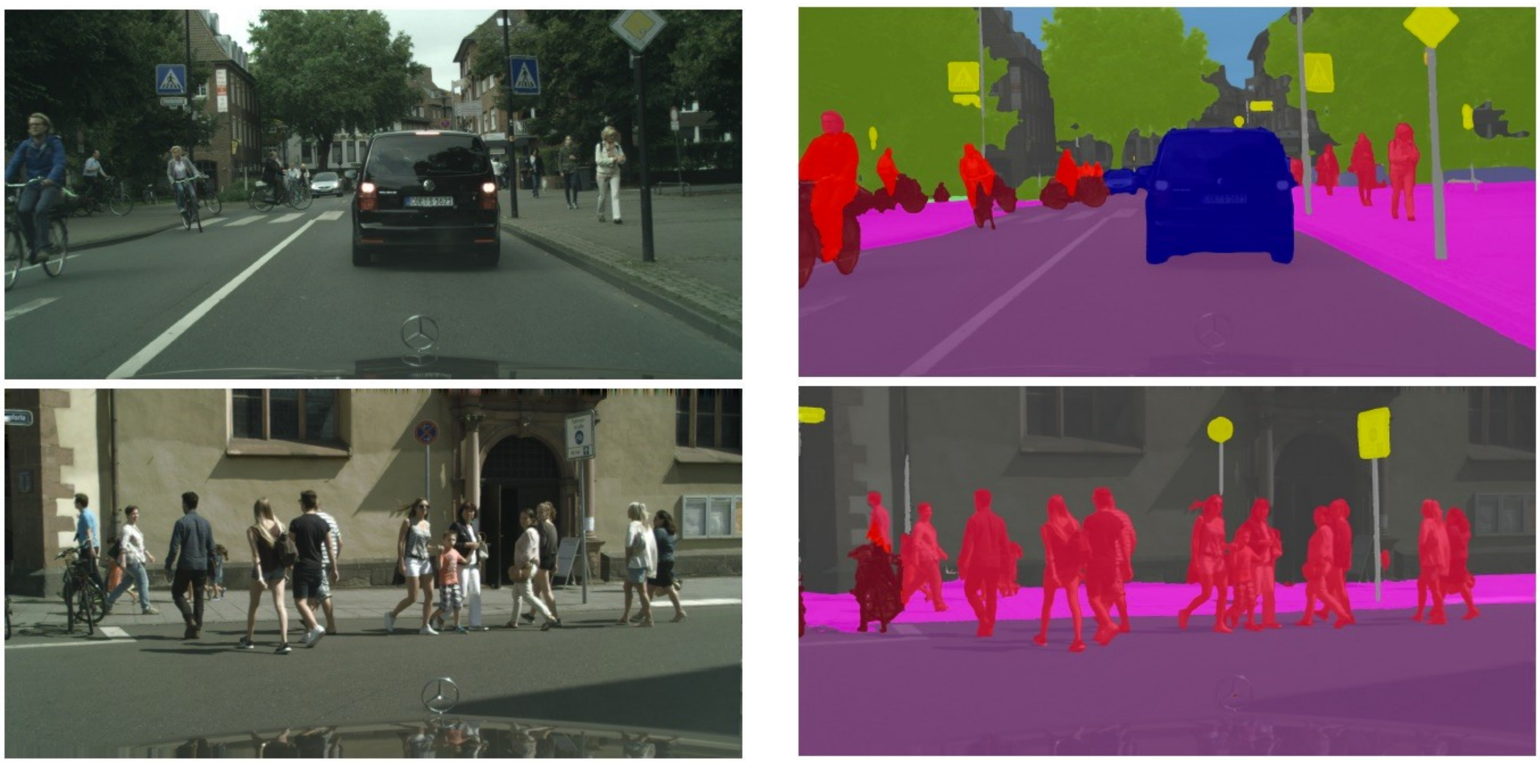
ARTMIP: producing several papers on AR uncertainty



Summary

- Detector uncertainty matters for our *qualitative* understanding of climate change
- This is an issue for multiple weather phenomena:
  - Tropical Cyclones
  - Extratropical Cyclones
  - Atmospheric Rivers
  - Likely others…?
- Bayesian methods + expert input can help quantity detector uncertainty

Machine Learning (Computer Vision) for Detecting ARs

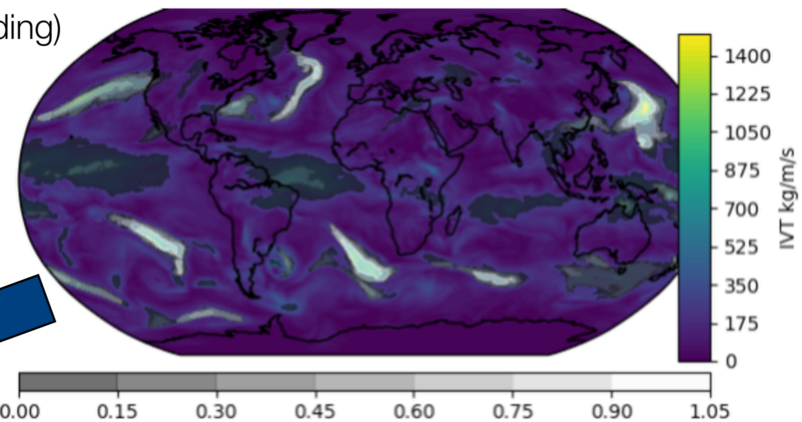


People, bicycles, sidewalk, signposts, roads, and cars are all recognized

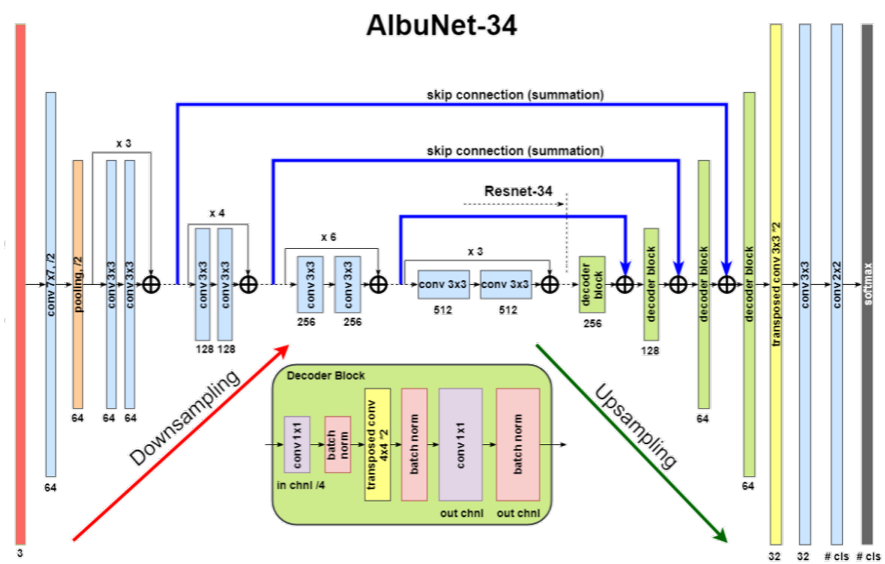
Source: Kundu, et al. Feature Space Optimization for Semantic Video Segmentation, 2016.

Machine learning for probabilistic AR detection

Ground Truth
(white shading)



Deep learning method

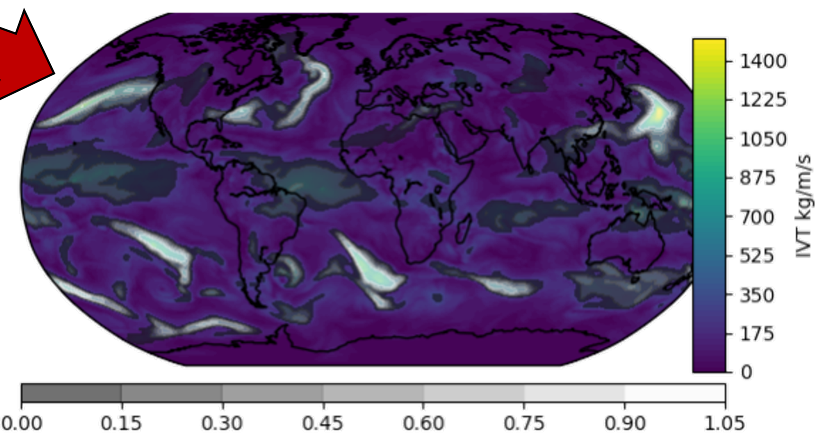


Input Field: IVT

figure source: courtesy of Ankur Mahesh, UCB undergraduate researcher

Output Field: AR Prob.

figure source: Shvetz et al. (2018), Proceedings of 17th IEEE ICMLA



Machine learning method output
(white shading)

Thank you!

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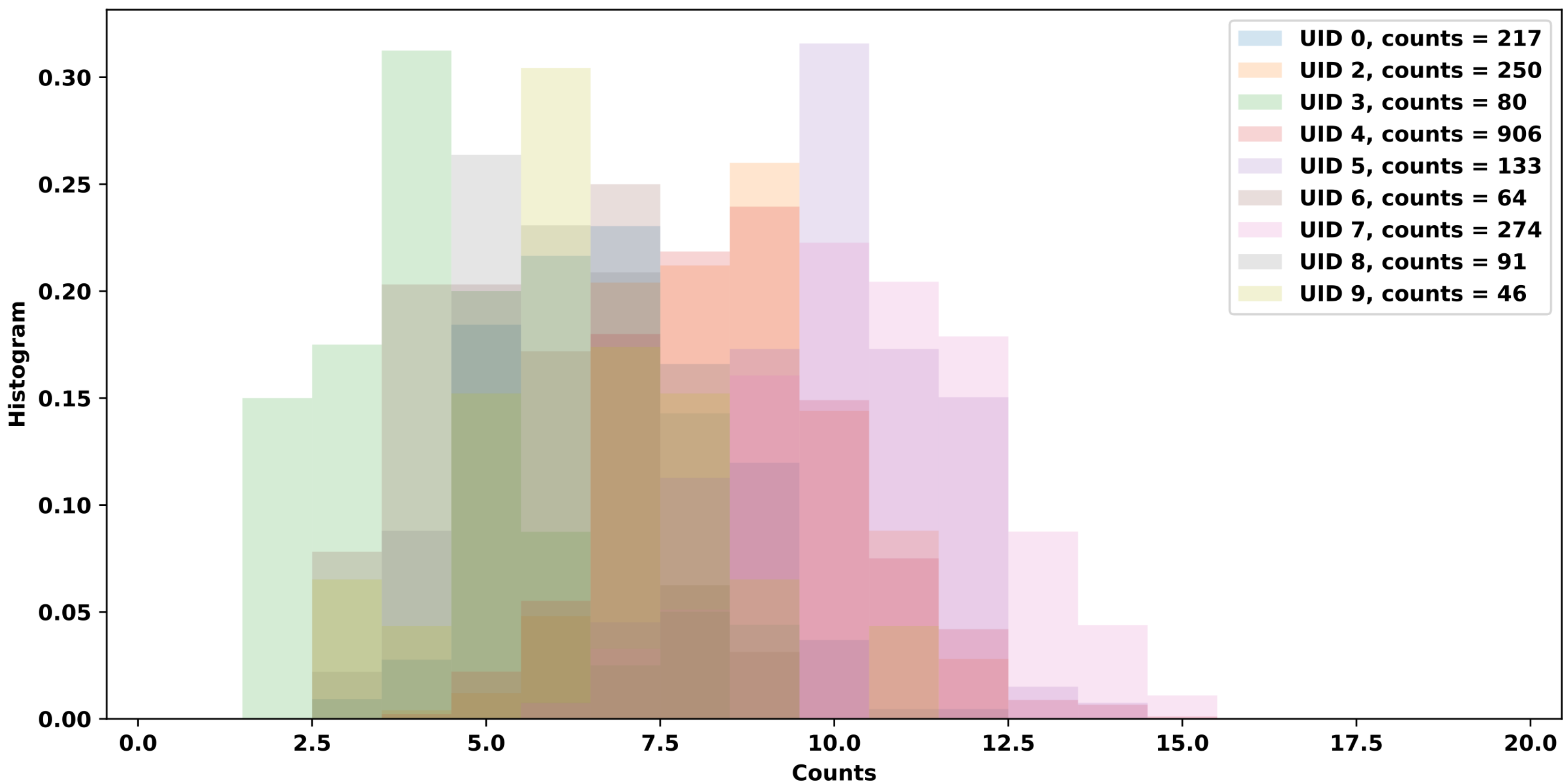
Huge uncertainty in expert evaluation of ARs



Comparing expert counters