Using Spaceborne Sensors to Detect Hailstorms and Build Climatologies

Dr. Daniel J. Cecil

NASA Marshall Space Flight Center

Daniel.J.Cecil@nasa.gov

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Goal: Overcome the artificial inhomogeneities in ground-based reporting of severe thunderstorms

- Ground-based reporting is inconsistent across political / administrative boundaries, and eras
  - Large nation-to-nation differences in how reliably events are reported, how those reports are compiled, and the standards used for defining which events are worthy of report (e.g., do ice particles several mm in diameter count, or only ~2+ cm diameters?)
  - Differences between NWS forecast offices in USA (some aggressively seek storm reports, some do not; whether or not a warning had been issued likely matters)
  - Diligence with reporting depends in part on local vulnerability of agriculture and infrastructure
  - Population density
  - Standards and practices change over time

Ground-based hail climatologies

Not many (global) in literature

Reporting standards vary

Graupel, small hail, or large hail?

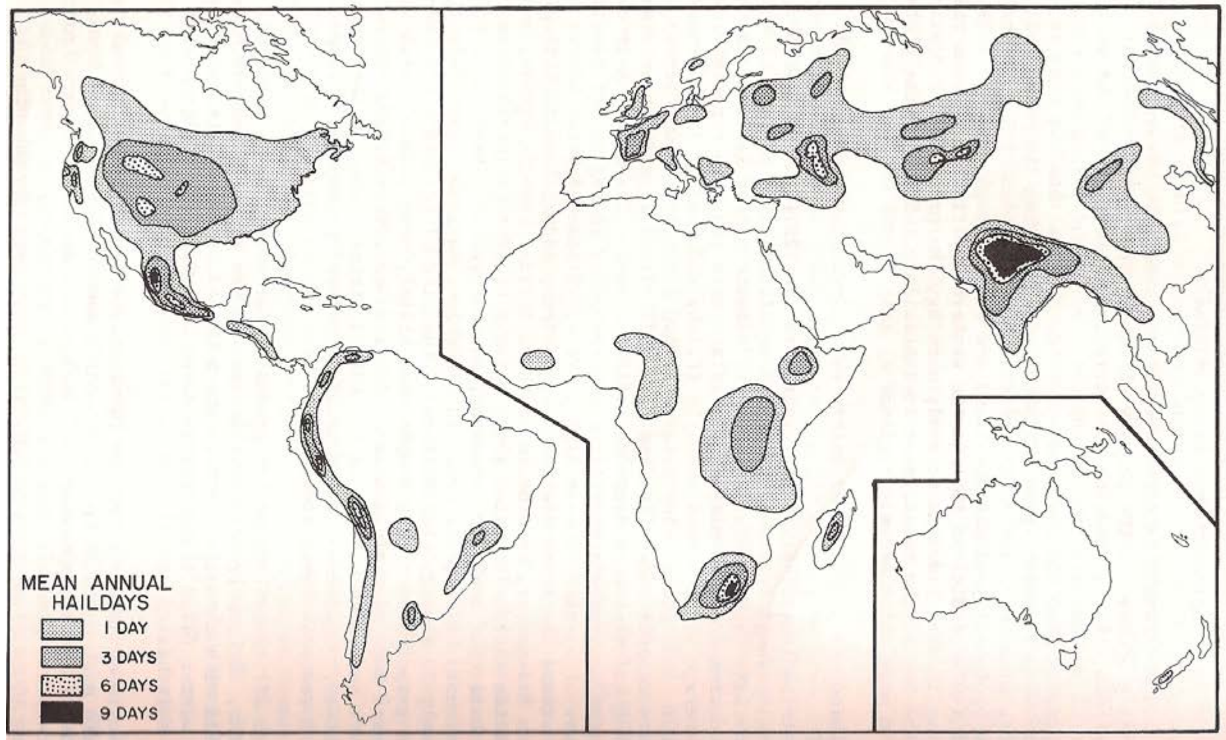
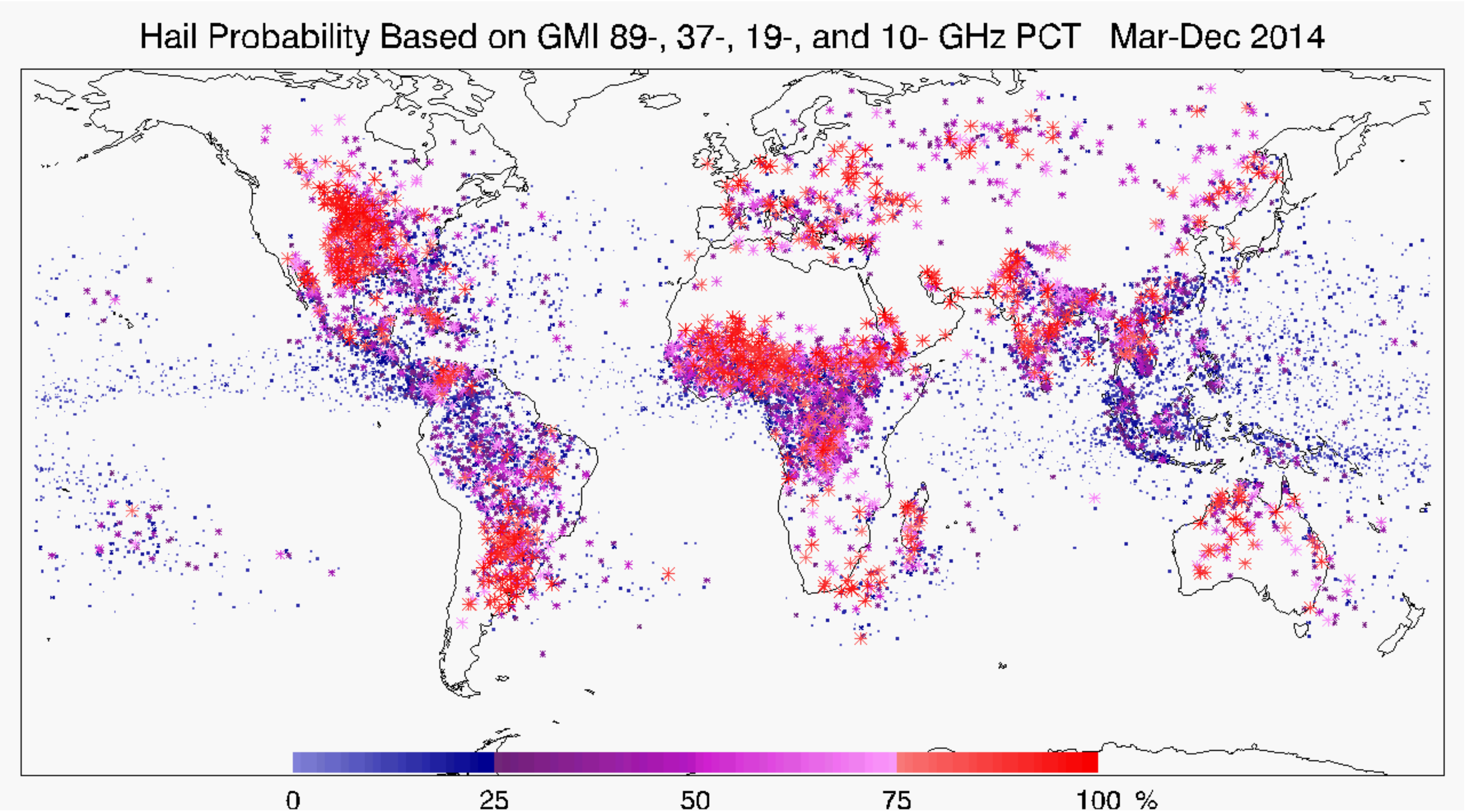


Figure 22.--Mean annual frequency of hail at a point (Frisby and Sansom, 1967).

Approach: Use satellite measurements to apply uniform measurement techniques

- Strengths:
  - Diverse regions are measured by the same sensor, with uniform measurement standard
  - Can compile near-global maps using consistent approach across regions
- Weaknesses:
  - Measurements are only ***proxies*** for hail, or for storm severity
  - Training data for the proxies are subject to the limitations of ground-based measurements
  - Accuracy of the proxies must vary with meteorological environment, but that cannot be robustly quantified for the full range of environments

Example: GPM 37 GHz used to assess likelihood of severe hail in individual storms



Note: This map used ~9 months of data, skewed toward N. Hemisphere (Mar-Dec 2014)

Types of Satellite Measurements

- **Radar (TRMM, GPM):**
  - ~250-m vertical resolution, ~4-km horizontal resolution
  - ~250-km wide swath, few satellites, so limited coverage
  - Ku-band – attenuation is an issue
- **Passive Microwave (TRMM, GPM, SSMI, AMSR, etc):**
  - Related to *column-integral* of ice mass
  - Lower frequencies (19, 37 GHz) have greater sensitivity to larger particles
  - Higher frequencies have better spatial resolution
    - 85 GHz: ~5x7 km 37 GHz: ~9x15 km 19 GHz: ~11x18 km (for GMI)
- **Overshooting Tops (Vis, IR sensors)**
  - Measurement *at cloud top*, so rely on correlation between very high altitude updraft and potential severe weather far below
  - Frequent sampling by GEO sensors
- **Lightning**
  - Related to mixed-phase ice mass, updraft strength, updraft volume
  - Frequent sampling by new-generation GEO sensors

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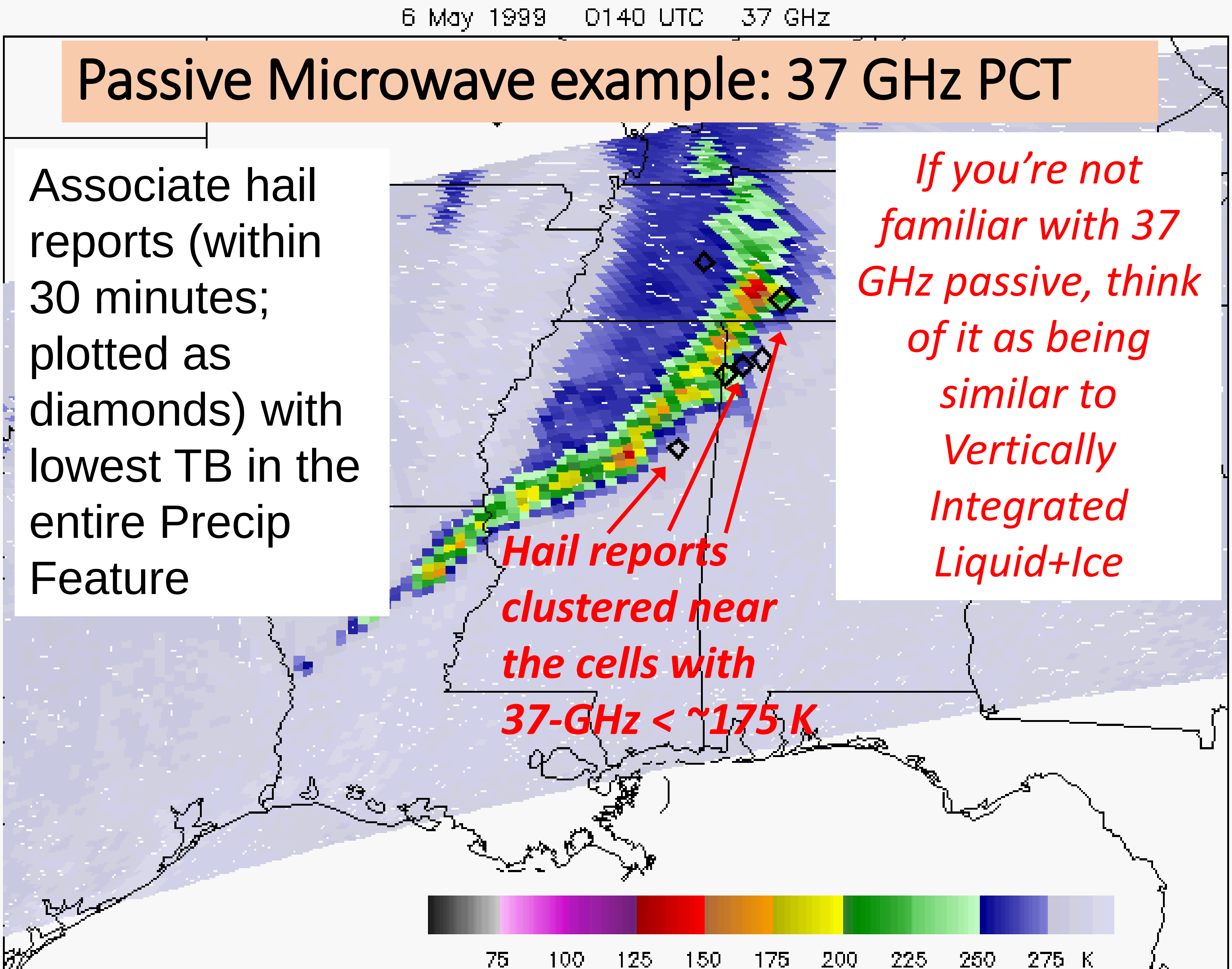
I'll focus on these two because I am most familiar with them, and they seem most direct

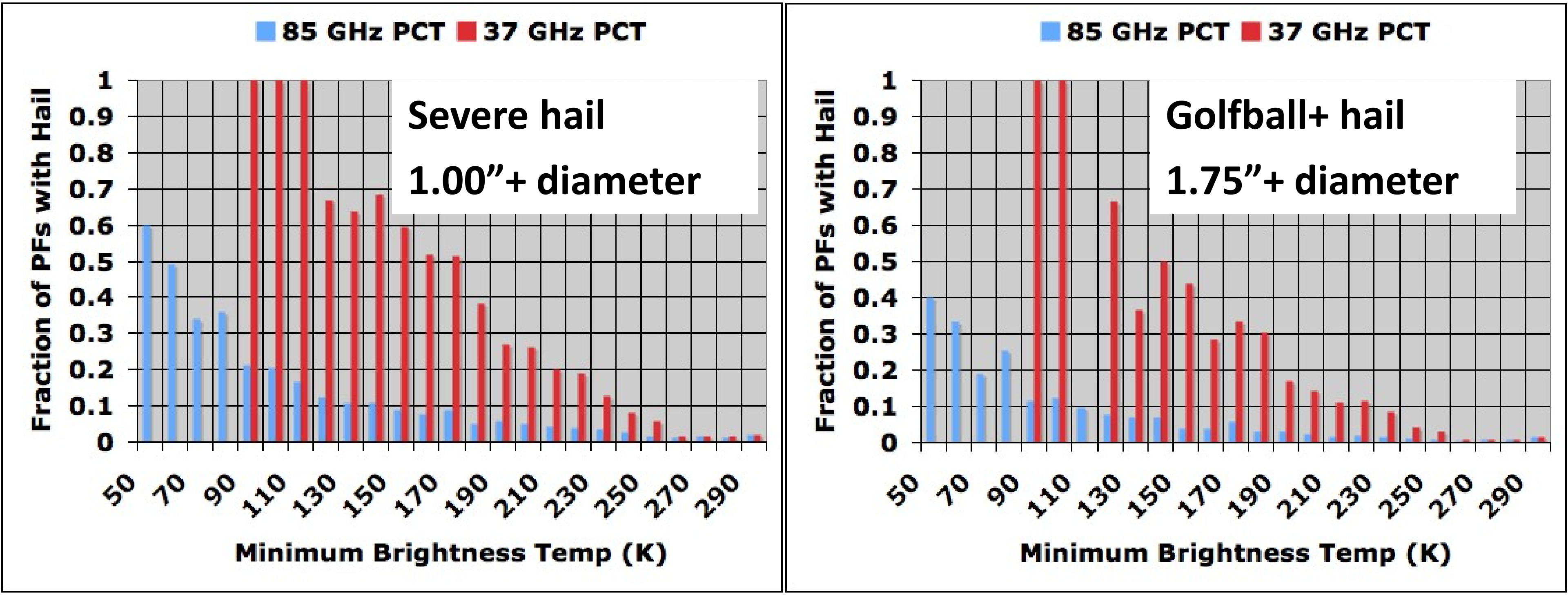
Passive Microwave example: 37 GHz PCT

Associate hail reports (within 30 minutes; plotted as diamonds) with lowest TB in the entire Precip Feature

If you're not familiar with 37 GHz passive, think of it as being similar to Vertically Integrated Liquid+Ice



Probability of Hail vs TB (Cecil 2009 JAMC)



37 GHz ~ 210 K: ~1/4 chance severe hail

37 GHz ~ 180 K: ~1/2 chance severe hail

37 GHz ~ 150 K: ~2/3 chance severe hail

85 GHz gives lower probabilities than 37 GHz

Variety of empirical approaches

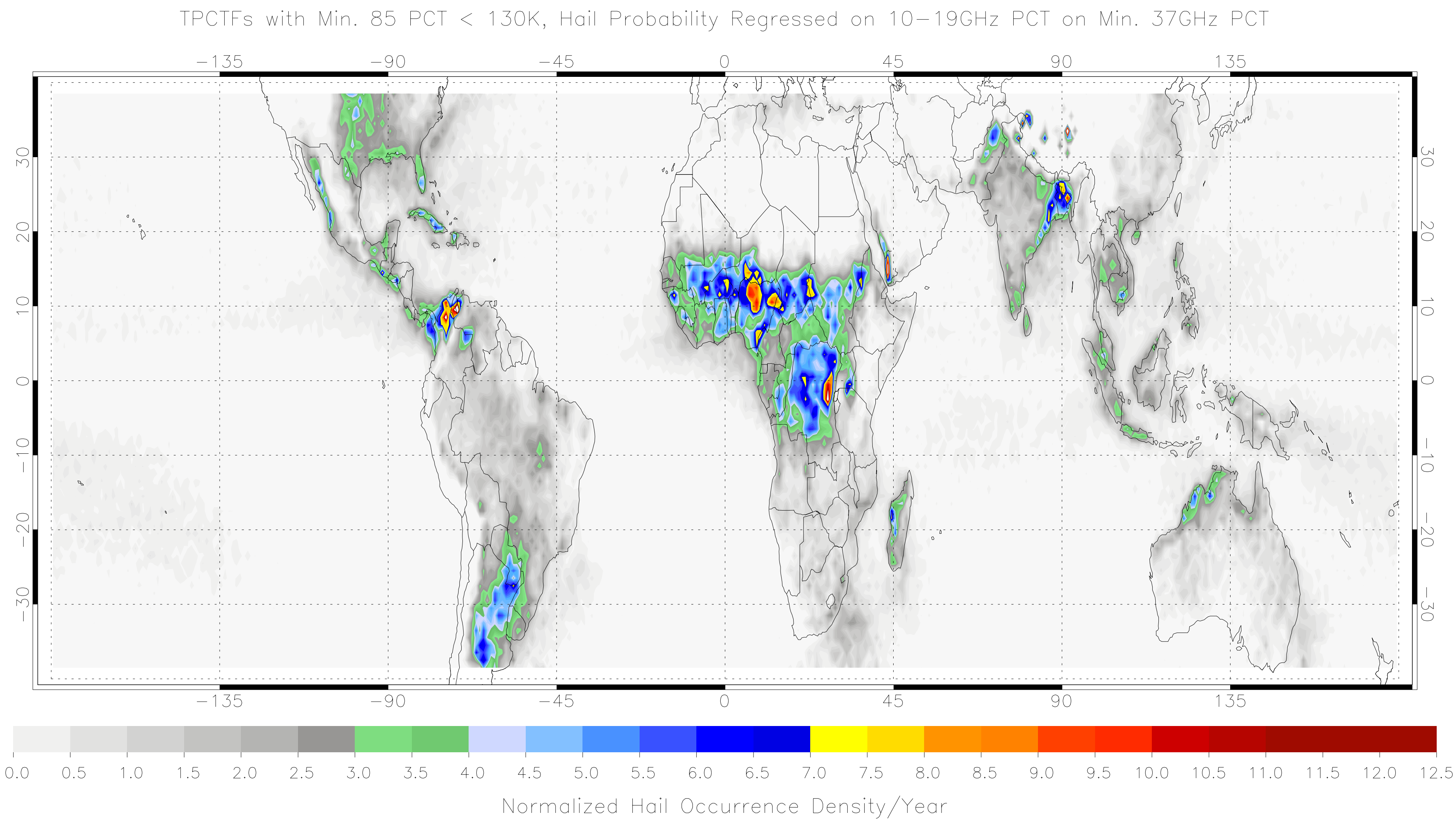
Considerations:

- Train against large hail or small hail (is there a size threshold?)
- Hail at the surface, aloft, or no distinction? *(doesn't matter for very large hail)*
- Is training set globally representative? *(no, it never is!)*
- Value high probability of hail / low False Alarm Rate?
    - Or high Probability of Detection (POD), at the expense of False Alarm Rate (FAR)?
    - Or a skill score combining both?
- What is the measurement really sensitive to?
    - Some particular altitude, or a column-weighted value?
    - Preferred particle sizes?
- Want to minimize unrealistic patterns of false alarms (e.g., ITCZ)

Consequences:

- POD, FAR likely depend on storm type -> meteorological environment -> geographic location
- Low POD probably biases against conditions with marginal hail cases
- High FAR probably biases in favor of non-severe strong/deep convection
- Resulting maps may depict thunderstorm distribution, more than hail distribution

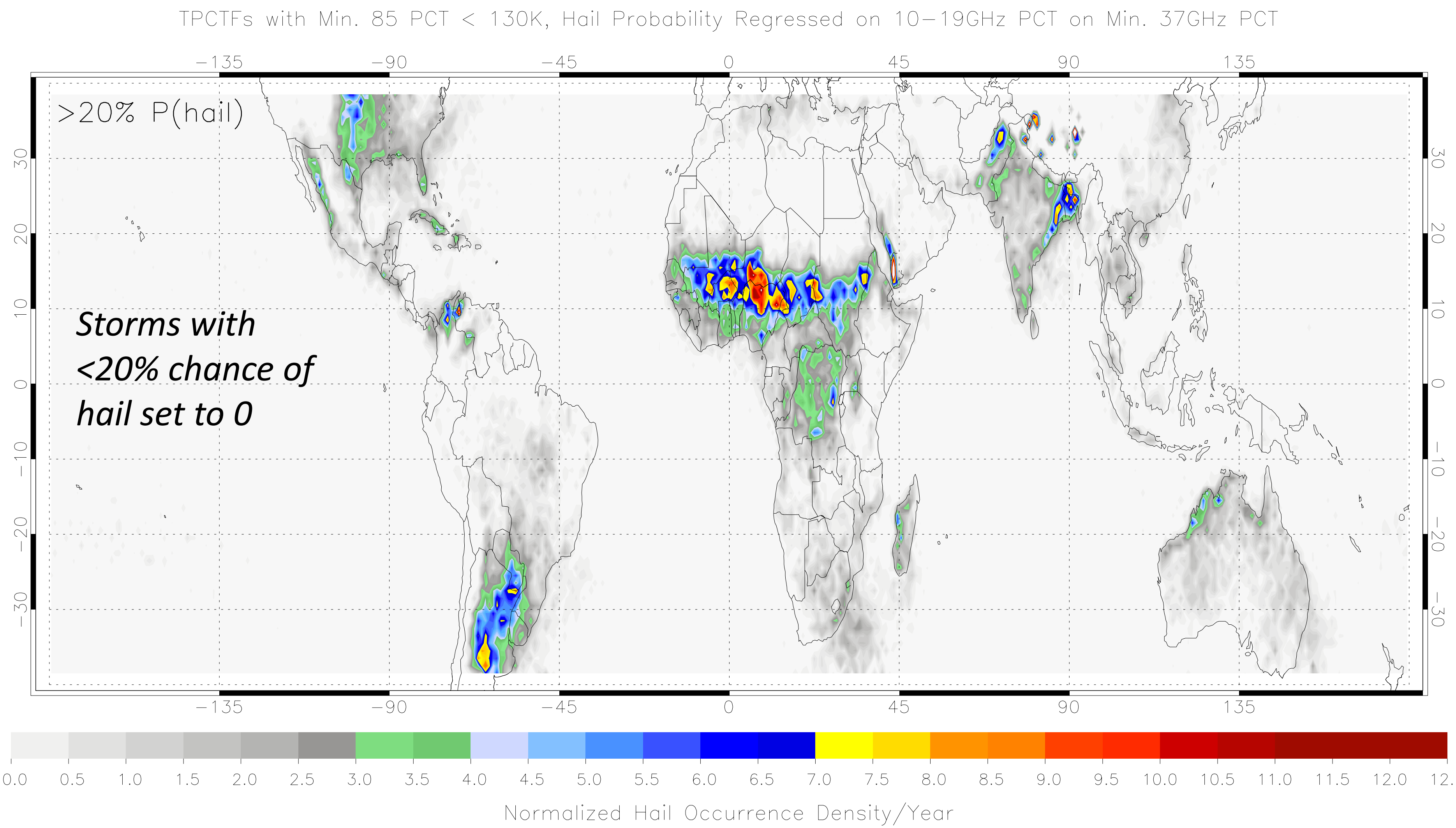
Higher POD, but Higher FAR



Accumulated Hail Probabilities based on TRMM 10, 19, 37, 85 GHz (1998-2014)

Bang and Cecil (2018, in preparation)

Lower POD, but Lower FAR



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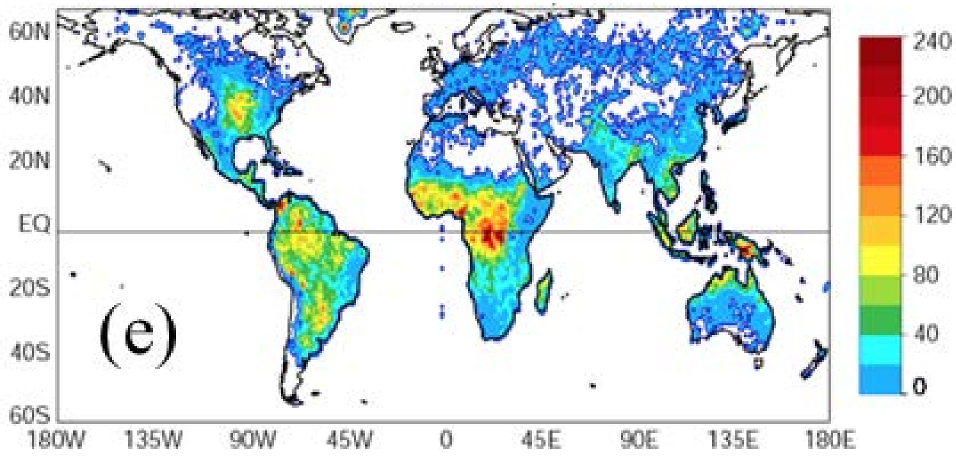
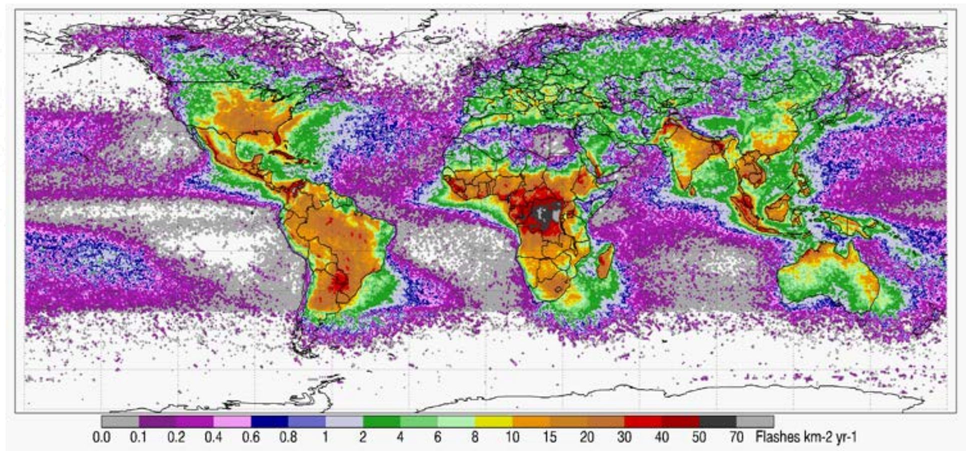
Bang and Cecil (2018, in preparation)

AMSU-retrieved Hail, compared to Lightning

AMSU Hail, 2008; Ferraro et al. 2015 *Atmos. Res.*



Lightning Flash Rate, 1995-2014; Cecil et al. 2014 *Atmos. Res.*

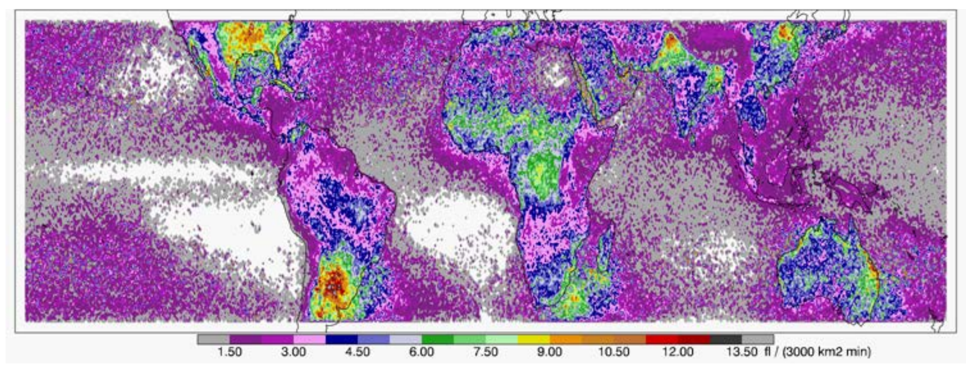


AMSU channels are about 2-6 mm wavelength, so they have strong response to graupel, not only to hail.

AMSU hail map looks right in the USA where it was trained, but looks like a map of lightning flash rate in much of the rest of the world.

- *E.g., thunderstorms occur often in Maritime Continent, but especially strong storms do not.*

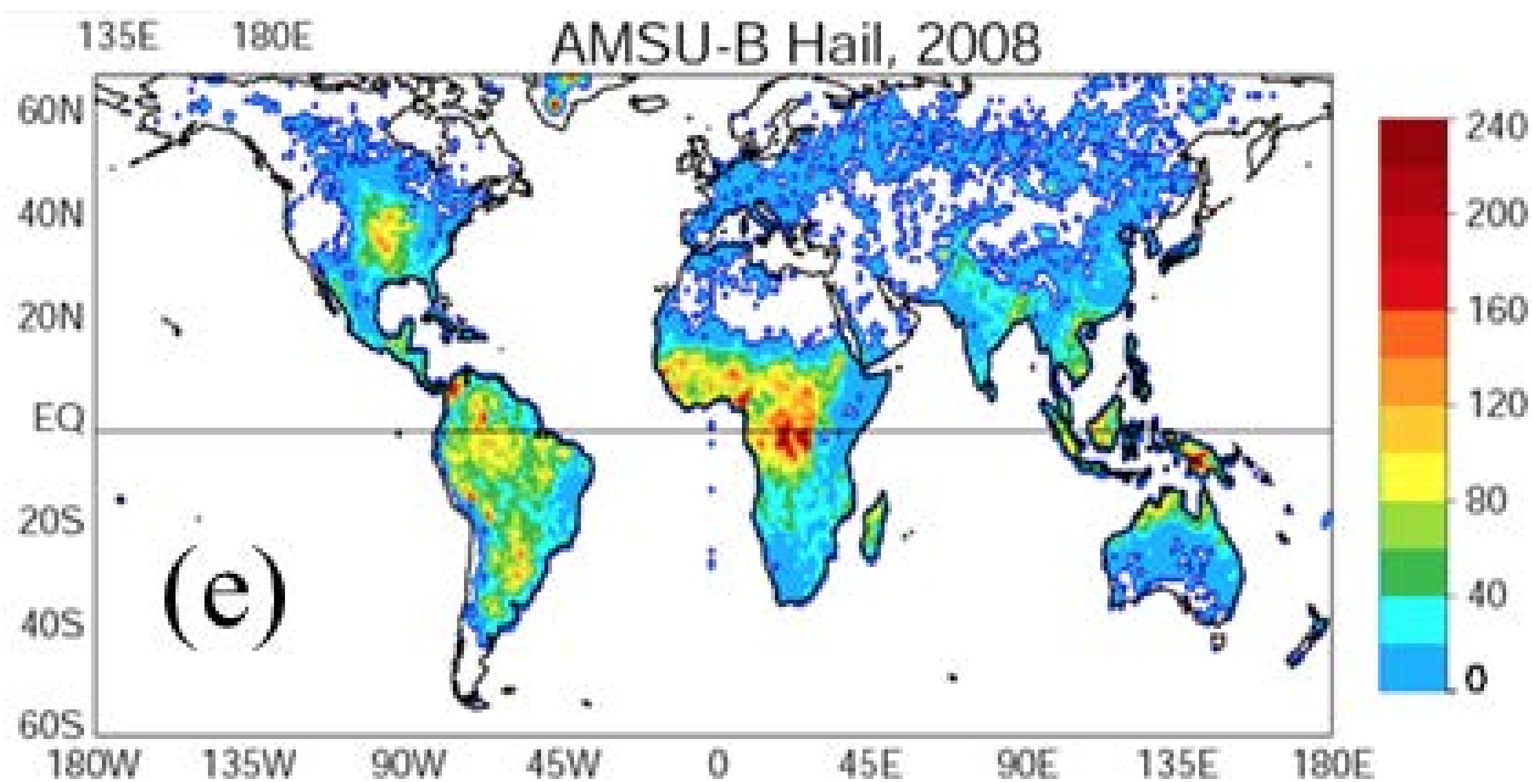
Conditional Mean Lightning Flash Rate, 1995-2014;
(i.e., how strong are the storms that do occur?)
Cecil et al. 2015 *J. Clim.*



AMSU / large hail – Ferraro et al. 2015

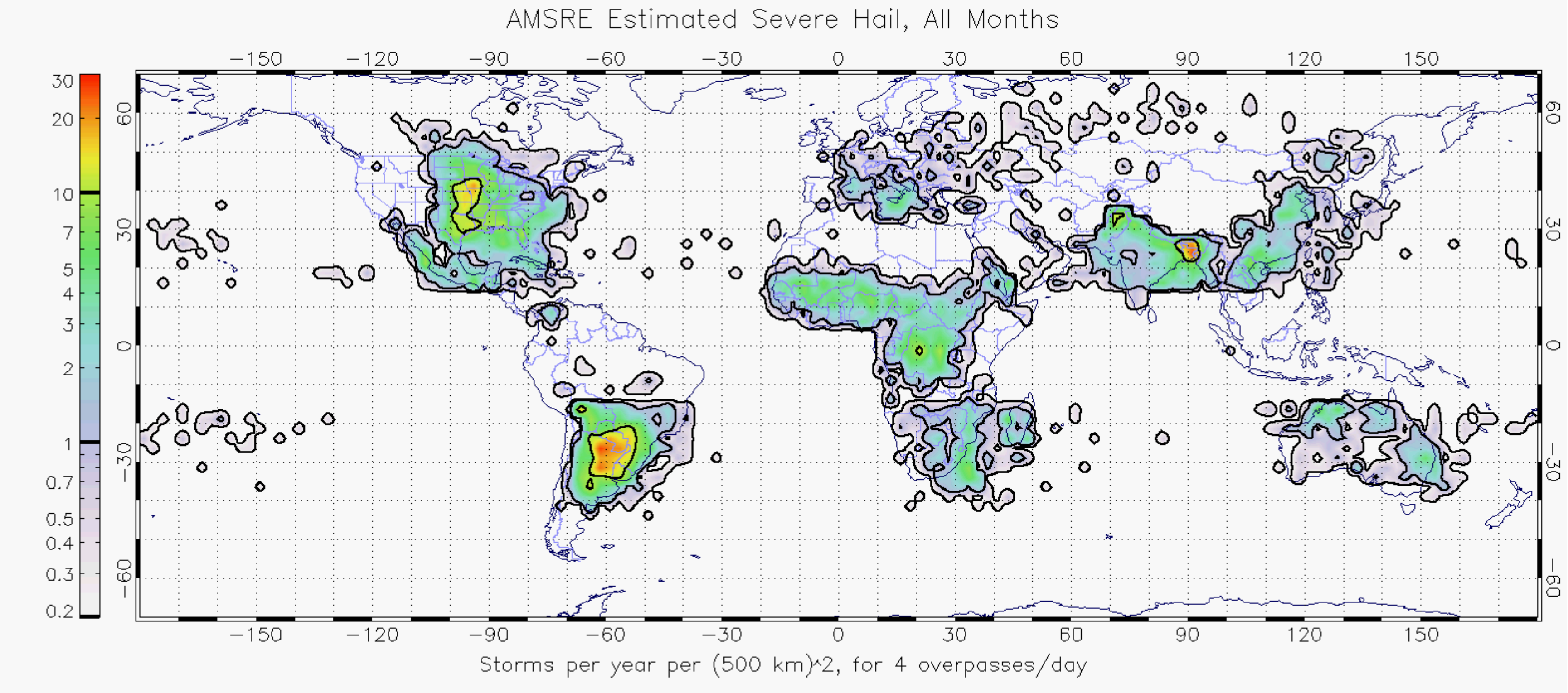
- Ferraro et al. (2015) trained AMSU vs USA reports of severe hail (1” and larger)
  - High frequencies from AMSU more sensitive to graupel than hail, but there is correlation
  - For operational application, tolerate more False Alarms to increase Probability of Detection
  - Set thresholds based on average brightness temperature associated with hail:

TB89 ≤ 228 K   TB150 ≤ 207 K   TB183+/-1 ≤ 211 K   TB183+/-3 ≤ 205 K   TB183+/-7 201 K



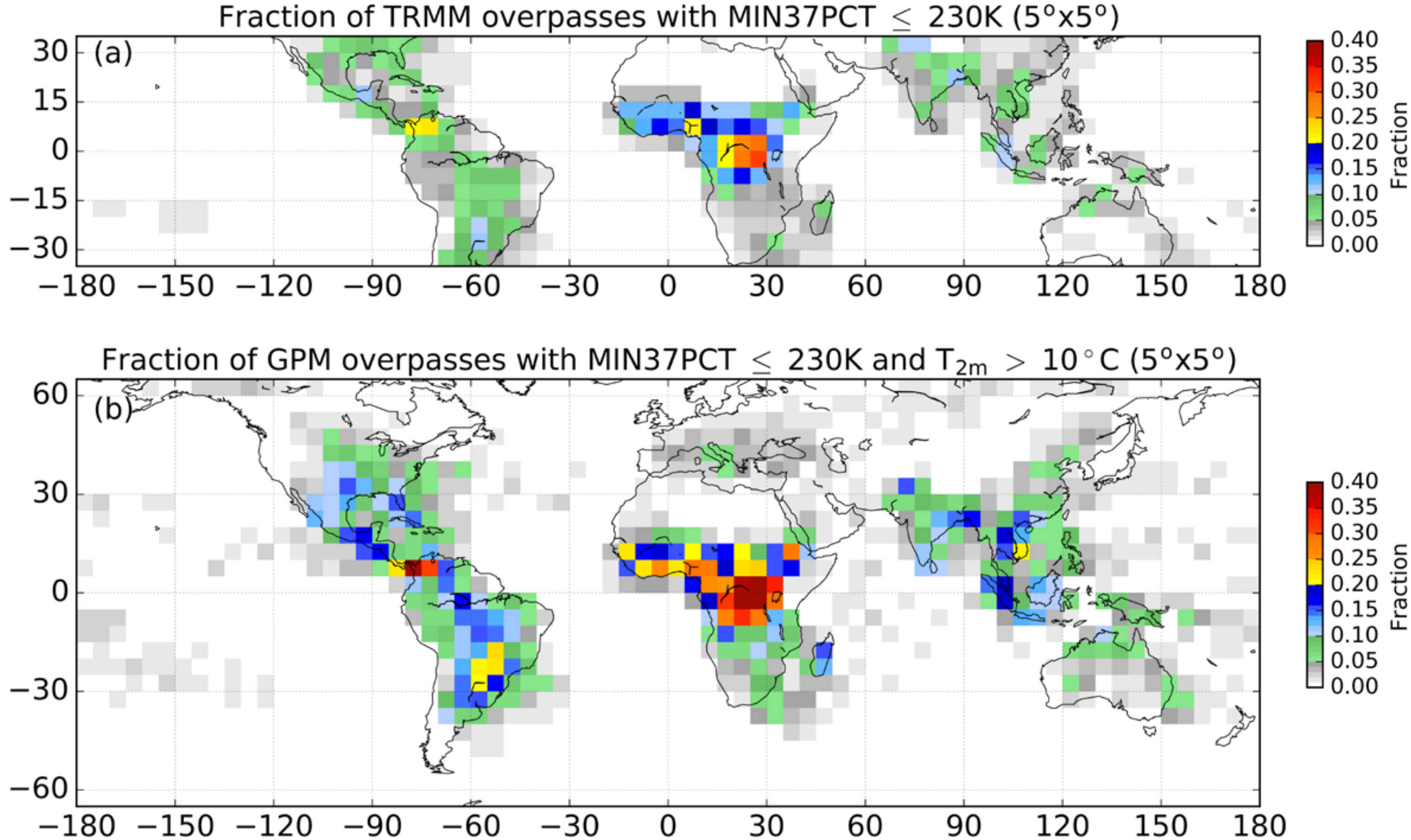
37 GHz / large hail – Cecil & Blankenship 2012

- Cecil and Blankenship (2012) trained 37 GHz vs USA reports of severe hail (1" and larger)
  - **Valued high probability of hail / low False Alarm Rate**
  - For climatology, overcome reduced Probability of Detection by accumulating samples and scaling
  - Want to minimize unrealistic patterns of false alarms (e.g., ITCZ)
  - *Separate thresholds for tropics vs subtropics, land vs ocean*



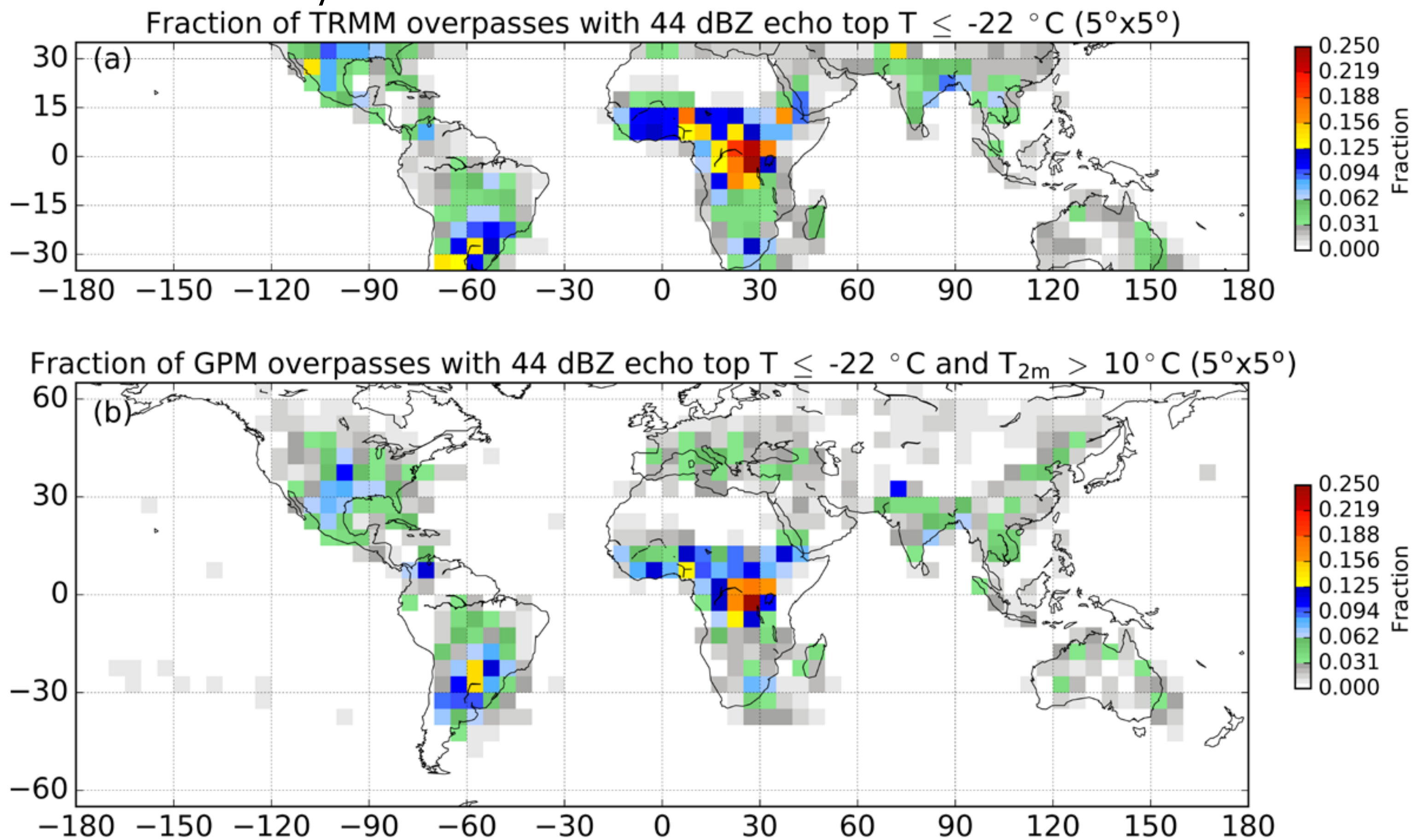
37 GHz / large hail – Ni et al. 2017

- Ni et al. (2017) trained 37 GHz vs USA reports of severe hail (1” and larger)
  - Set thresholds based on maximum Skill Scores – a tradeoff between False Alarm Rate and Probability of Detection



Ku-radar / large hail – Ni et al. 2017

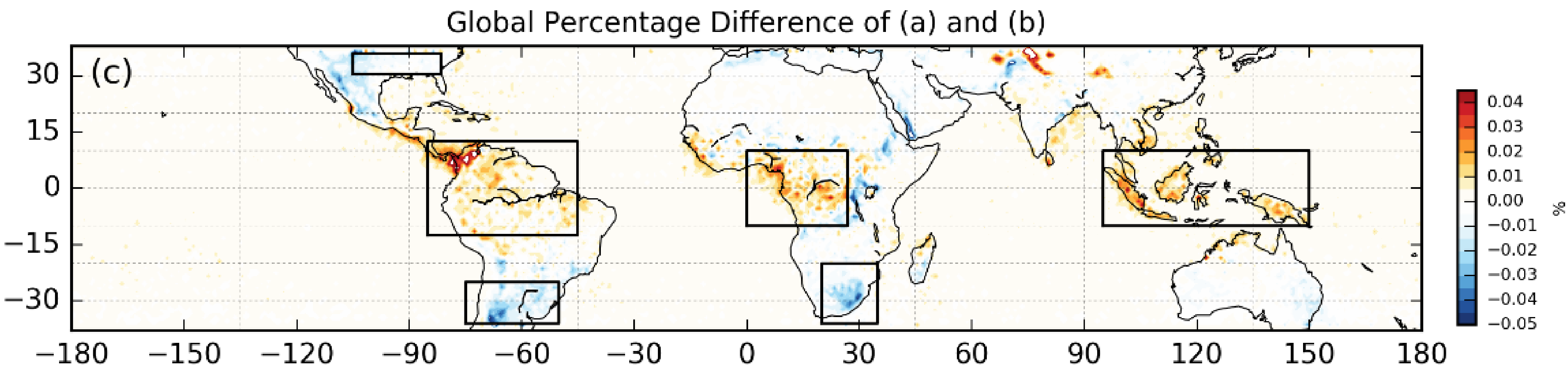
- Ni et al. (2017) trained TRMM/GPM radar vs USA reports of severe hail (1" and larger)
  - Set thresholds based on maximum Skill Scores – a tradeoff between False Alarm Rate and Probability of Detection



37 GHz vs Ku-radar / large hail – Ni et al. 2017

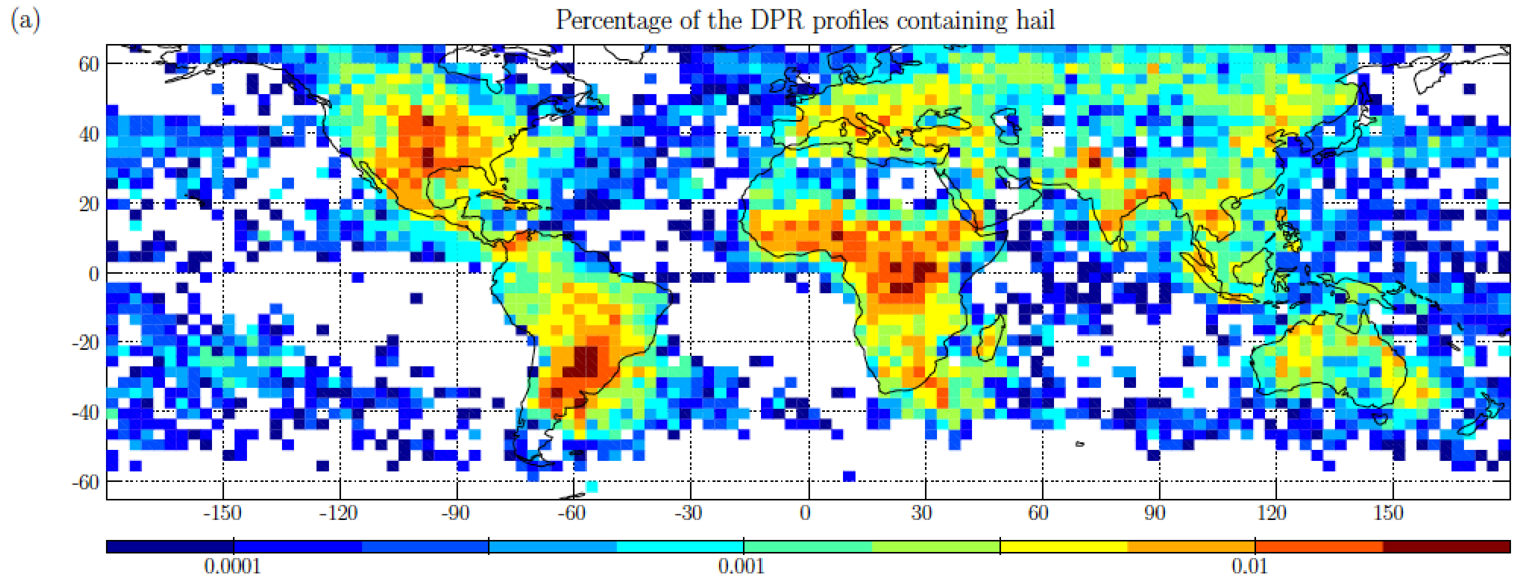
- Comparison applying the same approach (threshold w/ highest skill score) to:

37 GHz PCT ≤ 230 K Criterion for hail - **44 dBZ echo top height ≤ -22° C Criterion for hail** = **Difference** *Passive microwave overestimates tropics, underestimates subtropics relative to radar*



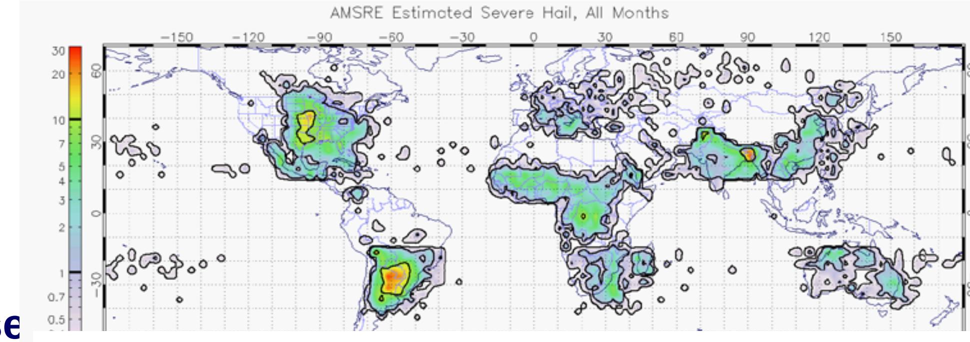
Passive Microwave, Radar / small hail – Mroz et al. 2017

- Mroz et al. (2017) trained 10-183 GHz channels and GPM radar vs USA **dual-pol radar identifications** of hail as the particle type
  - Set thresholds based on maximum Skill Scores – a tradeoff between False Alarm Rate and Probability of Detection

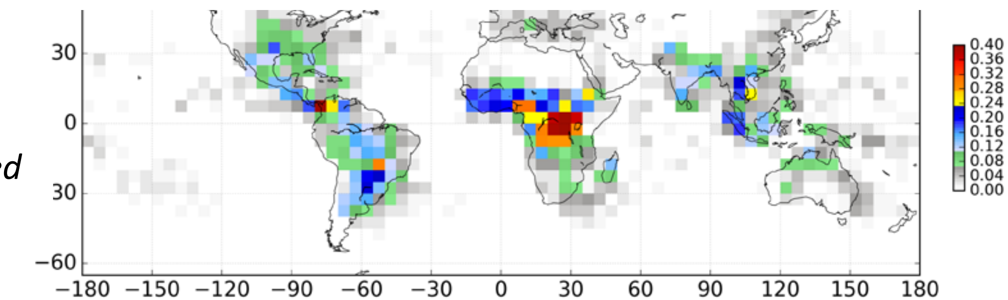


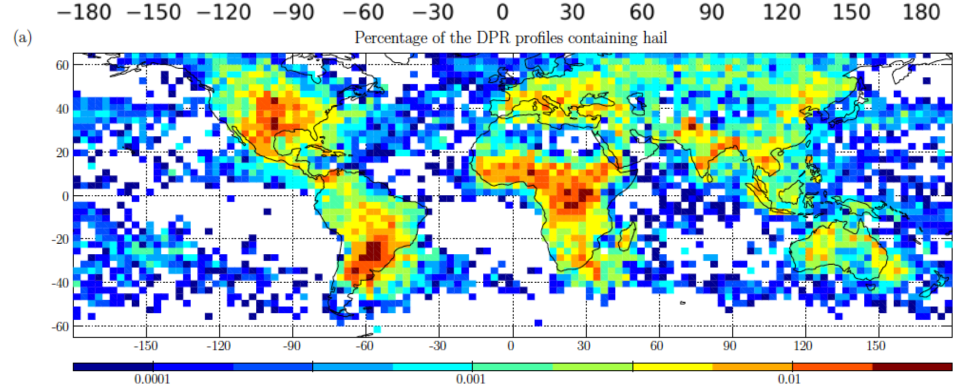
Variety of approaches, variety of answers

- Differences in approach:
  - **top plot** puts more emphasis on low FAR, **higher confidence that the storms are severe**
  - **Bottom plots** put more emphasis on higher skill scores, **accepting high false alarm rates in exchange for higher probability of detection**. I.e., try to identify all the potential hail storms, knowing that many of them are false alarms.
  - The false alarms may have regional biases; the bottom plots probably over-emphasize the tropics

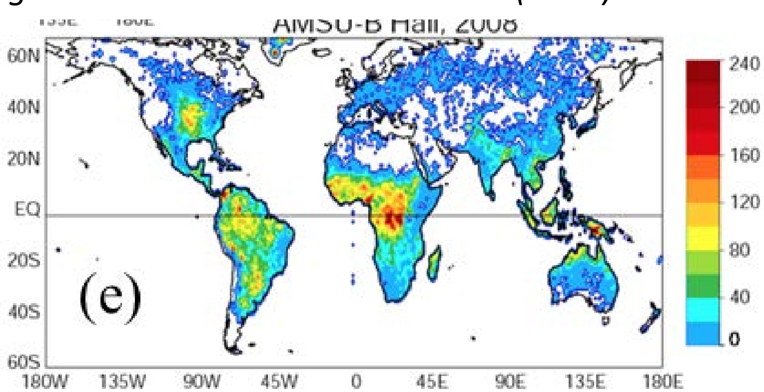


Above: *Global distribution of severe hailstorms estimated using AMSR-E data. Adapted from Cecil and Blankenship (2012).*
Middle: *Similar, but based on GPM radar. From Xiang Ni et al. (2017).*
Bottom: *Distribution of hail at surface or aloft, no size criteria, based on GPM radar; from Kamil Mroz et al. (2017).*





Below: *Global distribution of severe hailstorms estimated using AMSU data. From Ferraro et al. (2015).*



Summary

- Passive and active microwave sensors in Low Earth Orbit can produce *credible* global distributions of hail, without artificial inhomogeneities
- Relevant passive sensors date back to 1987 (SSMI)
- Active (radar) sensors limited to TRMM (1997-2015) and GPM (2014 -) radars
- Substantial variety in results, related to
  - Measurement type (active/passive? Low freq. or high freq.?)
  - Emphasis on *large* hail or *any* hail?
  - Erring on side of lower False Alarm Rate,
  - … or on side of higher Probability of Detection
- Lightning is easier to measure directly
  - some attempted hail retrievals look like pretty good lightning retrievals

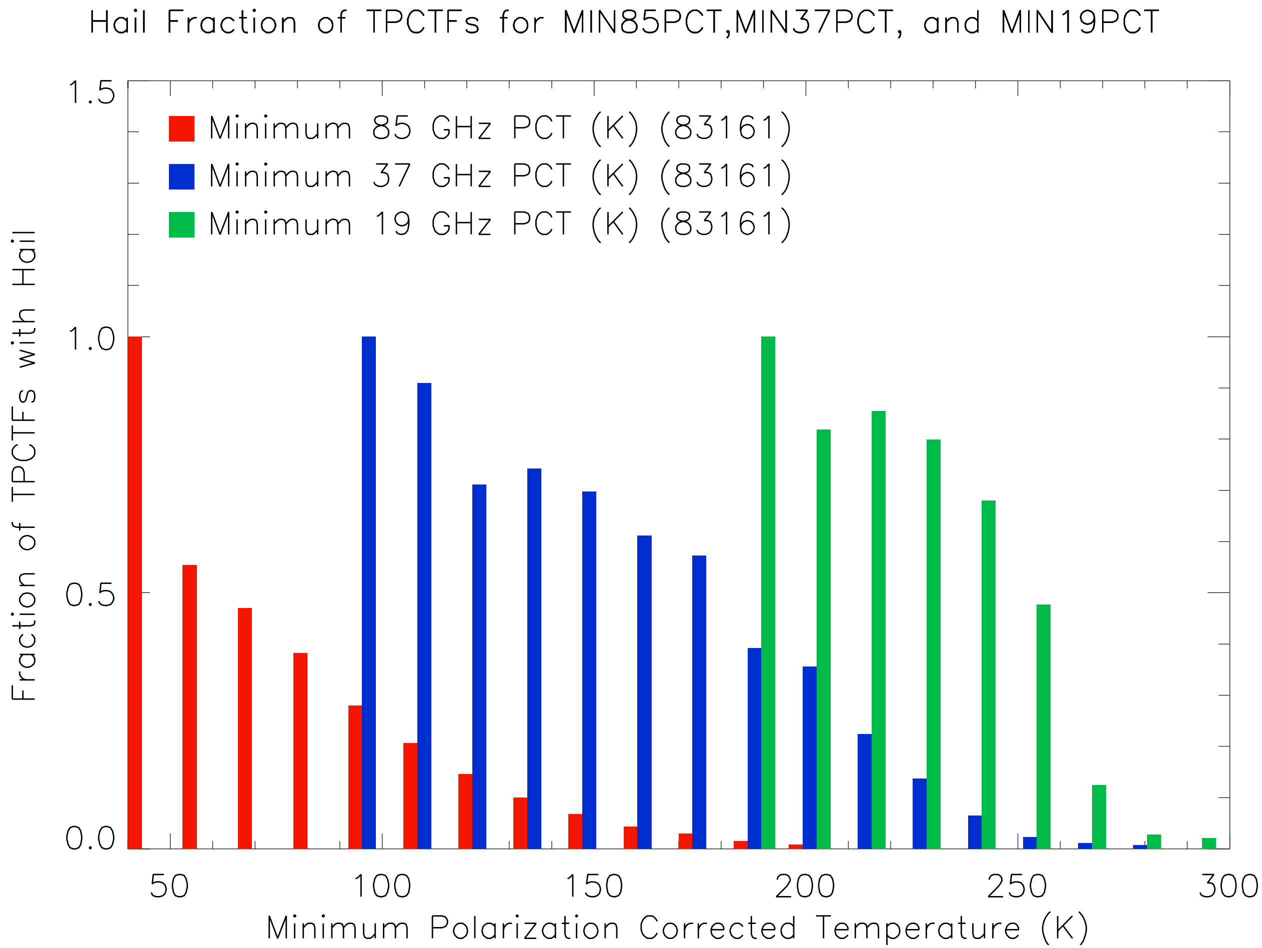
Extra slides – statistical details

Probability of Hail

Passive Microwave:
Lower frequency / longer wavelength channels have a sharper response to large hail than the higher frequency channels do

19 GHz PCT < 250 K:
hail very likely
19 GHz PCT > 260 K:
hail very unlikely

85 GHz PCT: even storms below 60 K include many cases without *reported* hail

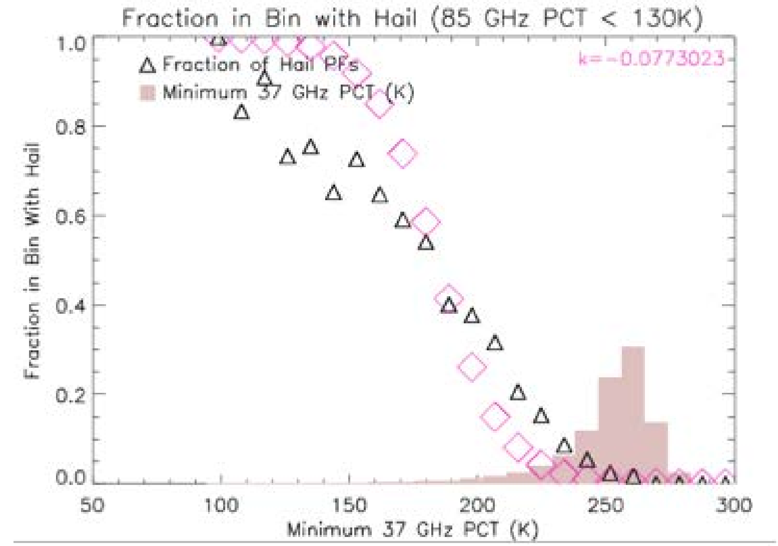


*Based on comparisons with **USA hail reports**, mostly ~25 mm (1")*

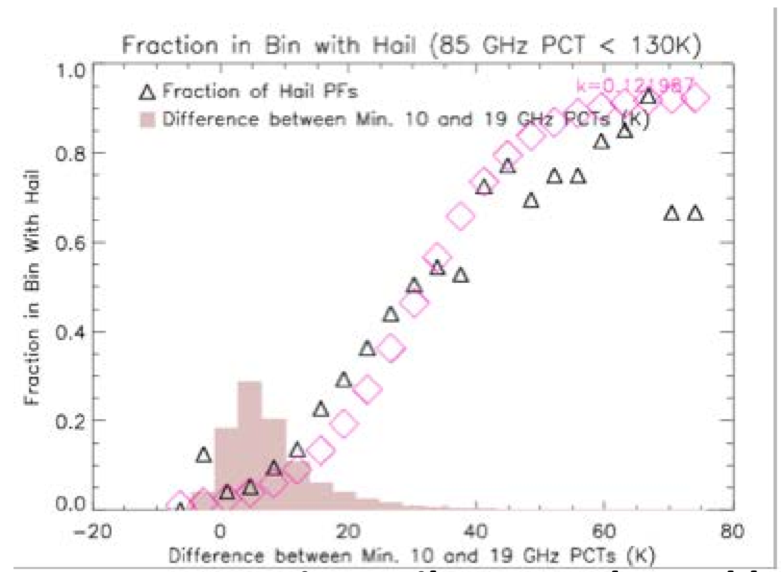
As in Cecil 2009, adapted by Sarah Bang

Probability of Hail

Passive Microwave:
Probability of hail increases with decreasing Polarization Corrected Temperature (PCT) in each channel



Frequency difference between 10 GHz – 19 GHz (bottom right) appears useful for depicting the magnitude of scattering, because 10 GHz has a large footprint and less sensitivity to scattering

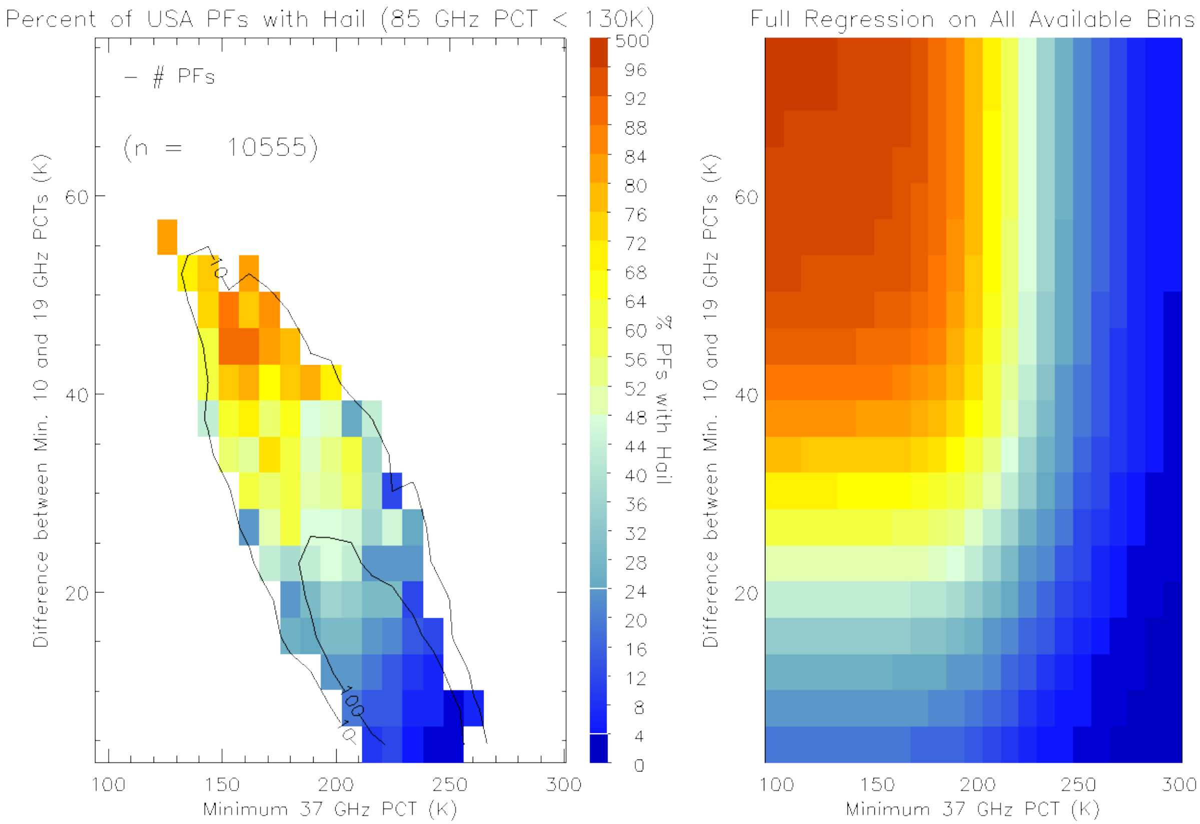


*Based on comparisons with **USA hail reports**, mostly ~25 mm (1")*

As in Cecil 2009, adapted by Sarah Bang

Probability of Hail

Passive Microwave:
Combine 37 GHz PCT hail probability with a probability based on the difference between 19 GHz PCT and 10 GHz PCT – that effectively conveys the magnitude of scattering relative to a background

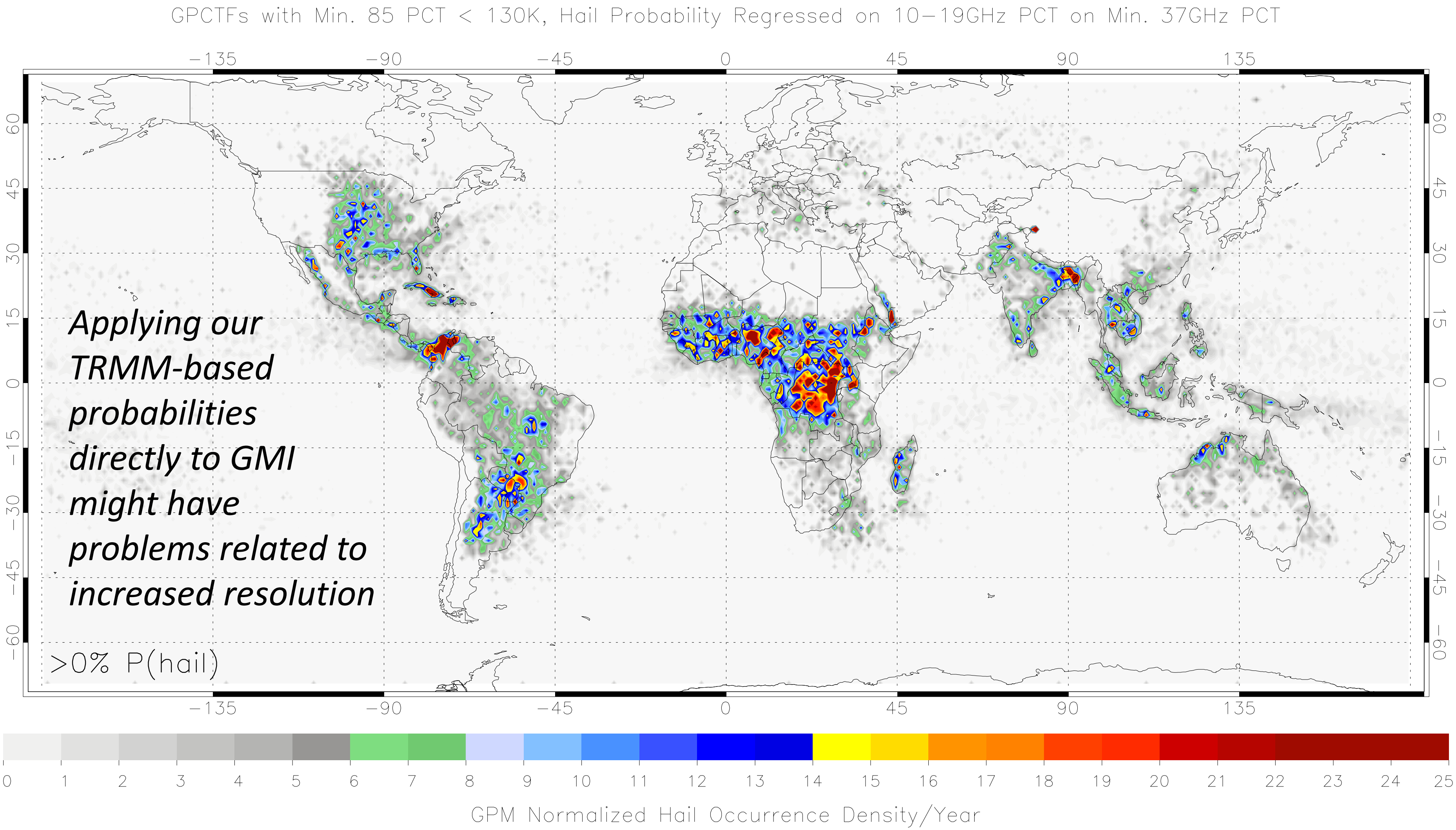


Observed probability ***Modeled probability***

*Based on comparisons with **USA hail reports,** mostly ~25 mm (1")*

Figures courtesy Sarah Bang

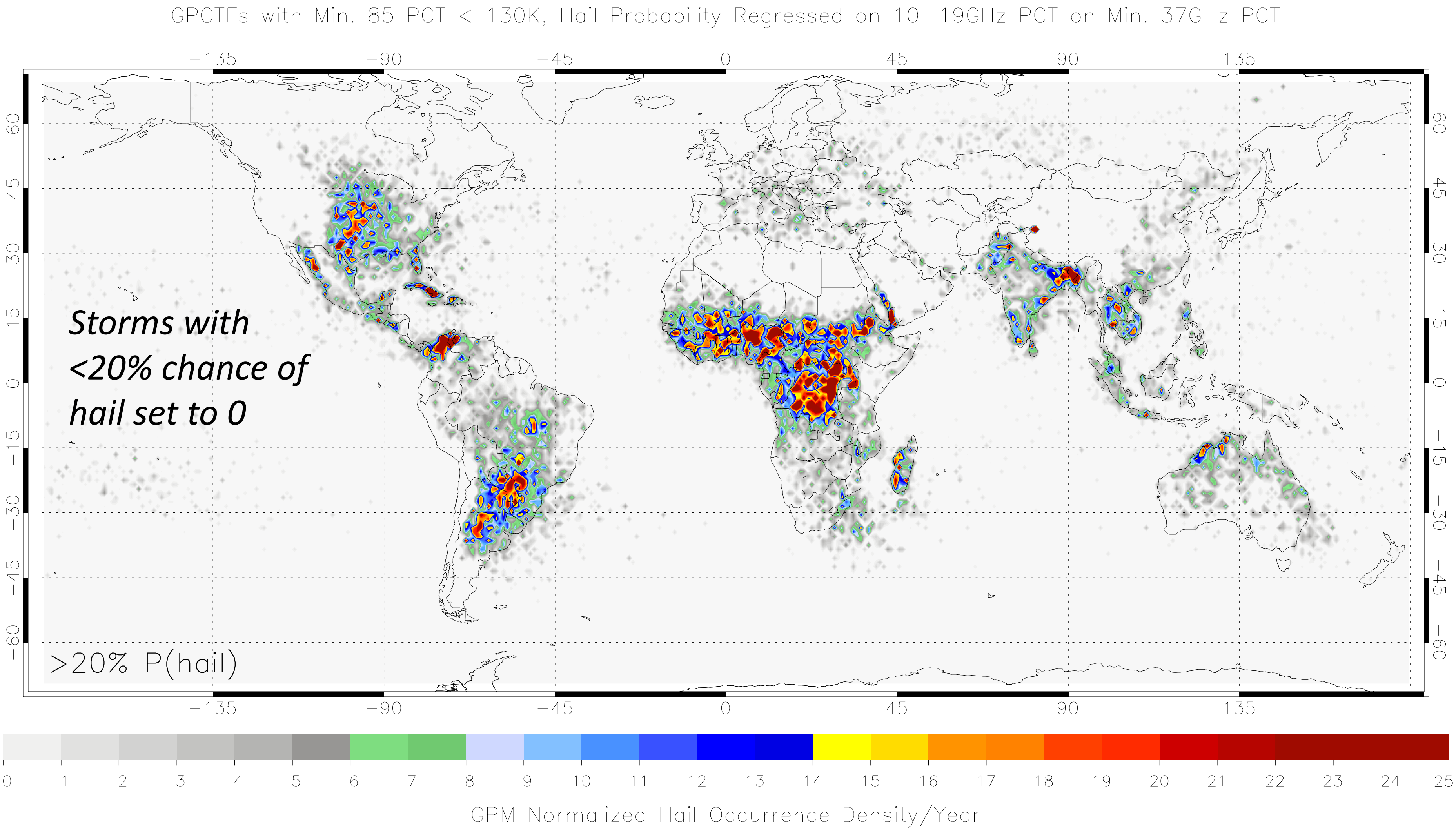
Higher POD, but Higher FAR



Accumulated Hail Probabilities based on GPM 10, 19, 37, 85 GHz (Apr 2014 – Mar 2018)

Bang and Cecil (2018, in preparation)

Lower POD, but Lower FAR



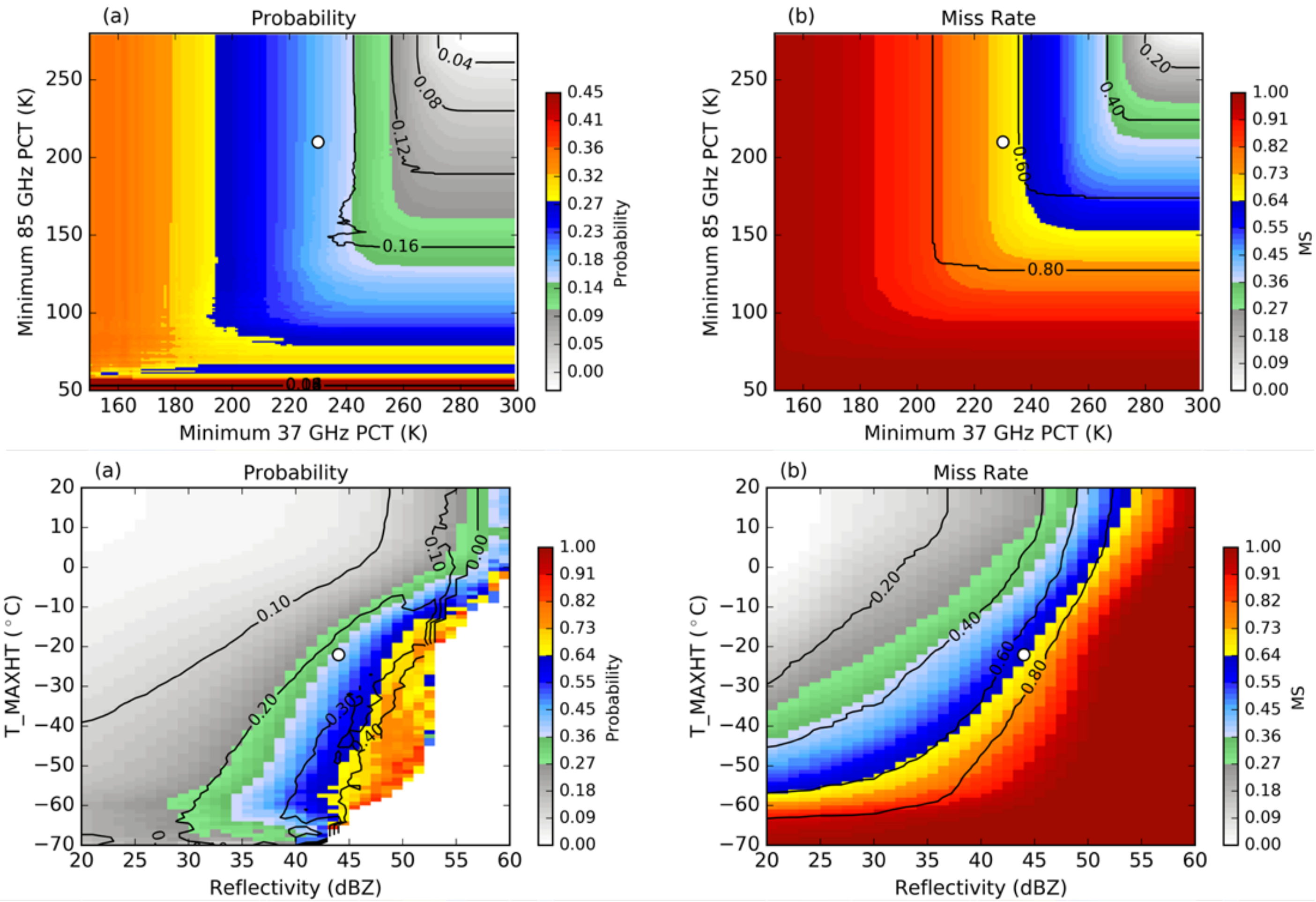
Accumulated Hail Probabilities based on GPM 10, 19, 37, 85 GHz (Apr 2014 – Mar 2018)

Bang and Cecil (2018, in preparation)

Skill Scores for detecting Severe Hail

Passive Microwave:
230 K @ 37 GHz and 210 K @ 85 GHz:
~0.15 CSI, ~80% FAR, ~30% POD

Radar:
44 dBZ @ -22° C:
0.24 CSI, ~65% FAR, ~35% POD

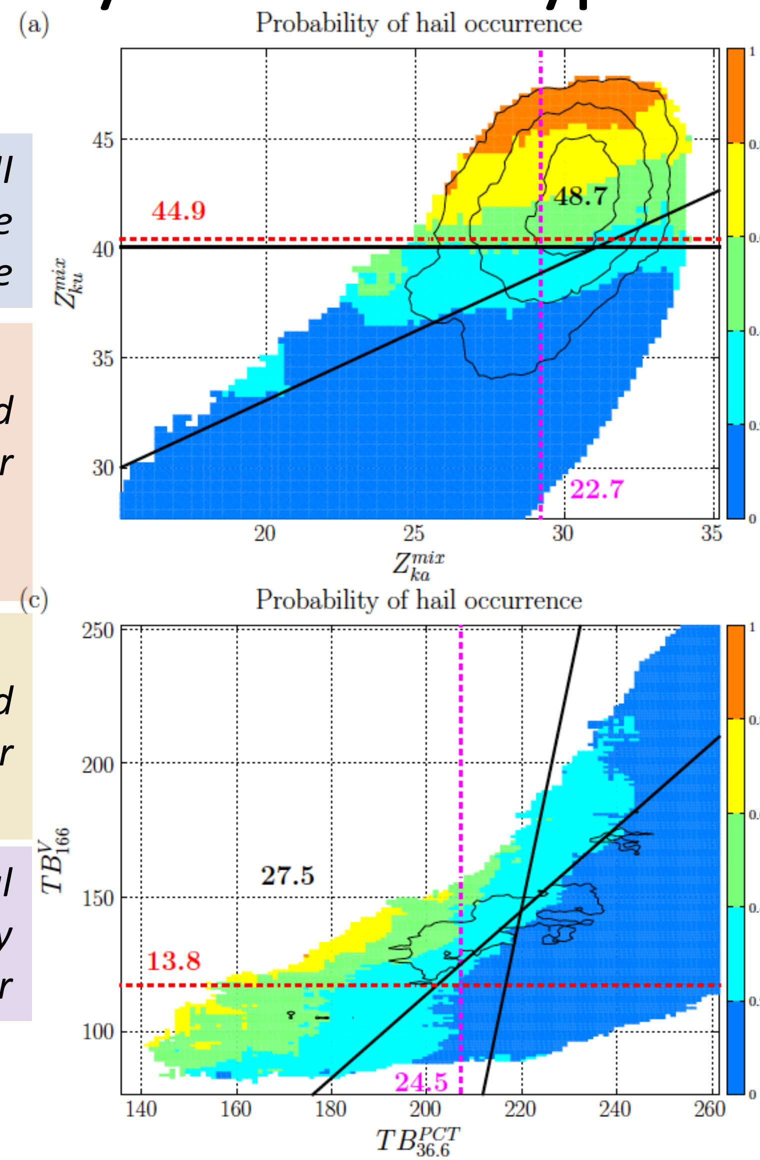


*Based on comparisons with **USA hail reports**, mostly 19-25 mm (0.75" - 1")*

From Ni et al., 2017

Skill Scores for detecting hail hydrometeor type

condition	CSI (%)	FAR (%)	POD (%)	
$TB^{PC}_{36.6} < 207.27$	24.5	62.8	41.9	*GMI passive microwave*
$TB^{PC}_{89} < 138.30$	18.2	73.7	37.3	
$TB^{PC}_{18.7} < 260.63$	25.7	62.2	44.7	
$Z^{mix}_{Ku} > 40.42$	44.9	41.0	65.3	*Ku-band Radar*
$Z^{int}_{Ku} > 79.32$	43.4	43.3	64.8	
$Z^{max}_{Ku} > 46.79$	25.2	64.1	45.8	
$H40^{AFL}_{Ku} > 3.26$	41.8	49.4	70.5	
$H40^{n}_{Ku} > 0.27$	39.7	52.1	70.0	
$Z^{mix}_{Ka} > 29.19$	22.7	73.7	62.1	*Ka-band Radar*
$Z^{int}_{Ka} > 68.79$	27.2	62.0	48.7	
$Z^{max}_{Ka} > 33.95$	11.5	81.6	23.3	
$H30^{AFL}_{Ka} > 5.23$	29.8	61.5	56.7	
$DWR_{max} > 21.77$	18.1	78.7	55.2	*Dual Frequency Radar*
$H^{AFL}_{10dB} > 4.50$	20.8	74.1	51.5	
$H^{n}_{10dB} > 0.41$	20.2	72.5	43.4	



*Based on comparisons with USA **dual-pol radar hydrometeor identification of hail** (no size requirement, not necessarily at surface)*

From Mroz et al., 2017