Tropical Cyclone Intensity Estimation Using Deep Convolutional Neural Networks

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https://youtu.be/9hOwnUOkNQ8

Overview

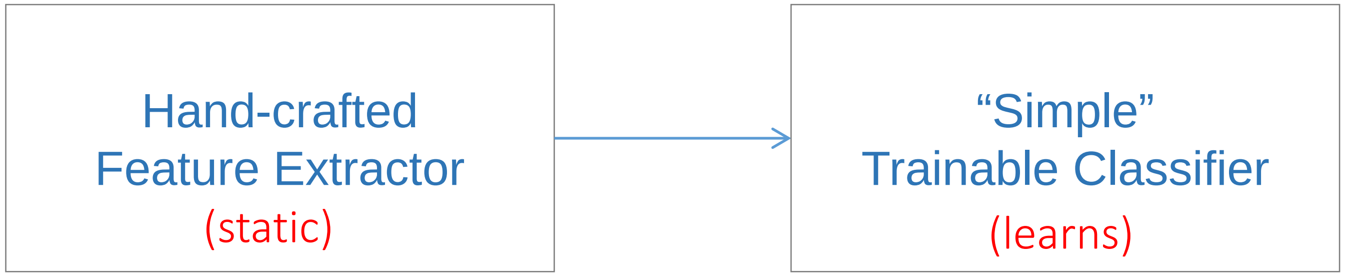
- Deep learning and Convolutional Neural Network
- CNN for Tropical Cyclone Intensity Estimation
- Preliminary results
- Work in progress

Deep Learning

- A subfield of machine learning
- Algorithms inspired by function of the brain
- Scales with amount of training data
- Powerful tool without the need for feature engineering
- Suitable for many Earth Science applications

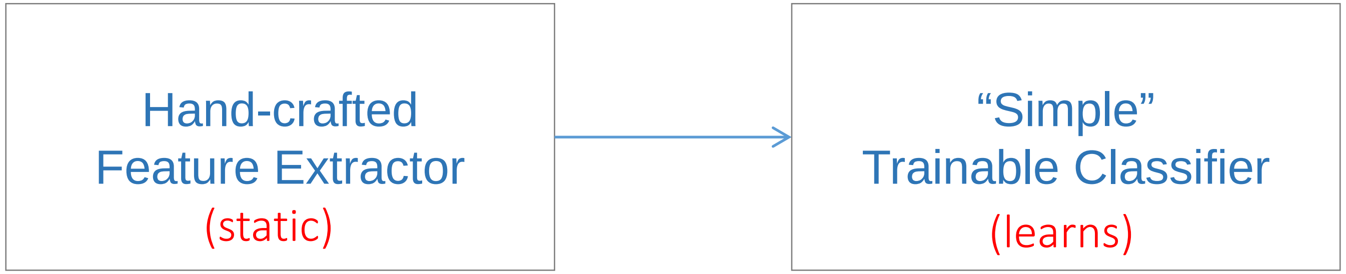
Traditional Image Classification Approach

- Image Features: Color, Texture, Edge histogram,…
- “Shallow” architecture
- Experts define features



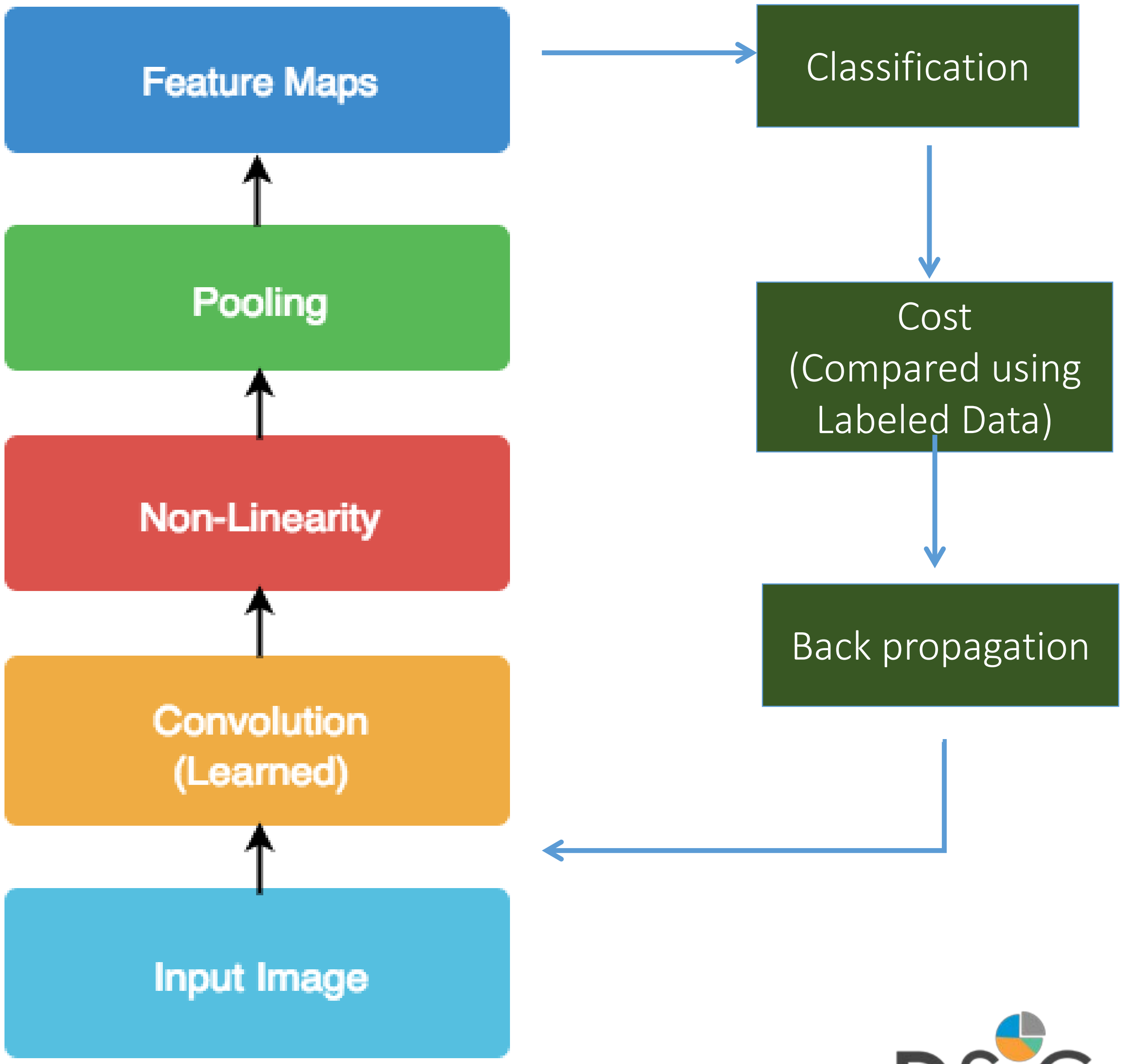
“DEEP” Architecture

- Features are key to recognition
- What about learning the features?
- Deep Learning
  - Hierarchical Learning
  - Modeled after human brain
  - Process information through multiple stages of transformation and representation



Convolutional Neural Network

- Input image – labeled training data
- Convolution Layers – filters are applied across input images (start with random filters)
- Non-linearity – a bias function so that the network is not remembering but rather generalizing
- Pooling – subsampling of the output so that the images do not grow exponentially
- Final output images are passed through a traditional neural network for classification
- Classification results are compared using a loss function to determine error
- Based on error the weights and filters are adjusted using gradient descent
- Iterate the process until the error is below some threshold



Convolutional Layer

Input (7x7), pad of 1

0	0	0	0	0	0	0
0	1	2	1	0	1	0
0	2	1	1	2	1	0
0	1	2	1	2	2	0
0	2	2	2	1	0	0
0	0	1	1	1	2	0
0	0	0	0	0	0	0

Kernel (3x3), stride of 2

1	1	-1
0	-1	1
-1	0	1

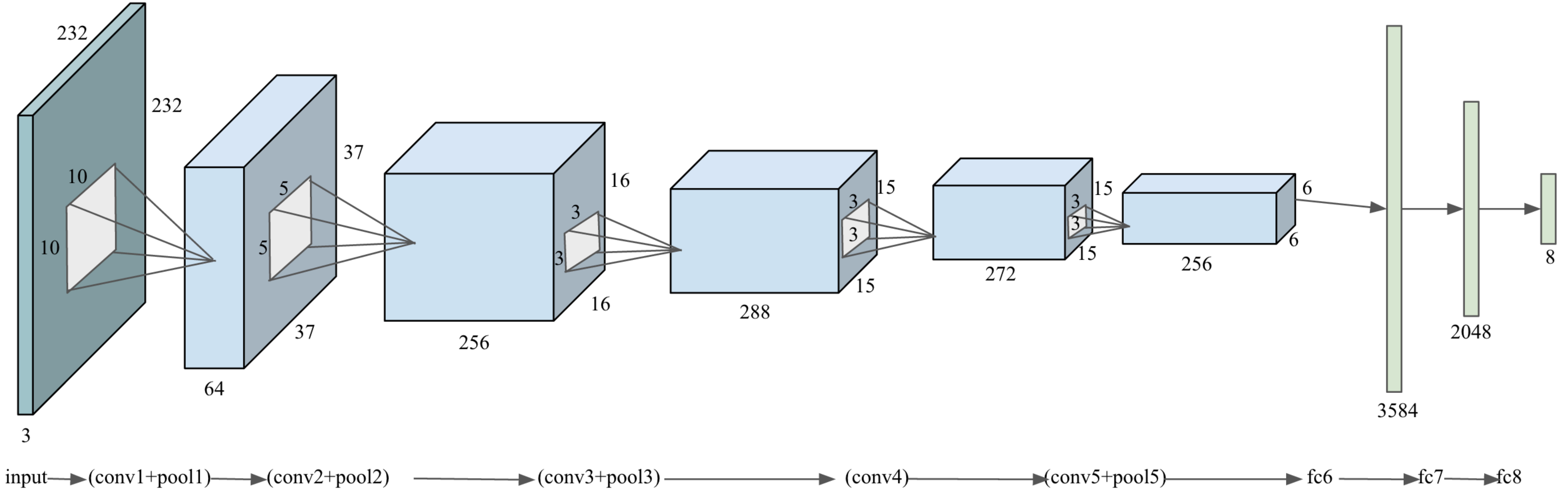
Output (3x3)

2	0	-3
4	0	0
1	3	-1

- Stride (s)
  - Jump/step with which filters move across width/height of input volume
- Padding (p)
  - Amount of wrapping used in input
- Output size (W_o) = $\mathbf{(W_i - k + 2*p)/s + 1}$

2D Convolution, Single Slice

Network architecture



Tropical Cyclone Intensity Estimation

- The Dvorak technique
  - Vernon Dvorak (1970s)
  - Satellite-based method
  - Cloud system measurements
  - Development patterns corresponds to T-number
- Deviation-angle variation technique (DAVT)
  - Piñeros et al. (2008)
  - Variance for quantification of cyclones
  - Calculates using center (eye) pixel
  - Directional gradient statistical analysis of the brightness of images

Issues

- Subjective/Uncertainty
- Lack of generalizability
- Inconsistency
- Complexity

15 UTC 10 Oct 17 NHC advisory on Tropical Storm Ophelia

"Dvorak intensity estimates range from T2.3/33 kt from UW-CIMSS to T3.0/45 kt from TAFB toT4.0/65 kt from SAB. For now, the initial intensity will remain at 45 kt, which is an average of the scatterometer winds and all of the other available intensity estimates."

Observation:
Two human experts at TAFB and SAB differed by 20 knots in their Dvorak analyses, and the automated version at the University of Wisconsin was 12 kt lower than either of them!

Can we objectively predict wind speed from images?

Data

- Images
  - US Naval Research Laboratory (http://www.nrlmry.navy.mil/tcdat)
  - From 1998 to 2014
  - Images at 15 minutes interval
- Cyclone data
  - National Hurricane Center (http://www.nhc.noaa.gov) (HURDAT and HURDAT2)
  - Hurricane Research Division (http://www.aoml.noaa.gov/hrd/hurdat/Data_Storm.html)
  - Every 6 hours
- 98 cyclones collected over Pacific and Atlantic regions
  - 68 from Atlantic
  - 30 from Pacific

Storms

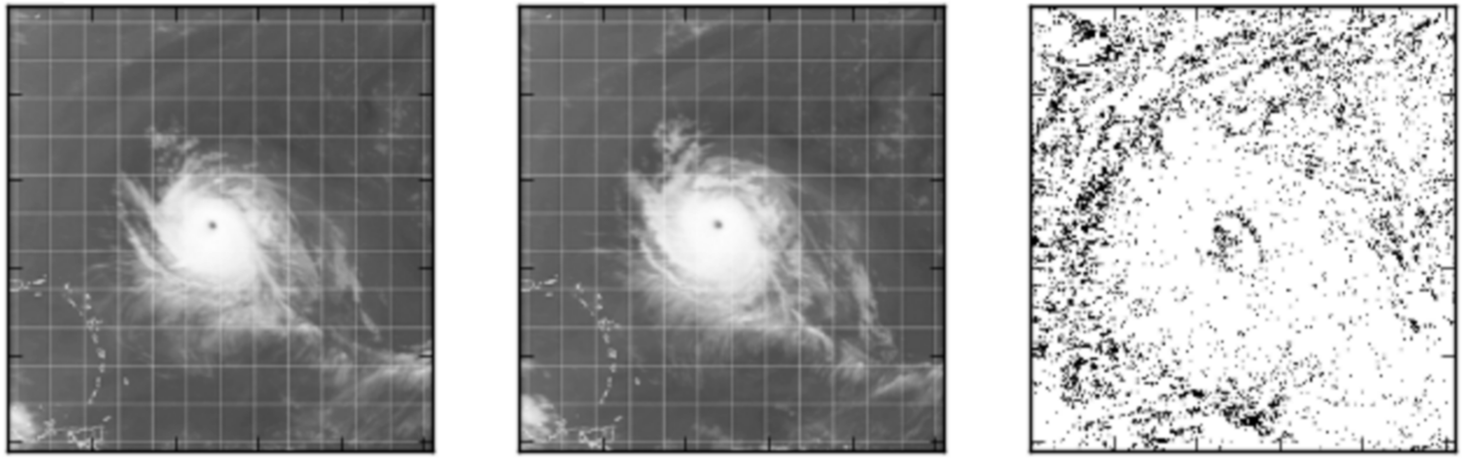
Region/Basin	Year	Cyclones
Atlantic	1998	Mitch
	2003	Isabel
	2004	Ivan
	2005	Emily, Katrina, Rita, Wilma
	2007	Dean, Felix
	2010	Alex, Bonnie, Colin, Danielle, Earl, Fiona, Five, Gaston, Igor, Julia, Karl, Lisa, Matthew, Nilcole, Otto, Paula, Richard, Shary, Tomas, Two
	2011	Arlene, Bret, Cindy, Don, Emily, Franklin, Gert, Harvey, Irene, Jose, Katia, Lee, Maria, Nate, Ophelia, Philippe, Rina, Sean, Ten
	2012	Alberto, Beryl, Chris, Debby, Ernesto, Florence, Gordon, Helene, Isaac, Joyce, Kirk, Leslie, Michael, Nadine, Oscar, Patty, Rafael, Sandy, Tony
	2014	Edouard
Pacific	2002	Elida, Fausto, Hernan, Kenna
	2005	Jova, Kenneth
	2006	Bud, Daniel, Ioke, John, Lane
	2007	Flossie
	2008	Hernan, Norbert
	2009	Felicia, Guillermo, Jimena, Rick
	2010	Celia, Darby
	2011	Adrian, Dora, Eugene, Hilary, Jova, Kenneth
	2012	Bud, Emilia, Miriam, Paul

Data augmentation

- Interpolate to increase even more
- 2 hours interpolated image differences

atl_ISABEL-A_2003-09-11:14_138.33-AND-B_2003-09-11:16_141.67k

(a) 2003-09-11:14 (138.33 kt) (b) 2003-09-11:16 (141.67 kt)



RMSE: 0.06, SSIM:0.78

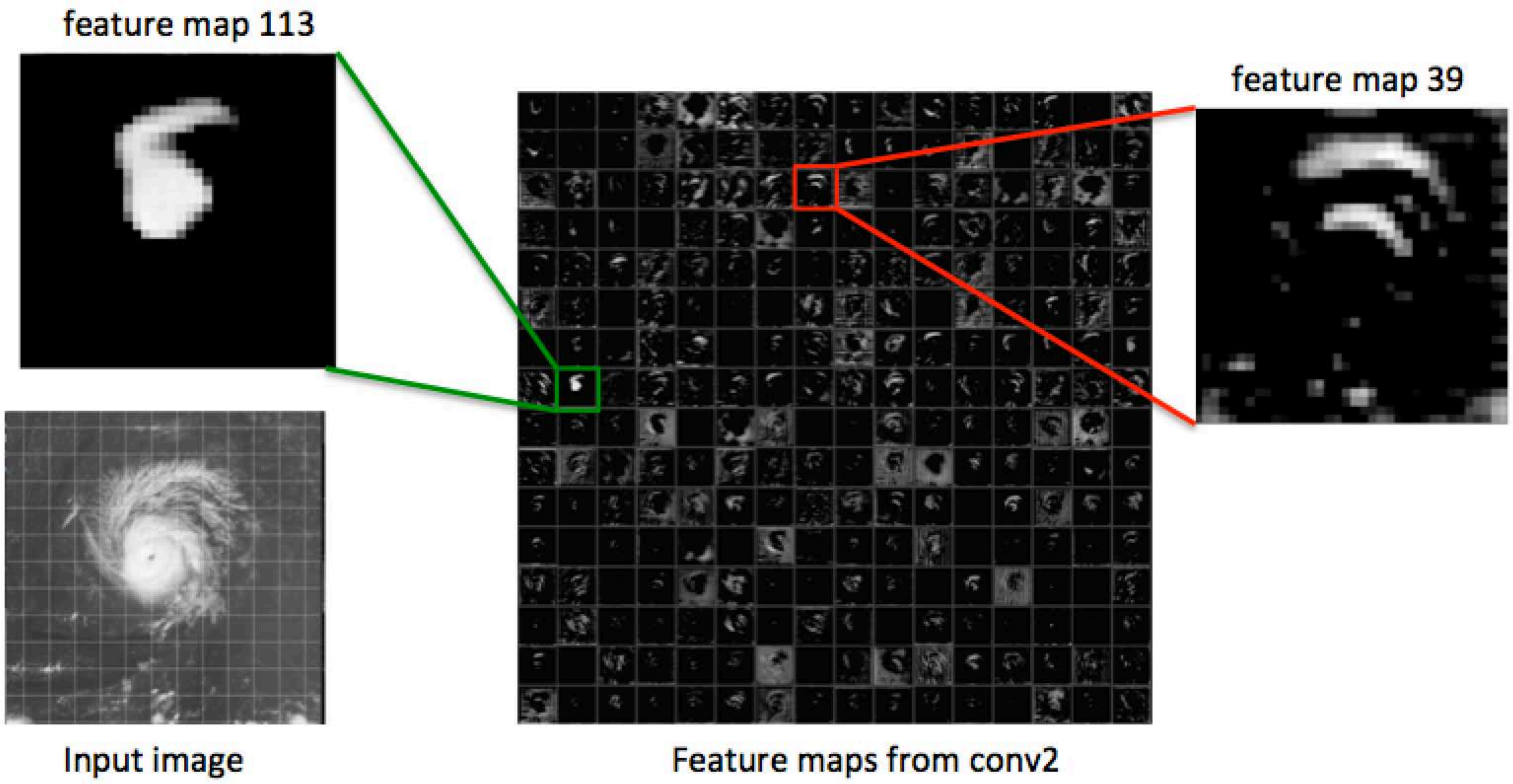
2 hour interpolated image differences

Training, test, and validation

- (Training + Validation) 70% - 30% (Test)
- (Training) 75% - 25% (Validation)

Hurricane Category	Train	Validation	Test	Total
H1	3314	1104	1816	6234
H2	1860	620	994	3474
H3	1848	616	992	3456
H4	1886	628	1032	3546
H5	603	201	306	1110
NC	126	42	54	222
TD	6363	2121	3576	12060
TS	9863	3288	5575	18726
Total	**25863**	**8620**	**14345**	**48828**

Visualization



Feature maps from second convolution

Initial performance

- Model with around 90% of **validation** accuracy
- Tested against 14,345 test images (Atlantic + Pacific)
  - Confusion Matrix
  - Classification Report
  - Accuracy
  - RMS Intensity Error

Accuracy

- Top-1: exact-hits
- Top-2: exact-hits + 2^{nd}-hits

	Total Counts	Accuracy
Top-1	11571	80.66%
Top-2	13695	95.47%

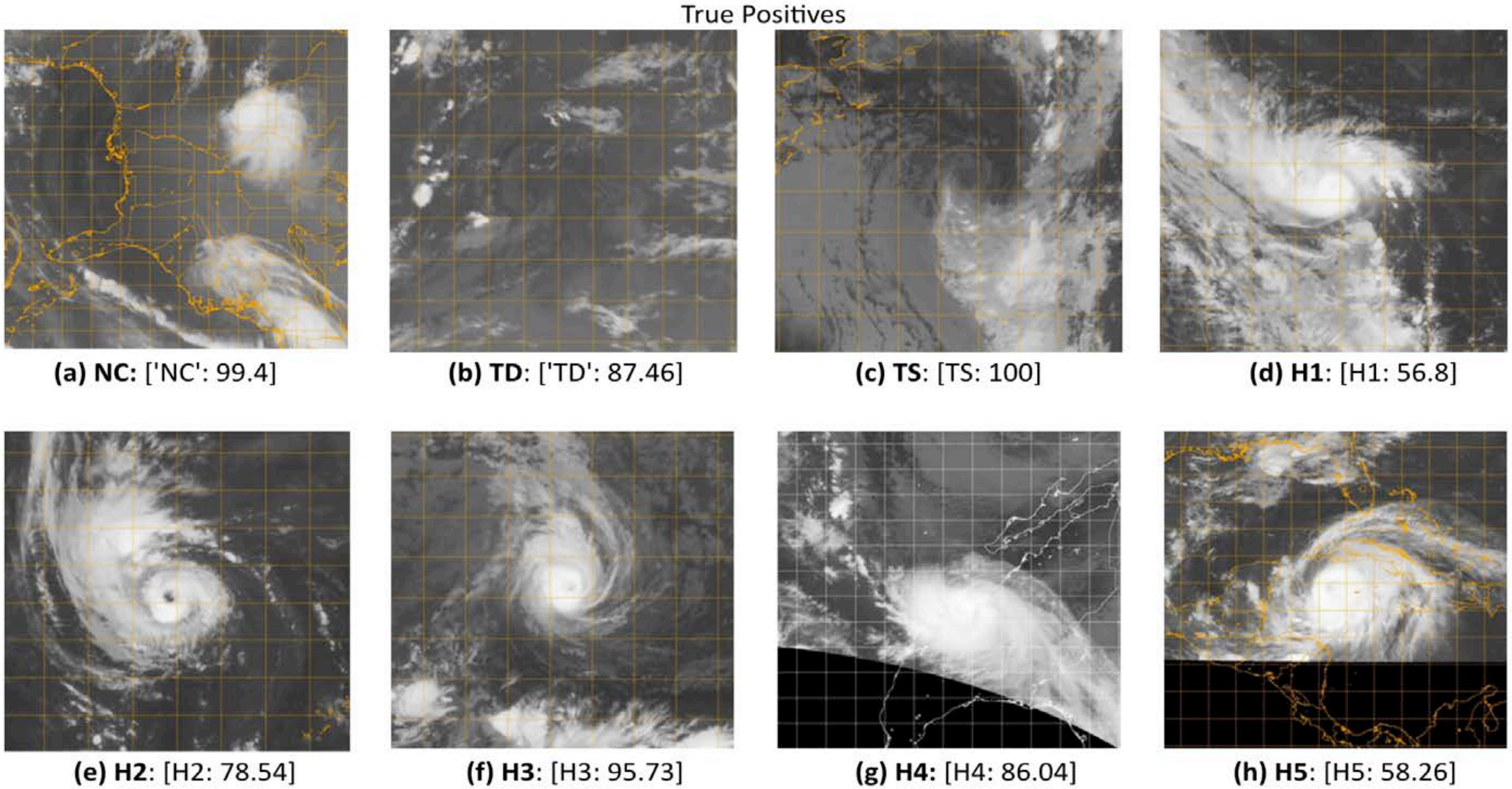
Category	Total	Top-1	2^{nd} hit	Top-2
NC	54	32	15	47
TD	3576	3174	364	3538
TS	5575	4838	665	5503
H1	1816	1235	432	1667
H2	994	614	215	829
H3	992	657	212	869
H4	1032	816	148	964
H5	306	205	73	278
Total	**14345**	**11571**	**2124**	**13695**

Error Metrics

- Our model
  - Across Atlantic and Pacific
  - Achieved RMSE of 9.19 *kt*
- North Atlantic
  - Piñeros et al. (2011): 14.7 *kt*
  - Ritchie et al. (2012): 12.9 *kt*
- North Pacific
  - Ritchie et al. (2014): 14.3 *kt*

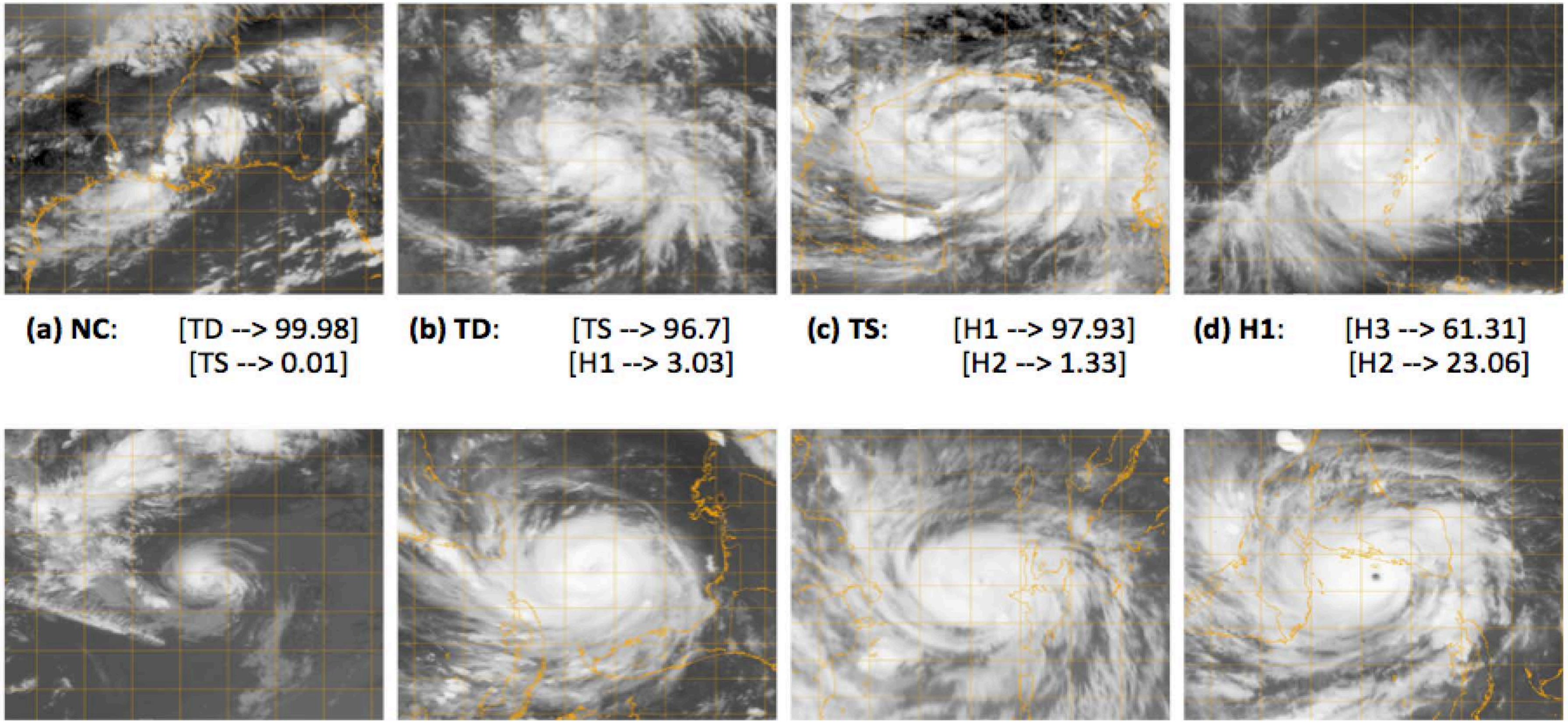
Category	RMSE	MAE
NC	10.14	6.19
TD	6.59	2.18
TS	7.68	2.71
H1	12.17	6.59
H2	12.43	6.82
H3	12.44	6.31
H4	10.50	4.09
H5	10.08	5.32
Total Average	**9.19**	**3.77**

Sample correct classifications



Sample incorrect classifications

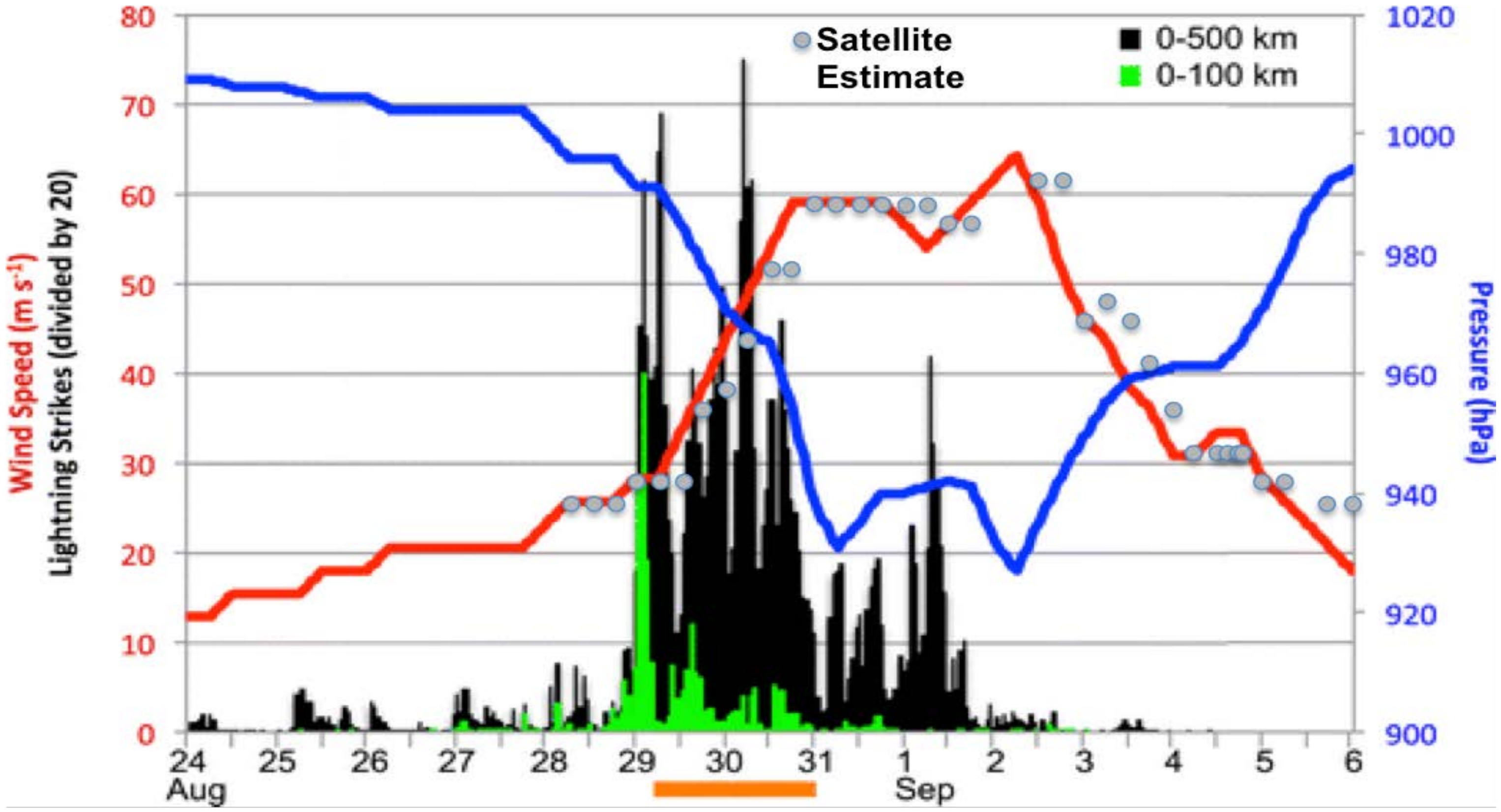
False Negatives



(a) NC: [TD --> 99.98] [TS --> 0.01]
(b) TD: [TS --> 96.7] [H1 --> 3.03]
(c) TS: [H1 --> 97.93] [H2 --> 1.33]
(d) H1: [H3 --> 61.31] [H2 --> 23.06]

(e) H2: [TS --> 100.0] [H1 --> 0.0]
(f) H3: [H4 --> 97.32] [H5 --> 2.22]
(g) H4: [H2 --> 54.0] [H3 --> 36.79]
(h) H5: [H4 --> 99.71] [H3 --> 0.13]

Detailed look: Hurricane Earl, 2010



Adapted from Stevenson et al. (2014). Time series of satellite-derived intensity estimates (circles) for Hurricane Earl (2010), added to best track intensities and lightning flash rate time series.

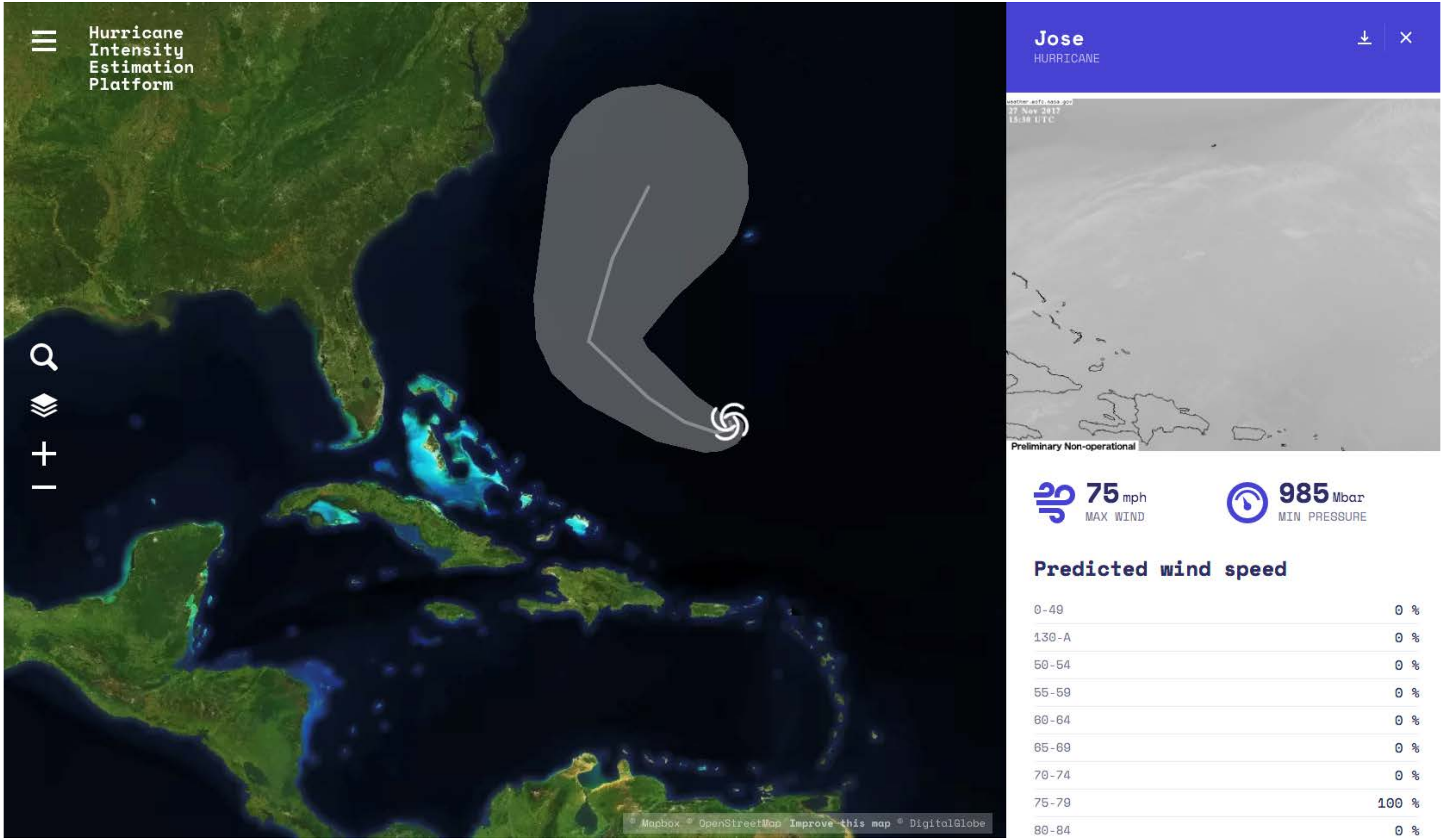
Work in progress

- Hurricane intensity estimation portal
- Use of passive microwave dataset
- Use of atmospheric conditions

Hurricane intensity estimation portal

- Develop a near real-time tropical cyclone intensity estimation services
  - Include additional image datasets
  - Algorithmic enhancements
  - Monitor NHC outlook for "invest" area for trigger
- Perform extensive evaluation with available observations
- Work with NASA/SPoRT to develop a website that will display current "invest" information along with estimated wind speed information and relevant overlays
- Develop OGC services (WFS and SOS): integration with AWIPS/N-AWIPS

Hurricane intensity estimation portal



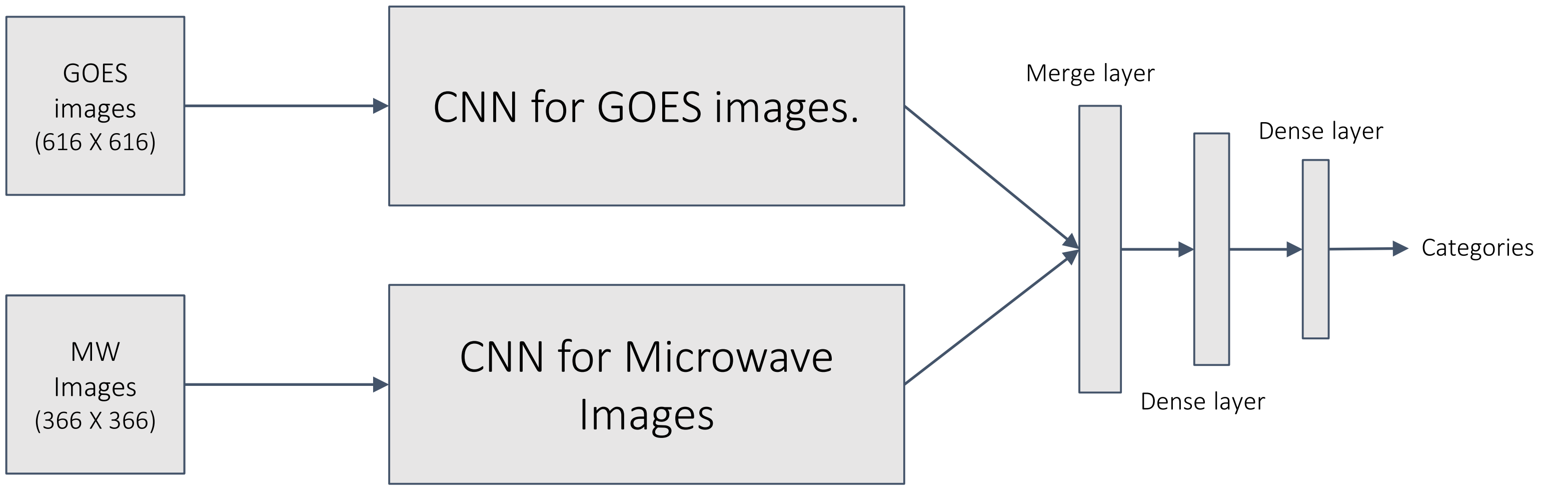
http://hiep.surge.sh/storms/9eee5297-d43d-4f84-9931-23bef5fbdbb4

Thank you.

Using Microwave Datasets

Instrument (85, 89 GHz)	Coverare years	Total storm centric images
SSMI17	2008-2016	1715
SSMI18	2010-2016	1378
TMI	1998-2014	3409
AMSRE	2003-2011	2230

Network

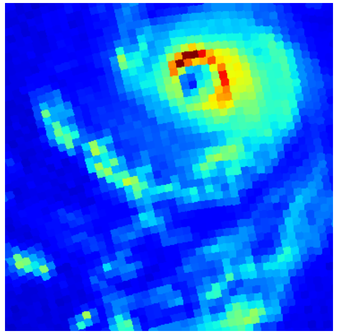


GOES images (616 X 616)
CNN for GOES images.
MW Images (366 X 366)
CNN for Microwave Images
Merge layer
Dense layer
Dense layer
Categories

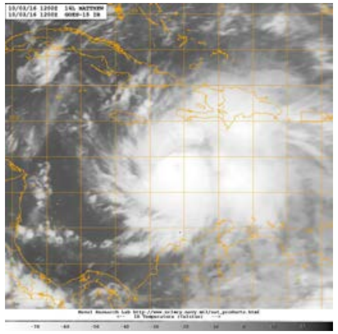
Process

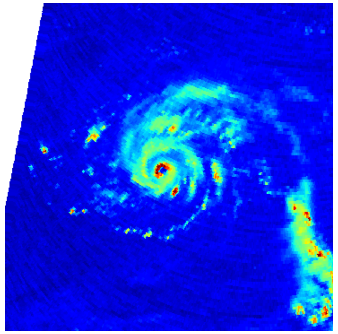
1. Collect Storm-centric PM data
2. Generate image
3. Match up images with NRL goes images
4. Add random rotation/flips to images (data augmentation).
5. Use corresponding GOES and Microwave images for training.
6. Start with 7 categories (ts, td, 1, 2, 3, 4, 5)

Samples

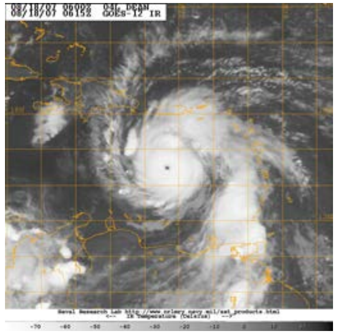


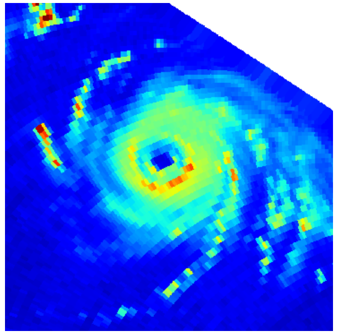
Source: SSMI18/GOES
Wind speed: 125
Hurricane: Matthew
Year: 2016





Source: AMSRE/GOES
Wind speed: 145
Hurricane: Dean
Year: 2007





Source: TMI/GOES
Wind speed: 125
Hurricane: Dean
Year: 2007