

# **Tropical cyclone morphology from spaceborne synthetic aperture radar**

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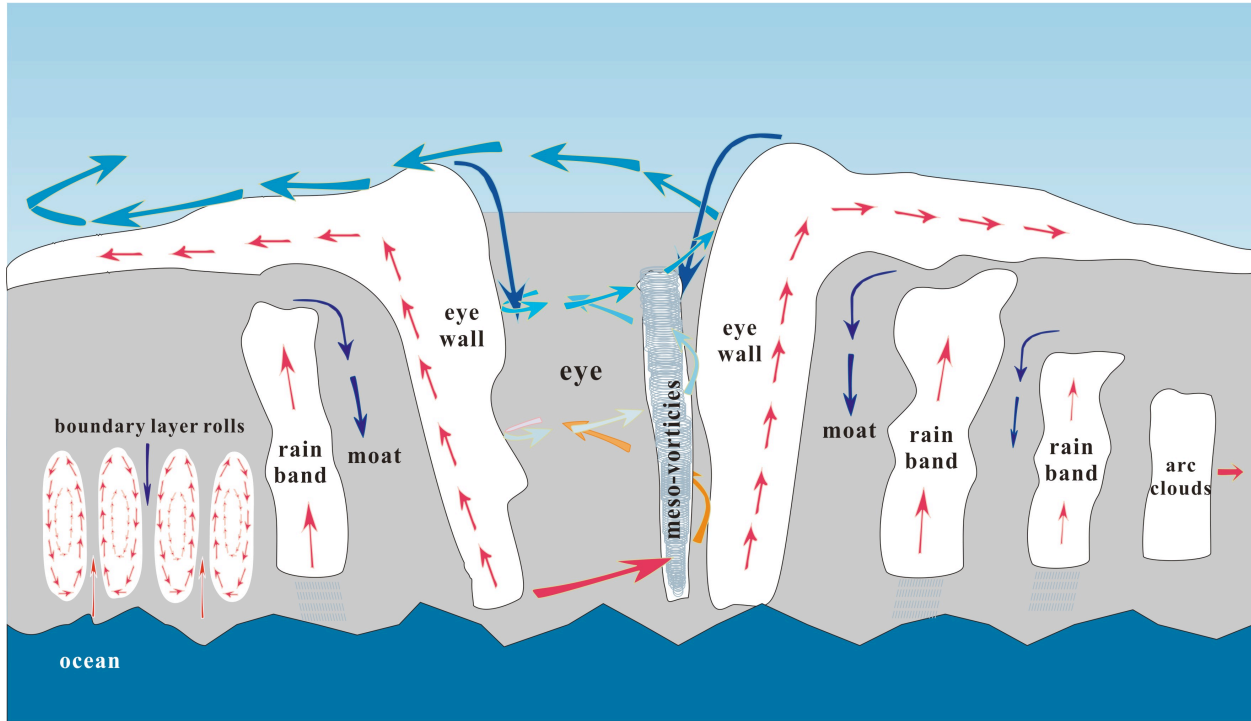


Figure 1. Schematic plot of tropical cyclone structure and atmospheric phenomena including eye/eyewall, rain band, boundary layer rolls, arc cloud, and meso-vortices (not to scale).

Basic tropical cyclone information derived from 83 tropical storms observed by SAR.

No.	Year	Mon	Day	time	Name	Cyclone location	Center Lat	Center Lon	Category	Vmax (knot)	Pressure (hPa)	SAR
1	2001	8	29	01:43:45	FLOSSIE	epa	19.8	-115.2	I	75	983	R1
2	2001	9	9	03:04:25	GIL	epa	21.3	-135.3	TD	30	1006	R1
3	2001	9	11	22:19:07	ERIN	atl	37.7	-64.5	I	80	976	R1
4	2001	9	13	10:03:10	ERIN	atl	38.5	-61.0	I	70	980	R1
5	2001	9	17	08:07:41	FELIX	atl	35.2	-31.6	I	70	981	R1
6	2001	9	26	21:41:18	HUMBERTO	atl	42.0	-56.0	I	80	977	R1
7	2001	9	27	13:21:06	JULIETTE	epa	20.9	-110.8	II	90	949	R1
8	2001	10	23	03:19:25	NARDA	epa	16.0	-135.7	TS	60	990	R1
9	2001	11	26	21:59:51	OLGA	atl	31.7	-56.2	I	65	977	R1
10	2001	11	28	09:47:55	OLGA	atl	32.4	-56.1	I	75	976	R1
11	2002	5	30	01:50:35	ALMA	epa	14.1	-115.5	II	93	966	R1
12	2002	9	2	11:20:35	EDOUARD	atl	30.3	-79.9	TS	35	1007	R1
13	2002	9	26	09:40:26	KYLE	atl	28.0	-57.9	I	73	982	R1
14	2002	9	27	22:03:02	KYLE	atl	26.2	-61.1	I	66	985	R1
15	2002	9	28	23:12:10	LILI	atl	18.8	-75.9	I	45	1001	R1
16	2002	9	30	11:07:06	LILI	atl	19.5	-79.4	I	60	990	R1
17	2002	10	3	22:28:55	KYLE	atl	29.0	-67.9	I	55	994	R1
18	2003	7	13	12:03:34	CLAUDETTE	atl	24.8	-92.6	TS	50	998	R1
19	2003	8	7	09:19:06	ETAU	wpa	28.2	129.1	II	82	947	R1
20	2003	8	23	22:14:03	KROVANH	wpa	18.4	115.2	TS	55	971	R1
21	2003	9	7	09:44:57	FABIAN	atl	39.8	-54.6	II	81	966	R1
22	2003	11	30	20:43:42	LUPIT	wpa	26.9	137.6	I	80	952	R1
23	2004	9	6	09:06:22	IVAN	atl	10.9	-51.5	IV	110	952	R1
24	2004	9	17	01:21:43	JAVIER	epa	20.2	-111.3	II	100	960	R1
25	2004	9	28	09:26:55	MEARI	wpa	29.4	127.4	I	65	965	R1
26	2004	10	23	21:18:39	NOCK-TEN	wpa	19.7	126.6	II	85	945	R1
27	2005	6	6	09:03:40	NESAT	wpa	21.4	133.7	II	85	945	R1
28	2005	7	13	20:06:29	HAITANG	wpa	21.2	145.1	I	68	966	R1
29	2005	7	21	19:30:21	NALGAE	wpa	-	-	TS	43	988	R1

30	2005	7	23	23:01:05	FRANKLIN	atl	29.6	-73.7	TS	60	1001	R1
31	2005	7	24	09:03:40	BANYAN	wpa	23.5	136.3	TS	55	975	R1
32	2005	7	25	20:53:54	BANYAN	wpa	31.7	137.0	TS	42	975	R1
33	2005	7	28	22:17:15	FRANKLIN	atl	36.7	-67.2	TS	53	995	R1
34	2005	7	29	21:49:10	FRANKLIN	atl	42.4	-58.8	TS	50	999	R1
35	2005	8	4	22:11:19	HARVEY	atl	31.7	-61.2	TS	58	993	R1
36	2005	8	5	09:55:08	MATSA	wpa	27.2	122.5	I	71	963	R1
37	2005	8	5	21:42:29	HARVEY	atl	32.2	-57.2	TS	41	998	R1
38	2005	8	13	02:36:09	SANVU	wpa	18.8	125.6	TS	50	985	R1
39	2005	8	22	20:38:52	MAWAR	wpa	24.6	137.0	I	80	950	R1
40	2005	8	27	11:28:41	KATRINA	atl	24.4	-84.6	II	99	942	R1
41	2005	9	5	21:37:58	MARIA	atl	32.2	-56.8	II	93	966	R1
42	2005	9	7	09:23:58	MARIA	atl	35.4	-52.7	I	72	981	R1
43	2005	9	9	21:21:42	NATE	atl	34.3	-52.0	TS	47	988	R1
44	2005	9	14	11:00:57	OPHELIA	atl	33.4	-77.6	I	74	980	R1
45	2005	9	18	03:25:08	JOVA	epa	12.8	-139.3	II	85	973	R1
46	2005	9	19	15:22:26	JOVA	epa	15.3	-142.6	II	102	957	R1
47	2005	9	22	03:08:42	KENNETH	epa	14.6	-134.1	TS	45	1000	R1
48	2005	9	25	03:21:45	KENNETH	epa	16.0	-139.3	I	65	988	R1
49	2005	9	30	13:19:18	OTIS	epa	20.9	-110.6	I	65	987	R1
50	2005	10	2	01:38:05	OTIS	epa	21.4	-111.9	I	68	980	R1
51	2005	10	3	13:30:24	OTIS	epa	24.9	-112.9	TS	28	1003	R1
52	2005	10	14	09:12:13	KIROGI	wpa	22.6	131.4	II	85	940	R1
53	2005	10	15	21:04:06	KIROGI	wpa	24.1	132.7	II	85	940	R1
54	2006	7	3	20:53:52	EWINIAR	wpa	15.0	133.2	II	85	950	R1
55	2006	7	11	09:35:42	BILIS	wpa	19.2	128.6	TS	55	987	R1
56	2006	7	12	21:29:32	BILIS	wpa	22.4	124.4	TS	55	975	R1
57	2006	7	15	02:36:20	BUD	epa	19.7	-129.8	TS	32	1003	R1
58	2006	7	24	03:12:39	DANIEL	epa	15.2	-138.4	II	89	970	R1
59	2006	8	10	10:02:54	SAOMAI	wpa	26.8	120.2	III	97	945	R1
60	2006	9	19	09:30:59	GORDON	atl	24.9	-52.2	II	84	974	R1
61	2006	9	20	21:52:31	HELENE	atl	25.9	-57.0	II	73	960	R1
62	2006	9	21	20:17:59	YAGI	wpa	22.9	144.3	II	105	910	R1
63	2006	9	23	09:10:32	HELENE	atl	36.8	-48.5	I	80	962	R1
64	2006	9	25	08:10:03	HELENE	atl	43.9	-32.4	I	63	966	R1
65	2006	9	30	22:38:38	XANGSANE	wpa	16.0	109.0	II	72	965	R1
66	2007	7	11	21:13:14	MAN-YI	wpa	17.4	124.9	II	95	929	R1
67	2007	7	13	09:33:45	MAN-YI	wpa	27.7	127.6	II	79	942	R1
68	2007	8	1	20:57:57	USAGI	wpa	29.7	133.2	II	90	945	R1
69	2007	8	17	09:50:33	DEAN	atl	14.3	-61.0	II	86	969	R1
70	2007	8	19	23:17:51	DEAN	atl	17.4	-77.6	IV	125	936	R1
71	2007	8	31	19:42:51	FITOW	wpa	27.8	152.9	I	63	971	R1
72	2007	10	4	21:33:56	KROSA	wpa	20.4	125.4	II	98	928	R1
73	2007	10	20	20:25:09	KAJIKI	wpa	26.8	142.8	II	92	942	R1
74	2004	8	25	01:52:41	AERE	wpa	25.5	121.0	I	75	960	ASA
75	2005	8	28	15:51:16	KATRINA	atl	26.2	-88.3	V	145	909	ASA
76	2005	8	30	01:24:39	TALIM	wpa	21.4	129.2	II	95	901	ASA
77	2005	9	11	01:46:11	KHANUN	wpa	27.5	112.3	I	80	950	ASA
78	2005	9	22	03:44:32	RITA	atl	26.1	-87.0	V	150	897	ASA
79	2008	4	18	02:31:50	NEOGURI	wpa	18.2	111.3	I	80	965	ASA
80	2008	9	1	03:59:19	GUSTAV	atl	27.0	-88.4	II	95	953	ASA
81	2008	9	13	04:23:09	IKE	atl	28.8	-94.6	II	95	940	ASA
82	2009	9	14	14:22:16	KOPPU	wpa	20.8	113.8	I	65	975	ASA
83	2010	9	2	02:44:23	EARL	atl	31.0	-75.0	IV	120	932	ASA

\*: epa: Eastern Pacific; wpa: Western Pacific; atl: Atlantic; R1: RADARSAT-1; ASA: Advanced SAR

\*\* : Saffir–Simpson Hurricane Scales based on wind speed: Tropical Depression (TD: 0-62 km/h), Tropical storm (TS: 63–117 km/h), Category I (118-153 km/h), II (154-177 km/h), III (178-209 km/h), IV (210-249 km/h), V ( $\geq 250$  km/h).

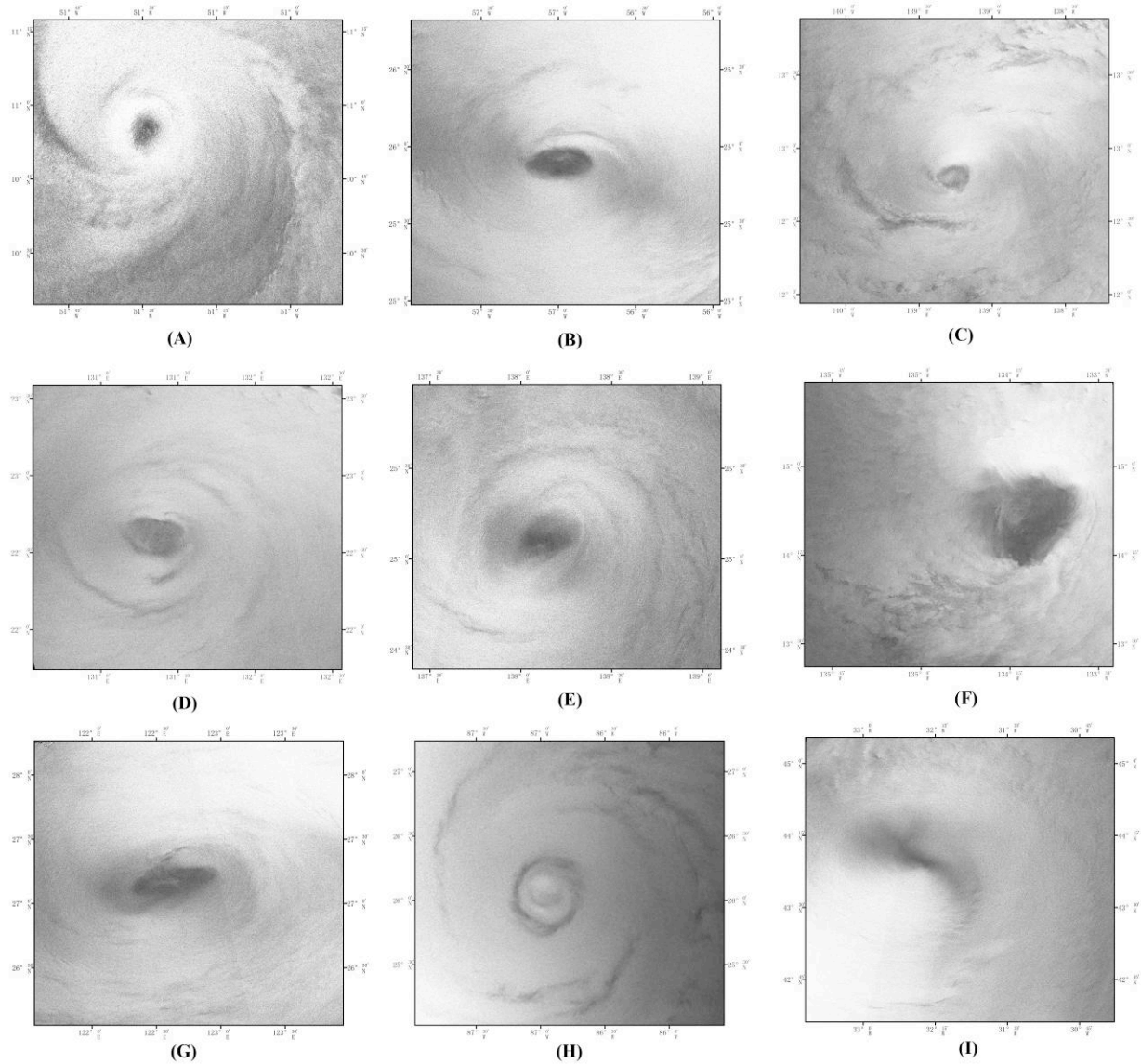


Figure 2. Examples of SAR hurricanes with different eye shapes

- (A) Circular eye. Hurricane IVAN, 2004-9-6 09:06:22
- (B) Elliptical eye. Hurricane HELENE, 2006-9-20 21:52:31
- (C) Triangular eye. Hurricane JOVA, 2005-9-18 03:25:08
- (D) Rectangular eye. Typhoon KIROGI, 2005-10-14 09:12:13
- (E) Elliptical to triangular eye. Typhoon GUCHOL, 2005-8-22 20:38:52
- (F) Triangular to square eye. Hurricane KENNETH, 2005-9-22 03:08:42
- (G) Sigma shaped eye, Typhoon MATSA, 2005-8-5 09:55:08
- (H) Bright eye, Hurricane RITA, 2005-9-22 03:44:32
- (I) Asymmetric eye, hurricane HELENE, 2006-9-25 08:10:03

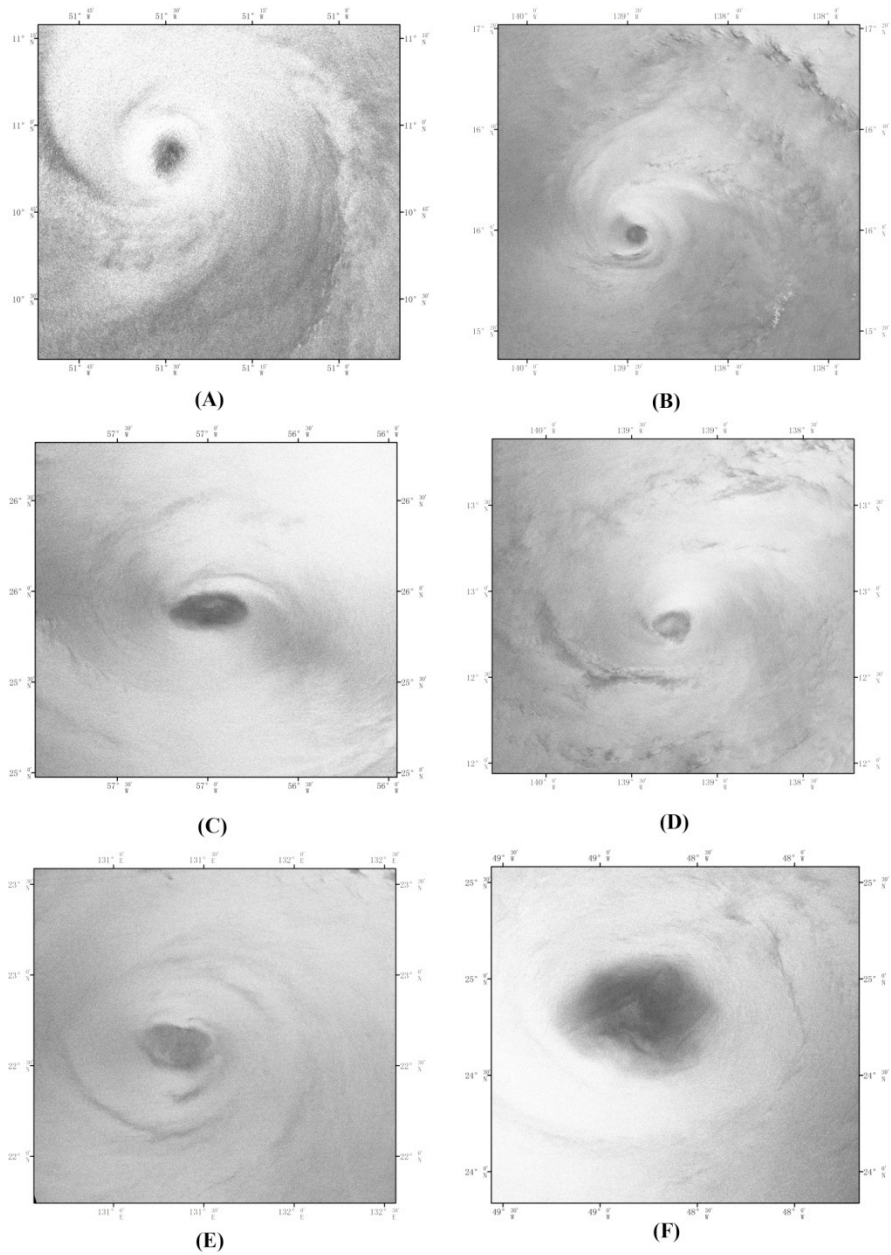


Figure 3. Examples of SAR hurricanes with different eye wall types.

- (A) Wavenumber 0. Hurricane IVAN, 2004-9-6 09:06:22
- (B) Wavenumber 1. Hurricane KENNETH, 2005-9-25 03:21:45
- (C) Wavenumber 2. Hurricane HELENE, 2006-9-20 21:52:31
- (D) Wavenumber 3. Hurricane JOVA, 2005-9-18 03:25:08
- (E) Wavenumber 4. Typhoon GUCHOL, 2005-8-22 20:38:52
- (F) Wavenumber 5. Hurricane ERIN, 2001-9-13 10:03:10

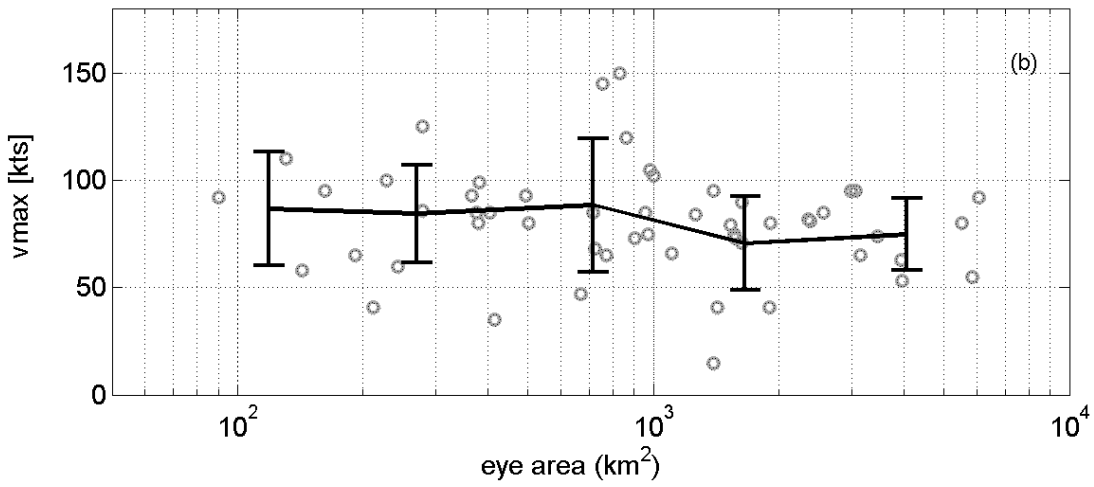
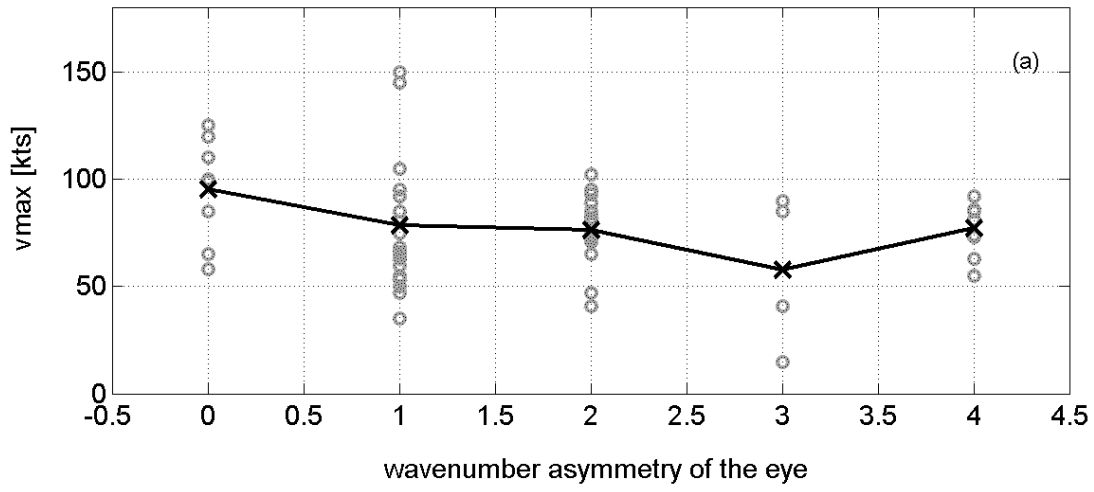


Figure 4. The wavenumber asymmetry and hurricane eye size versus maximum hurricane wind

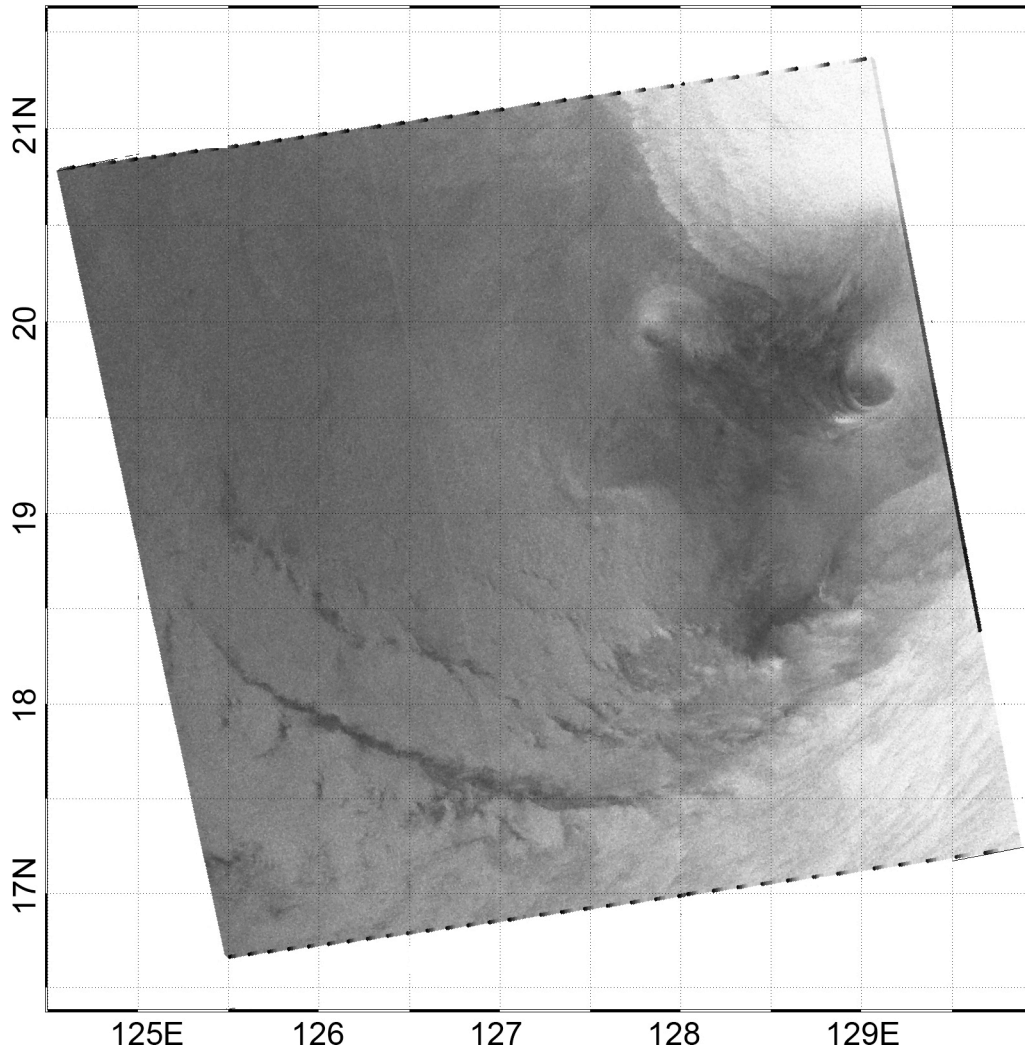


Figure 5. Hurricane Eye-eyewall mesovortices  
(Tropical storm Bilis, 09:35:42 UTC, 2006-7-11)

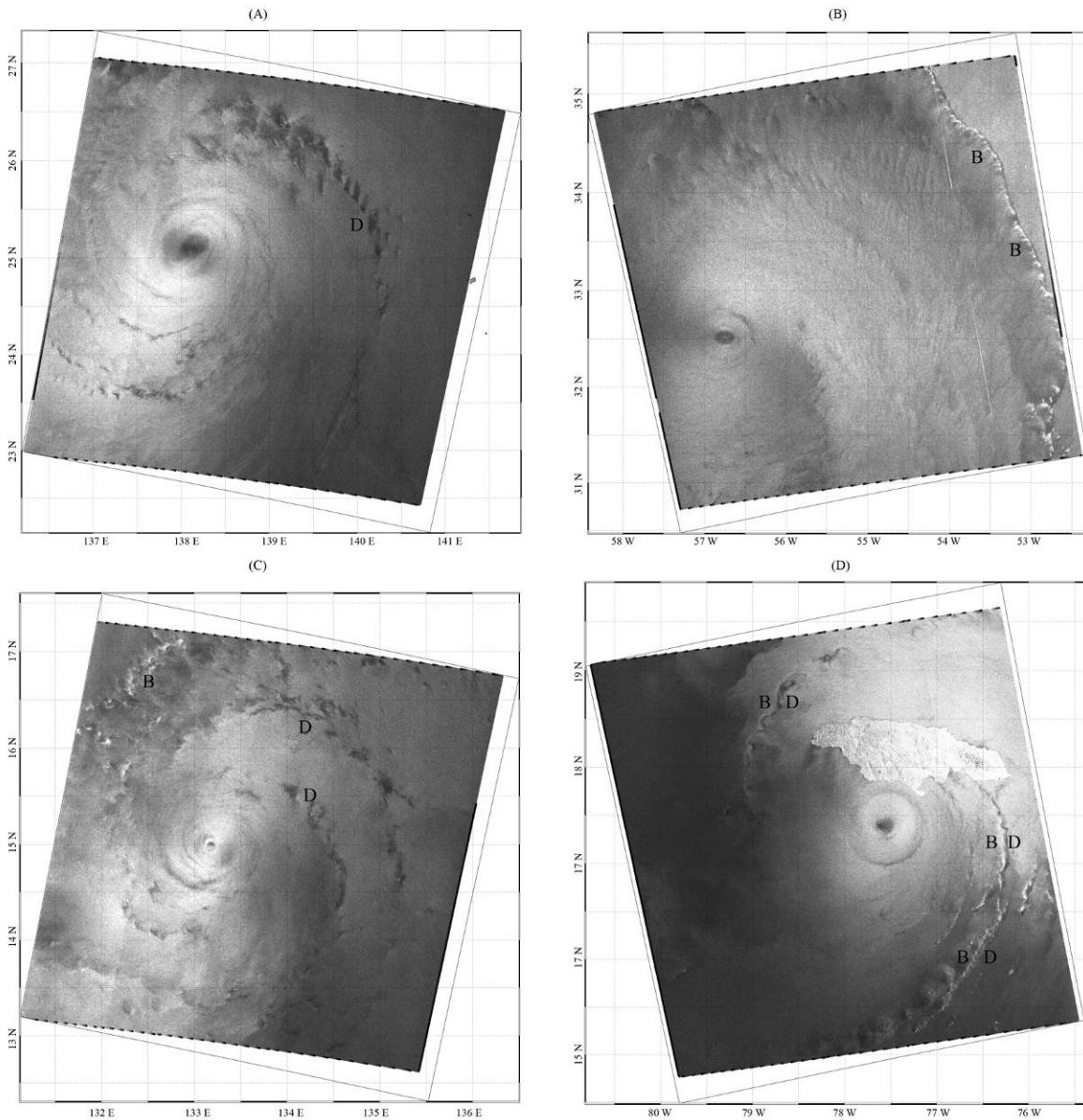


Figure 6. Different rain band patterns observed in SAR images (All RADARSAT-1 images) (A) Dark rain pattern. Typhoon Guchol, 20:38:49 UTC, August 22, 2005; (B) Bright rain pattern. Hurricane Maria, 21:37:58 UTC, September 5, 2005; (C) Dark pattern in inner rain circle, and bright pattern in outer rain circle. Typhoon Ewinari, 20:53:52 UTC, July 3, 2006; (D) Bright-dark rain pattern in the same rain band. Hurricane Dean, 23:16:40 UTC, August 19, 2007. Figures 5a and 5d also clearly reveal the signature of arc clouds. Letters “B” and “D” stand for “Bright” and “Dark”, respectively.



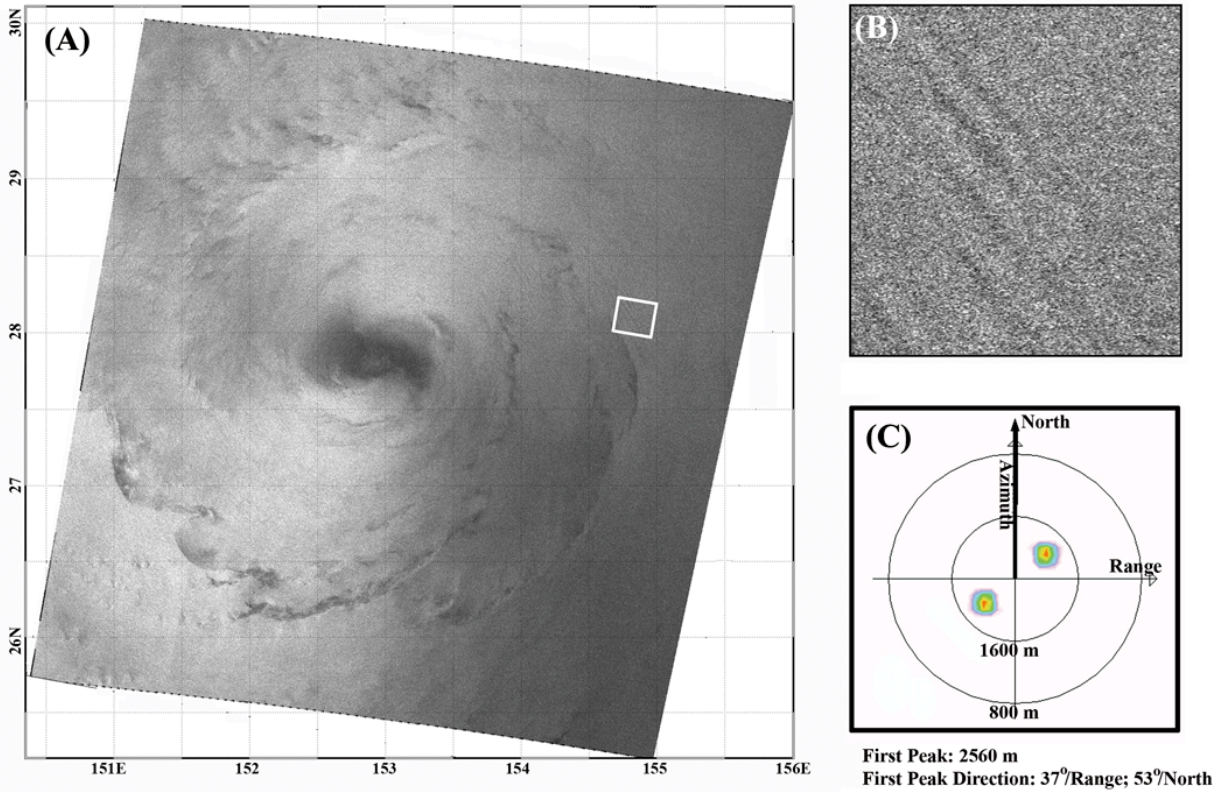


Figure 7, Analysis of boundary layer rolls within Typhoon Fitow. (A) is a SAR image acquired at 19:42:51 on August 1, 2007. Full resolution subimage in the white box is shown in (B) and its two dimensional FFT analysis in (C), shows the dominant wavelength and orientation of the boundary layer rolls with 180 degree ambiguity. The dominant wavelength is 2560 m and its direction is 37° (53°) with respect to the satellite flying range (true North) direction.

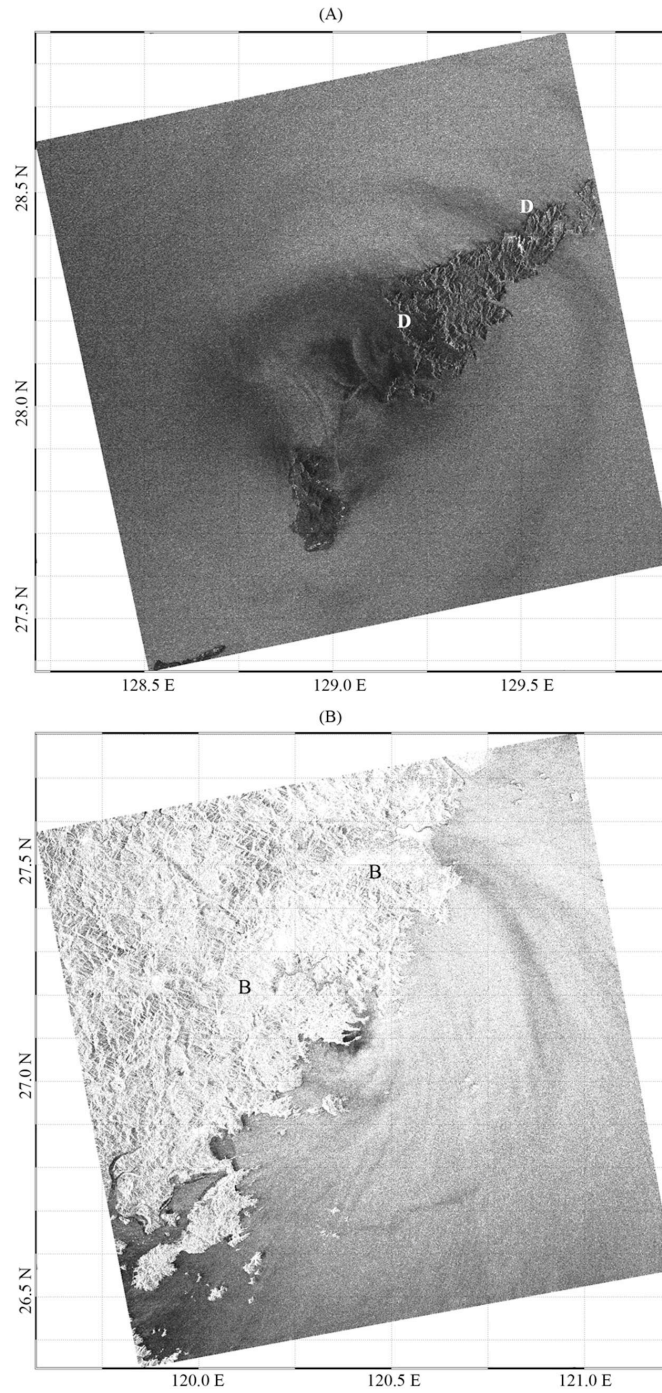


Figure 8. Hurricane patterns over ocean/land observed on SAR images:  
(A) Category 3 Typhoon Etai, 09:17:59 UTC, August 7, 2003; (B) Category 5 Typhoon Saomai,  
10:02:03 UTC, August 10, 2006.

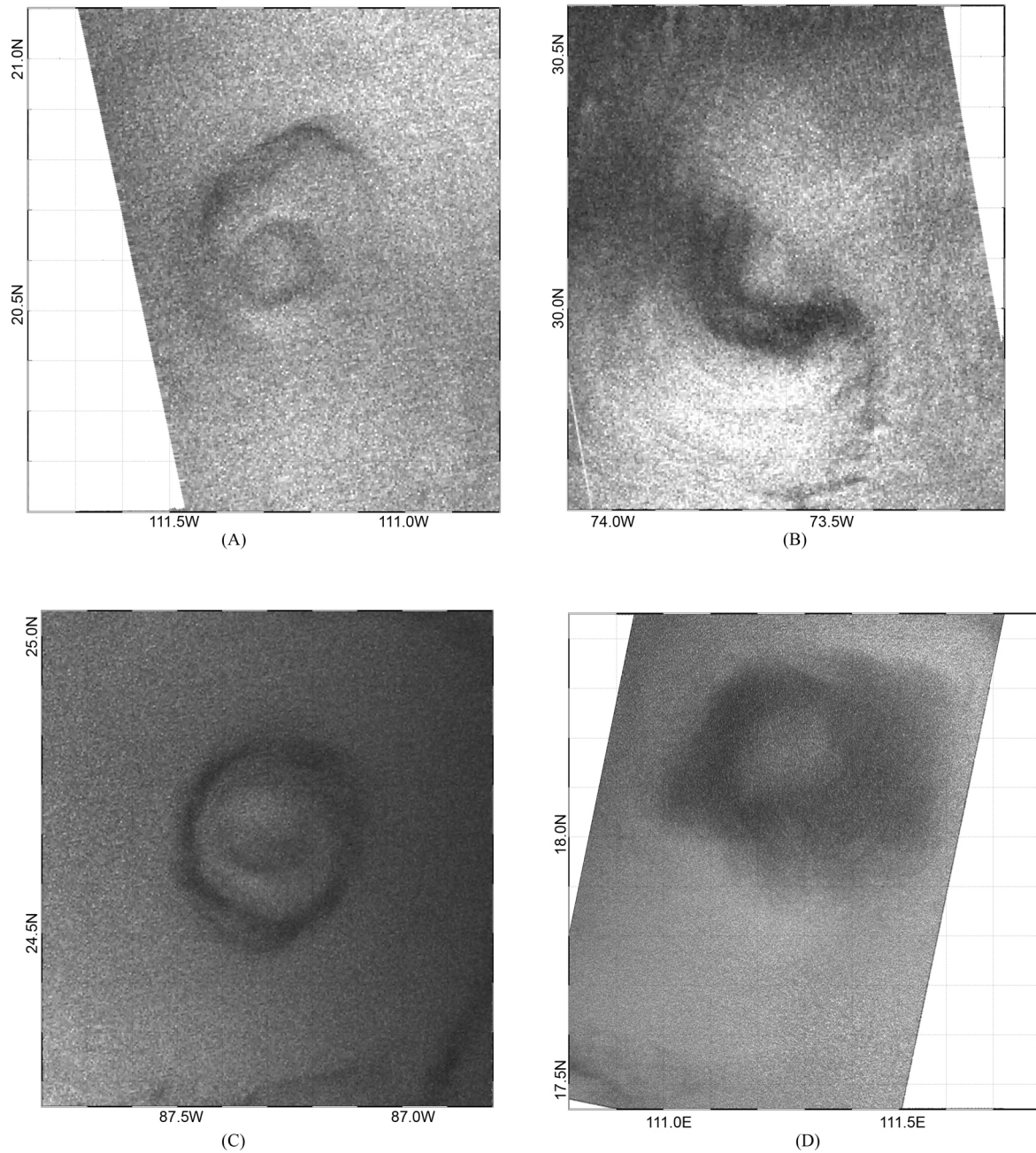


Figure 9. SAR images showing abnormally high roughness area within hurricane eyes. (A) 2004/9/17 1:21:43, RADARSAT-1, Hurricane Javier (Category 2), Bright circle eye; (B) 2005/7/23, RADARSAT-1, Tropical storm Franklin (TS) Bright eye; (C) 2005/9/22, Envisat, Hurricane Rita, Bright circle eye; (D) 2008/4/18, Envisat, Typhoon Neoguri (Category I).