Tropical Cyclone Intensity Estimation Using Deep Convolutional Neural Networks

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33rd Conference on Hurricanes and Tropical Meteorology
April 20, 2018. Pointe Vedra, FL
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

Hand-crafted Feature Extractor (static)  “Simple” Trainable Classifier (learns)
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

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Kernel (3x3), stride of 2

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Output (3x3)

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<tr>
<td>1</td>
<td>3</td>
<td>-1</td>
</tr>
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</table>

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

2D Convolution, Single Slice
Network architecture

input → (conv1+pool1) → (conv2+pool2) → (conv3+pool3) → (conv4) → (conv5+pool5) → fc6 → fc7 → fc8
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

Can we objectively predict wind speed from images?

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 to T4.0/65 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!
• 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
<table>
<thead>
<tr>
<th>Region/Basin</th>
<th>Year</th>
<th>Cyclones</th>
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<tbody>
<tr>
<td>Atlantic</td>
<td>1998</td>
<td>Mitch</td>
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<tr>
<td></td>
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<td>Isabel</td>
</tr>
<tr>
<td></td>
<td>2004</td>
<td>Ivan</td>
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<td></td>
<td>2005</td>
<td>Emily, Katrina, Rita, Wilma</td>
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<td></td>
<td>2007</td>
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<td>Alex, Bonnie, Colin, Danielle, Earl, Fiona, Five, Gaston, Igor, Julia, Karl, Lisa, Matthew, Nilcole, Otto, Paula, Richard, Shary, Tomas, Two</td>
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<td></td>
<td>2011</td>
<td>Arlene, Bret, Cindy, Don, Emily, Franklin, Gert, Harvey, Irene, Jose, Katia, Lee, Maria, Nate, Ophelia, Philippe, Rina, Sean, Ten</td>
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<tr>
<td></td>
<td>2012</td>
<td>Alberto, Beryl, Chris, Debby, Ernesto, Florence, Gordon, Helene, Isaac, Joyce, Kirk, Leslie, Michael, Nadine, Oscar, Patty, Rafael, Sandy, Tony</td>
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<tr>
<td></td>
<td>2014</td>
<td>Edouard</td>
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<tr>
<td>Pacific</td>
<td>2002</td>
<td>Elida, Fausto, Hernan, Kenna</td>
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<td>2005</td>
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<td>Felicia, Guillermo, Jimena, Rick</td>
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<td></td>
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<td>Celia, Darby</td>
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<td>Adrian, Dora, Eugene, Hilary, Jova, Kenneth</td>
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<td>Bud, Emilia, Miriam, Paul</td>
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Data augmentation

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

RMSE: 0.06, SSIM: 0.78
Training, test, and validation

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

<table>
<thead>
<tr>
<th>Hurricane Category</th>
<th>Train</th>
<th>Validation</th>
<th>Test</th>
<th>Total</th>
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<td>1104</td>
<td>1816</td>
<td>6234</td>
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<td>H2</td>
<td>1860</td>
<td>620</td>
<td>994</td>
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<td>H3</td>
<td>1848</td>
<td>616</td>
<td>992</td>
<td>3456</td>
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<td>H4</td>
<td>1886</td>
<td>628</td>
<td>1032</td>
<td>3546</td>
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<td>H5</td>
<td>603</td>
<td>201</td>
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<td>54</td>
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<td>TD</td>
<td>6363</td>
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<td>3576</td>
<td>12060</td>
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<td>TS</td>
<td>9863</td>
<td>3288</td>
<td>5575</td>
<td>18726</td>
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<td>Total</td>
<td>25863</td>
<td>8620</td>
<td>14345</td>
<td>48828</td>
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</table>
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

<table>
<thead>
<tr>
<th>Category</th>
<th>Total</th>
<th>Top-1</th>
<th>2^{nd} hit</th>
<th>Top-2</th>
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<td>TD</td>
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<tr>
<td>TS</td>
<td>5575</td>
<td>4838</td>
<td>665</td>
<td>5503</td>
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<tr>
<td>H1</td>
<td>1816</td>
<td>1235</td>
<td>432</td>
<td>1667</td>
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<tr>
<td>H2</td>
<td>994</td>
<td>614</td>
<td>215</td>
<td>829</td>
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<tr>
<td>H3</td>
<td>992</td>
<td>657</td>
<td>212</td>
<td>869</td>
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<tr>
<td>H4</td>
<td>1032</td>
<td>816</td>
<td>148</td>
<td>964</td>
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<td>H5</td>
<td>306</td>
<td>205</td>
<td>73</td>
<td>278</td>
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<tr>
<td>Total</td>
<td>14345</td>
<td>11571</td>
<td>2124</td>
<td>13695</td>
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<thead>
<tr>
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<th>Total Counts</th>
<th>Accuracy</th>
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<tr>
<td>Top-1</td>
<td>11571</td>
<td>80.66%</td>
</tr>
<tr>
<td>Top-2</td>
<td>13695</td>
<td>95.47%</td>
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</table>
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

<table>
<thead>
<tr>
<th>Category</th>
<th>RMSE</th>
<th>MAE</th>
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<tr>
<td>NC</td>
<td>10.14</td>
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<td>6.59</td>
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<td>TS</td>
<td>7.68</td>
<td>2.71</td>
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<tr>
<td>H1</td>
<td>12.17</td>
<td>6.59</td>
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<td>H2</td>
<td>12.43</td>
<td>6.82</td>
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<td>H3</td>
<td>12.44</td>
<td>6.31</td>
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<td>H4</td>
<td>10.50</td>
<td>4.09</td>
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<td>H5</td>
<td>10.08</td>
<td>5.32</td>
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<tr>
<td><strong>Total Average</strong></td>
<td><strong>9.19</strong></td>
<td><strong>3.77</strong></td>
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</table>
Sample correct classifications

True Positives

(a) NC: ['NC': 99.4]
(b) TD: ['TD': 87.46]
(c) TS: [TS: 100]
(d) H1: [H1: 56.8]
(e) H2: [H2: 78.54]
(f) H3: [H3: 95.73]
(g) H4: [H4: 86.04]
(h) H5: [H5: 58.26]

NASA

DSiG
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]
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
• 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

<table>
<thead>
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<th>Coverare years</th>
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<td>SSMI17</td>
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<td>1715</td>
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<tr>
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<td>2010-2016</td>
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<td>1998-2014</td>
<td>3409</td>
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<tr>
<td>AMSRE</td>
<td>2003-2011</td>
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</table>
Network

- GOES images (616 x 616)
- MW Images (366 x 366)
- CNN for GOES images
- CNN for Microwave Images
- Merge 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: AMSRE/GOES
Wind speed: 145
Hurricane: Dean
Year: 2007

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