Detecting and quantifying extreme weather in climate data

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(with some slides by **Paul Ullrich**)

DCMIP-2016
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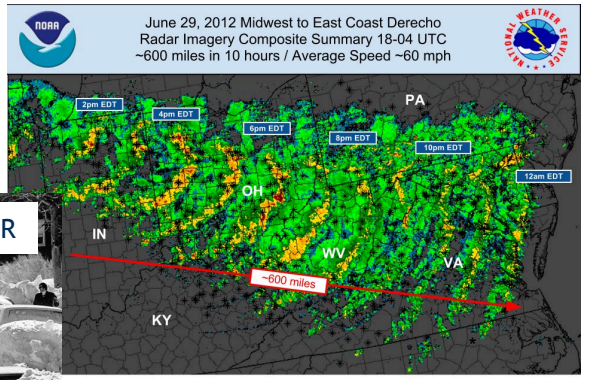
#dcmip2016

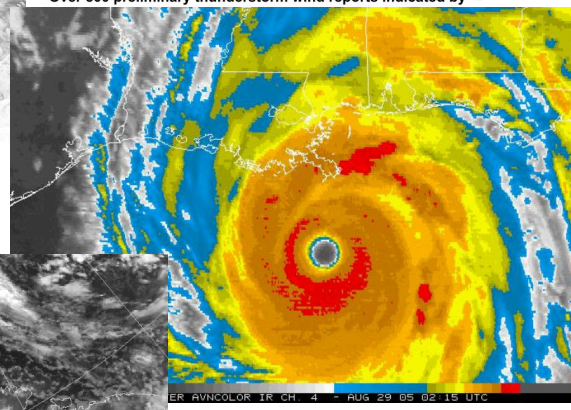
Students/postdocs working/visiting NCAR

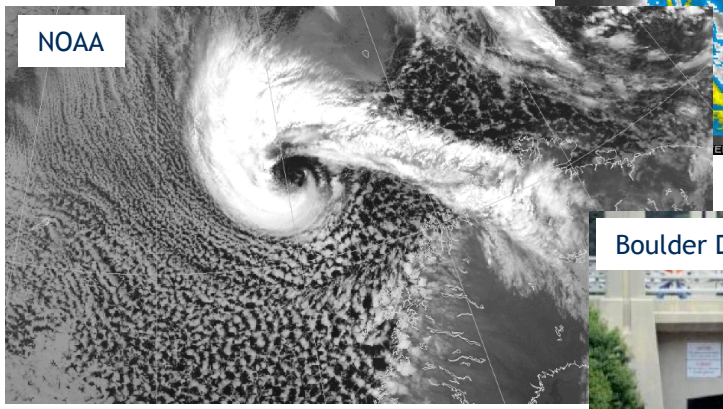
- NCAR Advanced Study Program (ASP)
  - **Postdoctoral fellowships**
    - 2-year fellowships
    - Fellows work with NCAR scientists but possess scientific freedom
  - **Faculty visitor program**
    - Faculty at U.S. universities to spend ~semester at NCAR
  - **Graduate student visitor program**
    - Students cannot directly apply
    - … work with thesis advisor to find NCAR mentor willing to sponsor (or contact ASP office for more advice)
- Alternative postdoctoral fellowships
  - NSF (such as AGS, Mathematical Science, Earth Science)
  - NOAA Climate and Global Change
  - Others…

Climate extremes

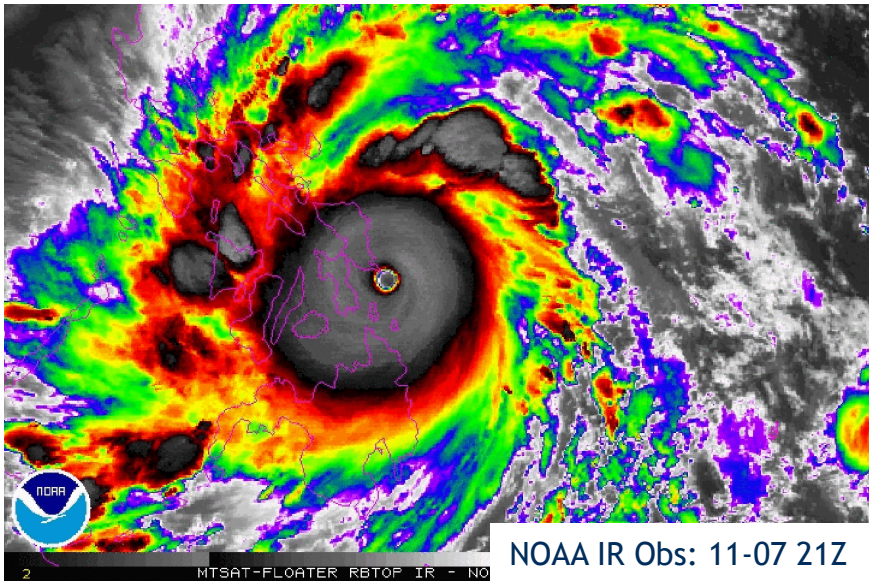
- EXTREMES!
- Better resolved with current and next-generation models
  - *Mesoscale convective storms*
  - *Nor'easters*
  - *Tropical cyclones*
  - *Polar lows*
  - *Flash floods*
  - *… and others*



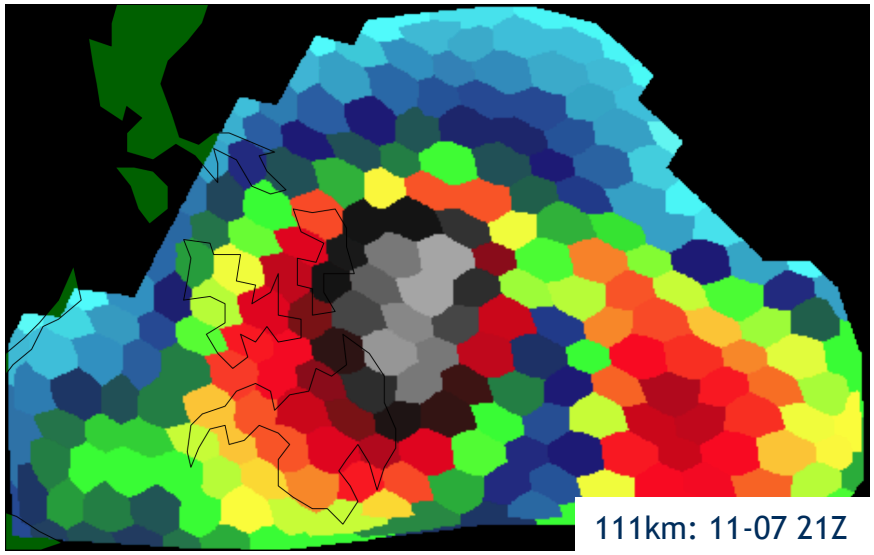




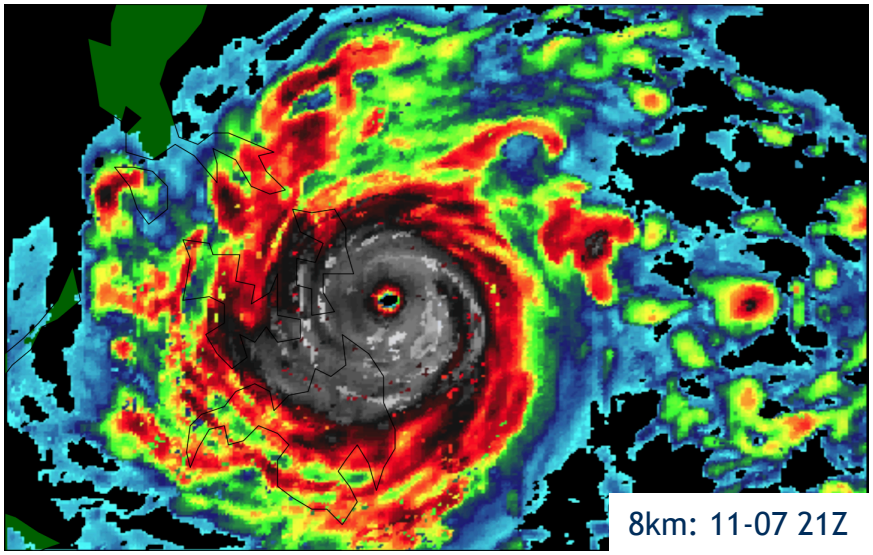
High-res climate: coming soon



NOAA IR Obs: 11-07 21Z



111km: 11-07 21Z



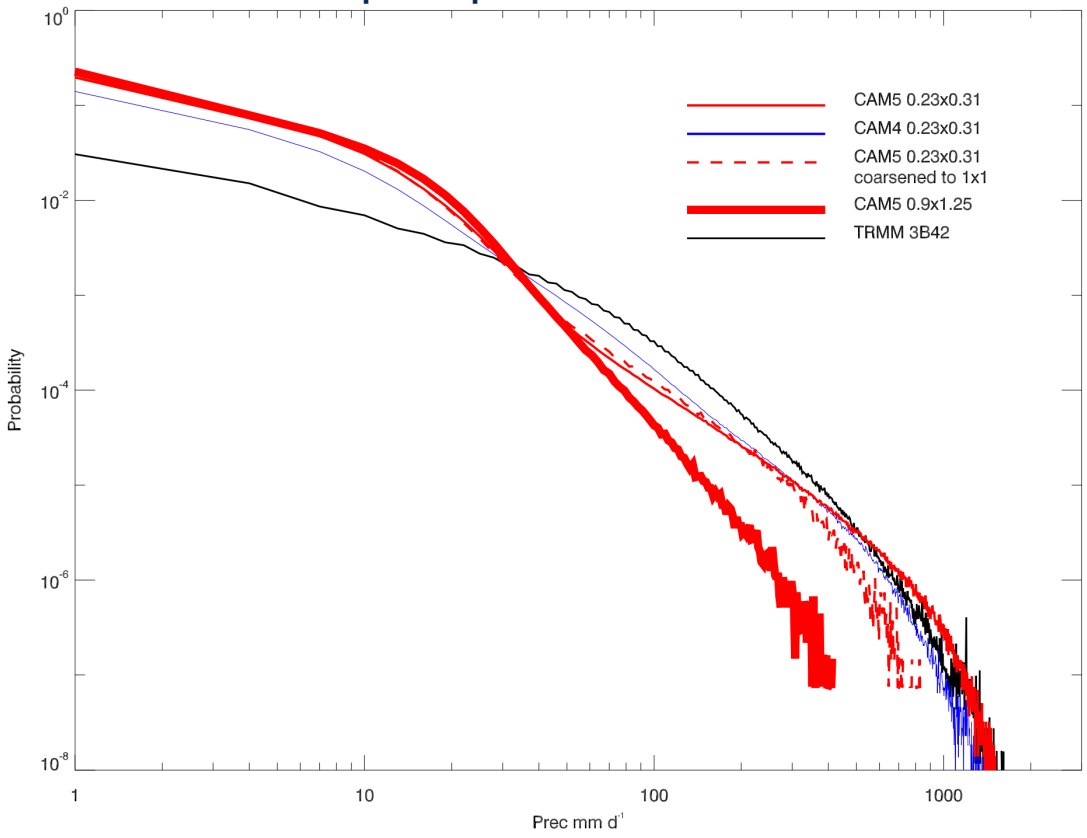
8km: 11-07 21Z

Why do we want to quantify extremes?

- Climate events disproportionately affect health and welfare if…
  - Rare
  - Severe
- Stakeholder importance!
- Extremes are generally transient and occur over relatively small timescales (hours to days)
- Mean climate state does not contain information about these events

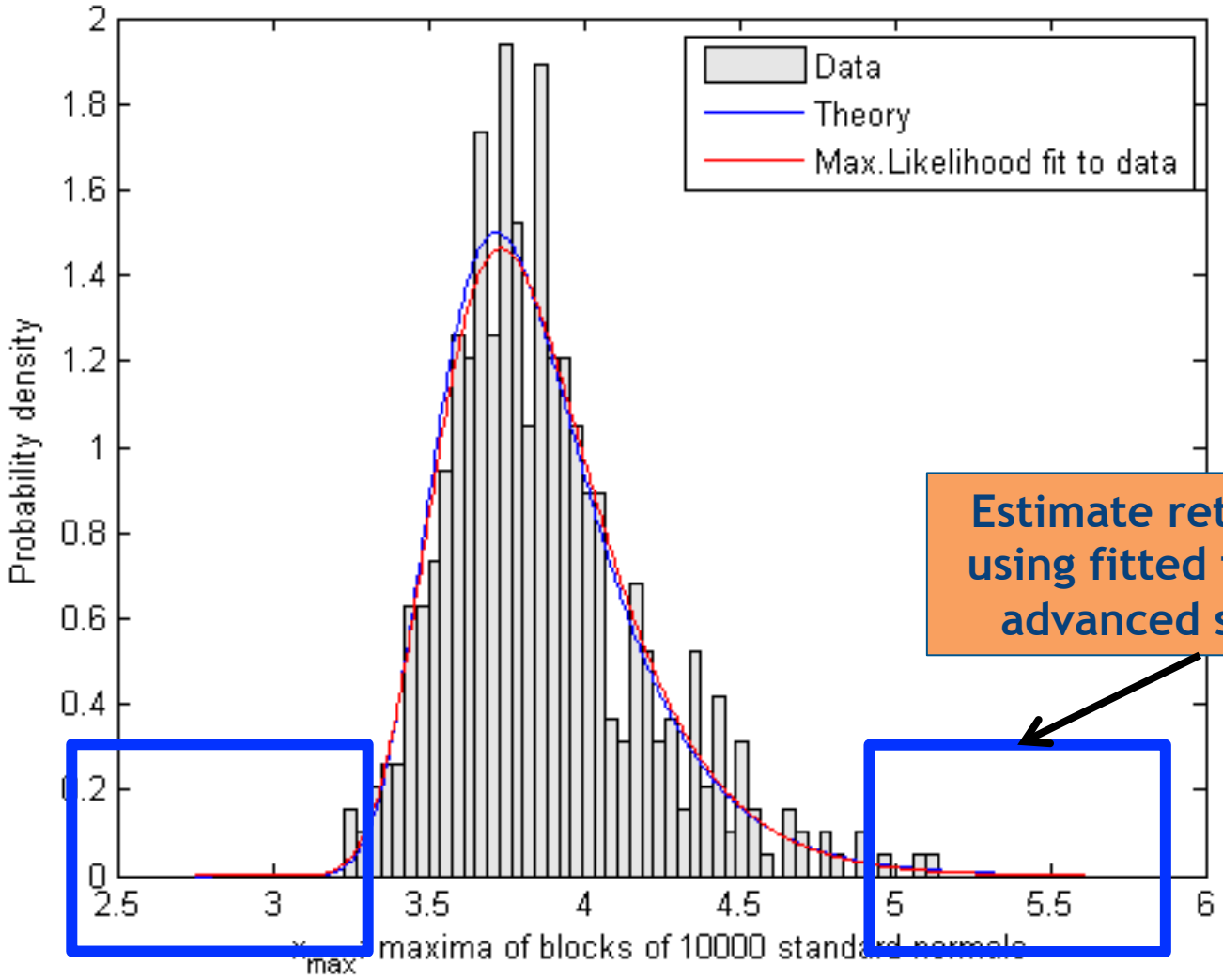
Quantity distributions

- Simplest technique?
- Aggregate all data
  - *Typically* at high frequency (<= daily)
  - *Typically* at grid scale
- Calculate PDF based on data, observe shifts



Bacmeister et al, 2014

Extreme value theory



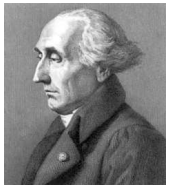
Why feature-based tracking?

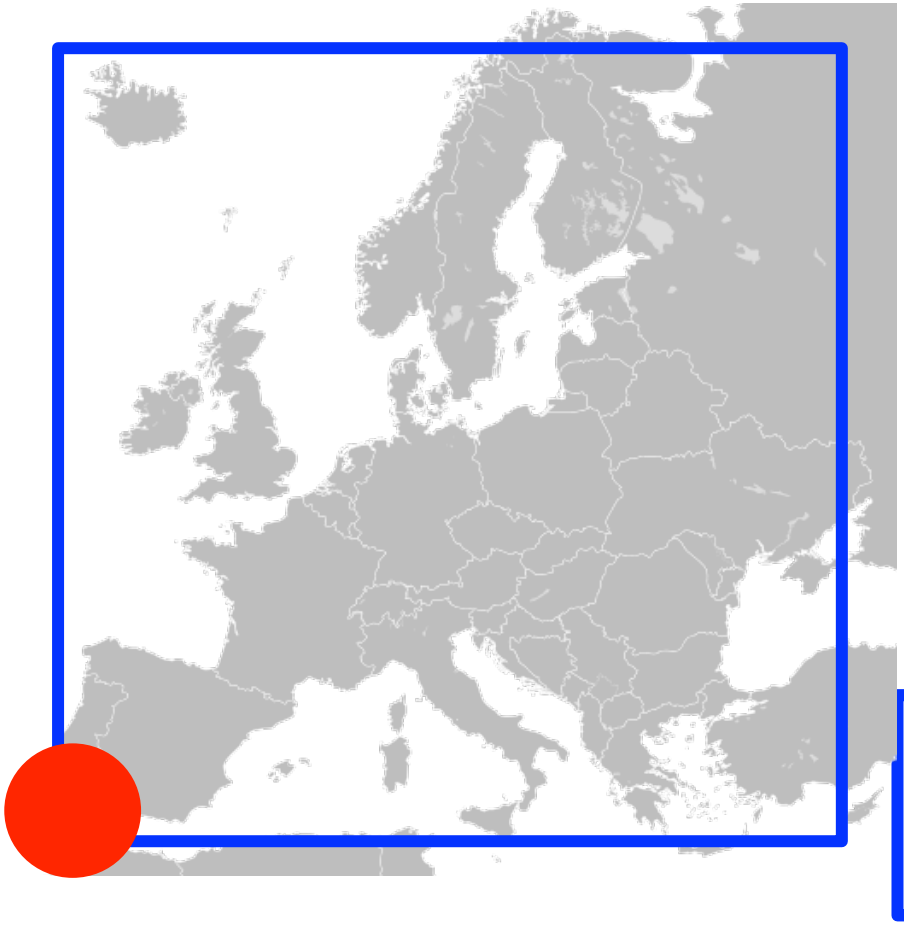
- General statistics (gridpoint or otherwise) lack information about dynamical features within model
  - No context within space and time
- Are precip maxes associated with tropical cyclones? Mesoscale convection? Orography?
- Do these features change in a warming world? Do they change as we increase our model resolution? Do they change as we change our dynamical core?

Feature tracking: two paradigms

Eulerian

Lagrangian

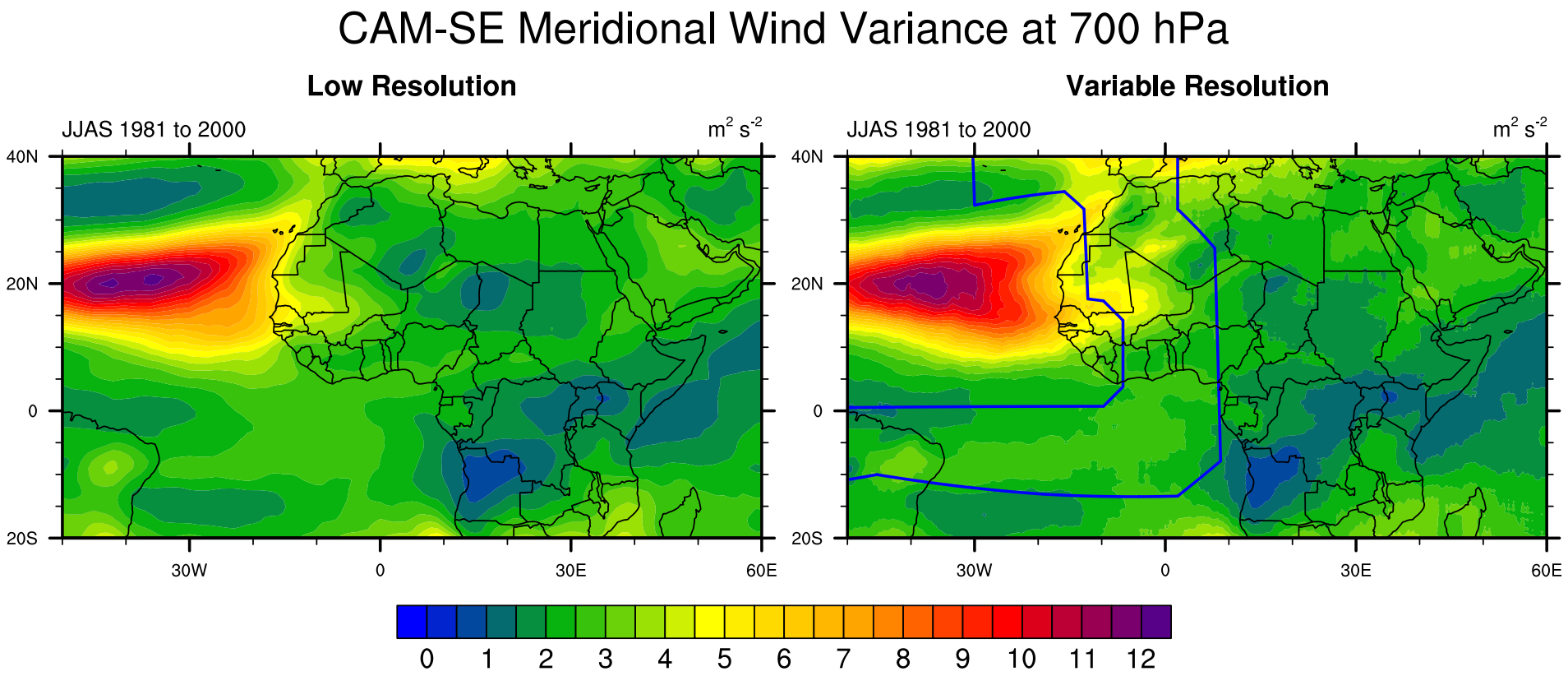




Eulerian techniques

- Generally apply filter (e.g., bandpass) to separate relevant temporal scales
- Good for features that occur with discernable frequency in particular geographic location
- Examples:
  - Mid-latitude cyclones
  - Tropical waves (MJO, Kelvin, African Easterly)
  - Mesoscale ocean eddies (Gulf Stream, Kuroshio)
  - Diurnal convection

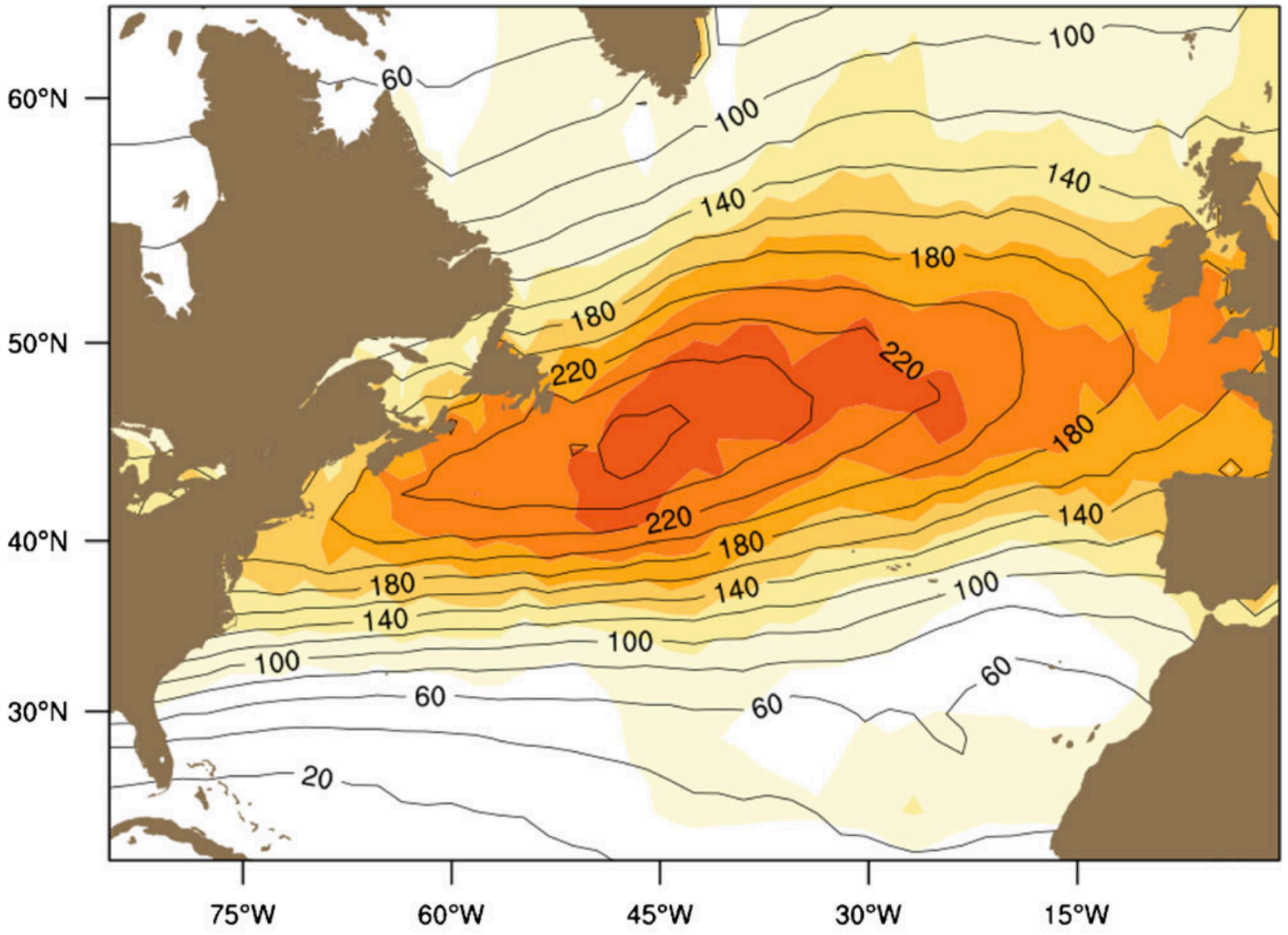
African Easterly Waves…



700 hPa V wind, 2-6 days

Zarzycki et al., 2015, J. Clim., technique from *Skinner and Diffenbaugh*, 2013

Extratropical cyclones…

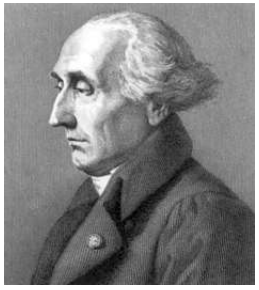


300 hPa V wind, 2-6 days

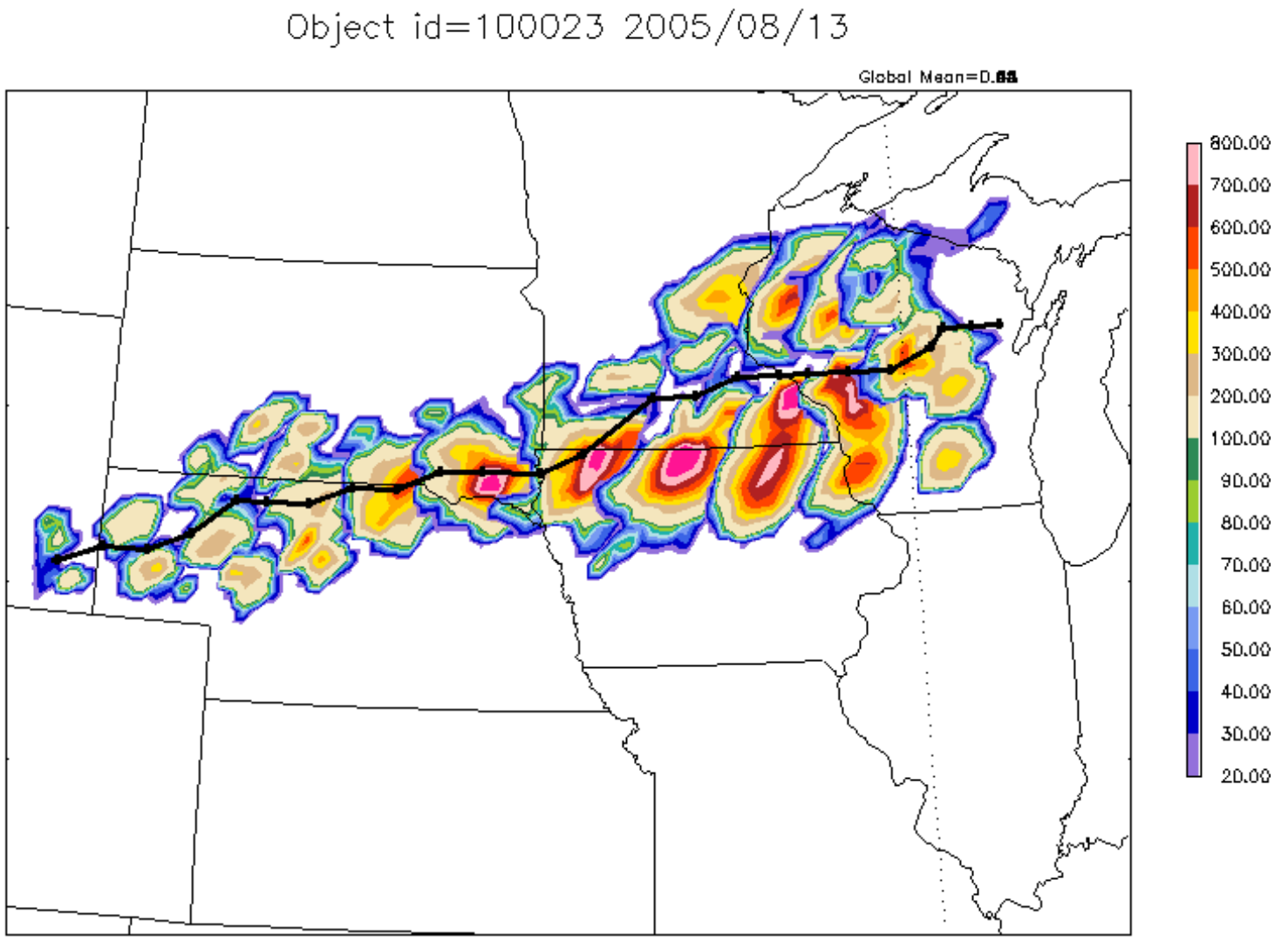
Colle et al., 2015, Clim. Dyn.

Lagrangian techniques

- Good for features that have defined characteristics but may appear chaotically or infrequently in space and time
- Require more sophisticated feature definition than Eulerian
- Examples:
  - Tropical cyclones
  - Mesoscale convective complexes
  - Atmospheric rivers

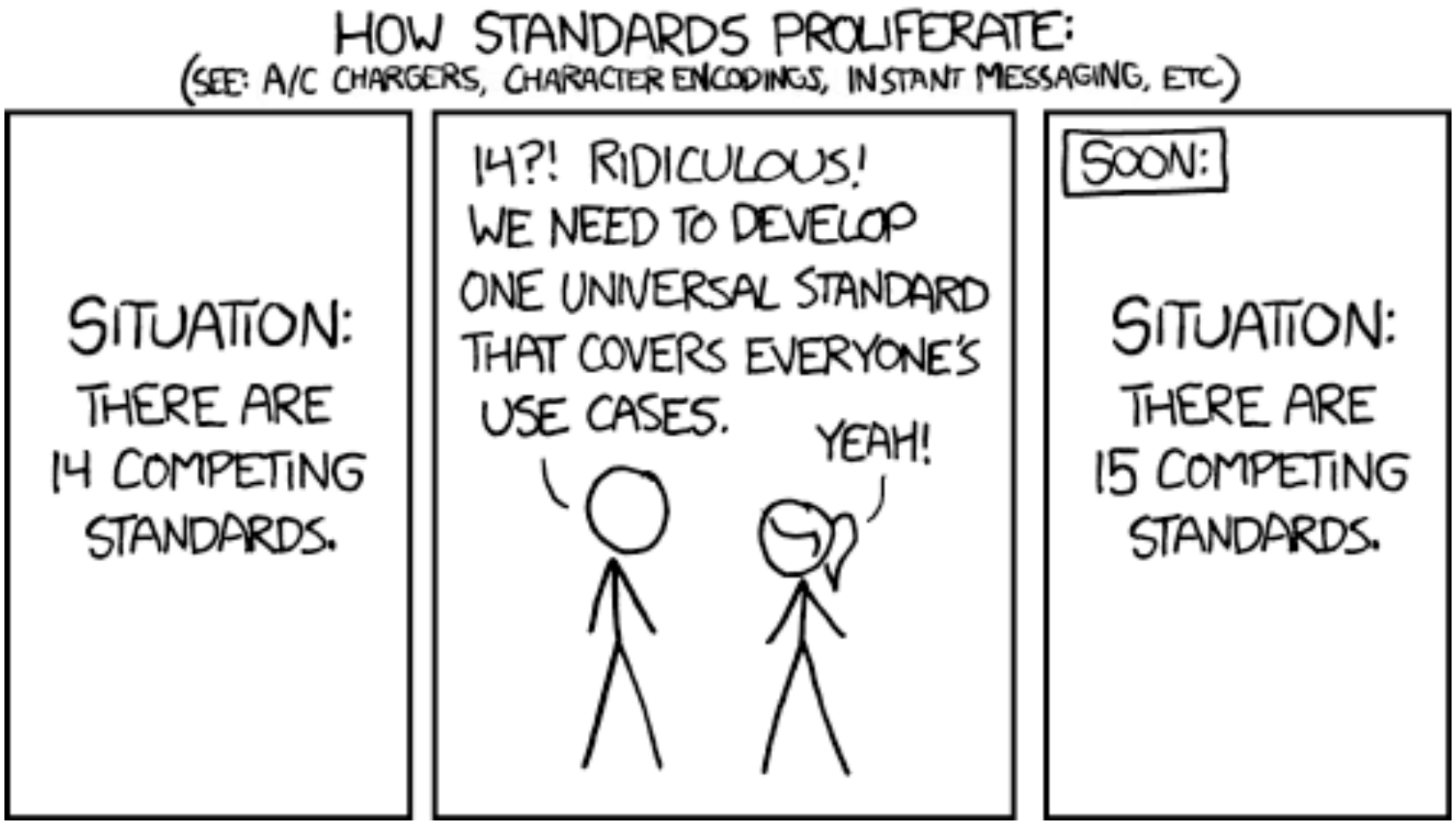


Mesoscale convective systems…



courtesy Julio Bacmeister, NCAR

Relevant XKCD



So. Many. Trackers.

- **Extratropical Cyclones:** Williamson (1981), Lambert (1988), Bell and Bosart (1989), Alpert et al. (1990), Le Treut and Kalnay (1990), Murray and Simmonds (1991), König (1993), Hodges et al. (1994), Hodges (1995), Serreze (1995); Blender et al. (1997); Sinclair (1997); Simmonds et al. (1999); Lionello et al. (2002); Benestad and Chen (2006); Trigo (2006); Wernli and Schwierz (2006); Akperov et al. (2007); Rudeva and Gulev (2007); Inatsu (2009); Kew et al. (2010); Hewson and Titley (2010); Hanley and Caballero (2012), Neu et al. (2013)
- **Tropical Cyclones:** Tsutsui and Kasahara (1996), Camargo and Zebiak (2002), Walsh et al. (2007), Bengtsson et al. (2007), Vitart et al. (1997), Zhao et al. (2009), Murakami and Sugi (2010), Murakami et al. (2012), Strachen et al. (2013), Zarzycki and Jablonowski (2014)

Basic Lagrangian detection workflow

DO i = 1,length(TIME)

- Load data into tracker
- Scan for local minima or maxima that defines characteristic

DO j = 1,length(FEATURES)

- Check to ensure local min/max meets additional criteria
- If yes, save as candidate cyclone

END DO

END DO

DO n = 1,length(CANDIDATES)

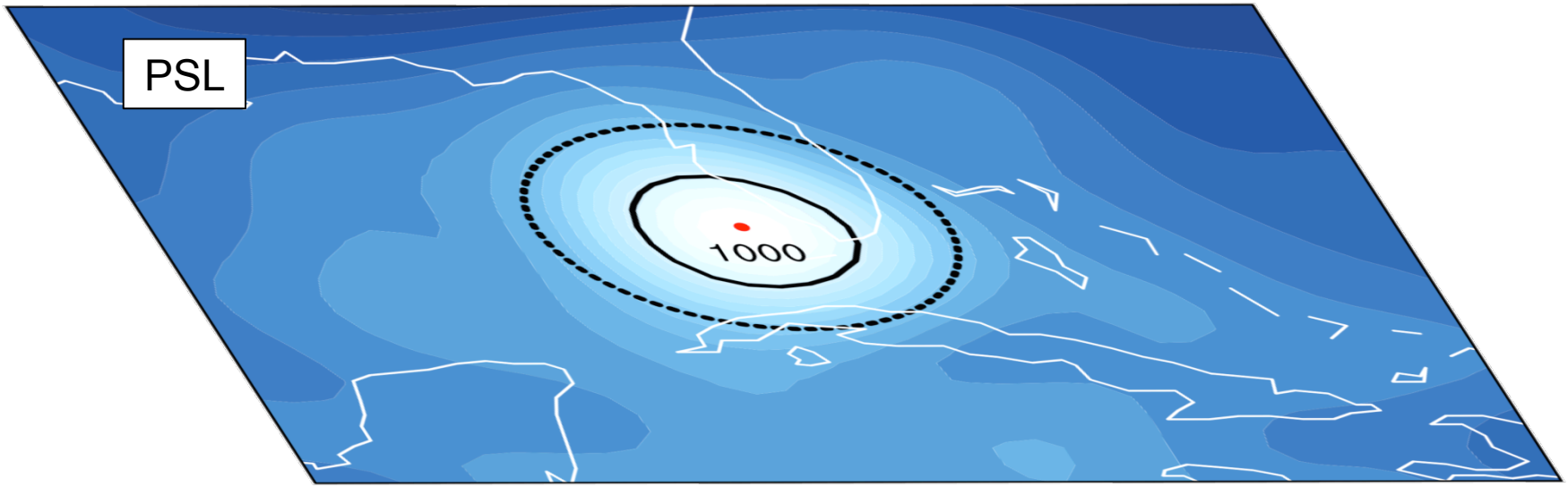
- Stitch to nearest candidates at previous timestep to build trajectory
- Filter based on trajectory length, other quantities

END DO

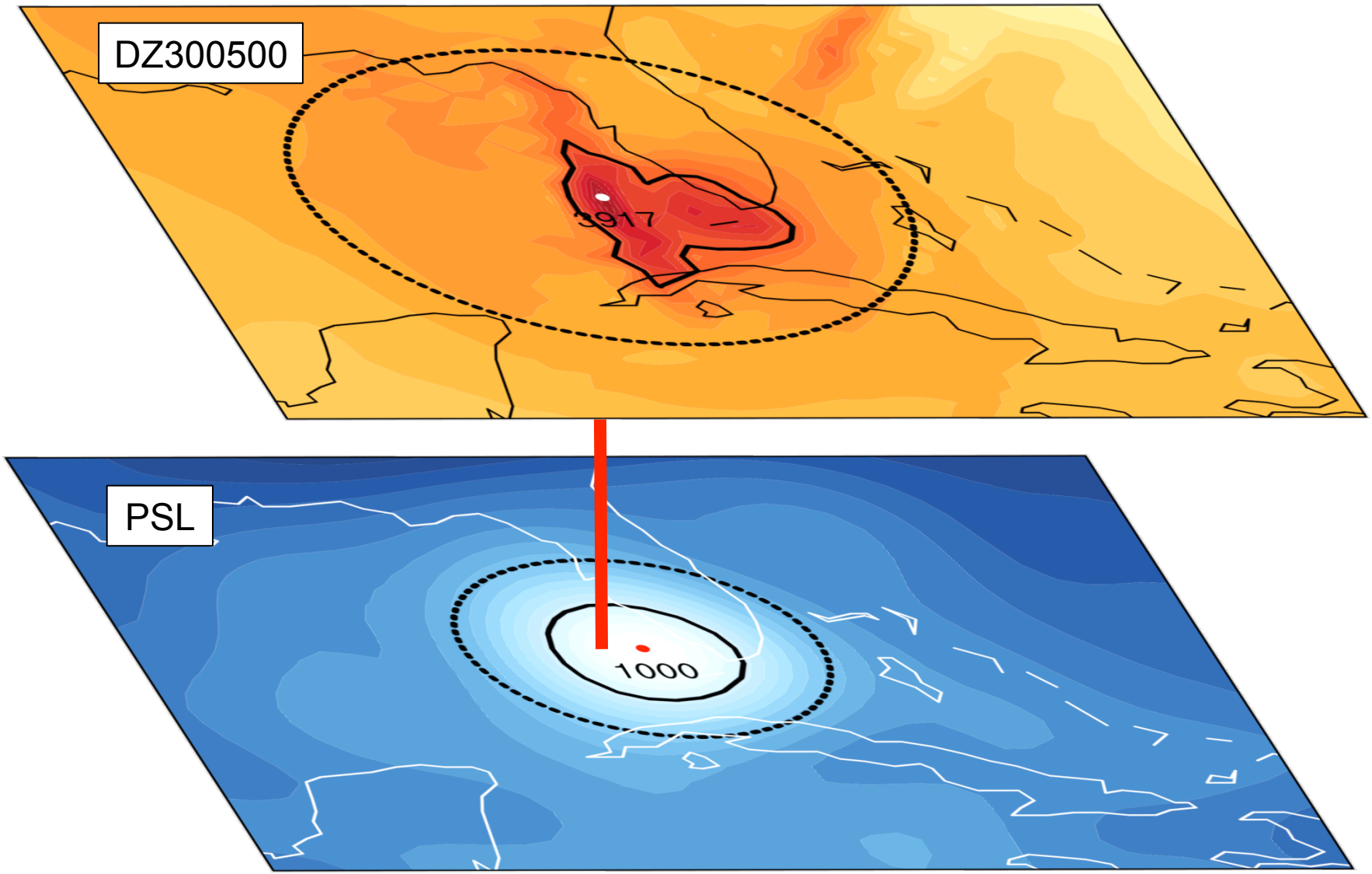
"DETECT"

"STITCH"

Detect

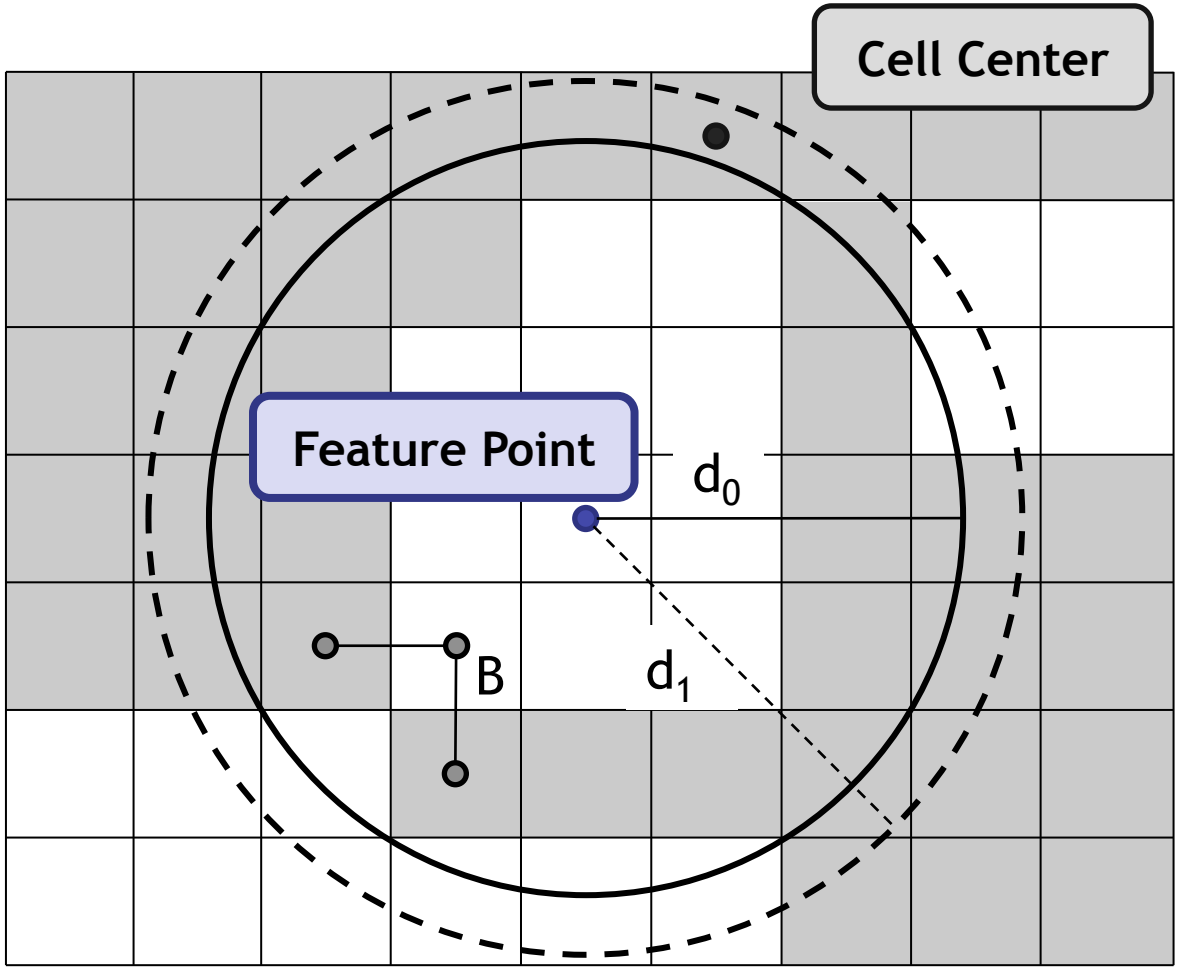


Detect



Detect

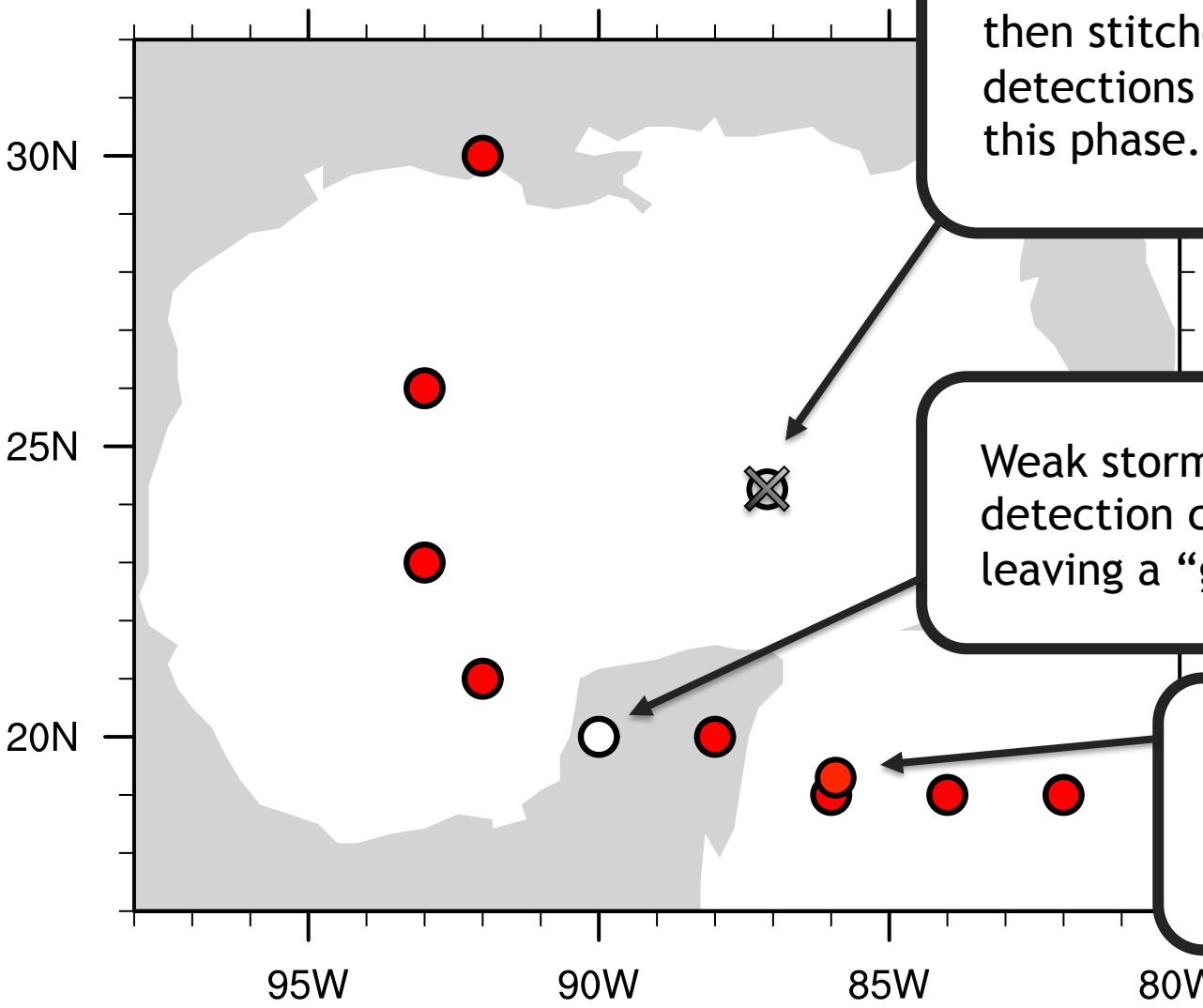
- Many newer trackers adopting closed contours for rather than specifying an absolute maximum/ minimum
- Closed contours are formulated as "<variable> must increase/decrease by at least <amount> over a distance of <degrees>"



Examples of tracking variables

- Tropical cyclones
  - Common tracking vars (PSL, VORT850)
  - Common “rejection” vars (T400, DZ300500, d(VORT)/dZ)
- Extratropical cyclones
  - Common tracking vars (PSL, VORT850)
  - Common “rejection” vars (PHIS, Z700)
- Atmospheric rivers
  - Common tracking vars (TPW, WIND850)
- Mesoscale convective systems
  - Common tracking vars (PRECT, OLR)

Stitch

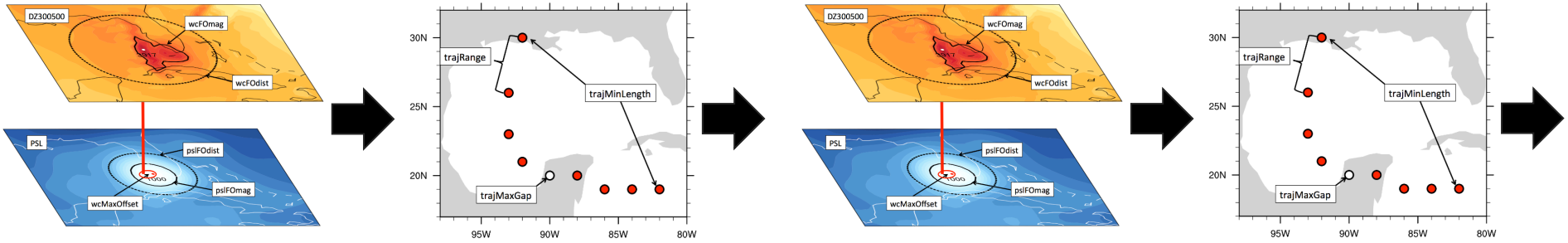


Candidate tropical cyclones are then stitched in time. Isolated detections can be eliminated at this phase.

Weak storms may not satisfy detection criteria at 1-2 points, leaving a "gap" in trajectory.

Multiple essentially collocated detections must be merged

Historical workflow



- Works fine on lower resolution data (~1° and coarser)
- Ex: with FORTRAN, Zarzycki and Jablonowski (2014) can do 20 years of 1° data in ~6 hours (night at The Dark Horse!)
- 0.25° data requires 16x more grid points
  - 4 days!
  - I/O memory bottlenecks?

MapReduce for parallel implementation

- **MapReduce:** A method for processing large datasets with a parallel, distributed algorithm.
- **Map():** Detect data from a single timestep to select candidate points or regions. Make this step embarrassingly parallel (out to one timestep per CPU)
- **Reduce():** Perform a summary operation on all candidate points (Stitch). This step requires communication between all threads performing Map(), but does not require much data exchange.

Example parallelization

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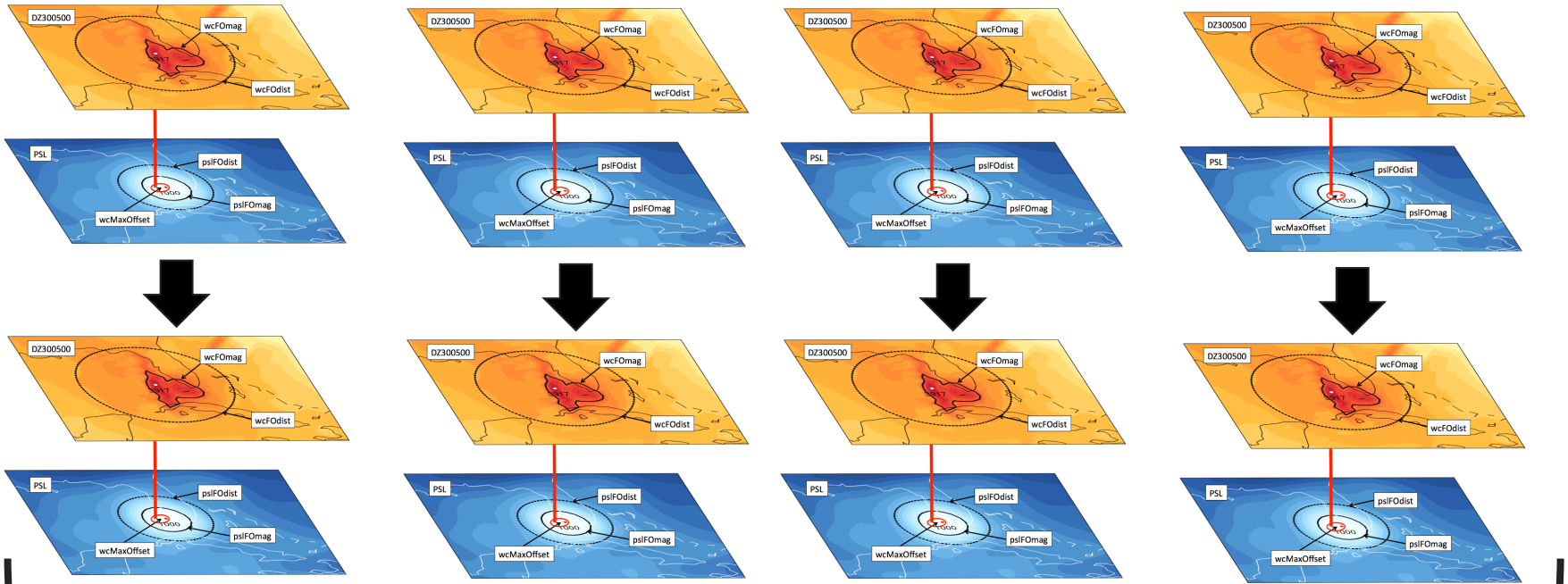
CPU #1 (July)

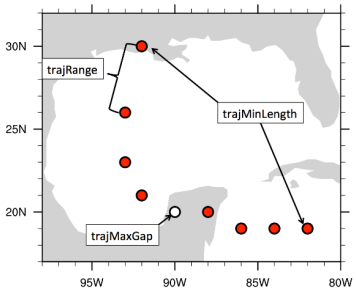
CPU #2 (Aug.)

CPU #3 (Sept.)

CPU #4 (Oct.)



SORT



Aggregate trajectories, statistics

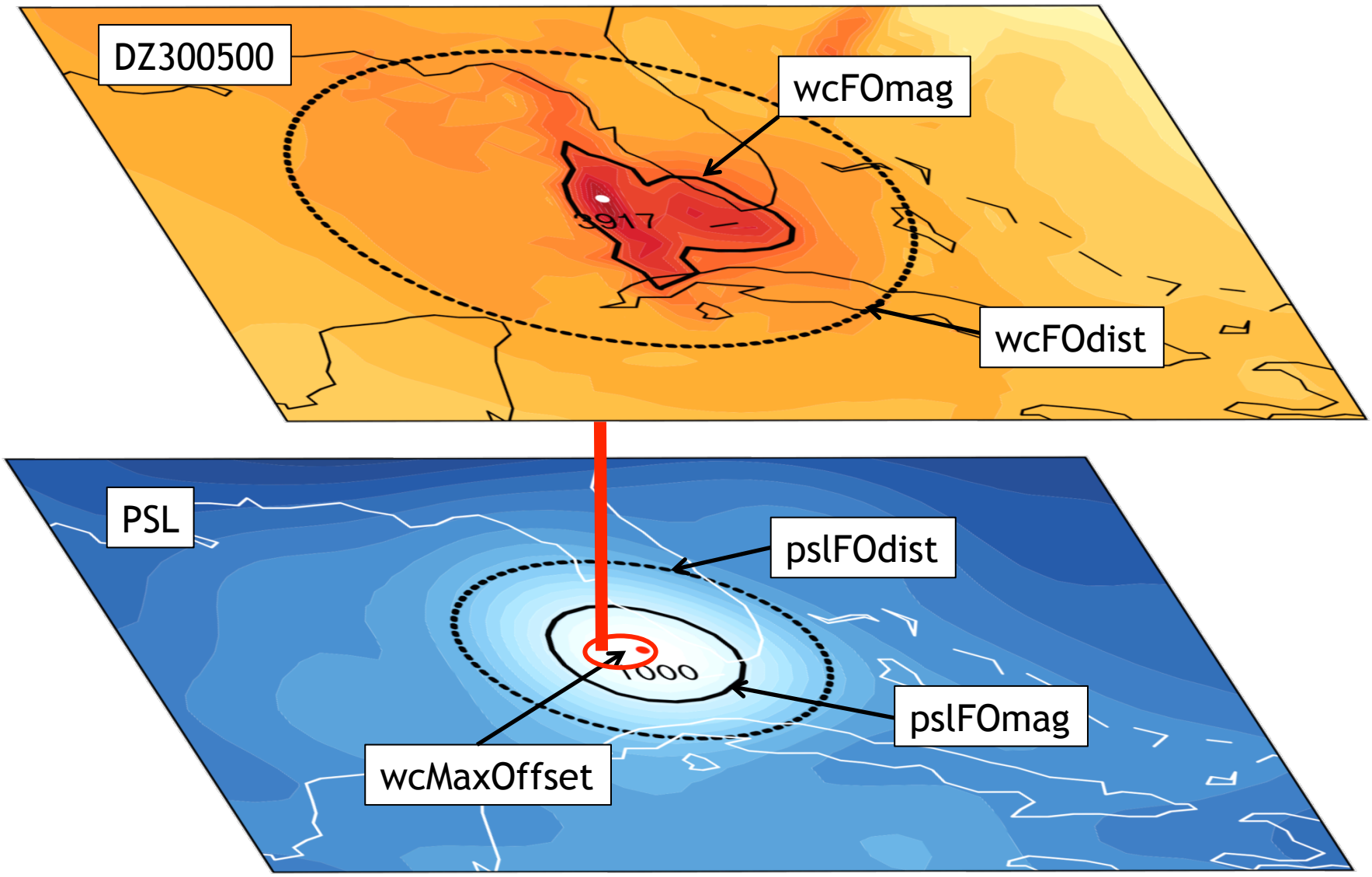
How to assess tracker performance?

- Developing/tuning trackers more of an art than a science
  - Generally physically-based but…
- Do we tune to match observations?
  - Very, very crude subgrid parameterization?
  - What observations?
    - Reanalysis products
    - Point observations?
- Do we care about actual storm counts? Storm track densities? Storm intensity distributions?

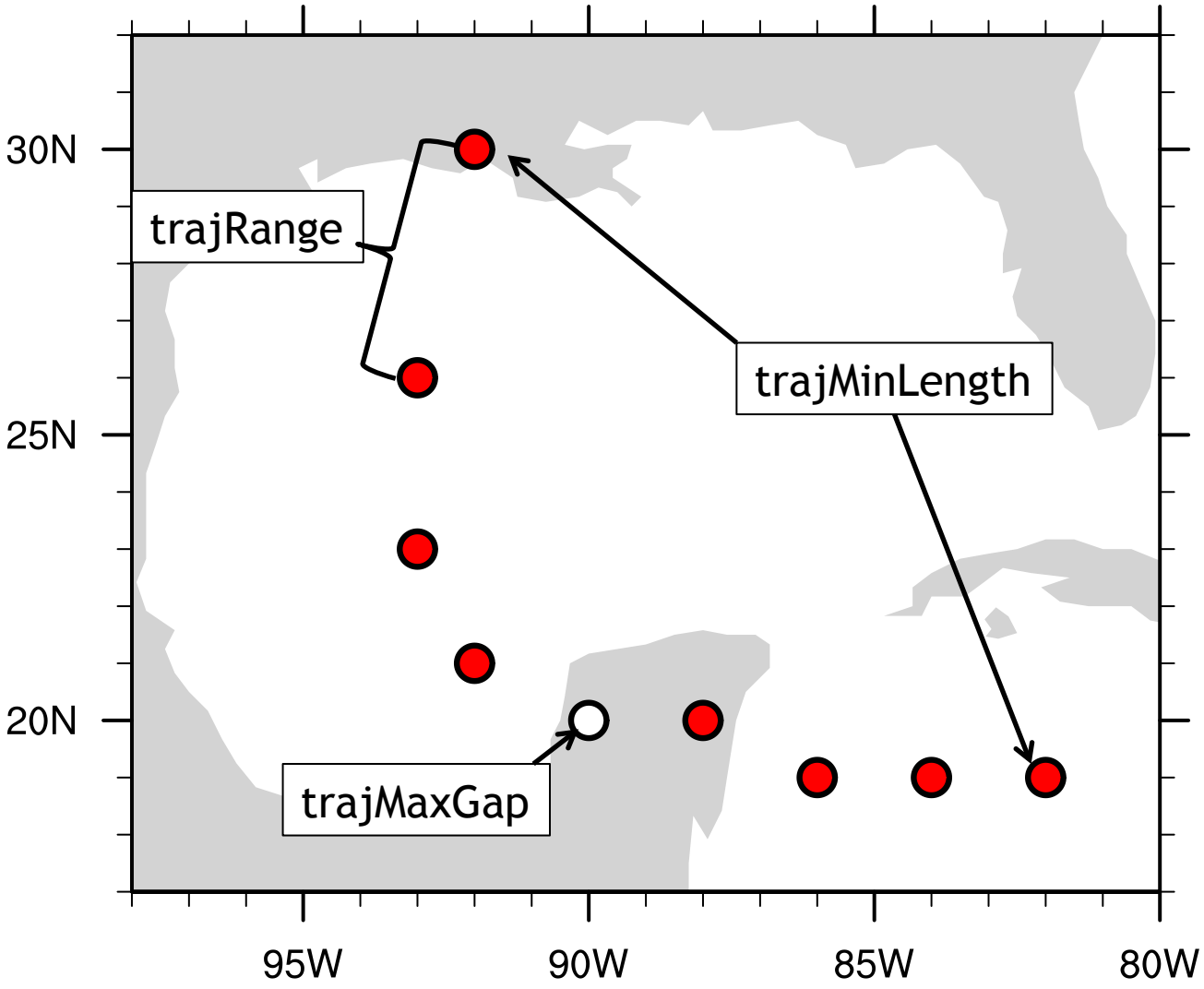
Morris method

- One area where trackers need to be more rigorously tested is sensitivity
- What parameters in tracking algorithms are most sensitive with respect to outputs like cyclone count, hit rate, false alarms, etc.?
- **Morris Method**
  - One at a time (OAT) sensitivity analysis method
  - Demonstrated to determine most sensitive parameters in multivariate model w/ significantly reduced cost vs. similar techniques (e.g., Sobel, LHS, Monte Carlo) (Herman et al., 2013)

“Detect” tuning parameters



“Stitch” tuning parameters



mergeDist

maxTopo

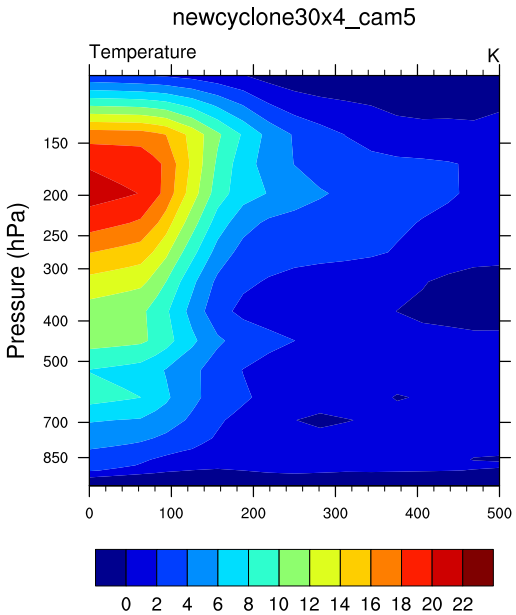
maxLat

Parameter space

VARIABLE	RANGE
pslFOmag	0.5 – 6 hPa
pslFOdist	1 – 8°
wcFOmag (T / DZ)	-2.0 – 0.1 K (-50 to -1 m)
wcFOdist	1 – 8°
wcMaxOffset	0 – 3°
mergeDist	0 – 10°
trajRange (6 hourly)	4 – 12°
trajMinLength	0.5 – 3 days
trajMaxGap	0 – 30 hours
maxTopo	10 – 6000 m
maxLat	40 – 90°

- Technique outlined in Campolongo et al., 2007
- 11 variables
- 12 steps / 12 iterations
- 144 simulations for each warm core variable
- Use 1998-2005 CFSR reanalysis as training set

Which bear… I mean WC… is best?

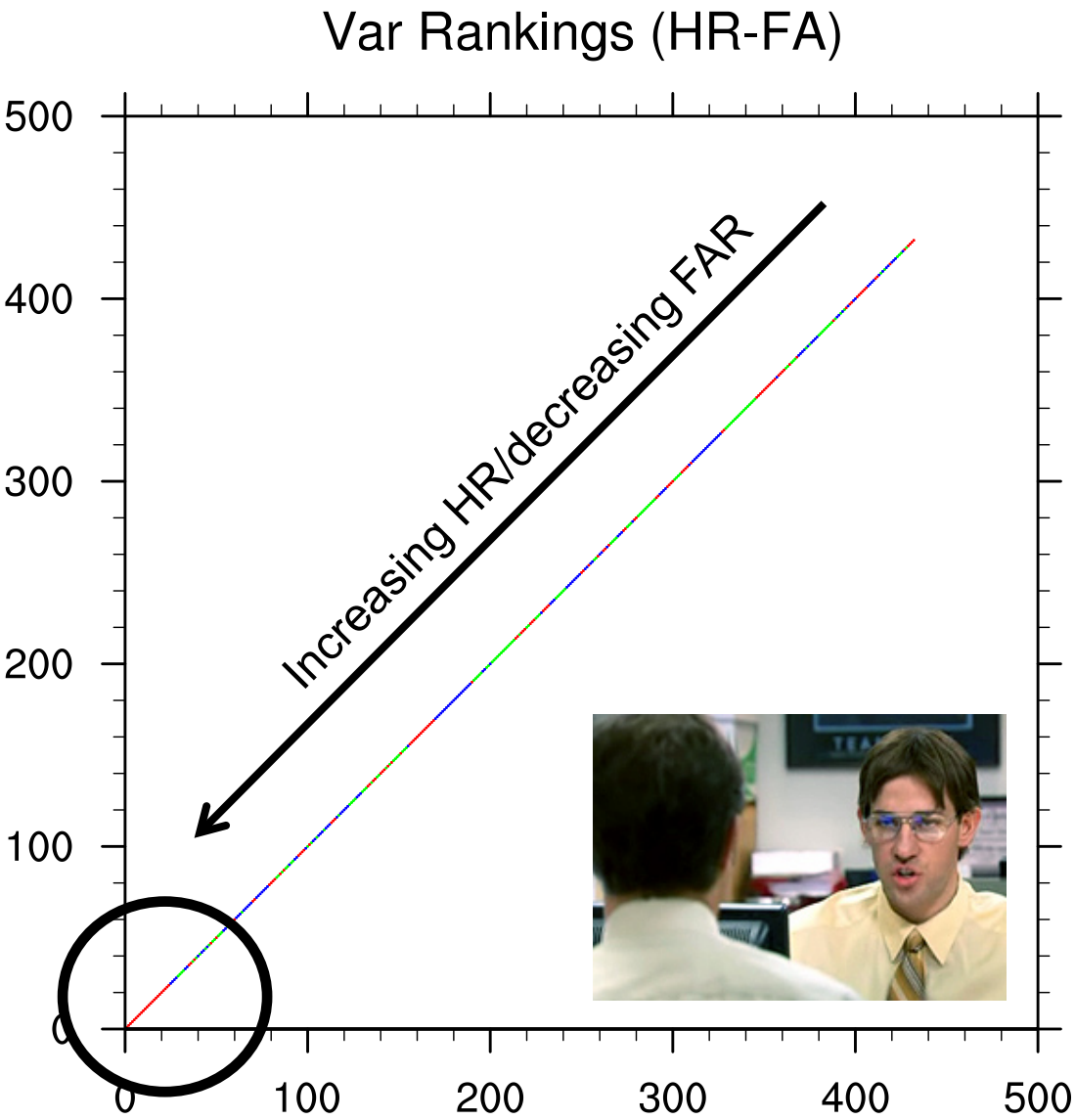


Choice of warm core parameter

DZ300500

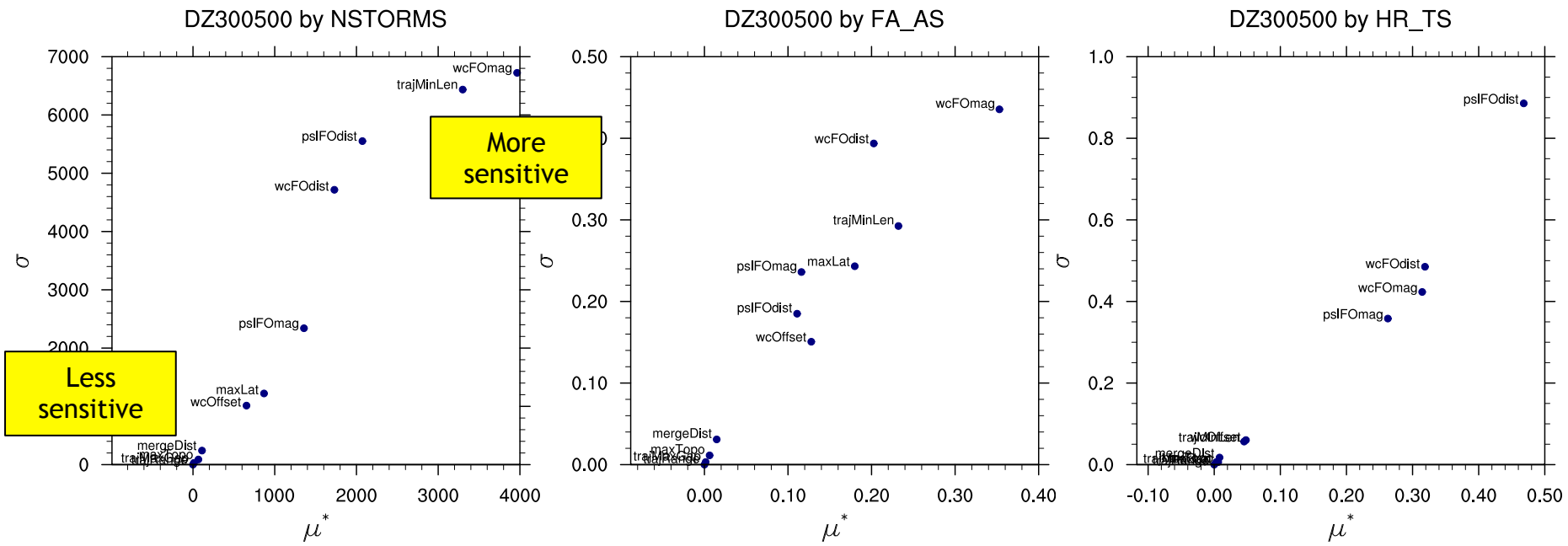
T400

T500



Most sensitive knobs?

Storm count | **False alarms** | **Hit rate**

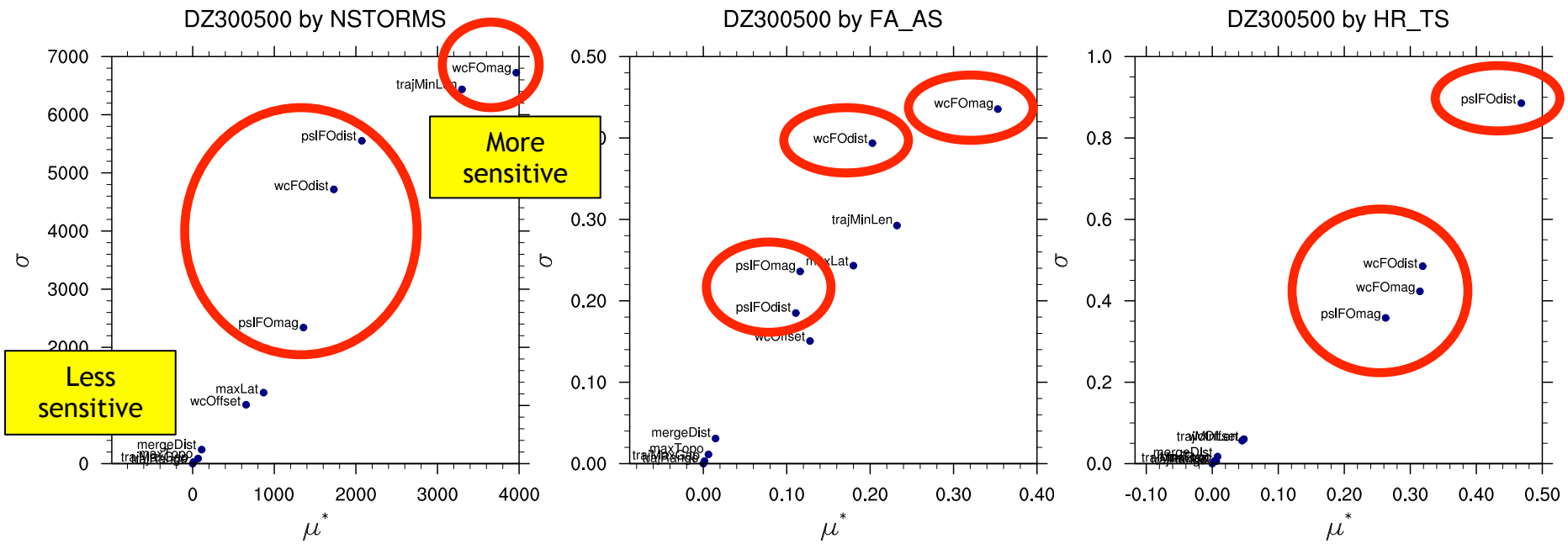


Target: *wcFOmag*, *wcFOdist*, *pslFOmag*, *pslFOdist*

Utilize "best choice:" *trajMinLen*, *maxLat*, *wcOffset*, *mergeDist*, *maxTopo*, *trajRange*, *mergeDist*

Most sensitive knobs?

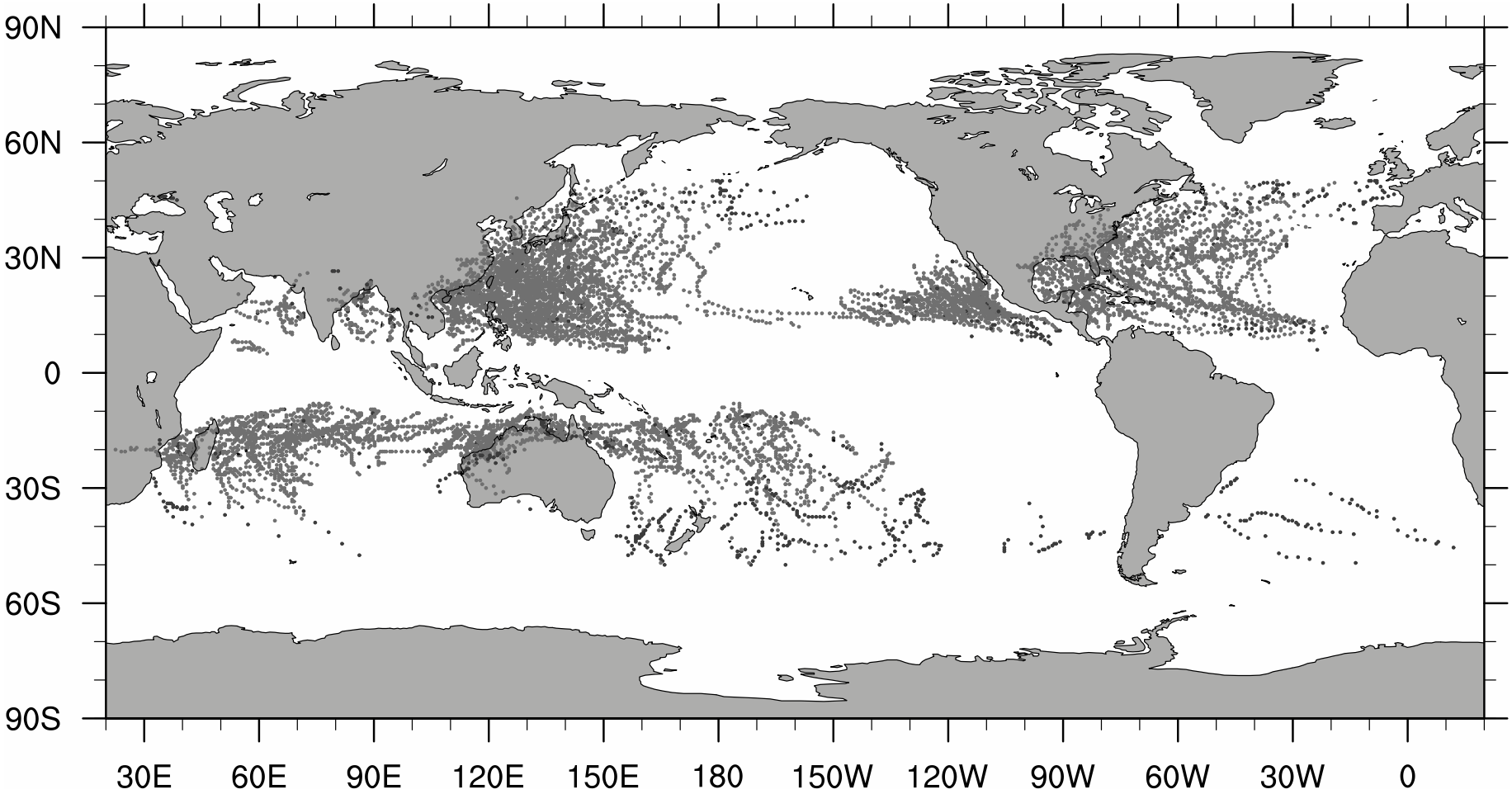
Storm count | **False alarms** | **Hit rate**



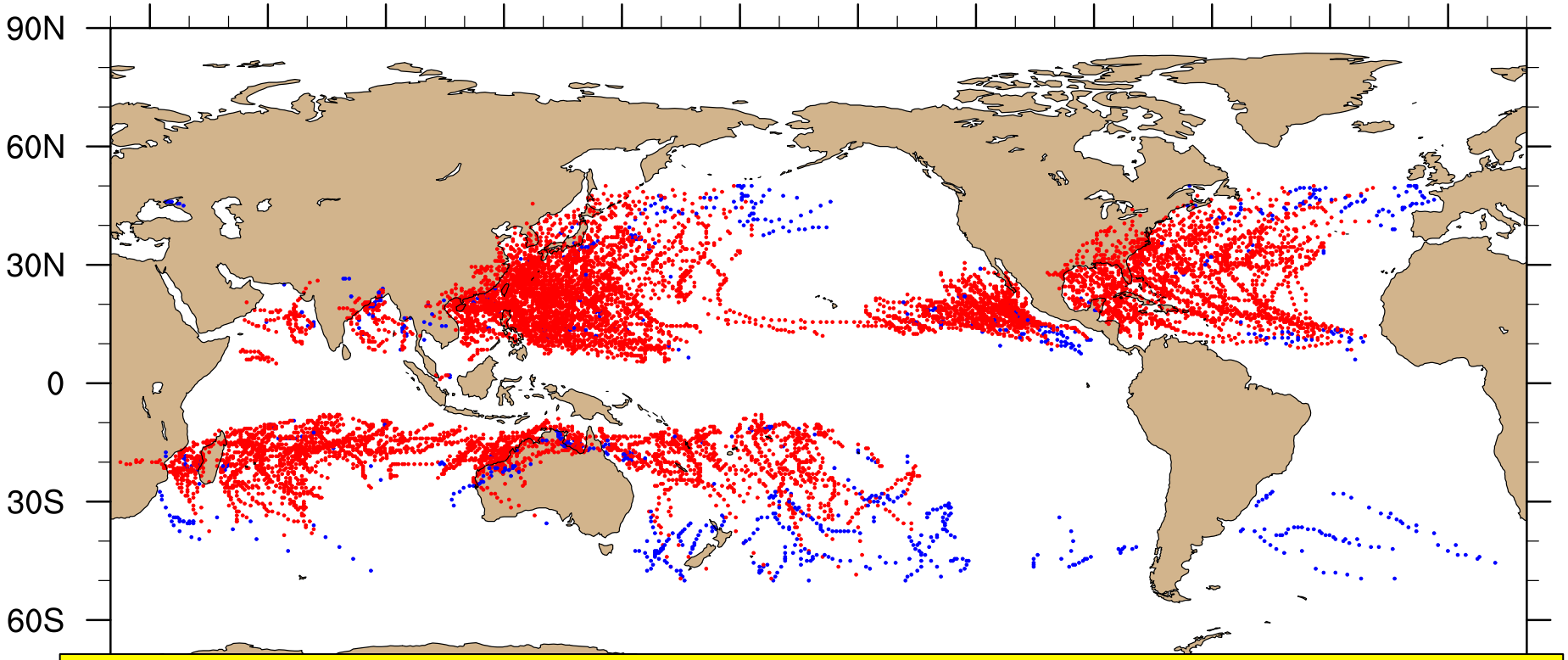
Target: *wcFOmag*, *wcFOdist*, *pslFOmag*, *pslFOdist*

Utilize "best choice:" *trajMinLen*, *maxLat*, *wcOffset*, *mergeDist*, *maxTopo*, *trajRange*, *mergeDist*

Tracked tracks…



Tracked tracks…

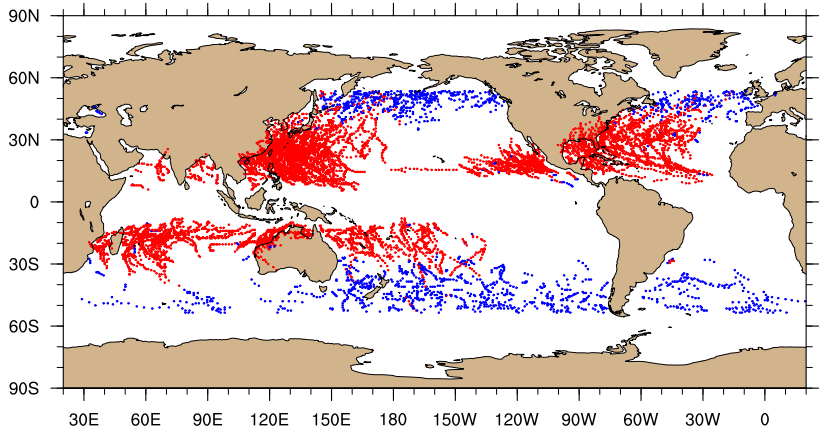


- SA provides understanding of what variables are targets + yields best skill score (added bonus!)
- Big questions?
  - Can we tune trackers against reanalysis?
  - Resolution sensitivity (next step – how to separate dynamical resolution from statistical resolution?)

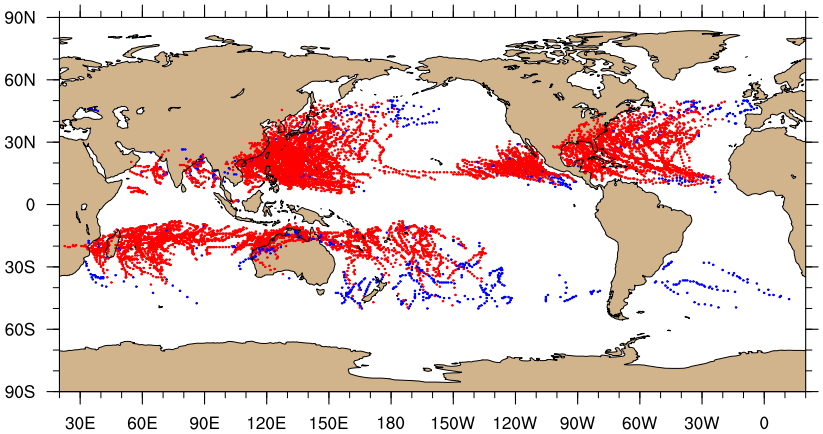
Considerations: tuning

- Some modeling groups have tuned low-medium resolution simulations to get accurate “observed” counts of storms
- Ex: WMO definition of tropical cyclone requires 17 m/s wind speed
  - 10 m/s wind threshold produces more realistic TC count in climate data
- **The ugly: many additional features not unresolved TCs, but rather, resolved non-TCs**
- Use integrated variables (ACE, etc.), hit rate, etc.

92 storms/yr



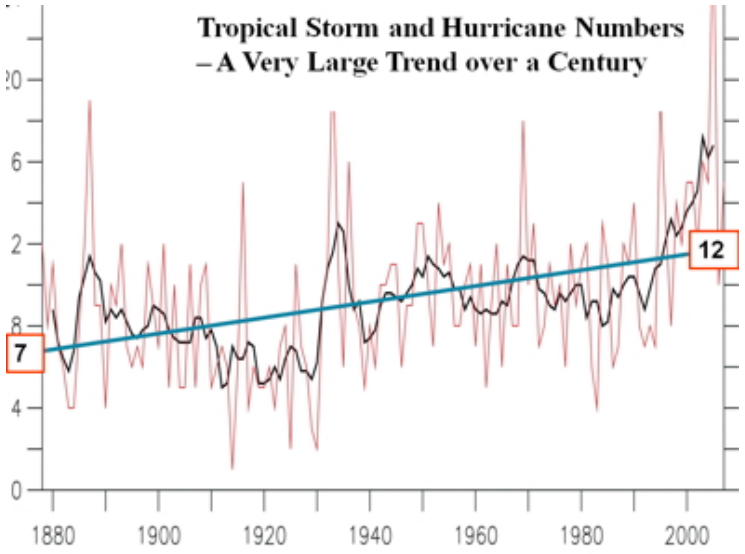
OBS: ~89 storms/yr

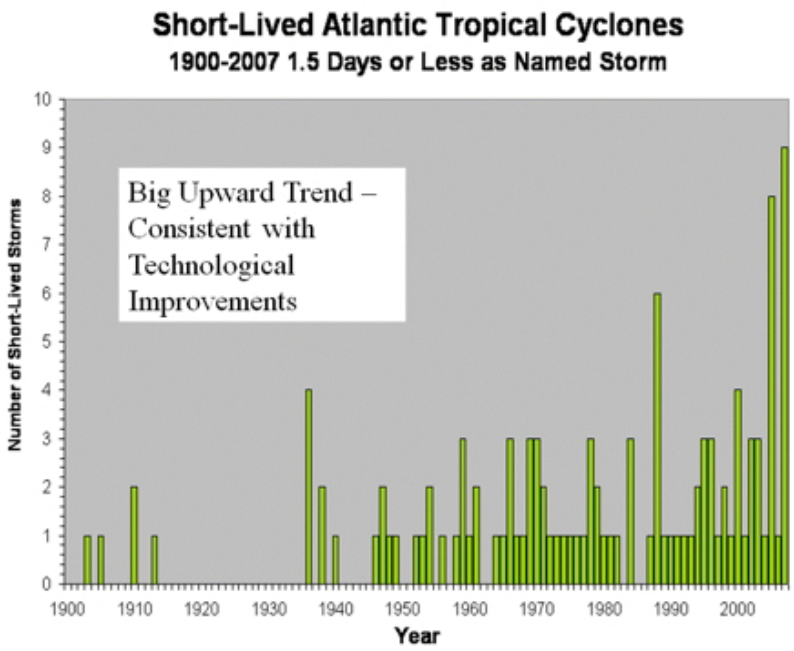


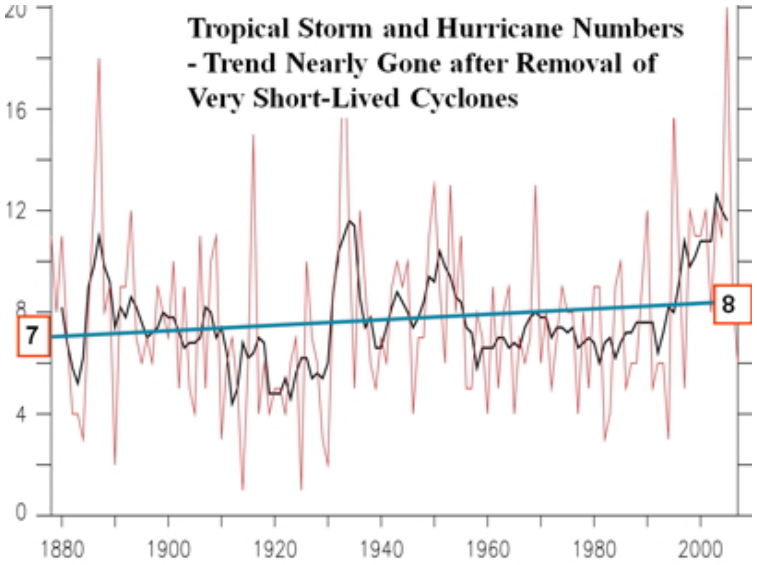
68 storms/yr

Considerations: Observational record

- Number of weak, short-lived observed tropical cyclones increased recently
- Skews observational record



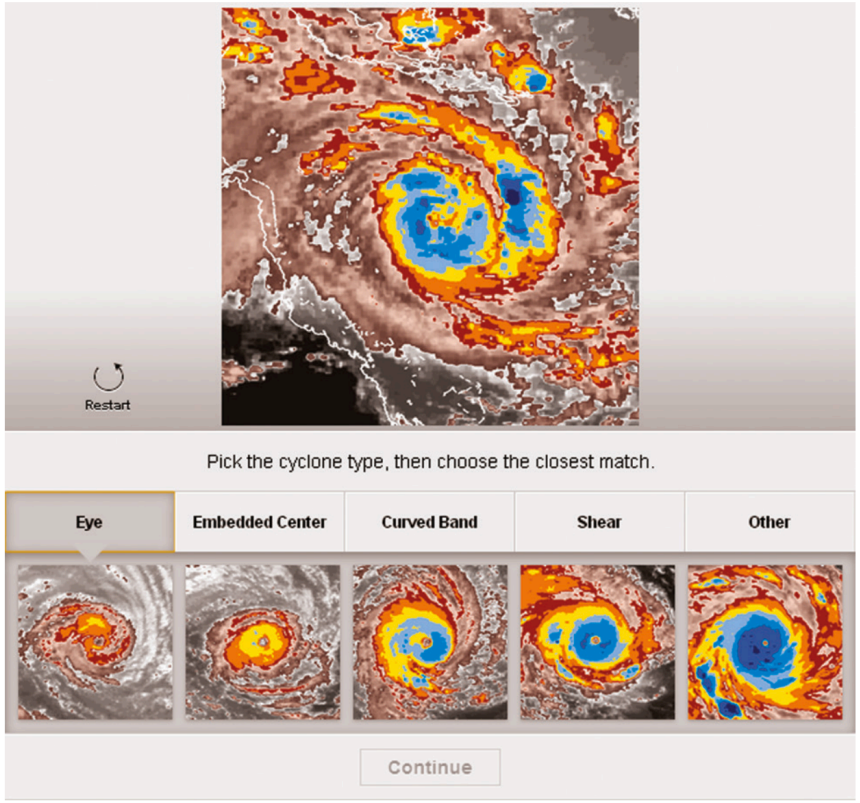


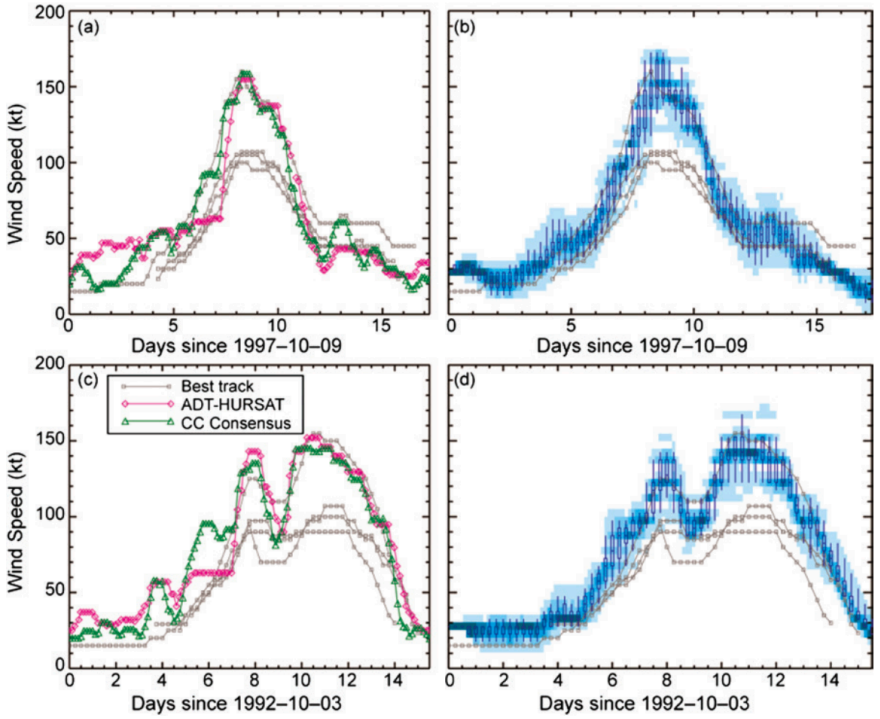


courtesy Chris Landsea, NOAA

The future: Crowdsourcing?

- Humans subjectively track many weather features already
- Are our climate models good enough to produce synthetic fields (ex: satellite images)
- Leverage those weenies!





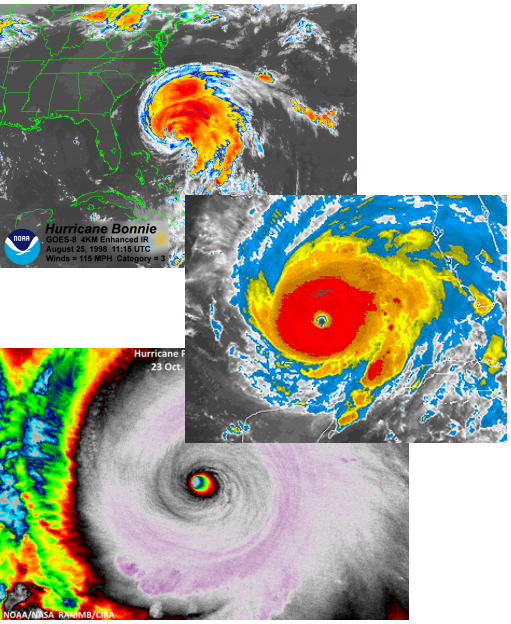
Hennon et al., 2015, BAMS

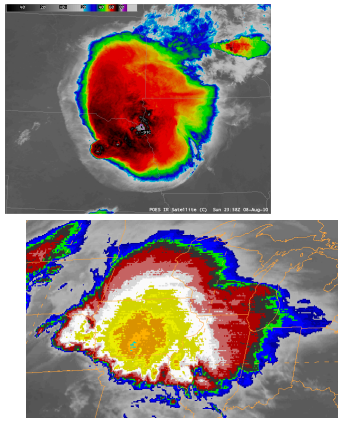
The future: Machine learning?

TRAINING DATA (observations)

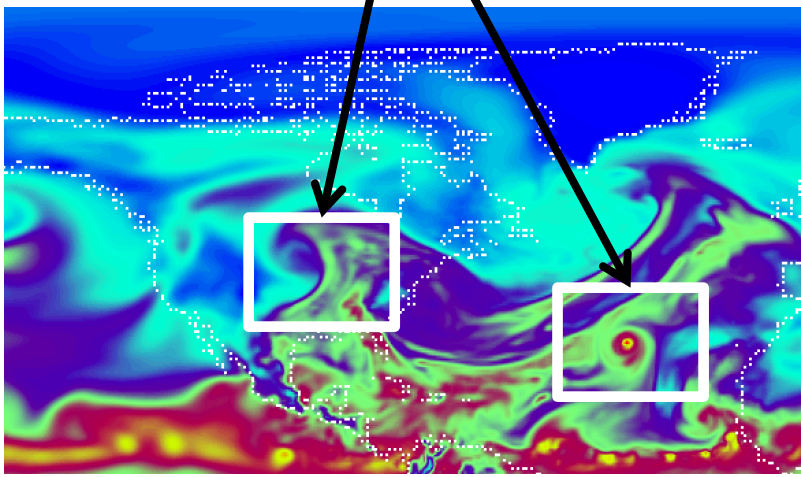
Tropical cyclones

Mesoscale convective systems





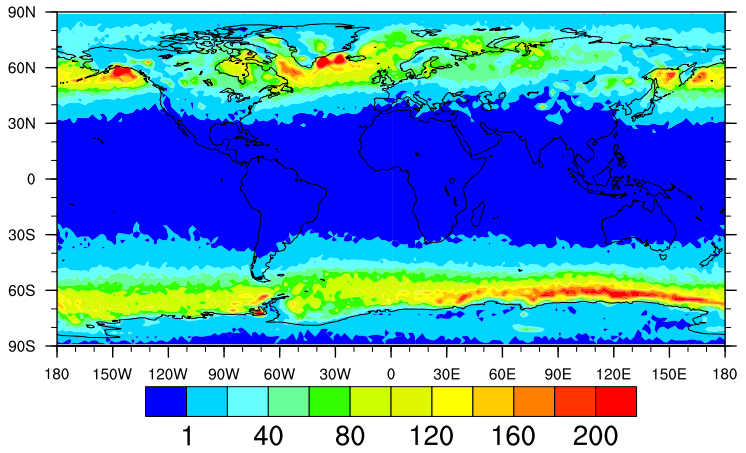
NEURAL NETWORK

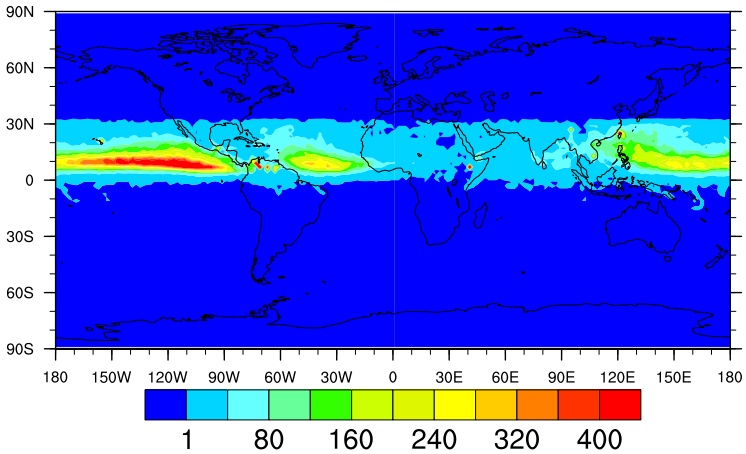


Objective tracking of extremes

(Ullrich and Zarzycki, in prep.)

- **TempestExtremes**: objective tracking algorithm for climate data
- C++, time-parallel
  - 100 years of 0.25° data in 2 minutes (1200 CPUs)
- Unstructured grid support
- Flexible command line, user-customizable I/O
- Already tracked
  - Extratropical cyclones
  - Tropical waves
  - Mesoscale convection complexes
  - Atmospheric rivers
- https://github.com/paullric/tempestextremes





Summary

- Weather/climate extremes are highly relevant for human health and welfare
- As model resolution increases, features of interest are better resolved, require tracking
- Lagrangian tracking favored for small-scale, rare, severe events
- Climate model data increasing in size, requiring sophisticated coding/software engineering to make data analysis practical
- Community needs to exercise caution…
  - Design choices rooted in theory
  - Objectively assess observational record
  - Understand uncertainty bounds on reported results