From Vern's Vision to Computer Vision: The Evolution of Tropical Cyclone Intensity Estimation from Satellite Data

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With contributions from

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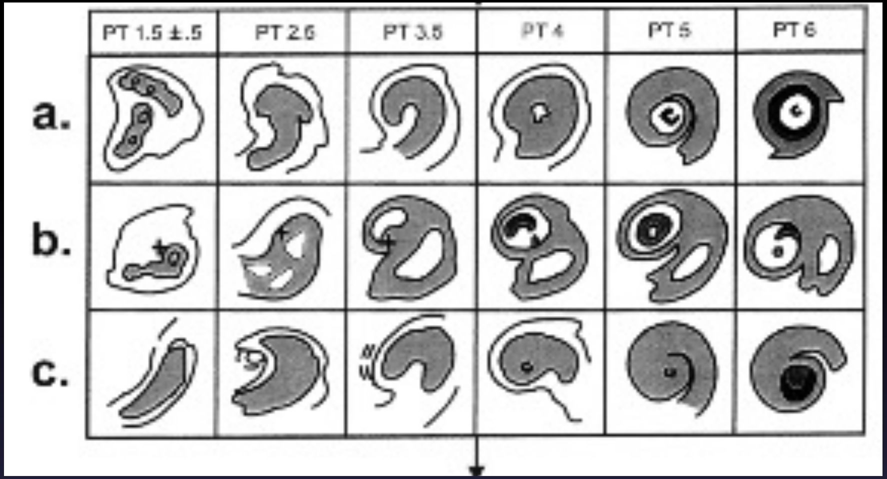
AMS Hurricane Conference 2024 Long Beach, CA

50^{th} Anniversary of the Dvorak Technique

The Dvorak Technique



"The Dvorak Technique's practical appeal and demonstrated skill in the face of dynamic complexity place it among the great meteorological innovations of our time. It is difficult to think of any other meteorological technique that has withstood the test of time and had the same life-saving impact. "

- Velden et al., 2006 BAMS

The Dvorak Technique's Legacy and Endurance

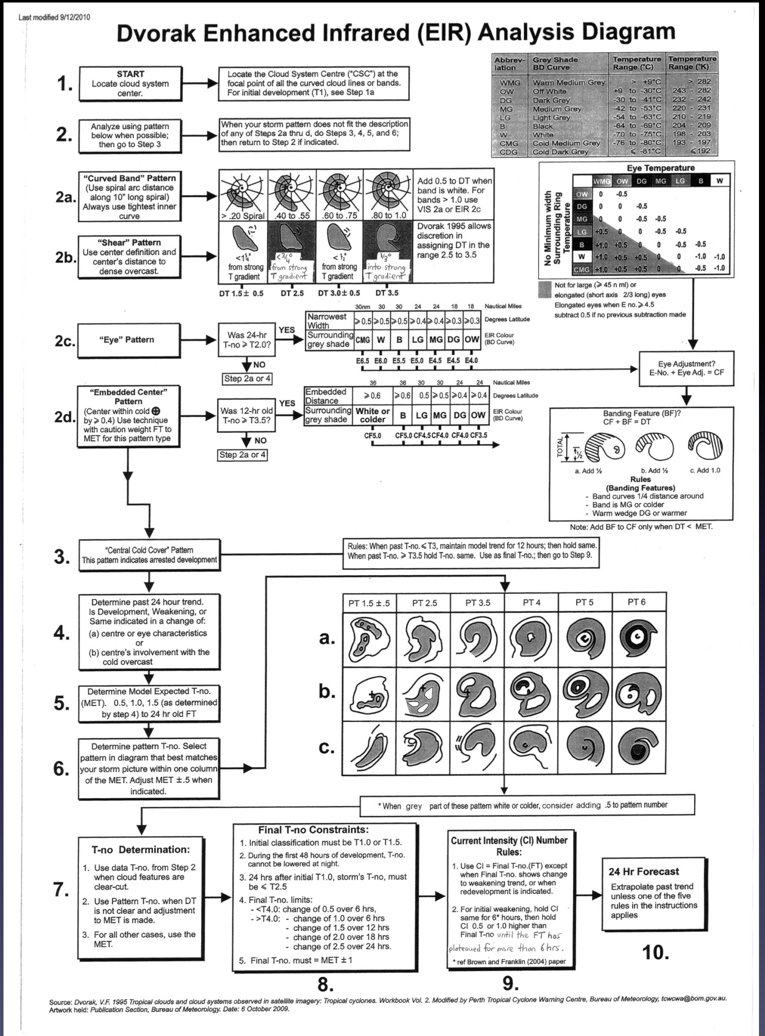
- The Dvorak method is so robust that it is used by TC analysis centers globally, even 50 years after its development
- A remarkable 50% of intensity estimates are within 5 knots of coincident recon measurements (Brown and Franklin 2004)
- Only a small number of storms (~2%) break technique constraints (Cangialosi et al 2015)
- Local modifications have been made over the years by TC centers due to basin tendencies, mainly wrt rapid intensity changes

The Dvorak Technique

<u>Challenges</u>

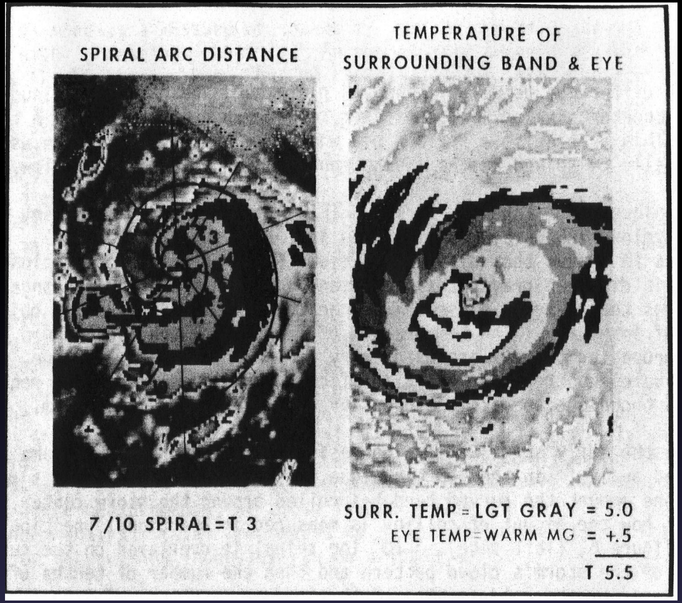
- Can be subjective, and takes time to get good at it
- Limited # of trained analysts
- Limited # of fixes per day (nominally every 3-6 hours)
- Does not work as well in certain storm structures
  - * Eyewall replacement cycles
  - * Rapid intensity changes
  - * Extratropical transitions
  - * Monsoon depressions
- Often sensitive to storm center location
- Tends to underestimate Cat4/5s, and extreme intensities (T8.0 to T8.5 can be difficult to attain)

A desire to address these issues along with the emergence of digital data and automated processing methods motivated the development of objective algorithms

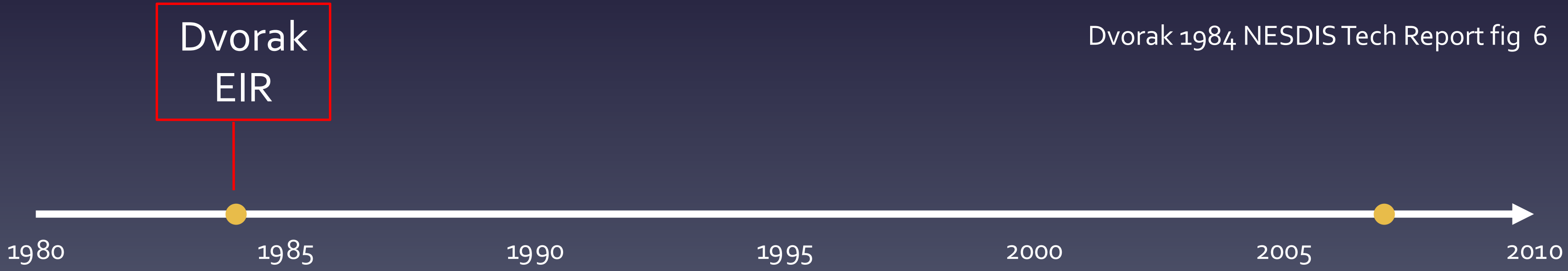


Modern Satellite-Based TC Intensity Estimation Evolution

1984 - Dvorak suggests use of digital enhanced infrared data



Dvorak 1984 NESDIS Tech Report fig 6

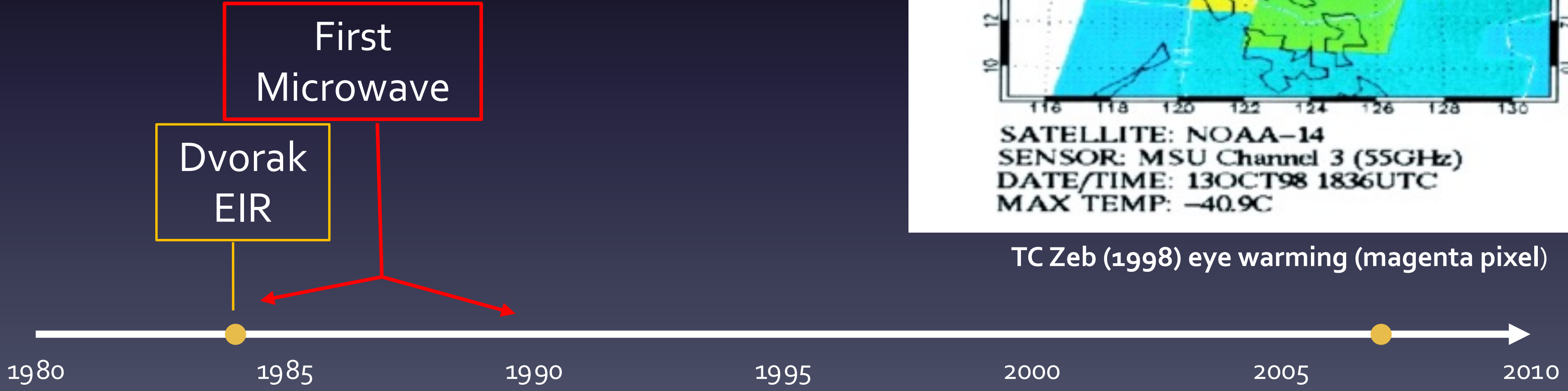


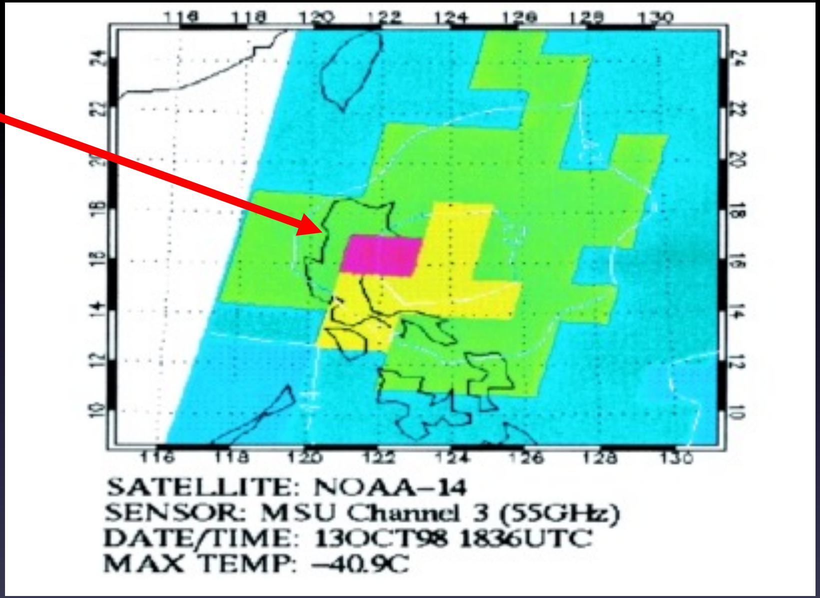
Modern Satellite-Based TC Intensity Estimation Evolution

1984 - Dvorak suggests use of digital enhanced infrared data

1980s – First use of microwave observations

- **Use of the Microwave Sounding Unit (MSU) on NOAA LEOs**
  - Depict strength of upper-level TC warm core anomaly
  - Decent correlation with TC intensity (Kidder et al; Velden et al)
  - Course spatial and temporal resolution
- **Launch of DMSP F-8 (1987) including SSM/I microwave imager**
  - 85 GHz frequency helpful to Dvorak Technique for locating TC centers for sheared and Central Dense Overcast (CDO) cases





TC Zeb (1998) eye warming (magenta pixel)

Modern Satellite-Based TC Intensity Estimation Evolution

1984 - Dvorak suggests use of digital enhanced infrared data

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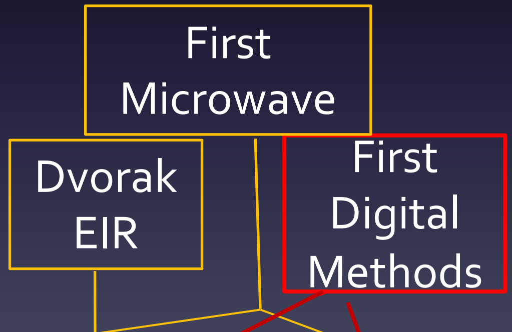
1986-89 - Initial development of objective Dvorak EIR intensity methods (for TCs with an eye)

- **In 1986, the University of Wisconsin McIDAS computer display system was installed at NHC with ability to objectively obtain a raw T-number based on Dvorak EIR in eye cases**
  - Position cursor over eye in IR image displayed and hit "D" key
    - (became Lixion's favorite tool !!)

- **1989: CSU "Digital Dvorak" developed by Ray Zehr**
  - Near-real-time global intensity estimation using geostationary IR satellite imagery
  - Only for TCs > 65 knots, best when an eye is present
  - Laid foundation for more complex automated methods that followed



Modern Satellite-Based TC Intensity Estimation Evolution

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1996 - Objective Dvorak Technique (ODT)

- **Developed by Velden and Olander (CIMSS) to mimic the logic and scene types of the Dvorak Technique**
- **Designed to produce automated and objective real-time, global TC intensity estimation using geostationary IR satellite imagery (demo on CIMSS TC site)**
- **First automated method to be competitive with Dvorak Technique estimates for full intensity range**

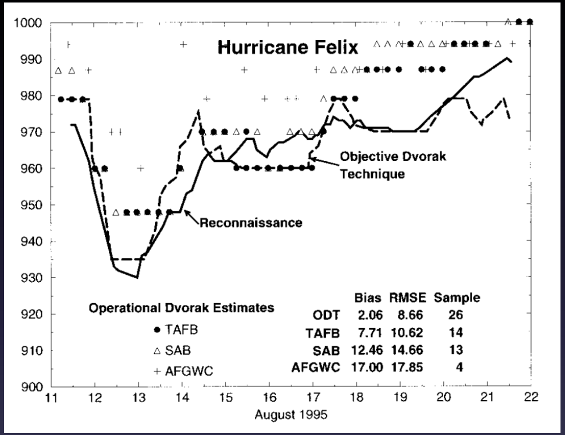
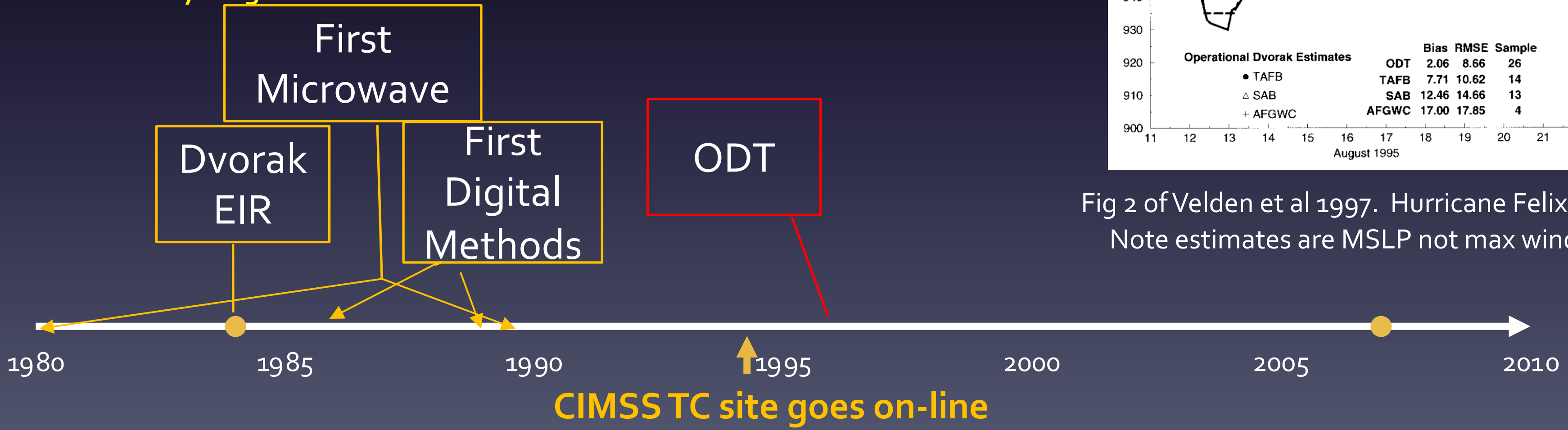


Fig 2 of Velden et al 1997. Hurricane Felix 1995
Note estimates are MSLP not max winds



Modern Satellite-Based TC Intensity Estimation Evolution

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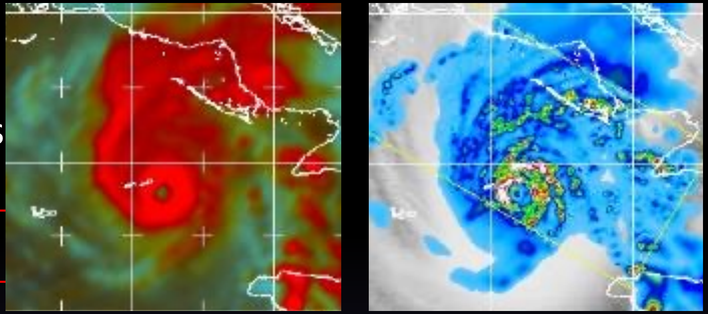
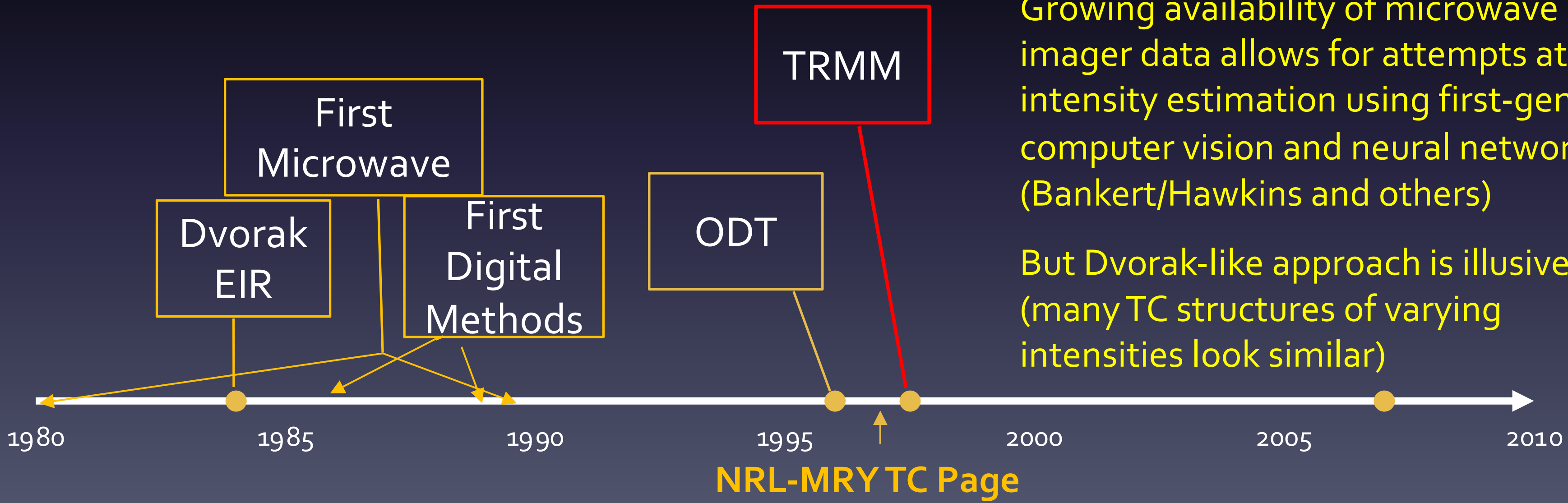


Hurricane Paloma (2008)- TRMM TMI/PR (NRL-MRY)



Growing availability of microwave imager data allows for attempts at intensity estimation using first-gen computer vision and neural networks (Bankert/Hawkins and others)

But Dvorak-like approach is illusive (many TC structures of varying intensities look similar)

Modern Satellite-Based TC Intensity Estimation Evolution

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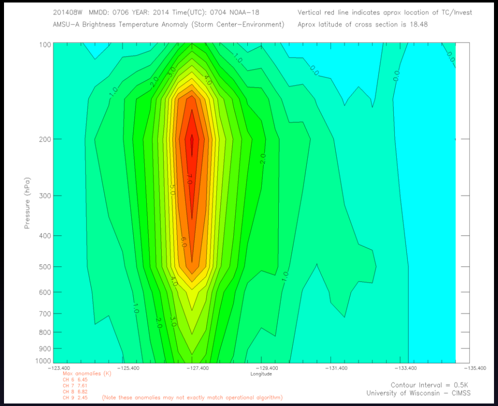
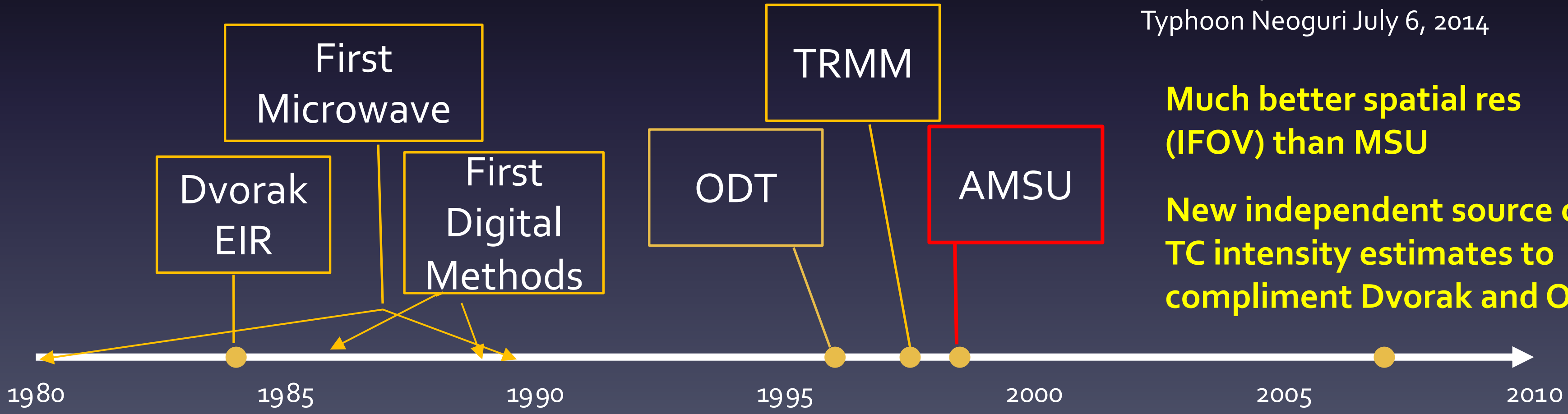
1997 - Launch of Tropical Rainfall Measuring Mission (TRMM)
1998 - NOAA-15 and Advanced Microwave Sounding Unit (AMSU)
- Intensity algorithms developed at CIMSS, CIRA and JMA a few years later



AMSU Tb perturbation cross section of Typhoon Neoguri July 6, 2014



Much better spatial res (IFOV) than MSU

New independent source of TC intensity estimates to compliment Dvorak and ODT

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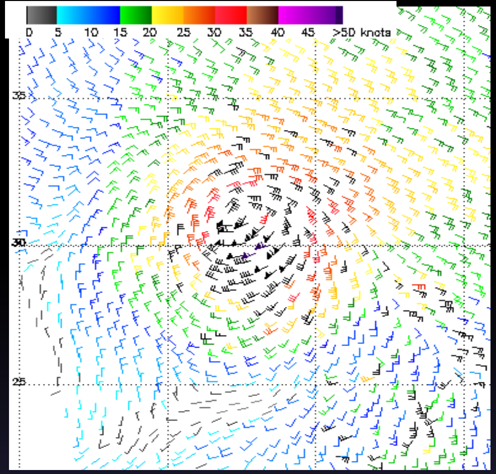
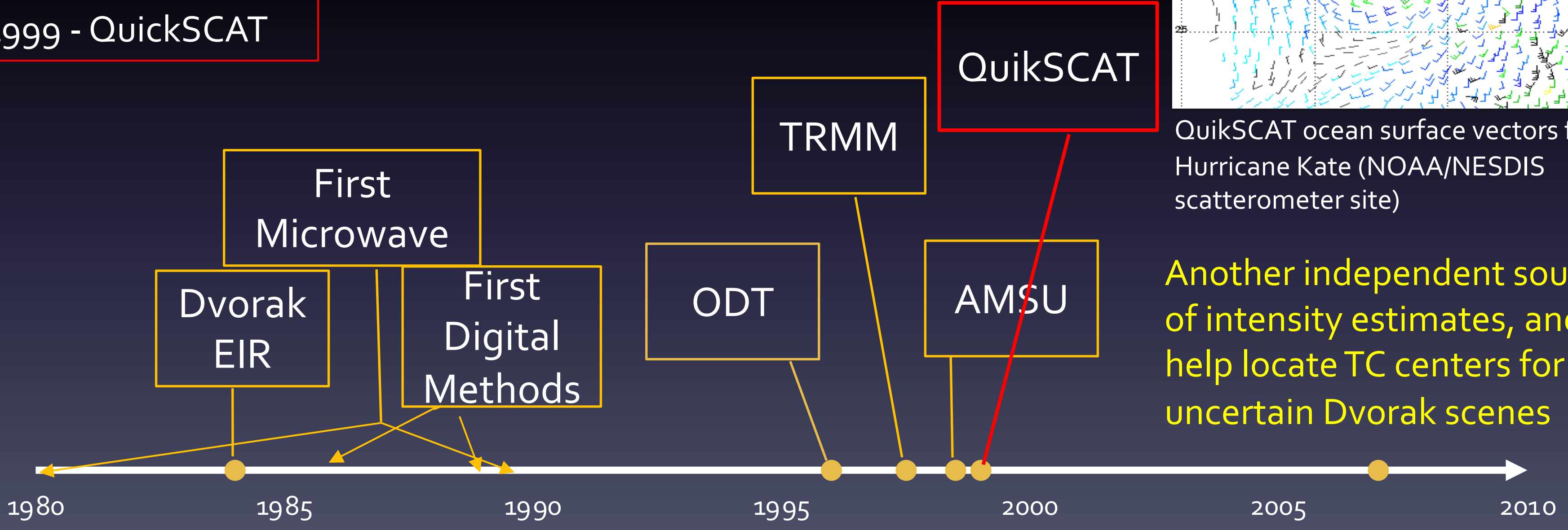
1999 - QuickSCAT



QuikSCAT ocean surface vectors from Hurricane Kate (NOAA/NESDIS scatterometer site)



Another independent source of intensity estimates, and to help locate TC centers for uncertain Dvorak scenes

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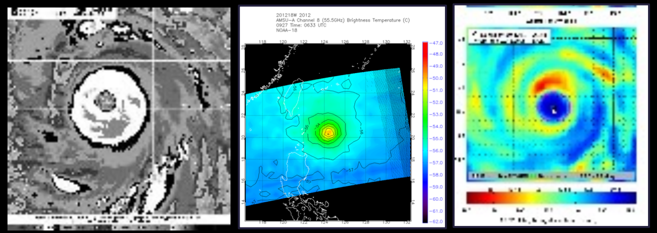
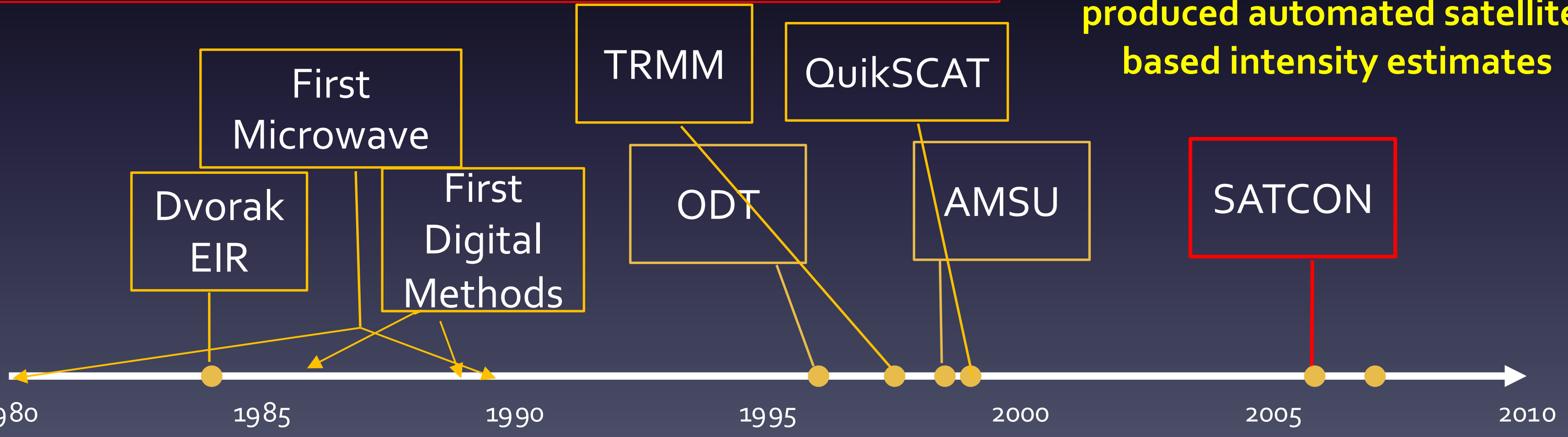
1998 - NOAA-15 and AMSU

2005 - Initial development of SATellite CONsensus (SATCON)
- Velden and Herndon (CIMSS)



IR Sounder Imager

SATCON is a NRT, weighted consensus of independently-produced automated satellite-based intensity estimates



Modern Satellite-Based TC Intensity Estimation Evolution

Current SATCON members:

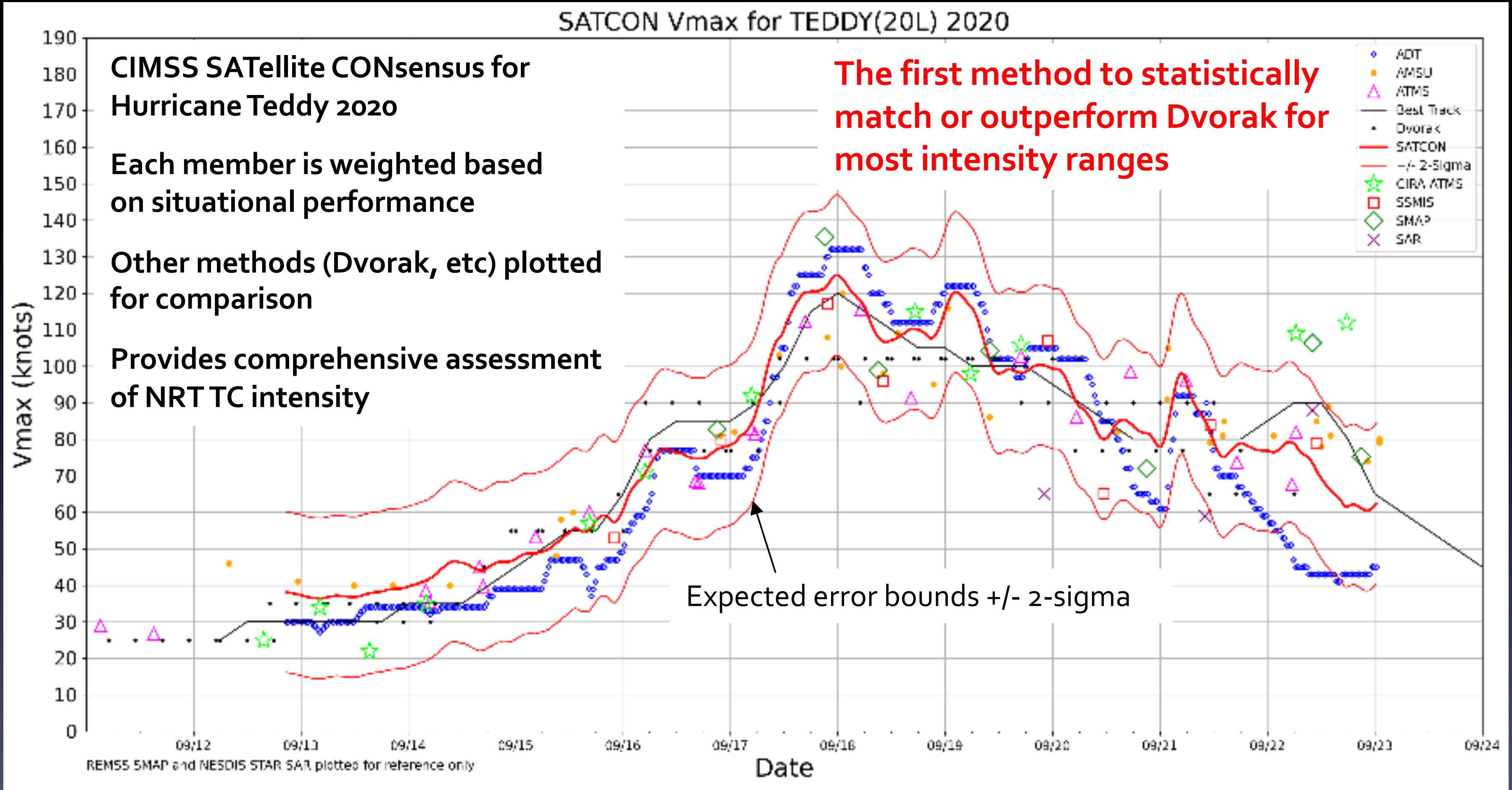
- **LEO microwave sounder-based**
  - **AMSU** (Channels 6-8 and 16)
    - NOAA-15,-18,-19 (N16 AMSU-A failure 2014)
    - Metop B-C (Metop-A Ch 7 failure 2008)
  - **SSMIS** (Channels 3-5 and 17)
    - F16-F17 (F18 sounder failure 2015, F19 failure 2016)
  - **CIMSS ATMS** (Channels 7-9)
    - SNPP/NOAA-20
  - **CIRA ATMS** (Channel 1-22 retrievals)
    - Used when eye > 40km
- **GEO IR imager-based**
  - **ADT**
  - **AiDT**

CIMSS ARCHER is not a member but contributes automated eye and structure information to several members

Non-members but also displayed on SATCON plots:

- Warning agency BT
- SMAP
- SAR
- Operational Dvorak

Modern Satellite-Based TC Intensity Estimation Evolution



Modern Satellite-Based TC Intensity Estimation Evolution

1984 - Dvorak suggests use of digital enhanced infrared data

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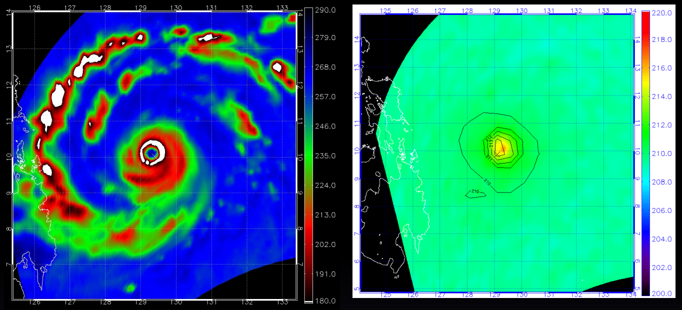
1998 - NOAA-15 and AMSU

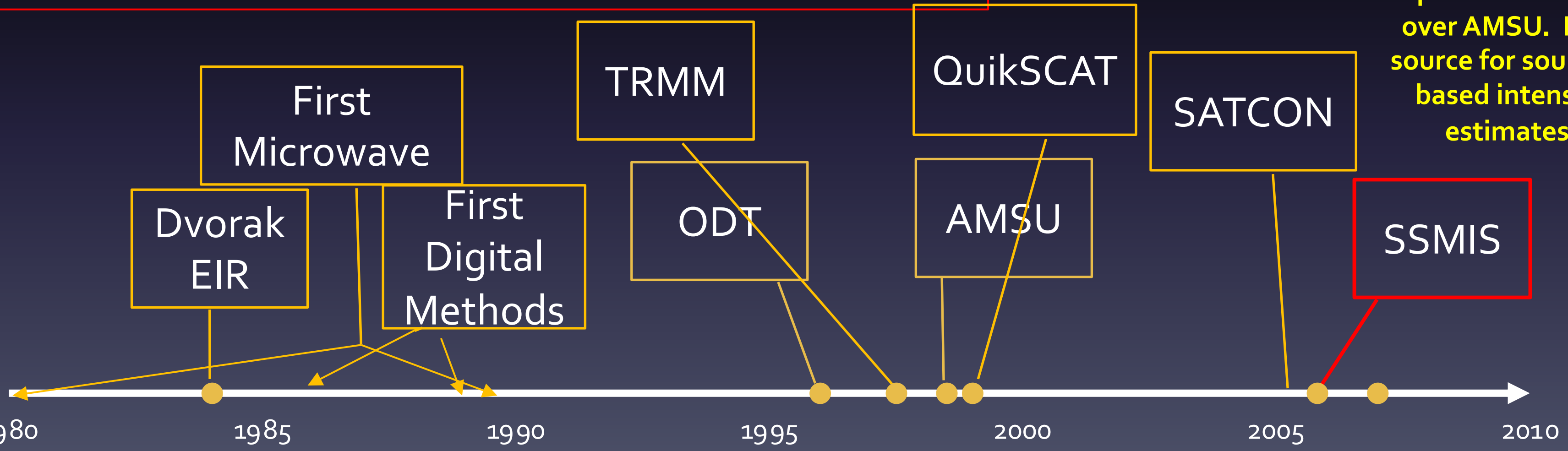
2005 - SATellite CONsensus (SATCON)

2005 - DMSP F-16 Special Sensor Microwave Imager/Sounder



SSMIS Imager 91 GHz (left) and Sounder ~55 GHz (right) for Super Typhoon Haiyan

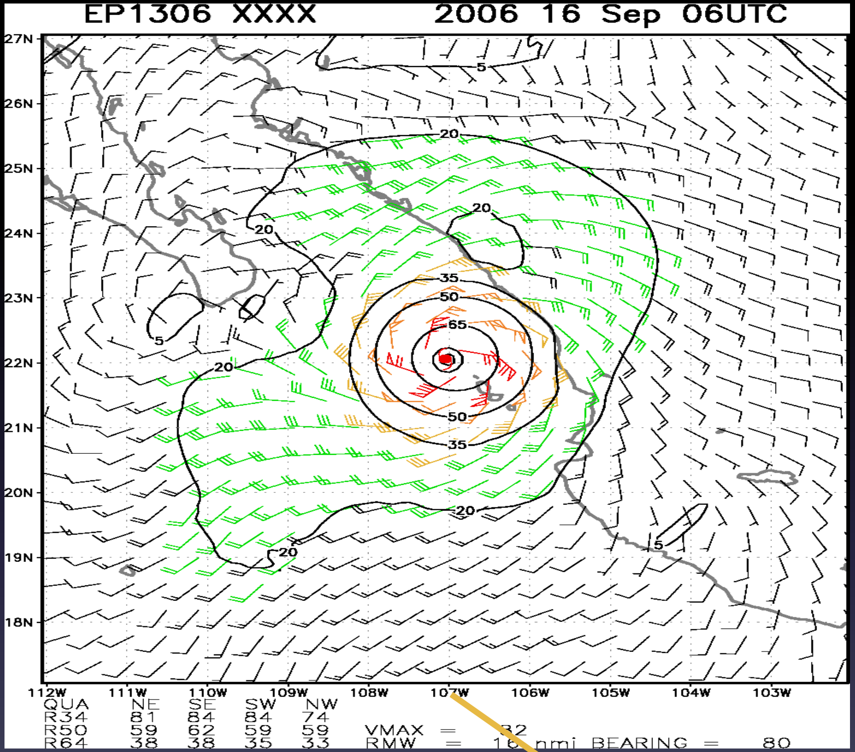
Improved resolution over AMSU. New source for sounder-based intensity estimates.



Modern Satellite-Based TC Intensity Estimation Evolution

2006 - Another integrated product—the CIRA Multi-Platform Tropical Cyclone Surface Wind Analysis
- Knaff et al. (NOAA/CIRA)

- First effort to produce a full 2D surface wind field in TCs from merged satellite data
- Analyzed wind field based on VIS/IR AMVs, AMSU, Scatterometers
- Not specifically designed for Vmax but does depict the radii of critical wind thresholds

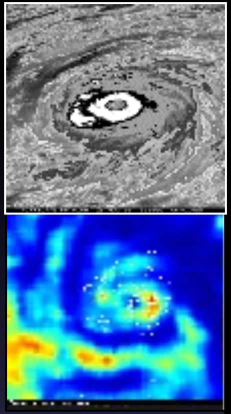


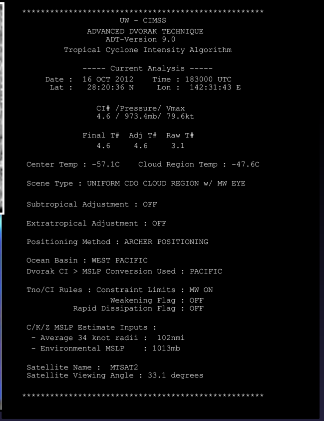
1980 1985 1990 1995 2000 2005 2010

Modern Satellite-Based TC Intensity Estimation Evolution

2008 - Advanced Dvorak Technique (ADT)

- Olander and Velden (CIMSS)





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                    UW - CIMSS
             ADVANCED DVORAK TECHNIQUE
                 ADT-Version 9.0
        Tropical Cyclone Intensity Algorithm

             ----- Current Analysis -----
     Date :  16 OCT 2012    Time : 183000 UTC
      Lat :   28:20:36 N     Lon :  142:31:43 E

                CI# /Pressure/ Vmax
                4.6 / 973.4mb/ 79.6kt

             Final T#  Adj T#  Raw T#
                4.6     4.6     3.1

 Center Temp : -57.1C    Cloud Region Temp : -47.6C

 Scene Type : UNIFORM CDO CLOUD REGION w/ MW EYE

 Subtropical Adjustment : OFF

 Extratropical Adjustment : OFF

 Positioning Method : ARCHER POSITIONING

 Ocean Basin : WEST PACIFIC
 Dvorak CI > MSLP Conversion Used : PACIFIC

 Tno/CI Rules : Constraint Limits : MW ON
                    Weakening Flag : OFF
           Rapid Dissipation Flag : OFF

 C/K/Z MSLP Estimate Inputs :
  - Average 34 knot radii :  102nmi
  - Environmental MSLP    : 1013mb

 Satellite Name :  MTSAT2
 Satellite Viewing Angle : 33.1 degrees

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https://tropic.ssec.wisc.edu/real-time/adt

ADT attributes:

- Computer-based, fully automated, real-time, global
- Modified ODT/AODT algorithms using new satellite image analysis and interrogation techniques
- Advanced the Dvorak methods beyond the original procedures and guidelines based on rigorous statistical analysis and situational performance
- Added LEO microwave image analysis to help identify emerging eye structures under CDO situations
- Implemented improved TC center fixing (ARCHER)
- Adjustments for ST and ET storm phases
- Later became operational at NOAA/NESDIS

Modern Satellite-Based TC Intensity Estimation Evolution

2008 - Advanced Dvorak Technique (ADT)

2008-2020 – Development of the Deviation Angle Variance Technique (DAVT)

- Liz Ritchie et al.

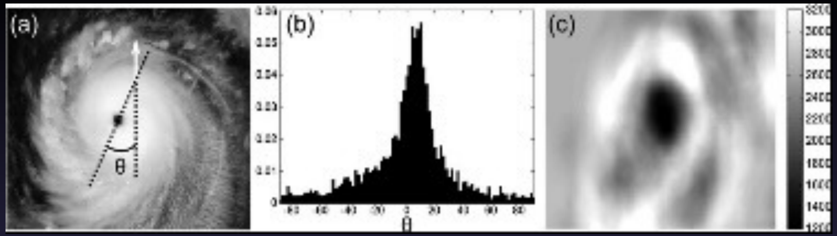
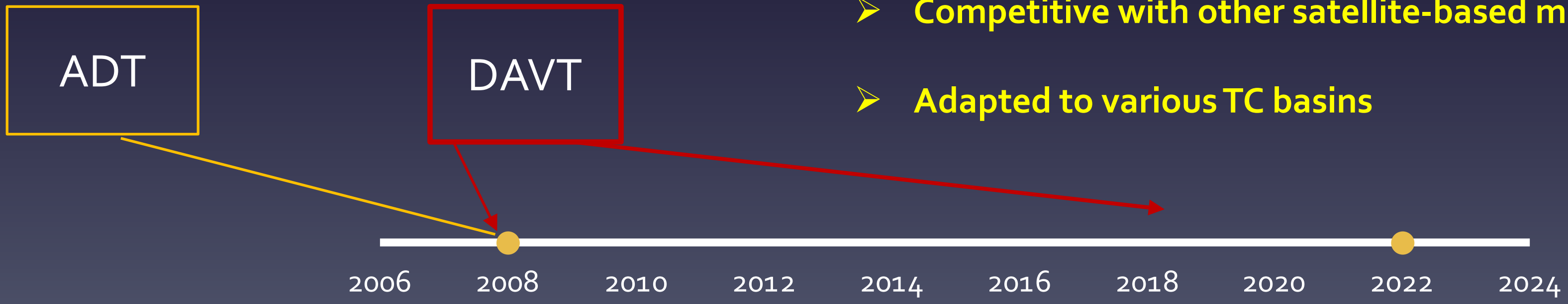


Fig. 2 from Ritchie et al. 2014



DAVT attributes:

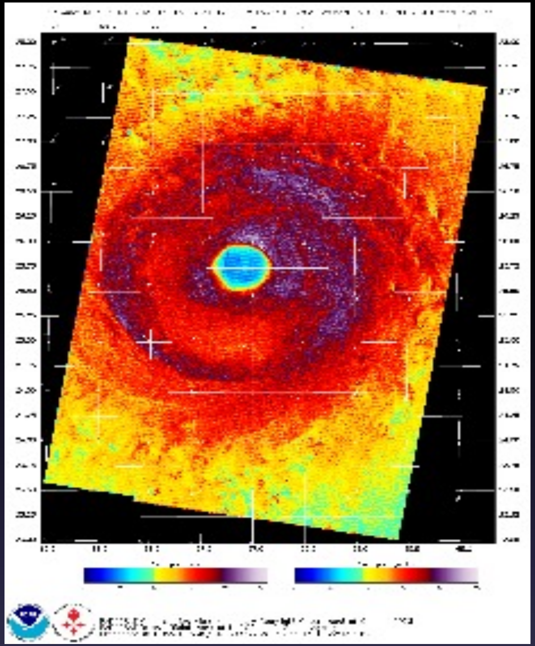
- Operates on GEO IR imagery
- The technique quantifies the level of organization or axisymmetry of the IR cloud signature of a TC as an indirect measurement of its maximum wind speed
- Calculates the gradient of the brightness temperatures and the departure of that gradient from a perfectly axisymmetric TC. A single value quantifies that departure (deviation angle) as an asymmetry
- Competitive with other satellite-based methods
- Adapted to various TC basins

Modern Satellite-Based TC Intensity Estimation Evolution

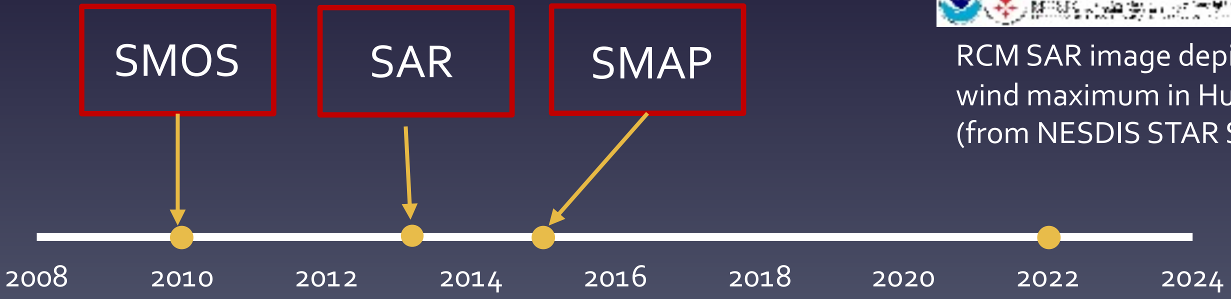
2010 - SMOS: L-band (1.4 GHz) microwave imagers on LEO sats
- 2D wind fields at moderate resolution

2013 - SAR: very high resolution (0.5 km) 2D wind fields
- Infrequent passes over TCs and at first not available in real time
- Wind retrievals mature to produce unprecedented detail of wind structure incl max wind speed estimates, eye size and RMW
- Products eventually made selectively available in NRT data

2015 - SMAP: L-band, not impacted by rain even in TC conditions
- Recently available in NRT by REMSS (Meissner and Ricciardulli)



RCM SAR image depicting secondary wind maximum in Hurricane Lee 2023 (from NESDIS STAR SAR site)



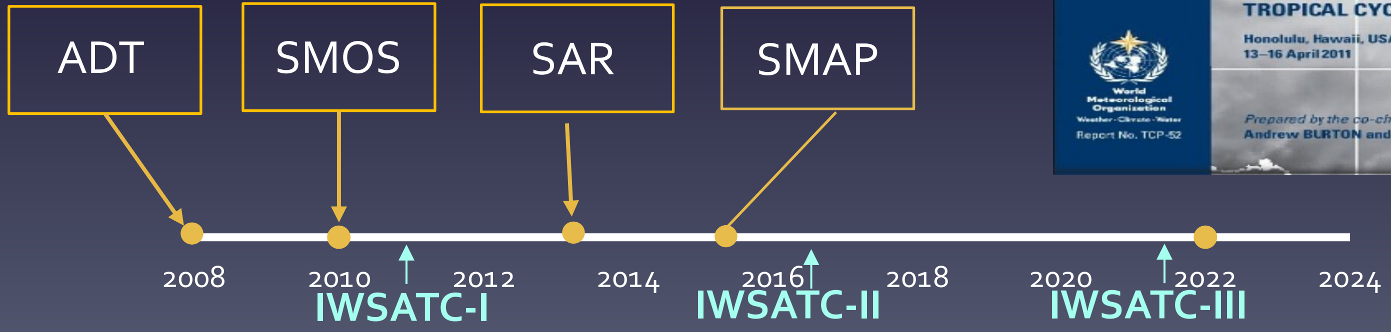
Modern Satellite-Based TC Intensity Estimation Evolution

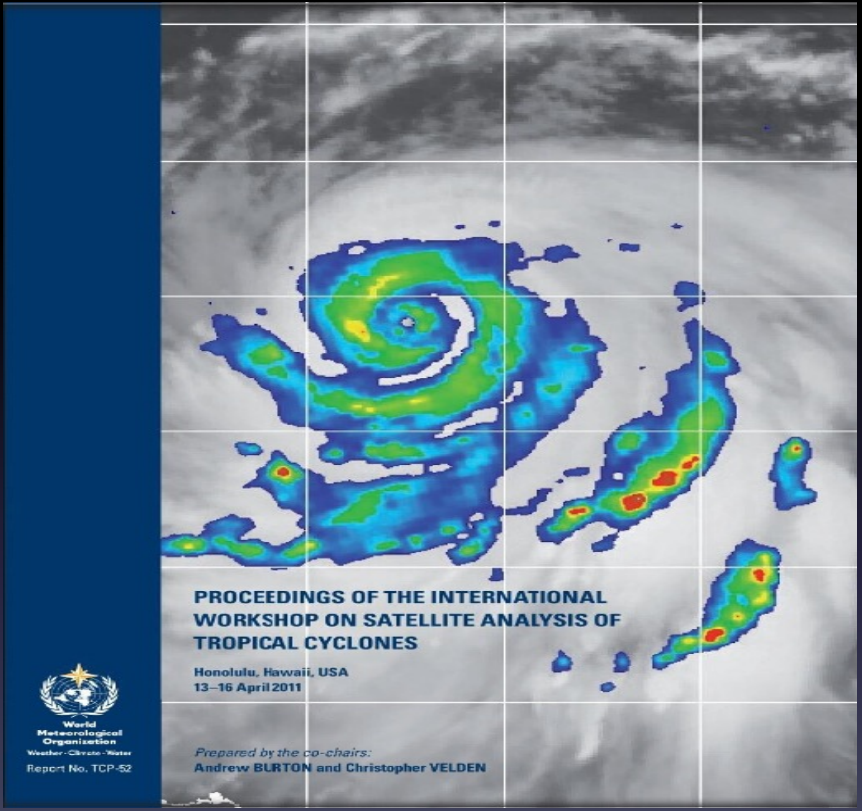
2008 – ADT
2010 – 2015 SMOS/SAR/SMAP

2011 –> 2021 WMO International Workshops on Satellite Analysis of Tropical Cyclones (IWSATC)

- Meets every ~5 years
- Includes global operational and research communities
- To present and share new satellite-based TC analysis methods and applications
- Many international efforts not shown in this presentation can be found here:

https://community.wmo.int/en/international-workshop-satellite-analysis-tropical-cyclones-iwsatc





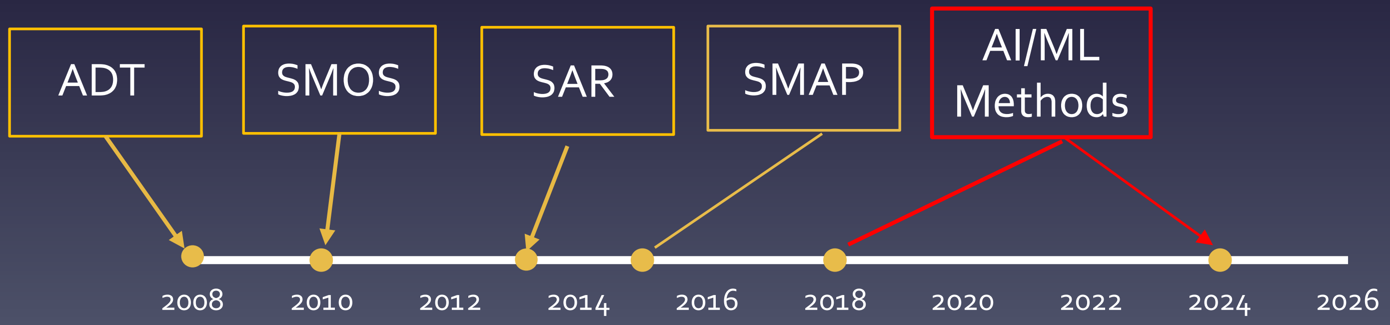
Modern Satellite-Based TC Intensity Estimation Evolution

2008 – ADT
2010 – 2015 SMOS/SAR/SMAP

2018 – New AI/Machine Learning approaches emerge

- Pradhan, R., R. Aygun, M. Maskey, R. Ramachandran, and D. Cecil, 2018: Tropical cyclone intensity estimation using a deep convolutional neural network. *IEEE Trans. Image Process.*, 27, 692–702.
- Wimmers, A., C. Velden, and J. H. Cossuth, 2019: Using deep learning to estimate tropical cyclone intensity from satellite passive microwave imagery. *Mon. Wea. Rev.*, 147, 2261–2282.
- Chen, B.-F., B. Chen, H.-T. Lin, and R. L. Elsberry, 2019: Estimating tropical cyclone intensity by satellite imagery utilizing convolutional neural networks. *Wea. Forecasting*, 34, 447–465.
- Lee, J., J. Im, D.-H. Cha, H. Park, and S. Sim, 2020: Tropical cyclone intensity estimation using multi-dimensional convolutional neural networks from geostationary satellite data. *Remote Sens.*, 12, 108-120.
- Zhuo, J.-Y., and Z.-M. Tan, 2021: Physics-augmented deep learning to improve tropical cyclone intensity and size estimation from satellite imagery. *Mon. Wea. Rev.*, 149, 2097–2113.

- Any many others…



Modern Satellite-Based TC Intensity Estimation Evolution

Example: 2 Deep-Learning models developed at CIMSS

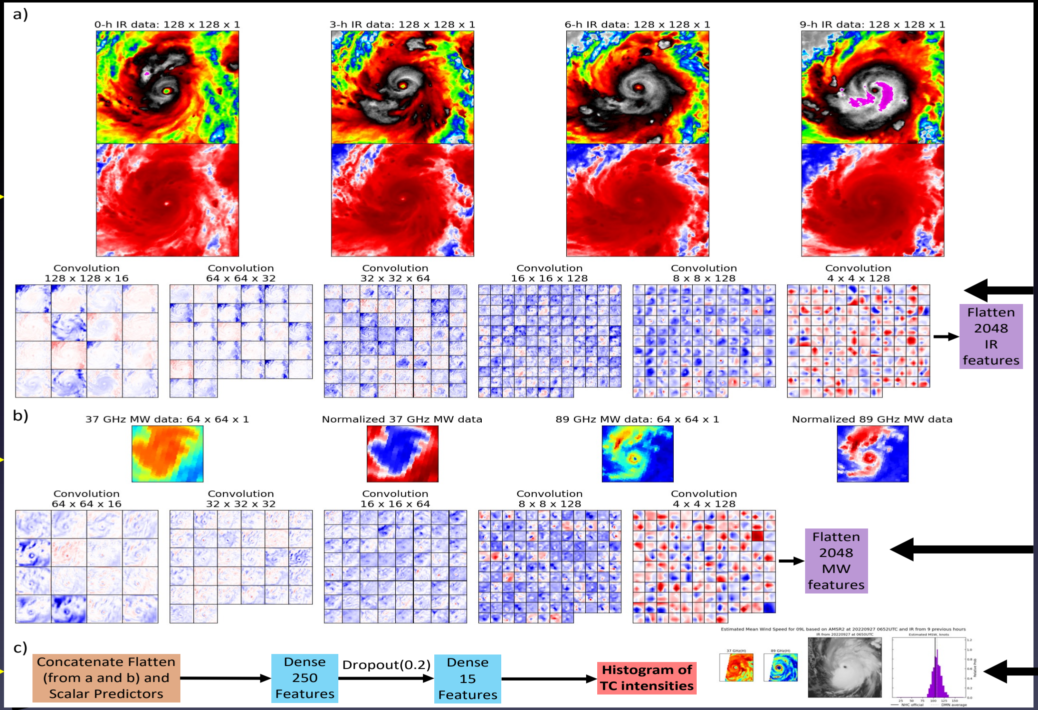
D-PRINT: ***D**ee**P** i**R** **INT**ensity estimator*

D-MINT: ***D**eep **M**ultispectral **INT**ensity estimator*

Input Features: IR data
128x128 grid over ~6 X 6° area centered on TC, normalized.

Input Features: MW data
64 x 64 grid over ~3.2 X 3.2° area centered on TC, normalized.

Input Features: Add normalized scalar, location, time features.



D-PRINT (IR only)
Steps a) and c) only

D-MINT (IR+MW)
Steps a), b) and c)

6 convolution layers where the scale gradually increases and more feature maps are added.

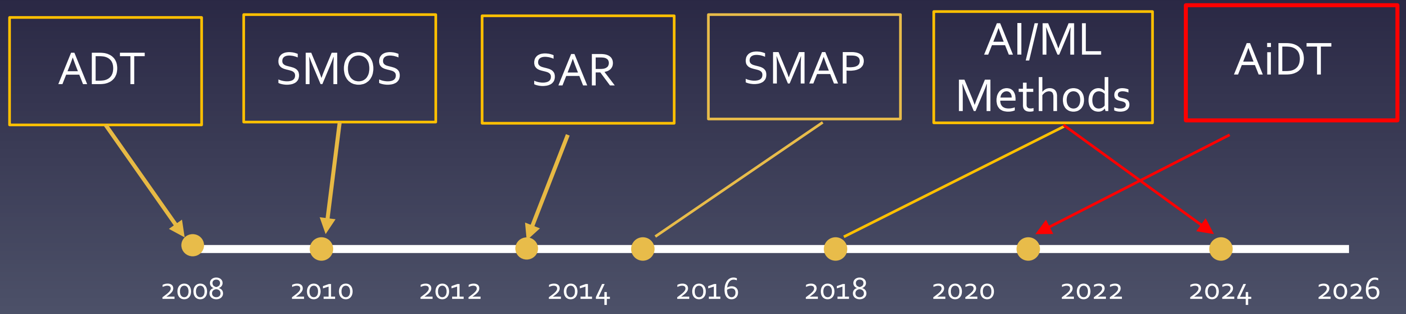
5 convolution layers (not included in D-PRINT)

Output: 15 quantiles of TC intensity probabilities

- **Promising performance, now being demonstrated in real time for all global TCs and evaluated by Ops Centers (JTWC, NHC, Aust BOM)**
  - Available on-line at the CIMSS TC site: https://tropic.ssec.wisc.edu/real-time/DMINT/ or /DPRINT/
- **See Griffin, Wimmers and Velden, 2024, *Weather and Forecasting*, for further details**

Modern Satellite-Based TC Intensity Estimation Evolution

2008 - Advanced Dvorak Technique
2008-2020 - DAVT
2009 - SMOS
2013 - SAR
2015 - SMAP
2018 - New AI-based approaches emerge
2021 - AI-enhanced Advanced Dvorak Technique (AiDT)

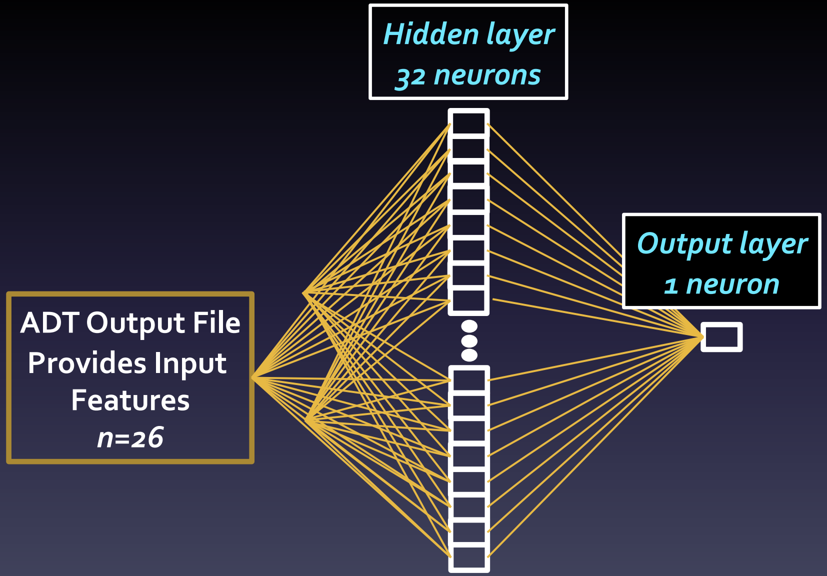


Advanced AI-enhanced Dvorak Technique (AiDT)
(ADT v10.0 -- Final ADT model)

Procedure: Run ADT image processing analysis, then apply a DNN to the ADT analysis output parameters to produce an adjusted intensity estimate

AiDT model:

- Fully-connected Deep Neural Network (DNN)
- Regression-based loss function
- Input: 26 ADT Analysis Output File Features
- One Hidden (Dense) layer with 32 neurons
- One Output layer neuron representing a single wind speed estimate value
- Overall, performs ~25% better than ADT (RMSE)
- Now being transitioned into NOAA operations

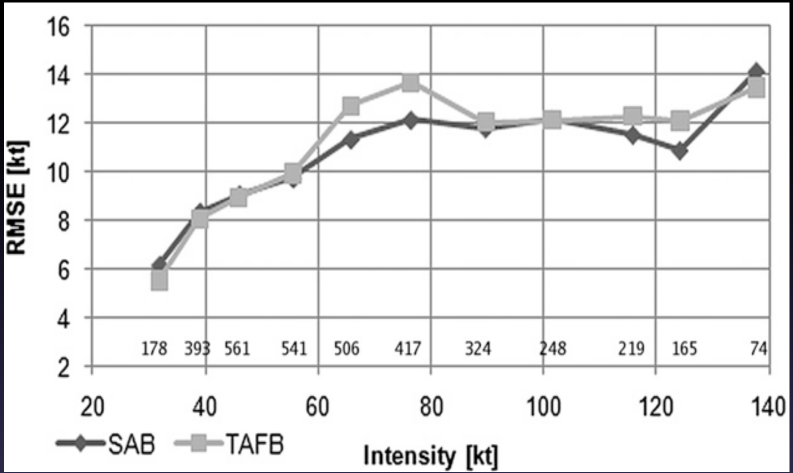


- **Now being demonstrated in real time for all global TCs and evaluated by Ops Centers (JTWC, NHC, Aust BOM, etc)**
  - **Available on-line at the CIMSS TC site: https://tropic.ssec.wisc.edu/real-time/adt/AiDT/aidt.html**
- **See Olander, Wimmers and Velden, 2021, *Weather and Forecasting*, for further details**

Modern Satellite-Based TC Intensity Estimation Evolution

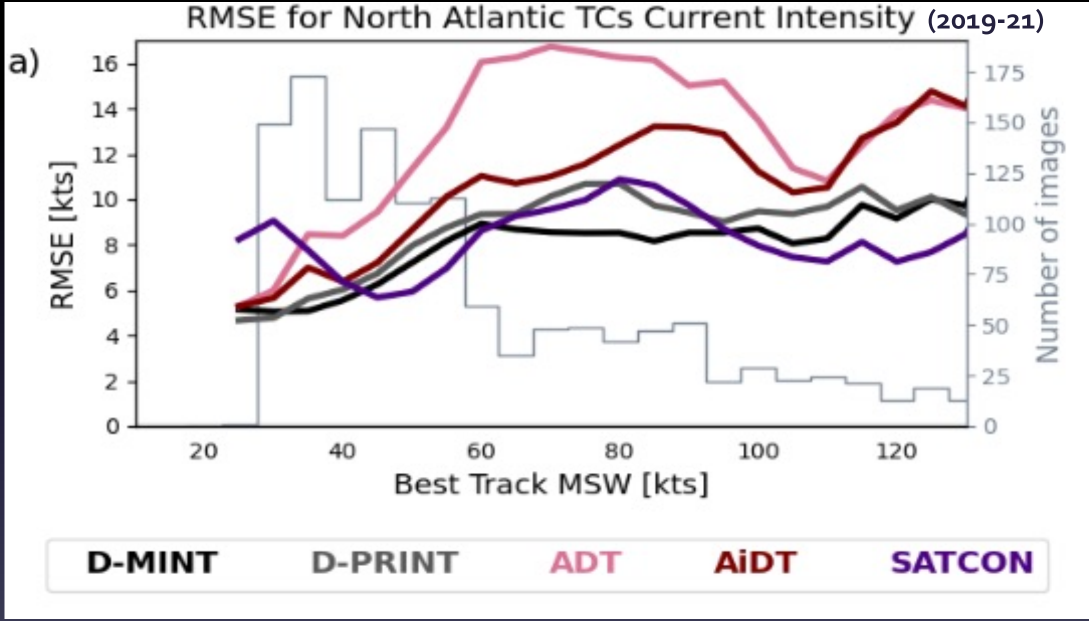
Statistical Evolution (non-homogeneous comparison)

Manual Dvorak Technique



Dvorak TC intensity estimates RMSE (kt) from SAB and TAFB in the Atlantic basin from 1989-2008 (number of cases is provided at the bottom). (From Fig. 3 of Knaff et al. 2010)

Modern Automated Methods



Note: D-MINT/D-PRINT are not yet incorporated into the SATCON consensus. We expect the SATCON skill will improve with addition of AI members.

- **Original automated methods (ODT, ADT, etc) were designed to mimic the DT with comparable results**
- ***Later contemporary methods (AI-based, SATCON) are showing improvements!***

Thank You Vern!

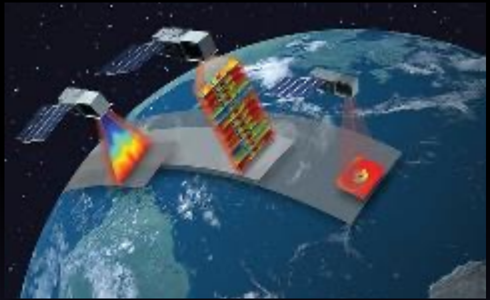
"There's great joy in being useful , and that's the satisfaction you get out of it."
- Maurice Hilleman (developer of the measles, mumps and 38 other vaccines)

Vern Dvorak's work has been beyond "useful", helping to save untold lives.

Despite all the modern techniques just discussed (and others not enough time to cover), 50 years on, it is a testament to the Dvorak Technique that it remains a mainstay of satellite-based TC intensity analysis. Even if replaced by modern methods, it's roots will endure and will long be a benchmark for comparisons.

Extra Slides

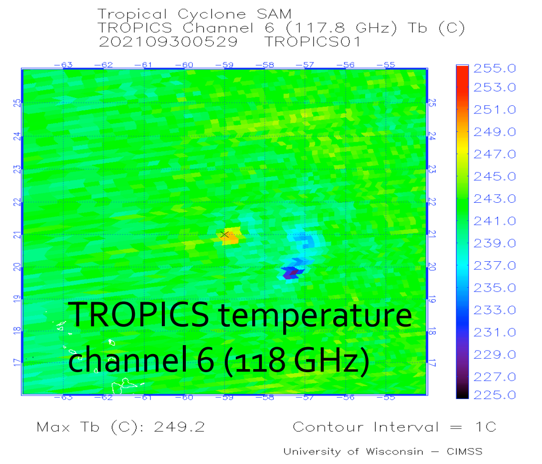
CubeSATS: TROPICS



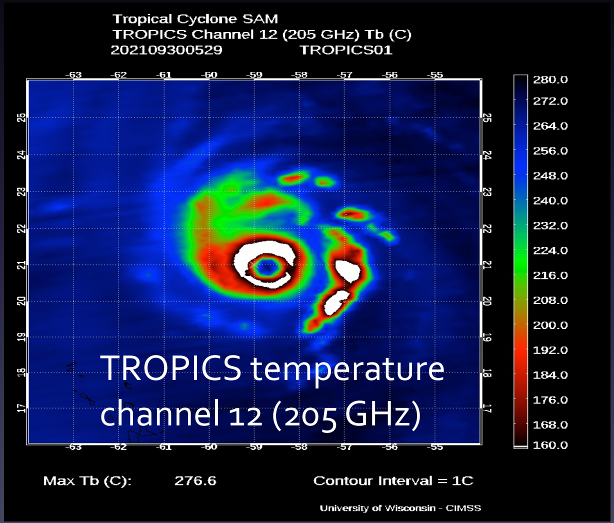
The Time-Resolved Observations of Precipitation structure and storm Intensity with a Constellation of Smallsats (TROPICS). NASA Earth Venture class mission that began with the launch of a single-unit TROPICS Pathfinder satellite on June 30th, 2021

4 Satellites launched in two phases May and June 2023

Temperature, moisture, TC intensity, structure and precipitation products.



Warm anomaly used to estimate TC intensity similar to AMSU/ATMS

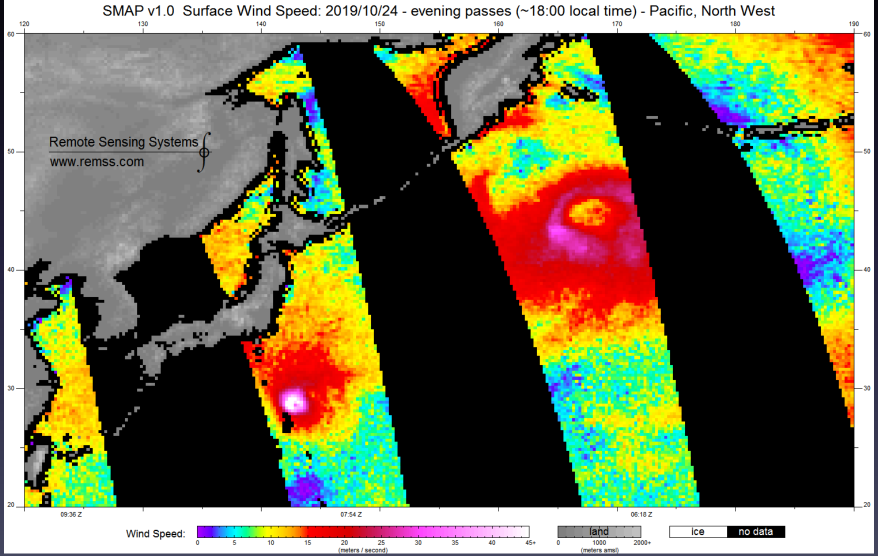


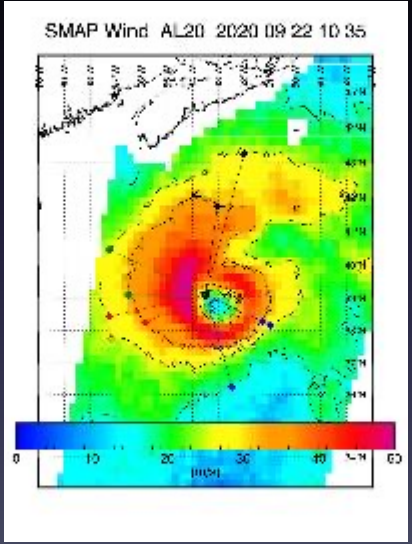
183 -205 GHz provides information about storm structure and inner core organization.

A number of government and private industry cubesat launches are planned over the next several years

SMAP/SMOS Passive Microwave Imagers

L-band (1.4 GHz) microwave imagers on LEO sats with huge antenna
SMAP: Soil Moisture Active Passive sensor
SMOS: Soil Moisture and Ocean Salinity sensor
- 1.4 GHz not impacted by rain even within TC conditions





Courtesy: REMSS

Strongest TCs in the satellite era using the Advanced Dvorak Technique

Dvorak DB infrared enhancements →

All assessed at Dvorak intensities of 7.0 or greater except Wilma (at 6.5). Only Haiyan assessed at 8.0

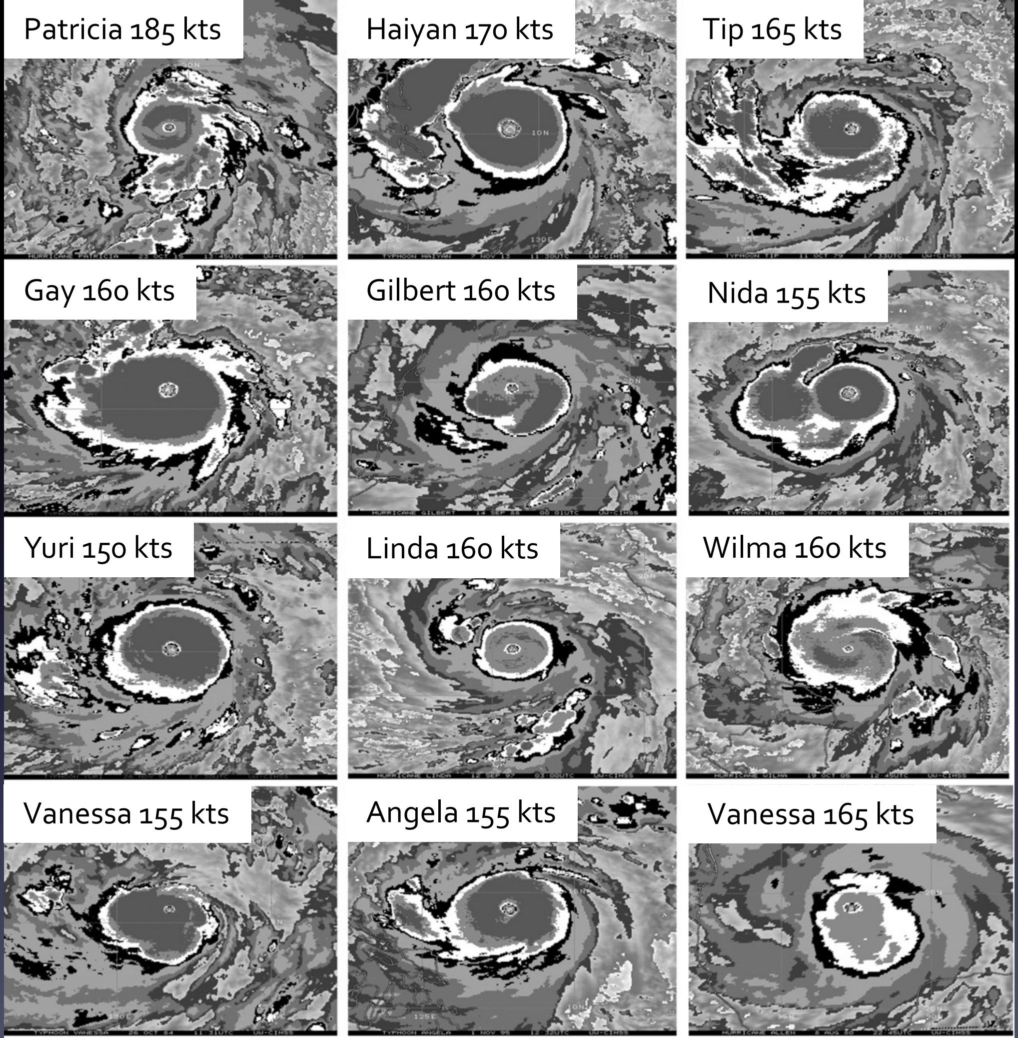


TABLE [illegible]. Rank of the most intense (in terms of maximum sustained 1-min wind) global tropical cyclones in the geostationary satellite era as determined by the objective, satellite-based ADT.

Rank (ADT Vmax)	Tropical cyclone name (year)	ADT final adjT#[a]	ADT estimated Vmax (1 min avg; kt)	ADT estimated MSLP (hPa) [rank][b]	Best track Vmax (1 min avg; kt)[c]	Best track MSLP (hPa)[c]	Operational Dvorak estimate (T#)[d]
1	Patricia (2015)	8.4	182	[illegible] [2]	185	872	7.0–[illegible]
2	Haiyan (2013)	8.2	176	878 [3]	170	895	8.0
3	Tip (1979)	8.1	173	[illegible] [1]	165	[illegible]	7.5
3	Gay (1992)	8.1	173	883 [4]	160	872	7.5
5	Gilbert (1988)	8.0	170	887 [6]	160	888	7.5
5	Yuri (1991)	8.0	170	887 [6]	150	[illegible]	7.5
5	Nida (2009)	8.0	170	892 [12]	155	[illegible]	7.5
8	Linda (1997)	7.9	167	884 [5]	160	[illegible]	7.5–8.0
8	Allen (1980)	7.9	167	[illegible] [8]	165	[illegible]	7.5
8	Vanessa (1984)	7.9	167	886 [6]	155	880	7.0
8	Wilma (2005)	7.9	167	888 [10]	160	882	6.5
8	Angela (1995)	7.9	167	889 [11]	155	[illegible]	7.5

[a] ADT final bias corrections based on reconnaissance aircraft calibrations, TC eye size, satellite view angle, IR image spatial resolution, and frequency.
[b] Based on Knaff–Zehr–Courtney wind–pressure relationship.
[c] NHC best tracks in Atlantic and eastern North Pacific. All other basins, JTWC best tracks.
[d] If more than one agency's estimate is available, the range is given if there is disagreement.

See "Reprocessing the Most Intense Historical Tropical Cyclones in the Satellite Era Using the Advanced Dvorak Technique" MWR 2017

NESDIS Synthetic Aperture Radar (SAR) for Hurricane Teddy Sep 22 10:17 UTC