An Algorithm to Identify and Track Objects on Spatial Grids

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Clustering, nowcasting and data mining spatial grids

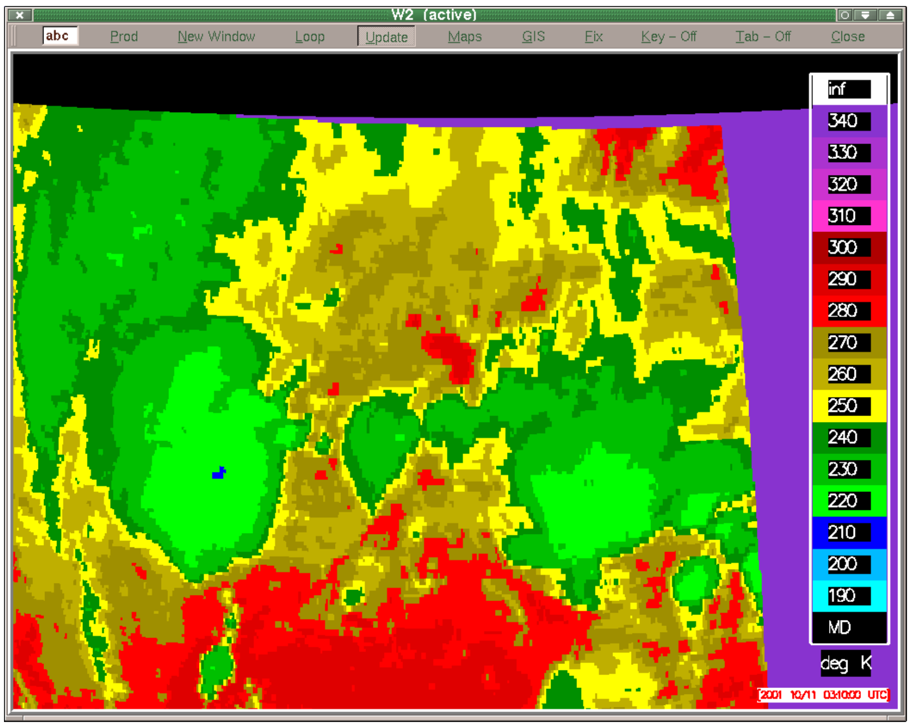
- **The "segmotion" algorithm**
- Example applications of algorithm
  - Infrared Imagery
  - Azimuthal Shear
  - Total Lightning
  - Cloud-to-ground lightning
- Extra information [website?]
  - Tuneable parameters
  - Objective evaluation of parameters
  - How to download software
  - Mathematical details
  - References

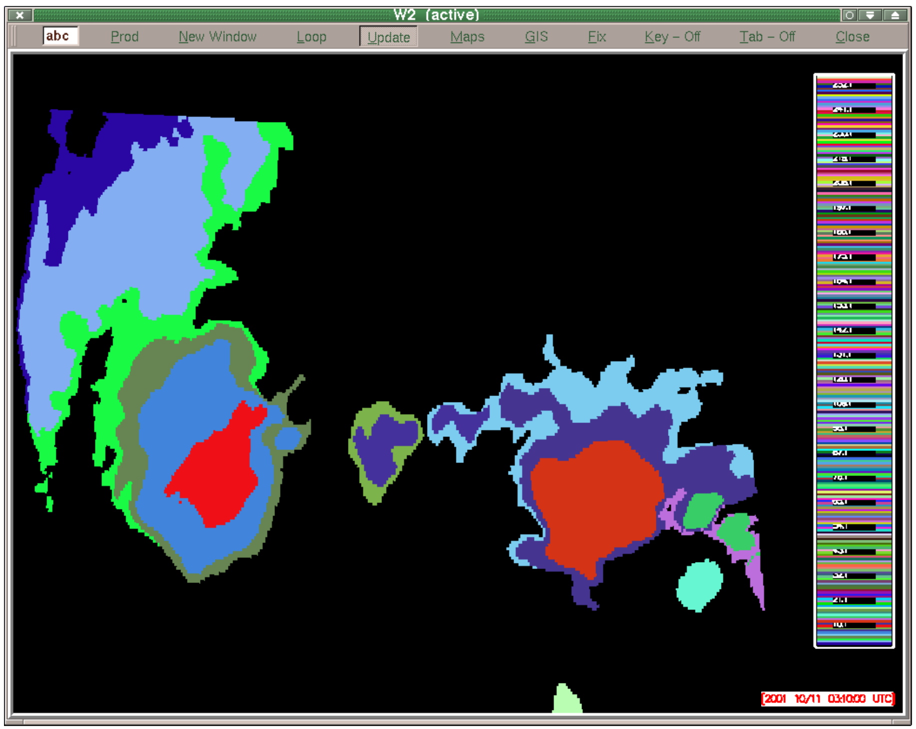
Algorithm for Tracking, Nowcasting & Data Mining

- Segmentation + Motion Estimation
  - Segmentation --> identifying parts ("segments") of an image
  - Here, the parts to be identified are storm cells
- segmotion consists of image processing steps for:
  - Identifying cells
  - Estimating motion
  - Associating cells across time
  - Extracting cell properties
  - Advecting grids based on motion field
- segmotion can be applied to any uniform spatial grid

Vector quantization via K-Means clustering [1]

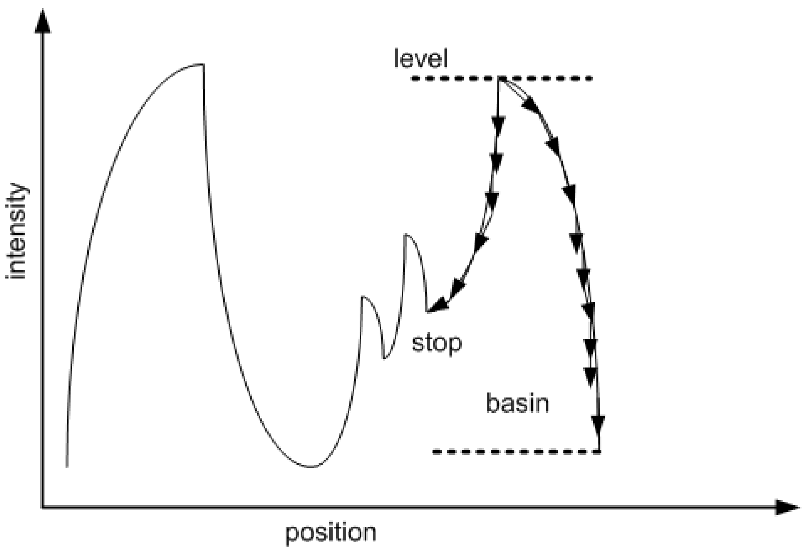
- Quantize the image into bands using K-Means
  - “Vector” quantization because pixel “value” could be many channels
  - Like contouring based on a cost function (pixel value & discontiguity)

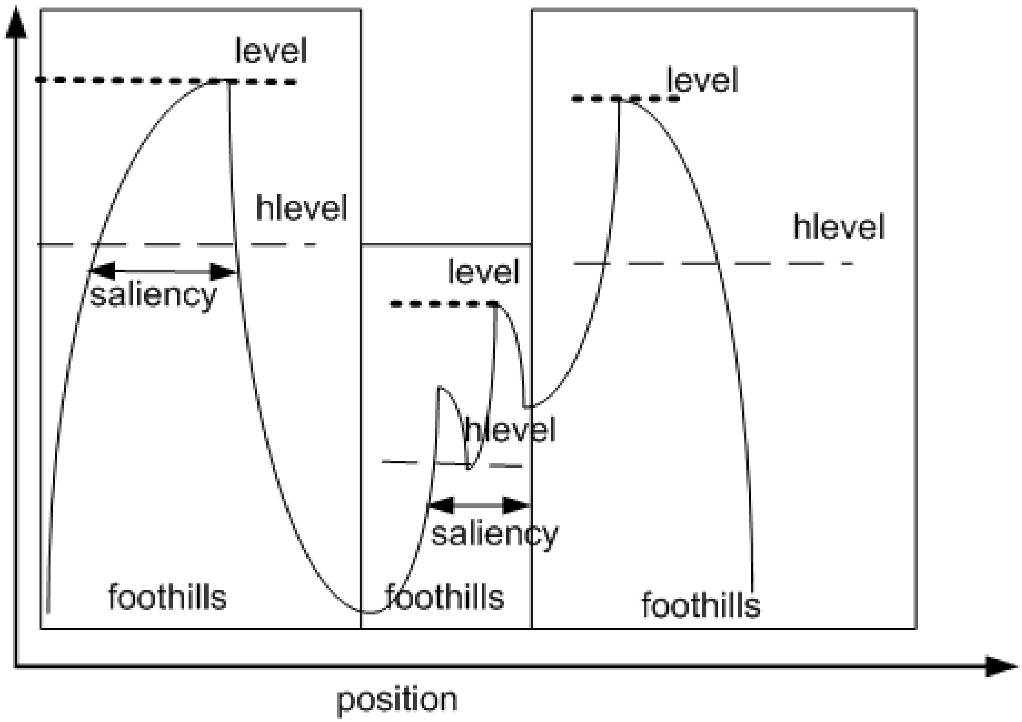




Enhanced Watershed Algorithm [2]

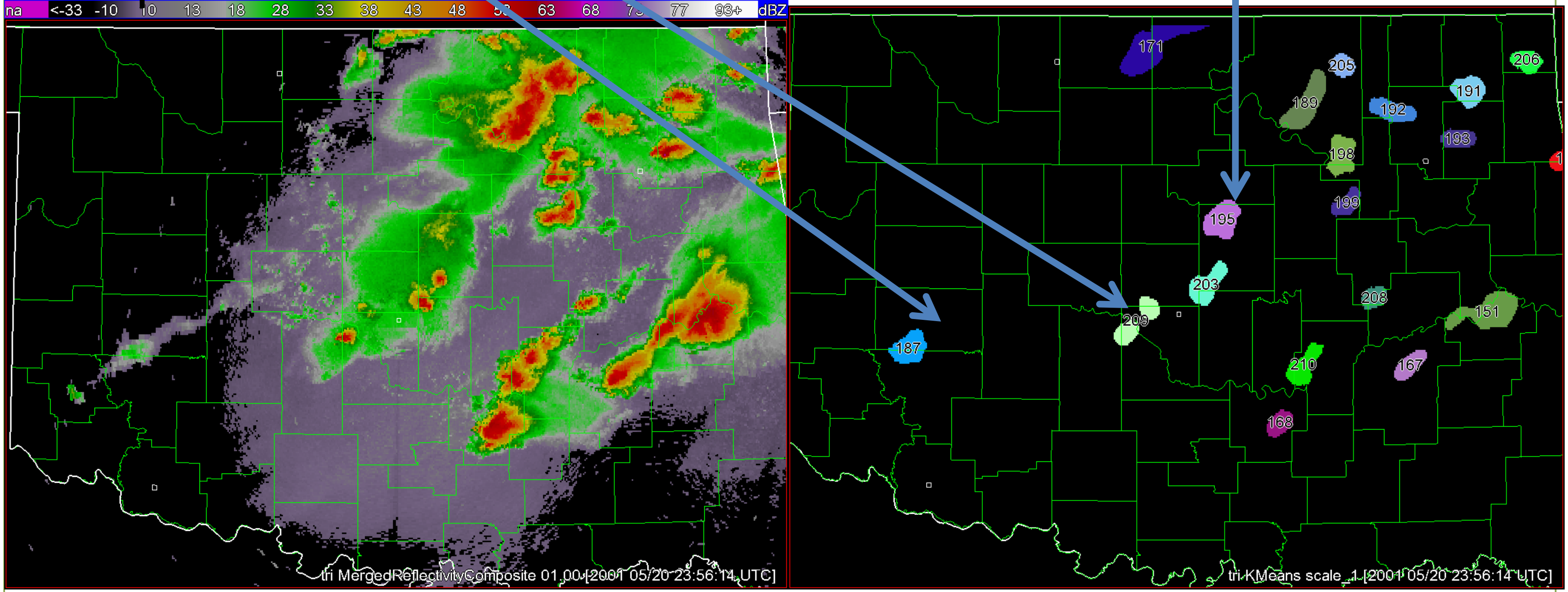
- Starting at a maximum, “flood” image
  - Until specific size threshold is met: resulting “basin” is a storm cell
  - Multiple (typically 3) size thresholds to create a multiscale algorithm





Storm Cell Identification: Characteristics

- Cells grow until they reach a specific size threshold
- Cells are local maxima (not based on a global threshold)
- Optional: cells combined to reach size threshold

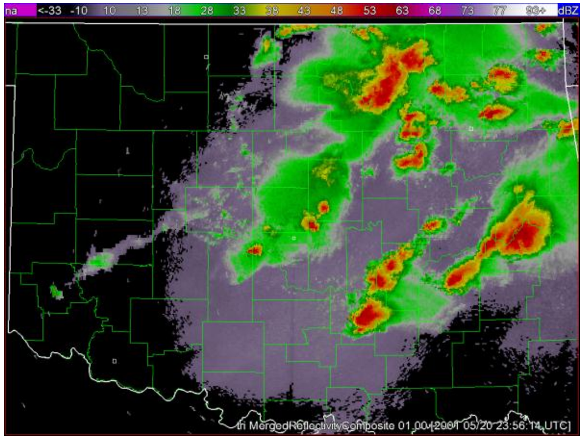


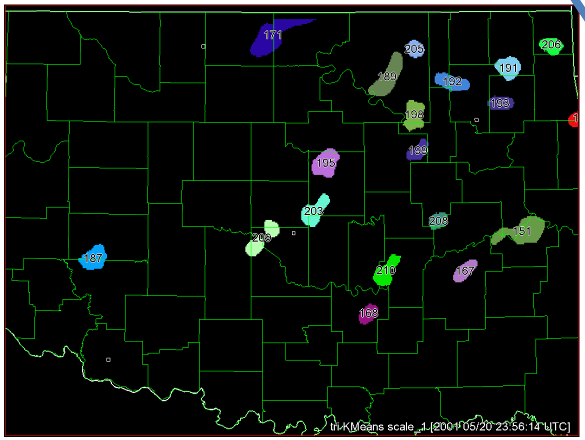
Cluster-to-image cross correlation [1]

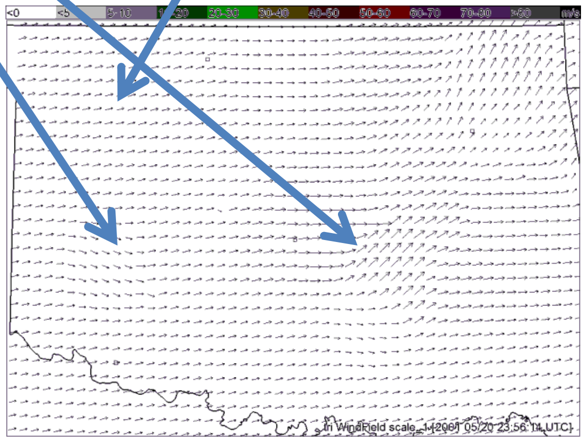
- Pixels in each cluster overlaid on previous image and shifted
  - The mean absolute error (MAE) is computed for each pixel shift
  - Lowest MAE -> motion vector at cluster centroid
- Motion vectors objectively analyzed
  - Forms a field of motion vectors u(x,y)
  - Field smoothed over time using Kalman filters

Motion Estimation: Characteristics

- Because of interpolation, motion field covers most places
  - Optionally, can default to model wind field far away from storms
- The field is smooth in space and time
  - Not tied too closely to storm centroids
- Storm cells do cause local perturbation in field

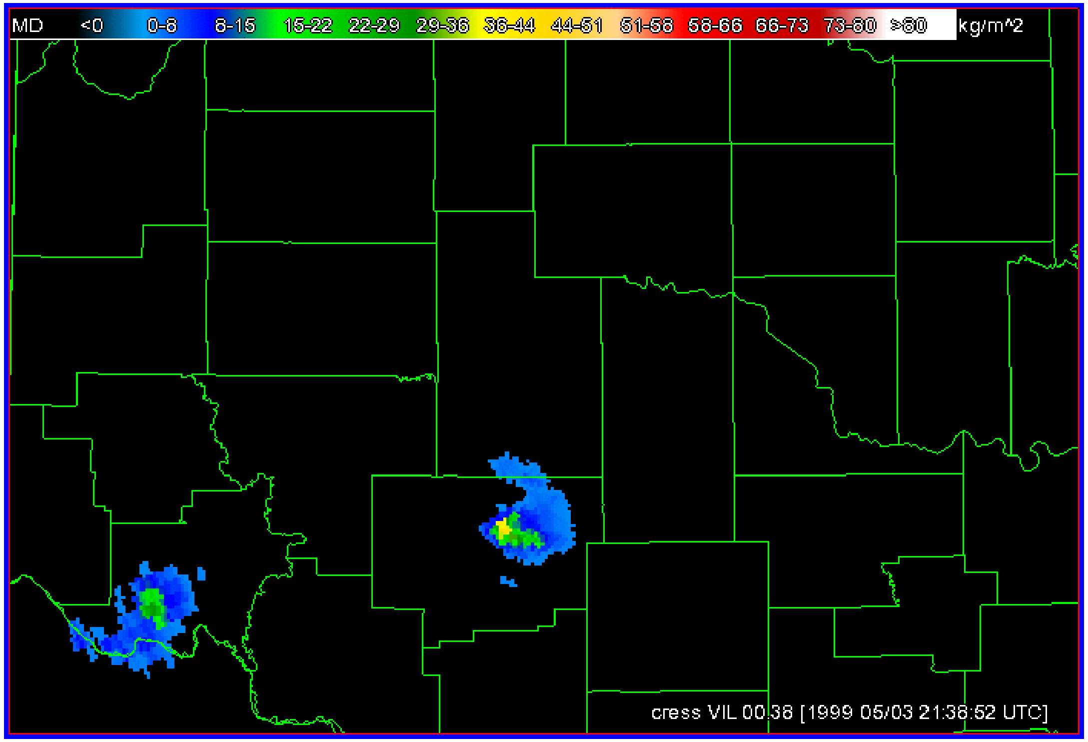






Nowcasting Uses Only the Motion Vectors

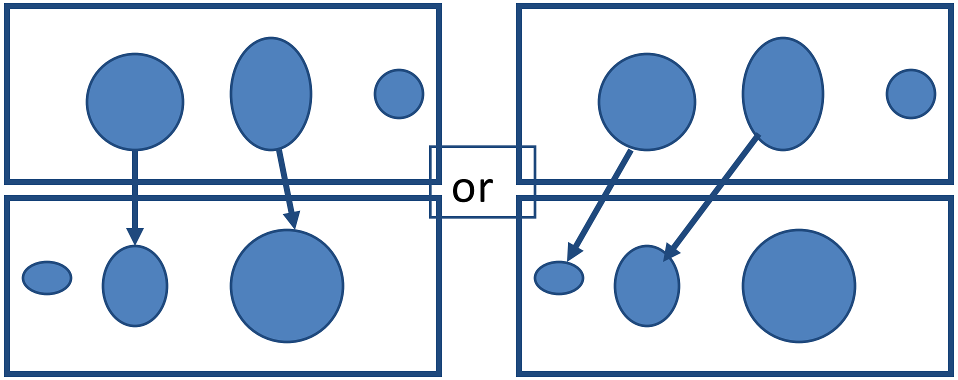
- No need to cluster predictand or track individual cells
  - Nowcast of VIL shown



Unique matches; size-based radius; longevity; cost [4]

- Project cells identified at t_{n-1} to expected location at t_n
- Sort cells at t_{n-1} by track length so that longer-lived tracks are considered first
- For each projected centroid, find all centroids that are within sqrt(A/pi) kms of centroid where A is area of storm
- If unique, then associate the two storms
- Repeat until no changes
- Resolve ties using cost

fn. based on size, intensity



Geometric, spatial and temporal attributes [3]

- Geometric:
  - Number of pixels -> area of cell
  - Fit each cluster to an ellipse: estimate orientation and aspect ratio
- Spatial: remap other spatial grids (model, radar, etc.)
  - Find pixel values on remapped grids
  - Compute scalar statistics (min, max, count, etc.) within each cell
- Temporal can be done in one of two ways:
  - Using association of cells: find change in spatial/geometric property
    - Assumes no split/merge
  - Project pixels backward using motion estimate: compute scalar statistics on older image
    - Assumes no growth/decay

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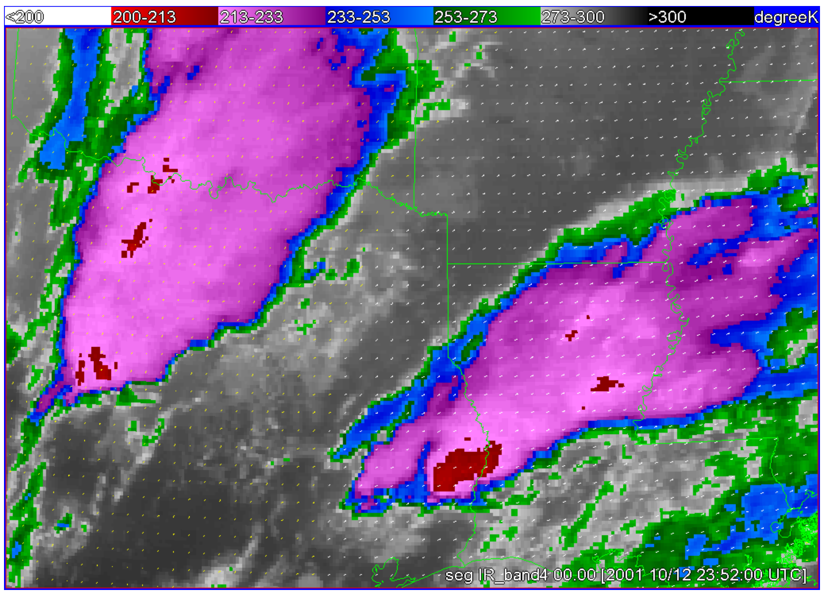
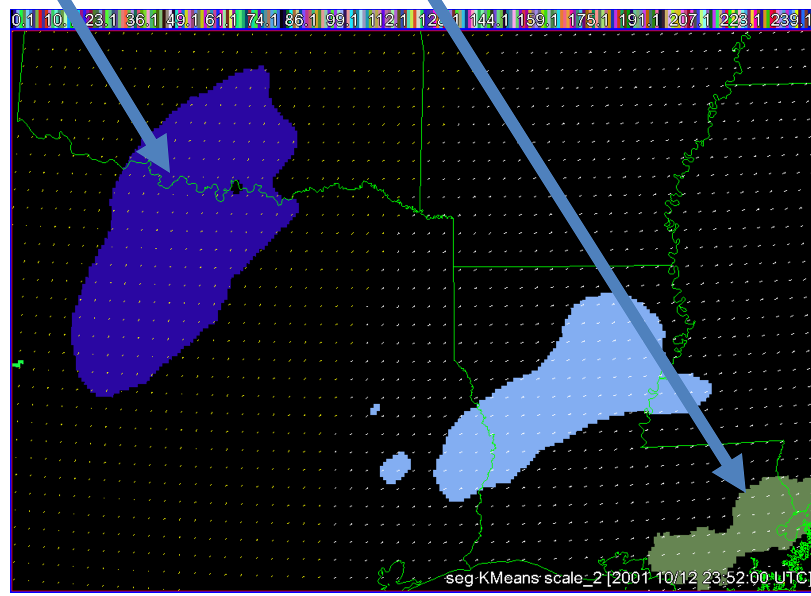
Identify and track cells on infrared images

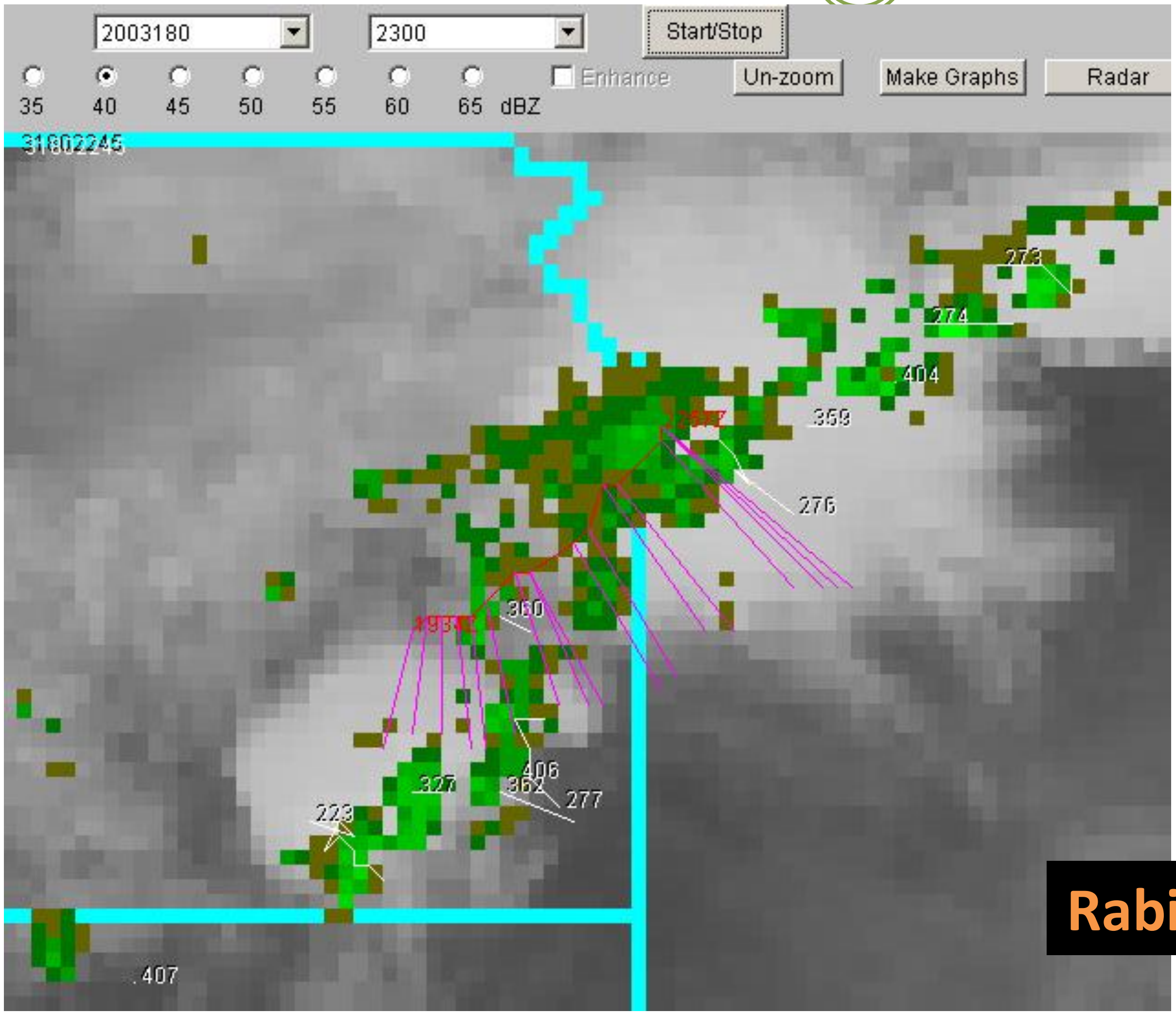
Not just a simple thresholding scheme





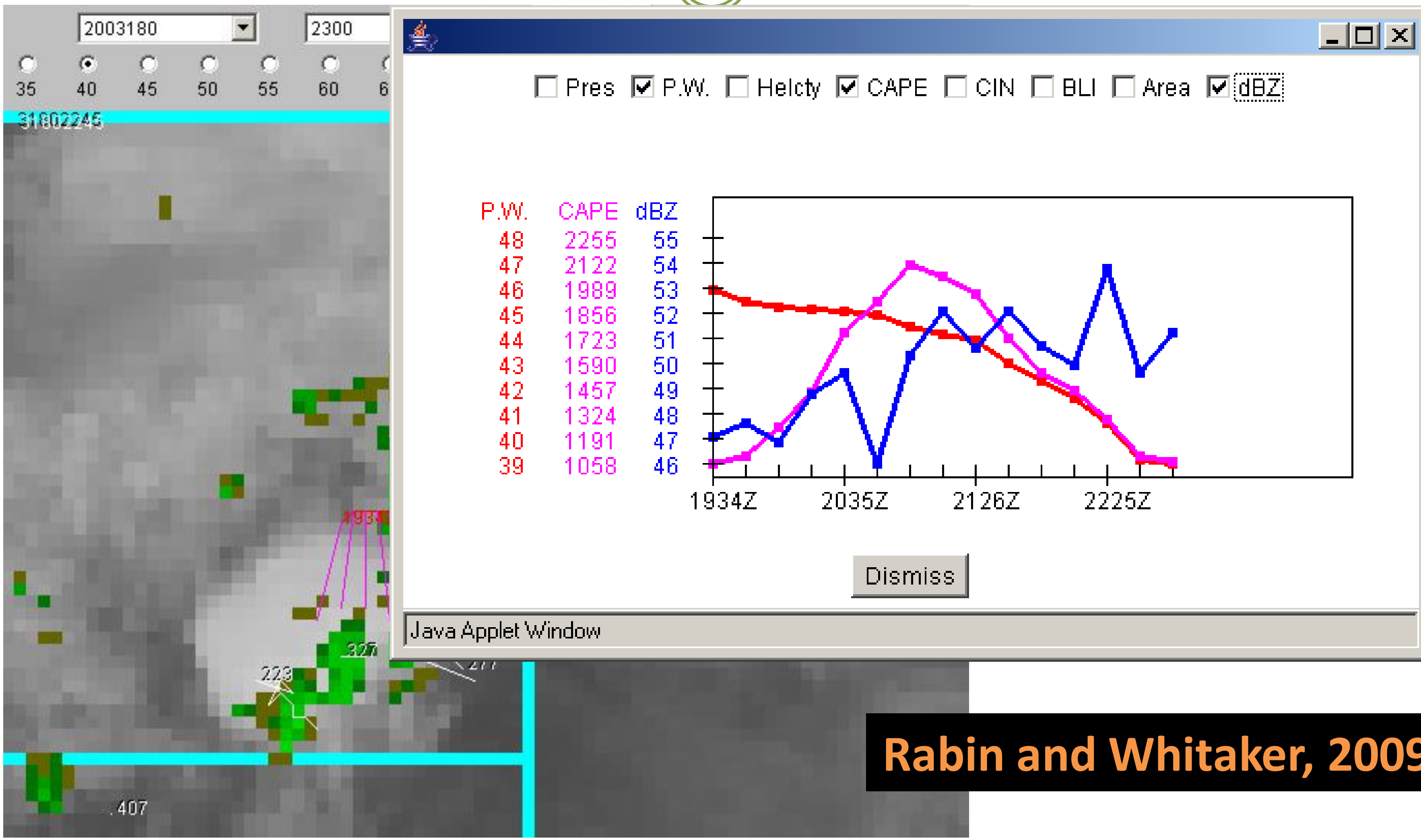
Coarsest scale shown because 1-3 hr forecasts desired.

Plot centroid locations along a track



Rabin and Whitaker, 2009

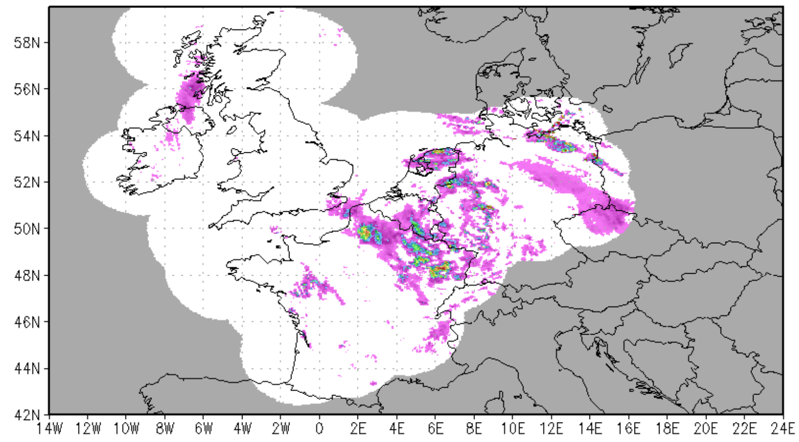
Associate model parameters with identified cells



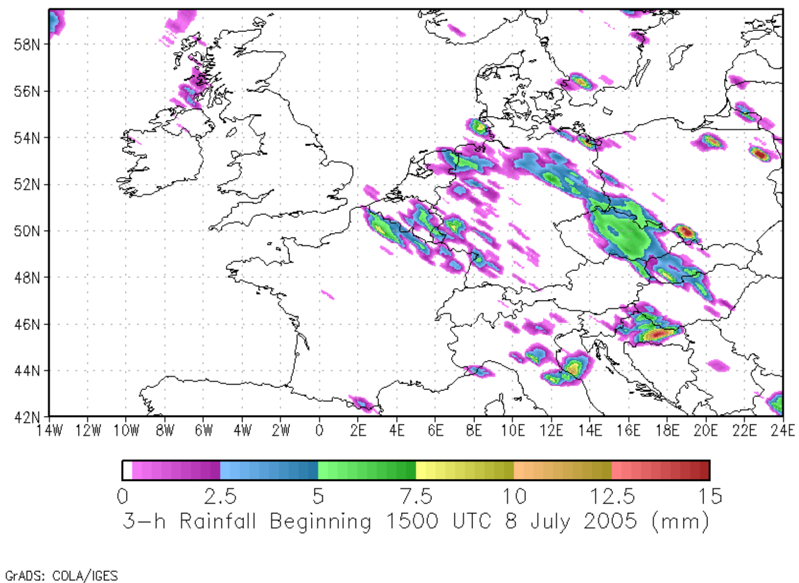
Rabin and Whitaker, 2009

Create 3-hr nowcasts of precipitation

NIMROD 3-hr precip accumulation



Rainfall Potential using Hydroestimator and advection on SEVIRI data



Kuligowski et. al, 2009

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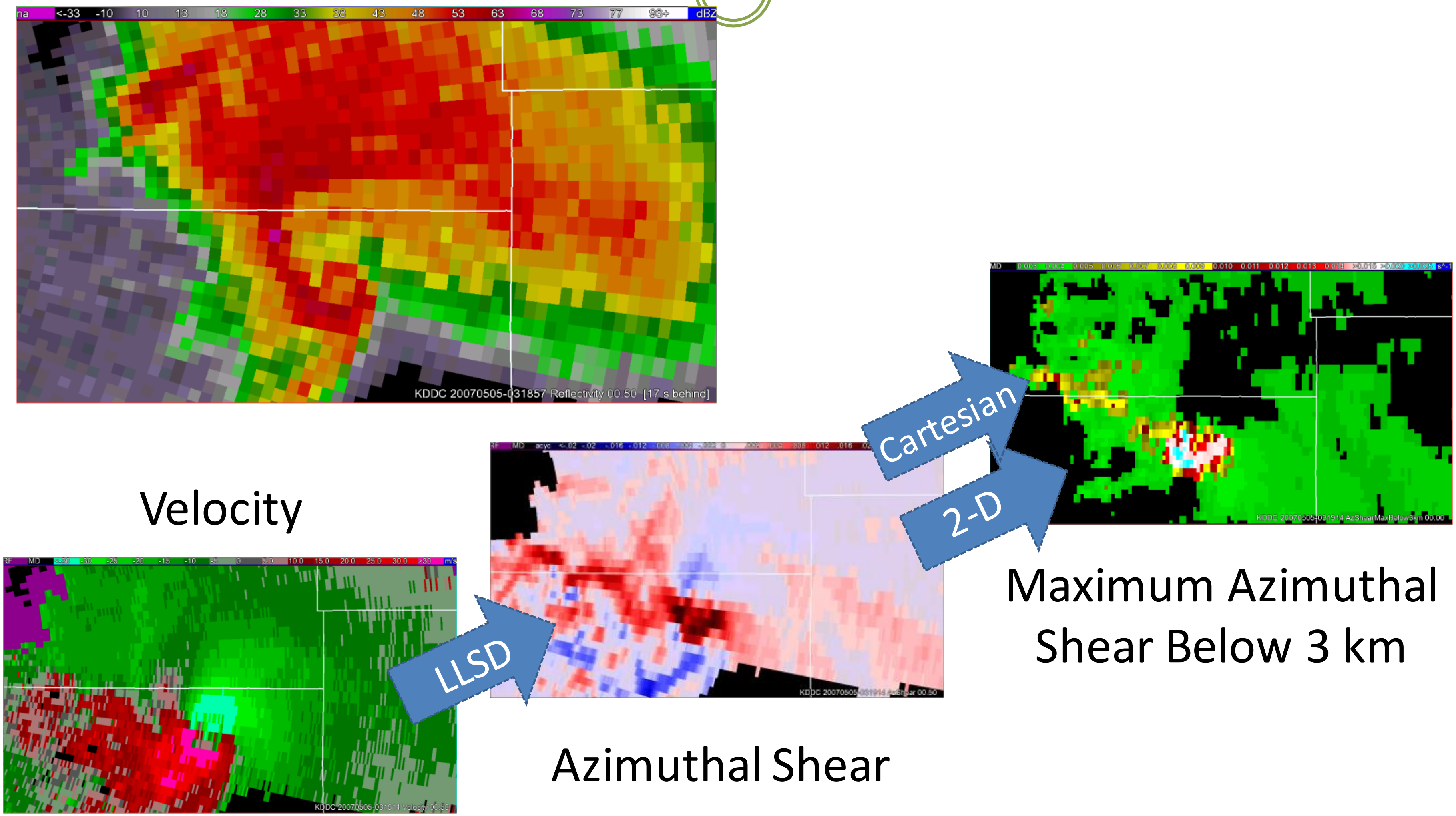
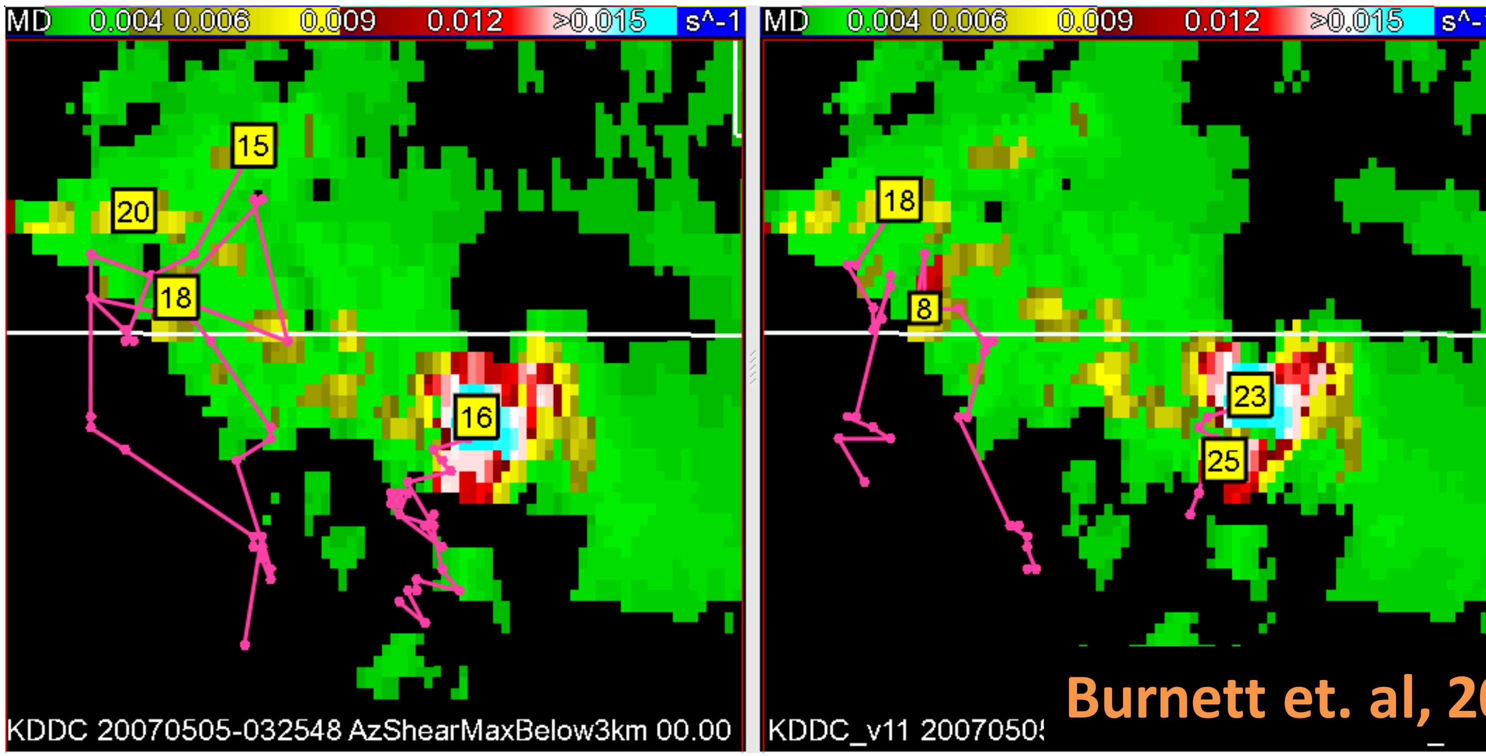
Create azimuthal shear layer product



Tune based on duration, mismatches and jumps



Burnett et. al, 2010

3x3 median filter;
10 km^2; 0.004 s^{-1} ; 0.002 s^{-1}

3x3 Erosion+Dilation filter;
6 km^2; 0.006 s^{-1} ; 0.001 s^{-1}

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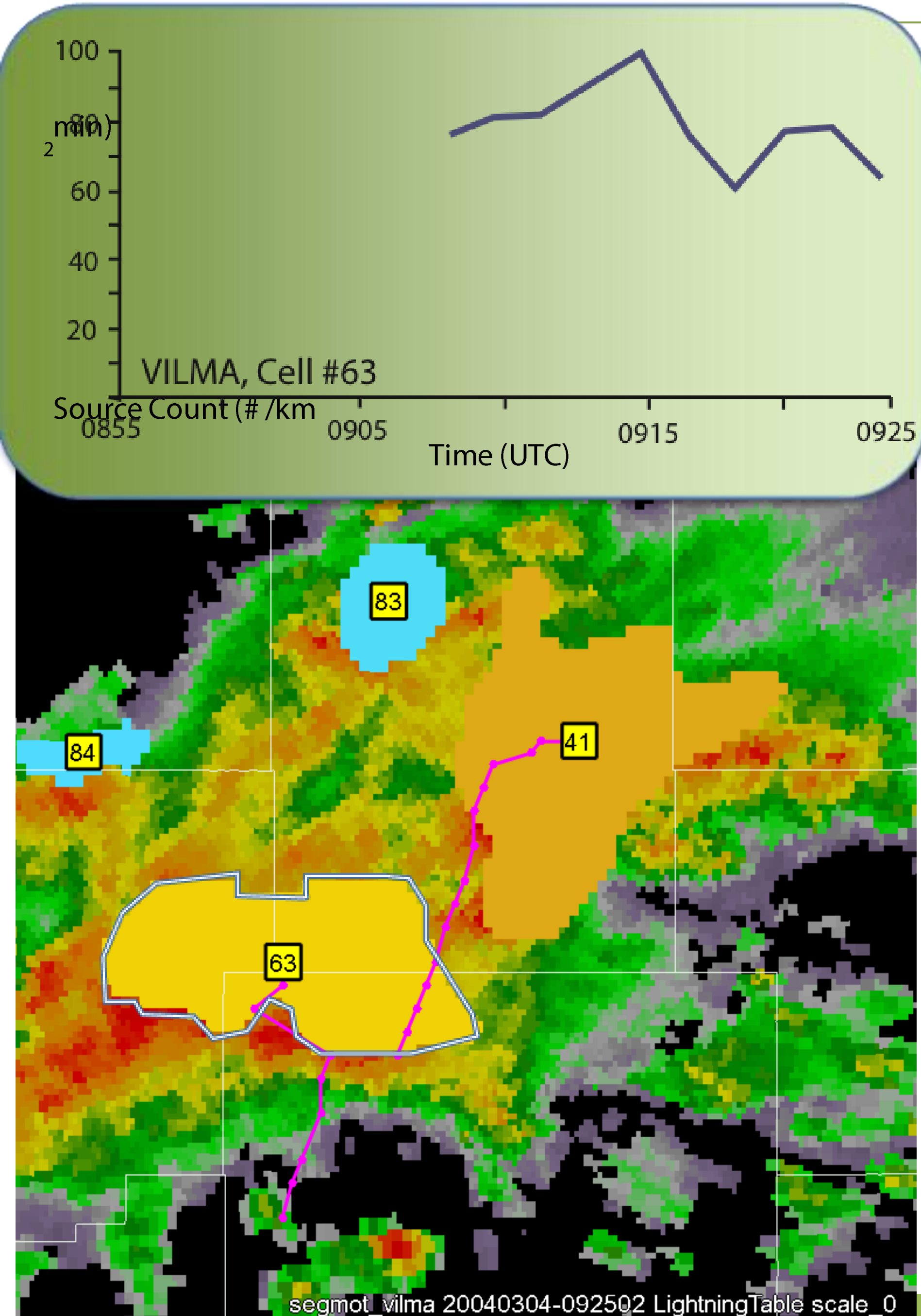
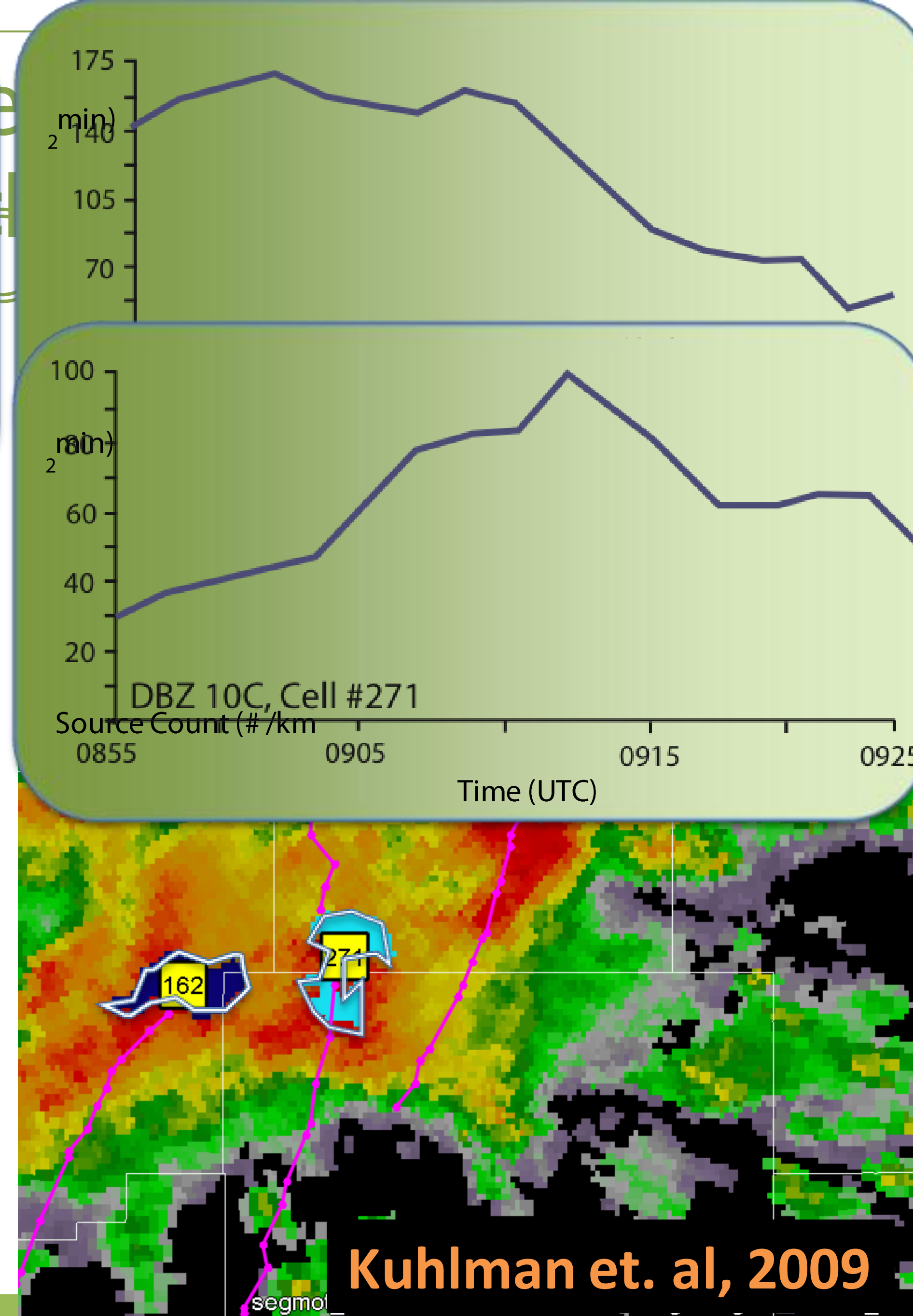
Compare different options to track total lightning

- Kuhlman et. al [Southern Thunder Workshop 2009] compared tracking cells on VILMA to tracking cells on Reflectivity at -10C and concluded:
  - Both Lightning Density and Refl. @ -10 C provide consistent tracks for storm clusters / cells (and perform better than tracks on Composite Reflectivity)
  - At smallest scales: Lightning Density provides longer, linear tracks than Ref.
  - Reverses at larger scales. Regions lightning tend to not be as consistent across large storm complexes.



VILMA



Reflectivity @ -10 C

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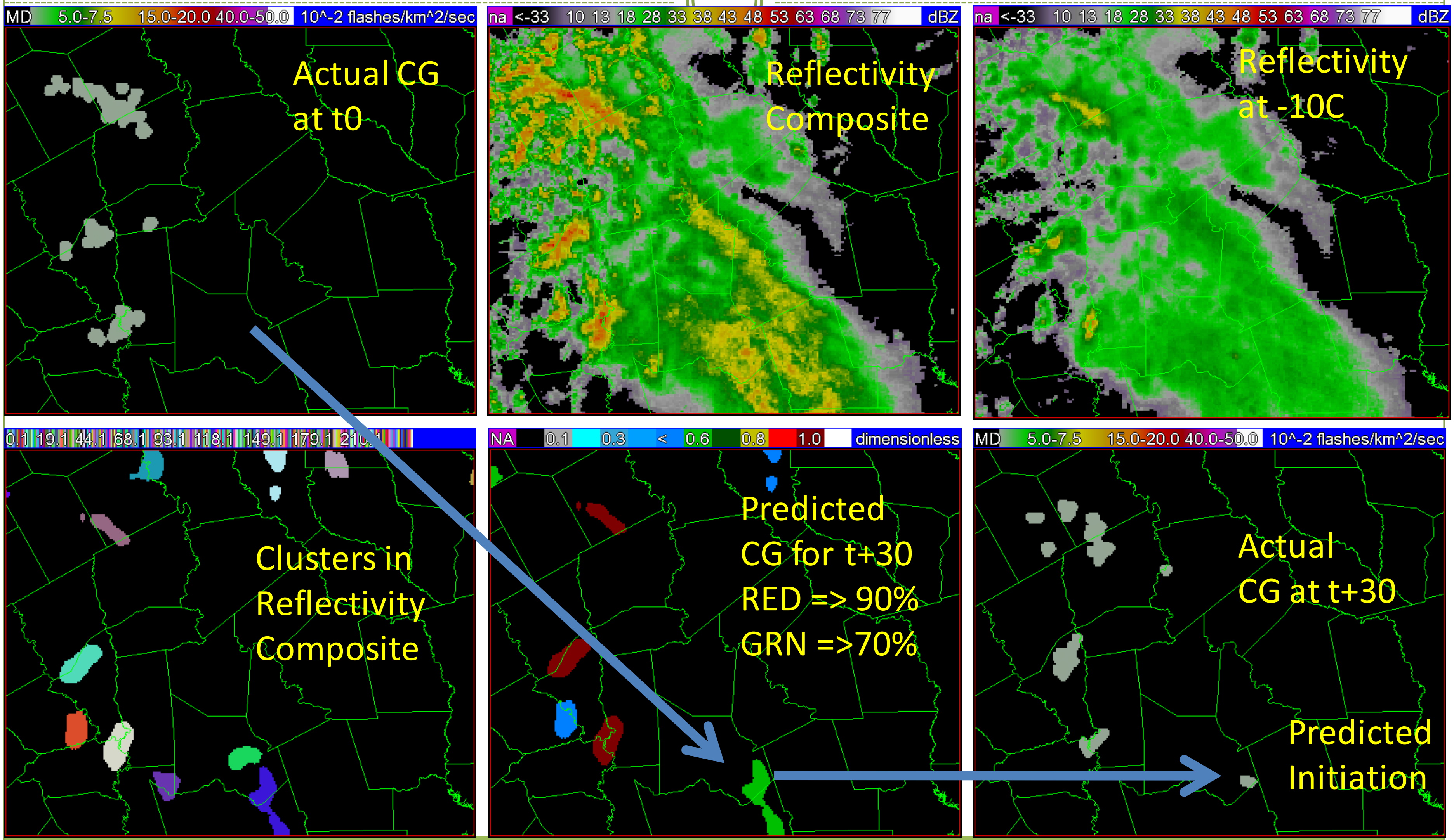
Goal: Predict probability of C-G lightning

- Form training data from radar reflectivity images
  - Find clusters (storms) in radar reflectivity image
  - For each cluster, compute properties
    - Such as reflectivity at -10C, VIL, current lightning density, etc.
  - Reverse advect lightning density from 30-minutes later
    - This is what an ideal algorithm will forecast
    - Threshold at zero to yield yes/no CG lightning field
- Train neural network
  - Inputs: radar attributes of storms,
  - Target output: reverse-advected CG density
  - Data: all data from CONUS for 12 days (1 day per month)

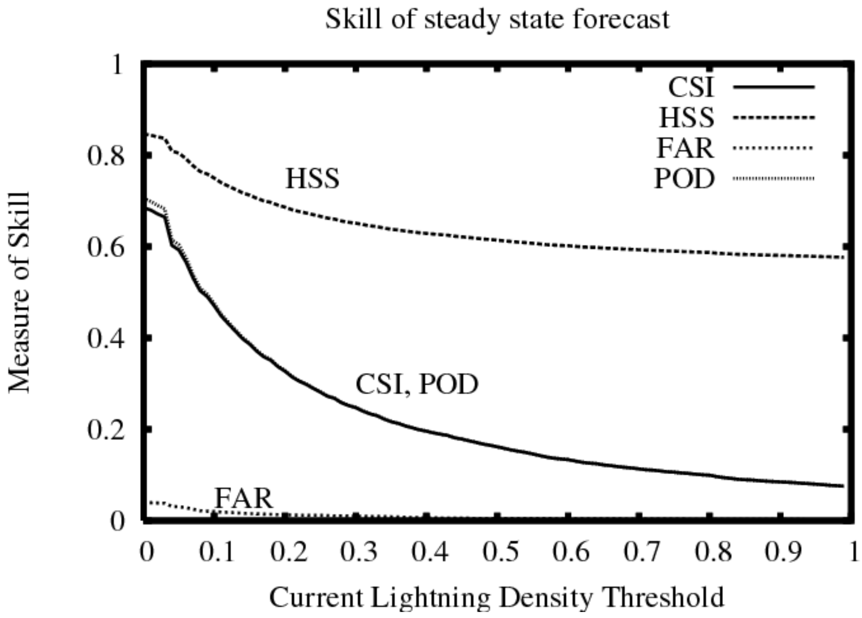
Algorithm in Real-time

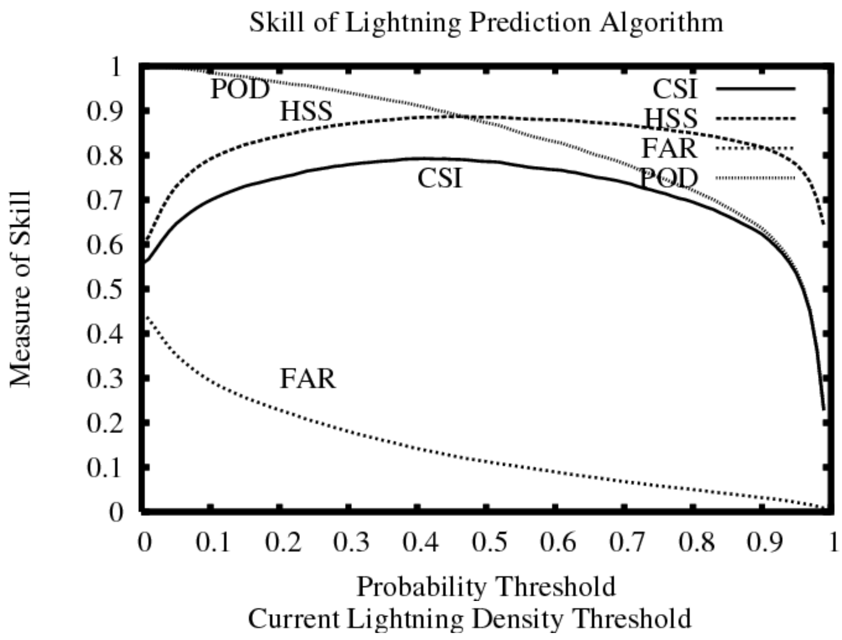
- Find probability that storm will produce lightning:
  - Find clusters (storms) in radar reflectivity image
  - For each cluster, compute properties
    - Such as reflectivity at -10C, VIL, current lightning density, etc.
  - Present storm attributes to neural network
- Find motion estimate from radar images
  - Advect NN output forward by 30 minutes

Algorithm Inputs, Output & Verification



More skill than just plain advection





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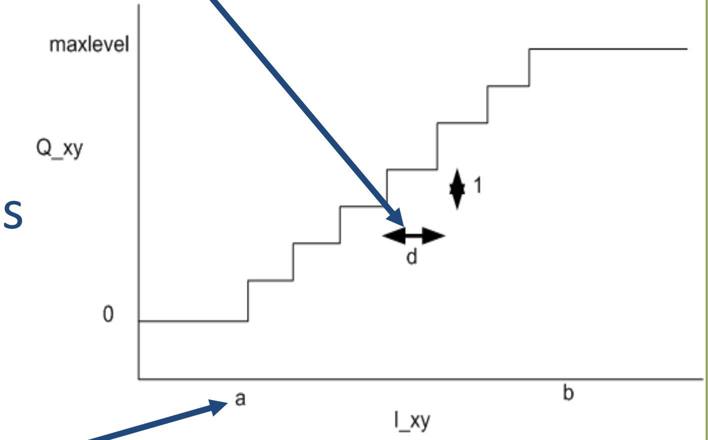
Tuning vector quantization (-d)

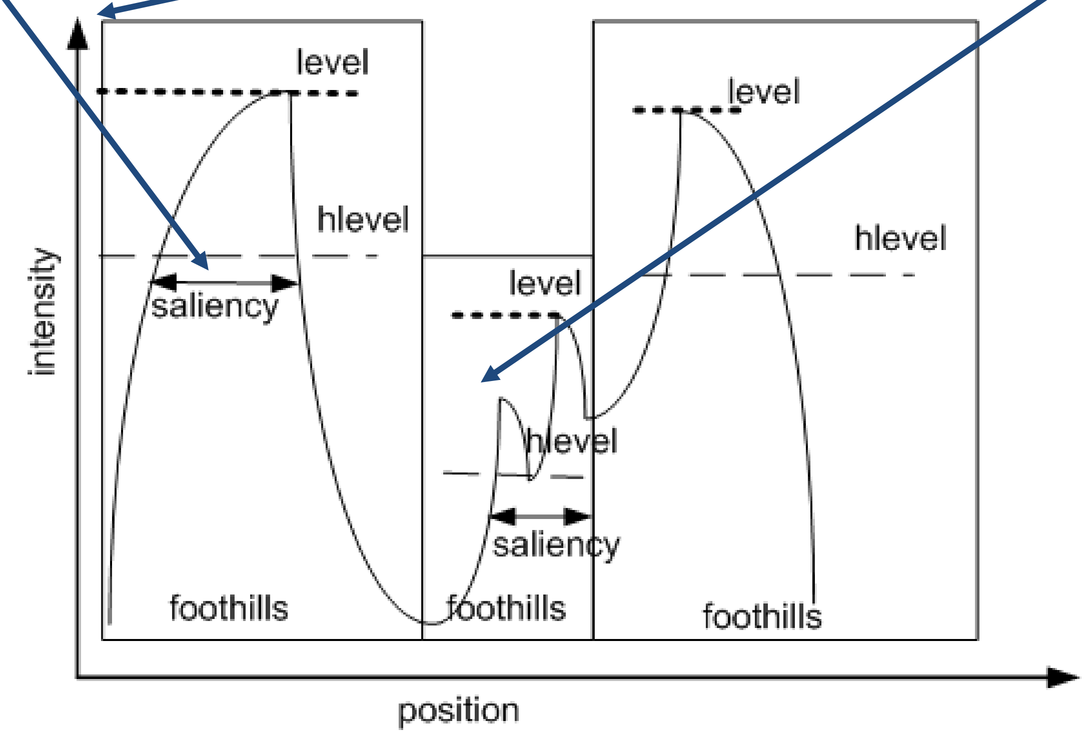
- The "K" in K-means is set by the data increment
  - Large increments result in fatter bands
    - Size of identified clusters will jump around more (addition/removal of bands to meet size threshold)
    - Subsequent processing is faster
    - Limiting case: single, global threshold
  - Smaller increments result in thinner bands
    - Size of identified clusters more consistent
    - Subsequent processing is slower
    - Extremely local maxima



- The minimum value determines probability of detection
  - Local maxima less intense than the minimum will not be identified

Tuning watershed transform (-d,-p)

- The watershed transform is driven from maximum until size threshold is reached up to a maximum depth



Tuning motion estimation (-O)

- Motion estimates are more robust if movement is on the order of several pixels
  - If time elapsed is too short, may get zero motion
  - If time elapsed is too long, storm evolution may cause "flat" cross-correlation function
    - Finding peaks of flat functions is error-prone!

Specifying attributes to extract (-X)

- Attributes should fall inside the cluster boundary
  - C-G lightning in anvil won't be picked up if only cores are identified
  - May need to smooth/dilate spatial fields before attribute extraction
- Should consider what statistic to extract
  - Average VIL?
  - Maximum VIL?
  - Area with VIL > 20?
  - Fraction of area with VIL > 20?
- Should choose method of computing temporal properties
  - Maximum hail? Project clusters backward
    - Hail tends to be in core of storm, so storm growth/decay not problem
  - Maximum shear? Use cell association
    - Tends to be at extremity of core

Preprocessing (-k) affects everything

- The degree of pre-smoothing has tremendous impact
  - Affects scale of cells that can be found
    - More smoothing -> less cells, larger cells only
    - Less smoothing -> smaller cells, more time to process image
  - Affects quality of cross-correlation and hence motion estimates
    - More smoothing -> flatter cross-correlation function, harder to find best match between images

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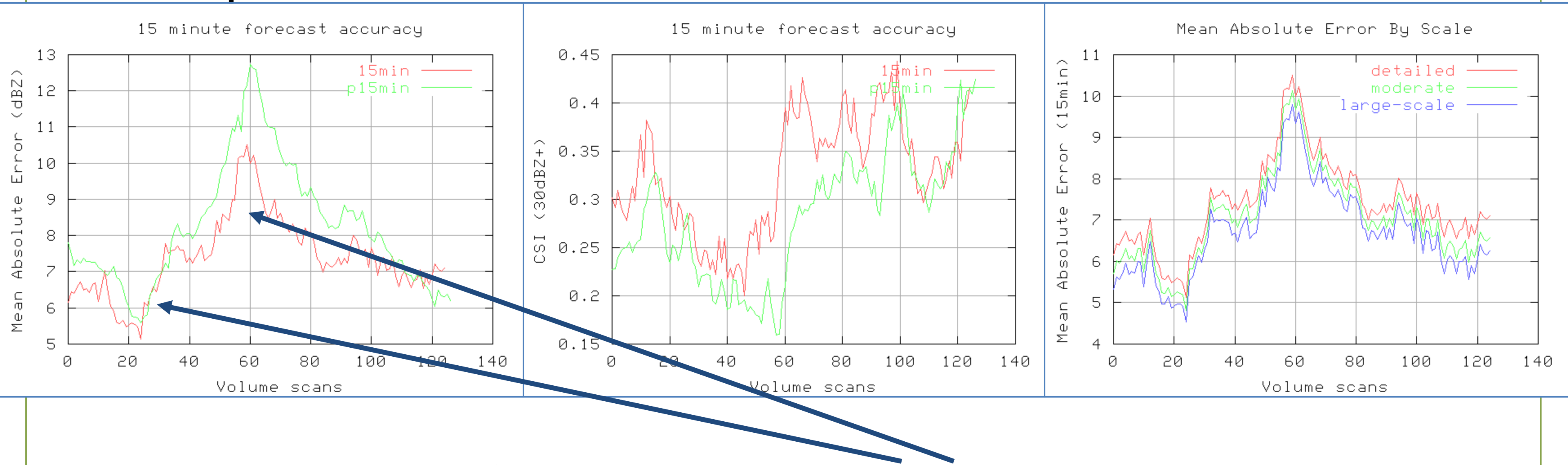
Evaluate advected field using motion estimate [1]

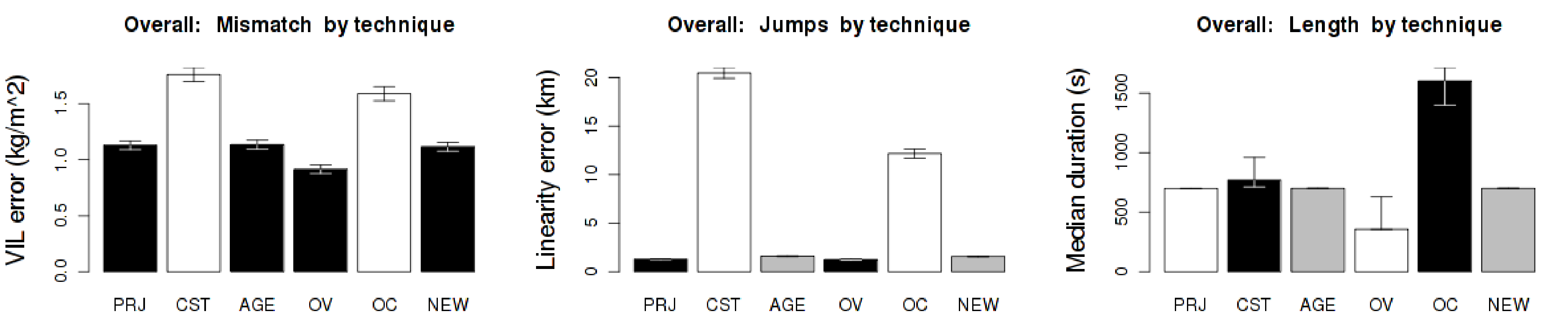
- Use motion estimate to project entire field forward
- Compare with actual observed field at the later time



- Caveat: much of the error is due to storm evolution
  - But can still ensure that speed/direction are reasonable

Evaluate tracks on mismatches, jumps & duration

- Better cell tracks:
  - Exhibit less variability in “consistent” properties such as VIL
  - Are more linear
  - Are longer



- Can use these criteria to choose best parameters for identification and tracking algorithm

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http://www.wdssii.org/

w2segmotionll	Multiscale cell identification and tracking: this is the program that much of this talk refers to.
w2advectorll	Uses the motion estimates produced by w2segmotionll (or any other motion estimate, such as that from a model) to project a spatial field forward
w2scoreforecast	The program used to evaluate a motion field. This is how the MAE and CSI charts were created
w2scoretrack	The program used to evaluate a cell track. This is how the mismatch, jump and duration bar plots were created.

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Mathematical Description: Clustering

- Each pixel is moved among every available cluster and the cost function E(k) for cluster k for pixel (x,y) is computed as

Weight of distance vs. discontiguity ($0 \le \lambda \le 1$)

$$E_{xy}(k) = \lambda d_{m,xy}(k) + (1-\lambda) d_{c,xy}(k)$$

Distance in measurement space (how similar are they?)

$$d_{m,xy}(k) = \left\| \mu_k - I_{xy} \right\|$$

Mean intensity value for cluster k

Pixel intensity value

Discontiguity measure (how physically close are they?)

$$d_{c,xy}(k) = \sum_{ij \in N_{xy}} \left(1 - \delta(S_{ij}^{n} - k)\right)$$

Number of pixels neighboring (x,y) that do NOT belong to cluster k

Cluster-to-image cross correlation [1]

- The pixels in each cluster are overlaid on the previous image and shifted, and the mean absolute error (MAE) is computed for each pixel shift:

Number of pixels in cluster k

Summation over all pixels in cluster k

$$MAE_k(x+\Delta x, y+\Delta y) = \frac{1}{n_k}\sum_{xy \in k}\left|I_t(x,y) - I_{t-\Delta t}(x+\Delta x, y+\Delta y)\right|$$

Intensity of pixel (x,y) at current time

Intensity of pixel (x,y) at previous time

- To reduce noise, the centroid of the offsets with MAE values within 20% of the minimum is used as the basis for the motion vector.

Interpolate spatially and temporally

- After computing the motion vectors for each cluster (which are assigned to its centroid, a <u>field</u> of motion vectors u(x,y) is created via interpolation:

$$u(x,y) = \frac{\sum_k u_k w_k(x,y)}{\sum_k w_k(x,y)}$$

$$w_k(x,y) = \frac{N_k}{\left\| xy - c_k \right\|}$$

Motion vector for cluster k

Sum over all motion vectors

Number of pixels in cluster k

Euclidean distance between point (x,y) and centroid of cluster k

- The motion vectors are smoothed over time using a Kalman filter (constant-acceleration model)

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Resolve "ties" using cost function

- Define a cost function to associate candidate cell i at t_n and cell j projected forward from t_{n-1} as:

$$c_{ij} = (x_i - x_j)^2 + (y_i - y_j)^2 + \frac{A_j}{\pi}\left(\frac{|A_i - A_j|}{A_i \bigwedge A_j} + \frac{|d_i - d_j|}{d_i \bigwedge d_j}\right)$$

Location (x,y) of centroid

Area of cluster

Peak value of cluster

Max

Mag-nitude

- For each unassociated centroid at t_n , associate the cell for which the cost function is minimum or call it a new cell

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References

1. Estimate motion

V. Lakshmanan, R. Rabin, and V. DeBrunner, ``Multiscale storm identification and forecast,'' *J. Atm. Res.*, vol. 67, pp. 367-380, July 2003.

2. Identify cells

V. Lakshmanan, K. Hondl, and R. Rabin, ``An efficient, general-purpose technique for identifying storm cells in geospatial images,'' *J. Ocean. Atmos. Tech.*, vol. 26, no. 3, pp. 523-37, 2009.

3. Extract attributes; example data mining applications

V. Lakshmanan and T. Smith, ``Data mining storm attributes from spatial grids,'' *J. Ocea. and Atmos. Tech.*, In Press, 2009b

4. Associate cells across time

V. Lakshmanan and T. Smith, ``An objective method of evaluating and devising storm tracking algorithms,'' *Wea. and Forecasting*, p. submitted, 2010