The Dvorak Technique

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NCEP

WHERE AMERICA'S CLIMATE AND WEATHER SERVICES BEGIN

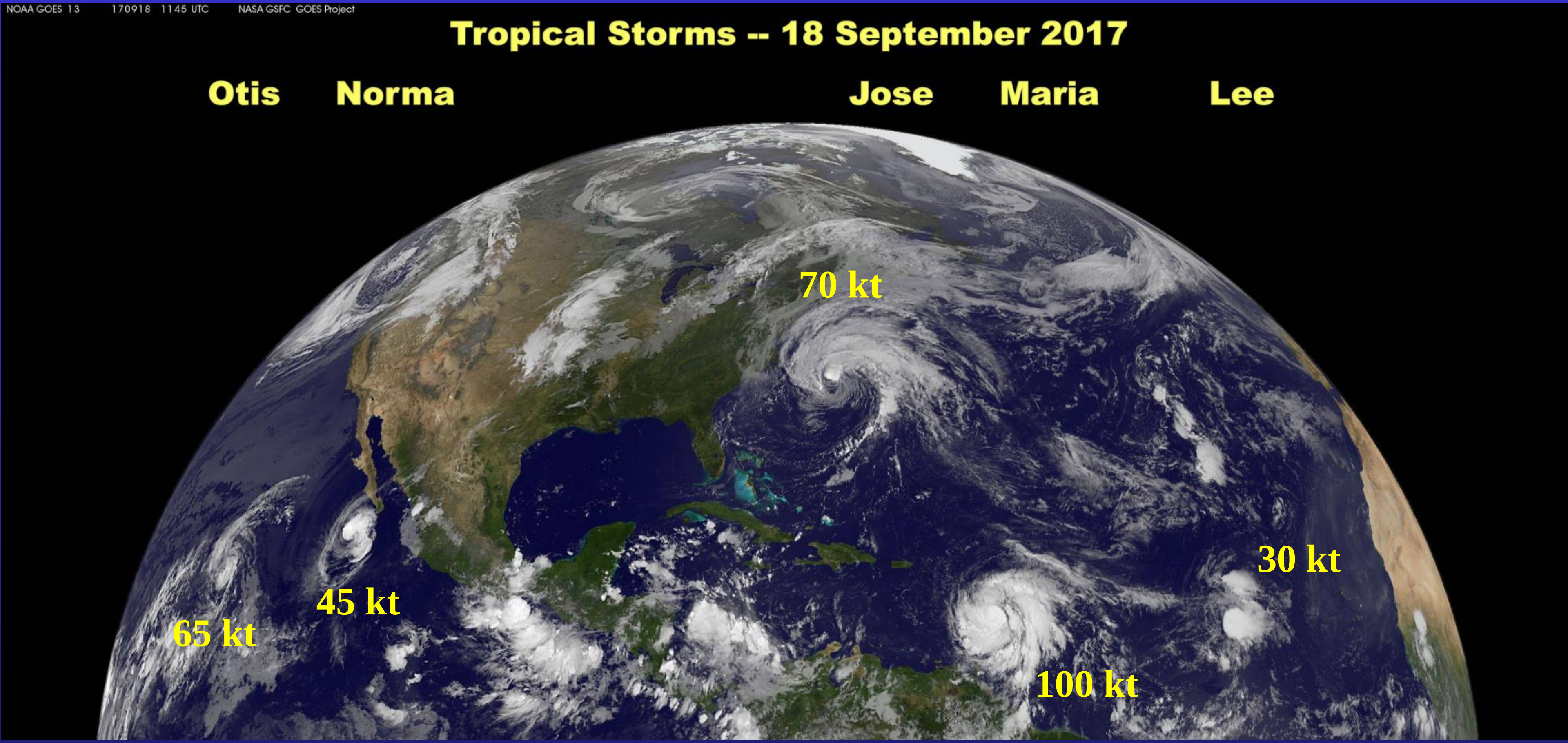
What is the Dvorak Technique?

- A statistical method for estimating the intensity of tropical cyclones (TCs) from interpretation of satellite imagery
- Uses regular Infrared and Visible imagery
- Based on a “measurement” of the cyclone’s convective cloud pattern and a set of rules
- It is used at tropical cyclone warning centers around the world

What the Dvorak Technique isn't

- A direct measurement of wind, pressure, or any other meteorological variable associated with a tropical cyclone!
- A replacement for *in situ* measurements of a tropical cyclone
- Based rigorously on the physical principles of the atmosphere

Dvorak Technique Premise



- There is a (imperfect) correlation between the intensity of a TC and its satellite observed cloud pattern during both development and decay.

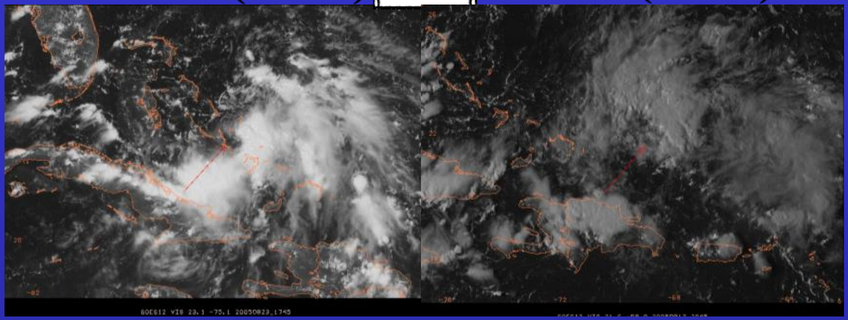
TC Cloud Patterns - Developing

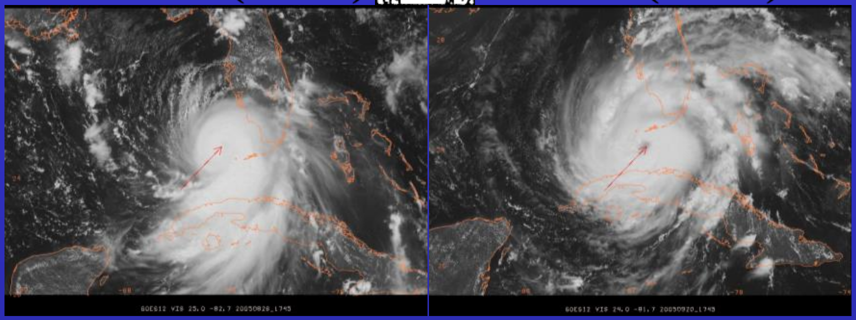
Katrina (2005)

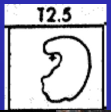
Rita (2005)

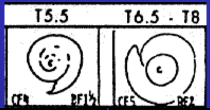
Katrina (2005)

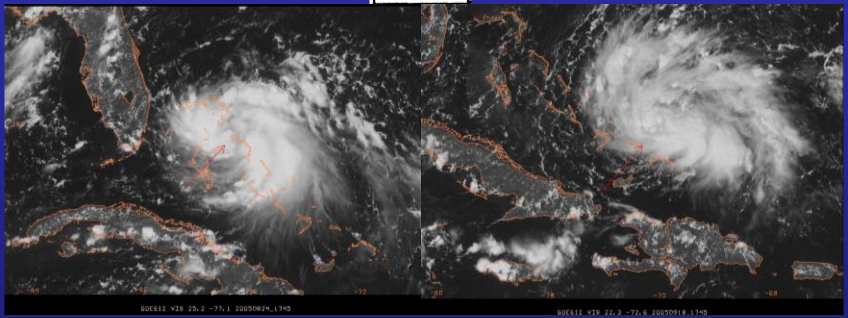
Rita (2005)

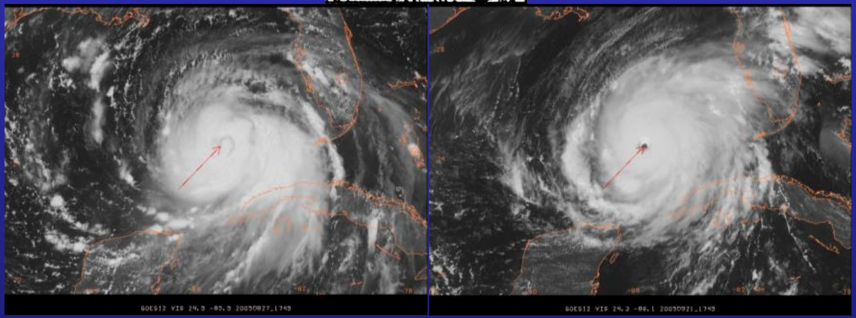


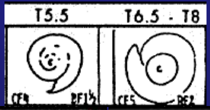


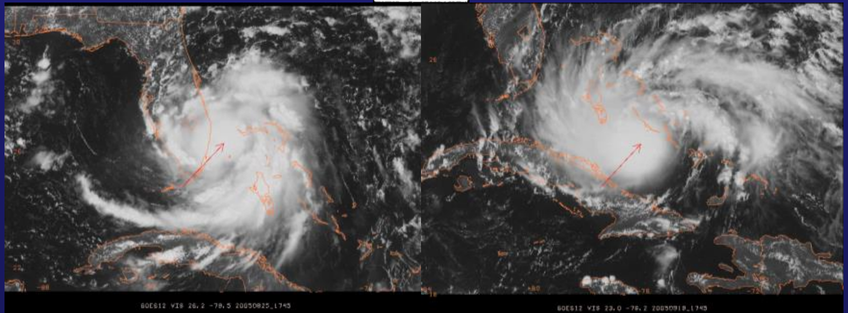


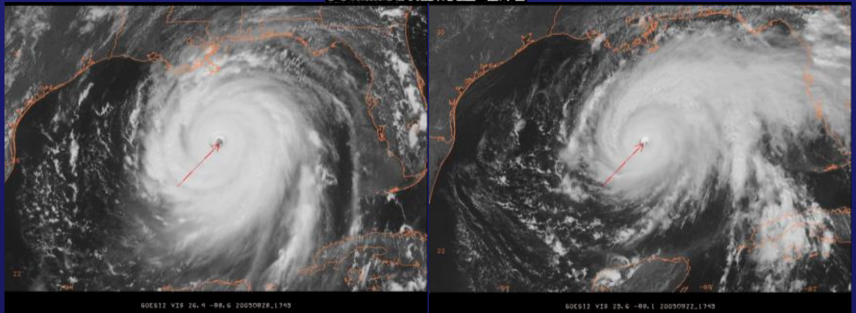






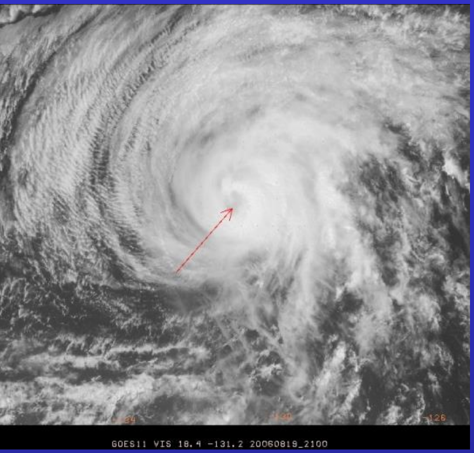






TC Cloud Patterns - Weakening

Hector 2006



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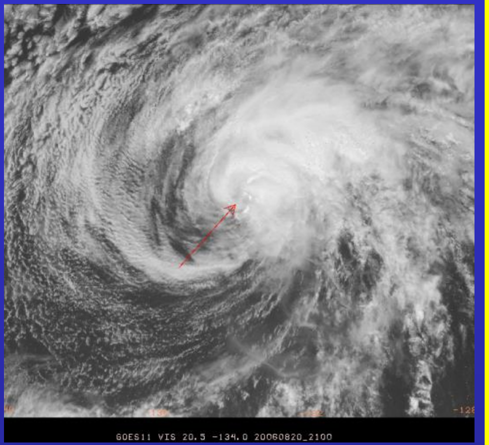
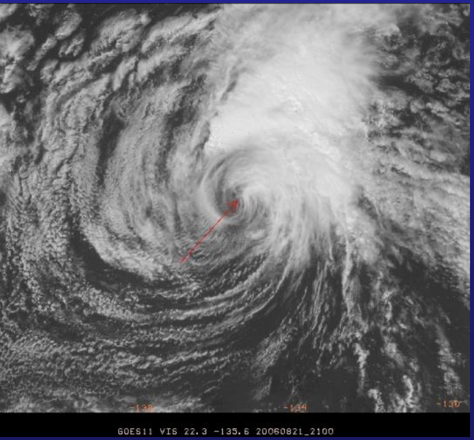


20 Aug. 2100 UTC



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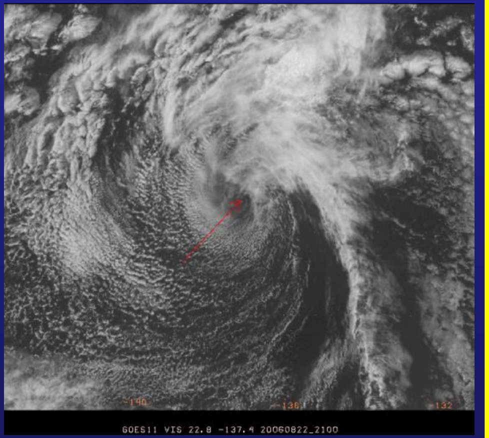

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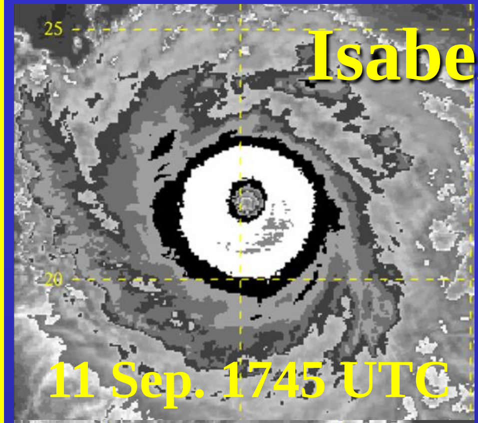
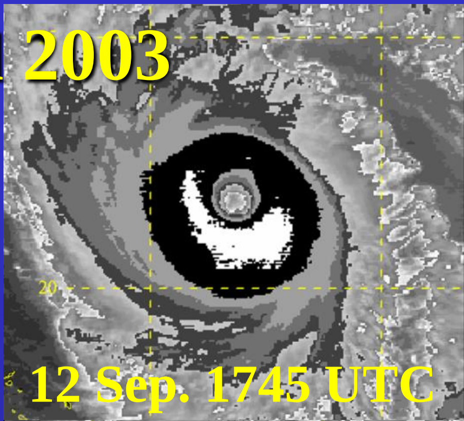
Isabel 2003



11 Sep. 1745 UTC



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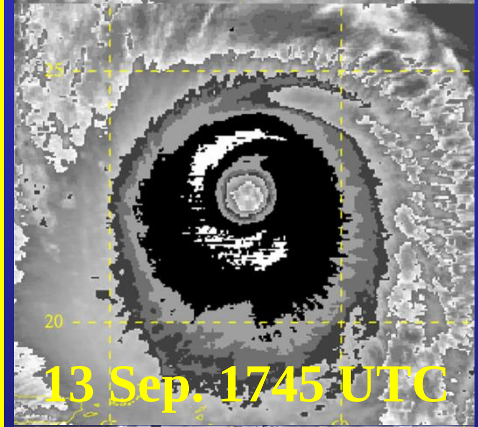
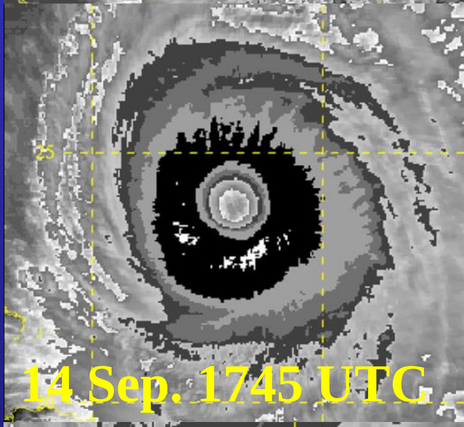
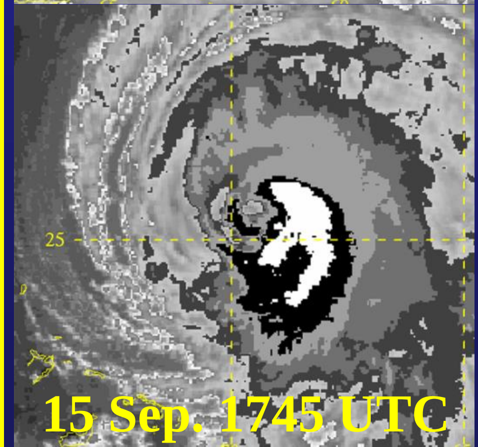


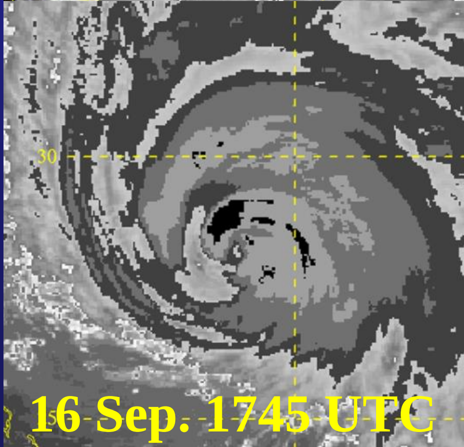
13 Sep. 1745 UTC



14 Sep. 1745 UTC



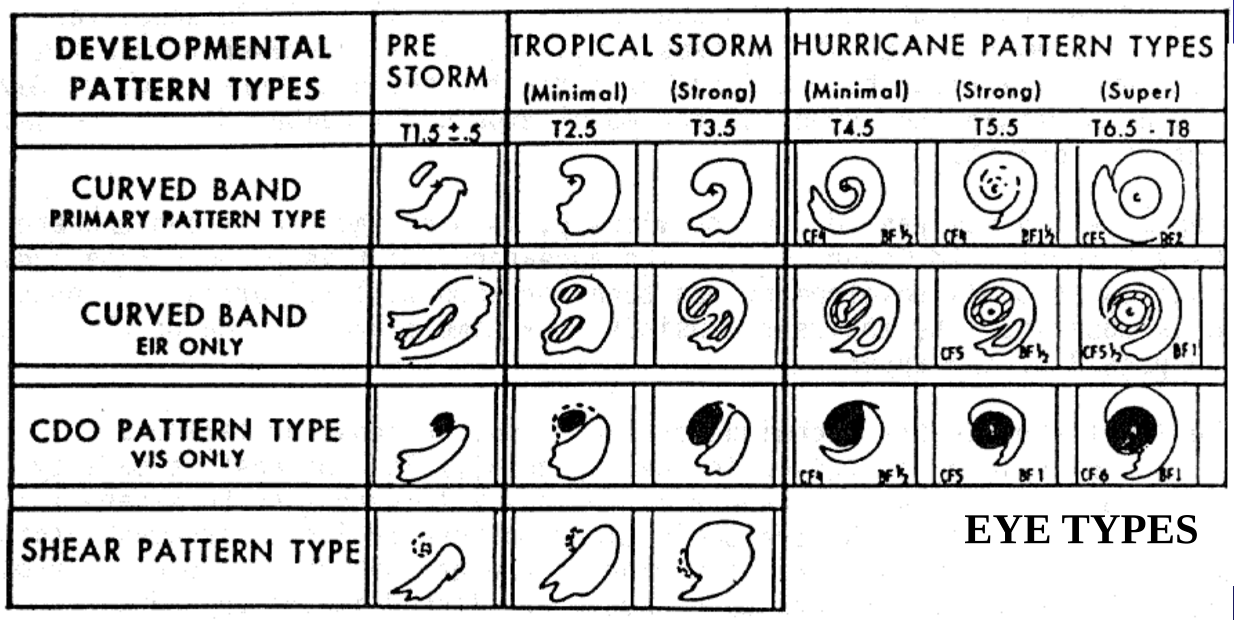
15 Sep. 1745 UTC

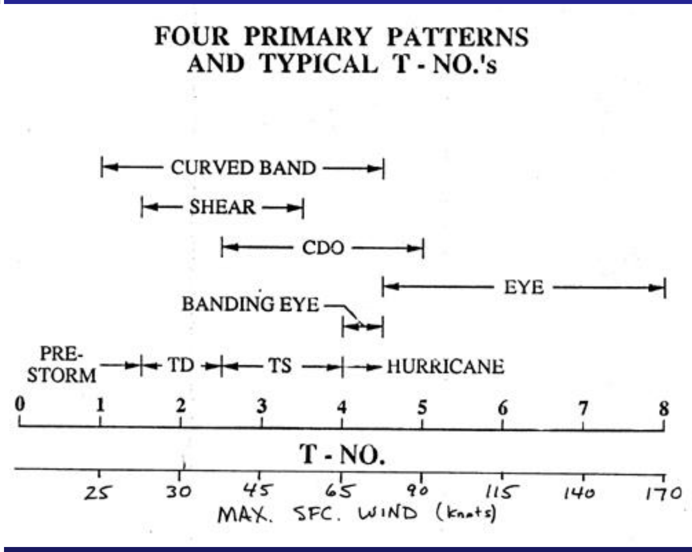


16 Sep. 1745 UTC

Dvorak Technique Cloud Patterns

- Curved Band (VIS and IR)
- Shear (VIS and IR)
- Eye (VIS and IR)
- Central Dense Overcast (VIS)
- Embedded Center (IR)
- Central Cold Cover (VIS and IR)





T-Numbers: How to Quantify the Cloud Patterns

- The Dvorak Technique quantifies TC intensity on a 1-8 scale (at 0.5 intervals) called T-Numbers, which are used in a variety of ways.
- The final output of the technique is the Current Intensity (CI) number.
- The CI number is driven by the Final-T (FT) Number.
- In turn, the FT is driven by the Data-T (DT) number, the Model Expected-T (MET) number, and the Pattern-T (PT or PAT) number.
- The DT is often created from other sub-numbers.

Dvorak Technique Output

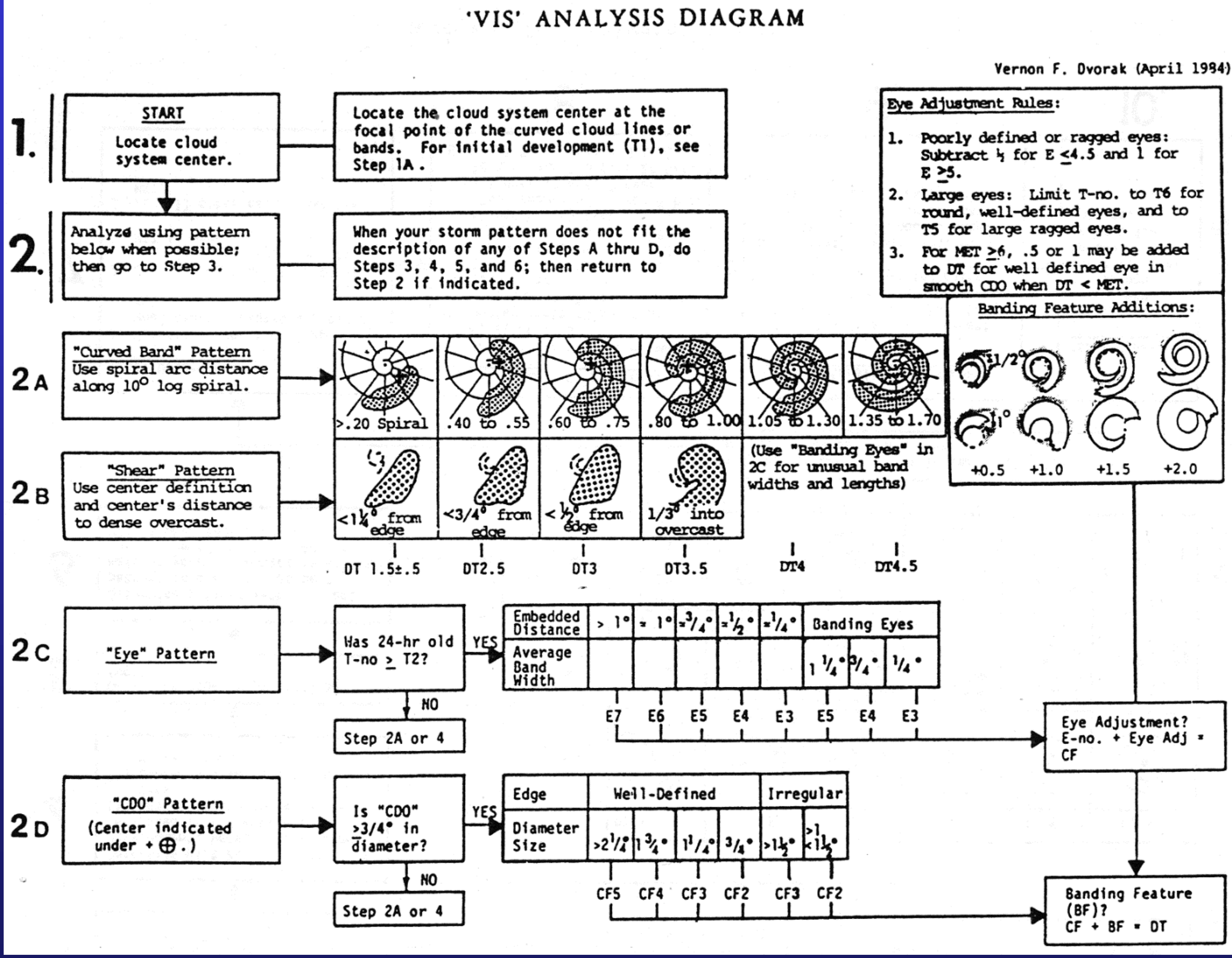
	1-minute MSW				NHC/CPHC/JTWC	
CI Number	(kt)	(mph)	(km/ hr)	(m/s)	MSLP (ATL/EPAC)	MSLP (NW Pacific)
1.0	25	29	46	13		
1.5	25	29	46	13		
2.0	30	35	56	15	1009 mb	1000 mb
2.5	35	40	65	18	1005 mb	997 mb
3.0	45	52	83	23	1000 mb	991 mb
3.5	55	63	102	28	994 mb	984 mb
4.0	65	75	120	33	987 mb	976 mb
4.5	77	89	143	40	979 mb	966 mb
5.0	90	104	167	46	970 mb	954 mb
5.5	102	117	189	52	960 mb	941 mb
6.0	115	132	213	59	948 mb	927 mb
6.5	127	146	235	65	935 mb	914 mb
7.0	140	161	259	72	921 mb	898 mb
7.5	155	178	287	80	906 mb	879 mb
8.0	170	196	315	87	890 mb	858 mb

Note: Other warning centers and basins use different pressures and wind averaging periods

Dvorak Technique Procedure - I

Dvorak (1984) 10 Steps:

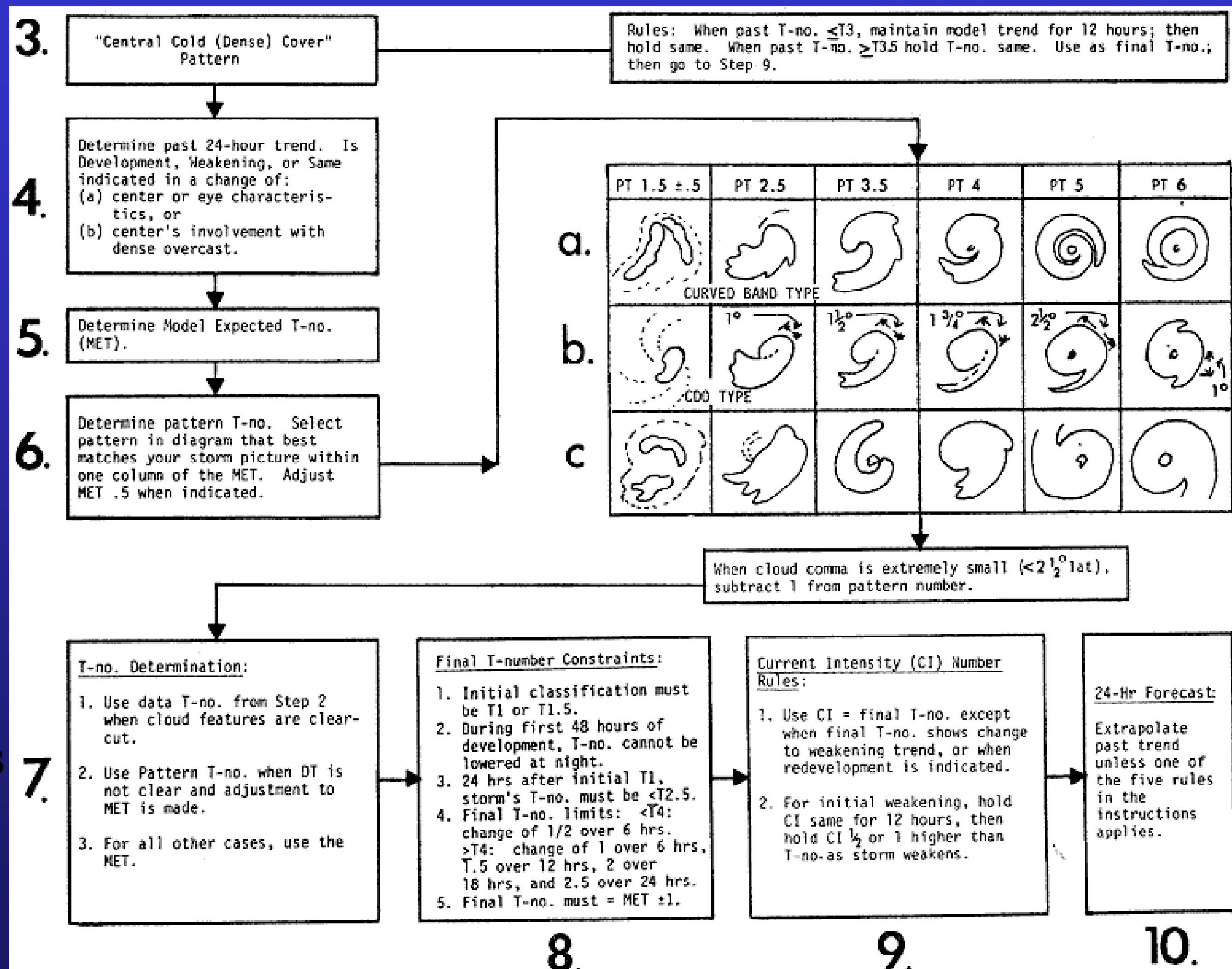
1. Locate center
2. Select cloud pattern and assign Data-T Number (DT)



Dvorak Technique Procedure - II

Dvorak (1984) 10 Steps:

3. Central Cold Cover (CCC; if applicable)
4. Analyze 24-h trend
5. Assign Model Expected T-Number (MET)
6. Assign Pattern T-Number (PT/PAT)
7. Use DT, MET, and PT to get Final T-Number (FT)
8. Apply FT constraints
9. Determine Current Intensity (CI)
10. Forecast 24-h Intensity (FI)



Dvorak Technique Worksheet

TROPICAL CYCLONE ANALYSIS WORKSHEET

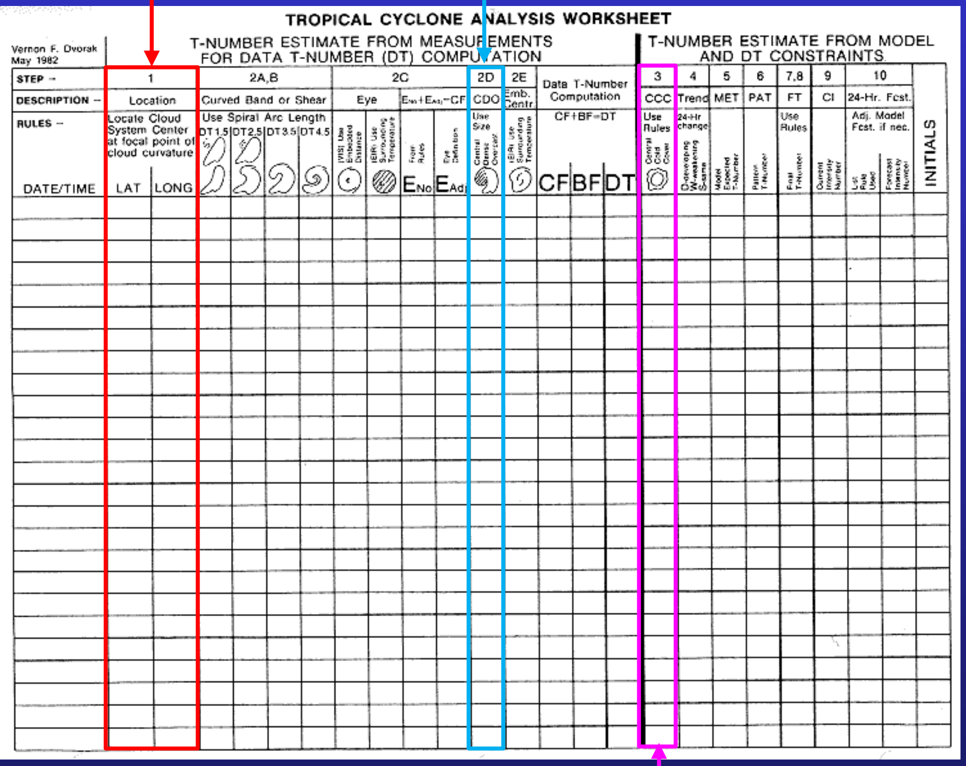
Vernon F. Dvorak
May 1982

T-NUMBER ESTIMATE FROM MEASUREMENTS FOR DATA T-NUMBER (DT) COMPUTATION

T-NUMBER ESTIMATE FROM MODEL AND DT CONSTRAINTS.

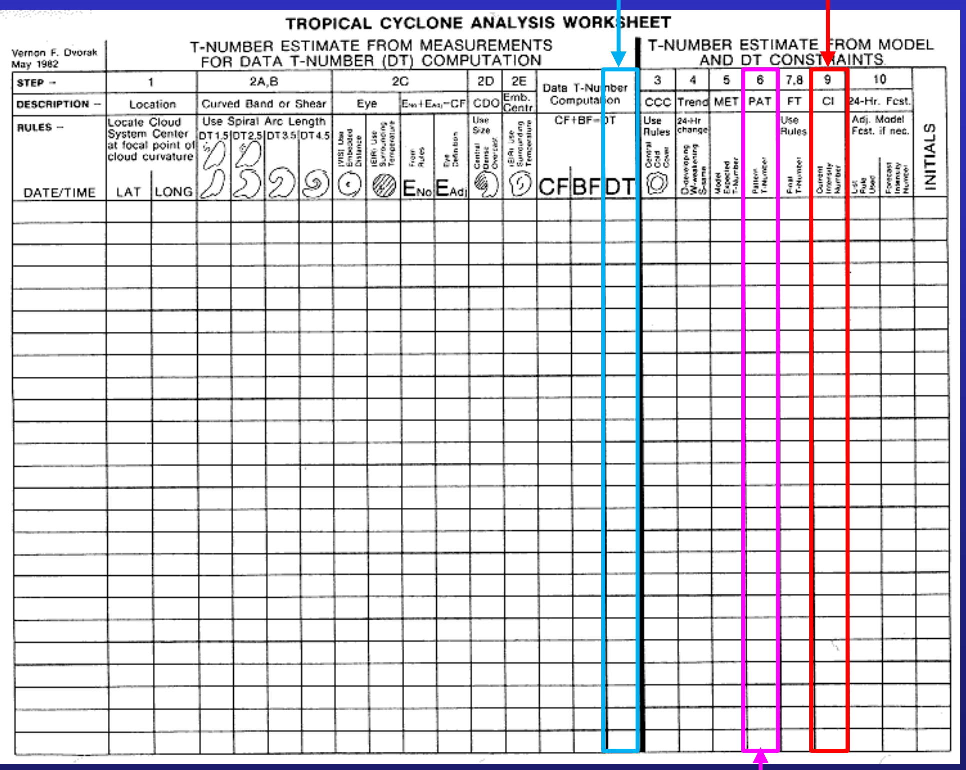
STEP –	1		2A,B				2C				2D	2E	Data T-Number Computation			3	4	5	6	7,8	9	10		INITIALS
DESCRIPTION –	Location		Curved Band or Shear				Eye		$E_{No}+E_{Adj}-CF$		CDO	Emb. Centr				CCC	Trend	MET	PAT	FT	CI	24-Hr. Fcst.		
RULES –	Locate Cloud System Center at focal point of cloud curvature		Use Spiral Arc Length								Use Size		CF+BF=DT			Use Rules	24-Hr change			Use Rules		Adj. Model Fcst. if nec.		
DATE/TIME	LAT	LONG	DT1.5	DT2.5	DT3.5	DT4.5	(VIS) Use Embedded Distance	(EIR) Use Surrounding Temperature	E_{No} From Rules	E_{Adj} Eye Definition	Central Dense Overcast	(EIR) Use Surrounding Temperature	CF	BF	DT	Central Cold Cover	D=developing W=weakening S=same	Model Expected T-Number	Pattern T-Number	Final T-Number	Current Intensity Number	List Rule Used	Forecast Intensity Number	

Dvorak Technique Terms



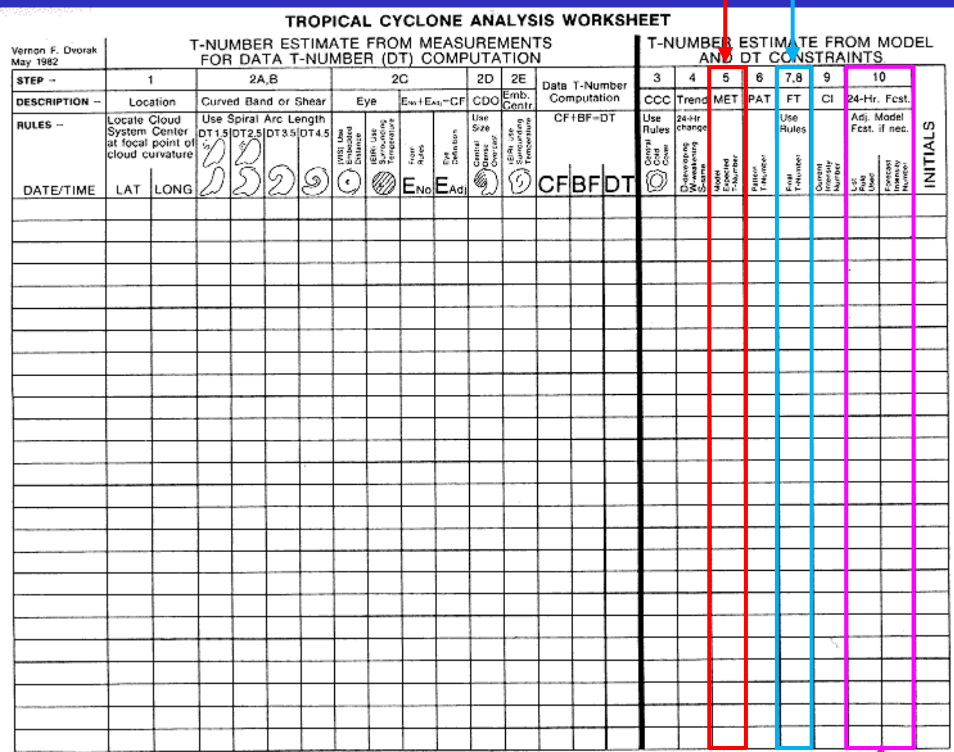
- *CSC* - Cloud System Center - The center of the disturbance or cyclone. It is usually defined by an eye, a low level circulation center, or by other cloud features.
- *CDO* - Central Dense Overcast - A dense solid-looking mass of clouds covering the CSC, often lying within the curve of the cyclone's curved cloud band.
- *CCC* - Central Cold Cover - A large cold or dense overcast covering the CSC that lacks structure and obscures the cyclone center.

Dvorak Technique Terms



- *CI Number* - Current Intensity number - The final output of the Dvorak technique and the estimated intensity of the cyclone.
- *DT Number* - Data-T number - The estimated intensity of the cyclone based on the convective cloud pattern.
- *PT or PAT Number* - Pattern-T number - The intensity estimate from comparing the cyclone cloud pattern to predetermined patterns.

Dvorak Technique Terms

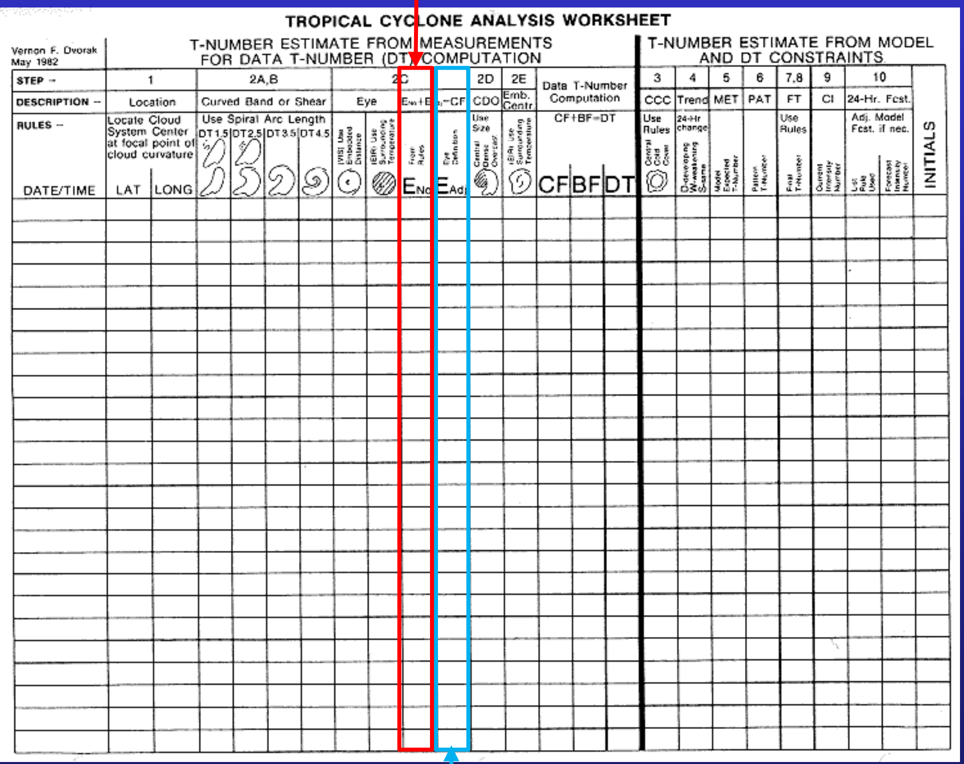

TROPICAL CYCLONE ANALYSIS WORKSHEET

Vernon F. Dvorak
May 1982

	T-NUMBER ESTIMATE FROM MEASUREMENTS FOR DATA T-NUMBER (DT) COMPUTATION						T-NUMBER ESTIMATE FROM MODEL AND DT CONSTRAINTS							
STEP →	1	2A,B	2C		2D	2E		3	4	5	6	7,8	9	10
DESCRIPTION →	Location	Curved Band or Shear	Eye	$E_{No}+E_{Adj}-CF$	CDO	Emb. Centr.	Data T-Number Computation	CCC	Trend	MET	PAT	FT	CI	24-Hr. Fcst.
RULES →	Locate Cloud System Center at focal point of cloud curvature	Use Spiral Arc Length DT1.5 DT2.5 DT3.5 DT4.5	(VIS) Use Embedded Distance; (EIR) Use Surrounding Temperature	From Rules; Eye Definition	Use Size; Central Dense Overcast	(EIR) Use Surrounding Temperature	CF+BF=DT	Use Rules; Central Cold Cover	24-Hr change; D-developing W-weakening S-same	Model Expected T-Number	Pattern T-Number	Use Rules; Final T-Number	Current Intensity Number	Adj. Model Fcst. if nec.; List Rule Used; Forecast Intensity Number
DATE/TIME	LAT / LONG			E_{No} / E_{Adj}			CF / BF / DT							INITIALS

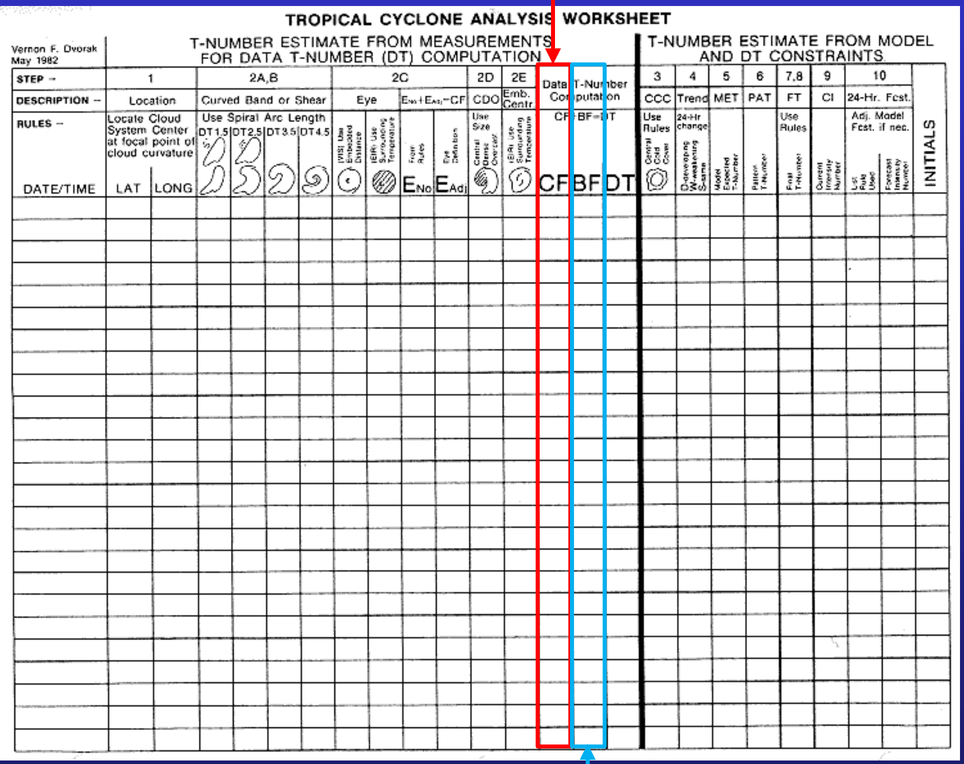
- *MET Number* - Model Expected-T number - The intensity estimate from the 24 hr old FT number and a determined intensity trend.
- *FT Number* - Final-T number - The intensity estimate for a given time selected from the DT, PT, or MET numbers. It is used with a set of rules to determine the CI number for this time and the MET number 24 hours later.
- *FI Number* - Forecast Intensity number - 24 hr intensity forecast based on the CI and observed signals in the cyclone cloud pattern and the environment.

Dvorak Technique Terms



- *Eye Number* - Part 1 of the intensity estimate for an eye pattern based on surrounding cloud top temperatures (IR) or embedded distance in a CDO (VIS).
- *Eye Adjustment* - Part 2 of the intensity estimate for an eye pattern based on eye temperature (IR) or eye size and clarity (VIS).

Dvorak Technique Terms



- *CF Number* - Central Feature number - The part of the intensity estimate based on the central features of a cyclone. This number is produced by the eye, CDO, and embedded center patterns.
- *BF Number* - Banding Feature number - The part of the intensity estimate based on the banding surrounding central features of a cyclone. This number can be used with the eye, CDO, and embedded center patterns.

Dvorak Steps 1 and 2

1.

START
Locate cloud system center
(Center fix)

Locate the cloud system center at the focal point of the curved cloud lines or bands. For initial development (T1), see Step 1A.

1A.

A T1 Classification can first be given upon meeting three criteria involving the existence and persistence of the CSC and associated convection

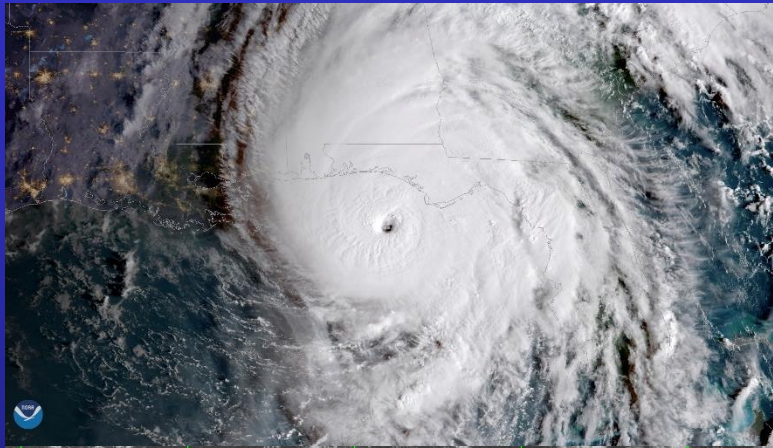
2.

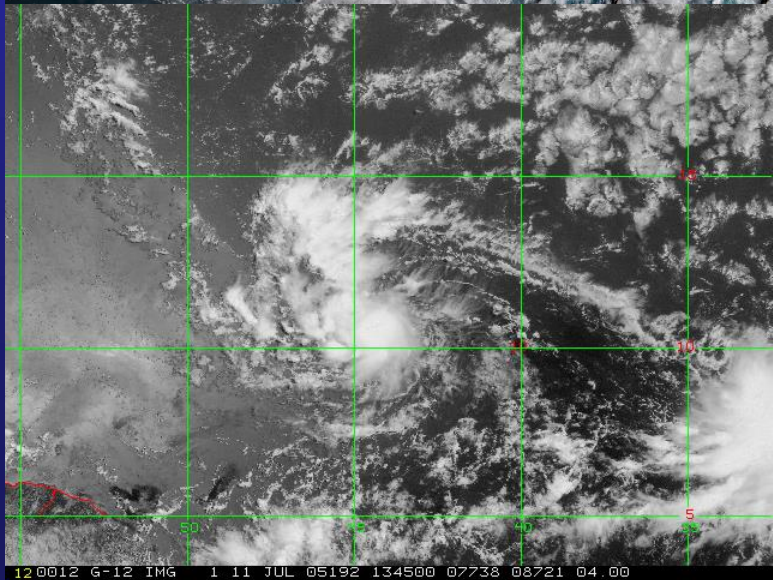
CLOUD PATTERN MEASUREMENT
Analyze using cloud pattern below when possible;
then goto Step 3

When the storm cloud pattern does not fit any of those in Steps 2A-2D, perform Steps 3, 4, 5, and 6; then return to Step 2 if indicated

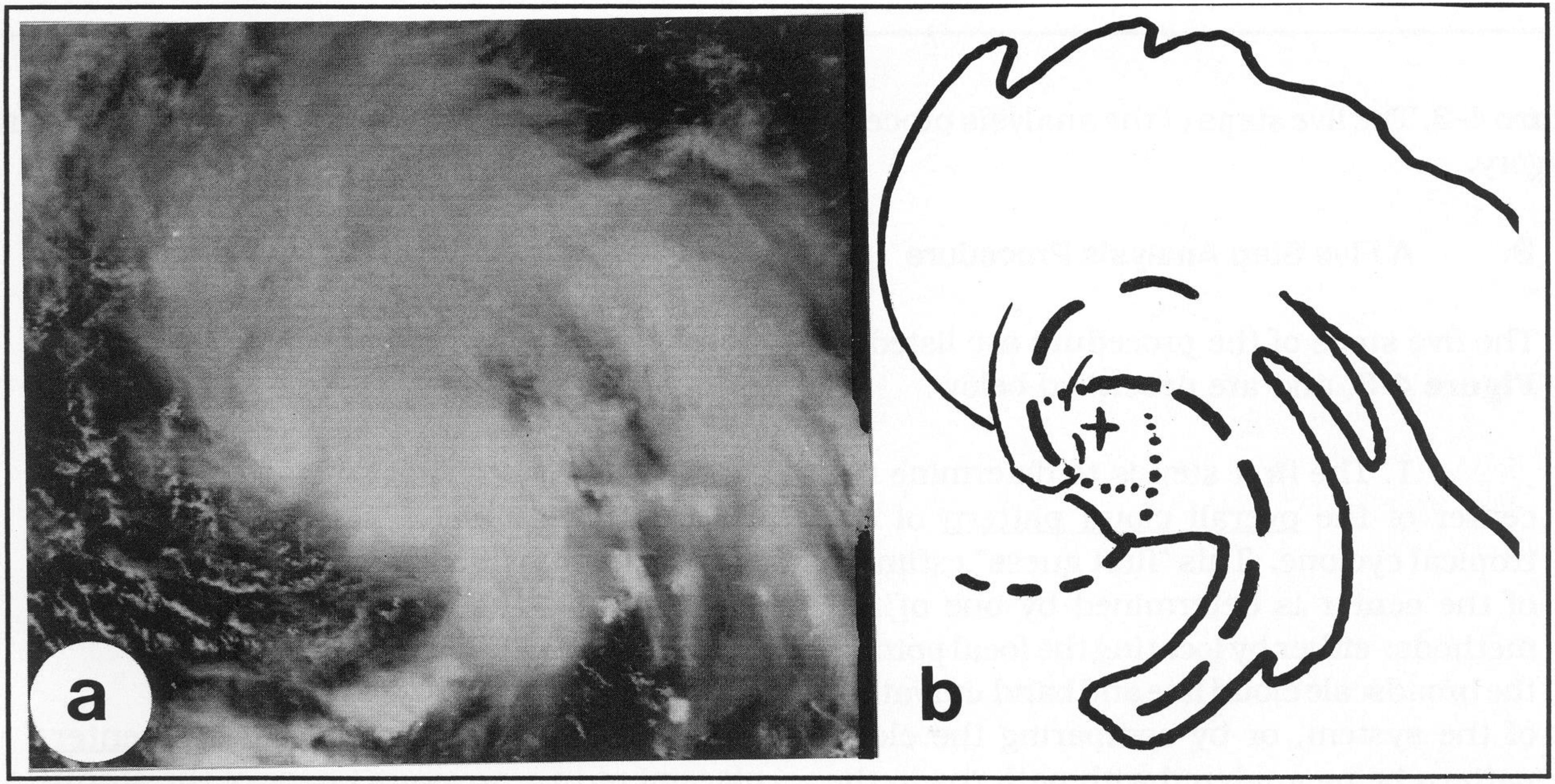
Step 1 – Locate the Cloud System Center (CSC)

- **Locate the overall pattern center**
- **Look for small scale features**
- **Compare center location with forecast**
- **Compare center with previous pattern center**
- **Make final location adjustments**
- **Looking for lowest possible center in terms of altitude (Surface center if possible)**



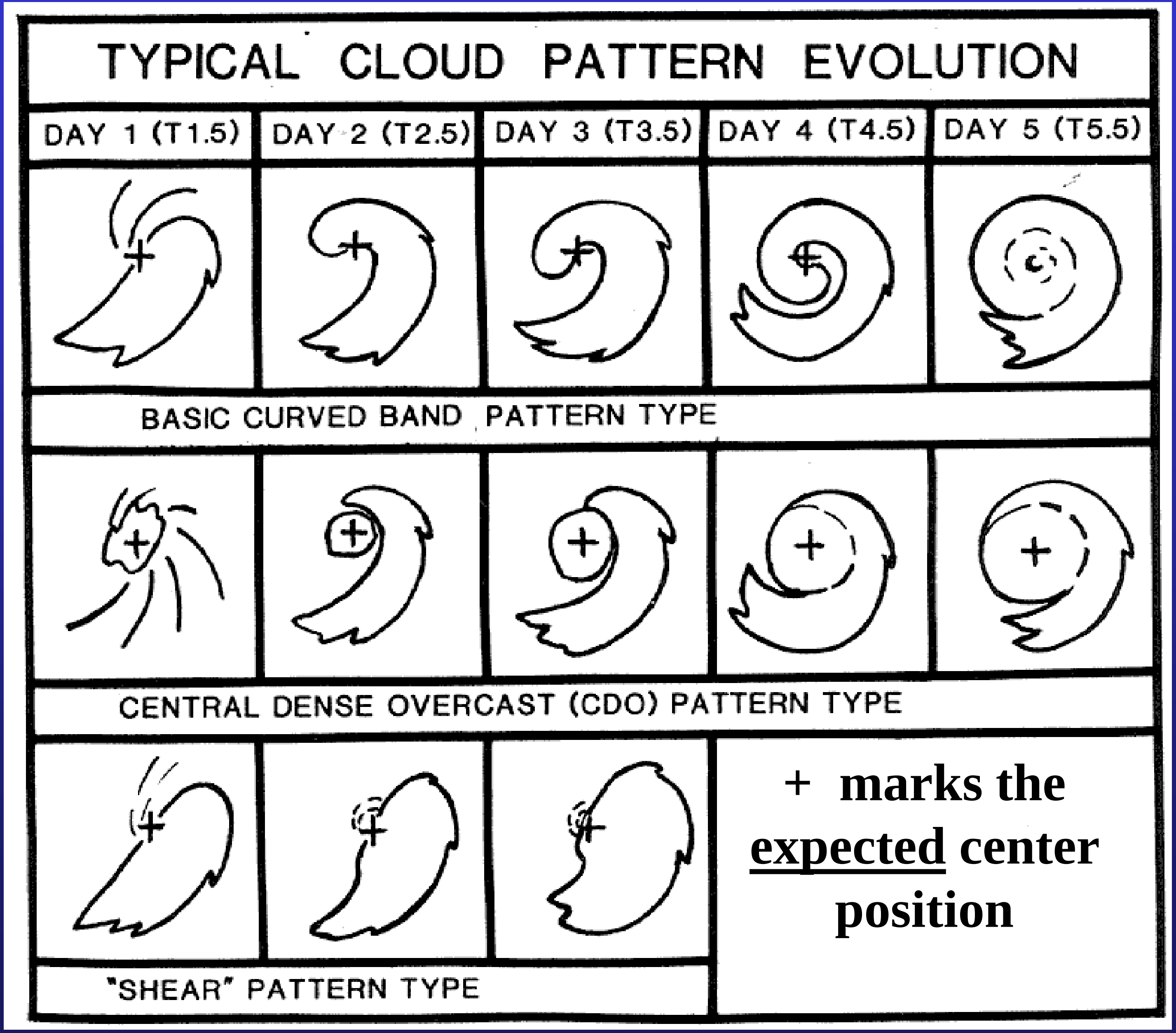


Step 1 – Locate the Cloud System Center (CSC)

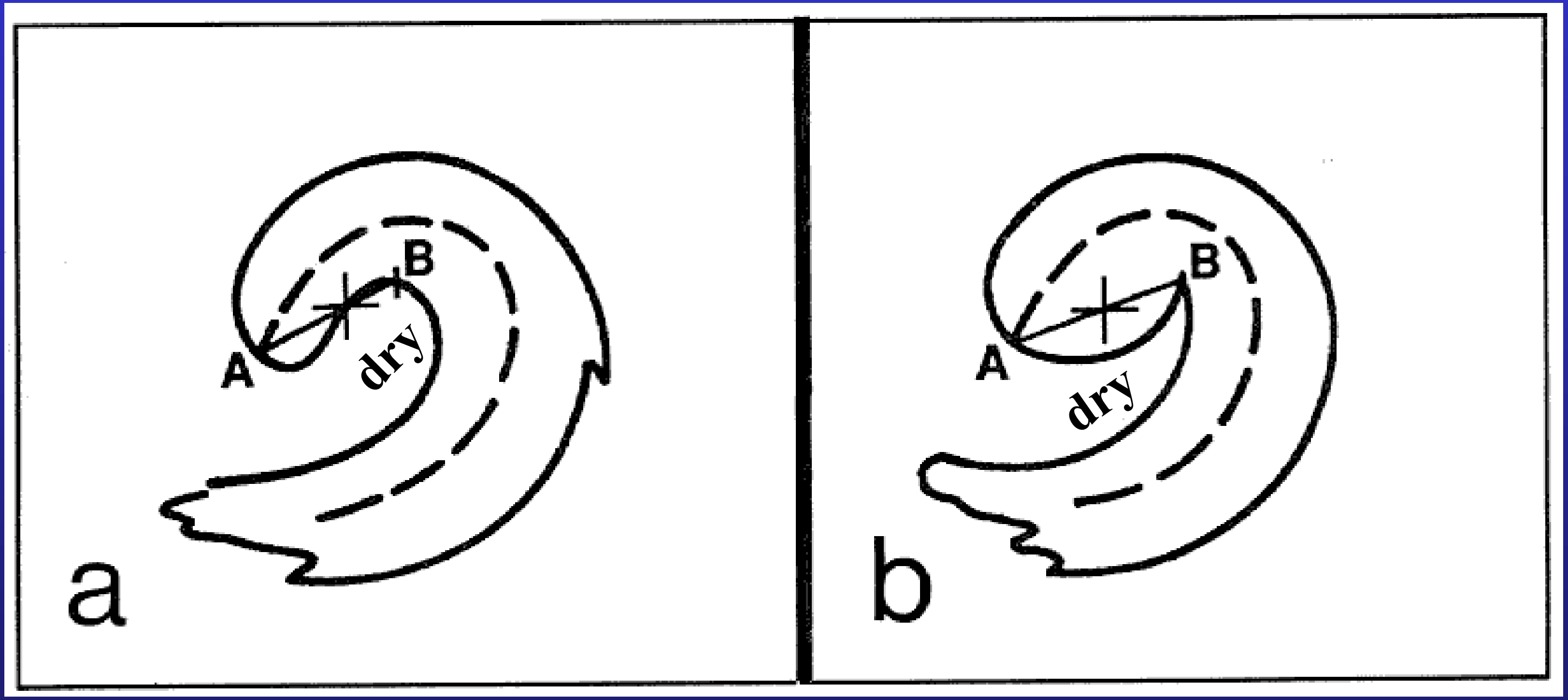


In this image the CSC is the focal point of curved cloud lines

Expected CSC Positions

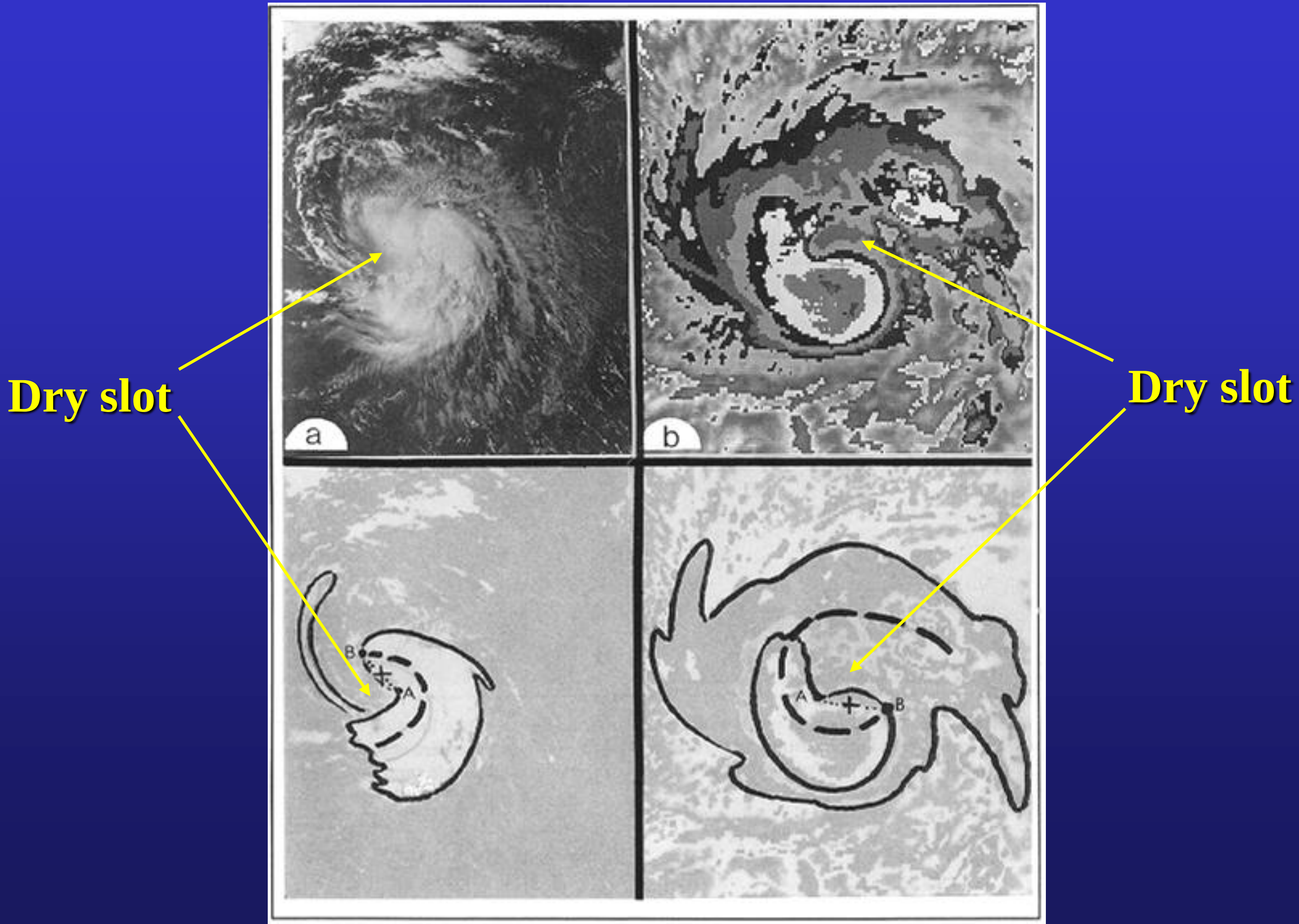


Expected CSC Positions for Curved Band Patterns (Wedge Method)



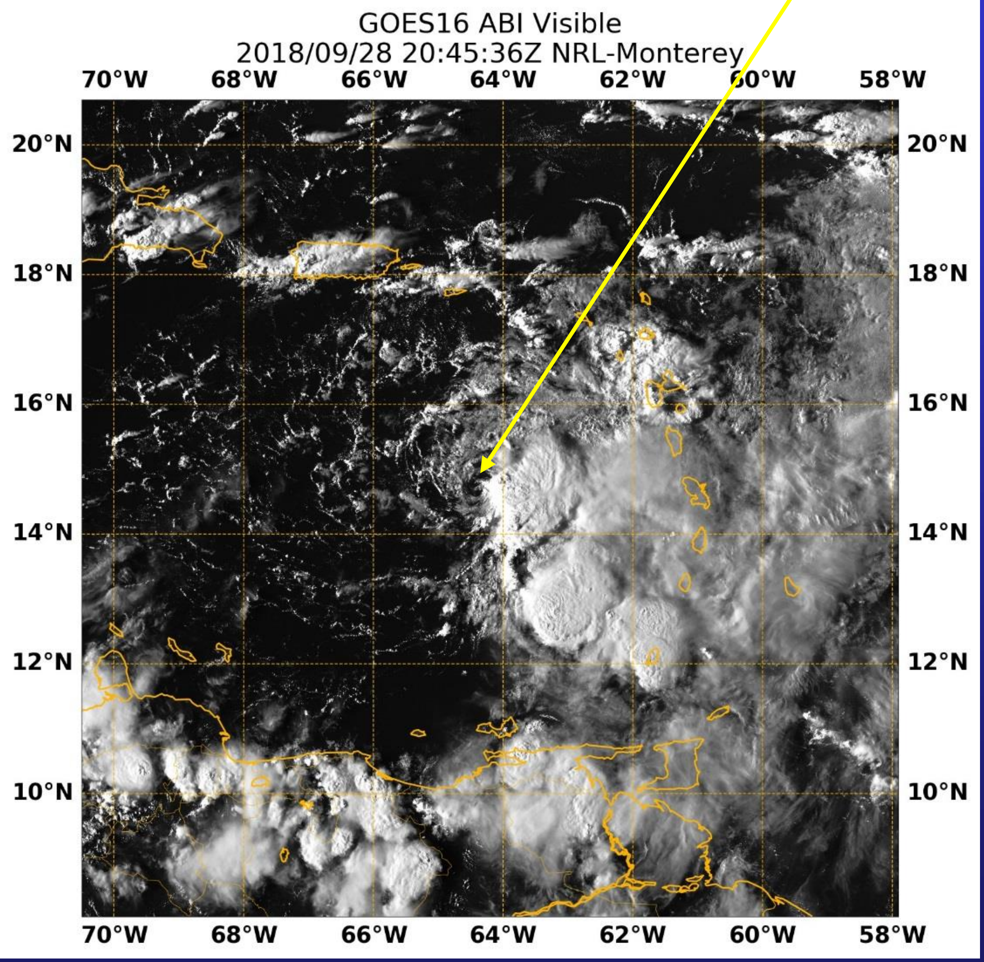
The expected center position is halfway between the end of the curved band (A) and the end of the associated dry slot or cloud minimum wedge (B).

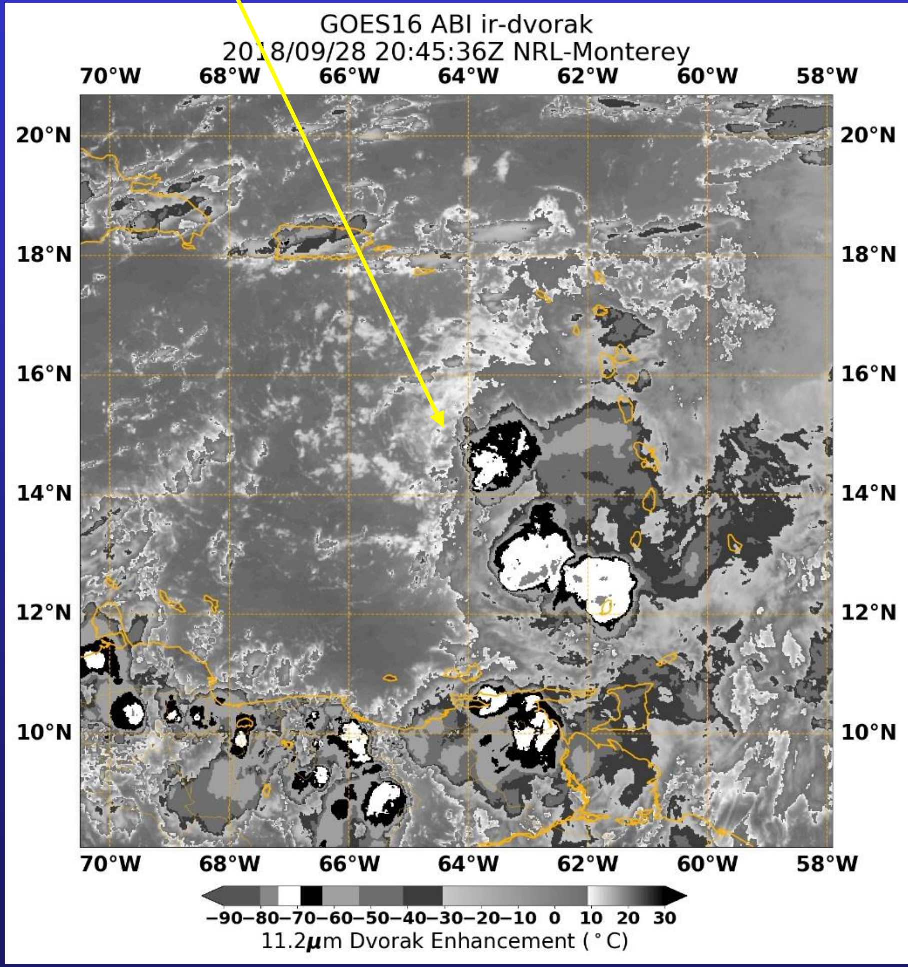
CSC Curved Band Examples



CSC Shear Pattern Examples

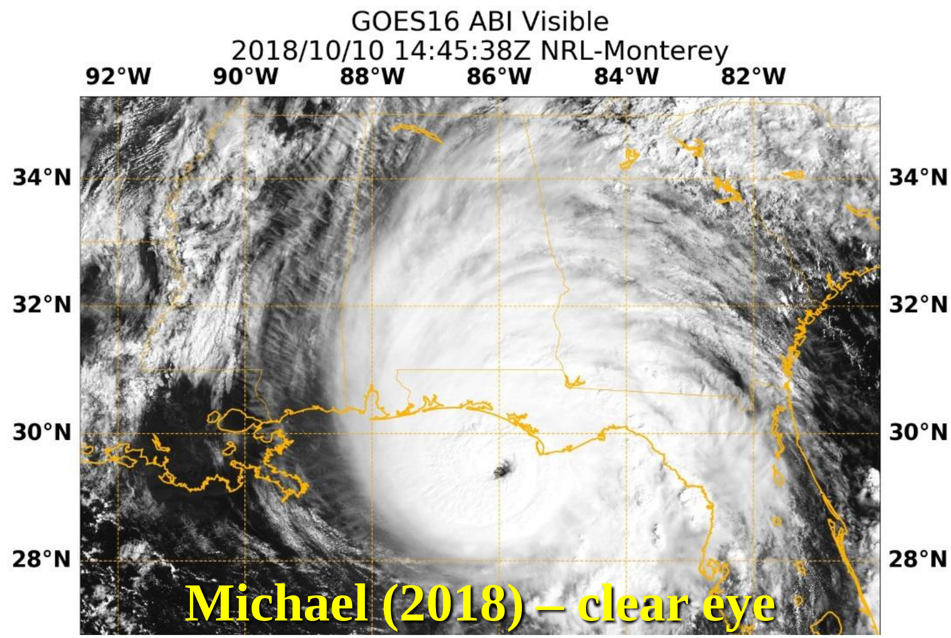
Low-level center



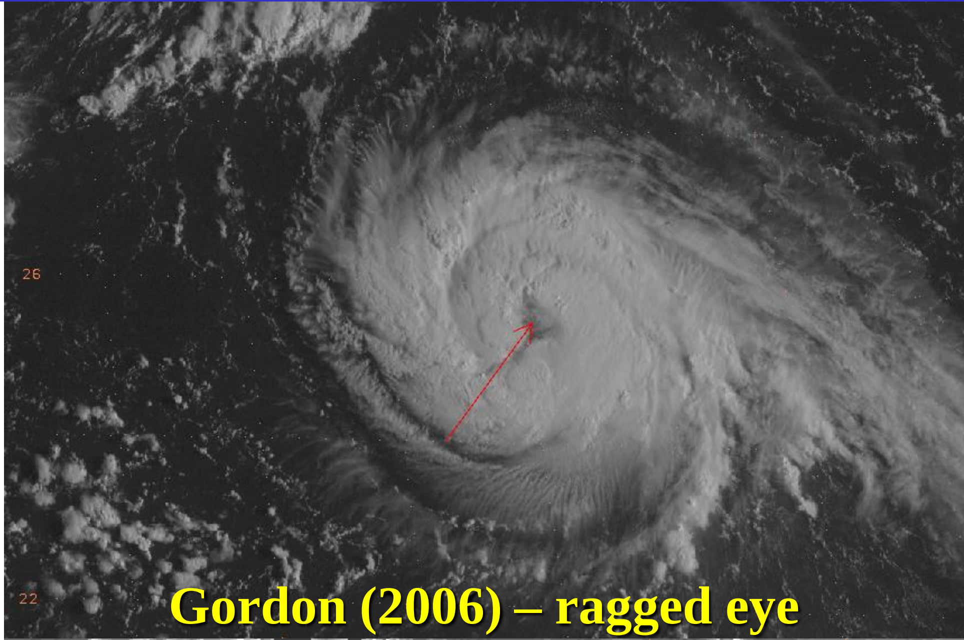


Good first guess position is the upshear side of the strongest convection

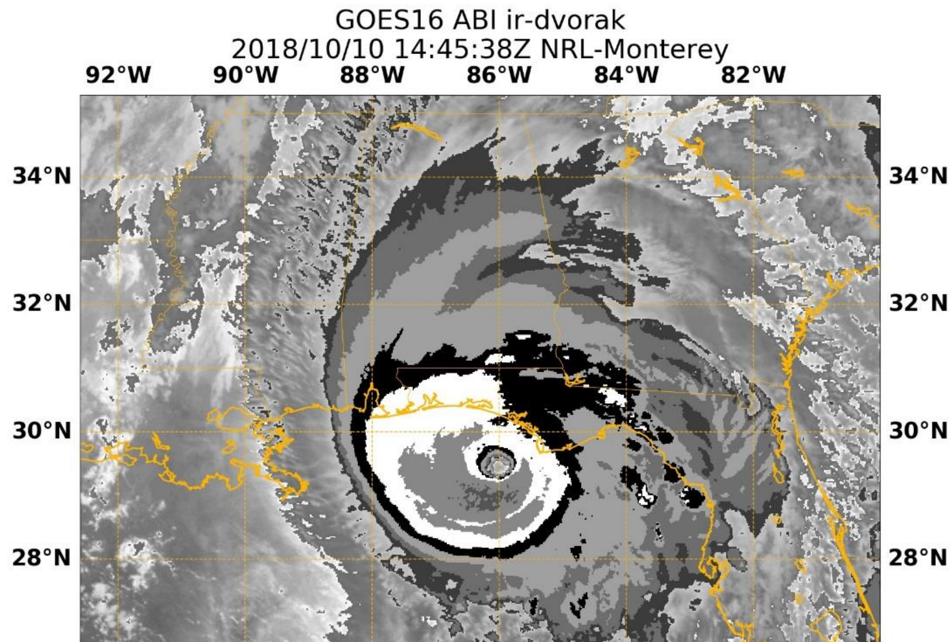
CSC Eye Pattern Examples

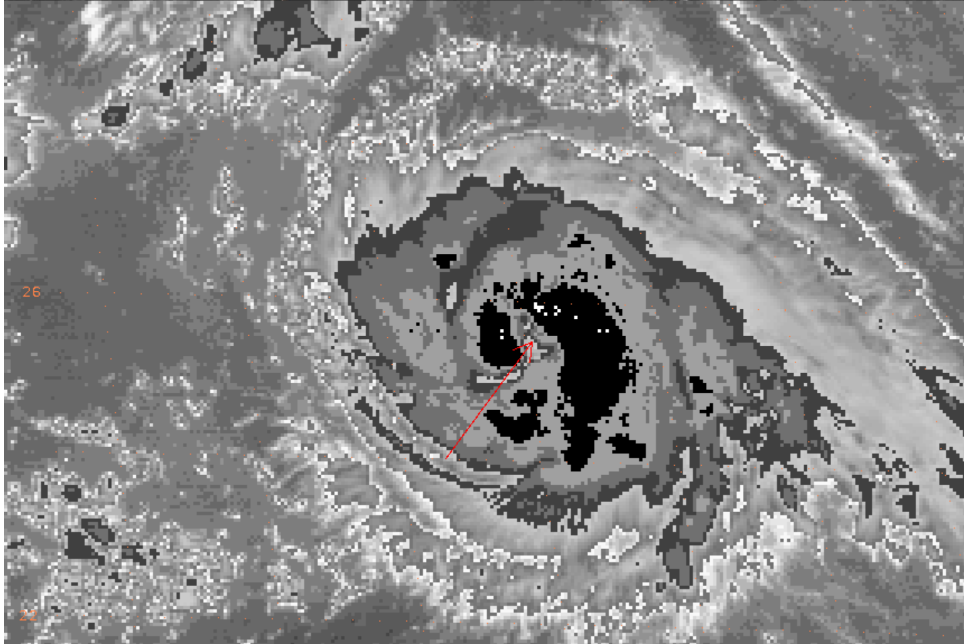


Michael (2018) – clear eye

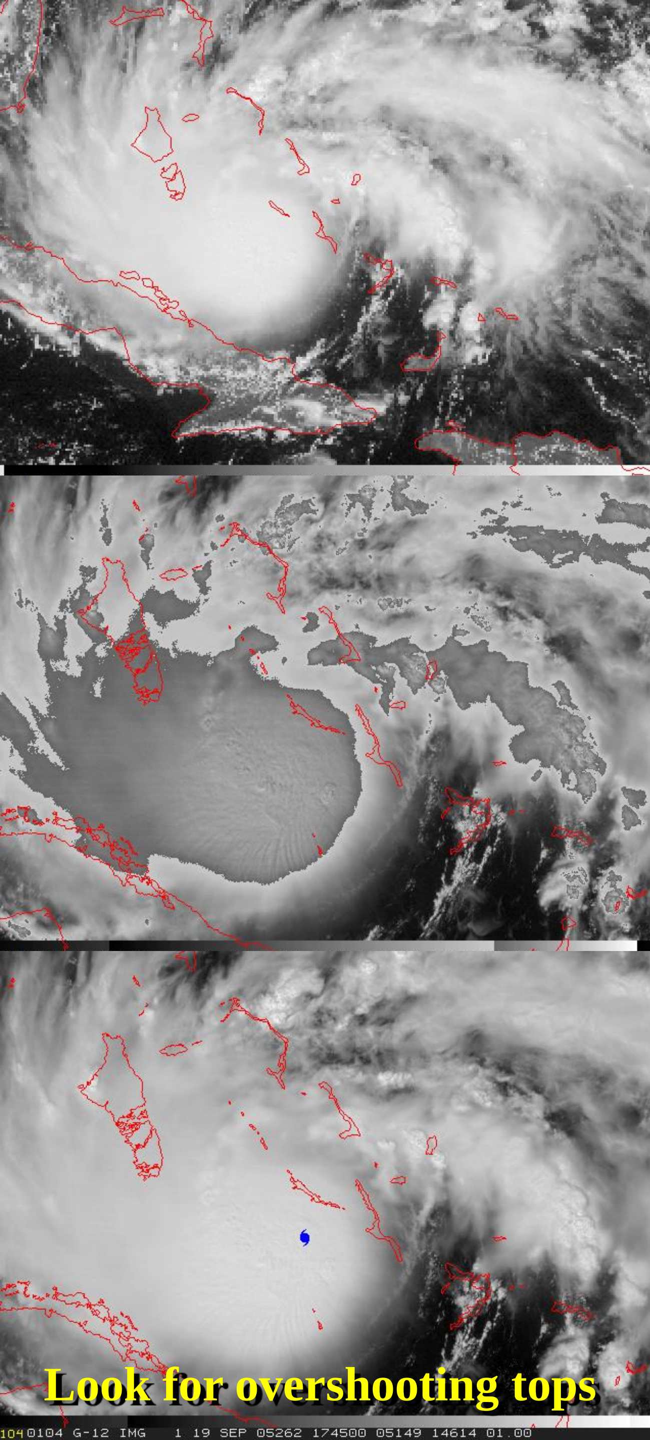


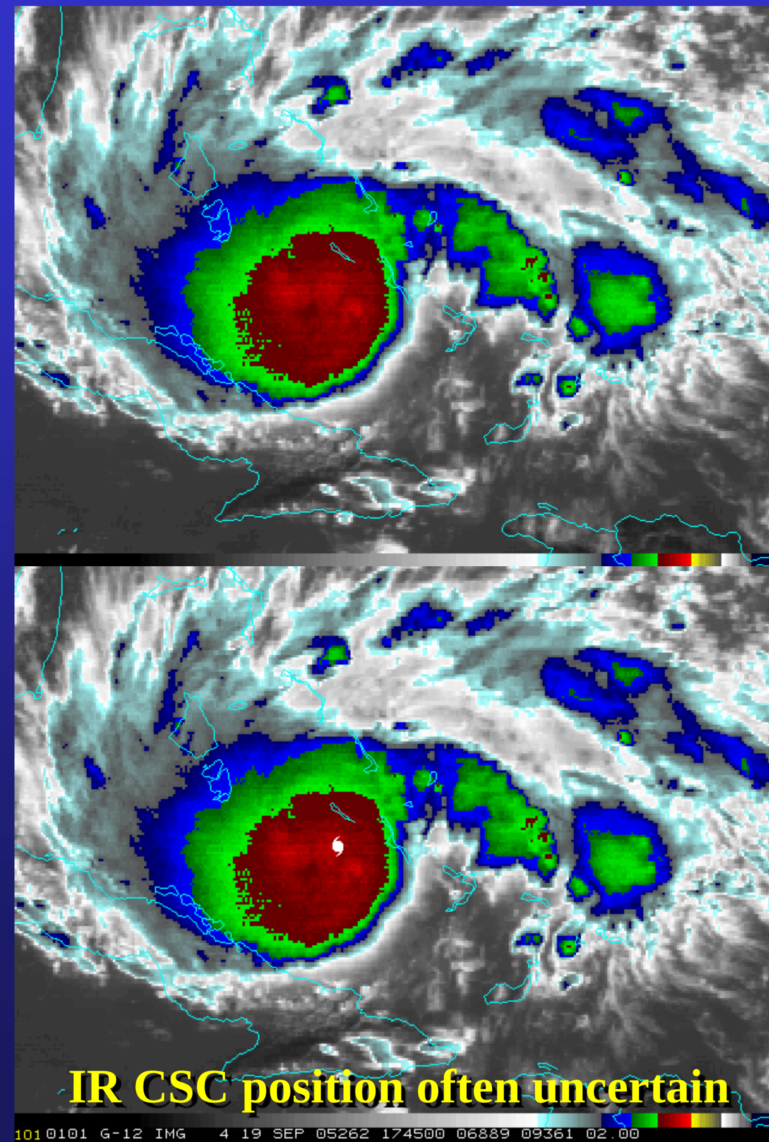
Gordon (2006) – ragged eye



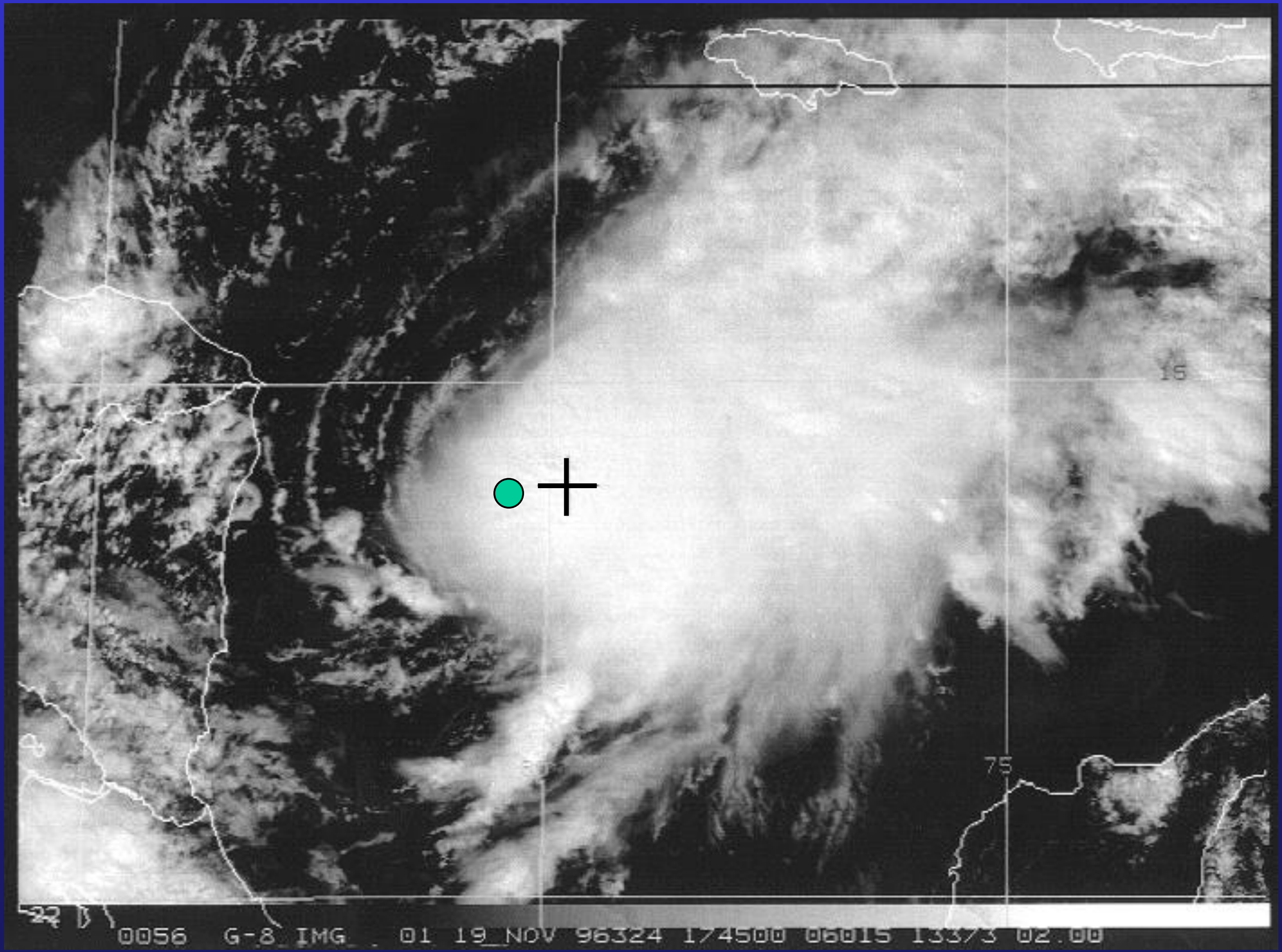


CDO/Embedded Center Pattern CSC Examples





CSC Location Error - Didn't Follow the Low Clouds



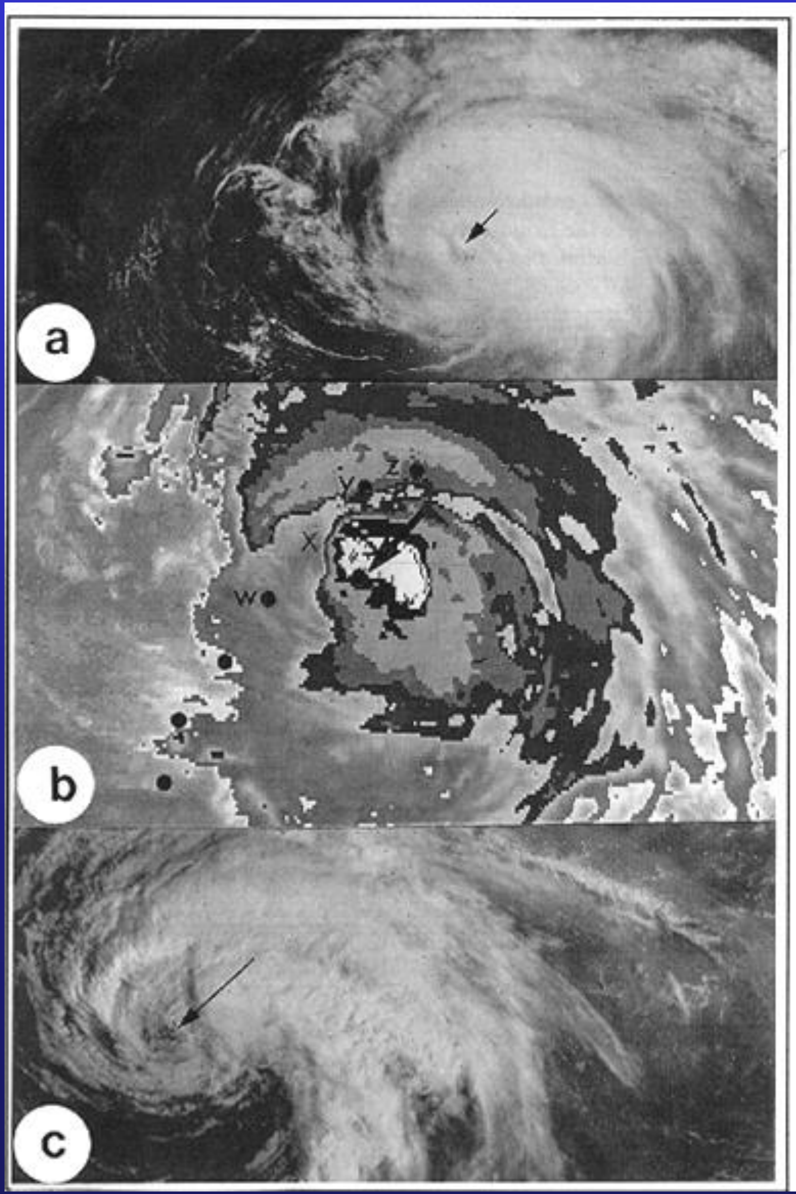
Marco (1996): A sheared and tilted system!

Potential Error - Shear Surprise

The previous day

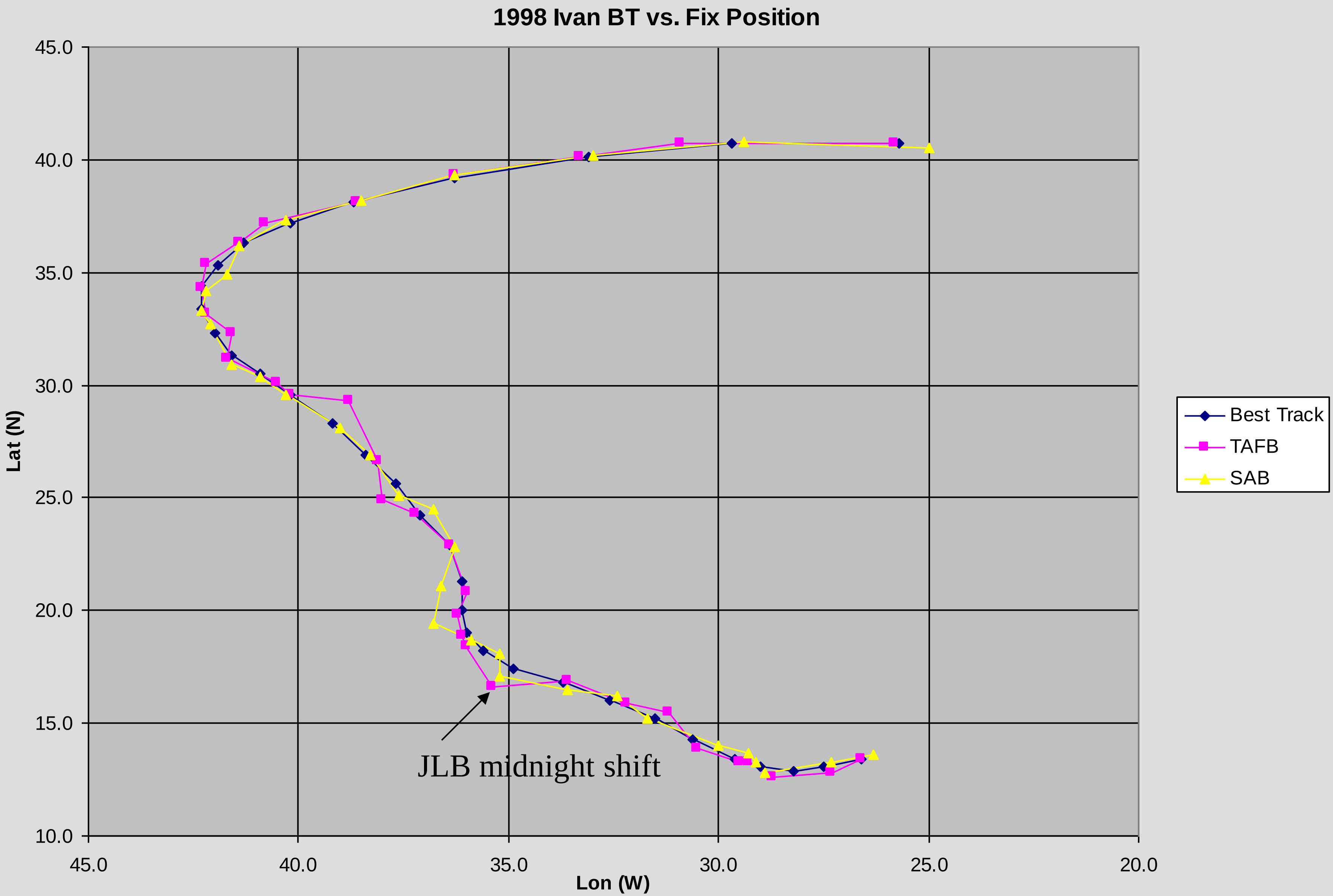
Overnight

Surprise!



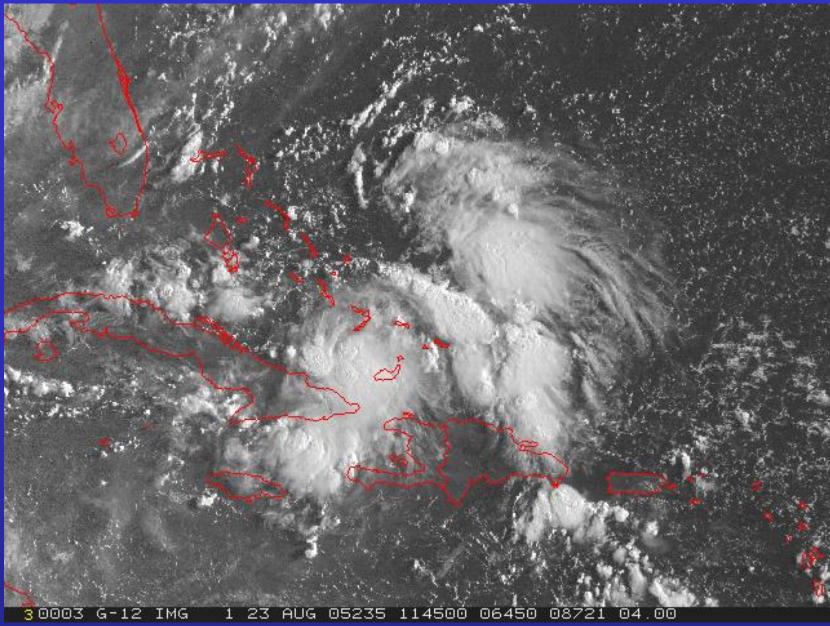
Hurricane Harvey (1981)

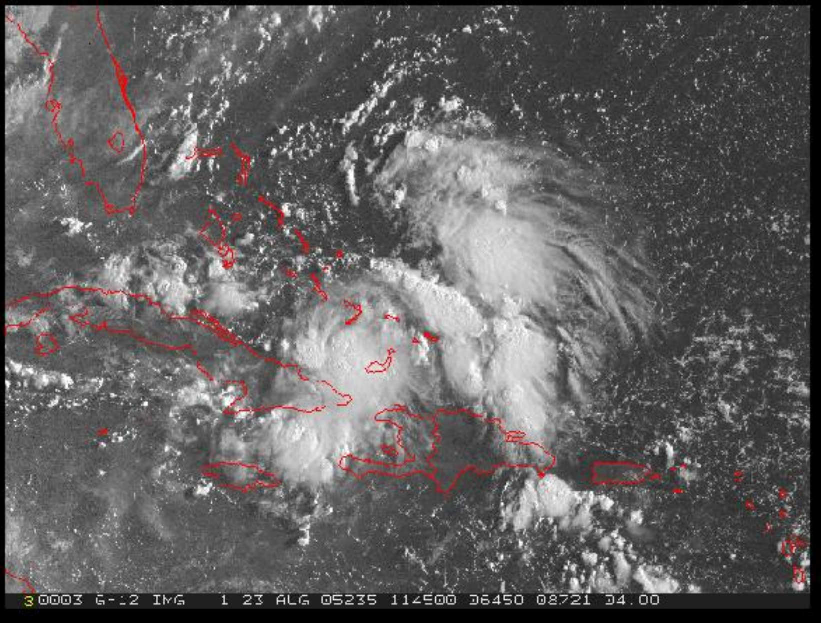
CSC Error - Deviated From Forecast



Animated Imagery

- The technique center finding principles were designed for single images and not animation.
- Animation can show the circulation associated with a tropical cyclone or disturbance and make center fixing easier
- Motions of high level clouds can complicate center fixing, especially when using IR imagery or if the system is tilted
- Use of animation does not guarantee a correct center location!





Dvorak Confidence Codes

Location Confidence (LCN)	
LCN	**Definition**
1	Well-defined eye
2	Well-defined eye with uncertain picture navigation
3	Well-defined circulation center
4	Well-defined circulation center with uncertain picture navigation
5	Poorly-defined circulation center
6	Poorly-defined circulation center with uncertain picture navigation

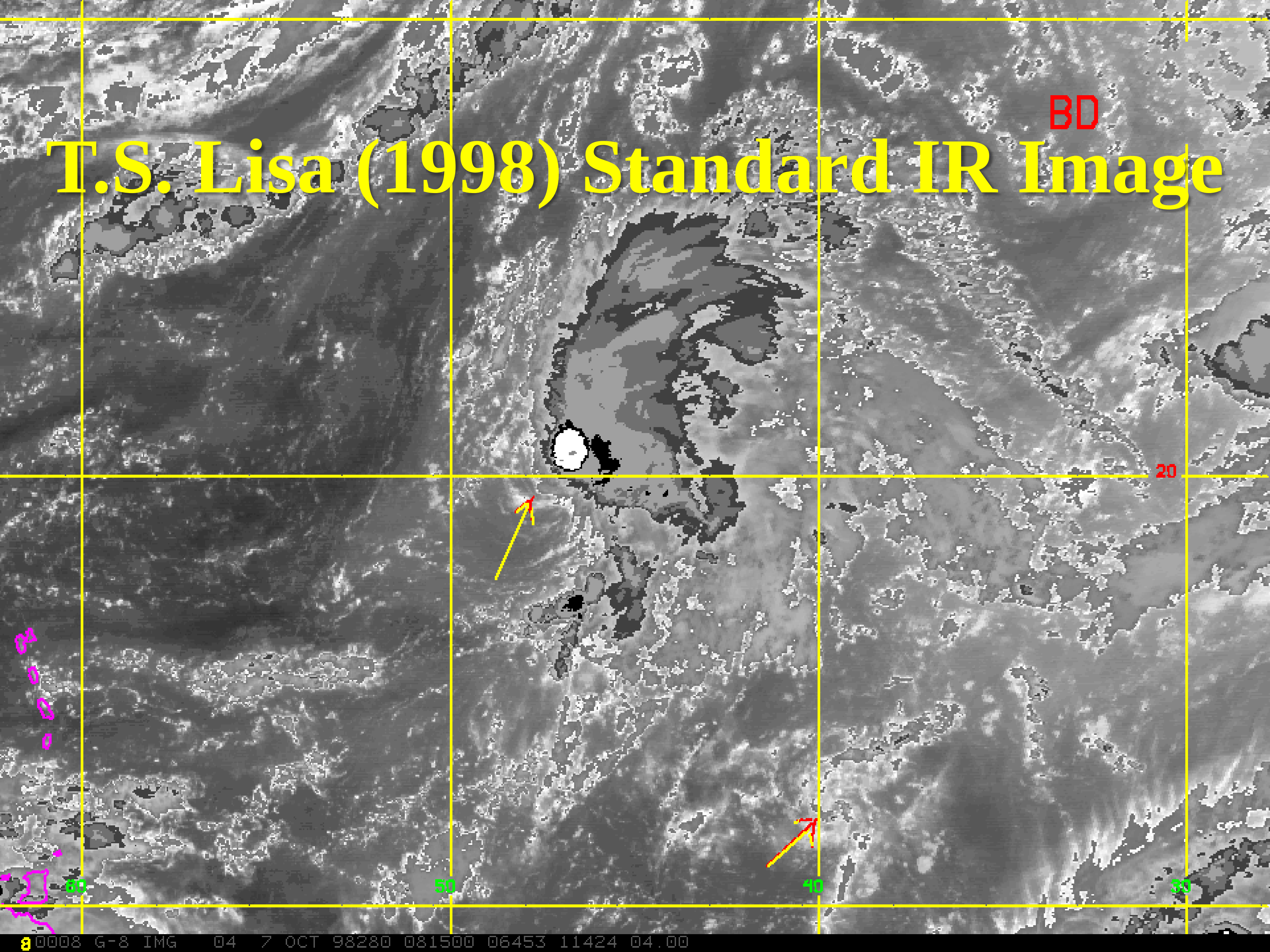
Intensity Confidence (ICN)	
ICN	**Definition**
1	Good confidence in T#
2	May vary T# up or down by 1/2
3	May vary T# up or down by 1

Cloud System Center Finding Exercise!

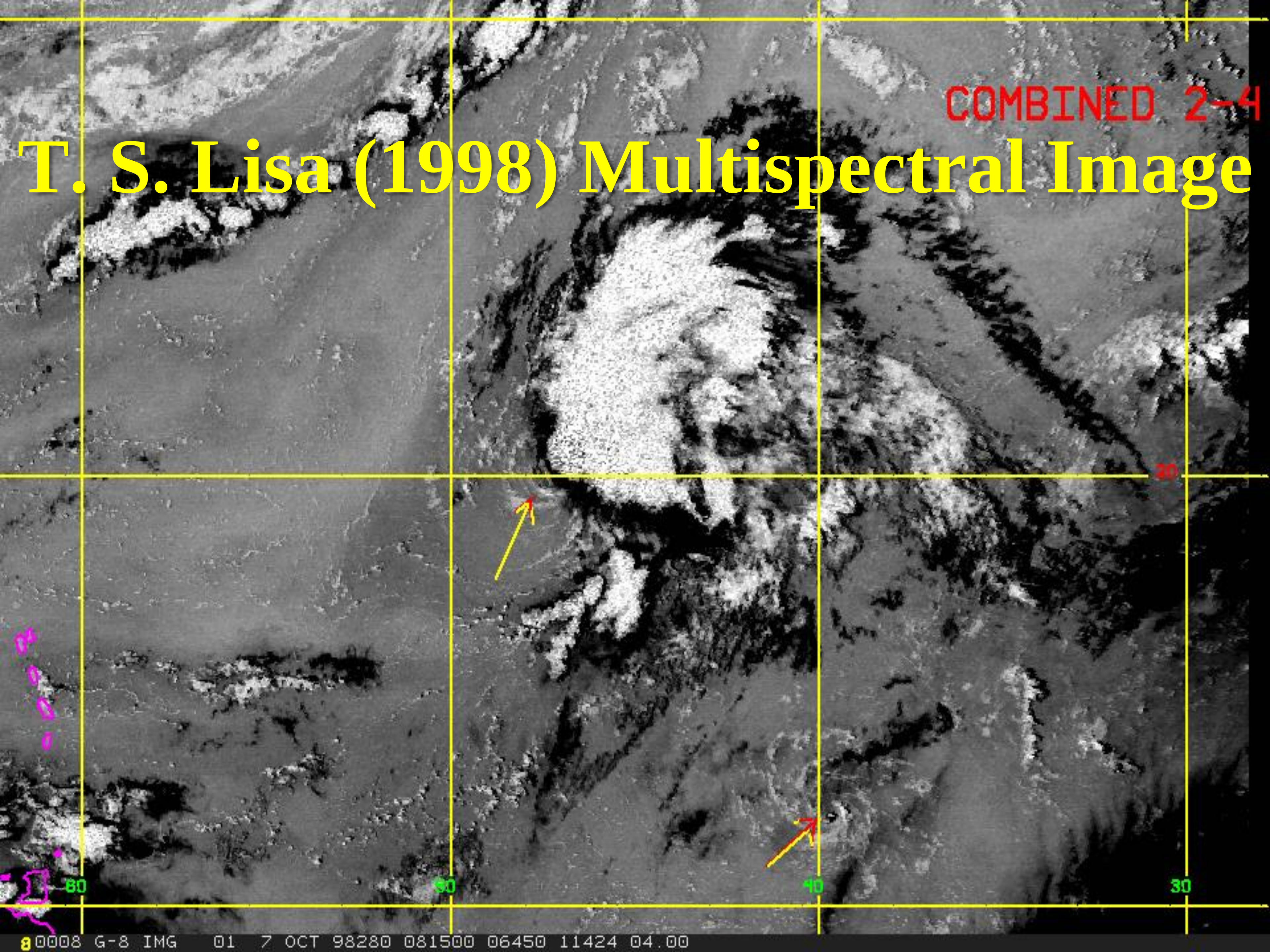
Notes on Step 1

- Other types of imagery (including microwave) and enhancements may be used in finding the CSC
- The CSC of a weak system is not always a closed circulation center
- In a system with multiple centers, use a mean center position between the centers
- It’s hard to analyze the intensity if you don’t know where the cyclone is!

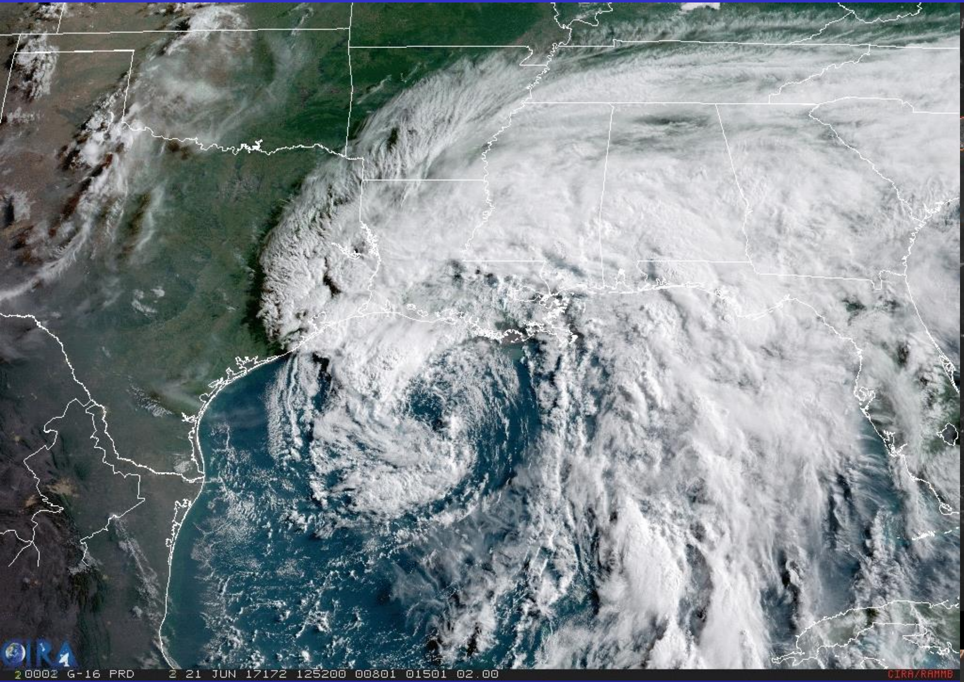
T.S. Lisa (1998) Standard IR Image

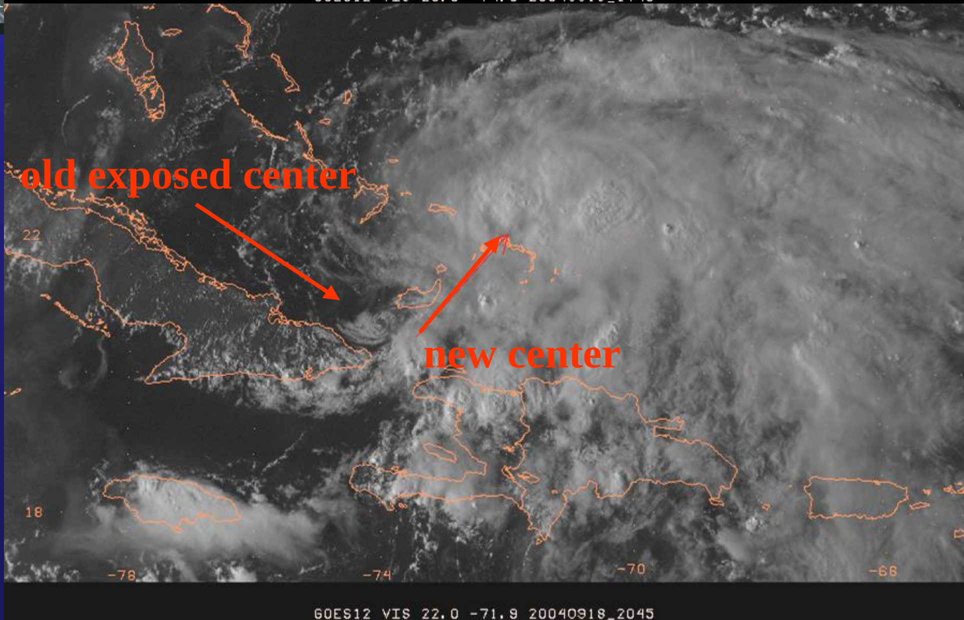


T. S. Lisa (1998) Multispectral Image



Cyclones with Multiple Centers





Cindy (2017) – Multiple swirls present SE of the convective mass – need to use a mean center

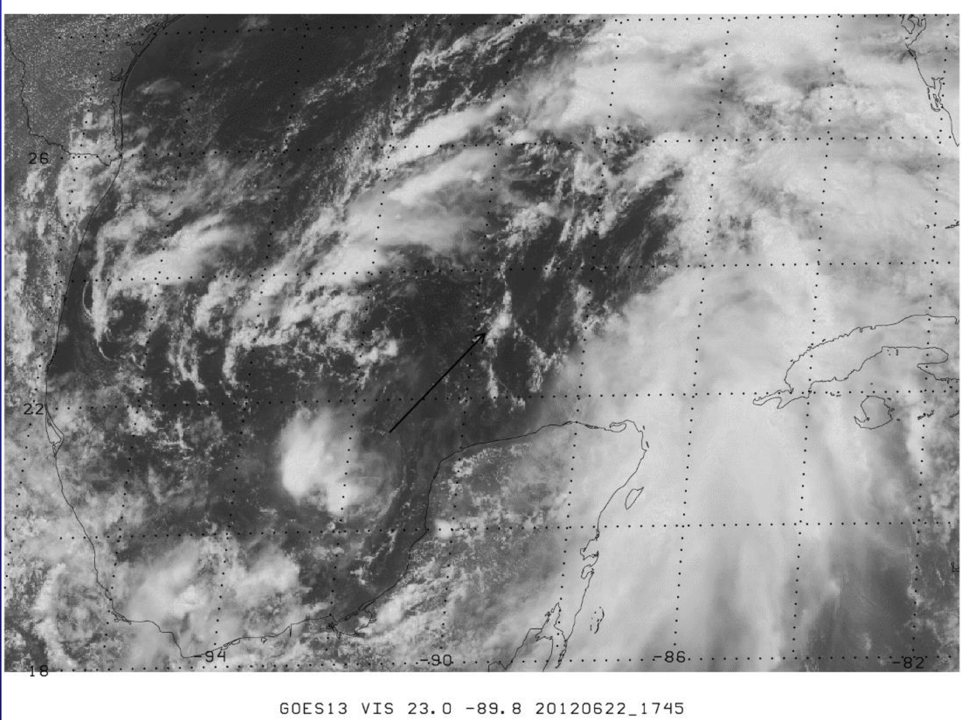
Jeanne (2004) - New center forms northeast of the old exposed center (images are 3 hr apart)

Step 1A - A T1 classification can be given when...

- A convective cluster has persisted for 12 hr or more
- The cluster has a CSC defined within a 2.5^o latitude wide or less area which has persisted for 6 hr
- Associated convection is dark gray (DG) or colder on the Dvorak BD enhancement curve over an area >1.5^o diameter less than 2^o from the center

Note on Step 1A

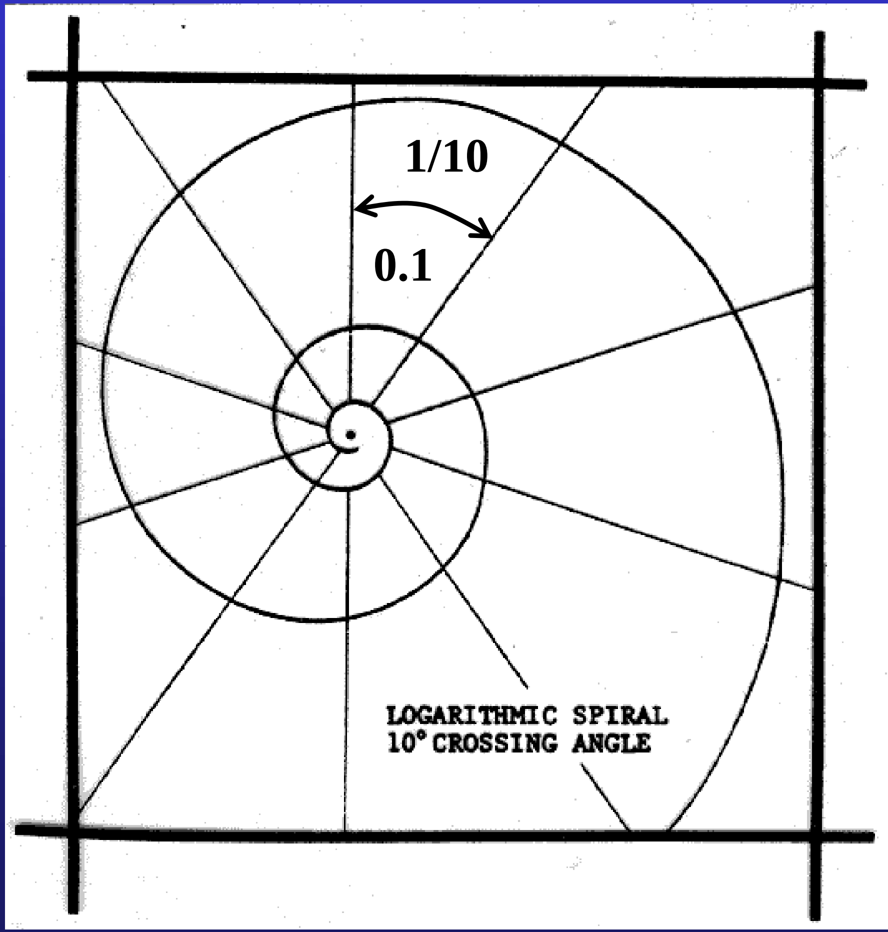
- An existing CSC that does not meet the criteria of Step 1A can be tracked as a system "too weak to classify" - a location without an intensity estimate



Pre-Debby (2012) low –
too weak to classify using the
Dvorak Technique

Step 2 - Analysis of the cyclone cloud pattern

- **The cloud pattern analysis produces the Data-T (DT) number intensity estimate**
- **Tool: Log 10º spiral for measuring curved bands**
- **Tool: BD enhancement for infrared imagery**
- **Cloud patterns can change considerably on time scales of a few hours**
- **Recognizing the correct cloud pattern is vital to a proper intensity analysis**

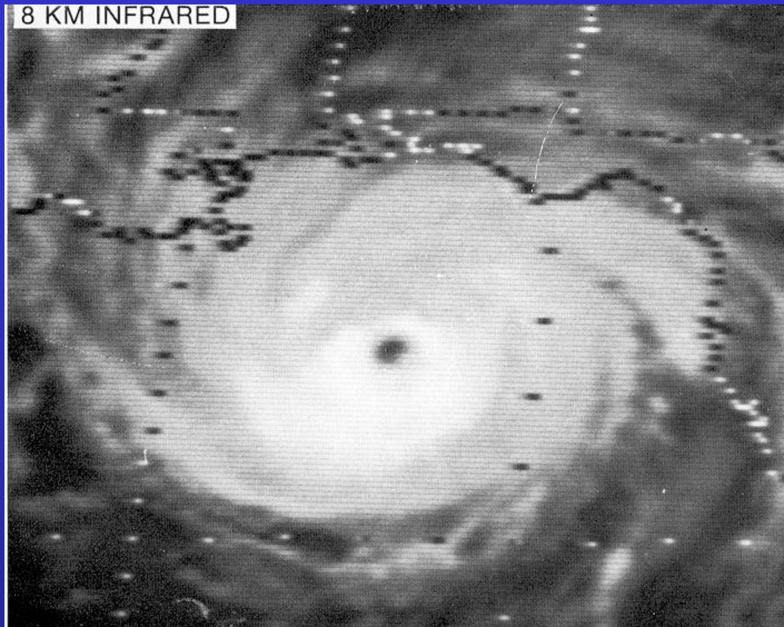


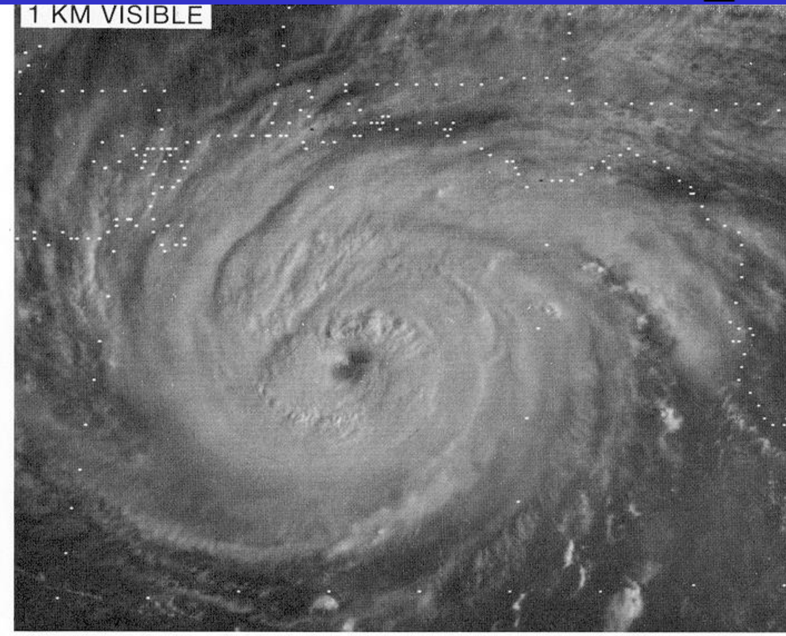
BD Enhancement Curve

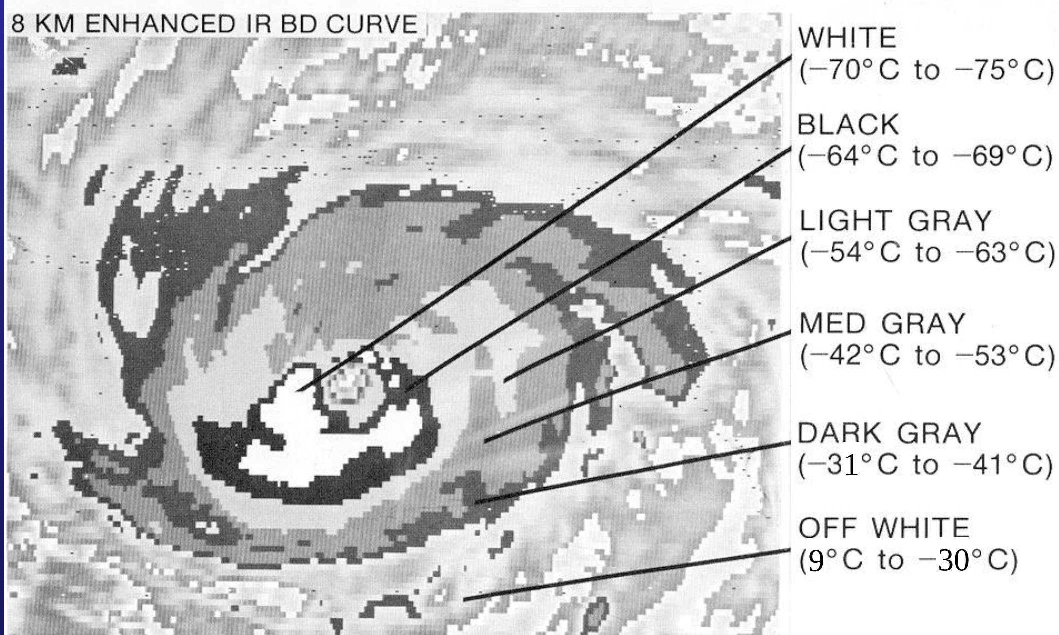
Segment Number	Color Range	Cloud Top Temperature Range (^{o}C)	Name/Abbreviation
2	0-255	>9.0	Warm Medium Gray (WMG)
3	109-202	9.0 to -30	Off White (OW)
4	60-60	-31 to -41	Dark Gray (DG)
5	110-110	-42 to -53	Medium Gray (MG)
6	160-160	-54 to -63	Light Gray (LG)
7	0-0	-64 to -69	Black (B)
8	255-255	-70 to -75	White (W)
9	135-135	-76 to -80	Cold Medium Gray (CMG)
10	85-85	<-80	Cold Dark Gray (CDG)

The BD enhancement curve was developed in an era of 256 shades of gray technology.

BD Enhancement Curve Example





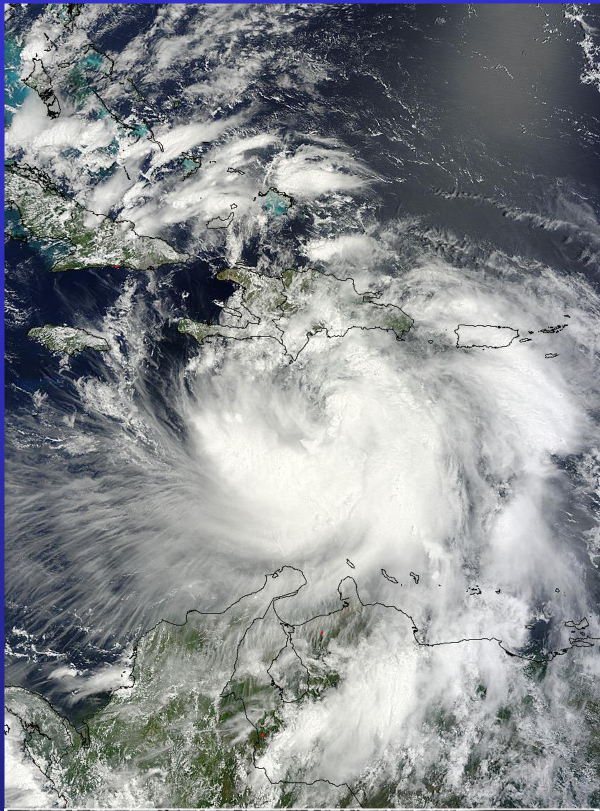


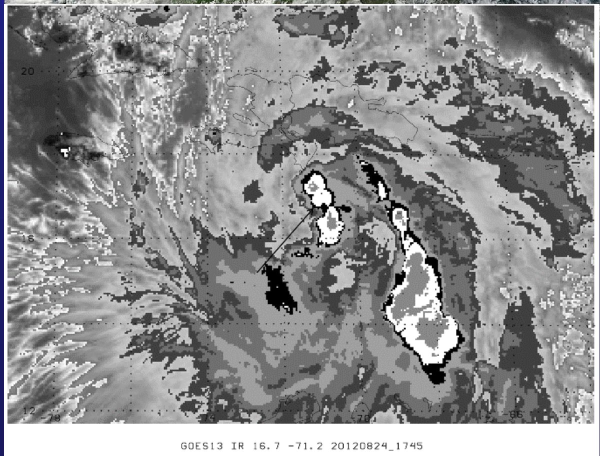
TROPICAL CYCLONE ANALYSIS
SATELLITE DATA COMPARISON EXERCISE
HURRICANE FREDERIC
1331 GMT 12 September 1979

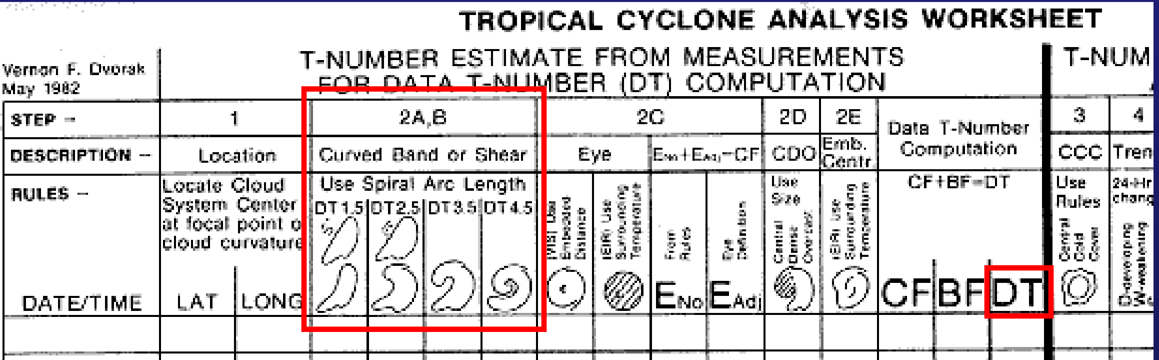
On this image, light gray (LG) is the coldest BD color shade that completely surrounds the eye.

Step 2A – Measuring Curved Bands

- **Fit the spiral parallel to the inner edge of the band (VIS) or to the coldest tops in the band (IR)**
- **Measure only the primary band of the cyclone - other bands don't count**
- **Endpoints of bands can be rather subjective**
- **Important: The center of the log 10^{o} spiral is usually <u>not</u> the center of the cyclone!**
- **Note: Nature does not always produce bands with 10 degrees crossing angles ☺**







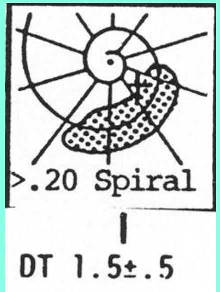
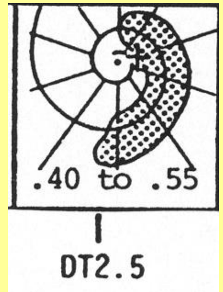
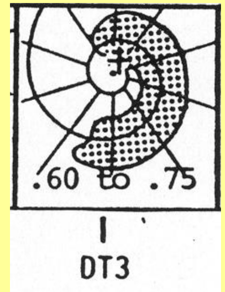
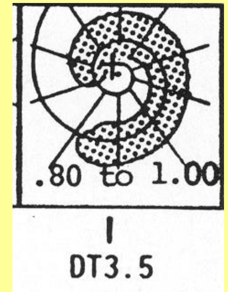
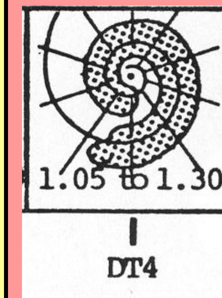
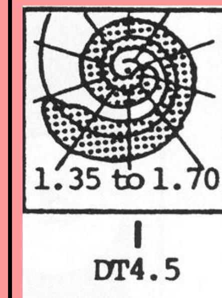
TROPICAL CYCLONE ANALYSIS WORKSHEET

Vernon F. Dvorak
May 1982

T-NUMBER ESTIMATE FROM MEASUREMENTS FOR DATA T-NUMBER (DT) COMPUTATION

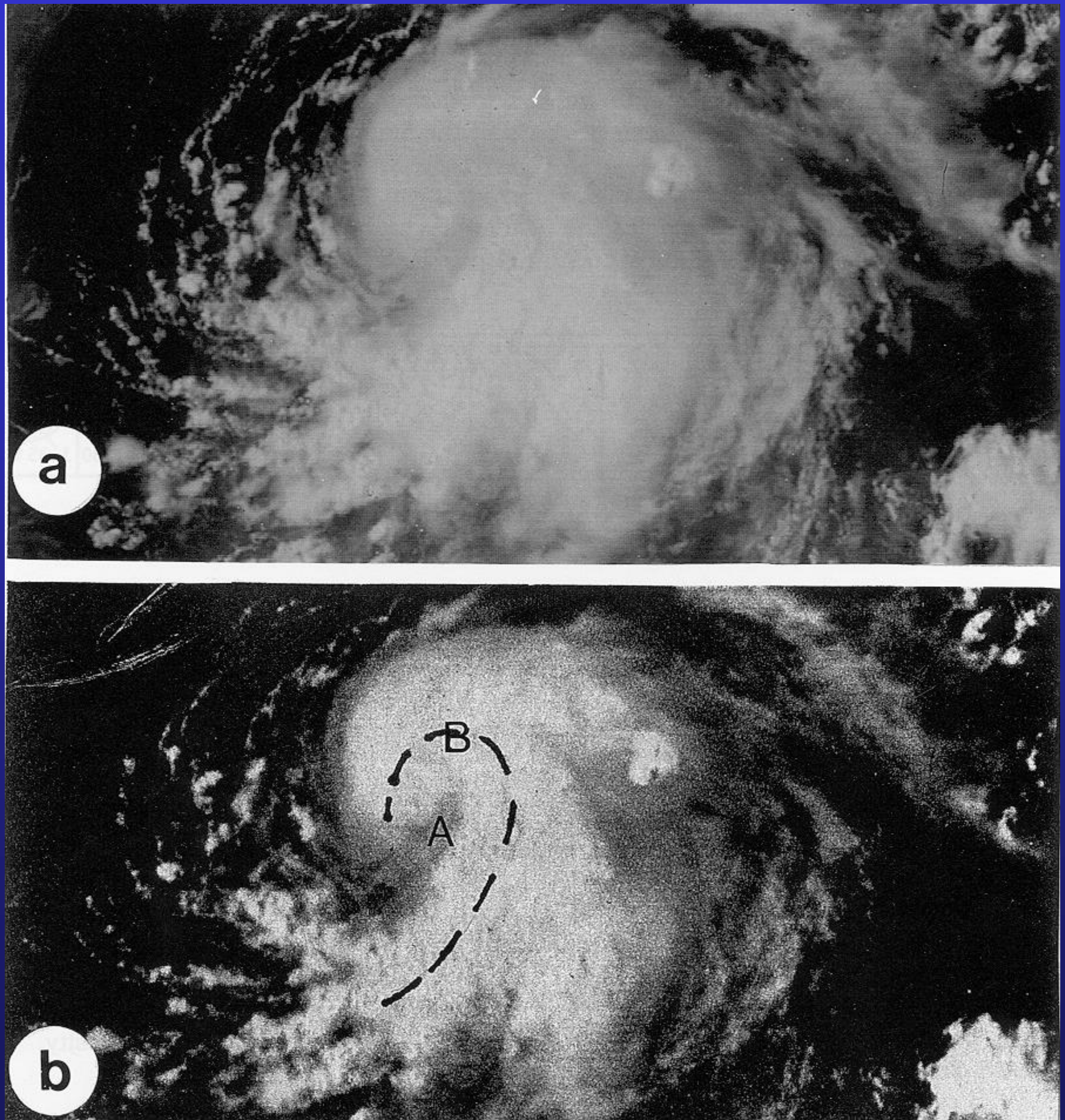
STEP –	1		2A,B				2C				2D	2E				3	4
DESCRIPTION –	Location		Curved Band or Shear				Eye		$E_{No}+E_{Adj}-CF$		CDO	Emb. Centr.	Data T-Number Computation			CCC	Tren
RULES –	Locate Cloud System Center at focal point o cloud curvature		Use Spiral Arc Length				(VIS) Use Embedded Distance	(EIR) Use Surrounding Temperature	From Rules	Eye Definition	Use Size Central Dense Overcast	(EIR) Use Surrounding Temperature	CF+BF=DT			Use Rules Central Cold Cover	24-Hr chang D-developing W-weakening
			DT 1.5	DT 2.5	DT 3.5	DT 4.5											
DATE/TIME	LAT	LONG							E_{No}	E_{Adj}			CF	BF	DT		

Step 2A - Curved Band Patterns

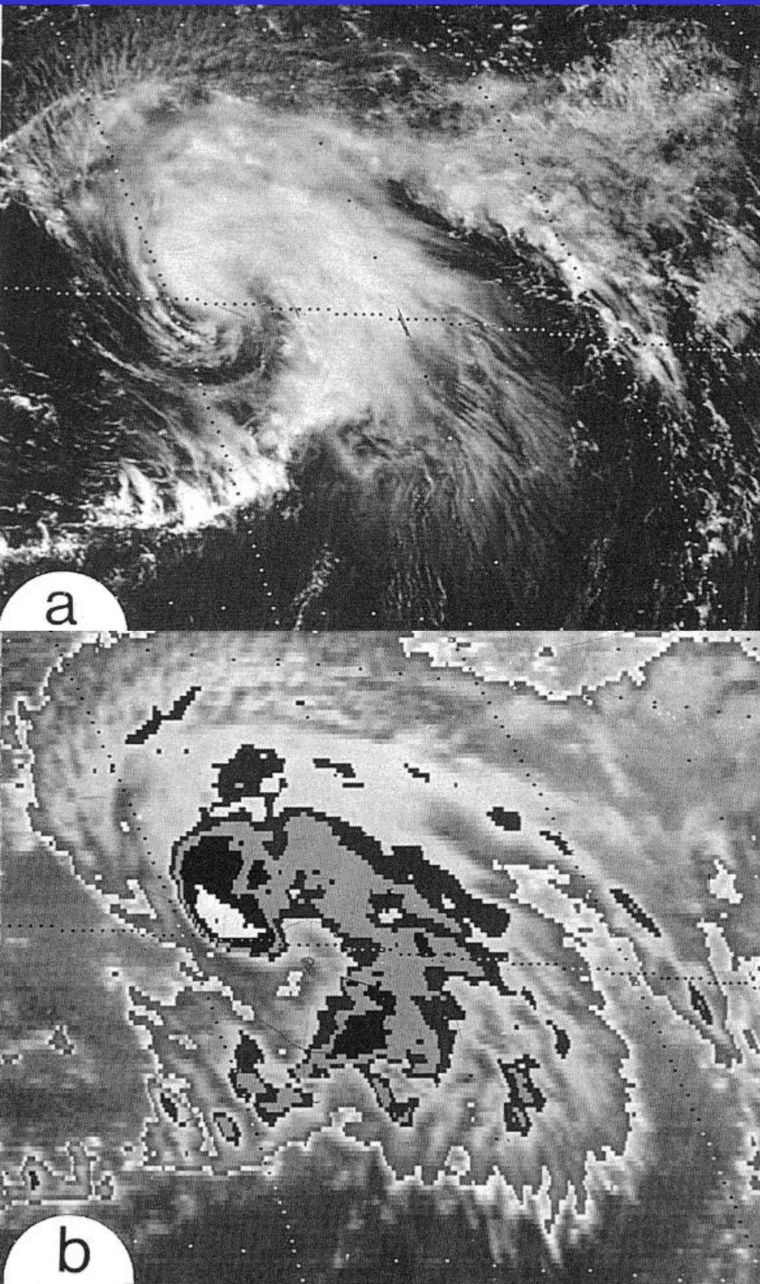
Flow chart images						
Spiral arc distance (tenths along log 10° spiral)	0.20 - 0.35	0.40 - 0.55	0.60 - 0.75	0.80 - 1.00	1.05 - 1.30	1.35 - 1.70
Data-T Number (DT)	1.0 to 2.0	2.5	3.0	3.5	4.0	4.5

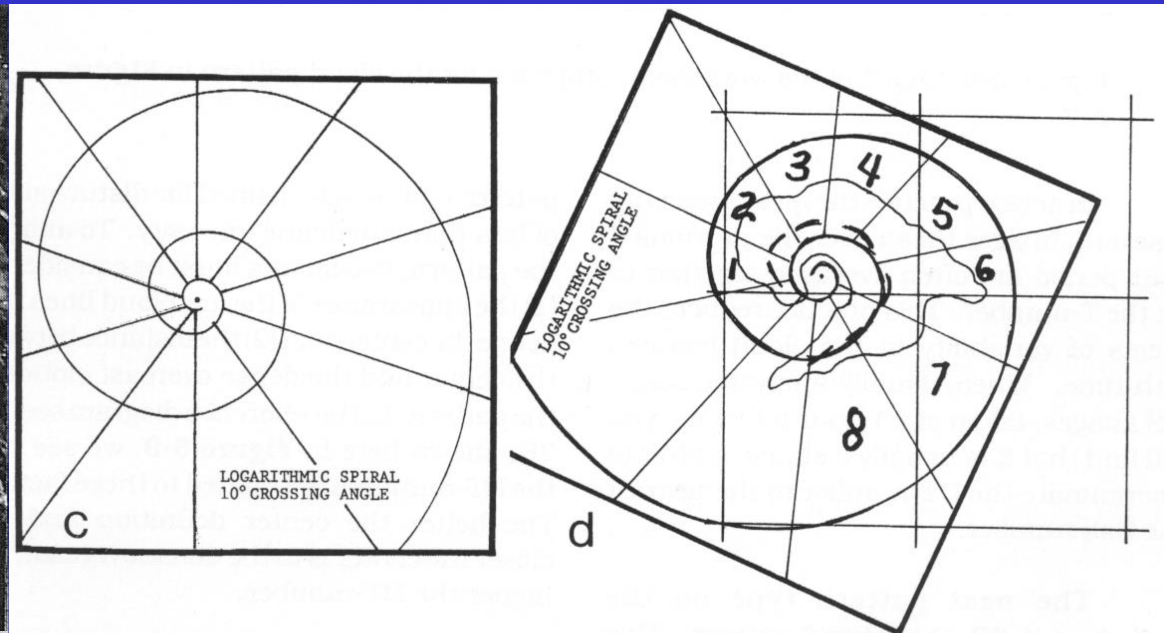
These patterns are for both visible and infrared imagery. Use banding eyes in Step 2C for unusual band widths and lengths in visible imagery.

Step 2A - Curved Band Example

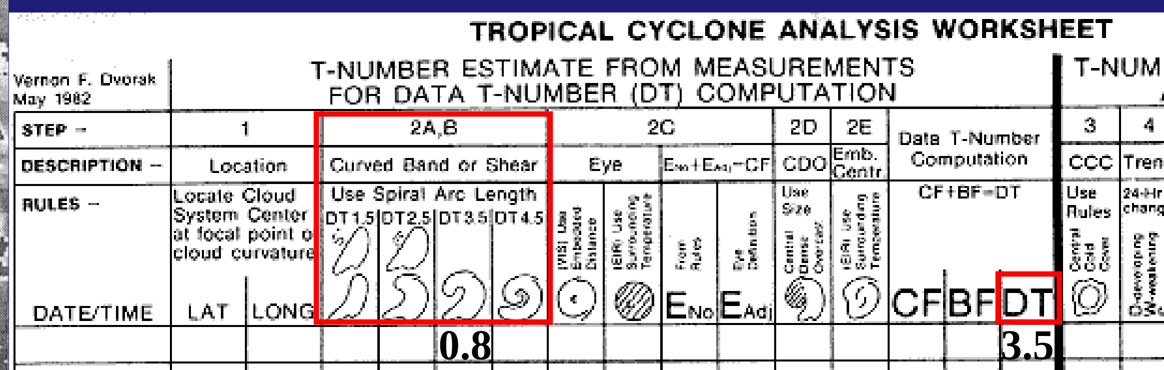


Step 2A – Measuring Curved Bands

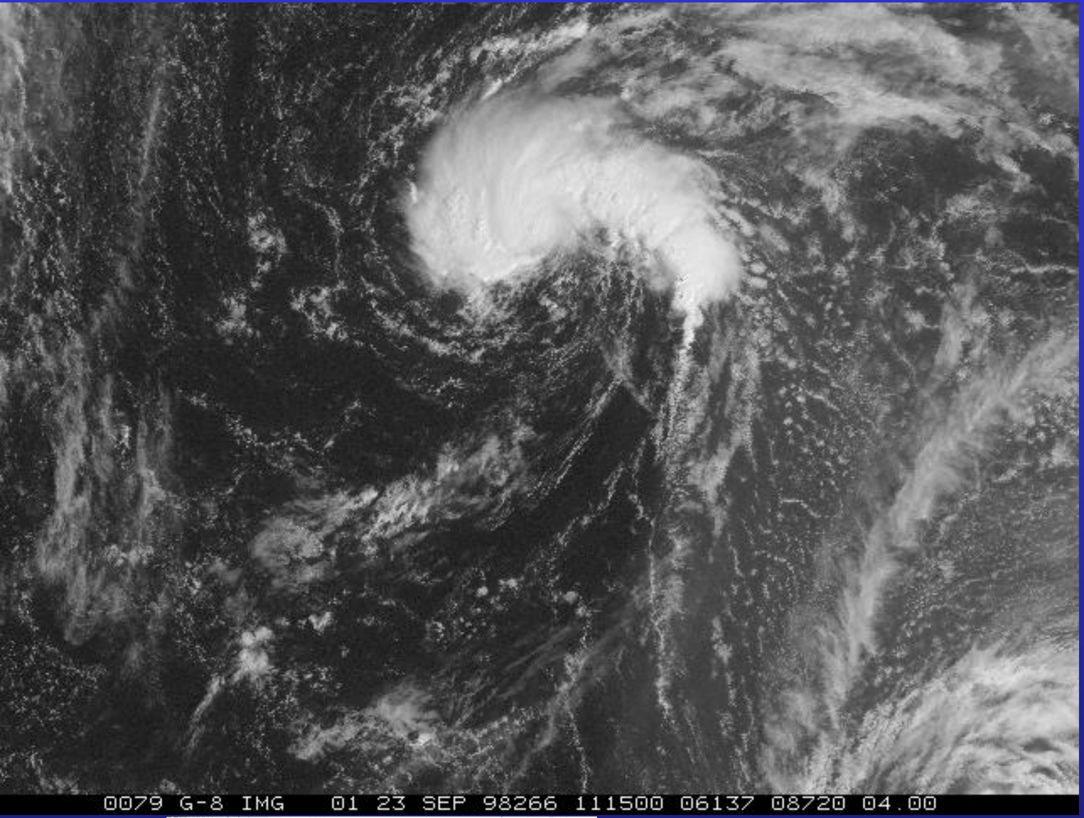


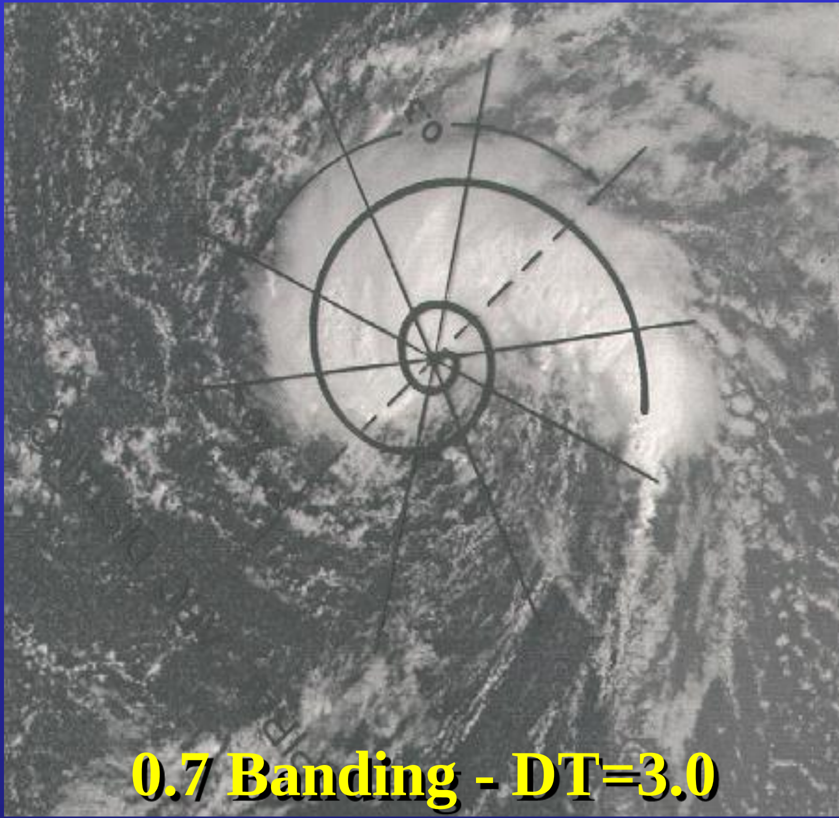


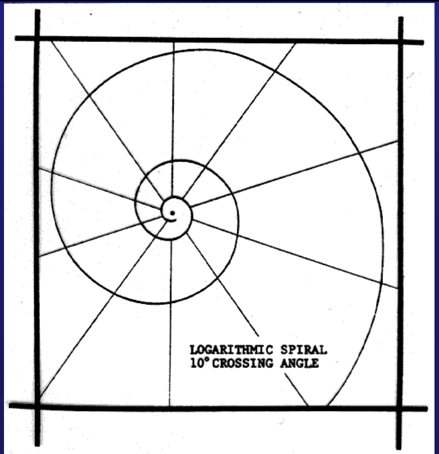
0.8 Banding - DT=3.5

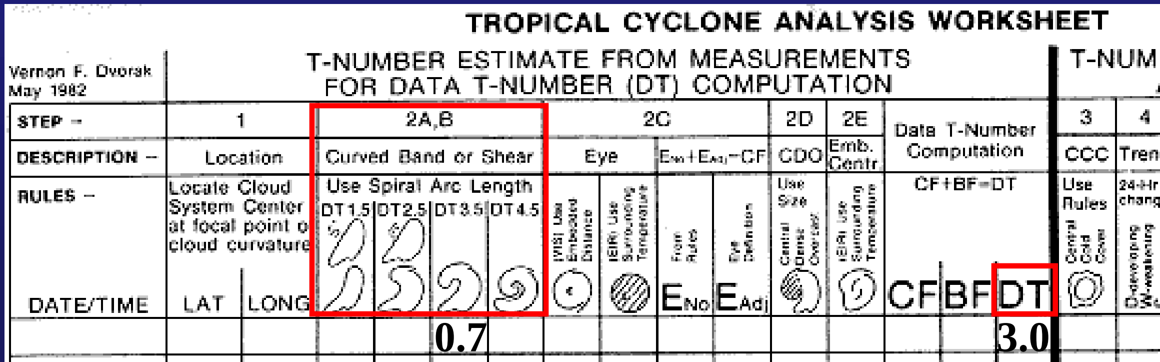


Step 2A – Measuring Curved Bands



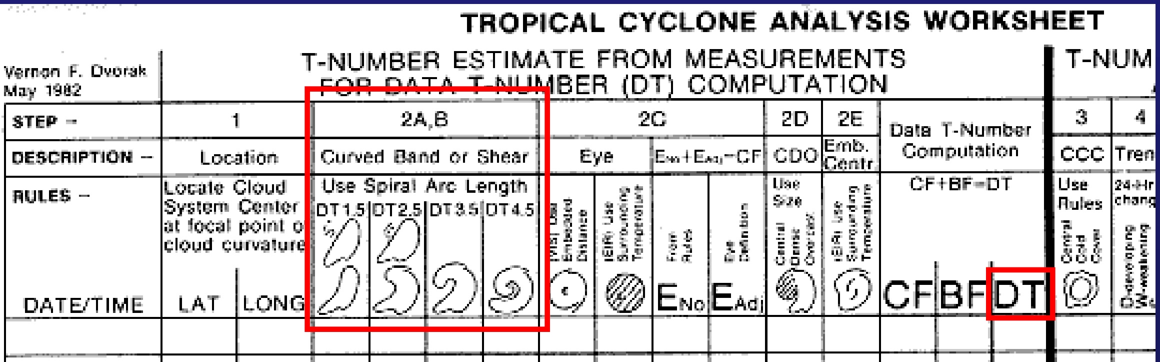


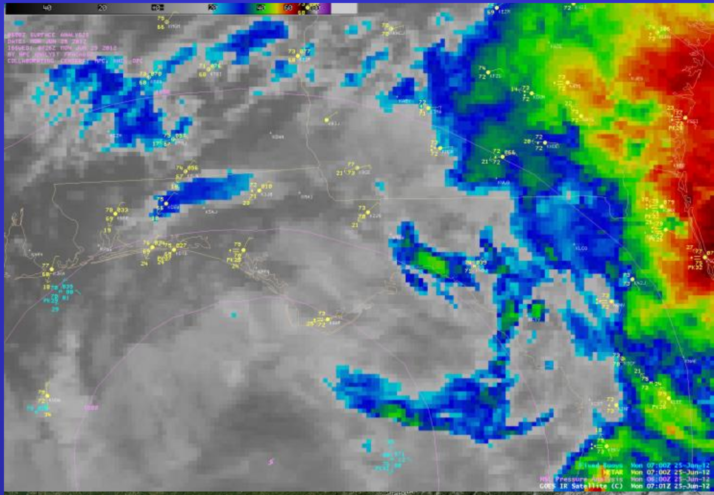


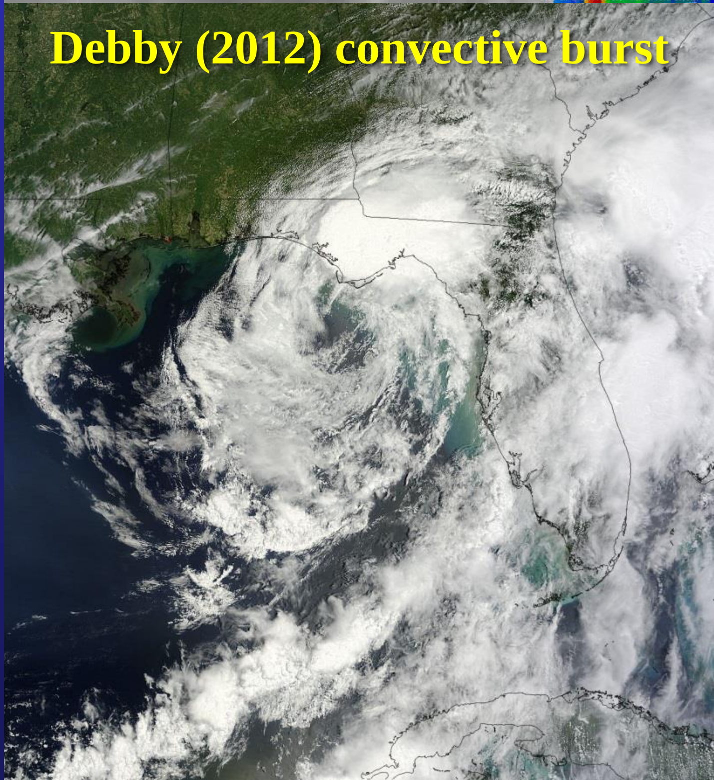


Step 2B – Measuring Shear Patterns

- Measure the distance (in degrees of latitude) from the low level center to the edge of the dense overcast (VIS) or to the edge of the DG shade (IR)
- The edge of the convection can be rather subjective
- Shear patterns tend to be rather unstable, as the convection often shows strong pulses or bursts. Therefore the DT is often considered not to be clear cut

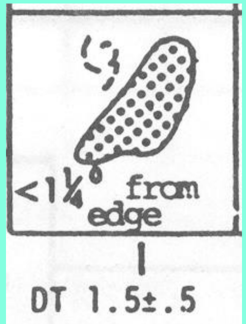
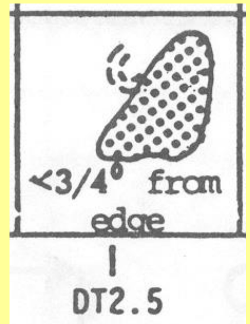
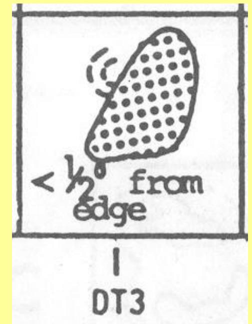
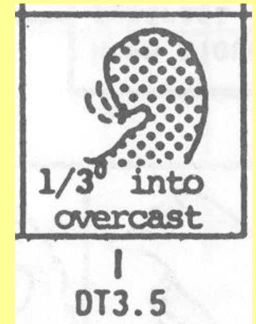






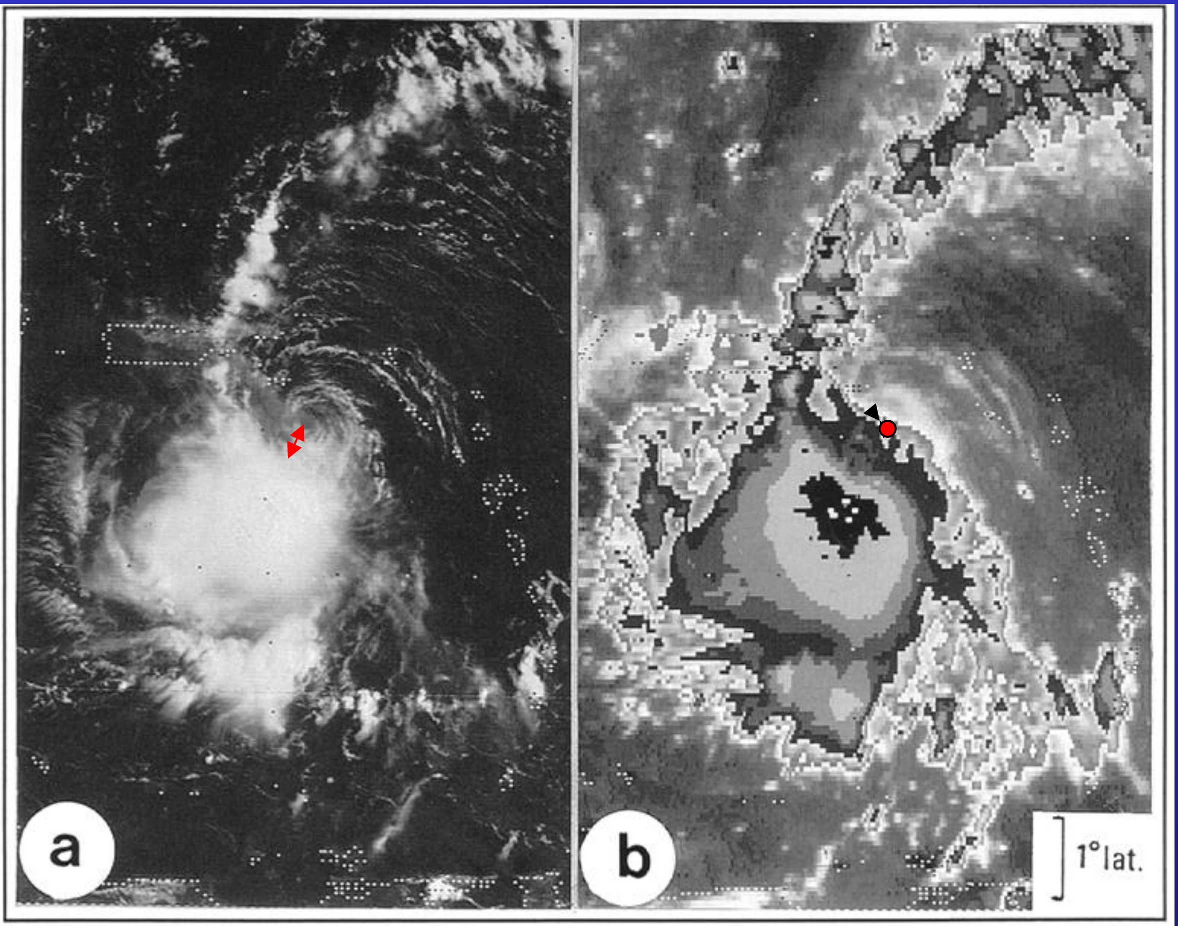
Debby (2012) convective burst

Step 2B - Shear Patterns

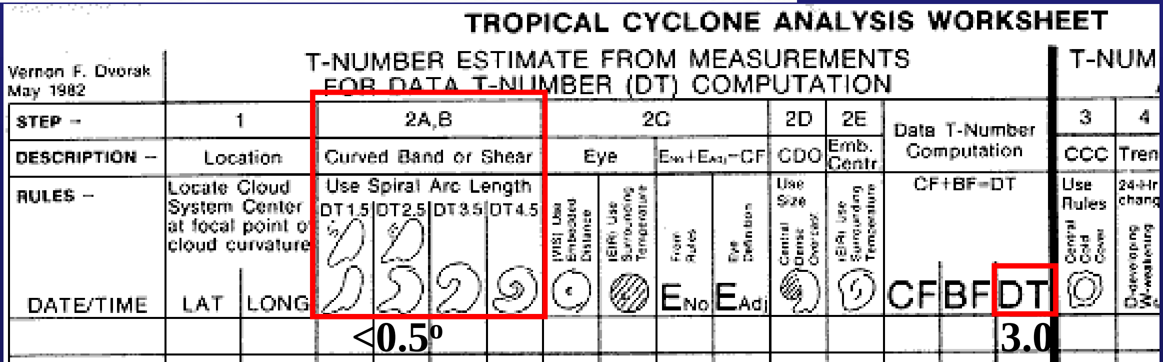
<table>
<tr><td>Flow chart images</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Distance from edge of convection or DG (tenths of deg latitude)</td><td>1.25 – 0.75</td><td>0.74 – 0.50</td><td>0.49 from Cnvtn to 0.32 into Cnvtn</td><td>>0.33 into Cnvtn</td></tr>
<tr><td>Data-T Number (DT)</td><td>1.0 to 2.0</td><td>2.5</td><td>3.0</td><td>3.5</td></tr>
</table>

Note: This is the 1984 version of the shear pattern measurements

Step 2B – Measuring Shear Patterns



Shear Distance < 0.5°
DT=3.0


TROPICAL CYCLONE ANALYSIS WORKSHEET

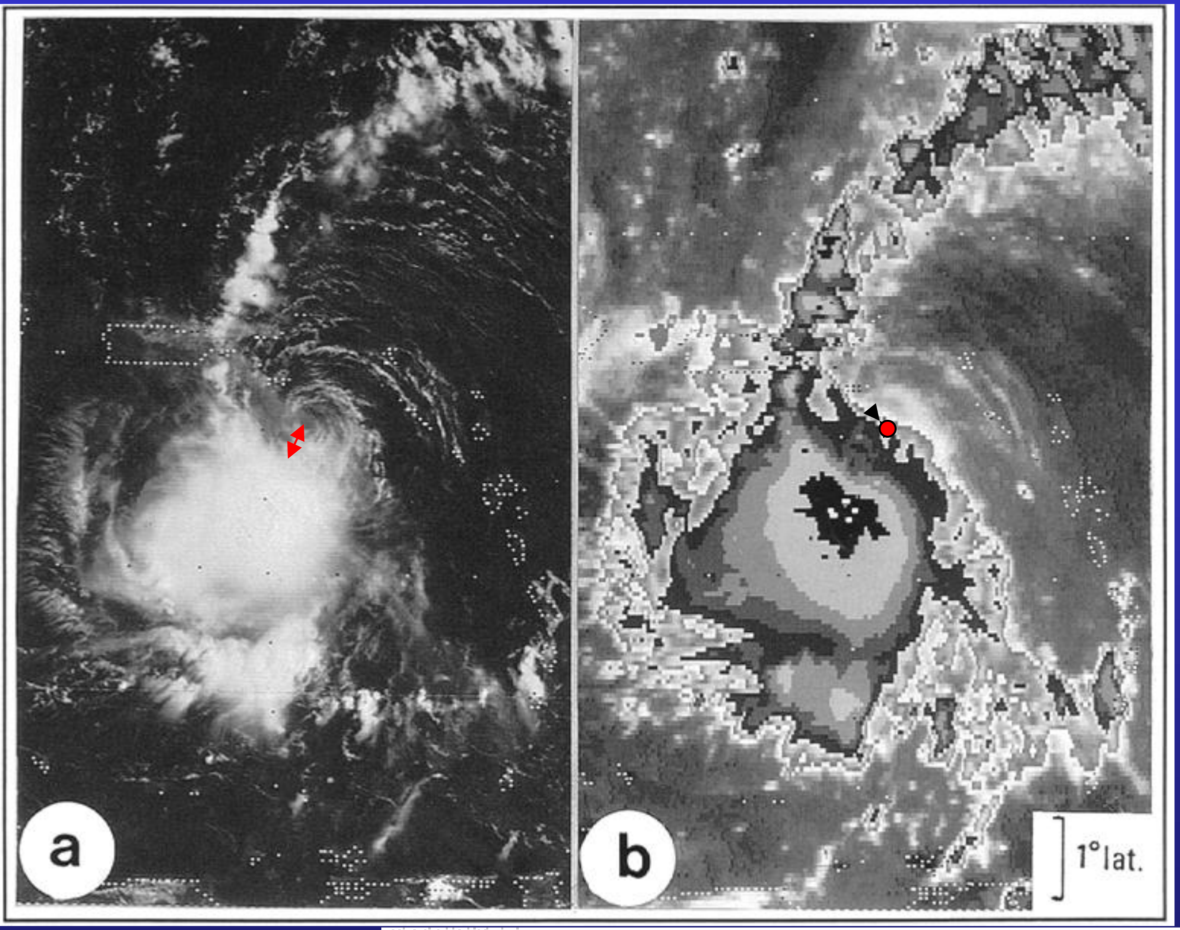
Vernon F. Dvorak
May 1982

T-NUMBER ESTIMATE FROM MEASUREMENTS FOR DATA T-NUMBER (DT) COMPUTATION

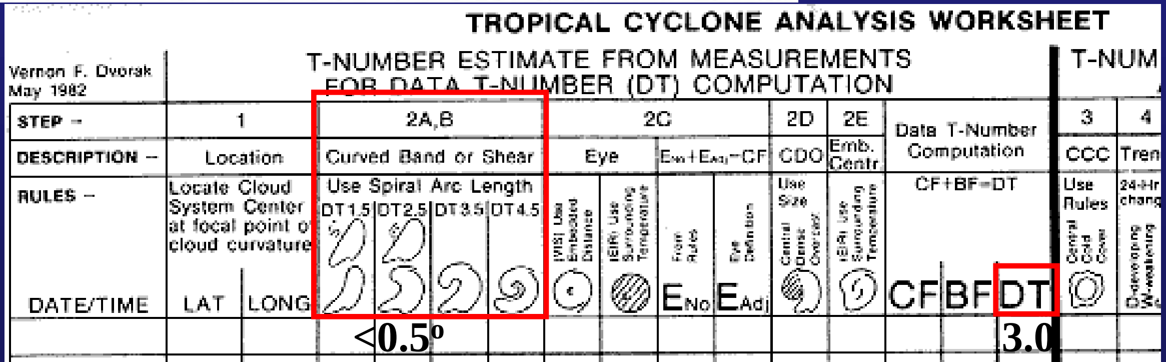
T-NUM

STEP –	1		2A,B				2C				2D	2E	Data T-Number Computation			3	4
DESCRIPTION –	Location		Curved Band or Shear				Eye		$E_{No}+E_{Adj}$–CF		CDO	Emb. Centr				CCC	Tren
RULES –	Locate Cloud System Center at focal point of cloud curvature		Use Spiral Arc Length				(VIS) Use Embedded Distance	(EIR) Use Surrounding Temperature	From Rules	Eye Definition	Use Size / Central Dense Overcast	(EIR) use Surrounding Temperature	CF+BF=DT			Use Rules / Central Cold Cover	24-Hr chang / D-developing W-weakening
DATE/TIME	LAT	LONG	DT1.5	DT2.5	DT3.5	DT4.5			E_{No}	E_{Adj}			CF	BF	DT		
			<0.5°												3.0		

Step 2B - Measuring Shear Patterns



Shear Distance < 0.5°
DT=3.0



TROPICAL CYCLONE ANALYSIS WORKSHEET

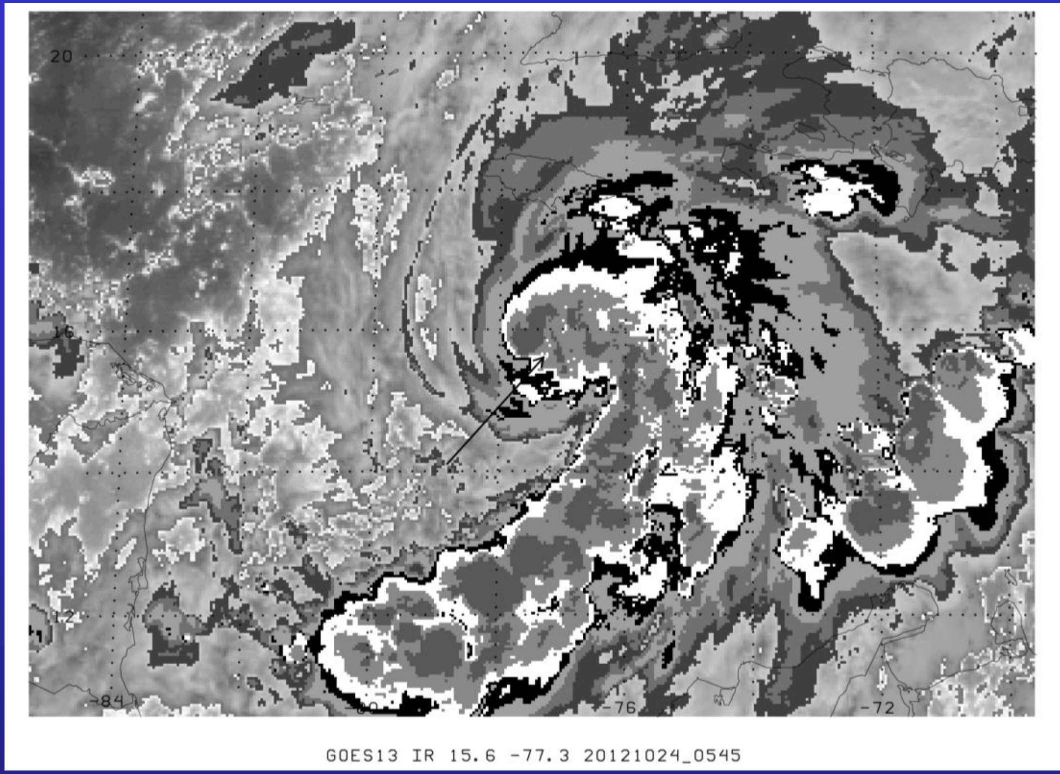
Vernon F. Dvorak
May 1982

T-NUMBER ESTIMATE FROM MEASUREMENTS FOR DATA T-NUMBER (DT) COMPUTATION

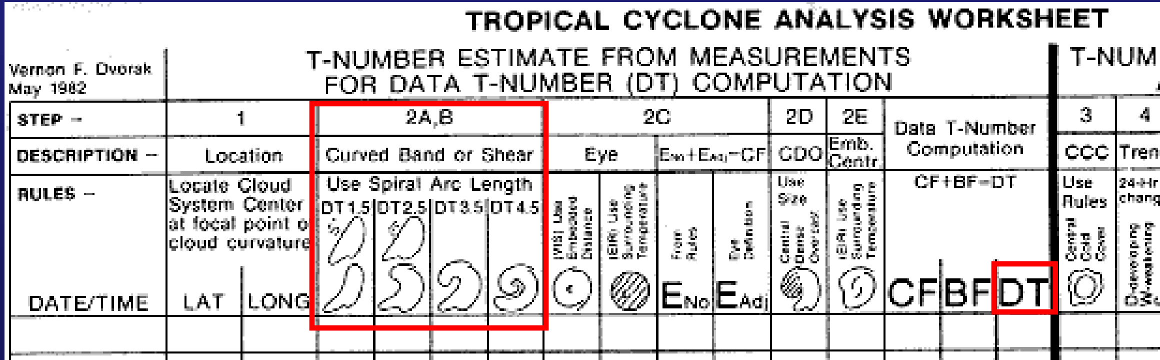
STEP →	1		2A,B				2C				2D	2E	Data T-Number Computation			3	4
DESCRIPTION →	Location		Curved Band or Shear				Eye		$E_{No}+E_{Adj}$−CF		CDO	Emb. Centr				CCC	Tren
RULES →	Locate Cloud System Center at focal point of cloud curvature		Use Spiral Arc Length DT1.5	DT2.5	DT3.5	DT4.5	(VIS) Use Embedded Distance	(EIR) Use Surrounding Temperature	From Rules	Eye Definition	Use Size Central Dense Overcast	(EIR) use Surrounding Temperature	CF+BF=DT			Use Rules Central Cold Cover	24-Hr chang D-developing W-weakening
DATE/TIME	LAT	LONG							E_{No}	E_{Adj}			CF	BF	DT		
			<0.5°												3.0		

Notes on Steps 2A and 2B

- **When available, VIS curved band and shear patterns are preferable to their IR counterparts**
- **Curved bands and shear patterns directly produce DT numbers**
- **The measurements are the same for both VIS and IR imagery**
- **A possible intensity adjustment in the IR curved band pattern: Add 0.5 to the DT if the curved band is White (W) or colder**

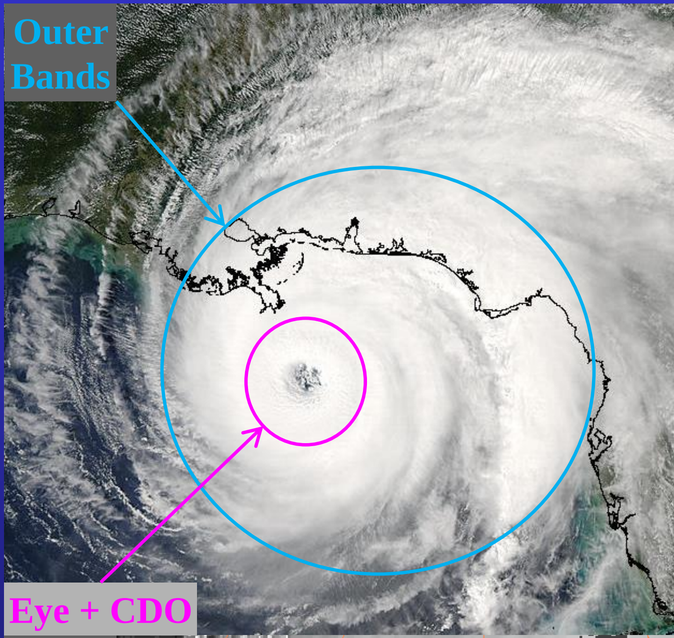


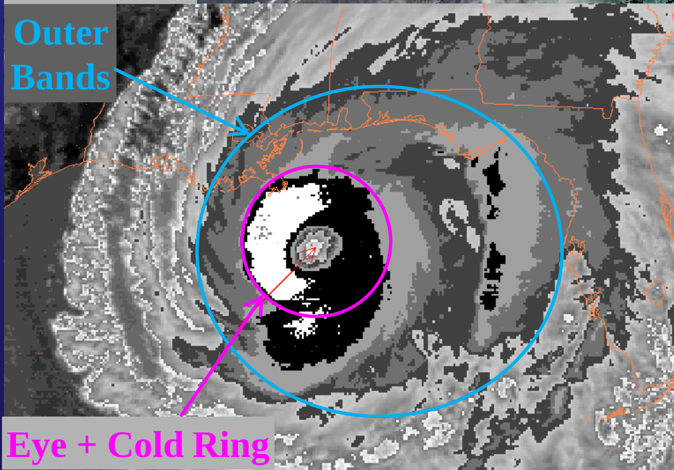
Sandy (2012) with a White (W) or colder band – add 0.5 to the band DT!

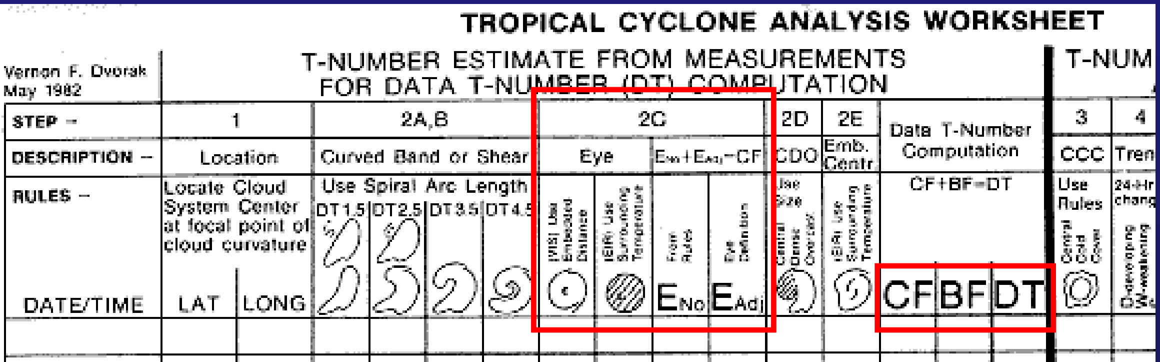


Step 2C – Measuring Eye Patterns
Some Assembly Required!

- Find the eye number (E-number)
- Perform an Eye Adjustment
- Create the Central Feature (CF) number from the E-number and Eye Adjustment
- Add applicable banding features (BF) to the CF number to get the DT number
- There are significant differences between how the VIS and IR patterns are measured!

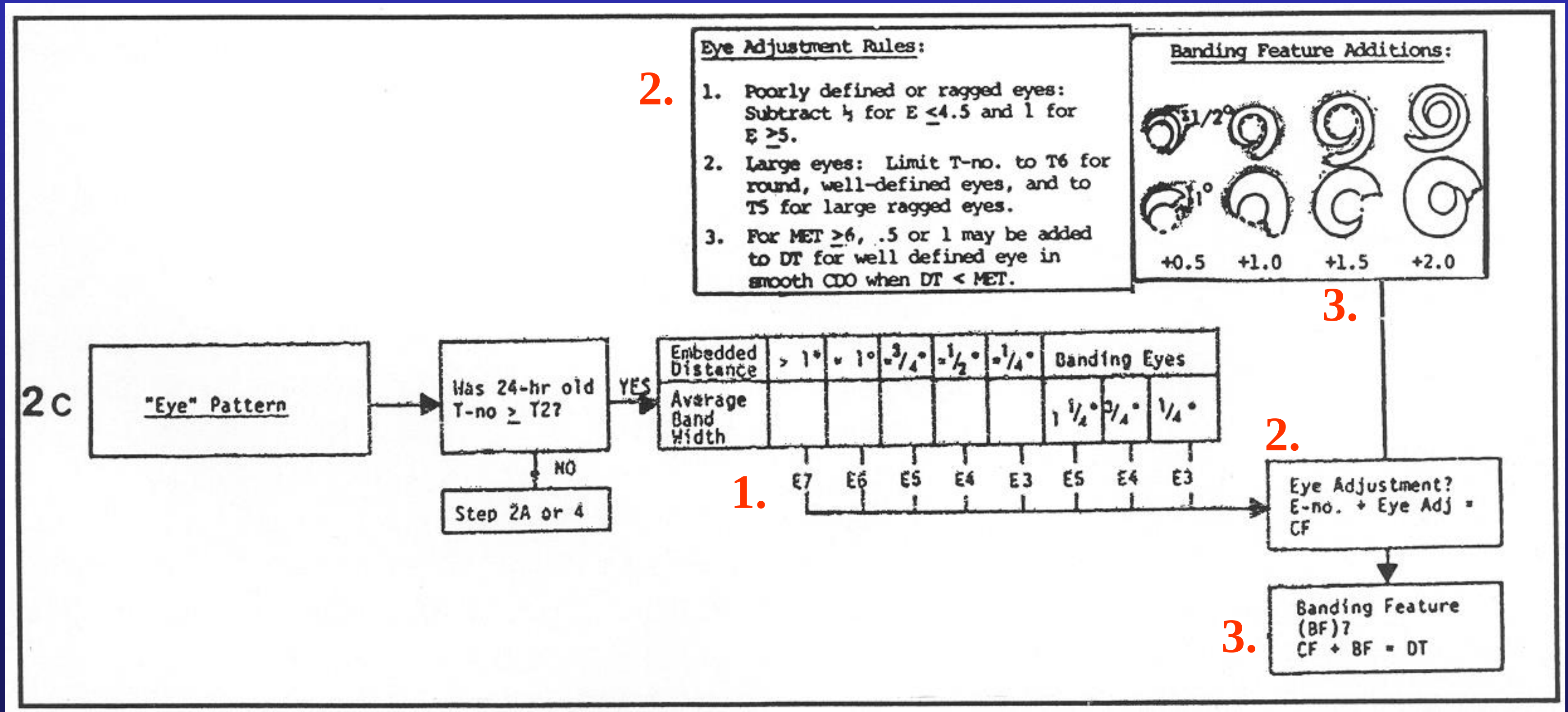






Step 2C - Visible Eye Patterns

1. Measure the distance ('embedded distance') from the center of the eye to the edge of the Central Dense Overcast (E-number)
2. Make eye adjustment based on size and clarity of eye (E-Number + Eye Adjustment = CF Number)
3. Add BF for applicable outer banding (CF + BF = DT)



Step 2C - Eye Patterns

Visible Technique

Is the 24 hour old FT > 2.0? If not, go to step 2A or step 4.

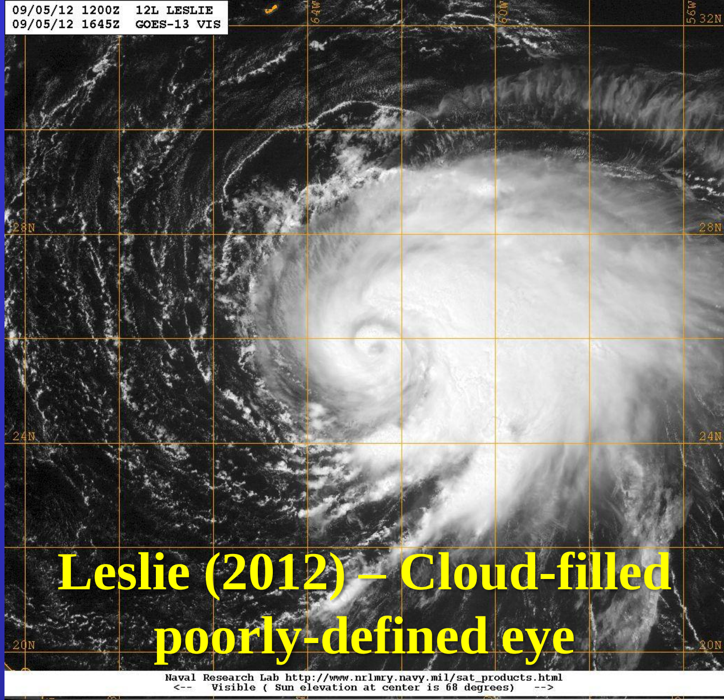
Eye in CDO - Embedded Distance (deg)	>1	~1	~0.75	~0.5	~0.25
Banding Eye - Avg. Width of Band Around Eye (deg)			1.25	0.75	0.25
Eye Number (E#)	7.0	6.0	5.0	4.0	3.0

Note: You can interpolate between the eye numbers when appropriate!

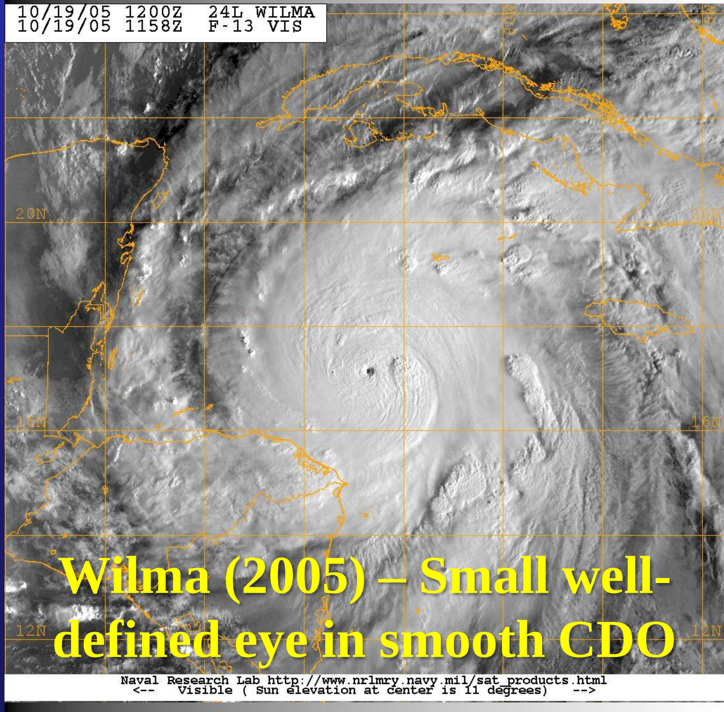
Step 2C - Visible Eye Adjustment

Eye Adjustment Rules

1. **Poorly defined or ragged eyes: subtract 0.5 for E≤4.5 and 1 for E≥5**
2. **Large eyes (30 nm/56 km or greater): Limit T-no to T6 for round well-defined eyes and to T5 for large ragged eyes**
3. **For MET≥6, 0.5 or 1 may be added to DT for well-defined eye in smooth CDO when DT<MET**

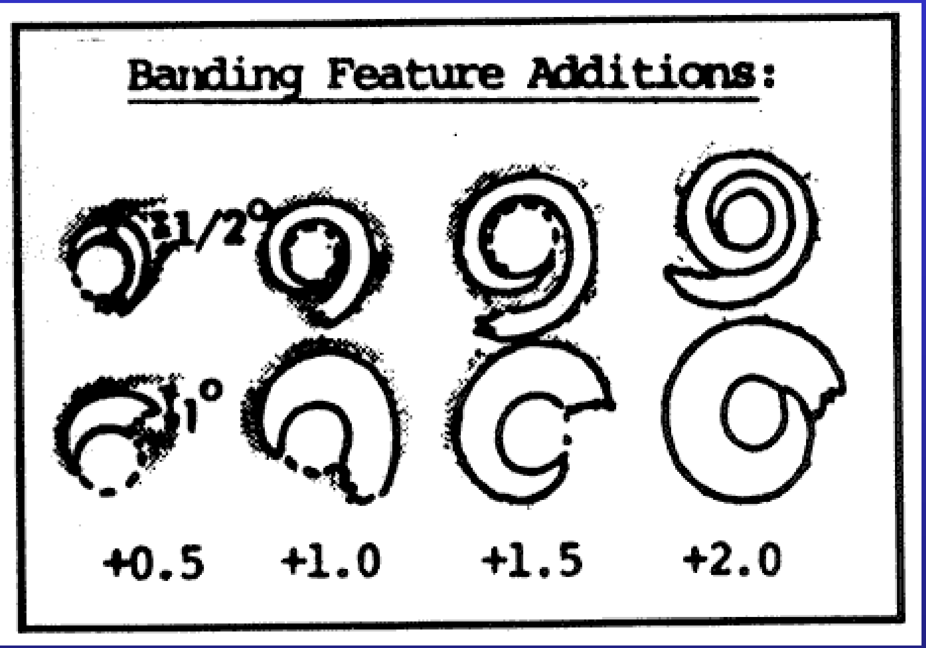


Leslie (2012) – Cloud-filled poorly-defined eye

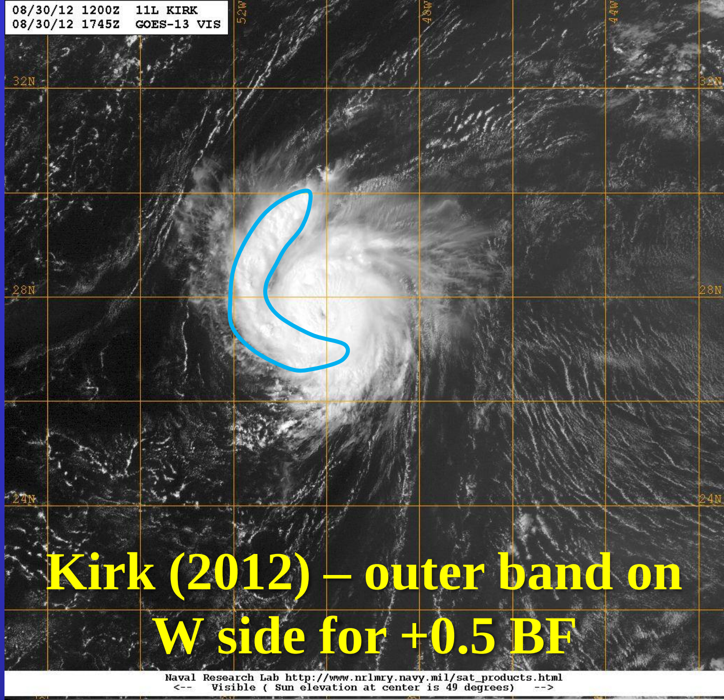


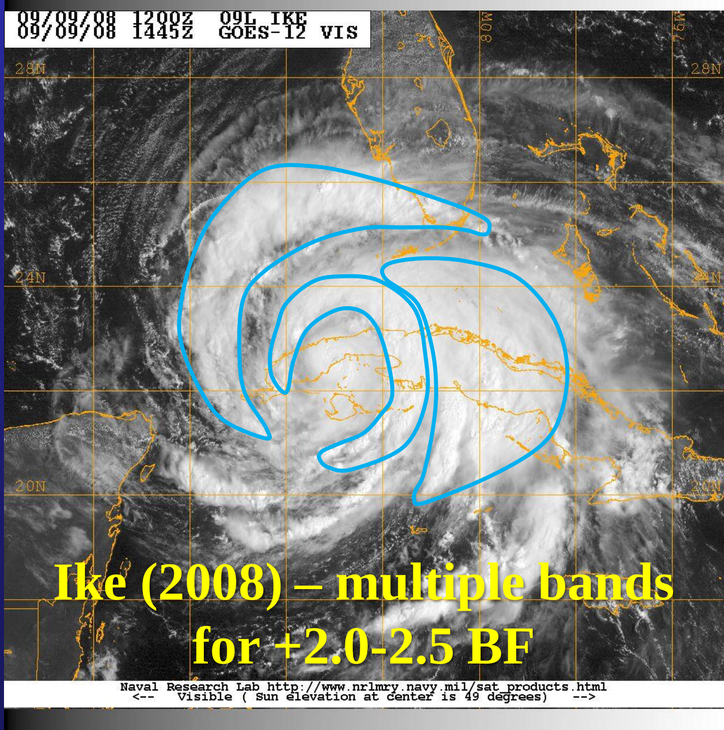
Wilma (2005) – Small well-defined eye in smooth CDO

Step 2C - Visible Outer Banding



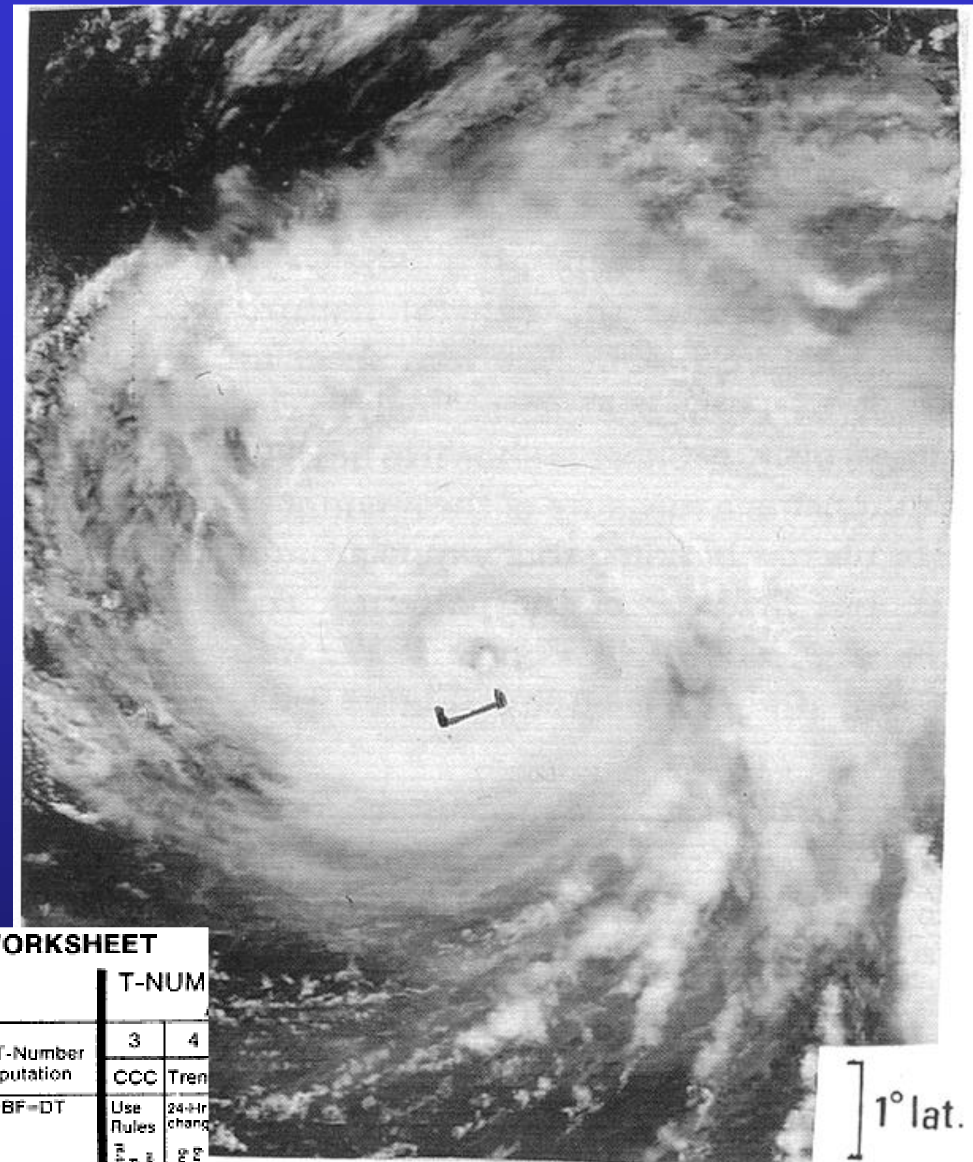
Banding Feature (BF) Numbers:
Match the banding outside of the central convection to that shown in the pictograph.
Note: You can add multiple bands when applicable up to a total of 2.5 BF numbers.

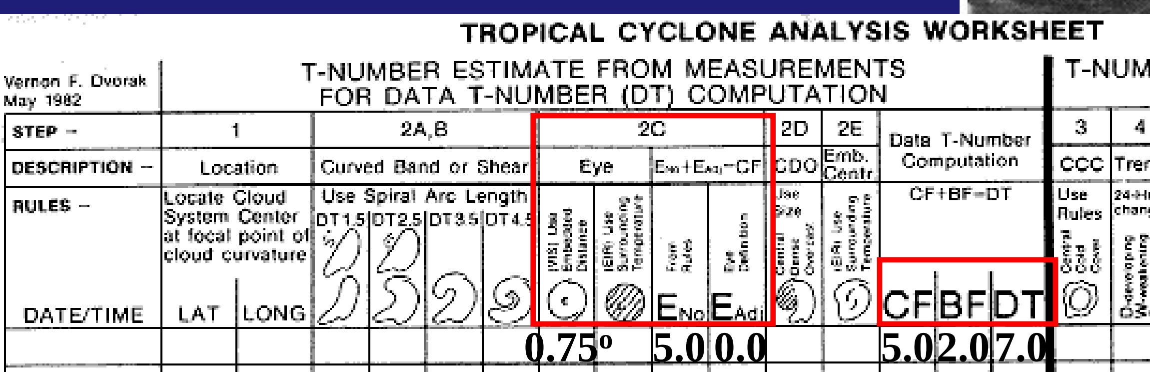




Step 2C - Measuring a Visible Eye

The eye is ¾ degrees into the CDO (Eye number 5.0), with no Eye adjustment (0.0). This produces a CF5 + 2.0 for banding features ➔ DT=7.0



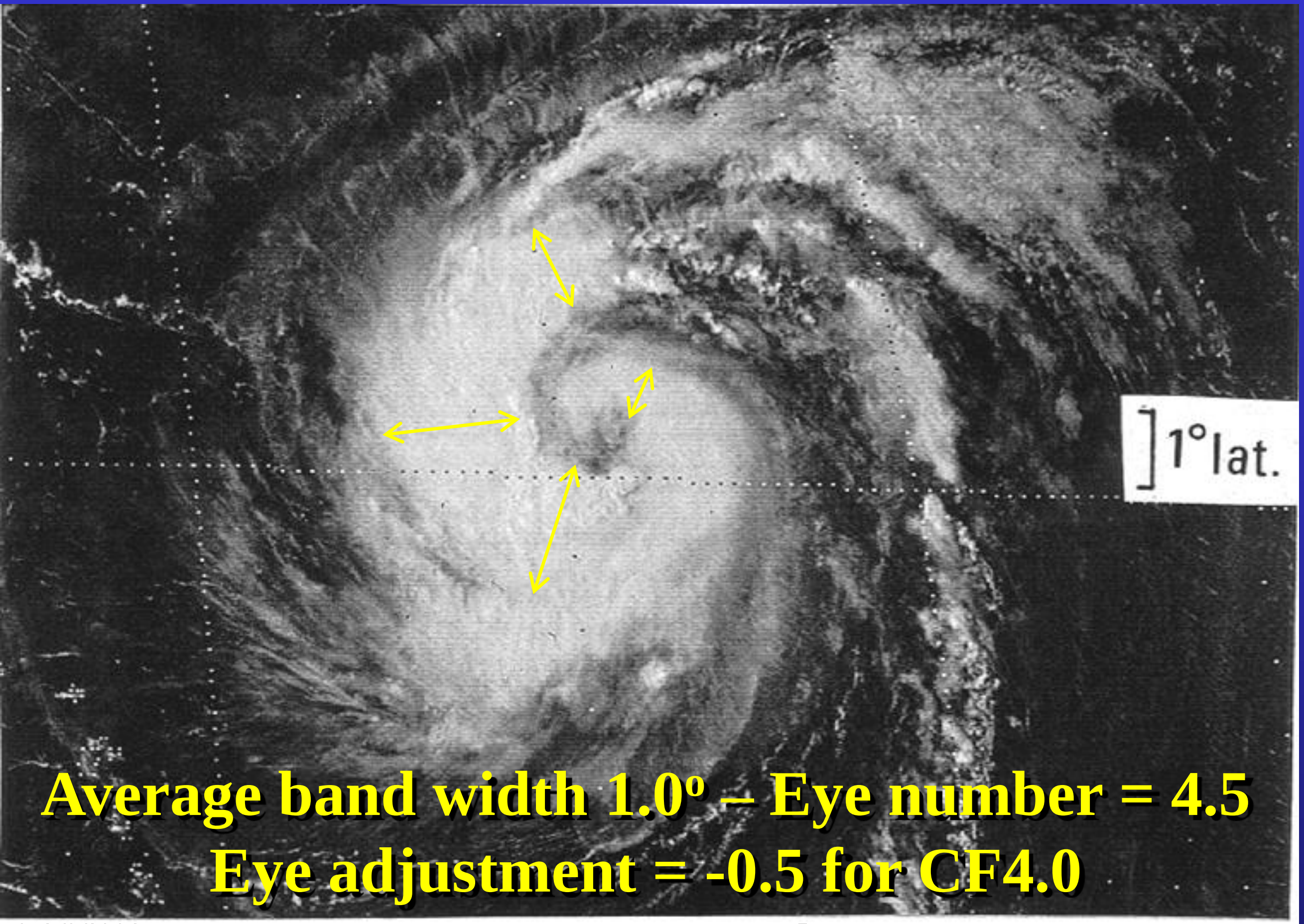

TROPICAL CYCLONE ANALYSIS WORKSHEET

Vernon F. Dvorak
May 1982

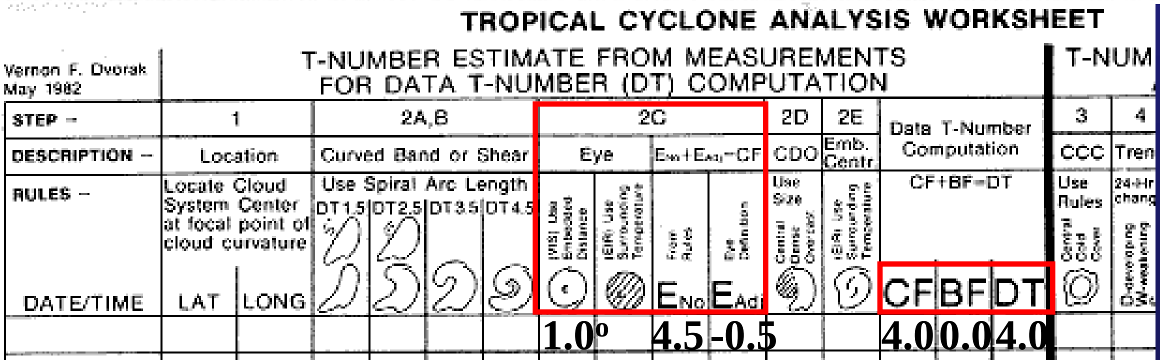
T-NUMBER ESTIMATE FROM MEASUREMENTS FOR DATA T-NUMBER (DT) COMPUTATION

STEP →	1		2A,B				2C				2D	2E				3	4
DESCRIPTION →	Location		Curved Band or Shear				Eye		$E_{No}+E_{Adj}=CF$		CDO	Emb. Centr	Data T-Number Computation			CCC	Tren
RULES →	Locate Cloud System Center at focal point of cloud curvature		Use Spiral Arc Length DT1.5	DT2.5	DT3.5	DT4.5	(VIS) Use Embedded Distance	(EIR) Use Surrounding Temperature	From Rules	Eye Definition	Use Size Central Dense Overcast	(EIR) Use Surrounding Temperature	CF+BF=DT			Use Rules Central Cold Cover	24-Hr change D-developing W-weakening
DATE/TIME	LAT	LONG							E_{No}	E_{Adj}			CF	BF	DT		
							0.75º		5.0	0.0			5.0	2.0	7.0		

Step 2C - VIS Banding Eyes



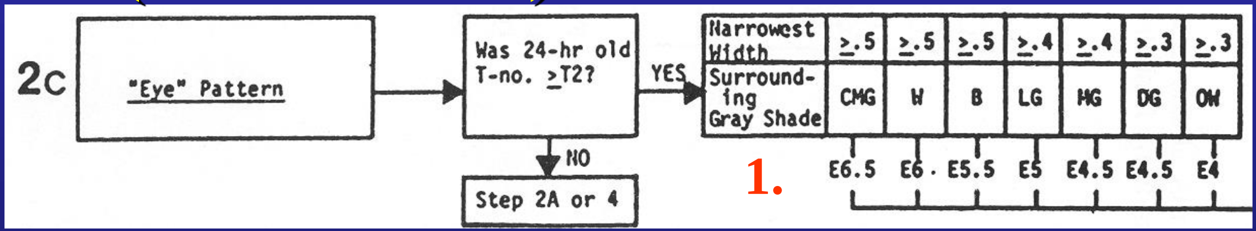
- E-number determined by the <u>average</u> width of the band surrounding the eye
- Also uses eye adjustment rules
- Only used with <u>visible</u> imagery



Can also used a curved band with 1.2-1.3 banding for a DT=4.0+

Step 2C - Infrared Eye Patterns

1. Find the coldest color on the BD enhancement that <u>completely surrounds</u> the eye with a thickness greater than the <u>specified width</u> (closed ring surrounding the eye)
2. Make eye adjustment based on the color on the <u>warmest</u> BD enhancement color in the eye (E-Number + Eye Adjustment = CF Number)
3. Add BF for applicable banding when IR banding rules apply (CF + BF = DT)



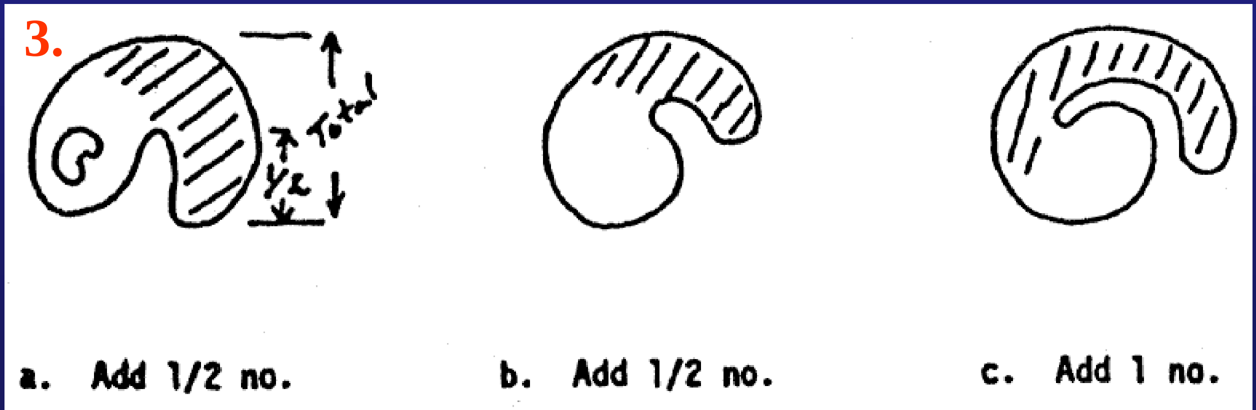
2.

GRAY SHADE CODE (BD CURVE)

WMG (Warm Medium Gray), > +9°C
OW (Off White), +9 to -30°C
DG (Dark Gray), -31 to -41°C
MG (Medium Gray), -42 to -53°C
LG (Light Gray), -54 to -63°C
B (Black) -64 to -69°C
W (White) -70 to -75°C
CMG (Cold Medium Gray), -76 to -80°
CDG (Cold Dark Gray), ≤ -81°C

EYE TEMPERATURE

SURR. RING TEMP.	WMG	OW	DG	MG	LG	B	W
OW	0	-0.5					
DG	0	0	-0.5				
MG	0	0	-0.5	-0.5			
LG	+0.5	0	0	-0.5	-0.5		
B	+1.0	+0.5	0	0	-0.5	-0.5	
W	+1.0	+0.5	+0.5	0	0	-1.0	-1.0
CMG	+1.0	+0.5	+0.5	0	0	-0.5	-1.0



Step 2C - Eye Patterns

Infrared Technique

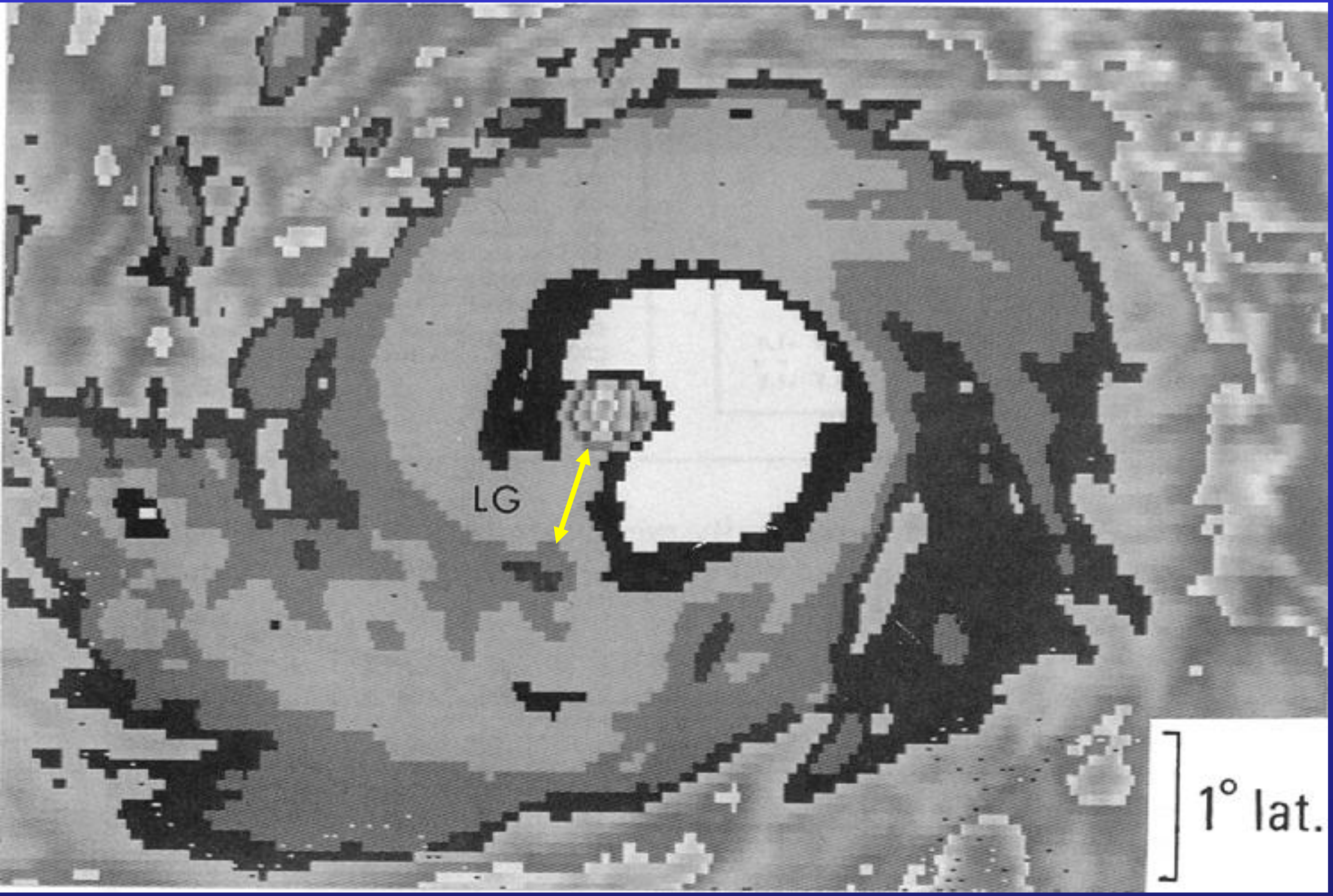
Is the 24 hour old FT > 2.0? If not, go to step 2A or step 4.

Surrounding BD Color	CMG	W	B	LG	MG	DG	OW
Narrowest width (deg)	≥0.5	≥0.5	≥0.5	≥0.4	≥0.4	≥0.3	≥0.3
Eye Number (E#)	6.5	6.0	5.5	5.0	4.5	4.5	4.0

Eye Adjustment:

Surr. BD Color \ Eye Temperature	WMG	OW	DG	MG	LG	B	W
OW	0	-0.5					
DG	0	0	-0.5				
MG	0	0	-0.5	-0.5			
LG	+0.5	0	0	-0.5	-0.5		
B	+1.0	+0.5	0	0	-0.5	-0.5	
W	+1.0	+0.5	+0.5	0	0	-1.0	-1.0
CMG	+1.0	+0.5	+0.5	0	0	-0.5	-1.0

Step 2C - Measuring an Infrared Eye



Light Gray (LG) is the coldest color <u>surrounding</u> the eye that meets the width criteria. The eye temperature is Warm Mediun Gray (WMG). The Eye number is 5.0, while the Eye adjustment is +0.5 - CF=5.5

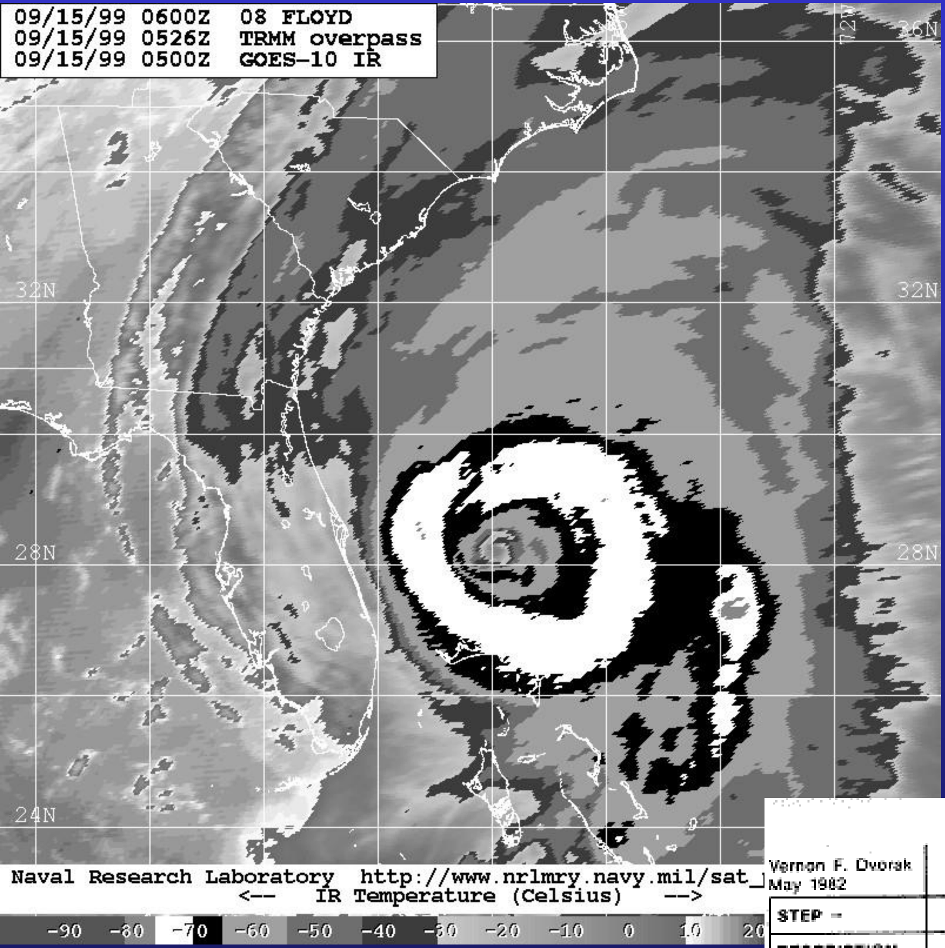
TROPICAL CYCLONE ANALYSIS WORKSHEET

Vernon F. Dvorak
May 1982

T-NUMBER ESTIMATE FROM MEASUREMENTS FOR DATA T-NUMBER (DT) COMPUTATION | T-NUM

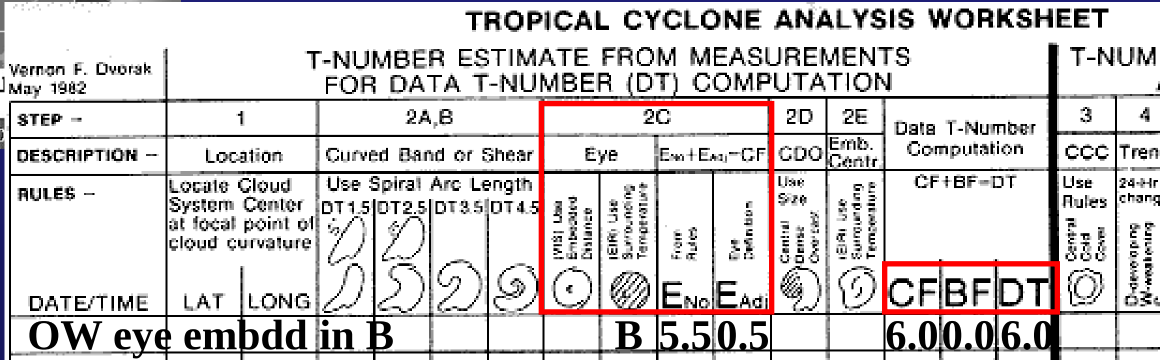
STEP →	1		2A,B				2C				2D	2E	Data T-Number Computation			3	4
DESCRIPTION →	Location		Curved Band or Shear				Eye		$E_{No}+E_{Adj}-CF$		CDO	Emb. Centr				CCC	Tren
RULES →	Locate Cloud System Center at focal point of cloud curvature		Use Spiral Arc Length				(VIS) Use Embedded Distance	(EIR) Use Surrounding Temperature	From Rules	Eye Definition	Use Size Central Dense Overcast	(EIR) Use Surrounding Temperature	CF+BF=DT			Use Rules Central Cold Cover	24-Hr chang D-developing W-weakening
DATE/TIME	LAT	LONG	DT1.5	DT2.5	DT3.5	DT4.5			E_{No}	E_{Adj}			CF	BF	DT		
WMG eye embdd in LG								LG	5.0	0.5			5.5	0.0	5.5		

Step 2C - Size Doesn't Matter for an Infrared Eye



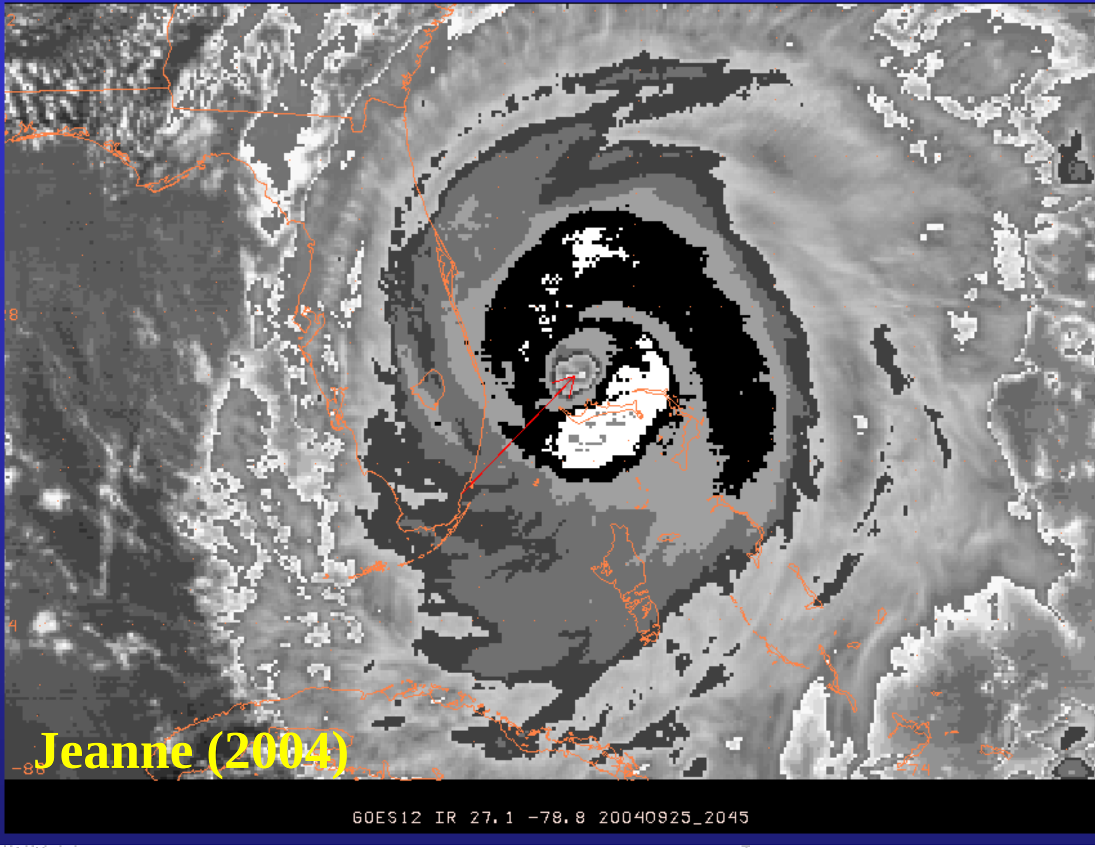
The coldest color completely surrounding the eye is Black (B) even though that color is more than 60 n mi from the eye in some areas. The eye temperature is Off White (OW). The Eye number is 5.5 and the Eye adjustment is 0.5 – CF=6.0

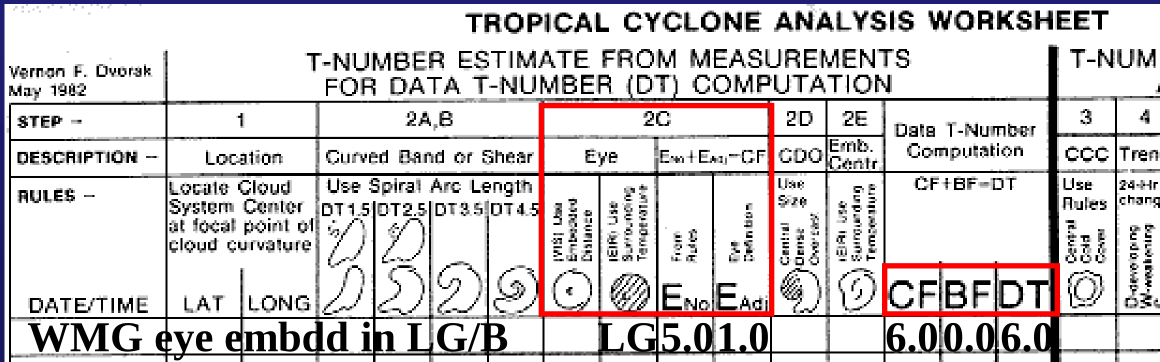
Note: This is not in total agreement with page 36 of the manual!



Step 2C - BD Color Used For Eye Adjustment Can Differ From Color Used For Eye Number

Black (B) completely surrounds the eye. However, the B ring is less than 0.5 degrees thick. So, it cannot be used for the eye number. The eye number uses Light Gray (LG) for a 5.0, while the eye adjustment is determined by a Warm Medium Gray (WMG) embedded in B (+1.0) - CF=6.0





TROPICAL CYCLONE ANALYSIS WORKSHEET

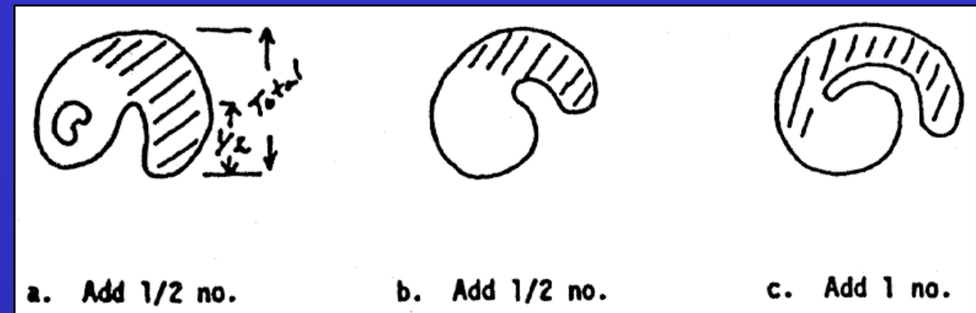
Vernon F. Dvorak
May 1982

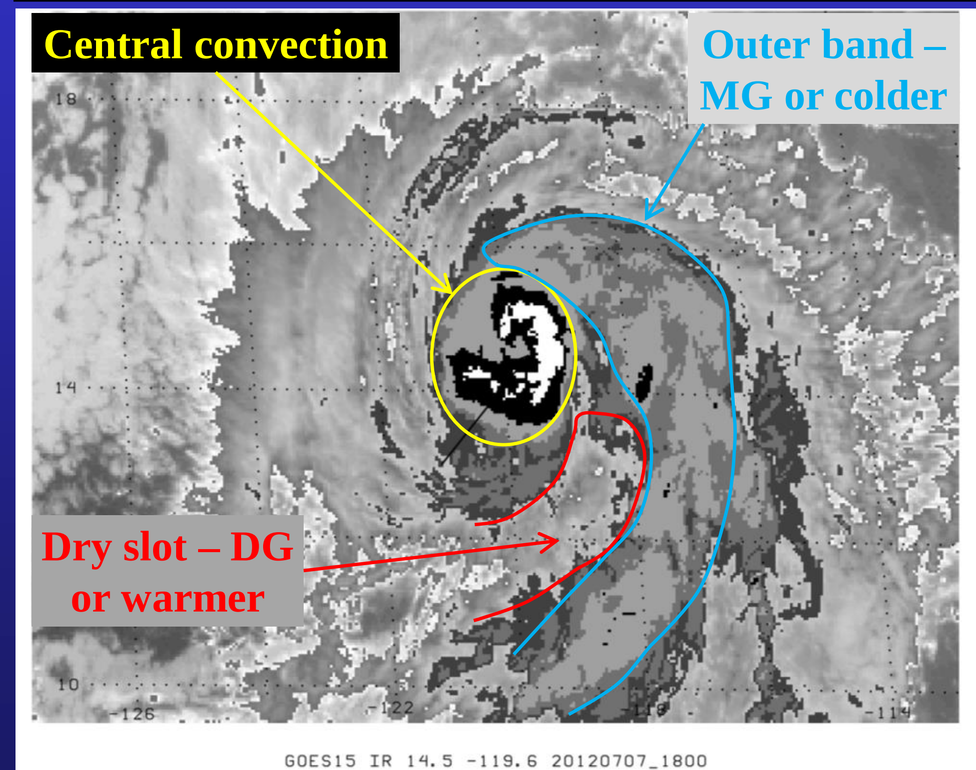
T-NUMBER ESTIMATE FROM MEASUREMENTS FOR DATA T-NUMBER (DT) COMPUTATION

STEP –	1		2A,B	2C		2D	2E	Data T-Number Computation	3	4
DESCRIPTION –	Location		Curved Band or Shear	Eye	$E_{No}+E_{Adj}-CF$	CDO	Emb. Centr		CCC	Tren
RULES –	Locate Cloud System Center at focal point of cloud curvature		Use Spiral Arc Length DT1.5 DT2.5 DT3.5 DT4.5			Use Size		CF+BF=DT	Use Rules	24-Hr chang
DATE/TIME	LAT	LONG			E_{No} E_{Adj}			CF BF DT		
WMG eye embdd in LG/B					LG 5.0 1.0			6.0 0.0 6.0		

Step 2C - Infrared banding

- Differs *significantly* from visible banding
- Used only when the CF/DT without banding is less than MET
- Used only for cloud patterns of CF=4 or more
- Band must be MG or colder while dry slot must be DG or warmer

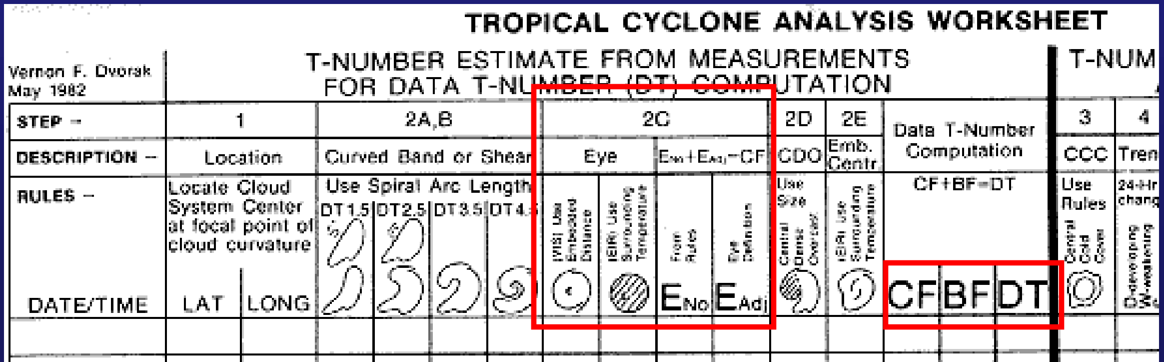




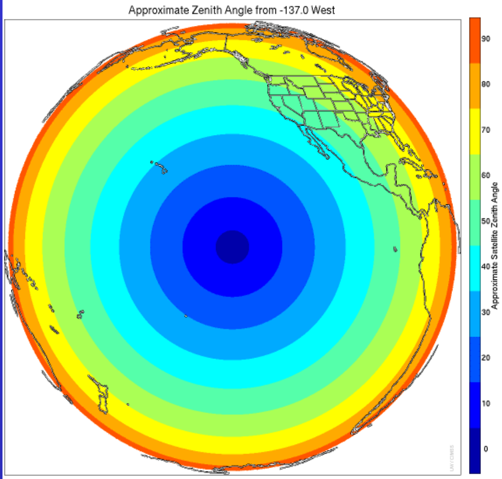
Daniel (2012) – A potentially eligible IR outer band

Notes on Step 2C

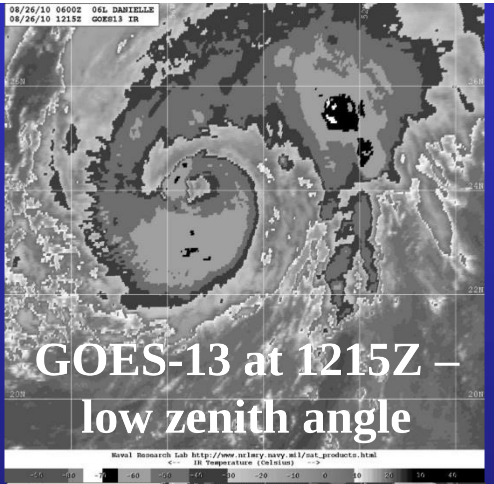
- VIS embedded distances are measured from the center of the eye for small eyes and the edge of the eye for large eyes (30 nm/56 km or more in diameter on VIS)
- IR Eye Pattern is the most objective of all Dvorak measurements, but it cannot produce a DT=8.0 without adding banding
- Beware large satellite zenith/viewing angles and not being able to see to the bottom of the eye
- Beware sucker holes!

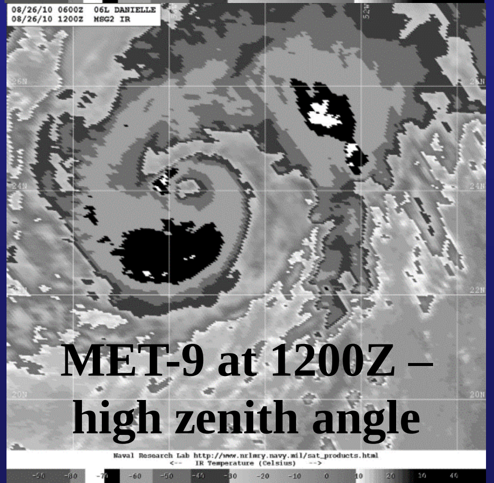


Problem: Satellite Zenith/Viewing Angle Cloud Top Temperatures



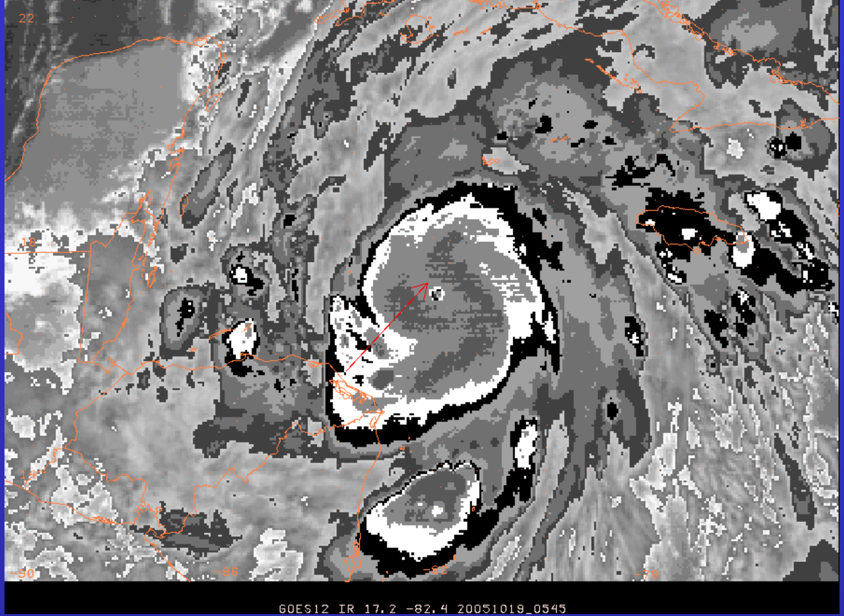
- The satellite zenith/viewing angle of a TC can impact the Dvorak analysis.
- TCs close to the satellite subpoint have low zenith/ viewing angles and thus are less of a problem.
- TCs far from the satellite (e. g. near the edge of a full disk scan) are a problem for IR analysis, as IR cloud top temperatures appear too cold.
- Use the satellite closest to the TC for a Dvorak analysis if at all possible, and use IR DT numbers made at high zenith/viewing angles with caution.
- METEOSAT is over the Equator at 0W, GOES-East at 75W, and GOES-West at 137W.

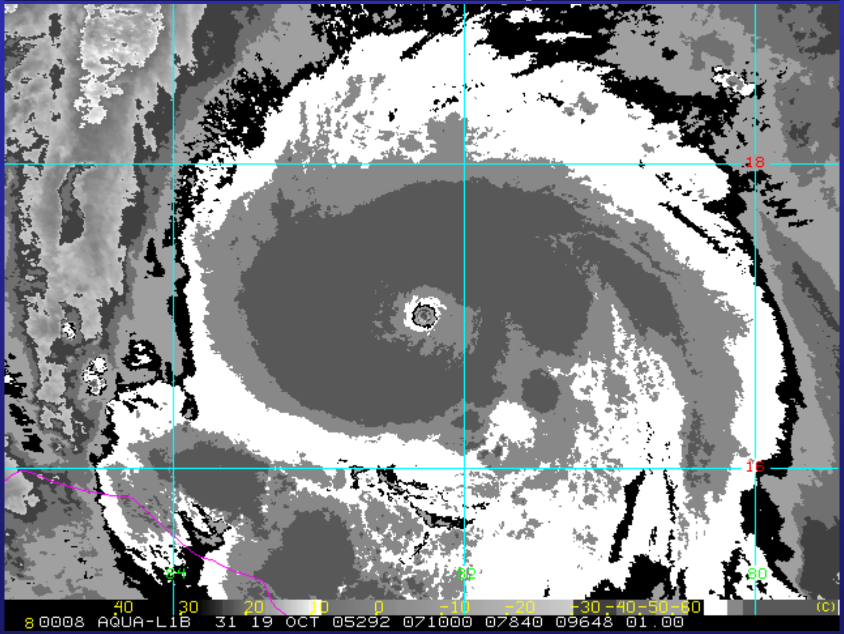




Problem: Can't See the Bottom of the Eye

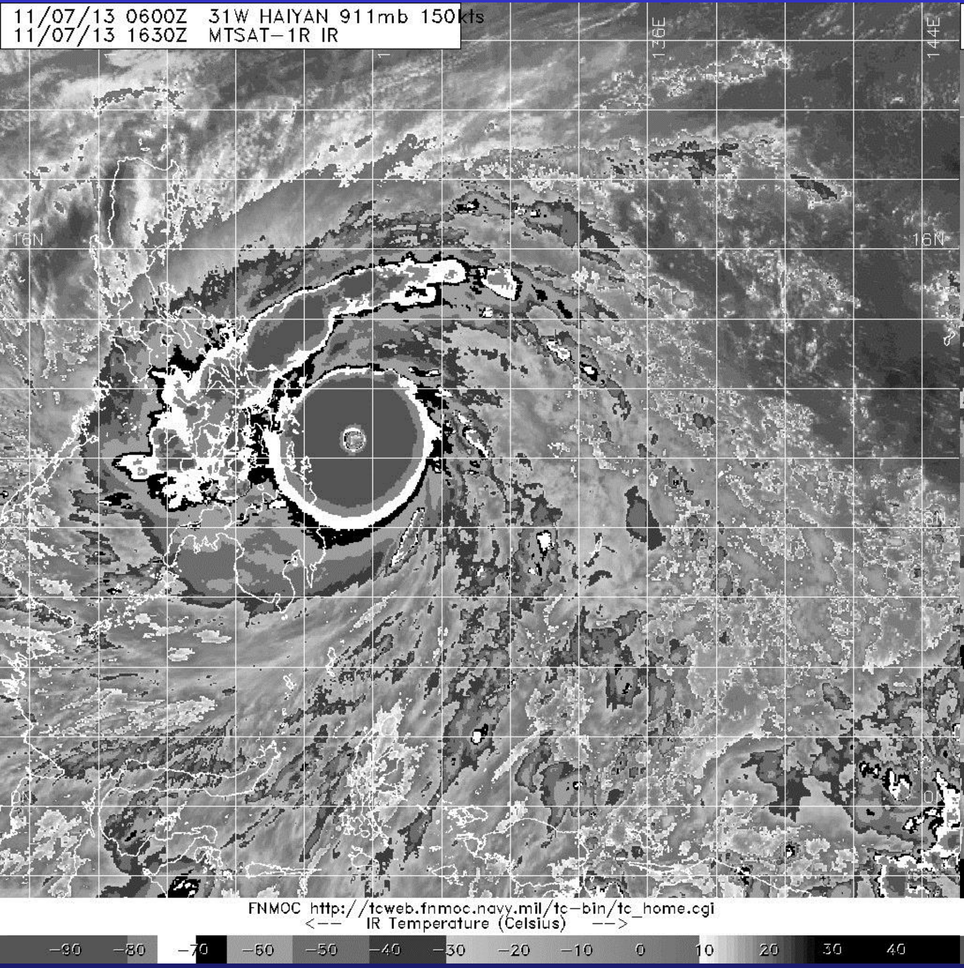
- High zenith/viewing angles can also make it difficult to see to the bottom of the eye.
- For small eyes (generally less than 10 n mi wide), the satellite may not be able to measure the true warmest temperature at the bottom of the eye. This can cause underestimated intensities in both subjective and objective Dvorak techniques.

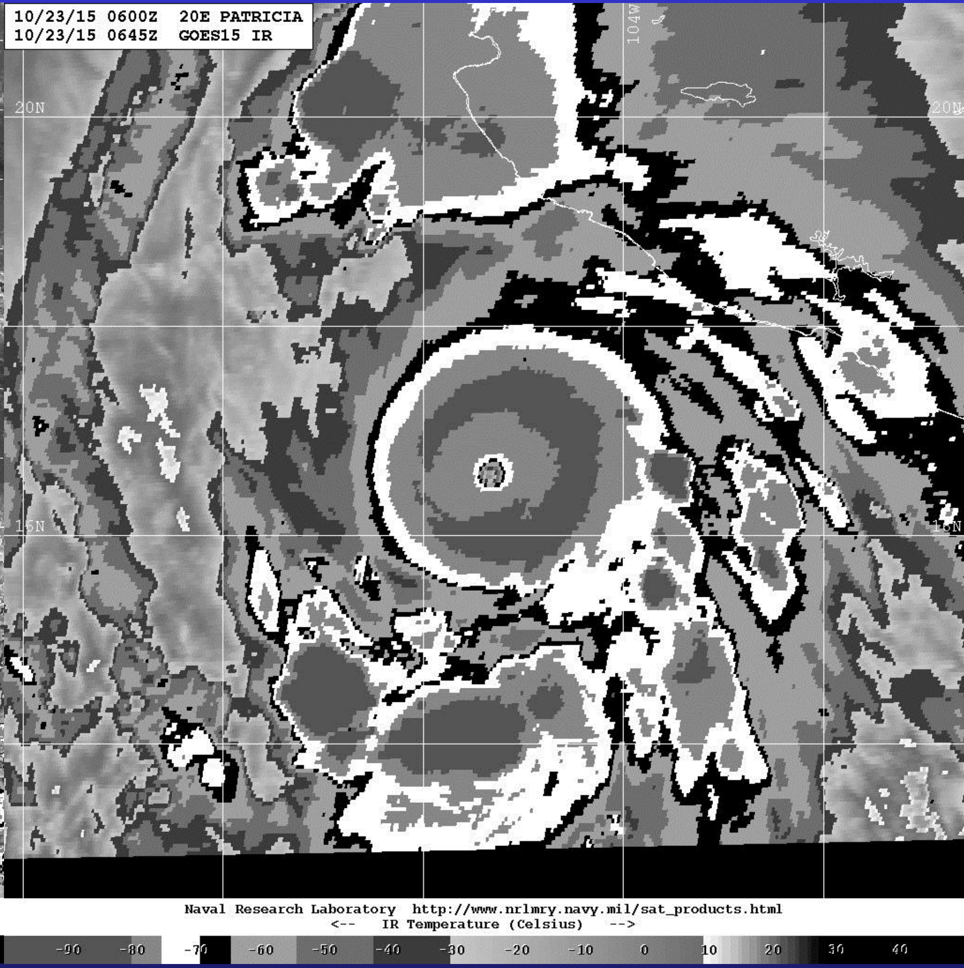




Wilma 2005 - Eye diameter 4 n mi
GOES Eye temperature ~ 0C
NOAA/Aqua Eye temperature ~ +20C

How strong are these?





Supertyphoon Haiyan (T8.0)

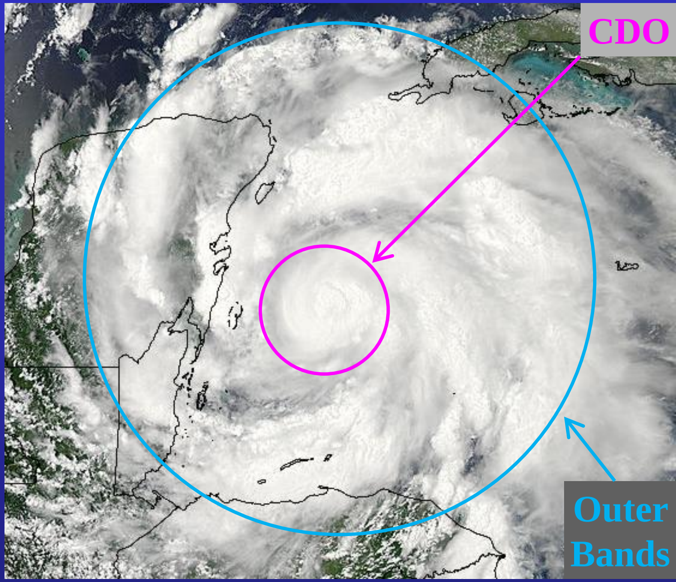
Western North Pacific, 1630Z 7 November 2013

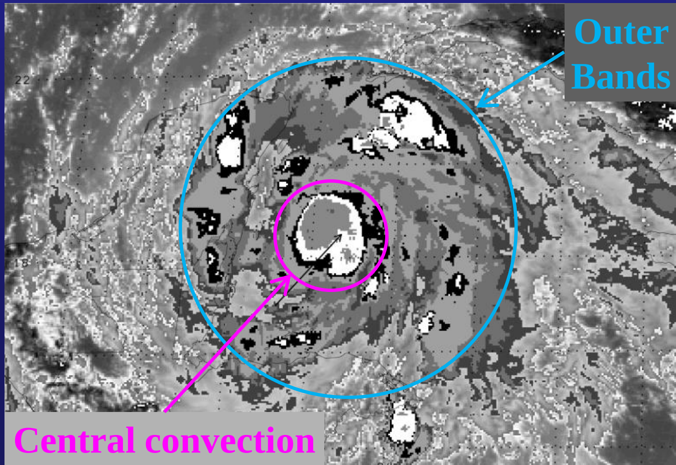
Hurricane Patricia (180 kt)

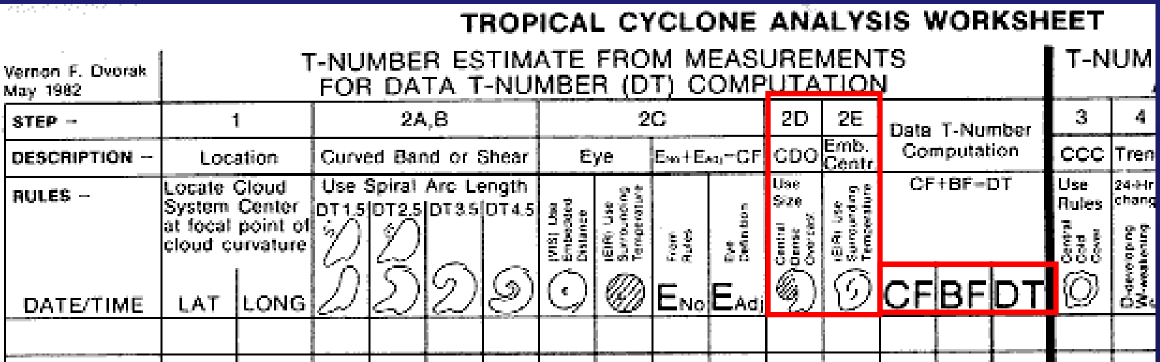
Eastern North Pacific, 0645Z 23 October 2015

Steps 2D and 2E - Central Dense Overcast (CDO) and Embedded Center Patterns

- Patterns are complimentary - CDO uses VIS imagery and Embedded Center uses IR
- Both patterns directly produce CF numbers
- CDO pattern measures the size of the CDO
- Embedded Center pattern measures how far the CSC is embedded into specified colors on the BD curve
- All banding rules from Eye patterns apply to CDO and Embedded Center patterns






TROPICAL CYCLONE ANALYSIS WORKSHEET

Vernon F. Dvorak
May 1982

T-NUMBER ESTIMATE FROM MEASUREMENTS FOR DATA T-NUMBER (DT) COMPUTATION

T-NUM

STEP →	1		2A,B				2C				2D	2E	Data T-Number Computation			3	4
DESCRIPTION →	Location		Curved Band or Shear				Eye		$E_{No}+E_{Adj}=CF$		CDO	Emb. Centr				CCC	Tren
RULES →	Locate Cloud System Center at focal point of cloud curvature		Use Spiral Arc Length DT1.5	DT2.5	DT3.5	DT4.5	(VIS) Use Embedded Distance	(EIR) Use Surrounding Temperature	From Rules	Eye Definition	Use Size Central Dense Overcast	(EIR) Use Surrounding Temperature	CF+BF=DT			Use Rules Central Cold Cover	24-Hr chang Developing Weakening
DATE/TIME	LAT	LONG							E_{No}	E_{Adj}			CF	BF	DT		

Steps 2D and 2E - CDO and Embedded Center Patterns

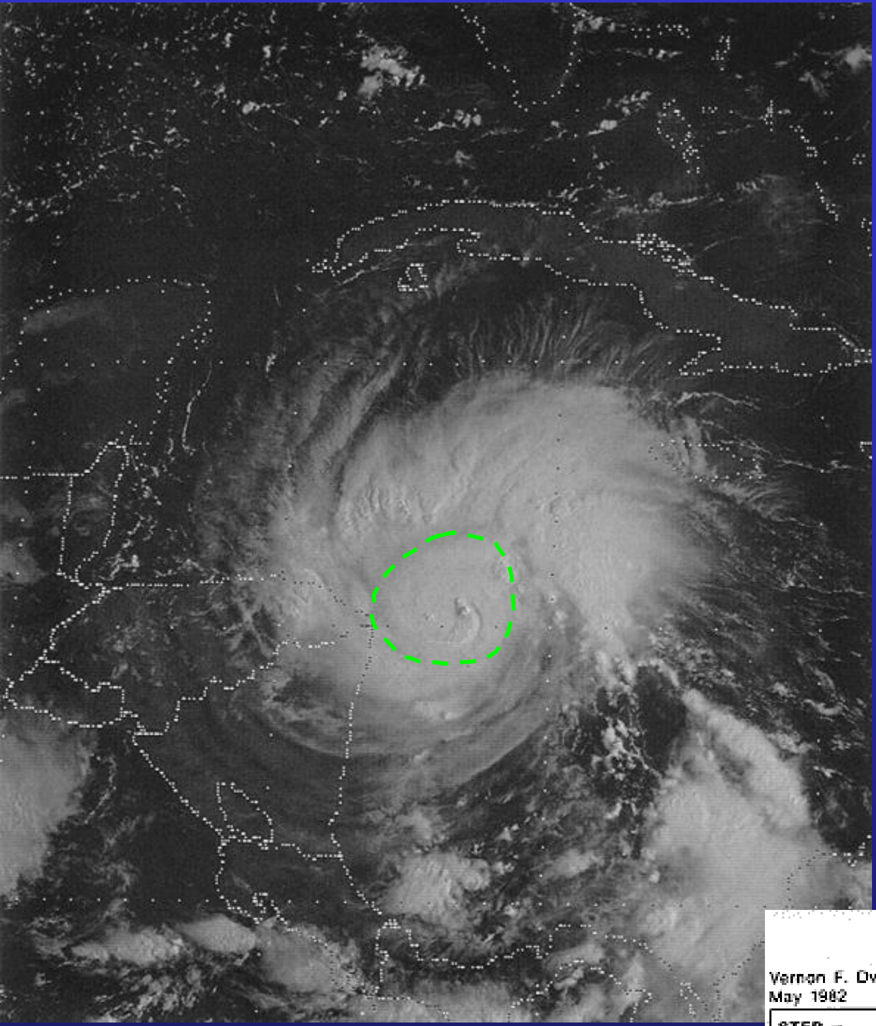
Step 2D - Is the CDO ≥ 0.75 deg wide? If not, go to step 2A or step 4.

CDO edge is:	Well-defined				Irregular	
Diameter (deg)	≥2.25	1.75	1.25	0.75	>1.5	1.0-1.5
Central Feature Number (CF)	5.0	4.0	3.0	2.0	3.0	2.0

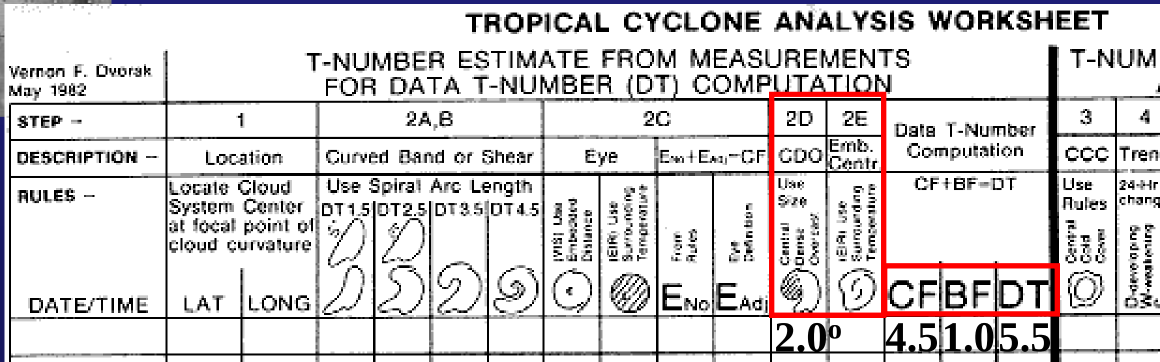
Step 2E - Is the 12 hour old FT ≥ 3.5? If not, go to step 2A or step 4.

Surrounding BD Color	W or colder	B	LG	MG	DG	OW
Embedded distance (deg)	≥0.6	≥0.6	≥0.5	≥0.5	≥0.4	≥0.4
Central Feature Number (CF)	5.0	5.0	4.5	4.0	4.0	3.5

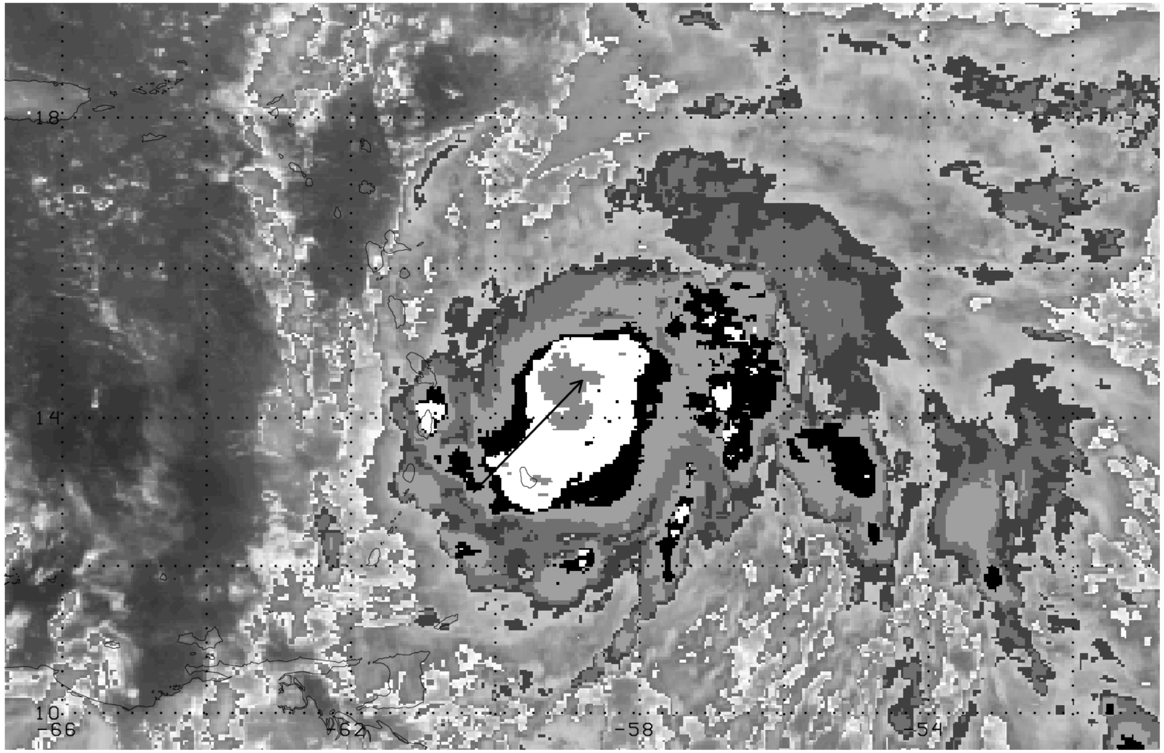
Step 2D - Measuring a CDO



The CDO is about 2 deg wide – CF=4.5 + 1.0 for banding around the CDO ➔ DT=5.5



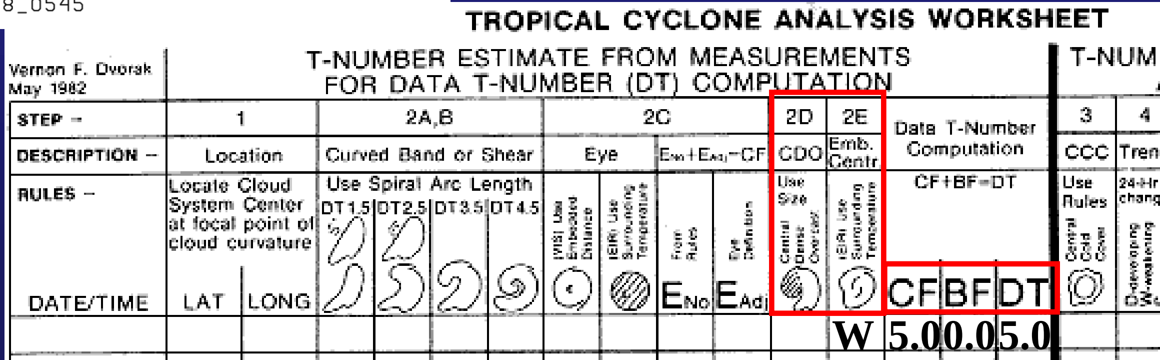
Step 2E - Measuring an Embedded Center



GOES-E IR 14.5 -58.8 20170918_0545

Maria (2017)

CSC embedded in W - DT=5.0



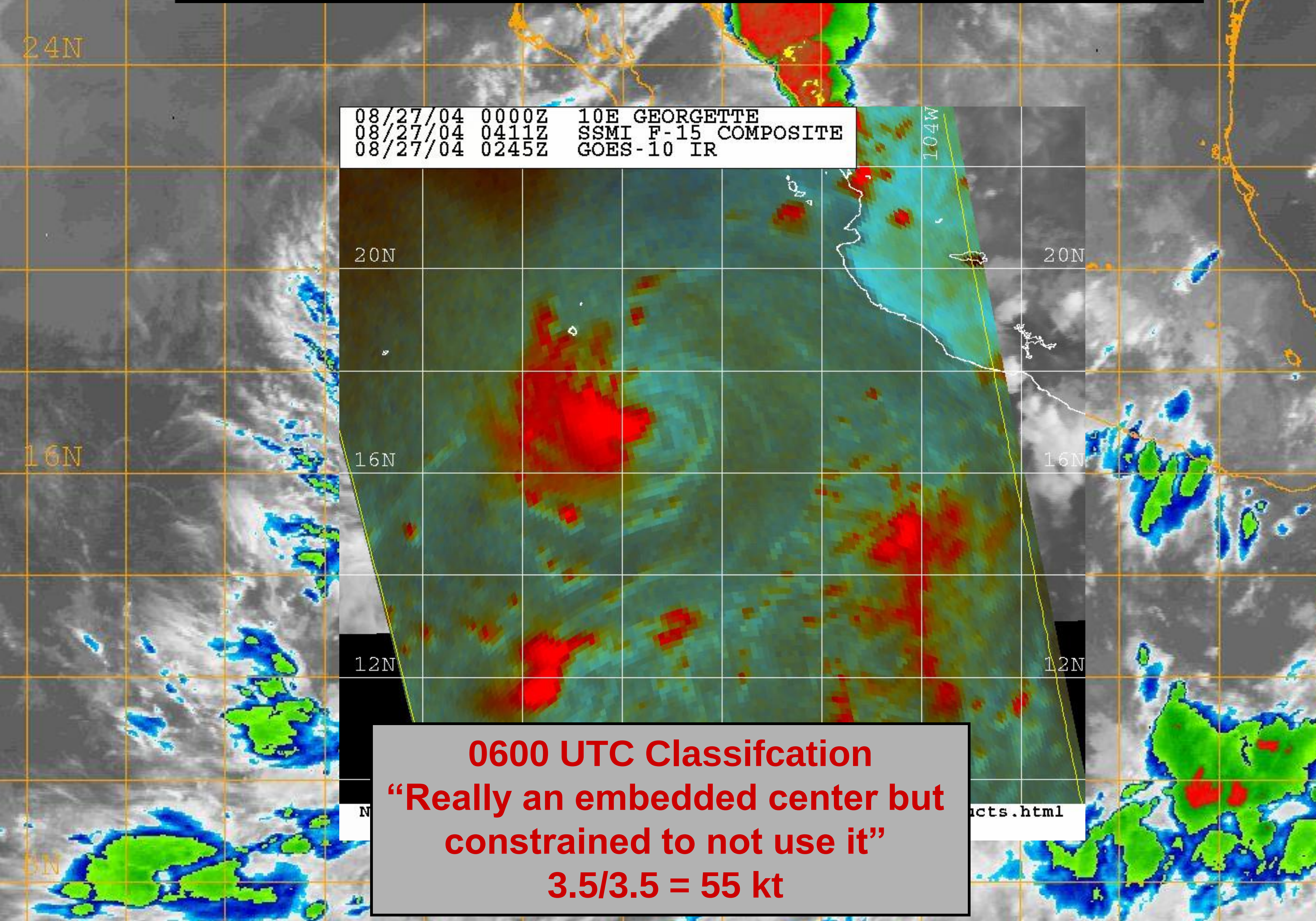
TROPICAL CYCLONE ANALYSIS WORKSHEET

Vernon F. Dvorak
May 1982

T-NUMBER ESTIMATE FROM MEASUREMENTS FOR DATA T-NUMBER (DT) COMPUTATION

STEP →	1		2A,B				2C				2D	2E	Data T-Number Computation			3	4
DESCRIPTION →	Location		Curved Band or Shear				Eye		$E_{No}+E_{Adj}-CF$		CDO	Emb. Centr				CCC	Tren
RULES →	Locate Cloud System Center at focal point of cloud curvature		Use Spiral Arc Length								Use Size		CF+BF=DT			Use Rules	24-Hr chang
			DT1.5	DT2.5	DT3.5	DT4.5											
DATE/TIME	LAT	LONG							E_{No}	E_{Adj}			CF	BF	DT		
												W	5.0	0.0	5.0		
T-NUM

0430 UTC 27 August 2004 GOES-10 IR TS Georgette



0600 UTC Classifcation
“Really an embedded center but constrained to not use it”
3.5/3.5 = 55 kt

Notes on Steps 2D and 2E

- Edge of CDO is often subjective
- You can interpolate between the CDO CF numbers when appropriate
- For an elliptical CDO, the CDO size is the average of the sizes of the long and short axes of the ellipse.
- Embedded Center pattern can only be used when the 12 hr old FT is 3.5 or greater. Otherwise it can produce unrealistically high intensity estimates
- Embedded Center pattern is the most uncertain of all Dvorak measurements - where the classifier puts the CSC makes a big difference in the intensity estimate
- *When available and appropriate, use of VIS CDO is preferable to use of IR embedded center*

Pattern Recognition Exercise!

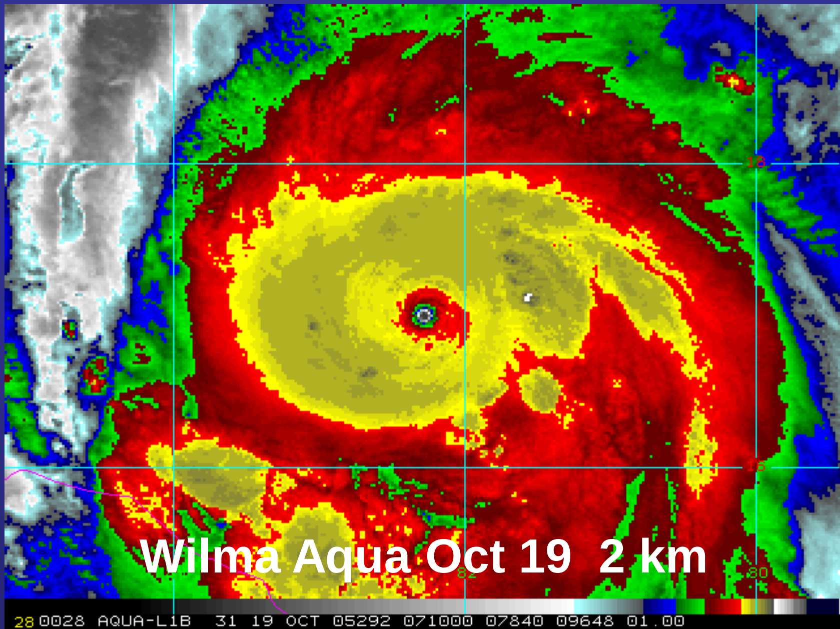
To summarize the cloud pattern types...

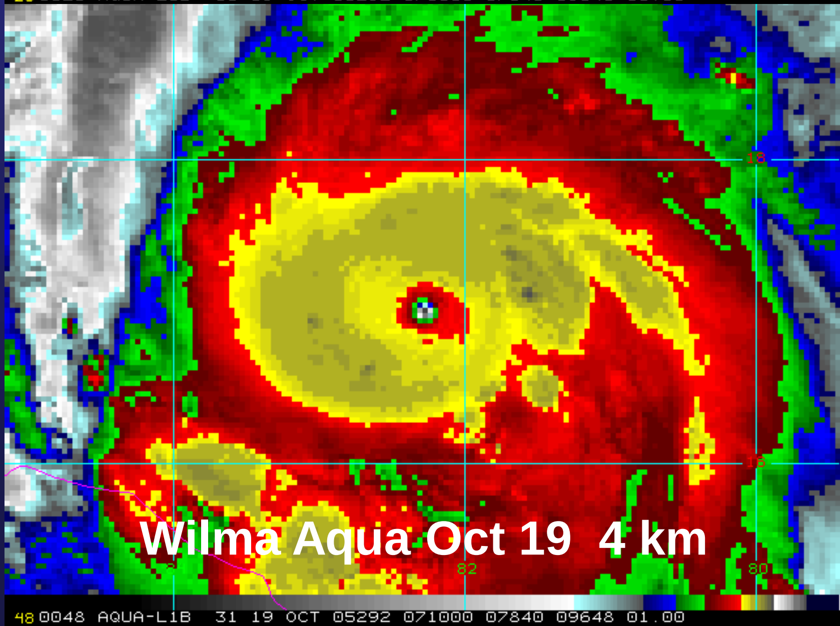
SUMMARY OF SATELLITE ESTIMATES OF T.C. INTENSITY

PATTERN	IMAGE	INTENSITY GIVEN BY:
CURVED BAND	VIS, EIR	SPIRAL DISTANCE OF BAND SURROUNDING CENTER
SHEAR	VIS, EIR	DISTANCE OF CENTER FROM EDGE OF DEEP CB CLOUDS AND CENTER DEFINITION
CDO (Central Dense Overcast)	VIS	SIZE OF CDO AND BANDING
CDO (Embedded Center)	EIR	SURROUNDING TEMP.
EYE	VIS	DISTANCE OF EYE FROM CDO EDGE AND BANDING
EYE	EIR	SURROUNDING TEMP. AND EYE TEMP.

Data-T Numbers in the ABI/AHI Era

- **Most measurements of the Dvorak cloud patterns are relatively insensitive to the higher resolution and slight spectral changes of the imagers on the GOES-R/ Himawari satellites.**
- **Infrared eye patterns could see Data-T changes caused by 1) seeing warmer eye temperatures, and 2) seeing less uniform cloud tops surrounding the eye.**
- **In most cases, the Data-T numbers change little, although some cases could change 0.5 T-numbers.**
- ***There is a need to develop a Dvorak-like algorithm for the more advanced ABI/AHI data!***

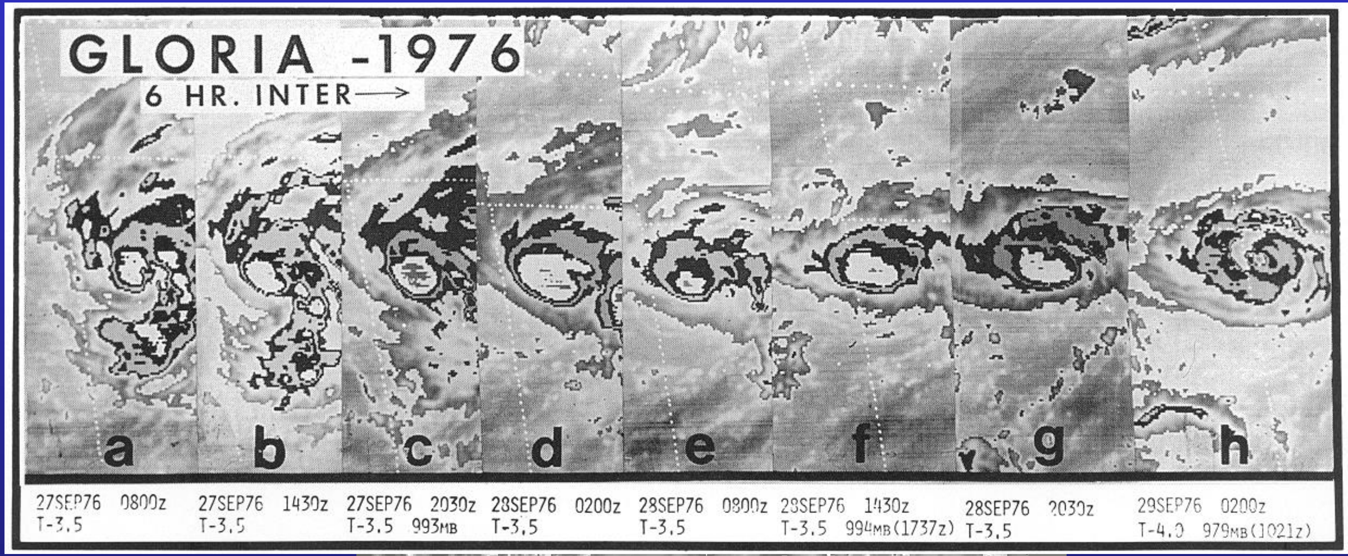




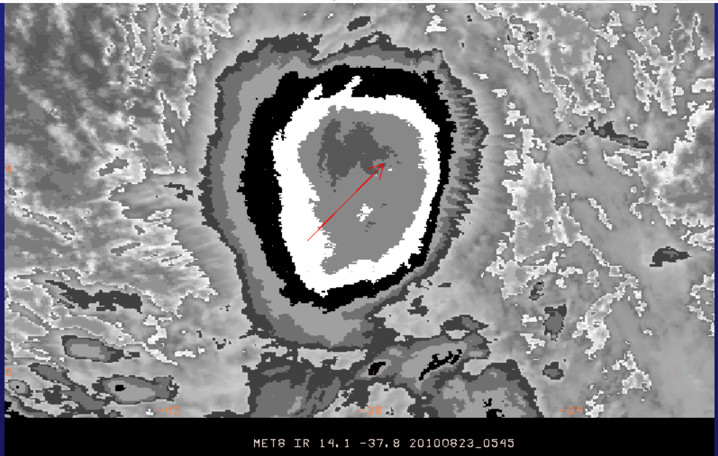
Step 3 - Central Cold Cover Pattern

Central Cold (Dense) Cover Pattern

Rules: When past T-no. ≤T3, maintain model trend for 12 hours; then hold same. When past T-no ≥T3.5 hold T-no same. Use as final T-no; then go to Step 9



- **Also known as "bursting" pattern**
- **Can resemble shear or CDO/embedded center patterns**



Danielle (2010) – a likely CCC pattern

Steps 4 and 5 - Determine 24 hr Trend and Model Expected T-Number (MET)

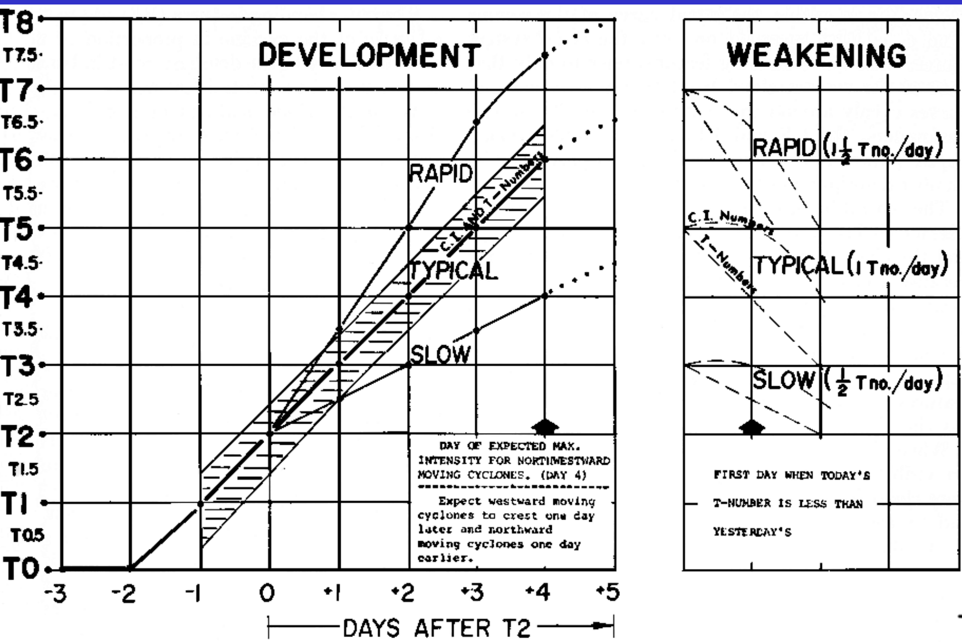
- The Dvorak Technique employs a conceptual model of TC growth and decay rates over 24 hr periods
- 24 hr comparisons avoid the diurnal convective variations observed in TC cloud patterns
- For trend purposes, always use 24 hr comparisons even though intensity estimate are made more frequently (e. g. every 6 hr)
- 24 hr trends are reported as Developing, Weakening, or Steady

T-NUMBER ESTIMATE FROM MODEL AND DT CONSTRAINTS								
3	4	5	6	7,8	9	10		
CCC	Trend	MET	PAT	FT	CI	24-Hr. Fcst.		
Use Rules Central Cold Cover	24-Hr change D-developing W-weakening S-same	Model Expected T-Number	Pattern T-Number	Use Rules Final T-Number	Current Intensity Number	Adj. Model Fcst. if nec. List Rule Used	Forecast Intensity Number	INITIALS

Step 4 - Determine 24 hr Trend

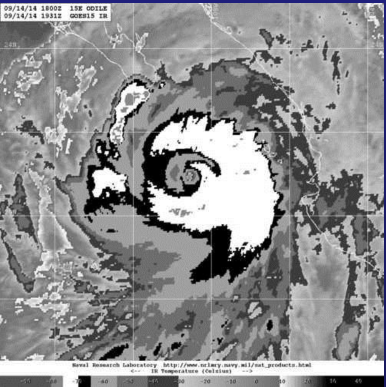
Developing	Weakening	Steady
Increased convection near CSC (larger or colder CDO)	Decreased convection near CSC (smaller or warmer CDO)	No noticeable 24 hr change
Increased curved banding (primary band or bands around the CDO)	Decreased curved banding	Both developing and weakening signs present (mixed signals)
Eye forms, or becomes warmer, or more distinct	Eye disappears, or becomes cooler, or less distinct	CCC in a cyclone of T3.5 or greater or CCC for 12 hr or more in a weaker cyclone
Exposed center closer to overcast	Exposed center further from overcast or covered center becomes exposed	
Increased curvature of low clouds near CSC	Decreased curvature of low clouds near CSC	

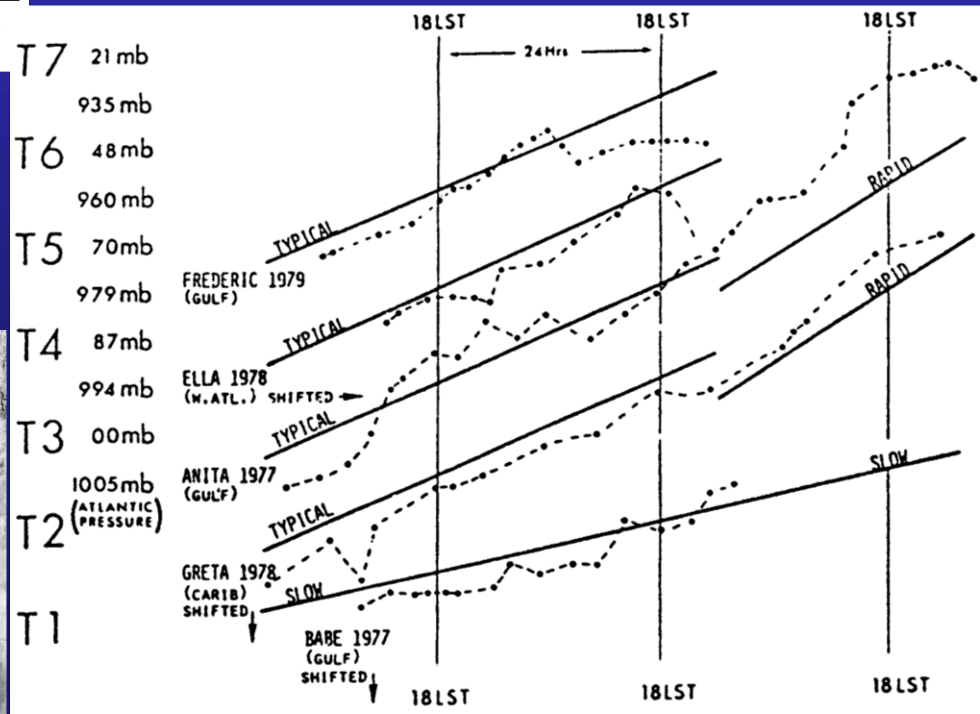
Dvorak Model Development Curves



In the Dvorak conceptual model, 'normal' strengthening or weakening is 1 T-number/day. Rapid changes are 1.5 T-numbers per day, while slow changes are 0.5 T-numbers/day.

Note: Eyewall replacement cycles are <u>not</u> part of the Dvorak conceptual model.

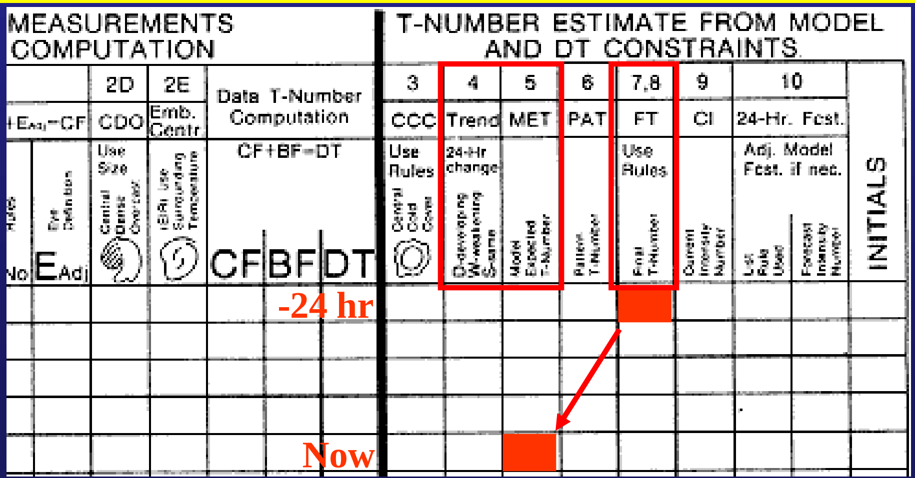




Step 5 - Model Expected T-Number

- The MET is a first guess estimate of the intensity based on the 24 hr old Final T-Number and the current determined 24 hr trend
- For a Steady trend, the MET = the 24 hr old FT
- The MET for first classification is 1.0

	Developing	Weakening
Rapid	MET=24 hr old FT+1.5	MET=24 hr old FT-1.5
Normal	MET=24 hr old FT+1.0	MET=24 hr old FT-1.0
Slow	MET=24 hr old FT+0.5	MET=24 hr old FT-0.5



Step 5 - Model Expected T-Number Rapid or Slow Changes

- **Two consecutive previous Dvorak measurements of rapid or slow development/weakening are needed to establish rapid or slow 24 hr changes**
  - *Look at the previous two FT values and compare them to the respective FT values from 24 hours prior*
  - *If the difference between both of these values is more (less) than 1.0, then you have rapid (slow) development/weakening (add the +/- to the D or W)*
  - *This does not count the measurement your currently making*
- **Or, one previous Dvorak measurement and signs of strong intensification or weakening (Step 10)**

Step 5 - Model Expected T-Number Rapid or Slow Changes

Example: For the upcoming fix for 00Z/14 Oct 2014, note there are two consecutive 24 hour changes in the column labeled "FT 24h Change". If the 24 hour trend for the 00Z /14 Oct fix is weakening, the prior trends justify a W+, since there are two consecutive 24 hr changes for FT that are more than 1.0.

Dvorak Fix History

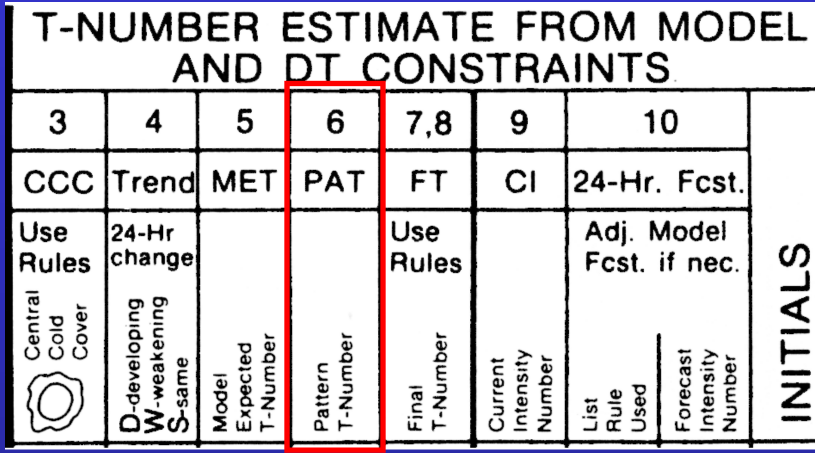
Name	Satellite Image Info		Cloud System Center Location		Classification Type	Tropical Pattern	FT	CI	FT -24h	FT 24h Change	FT 12h Change	Fc
	Date	Time	Lat	Lon								
AL072014 Print | Edit	13 Oct	17:45	33.7	-51.0	Weak	---	1.5	2.5	4.5	-3.0	-2.0	S
AL072014 Print | Edit	13 Oct	11:45	34.2	-53.6	Trop	shr	2.5	3.5	4.0	-1.5	-2.0	S
AL072014 Print | Edit	13 Oct	5:45	34.4	-57.0	Trop	shr	3.5	4.5	3.5	0.0	-1.0	C
AL072014 Print | Edit	12 Oct	23:45	35.7	-59.0	Trop	embctr	4.5	4.5	3.5	1.0	0.5	M
AL072014 Print | Edit	12 Oct	17:45	34.3	-62.2	Trop	embctr	4.5	4.5	3.0	1.5	1.0	S
AL072014 Print | Edit	12 Oct	11:45	33.1	-63.8	Trop	embctr	4.0	4.0	3.0	1.0	0.5	S
AL072014 Print | Edit	12 Oct	5:45	31.6	-64.7	Trop	shr	3.5	3.5	3.0	0.5	0.5	C

Notes on steps 4 and 5

- The trend for step 4 is determined by examining satellite images 24 hours apart.
- The trend for the initial classification is always a normal D.
- You need at least 24 hours of Dvorak classifications to change the development trend. The first 18 hours after the initial T1 are always a normal D.
- Changes in the development rate for step 5 from D to D- or D+ (or W to W- or W+) need to use the technique rules. Just because you think you are on a different development rate does not allow you to change it arbitrarily!

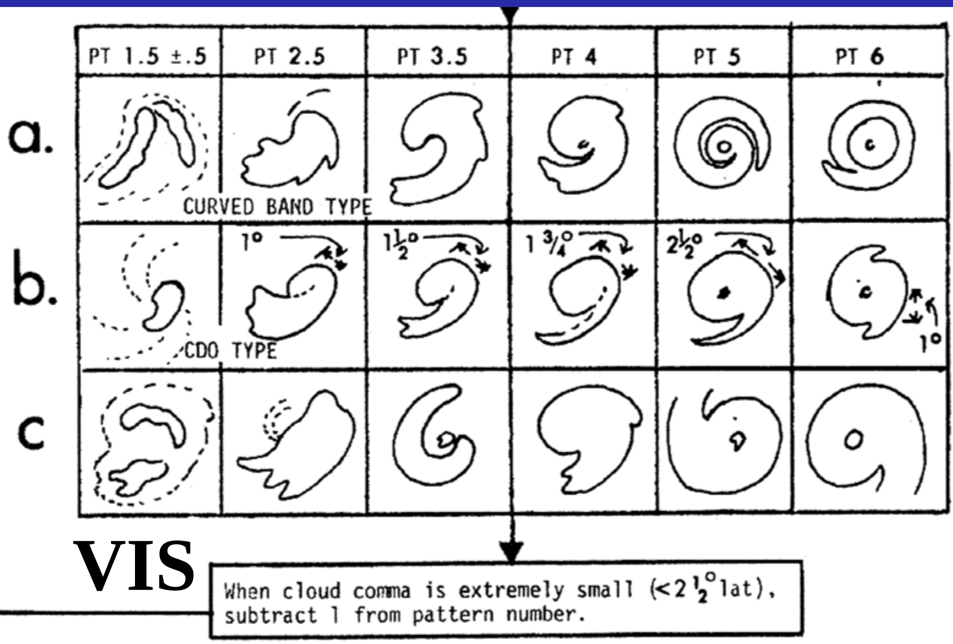
Step 6 - Pattern T-Number (PT or PAT)

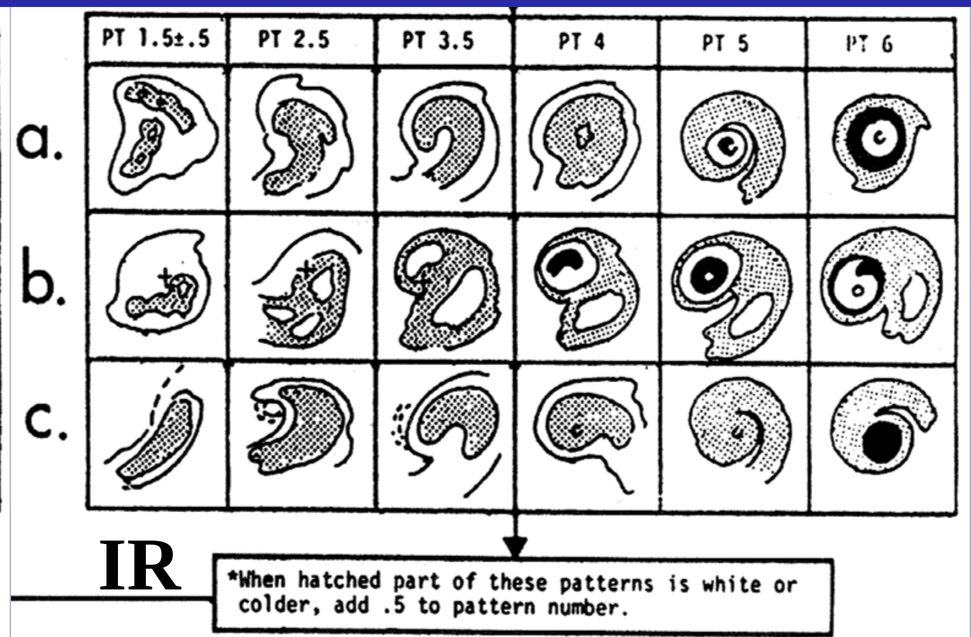
- Choose the Pattern T-number by comparing the cyclone cloud pattern to the diagrams on the flow charts
- PATs above T6 require extrapolation



T-NUMBER ESTIMATE FROM MODEL AND DT CONSTRAINTS

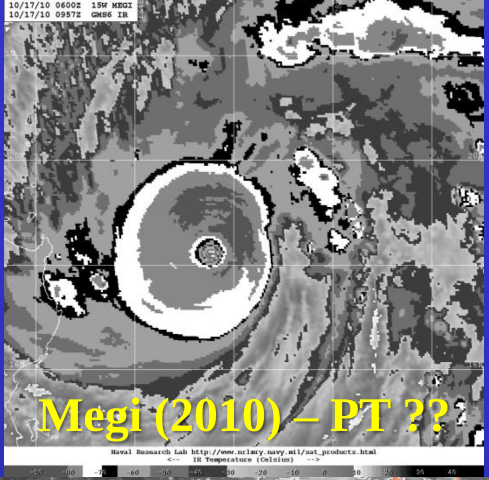
3	4	5	6	7,8	9	10	
CCC	Trend	MET	PAT	FT	CI	24-Hr. Fcst.	
Use Rules Central Cold Cover	24-Hr change D-developing W-weakening S-same	Model Expected T-Number	Pattern T-Number	Use Rules Final T-Number	Current Intensity Number	Adj. Model Fcst. if nec. List Rule Used Forecast Intensity Number	INITIALS

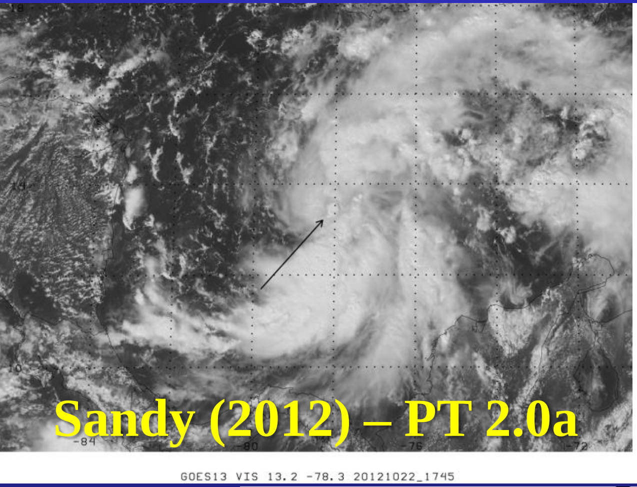


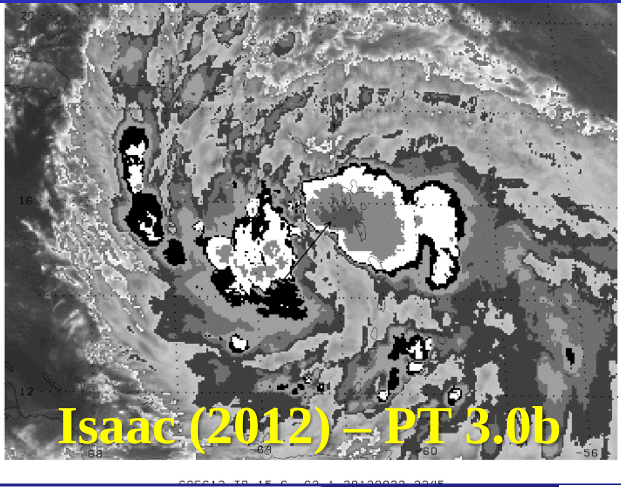


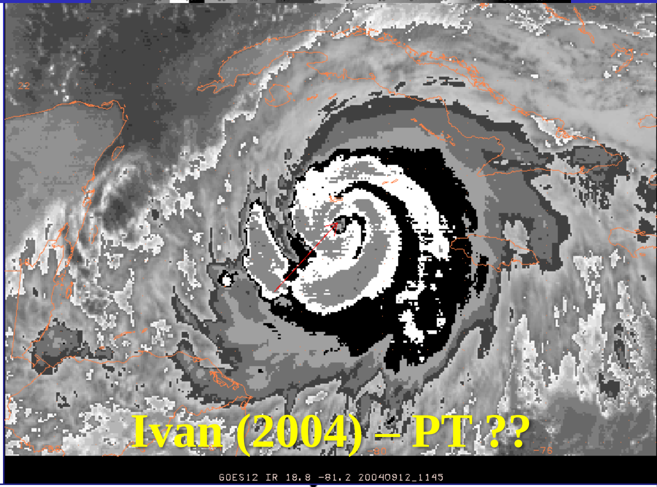
If the PT is 1 or more T-numbers from the MET, check your work!

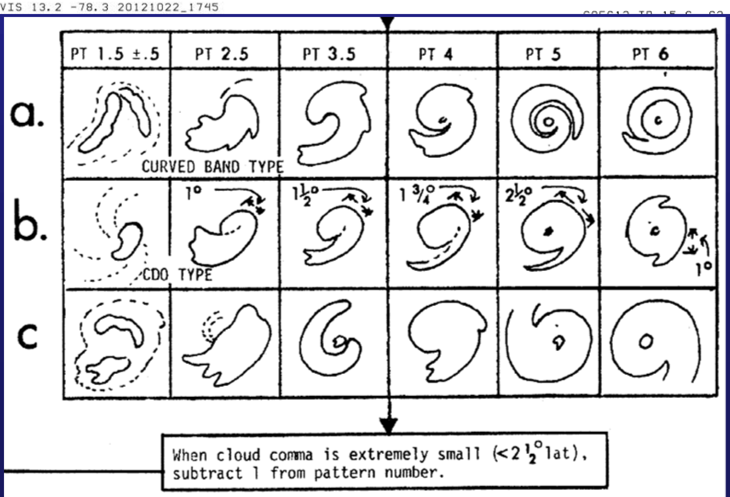
Step 6 - Pattern T-Number (PT or PAT)

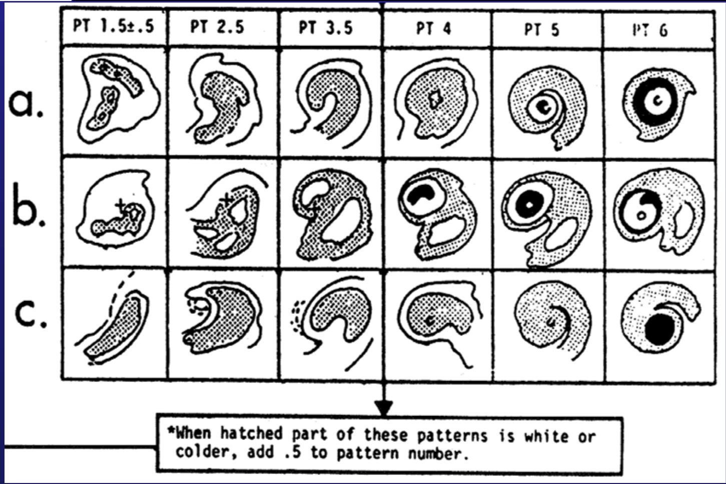












Pattern and Trend Exercise!

Step 7 - Final T-Number (FT)

- **Choose the FT from the DT, PT and MET:**
  - Use DT from Step 2 when cloud features are clear-cut
  - Use PT from Step 6 when DT is not clear <u>and</u> when PT is different from MET
  - For all other cases, use the MET from step 5
- **Beware constraints! (Step 8)**

T-NUMBER ESTIMATE FROM MODEL AND DT CONSTRAINTS

3	4	5	6	7,8	9	10		INITIALS
CCC	Trend	MET	PAT	FT	CI	24-Hr. Fcst.		
Use Rules Central Cold Cover	24-Hr change D-developing W-weakening S-same	Model Expected T-Number	Pattern T-Number	Use Rules Final T-Number	Current Intensity Number	Adj. Model Fcst. if nec. List Rule Used	Forecast Intensity Number	

What comprises a clear-cut DT?

- What comprises clear cut:
  - An unambiguous cloud pattern measurement. For example, an infrared eye measurement is often considered clear cut.
  - Measurements using multiple cloud pattern types that give the same DT

- What does not:
  - Ambiguous or hard to measure/interpret cloud pattern measurements. For example, shear pattern measurements are often not clear cut.
  - Measurements using multiple cloud pattern types that give different DTs

Step 8 - FT Constraints

1. Initial classification must be T1 or T1.5
2. During first 24 hours of development, FT cannot be lowered at night
3. 24 hr after initial T1, FT must be ≤ 2.5
4. Modified FT limits (next slide)
5. FT must = MET ± 1

T-NUMBER ESTIMATE FROM MODEL AND DT CONSTRAINTS

3	4	5	6	7,8	9	10		
CCC	Trend	MET	PAT	FT	CI	24-Hr. Fcst.		
Use Rules Central Cold Cover	24-Hr change D-developing W-weakening S-same	Model Expected T-Number	Pattern T-Number	Use Rules Final T-Number	Current Intensity Number	Adj. Model Fcst. if nec. List Rule Used	Forecast Intensity Number	INITIALS

Note: The CI <u>never</u> constrains the FT!

Step 8 - FT Number Change Limits

For early development: 0.5 T-numbers over 6 hr

Original FT Constraints for storms with T≥4.0 (Dvorak):	Modified FT Constraints now used for developing storms above T1.5 (24 hr or more after the initial T1) (Pike NHC study):
1.0 T-numbers over 6 hr	
1.5 T-numbers over 12 hr	
2.0 T-numbers over 18 hr (2.5)	
2.5 T-numbers over 24 hr (3.0)	

These are the maximum changes in FT number allowed over the given time periods.

Step 9 - Current Intensity Number (CI)

- During the initial development and some stages of re-development, CI=FT
- For weakening or re-developing systems, hold the CI to the highest FT during the preceding 12 hr, but never more than 1.0 above the current FT
- CI is never < FT!

T-NUMBER ESTIMATE FROM MODEL AND DT CONSTRAINTS							
3	4	5	6	7,8	9	10	
CCC	Trend	MET	PAT	FT	CI	24-Hr. Fcst.	
Use Rules Central Cold Cover	24-Hr change D-developing W-weakening S-same	Model Expected T-Number	Pattern T-Number	Use Rules Final T-Number	Current Intensity Number	Adj. Model Fcst. if nec. List Rule Used / Forecast Intensity Number	INITIALS

Step 9 - CI Examples
(6 hr intervals)

FT/CI	FT/CI	FT/CI	FT/CI
1.5/1.5	6.0/6.0	6.0/6.0	5.5/5.5
2.0/2.0	5.5/6.0	5.0/6.0	5.0/5.5
2.5/2.5	4.5/5.5	4.5/5.5	4.5/5.5
3.0/3.0	4.0/5.0	4.5/5.0	3.5/4.5
3.5/3.5	3.5/4.5	4.5/4.5	4.0/4.5
4.0/4.0	3.0/4.0	4.0/4.5	4.5/4.5
4.5/4.5	2.0/3.0	3.5/4.5	5.0/5.0
Steady rapid development	Accelerating weakening	Interrupted weakening	Weakening, then re-development

Step 9 - What's wrong here?
(6 hr intervals)

FT/CI	FT/CI	FT/CI	FT/CI
1.0/1.0	6.0/6.0	6.0/6.0	5.5/5.5
2.5/2.5	5.0/6.0	5.5/6.0	5.0/5.5
3.5/3.5	4.5/6.0	4.5/5.5	5.0/5.5
5.0/5.0	4.0/5.0	4.5/5.5	5.0/5.5
6.5/6.5	3.5/4.5	4.5/5.5	5.0/5.5
7.0/7.0	2.5/4.0	4.0/5.0	5.0/5.5
7.5/7.5	2.0/3.5	3.5/4.5	5.0/5.5

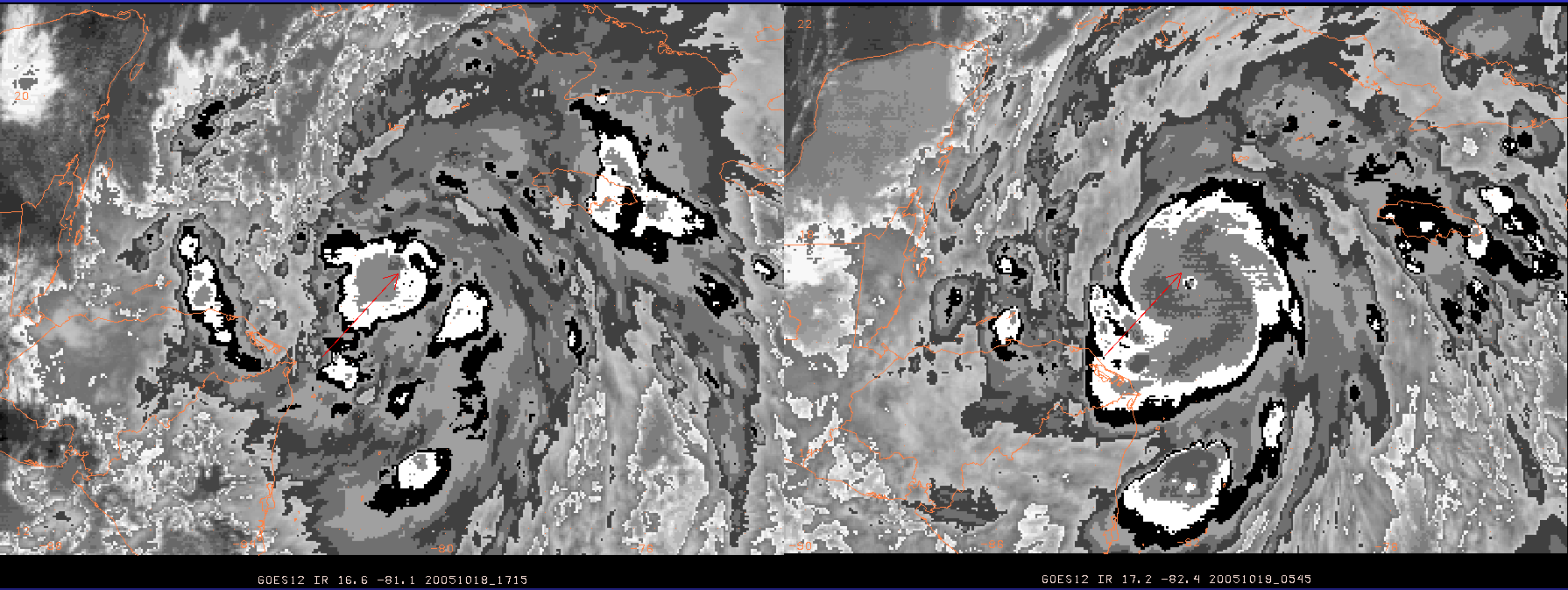
Step 9 - What's wrong here?
(6 hr intervals)

FT/CI	FT/CI	FT/CI	FT/CI
1.0/1.0	6.0/6.0	6.0/6.0	5.5/5.5
2.5/2.5	5.0/6.0	5.5/6.0	5.0/5.5
3.5/3.5	4.5/6.0	4.5/5.5	5.0/5.5
5.0/5.0	4.0/5.0	4.5/5.5	5.0/5.5
6.5/6.5	3.5/4.5	4.5/5.5	5.0/5.5
7.0/7.0	2.5/4.0	4.0/5.0	5.0/5.5
7.5/7.5	2.0/3.5	3.5/4.5	5.0/5.5
Development constraints all broken	CI > 1.0 above FT	CI needs to be held to highest FT during the past 12 hr	

Why are there constraints?

- Weak systems sometimes lose all convection during the diurnal minimum
- Cloud patterns for weak systems sometimes look unrealistically strong
- Strong systems sometimes don't intensify as quickly as the cloud pattern suggests
- In weakening systems, the decay of winds and pressures usually somewhat lags behind that of the cloud pattern
- Issue of constraints can be quite controversial

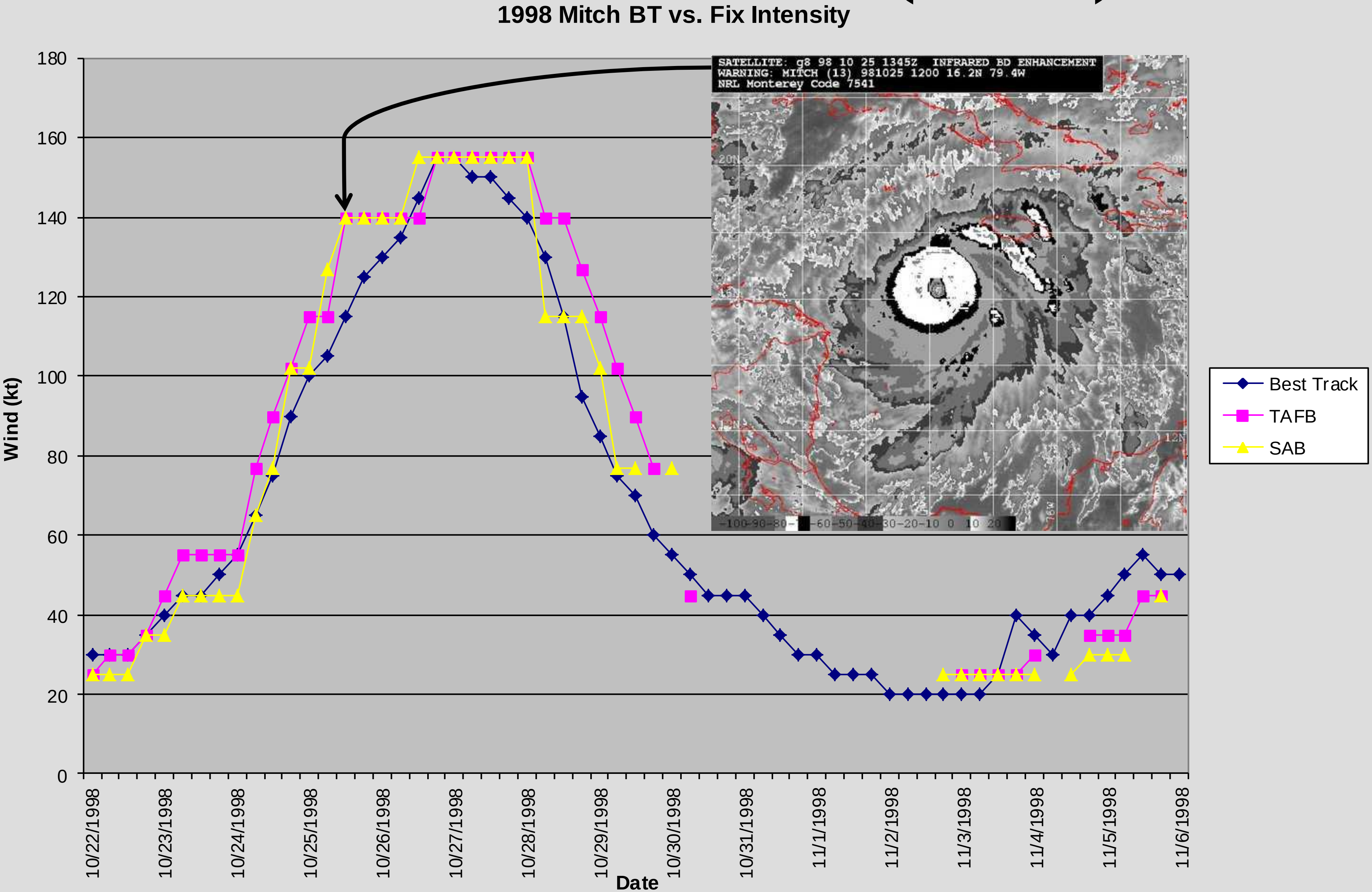
Hurricane Wilma (2005)



75 kt/975 mb **(Images ~12 hr apart)** **150 kt/892 mb**

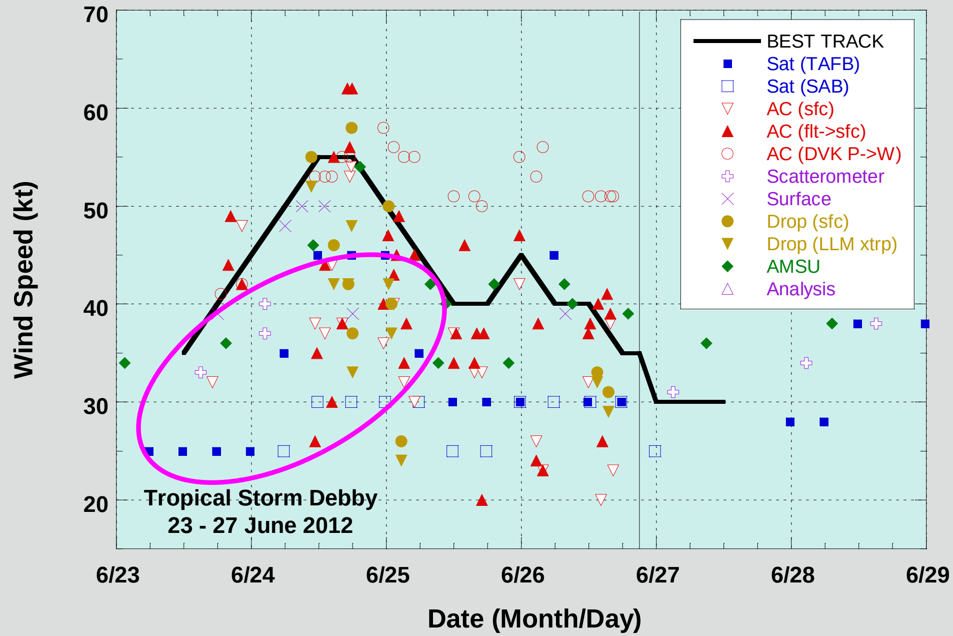
Some tropical cyclones clearly violate the Dvorak development constraints. Wilma deepened from 970 mb to 882 mb in ~12 hr.

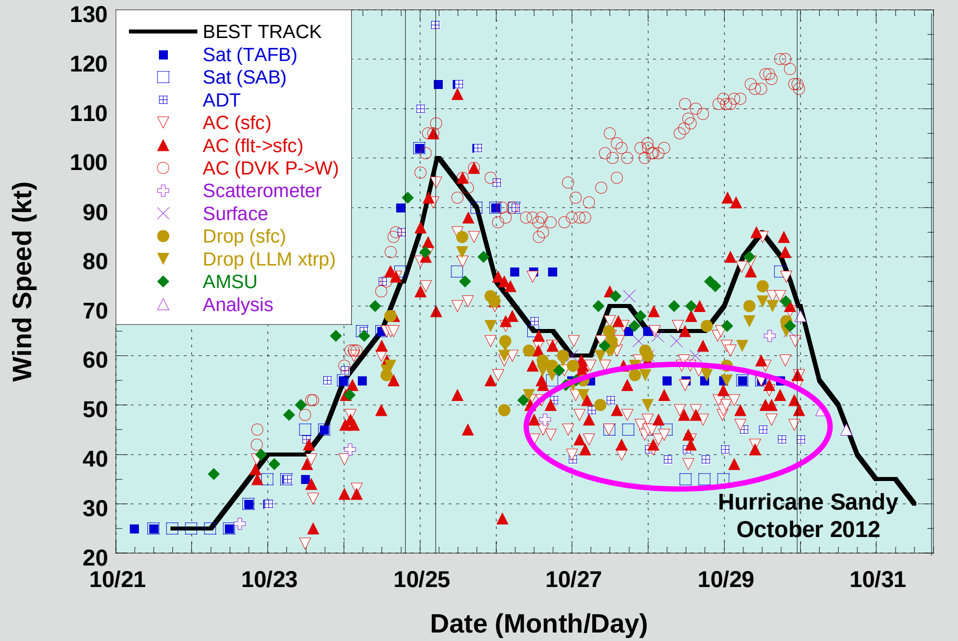
Hurricane Mitch (1998)

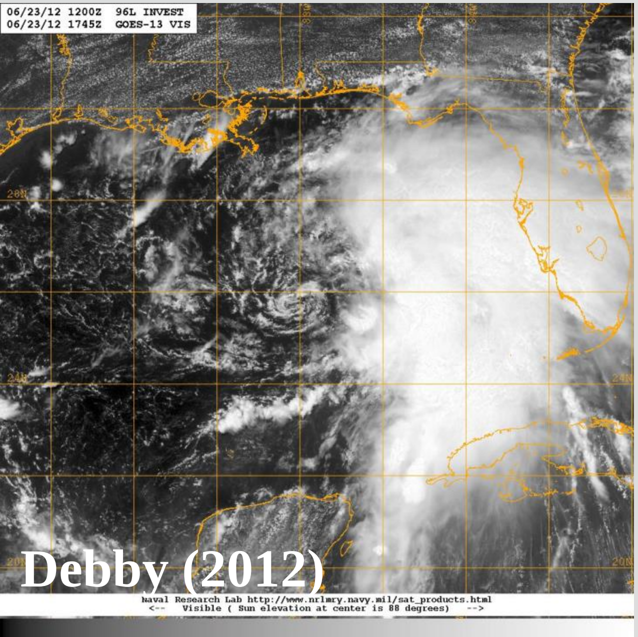


Air recon intensity lagged behind Dvorak estimates during intensification.

Cyclones Stronger Than They Appeared

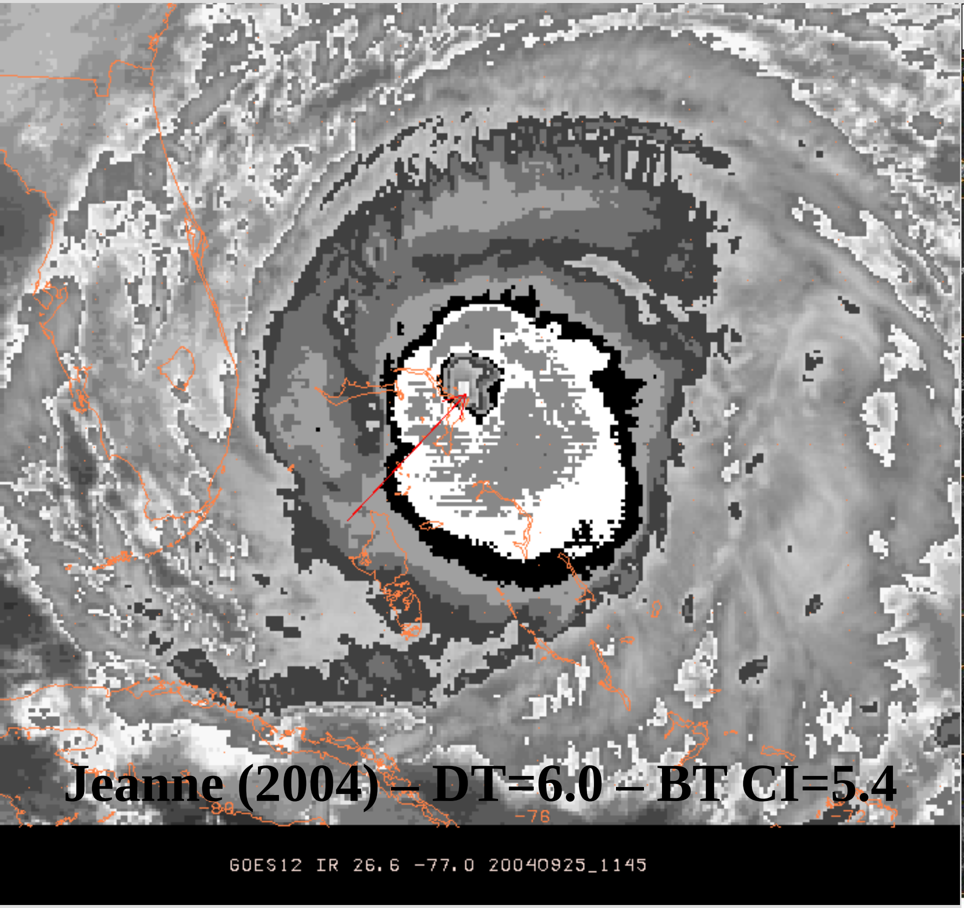


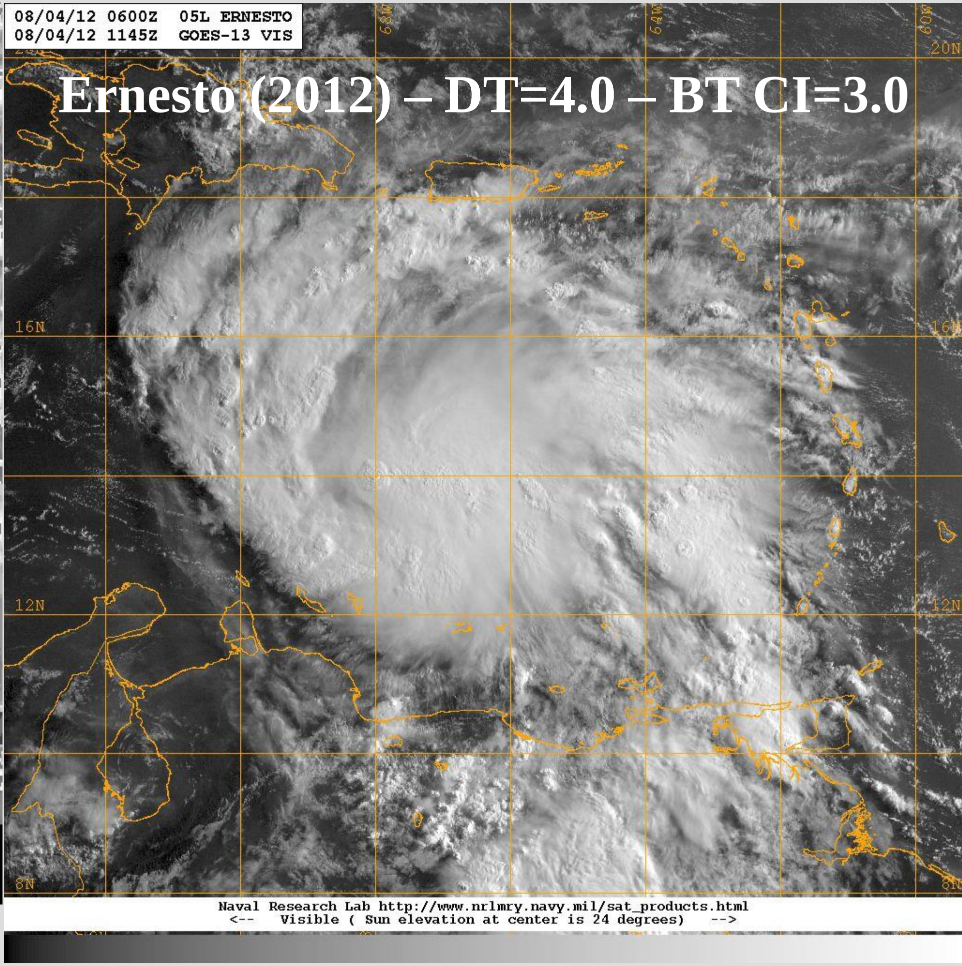




Reconnaissance data showed Debby and Sandy were stronger than their Dvorak intensity estimates. Dvorak estimates are less reliable for monsoonish cyclones (Debby) and partly baroclinic cyclones (Sandy).

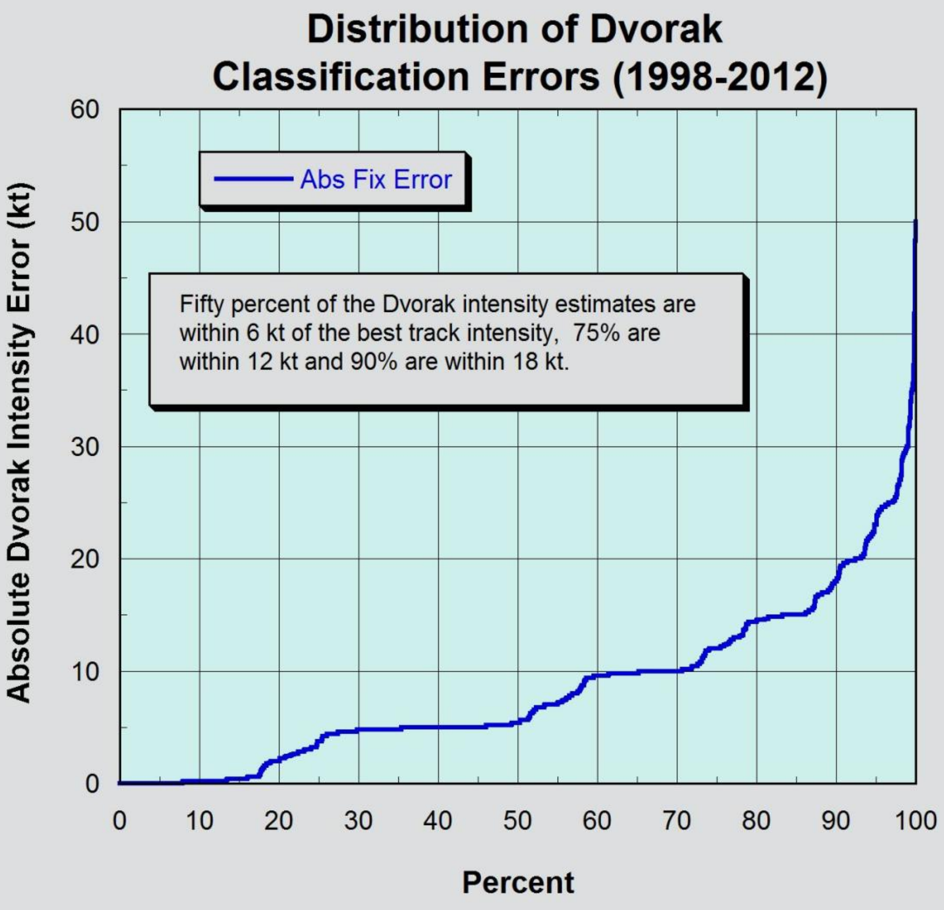
False Alarm Strong Appearances

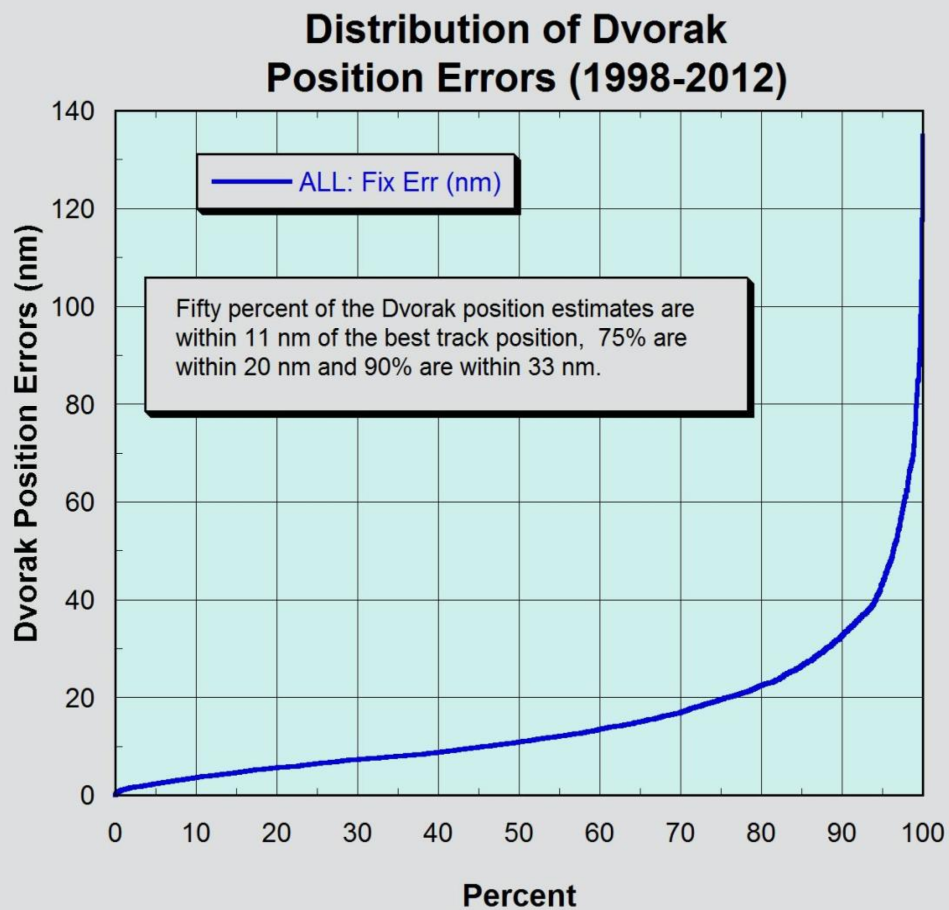




Reconnaissance data showed Jeanne and Ernesto were not as strong as their satellite appearance. The cloud patterns weakened after these images.

Dvorak Error Distribution

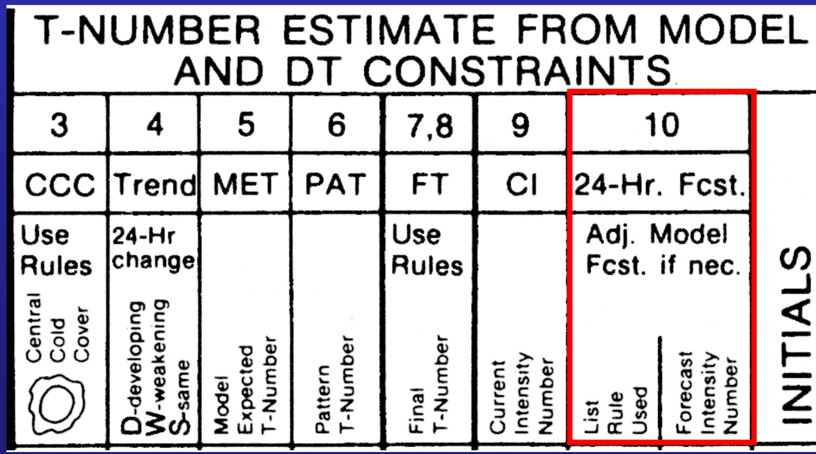




Images courtesy of Brown and Franklin

Step 10 - Forecast Intensity (FI)

- This is a 24 hr forecast of the intensity based on the current CI and satellite-observed signals in the cyclone cloud pattern and the environment
- The set of rules has not been consistent through the revisions of the technique



T-NUMBER ESTIMATE FROM MODEL AND DT CONSTRAINTS

3	4	5	6	7,8	9	10		
CCC	Trend	MET	PAT	FT	CI	24-Hr. Fcst.		
Use Rules	24-Hr change			Use Rules		Adj. Model Fcst. if nec.		INITIALS
Central Cold Cover	D-developing W-weakening S-same	Model Expected T-Number	Pattern T-Number	Final T-Number	Current Intensity Number	List Rule Used	Forecast Intensity Number	

Step 10 - Forecast Intensity

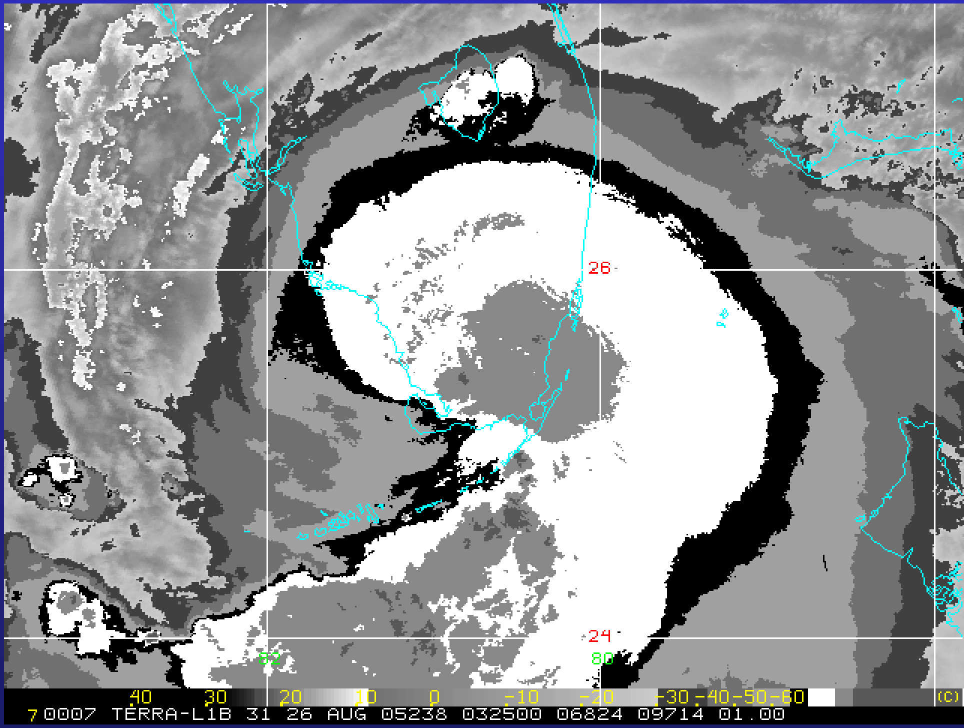
Rule A - Strong Unfavorable Signs in Cloud Pattern:	Rule B - Strong Unfavorable Signs in Environment:
Persistent convective warming for > 12 hr	Cyclone about to move into stratocumulus clouds
CCC persisting for > 3 hr	Cyclone about to move onto land
Signs of shear or pattern elongation	Signs of shear

Forecast: No development or half of the previous development rate

(Note: These two rules can work together.)

Step 10 - Forecast Intensity Rule C - Strong Favorable Signs in Cloud Pattern

- Two successive observations of rapid development (24 hr change)
- Or, one observation of rapid development and either a cold comma cloud pattern or multiple outflow channels
- Forecast: If FT ≤ 5.5, forecast rapid development (1.5 T-Numbers in 24 hr)



Katrina (2005) – cold comma cloud pattern

Step 10 - Forecast Intensity

Rule D - Weakened Cyclone Leaving Unfavorable Environment	Rule E - Cyclone Leaving Environment Where Development was Slowed	Rule F - Developing Cyclone Leaving Unfavorable Environment
Cyclone leaving conditions of Rule B	Cyclone leaving conditions of Rule B	Cyclone leaving conditions of Rule B
Forecast rapid development to prior maximum intensity, followed by normal development	Forecast previous rate of development	Forecast increase of 1 T-Number per day in rate of development (YIKES!)

Step 10 - Forecast Intensity
Rule G - Cyclone Peaking

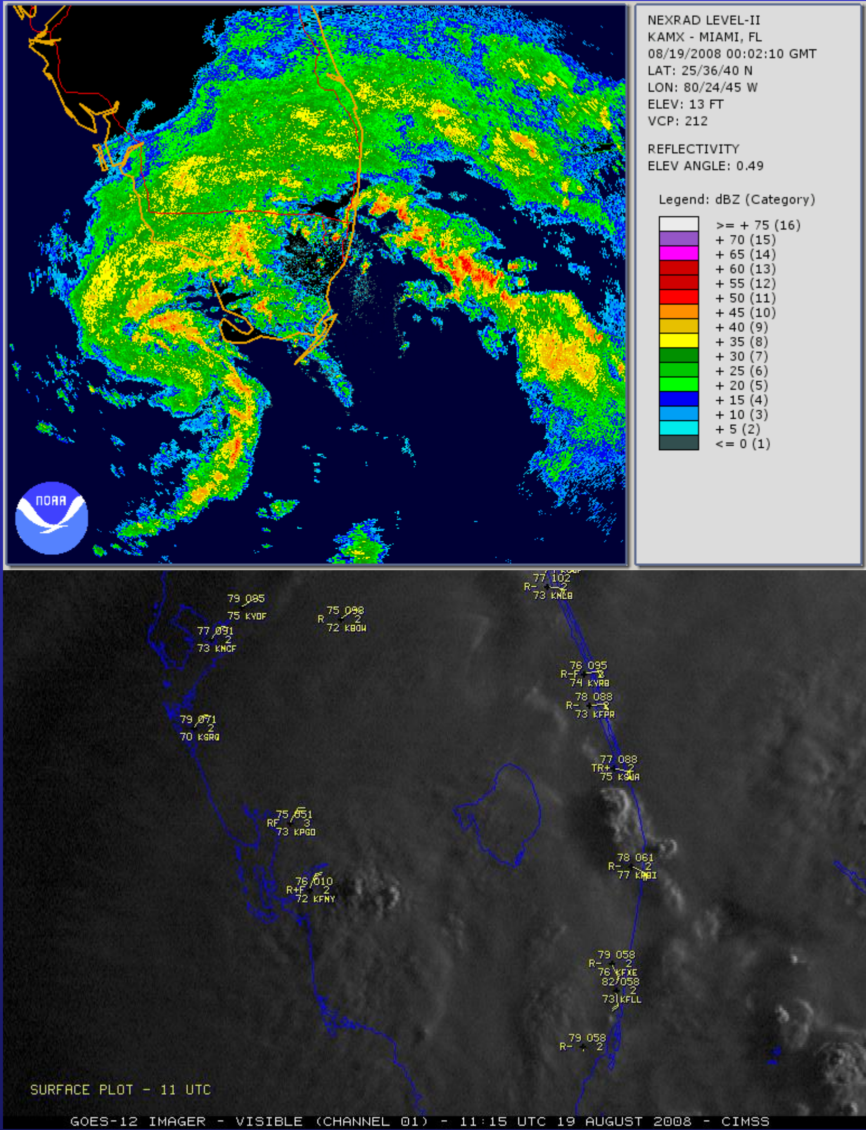
- Northward moving cyclones expected to peak 4 days after first T1
- Westward moving cyclones expected to peak 6 days after first T1
- All other cyclones expected to peak 5 days after first T1
- Forecast no change in intensity
- This rule is based mostly on climatology

Step 10 - Forecast Intensity

Rule L - Large Eyes	Rule P - Persistence
For eyes 30 nm/56 km wide or larger with FT ≥ 6.0	Use when no strong signals are present
Limit FI to 6.0	Forecast trend from past 24 hr to continue

What to do for systems over land?

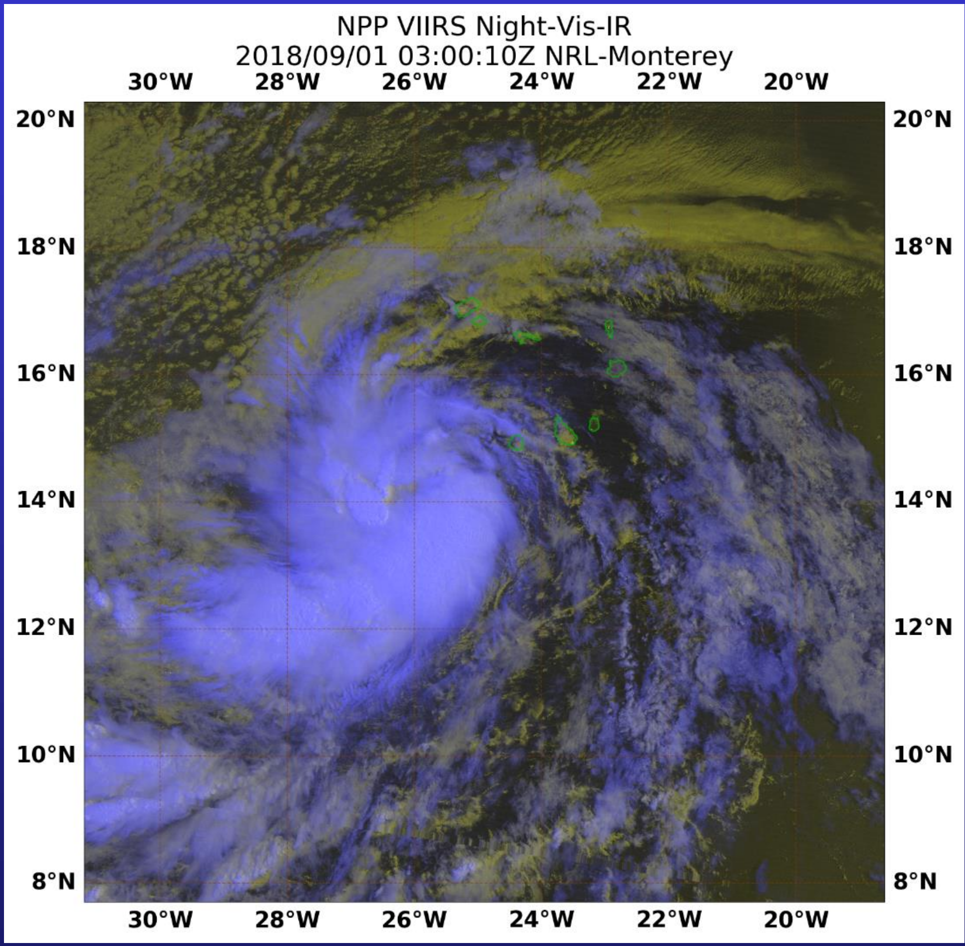
- **Passage over land changes the TC energetics and the cloud pattern-intensity relationship.**
- **As a rule, don't classify systems over land. The Japanese Metrological Agency and the Joint Typhoon Warning Center classify systems over land, but the National Hurricane Center normally does not.**
- **Subjective exceptions to the rule:**
  - *Cyclone close to the coast*
  - *Over small islands*
  - *Over marsh land such as the Everglades or southern Louisiana.*
  - *Forming an eye while over land.*
- **If the system moves back over water after classifications have been stopped, re-start classifications using the observed DT or PT.**



Tropical Storm Fay (2008) – trying to form an eye after landfall!

A Few More Tips

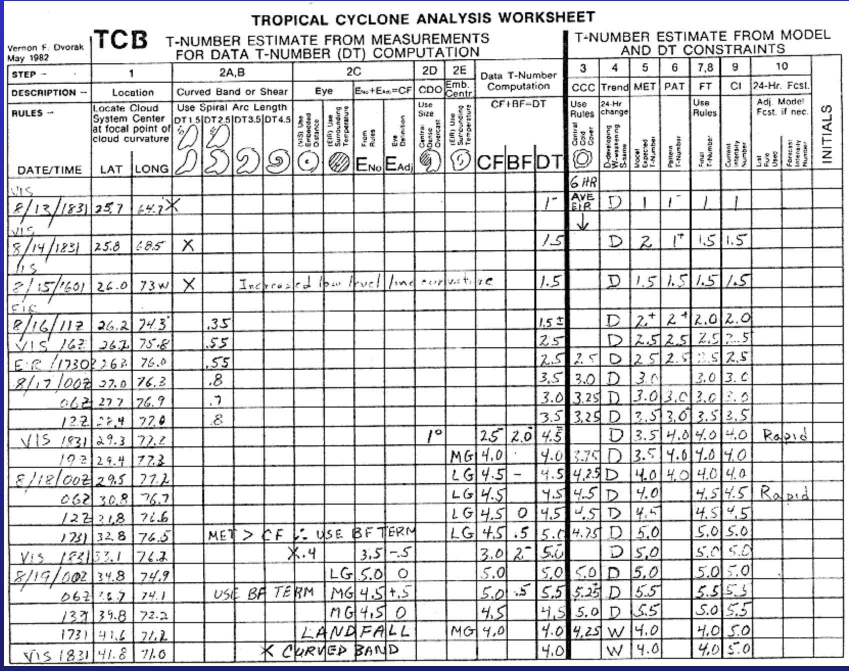
- Previous daylight satellite imagery may help locate CSCs during night shifts
- If time permits, try multiple methods of classifying one system to see if the Data-T numbers agree (e.g. curved band and CDO or VIS and IR eyes) - if they don’t, use the Data-T number closest to the MET
- Some imagers (DMSP/OLS, NPP/VIIRS) are sensitive enough to provide moonlight visible imagery, thus allowing use of VIS cloud patterns and center location at night



Florence (2018) NPP Satellite Day-Night Moonlight Imagery

Mistakes to Avoid

- Adding BF numbers to a curved band DT!
- Overuse of <u>IR</u> curved band, shear, and embedded center patterns instead of <u>VIS</u> curved band, shear, and CDO patterns
- Incorrect 24 hr trends and METs, most notably during the early stages of development
- Arbitrarily changing the development rate
- Improperly filled out worksheets and classification forms – these are how people can see what decisions you made!
- Not making copies of images (paper or electronic)
- Not using BD enhancement on IR images



TROPICAL CYCLONE ANALYSIS WORKSHEET

Vernon F. Dvorak May 1982

TCB — T-NUMBER ESTIMATE FROM MEASUREMENTS FOR DATA T-NUMBER (DT) COMPUTATION | T-NUMBER ESTIMATE FROM MODEL AND DT CONSTRAINTS

STEP –	1		2A,B				2C				2D	2E	Data T-Number Computation			3	4	5	6	7,8	9	10		INITIALS
DESCRIPTION –	Location		Curved Band or Shear				Eye		$E_{No}+E_{Adj}=CF$		CDO	Emb. Centr.	CF+BF=DT			CCC	Trend	MET	PAT	FT	CI	24-Hr. Fcst.		
RULES –	Locate Cloud System Center at focal point of cloud curvature		Use Spiral Arc Length				(VIS) Use Embedded Distance	(EIR) Use Surrounding Temperature	From Rules	Eye Definition	Use Size: Central Dense Overcast	(EIR) Use Surrounding Temperature				Use Rules: Central Cold Cover	24-Hr change: D-developing W-weakening S-same	Model Expected T-Number	Pattern T-Number	Use Rules: Final T-Number	Current Intensity Number	Adj. Model Fcst. if nec.: Last Rule Used	Forecast Intensity Number	
DATE/TIME	LAT	LONG	DT1.5	DT2.5	DT3.5	DT4.5			E_{No}	E_{Adj}			CF	BF	DT									
																6 HR								
VIS 8/13/1831	25.7	64.7	X												1-	AVE EIR	D	1	1-	1	1			
VIS 8/14/1831	25.8	68.5	X												1.5	↓	D	2	1+	1.5	1.5			
IR 8/15/1601	26.0	73W	X		Increased low level line curvature										1.5		D	1.5	1.5	1.5	1.5			
EIR 8/16/1117	26.2	74.3		.35											1.5±		D	2.+	2+	2.0	2.0			
VIS 1627	26.2	75.8		.55											2.5		D	2.5	2.5	2.5	2.5			
EIR 1730	26.2	76.0		.55											2.5	2.5	D	2.5	2.5	2.5	2.5			
8/17/0027	27.0	76.3		.8											3.5	3.0	D	3.0		3.0	3.0			
0627	27.7	76.9		.7											3.0	3.25	D	3.0	3.0	3.0	3.0			
1227	28.4	77.0		.8											3.5	3.25	D	3.5	3.0	3.5	3.5			
VIS 1831	29.3	77.2									1°		2.5	2.0	4.5		D	3.5	4.0	4.0	4.0	Rapid		
1927	29.4	77.3										MG	4.0		4.0	3.75	D	3.5	4.0	4.0	4.0			
8/18/0027	29.5	77.2										LG	4.5	–	4.5	4.25	D	4.0	4.0	4.0	4.0			
0627	30.8	76.7										LG	4.5		4.5	4.5	D	4.0		4.5	4.5	Rapid		
1227	31.8	76.6										LG	4.5	0	4.5	4.5	D	4.5		4.5	4.5			
1731	32.8	76.5		MET > CF ∴ USE BF TERM								LG	4.5	.5	5.0	4.75	D	5.0		5.0	5.0			
VIS 1831	33.1	76.2					X.4		3.5	–.5			3.0	2-	5.0		D	5.0		5.0	5.0			
8/19/0027	34.8	74.9						LG	5.0	0			5.0		5.0	5.0	D	5.0		5.0	5.0			
0627	[illegible]	74.1		USE BF TERM				MG	4.5	+.5			5.0	.5	5.5	5.25	D	5.5		5.5	5.5			
1327	39.8	72.2						MG	4.5	0			4.5		4.5	5.0	D	5.5		5.0	5.5			
1731	41.6	71.2					LANDFALL					MG	4.0		4.0	4.25	W	4.0		4.0	5.0			
VIS 1831	41.8	71.0				X CURVED BAND									4.0		W	4.0		4.0	5.0			

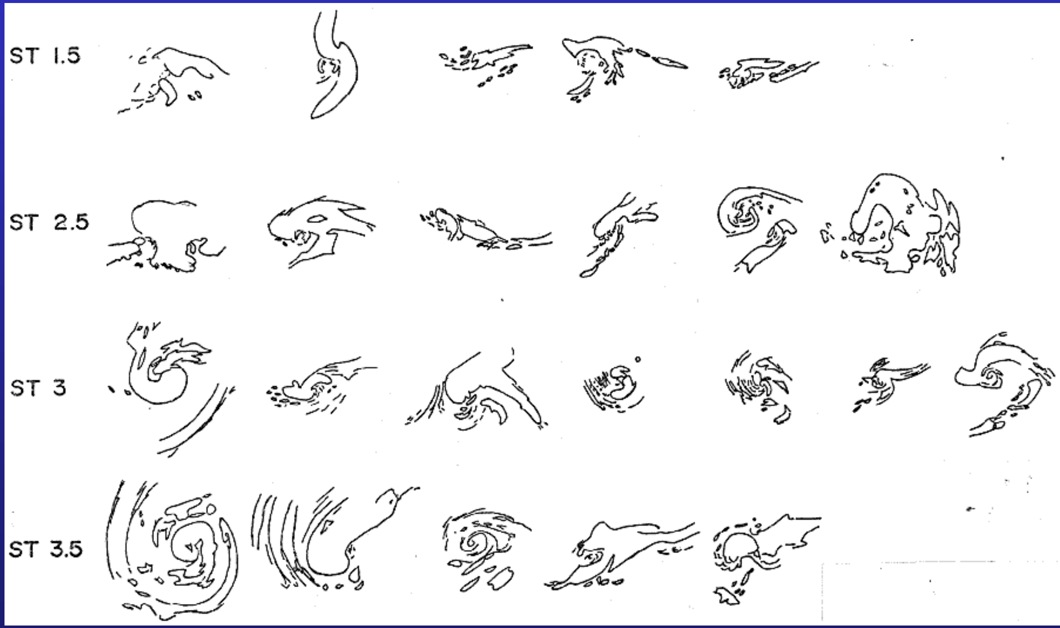
Be sure to properly fill out the worksheet!

Related Techniques

- Hebert-Poteat Subtropical Cyclones Technique
- Automated/Objective Dvorak Technique
- ARCHER Objective TC center location
- Microwave-based TC intensity estimates
- Satellite Consensus (SATCON) Technique
- Experimental Techniques - Microwave Data and Other Approaches

Hebert-Poteat Subtropical Cyclone Technique

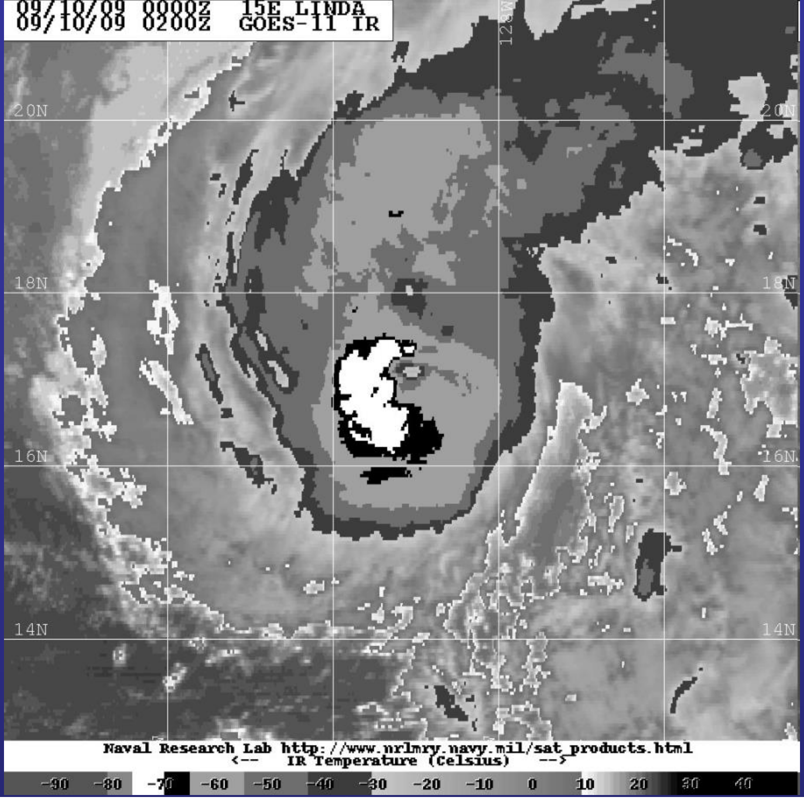
- Technique designed for subtropical cyclones, a 'hybrid' cyclone with characteristics of both tropical and extratropical cyclones.
- It is designed as a complement to the Dvorak technique and to lead to the Dvorak technique when the cyclone acquires fully tropical characteristics.
- Used operationally by satellite centers worldwide.
- Needs more rigorous scientific basis!



CIMSS Advanced Dvorak Technique (ADT)

- The latest in a series of objective versions of the Dvorak technique from CIMSS
- Can provide intensity estimates on <u>every</u> satellite image of a TC – some averaging is required!
- Includes Dvorak cloud patterns and some rules
- Currently uses microwave imagery for improved intensity estimates of some cloud patterns.
- Automated center fixing and cloud pattern types occasionally need manual intervention.
- It is operational at NESDIS/SAB and used in NHC operations.

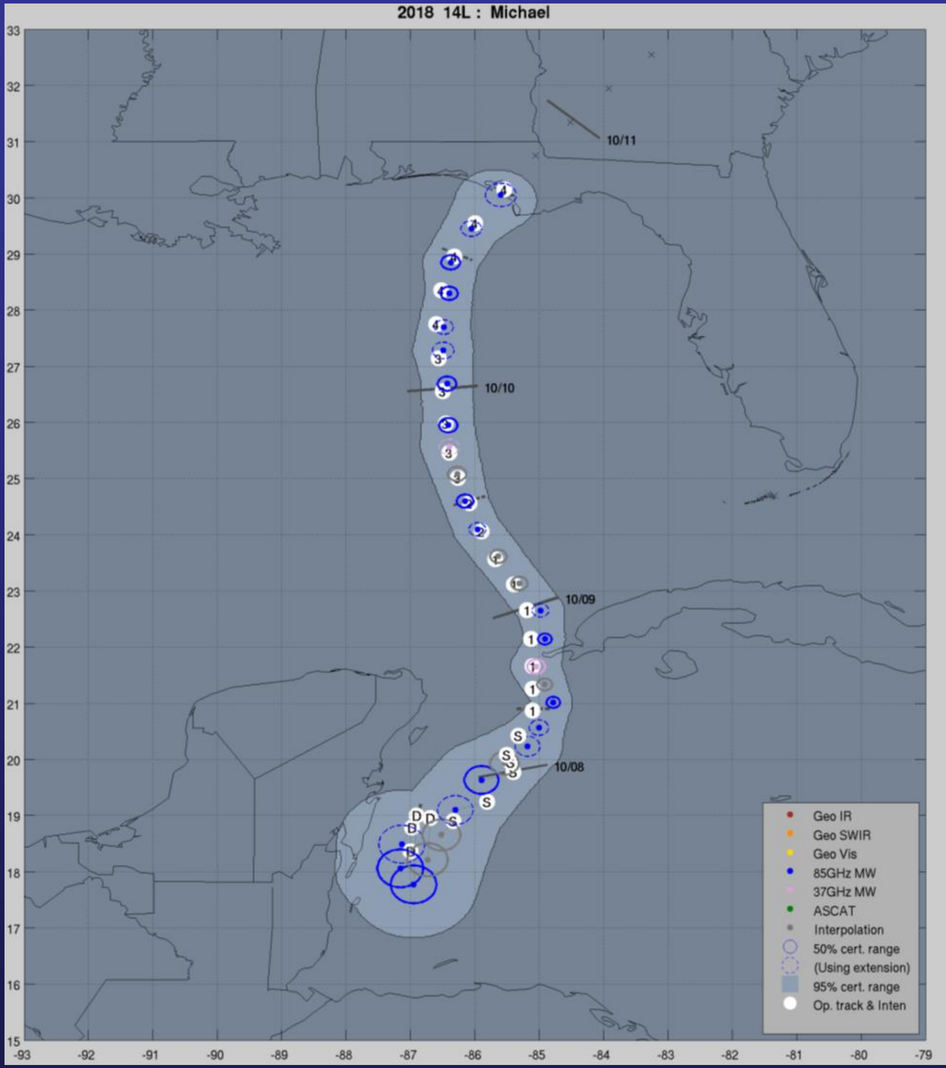
http://cimss.ssec.wisc.edu/tropic2/misc/adt/info.html



Date/ Time	CI	Adj. Raw	Ini. Raw	Scene	Lat.	Lon.	Fix Method
09/2330	3.9	4.0	4.0	EMBC	16.87	129.17	FCST
10/0000	3.9	4.0	4.0	EMBC	16.91	129.20	FCST
10/0030	3.9	3.9	3.9	EMBC	16.92	129.08	SPRL
10/0100	3.9	3.9	3.9	UNIFRM	16.86	129.11	SPRL
10/0130	4.0	4.4	5.5	EYE	17.02	129.14	COMBO
10/0200	4.0	3.7	3.7	EMBC	17.88	128.97	SPRL
10/0230	4.0	4.5	5.5	EYE	17.10	129.10	SPRL
10/0300	4.1	4.4	5.6	EYE	17.15	129.03	SPRL
10/0330	4.1	4.5	5.8	EYE	17.20	129.07	SPRL

CIMSS ARCHER Center Location

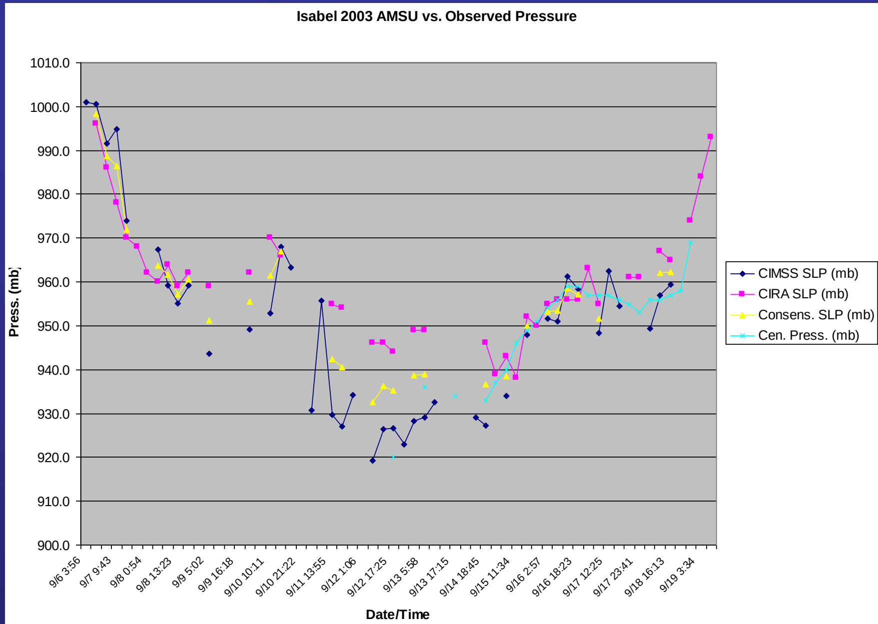
- The ARCHER algorithm objectively locates the centers of TCs using conventional and MW satellite data.
- The ADT can use these position estimates for center locations for its algorithm.
- ARCHER is being tested experimentally at the NHC.

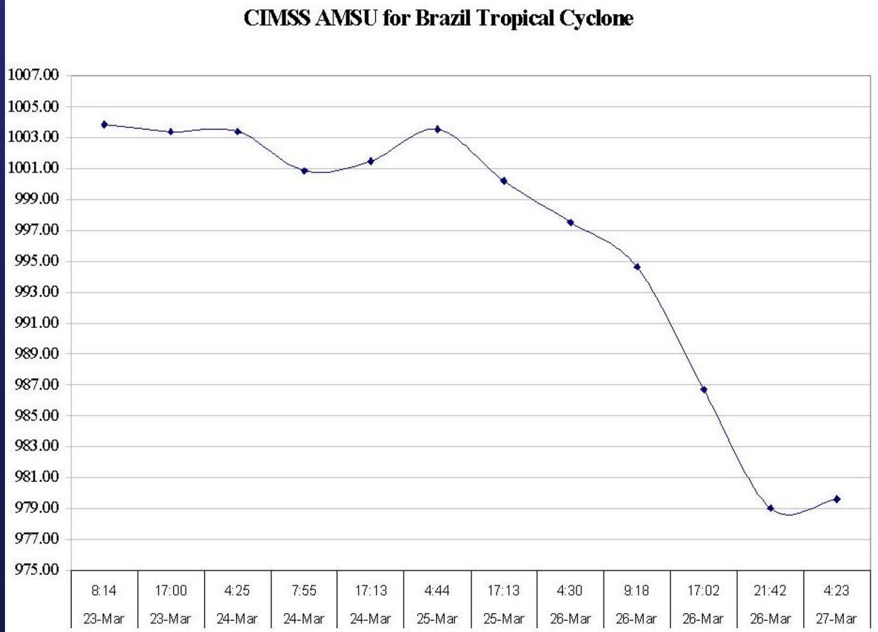


http://tropic.ssec.wisc.edu/real-time/archerOnline/web/index.shtml

Microwave-Based Intensity Estimates

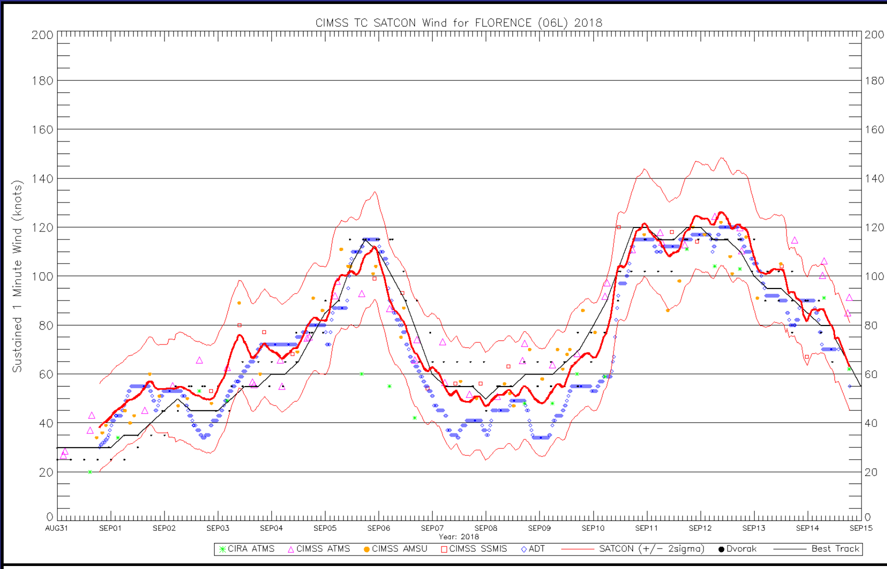
- **AMSU and ATMS microwave sounders fly on NOAA/METOP Polar Orbiters, while the SSM/IS imager/sounder flies on the DMSP Polar Orbiters.**
- **MW sounders measure temperatures of the warm core at the top of a TC and derives the intensity from the core strength.**
- **Sounder footprint is normally larger than the TC core – problem with undersampling small cores.**
- **MW estimates are also suspect for subtropical systems, which have a different thermal structure**
- **NHC uses several MW algorithms in operations.**

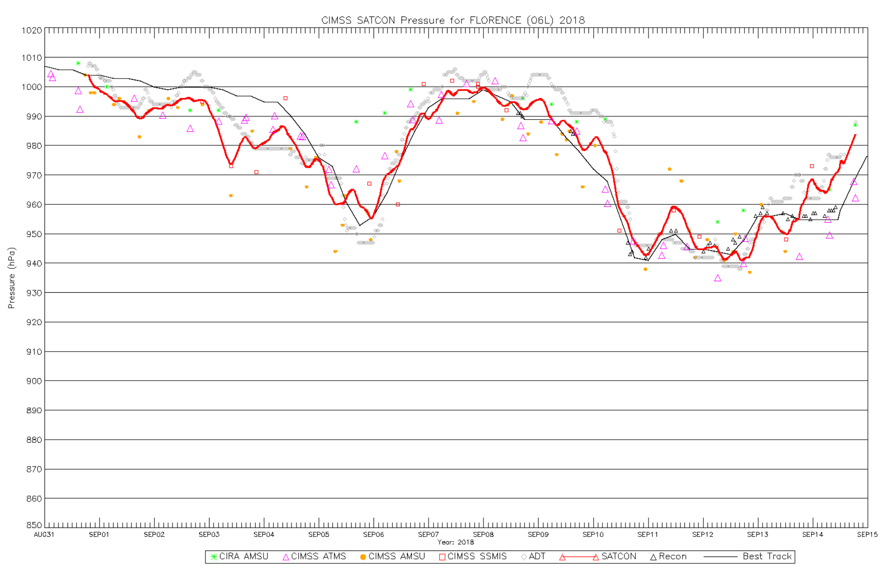




CIMSS SATCON Technique

- ADT and microwave intensity estimates work well for certain ranges of TC intensity, structure, and satellite scanning geometry and less well for others.
- Weighted averages of the estimates often produce a better result than any of the individual components. This is the basis of the CIMSS Satellite Consensus (SATCON) technique.
- SATCON is used operationally at the NHC.

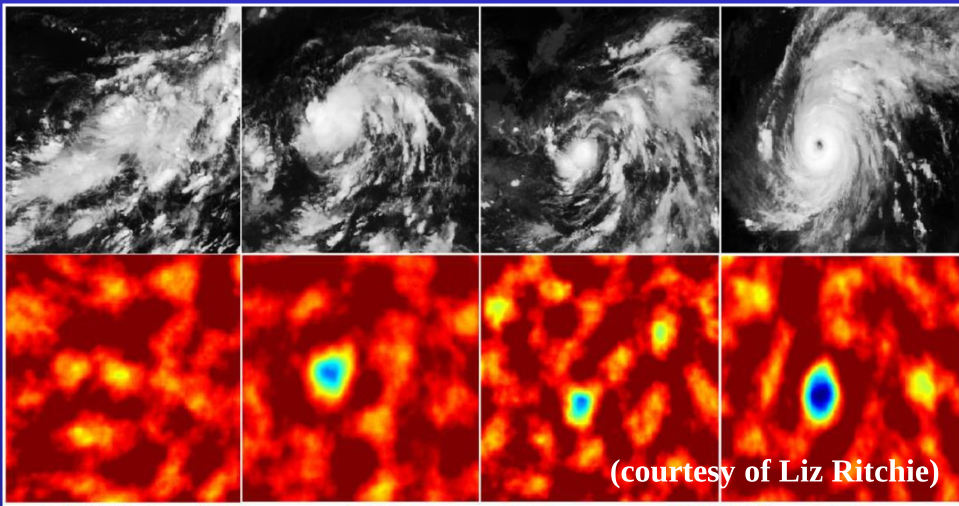




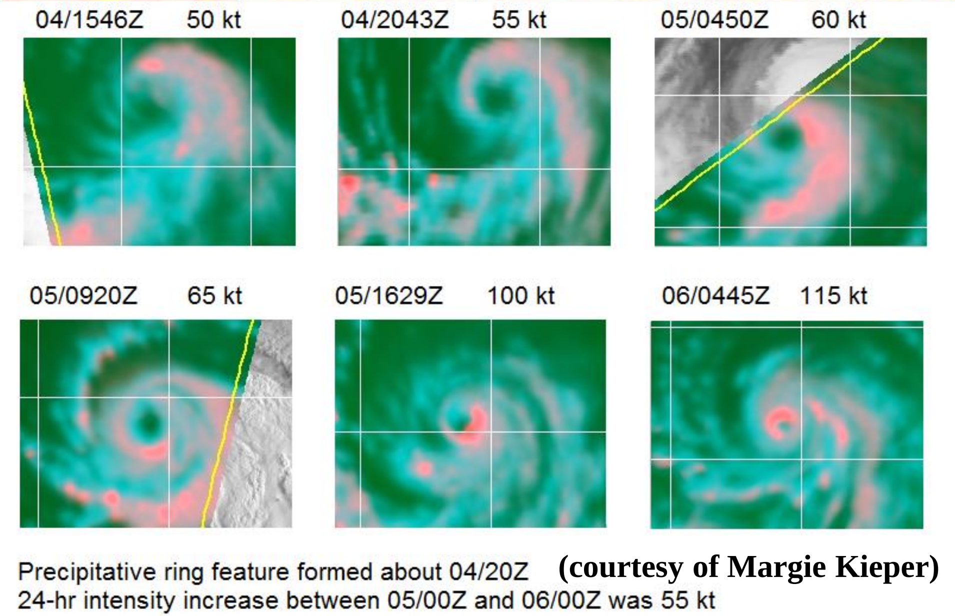
http://cimss.ssec.wisc.edu/tropic2/real-time/satcon/

Experimental techniques and other possible future developments

- **Ritchie Deviation Angle Variance Technique**
- **Microwave-imagery-based equivalents of the Dvorak technique**
- **Dvorak-like techniques based on multispectral imagery (METEOSAT-Second Generation, GOES-R)**



(courtesy of Liz Ritchie)



(courtesy of Margie Kieper)

Acknowledgements

- Vernon Dvorak – creator of the technique and of much of the material in these presentations
- Max Mayfield (former NHC director) – the previous teacher of the technique whose class material was the foundation for these presentations
- Ray Zehr (formerly of the Cooperative Institute For Research in the Atmosphere at Colorado State University) – several examples are from his Dvorak training module
- Andrew Burton (Australia Bureau of Meteorology) – whose comments helped improve the presentations
- Todd Kimberlain (formerly of NHC) – earlier collaborator in updating these presentations
- James Franklin and Dan Brown (NHC) – Dvorak Technique error slide
- The Cooperative Institute for Meteorological Satellite Studies at the University of Wisconsin – many satellite images and related technique material
- The Naval Research Laboratory, Monterey, CA – satellite images
- NASA – satellite images
- Liz Ritchie (UNSW) and Margie Kieper (FIU) for related technique material