SAR Maritime Applications

Wind and Waves

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SAR Maritime Applications

Friday, 11 Sep, Morning:

1 - History & Basics
- Introduction
- Radar/SAR History
- Basics
- Scatterometer

2 - Wind and Waves
- SAR Wind Fields
- Storms, Tropical Cyclones
- Ocean Surface Waves
- Oceanic Internal Waves
- Marine Surface Films
- Rain

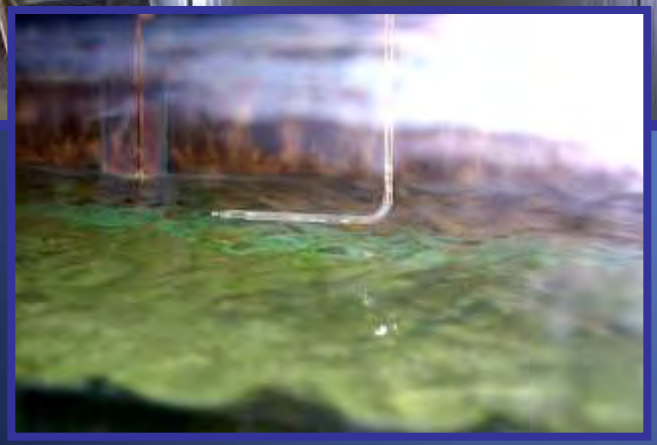
Friday, 11 Sep, Afternoon:

3 - Currents and Objects
- Surface Currents
- Sea Bottom Topography
- Ship Detection
- Oil Pollution Monitoring
- Sea Ice

4 - Exercises
- Sentinel 1 Toolbox:
- Calibration, Georeferencing,
- Wind Fields, Oil Pollution,
- Radar Contrast,
- Statistics

SAR Wind Fields

Wind-Wave Tank of the University of Hamburg



UHH's Wind-Wave Tank

Size: 24 m × 1 m × 1.5 m
Water depth: 0.5 m (freshwater)
Wind: 2 – 20 m/s
Rain: up to 160 mm/h @ 12.5 – 14.8 m

Wind-Roughened Water Surface

Geophysical Model Function

CMOD4 (Stoffelen and Anderson, 1997)

$$\sigma_0 = b_0[1 + b_1 \cos\chi + b_3 \tanh(b_2 \cos 2\chi)]^{1.6}$$

with

$$b_0 = c_r \times 10^{\alpha+\gamma \cdot f_1(U_{10}+\beta)}$$

$f_1(y) = -10$ for $y \le 10^{-10}$ (negligibly small winds)

$= \log y$ for $10^{-10} < y \le 5$ (low to moderate winds)

$= \frac{\sqrt{y}}{3.2}$ for $y > 5$ (moderate to high winds)

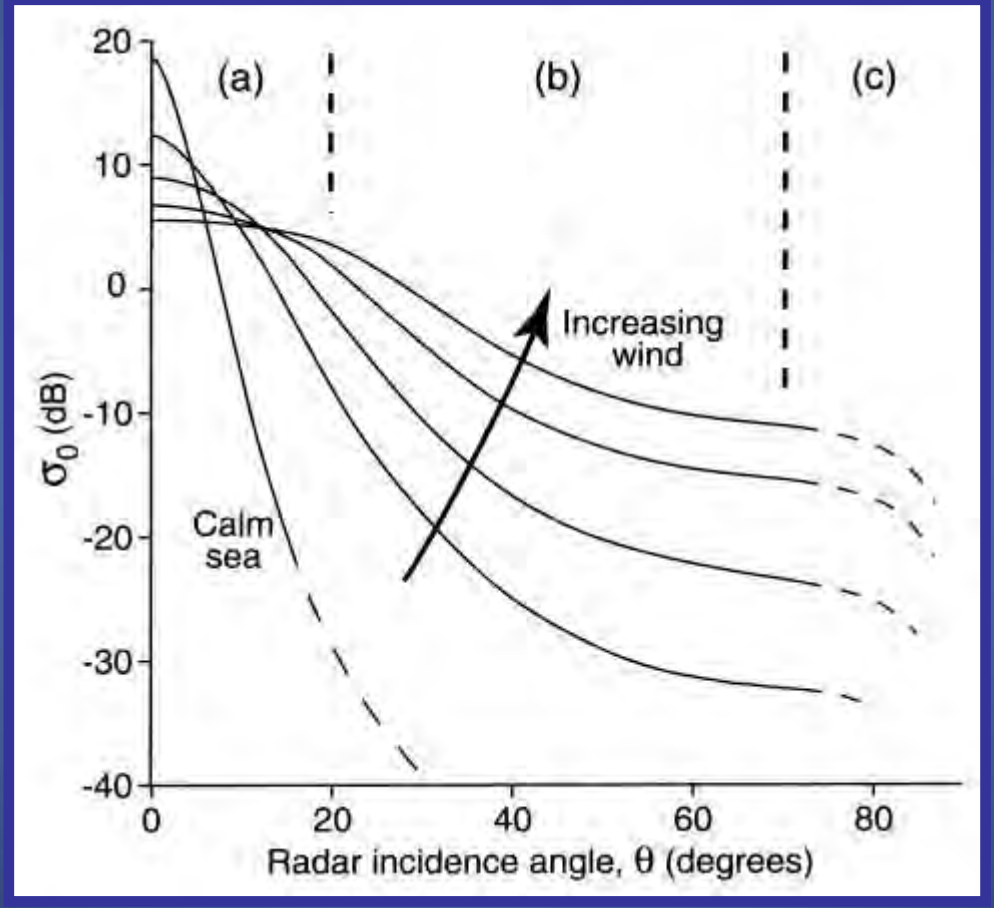
$$\alpha = c_1 P_0 + c_2 P_1 + c_3 P_2$$
$$\gamma = c_4 P_0 + c_5 P_1 + c_6 P_2$$
$$\beta = c_7 P_0 + c_8 P_1 + c_9 P_2$$
$$b_1 = c_{10} P_0 + c_{11} U_{10} + (c_{12} P_0 + c_{13} U_{10}) f_2(x)$$
$$b_2 = c_{14} P_0 + c_{15}(1 + P_1) U_{10}$$
$$b_3 = 0.42 \cdot [1 + c_{16}(c_{17} + x)(c_{18} + U_{10})]$$
$$f_2(x) = \tanh[2.5(x + 0.35)] - 0.61(x + 0.35)$$

$P_0 = 1$ $P_1 = x$ $P_2 = \frac{3x^2-1}{2}$ $x = \frac{\theta-40}{25}$

c_n: coefficients c_r: residual correction term

Microwave Basics

Radar backscattering from the sea surface



[Robinson, 2003]

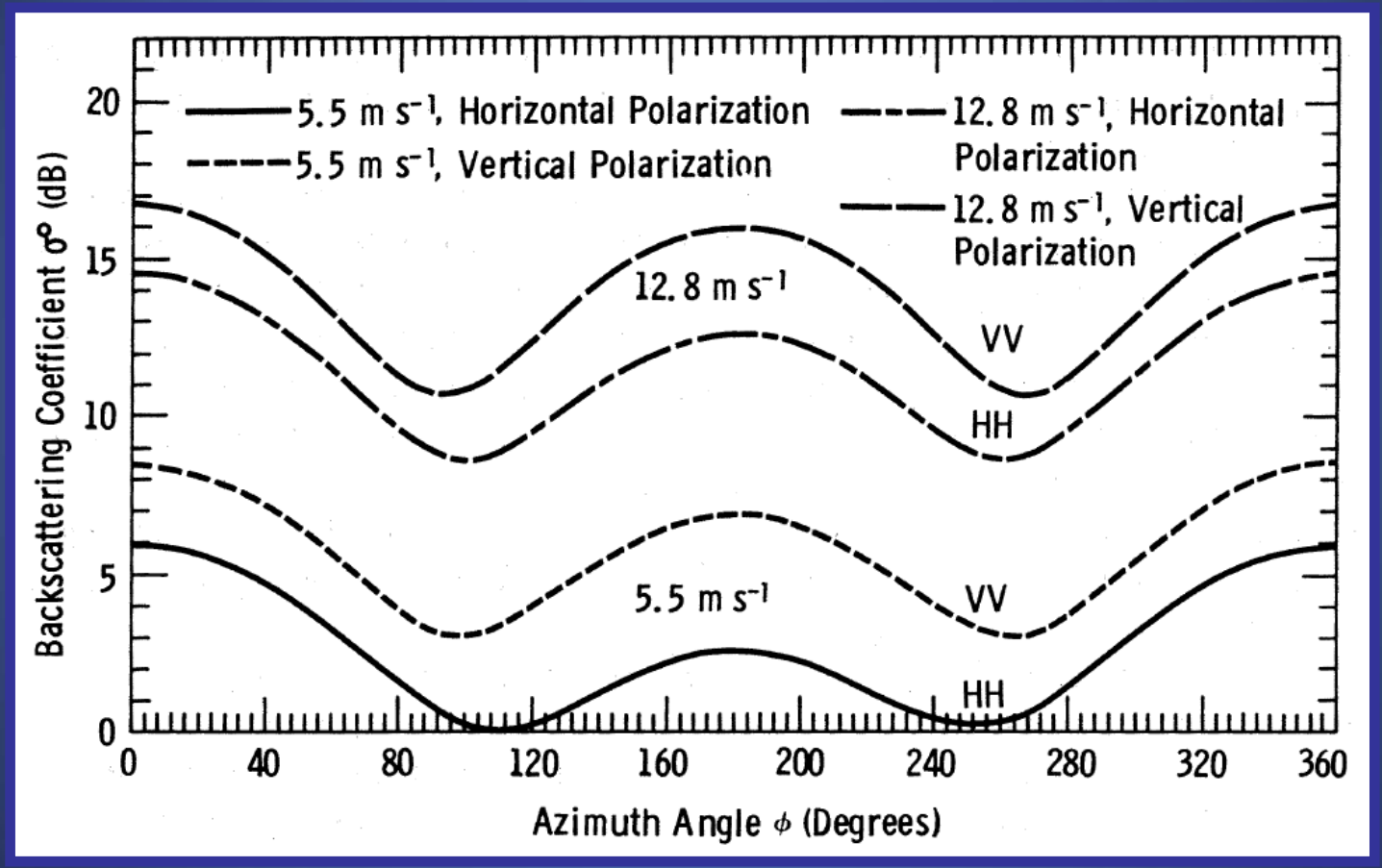
(a) specular

(b) Bragg

(c) edges & shadowing

SAR Wind Fields

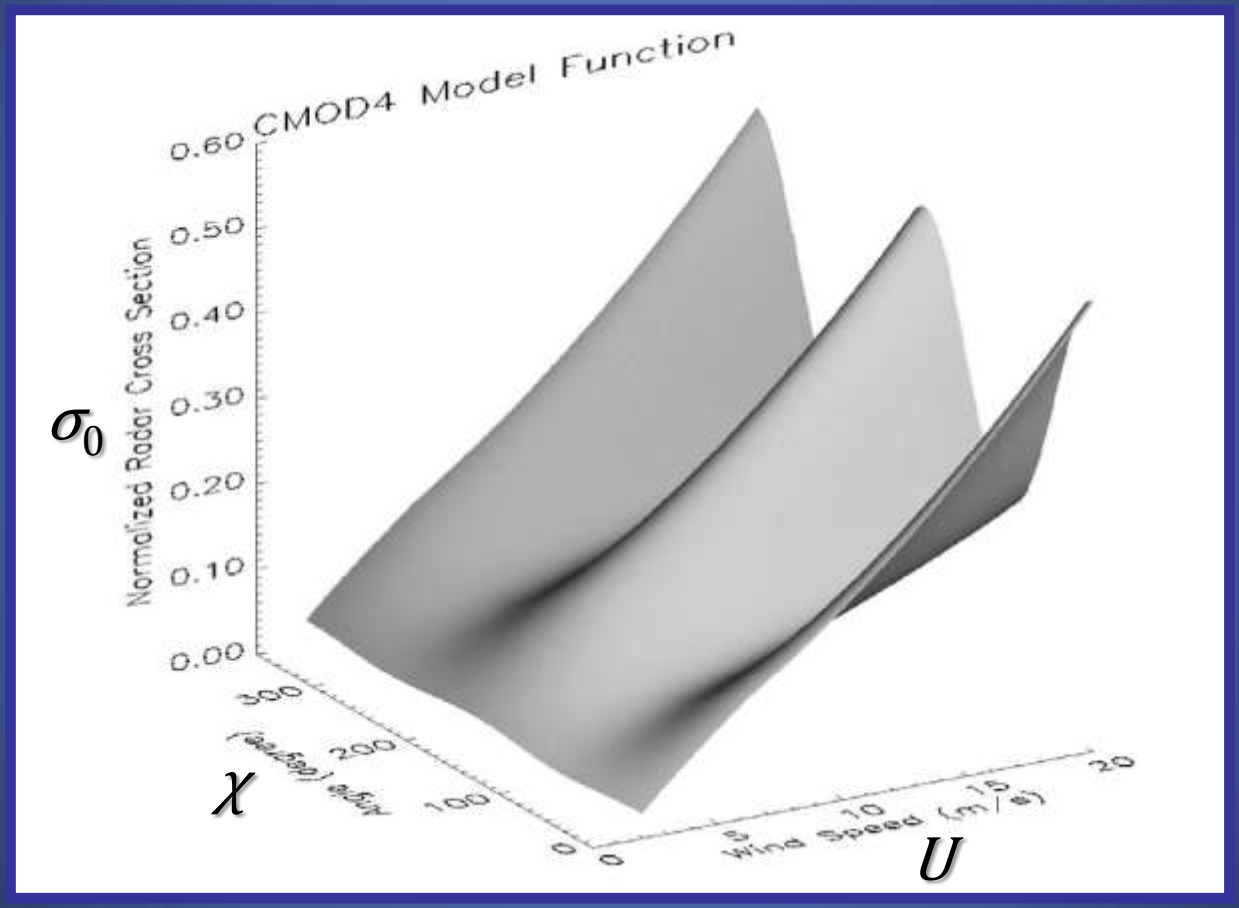
Measuring wind speed and direction



[Jackson and Apel, 2004]

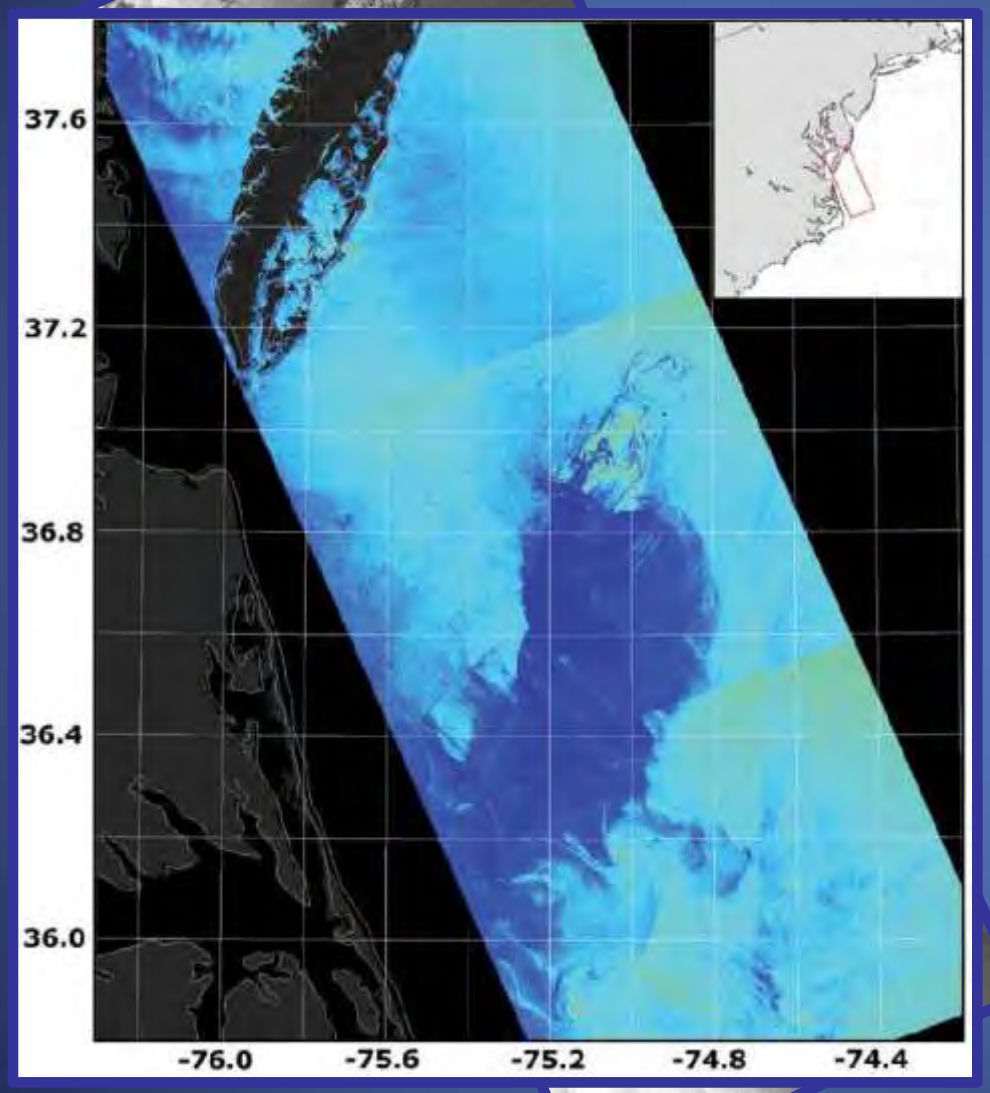
SAR Wind Fields

Measuring wind speed and direction

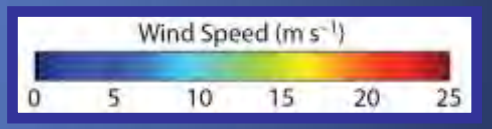


[Jackson and Apel, 2004]

SAR Wind Fields



Ocean winds



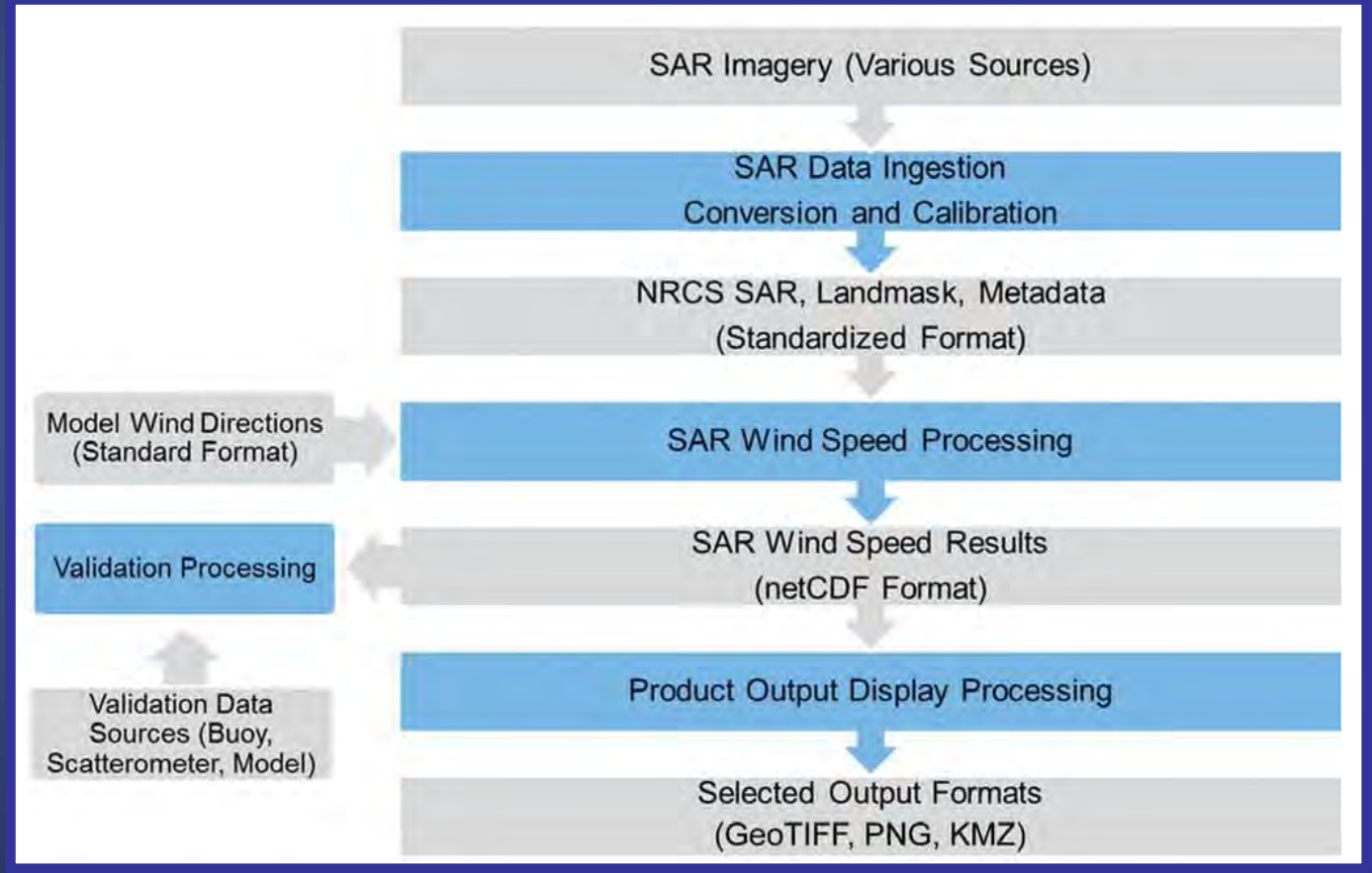
Data basis:

Seasat SAR Image (L-HH)
U.S. East Coast
(28 September 1978, 15:20 UTC)
© NASA

[Monaldo et al., 2013]

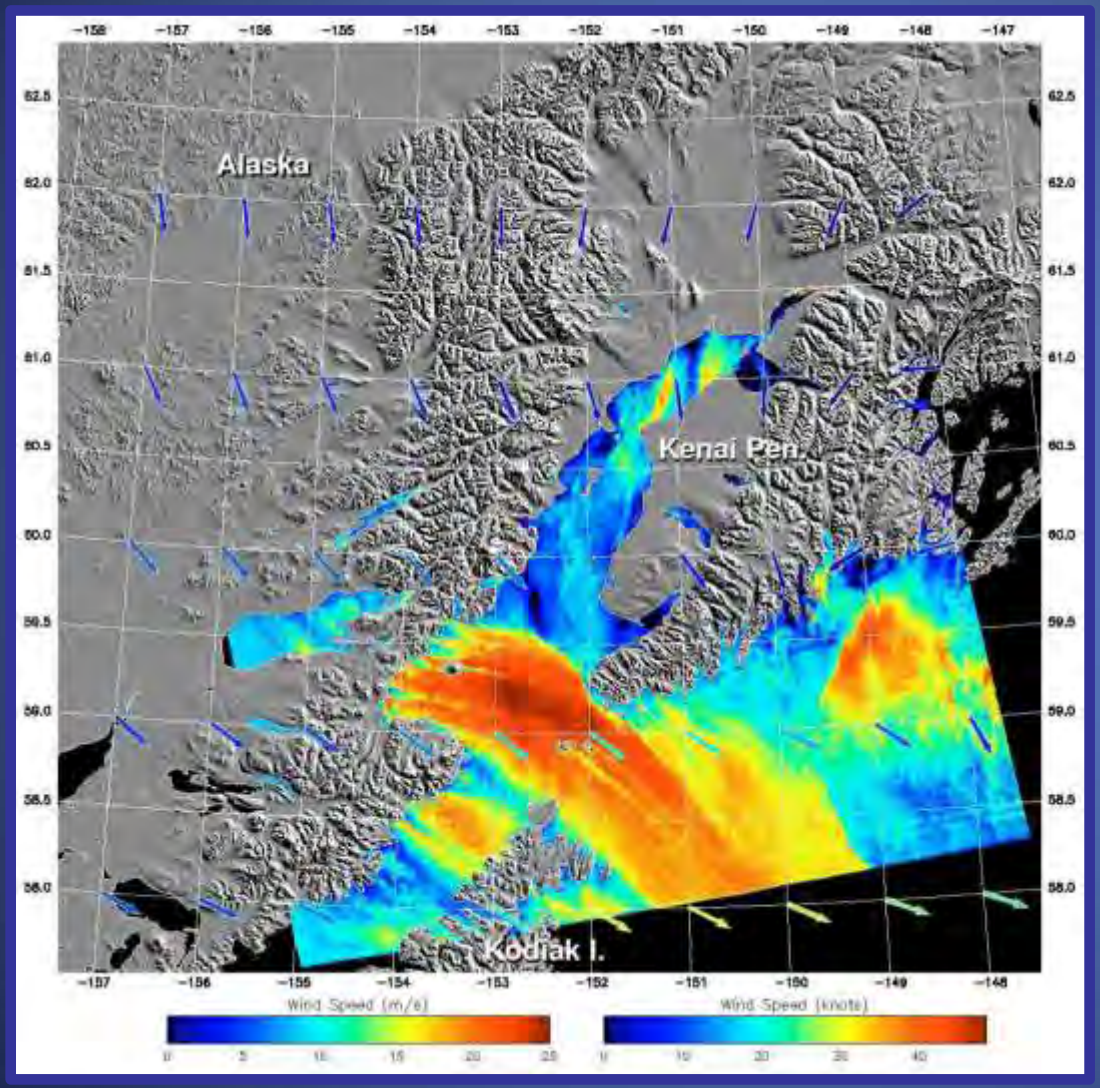
SAR Wind Fields

Processing flow (NOAA)



[Monaldo et al., 2013]

SAR Wind Fields



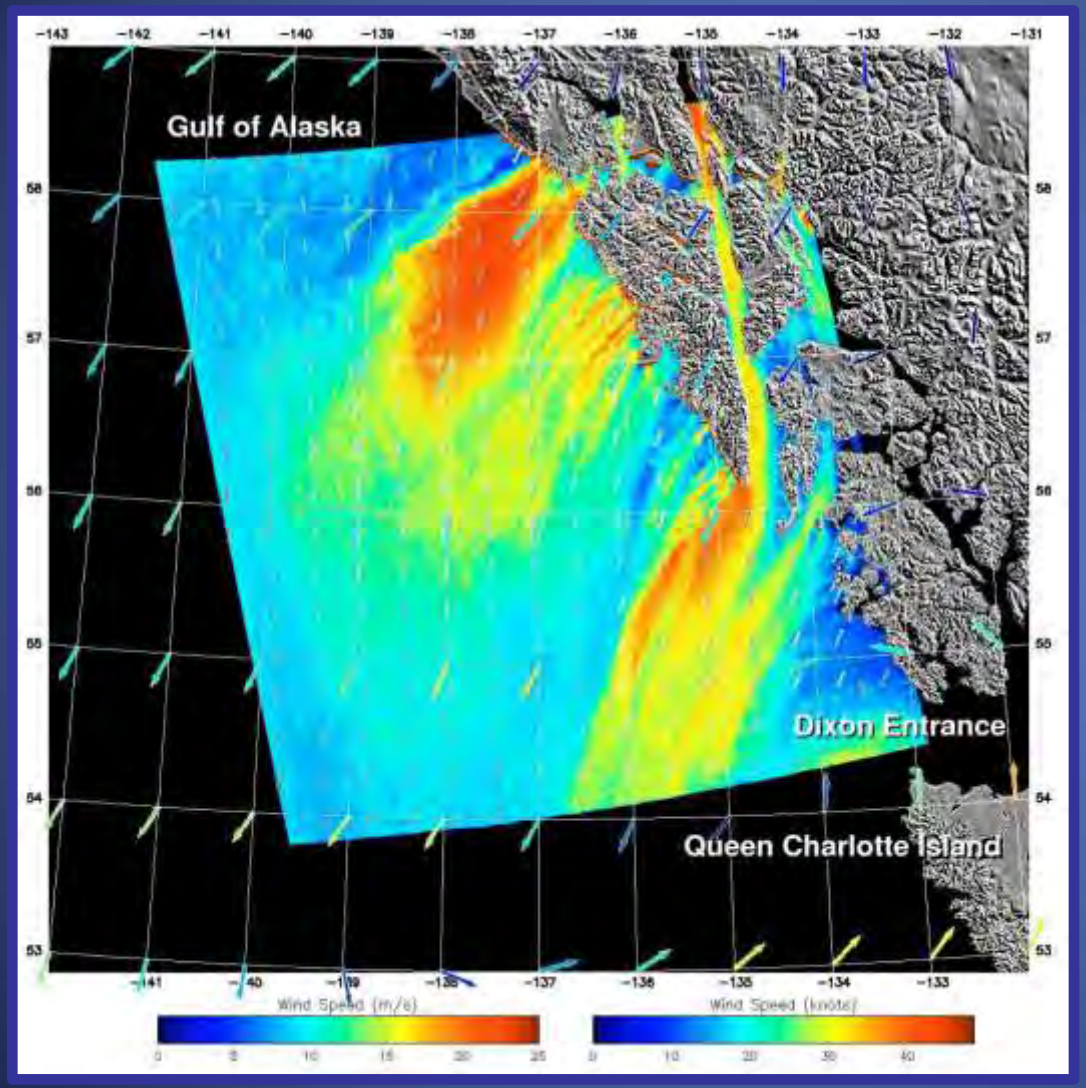
Ocean winds

Data basis:

Radarsat-1 SAR Image (C-HH)
Kodiak Island
(31 October 2000, 03:44 UTC)
© CSA

[Jackson & Apel, 2004]

SAR Wind Fields



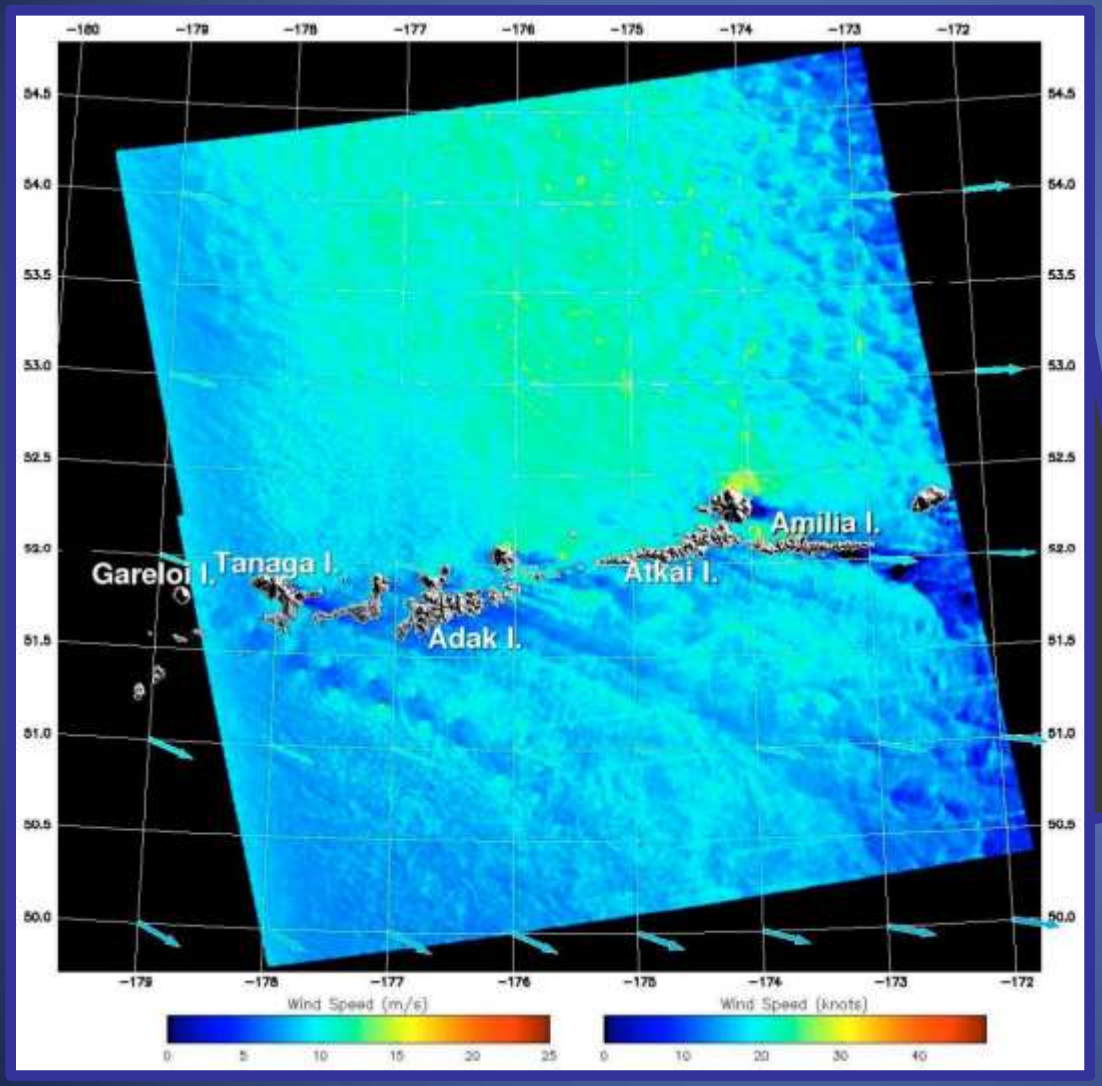
Ocean winds

Data basis:

Radarsat-1 SAR Image (C-HH)
Gulf of Alaska
(19 March 2001, 02:48 UTC)
© CSA

[Jackson & Apel, 2004]

SAR Wind Fields



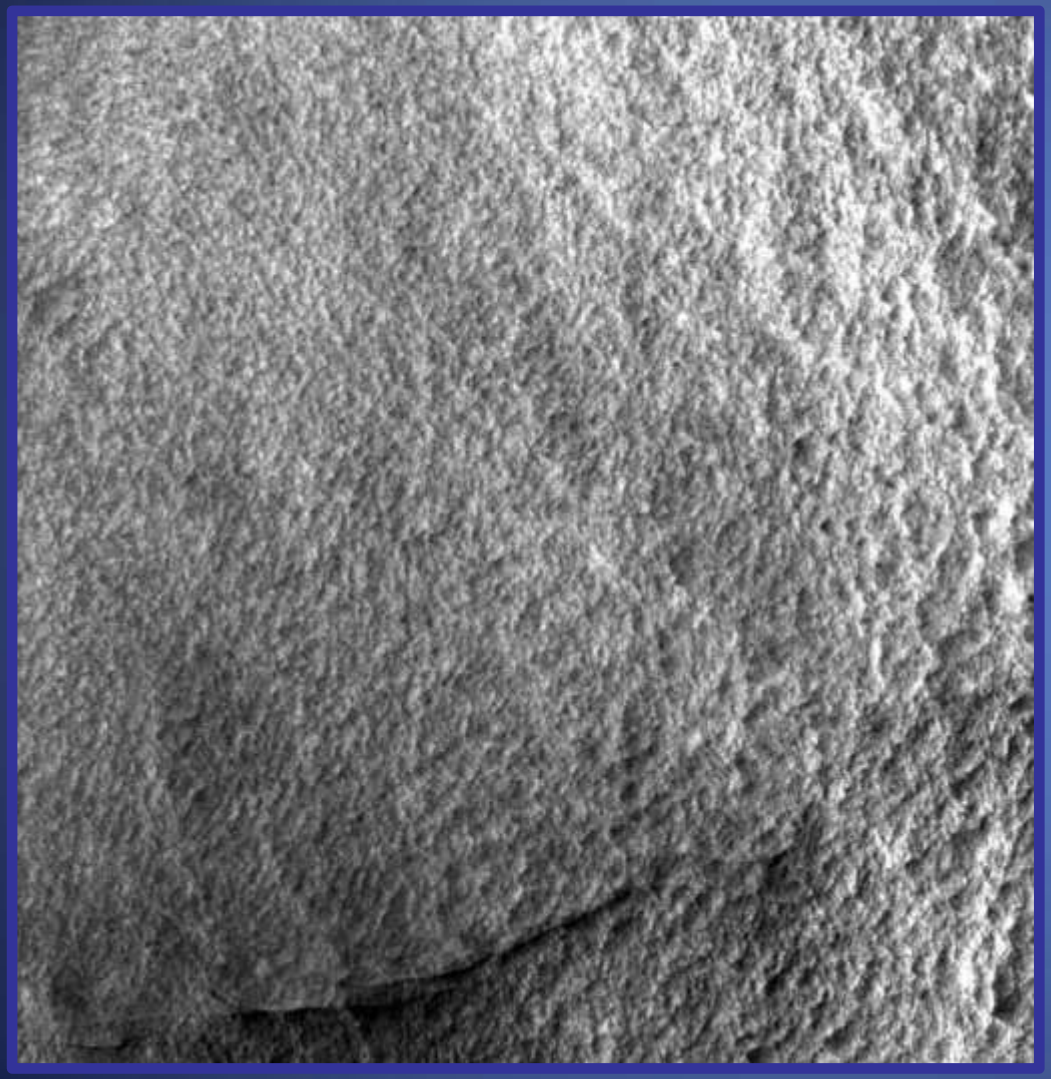
Ocean winds

Data basis:

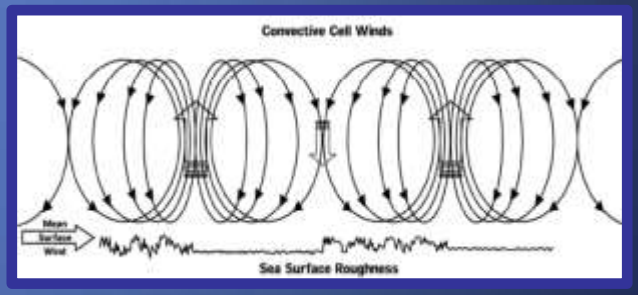
Radarsat-1 SAR Image (C-HH)
Aleutian Islands
(04 May 2001, 05:26 UTC)
© CSA

[Jackson & Apel, 2004]

SAR Wind Fields



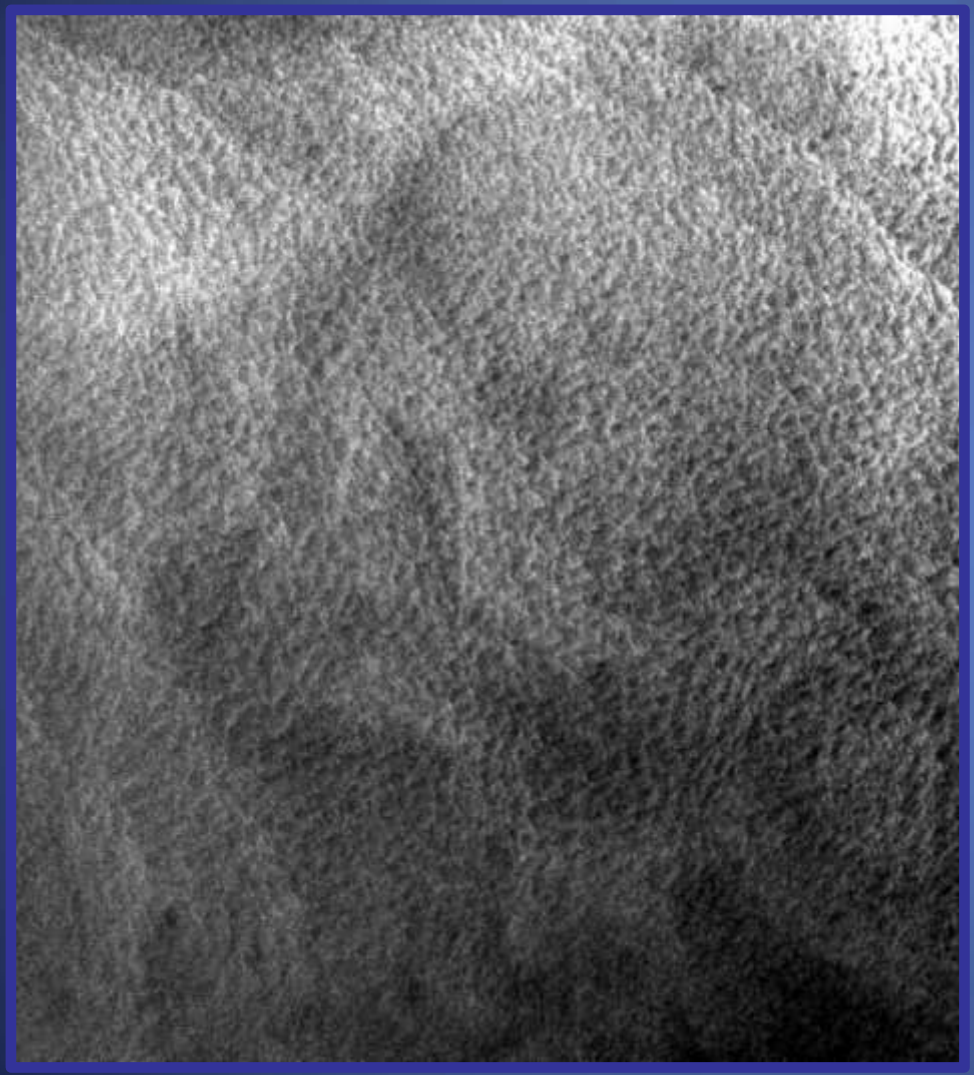
Atmospheric convective cells



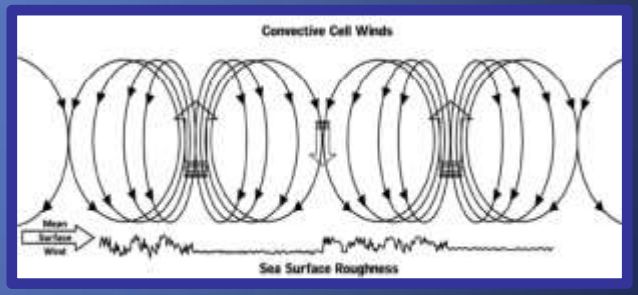
[Jackson & Apel, 2004]

Radarsat-1 SAR Image (C-HH, 300 km × 300 km) U.S. East Coast (17 January 1997, 22:42 UTC, © CSA)

SAR Wind Fields



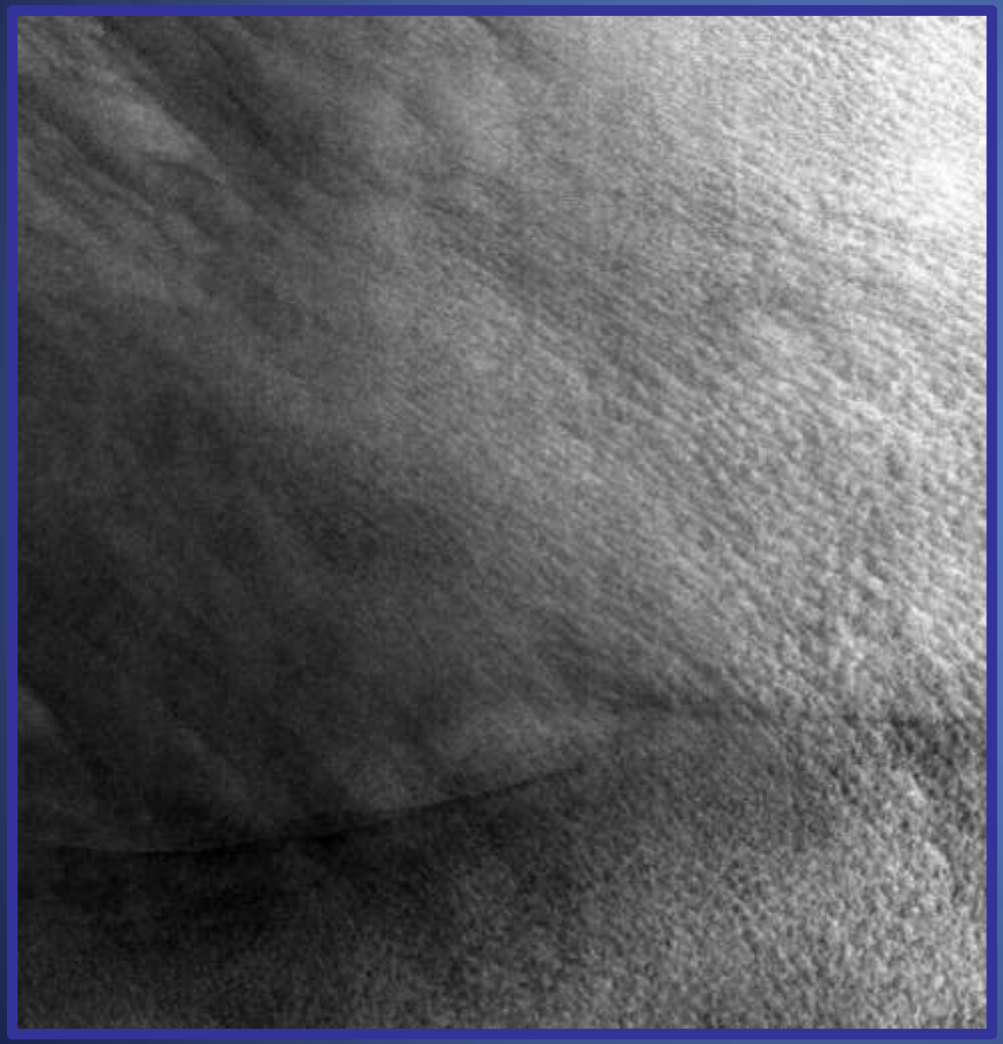
Atmospheric convective cells



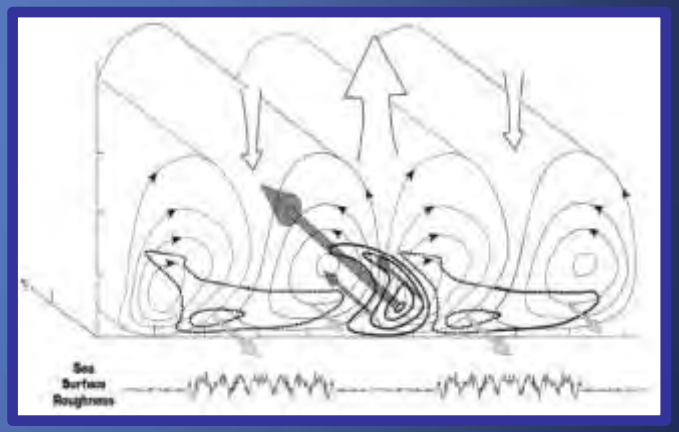
[Jackson & Apel, 2004]

Radarsat-1 SAR Image (C-HH, 300 km × 300 km) U.S. East Coast (6 March 1997, 22:42 UTC, © CSA)

SAR Wind Fields



Atmospheric roll vortices

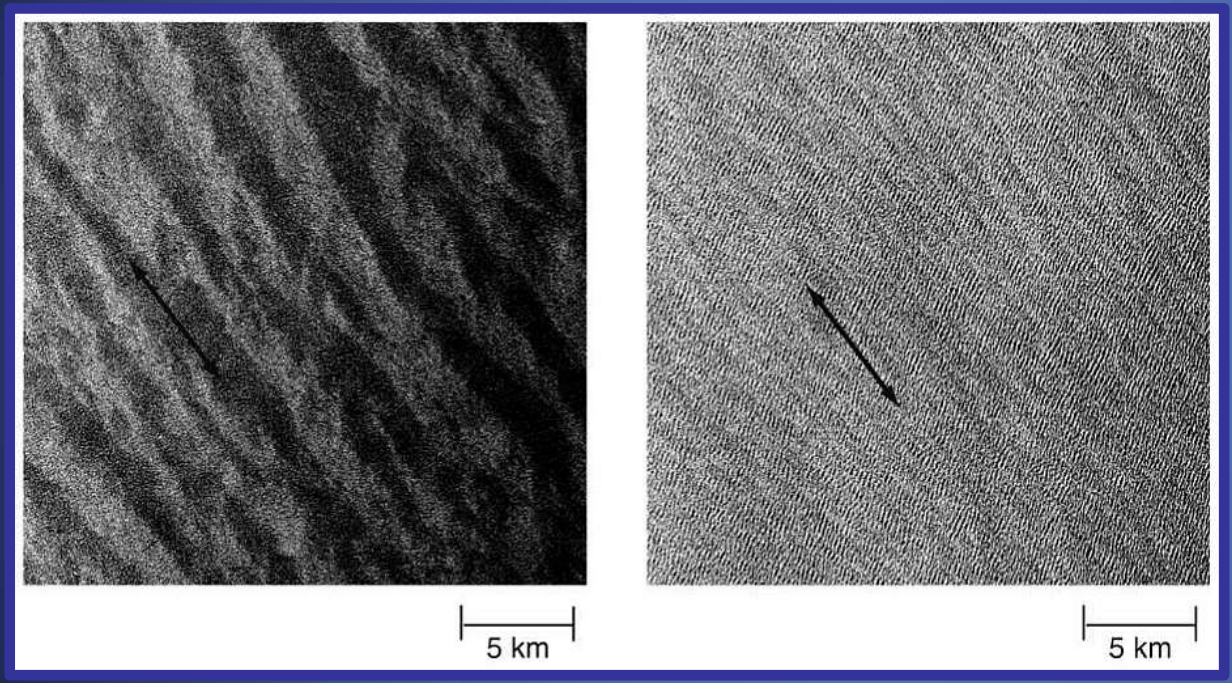


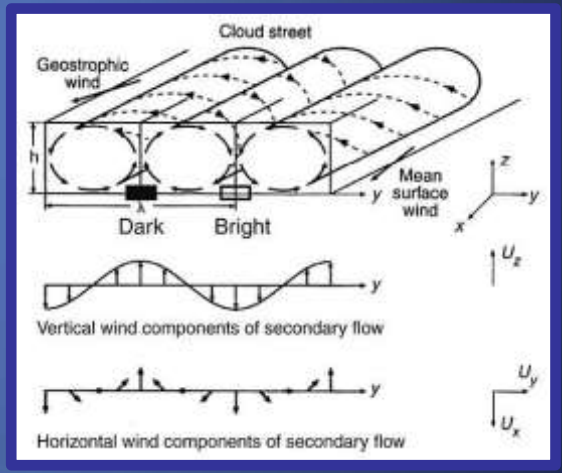
[Jackson & Apel, 2004]

Radarsat-1 SAR Image (C-HH, 300 km × 300 km) U.S. East Coast (6 March 1997, 22:42 UTC, © CSA)

SAR Wind Fields

Atmospheric roll vortices



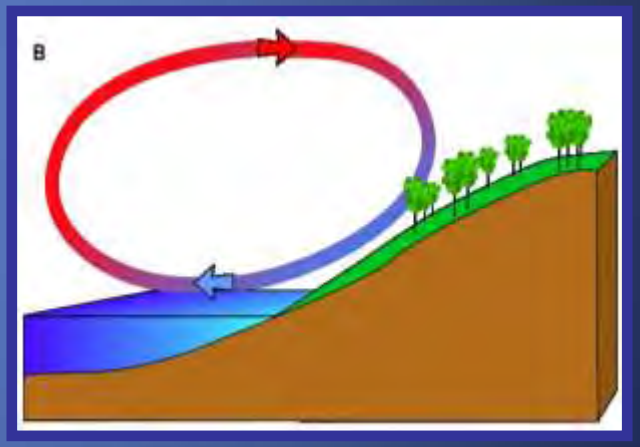


[Jackson & Apel, 2004]

Radarsat-1 Images (C-HH, 25 km × 25 km)
off Southern California
(left: 12 June 1999, right: 2 December 1998, © CSA)

SAR Wind Fields

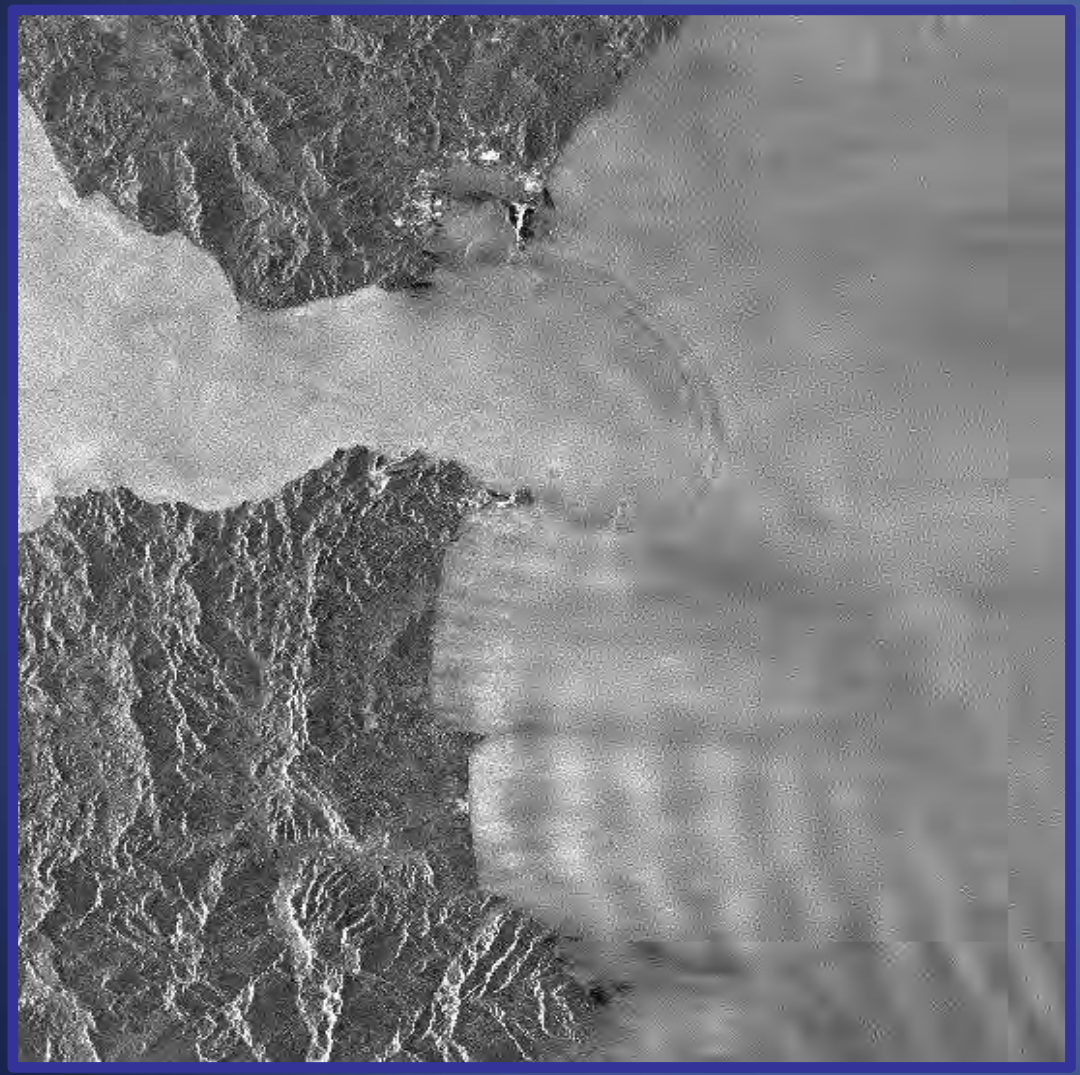
Katabatic winds &
Atmospheric convective cells



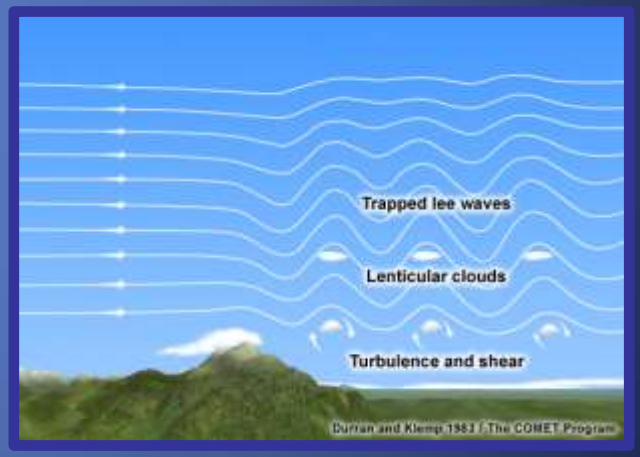
[Wikipedia, 6/2013]

ERS SAR Image (C-VV, 100 km × 100 km)
Strait of Messina
(8 September 1992, 21:13 UTC, © ESA)

SAR Wind Fields

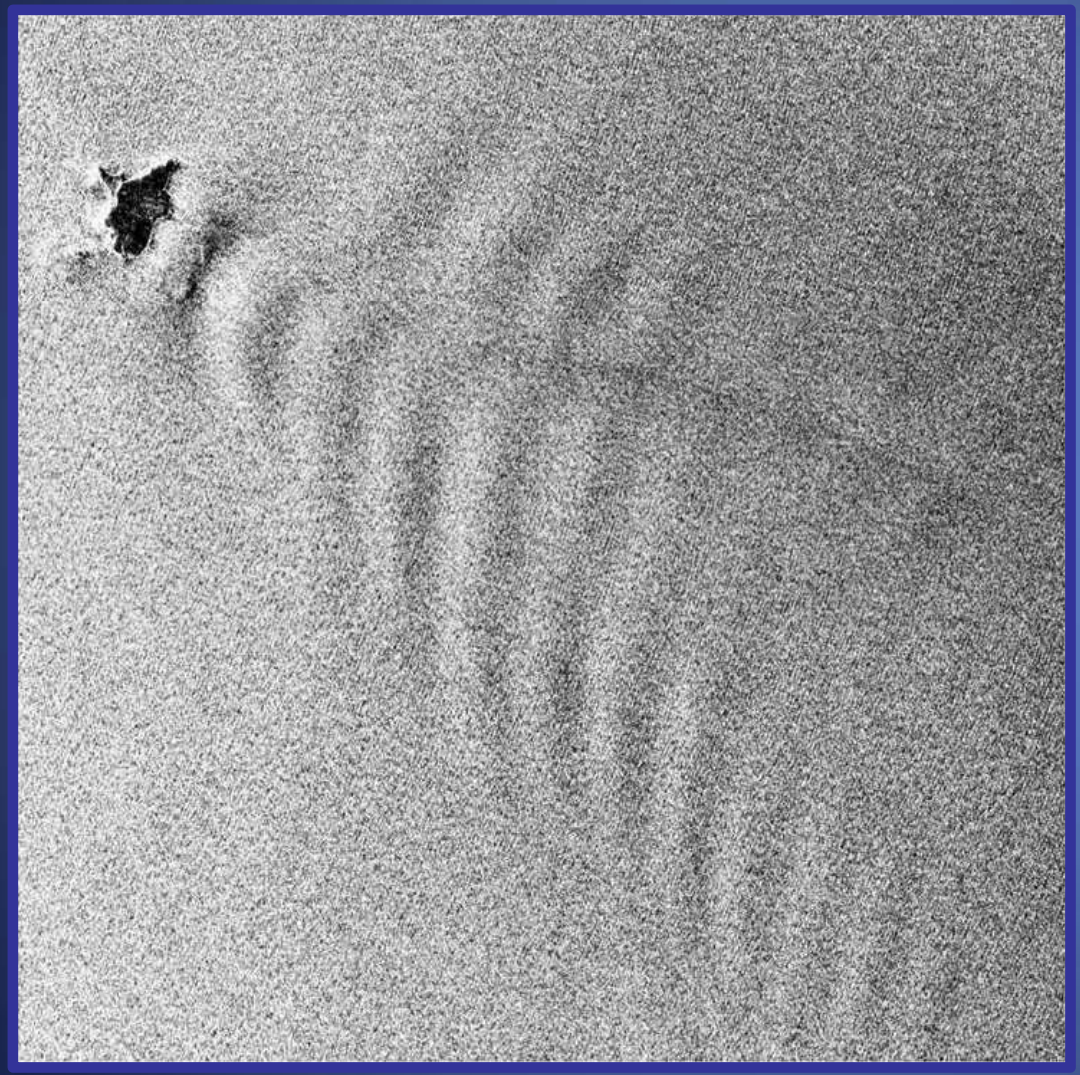


Internal waves
&
Atmospheric gravity waves

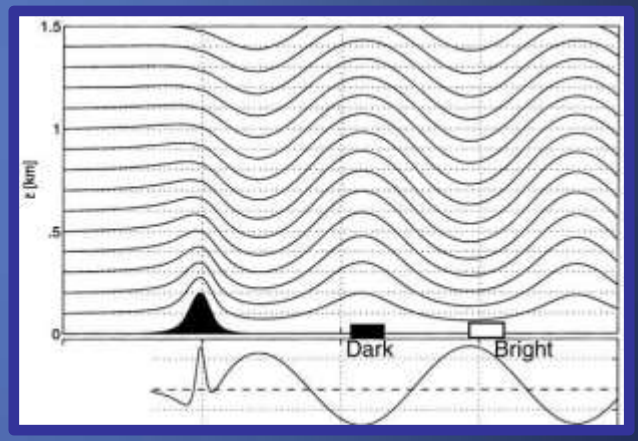


ERS SAR Image (C-VV, 100 km × 100 km)
Strait of Gibraltar
(3 September 1993, 22:39 UTC, © ESA)

SAR Wind Fields



Atmospheric lee waves (gravity waves)



[Jackson & Apel, 2004]

Radarsat-1 SAR Image (C-HH, 20km × 20km)
Santa Barbara Island
(28 July 1998, © CSA)

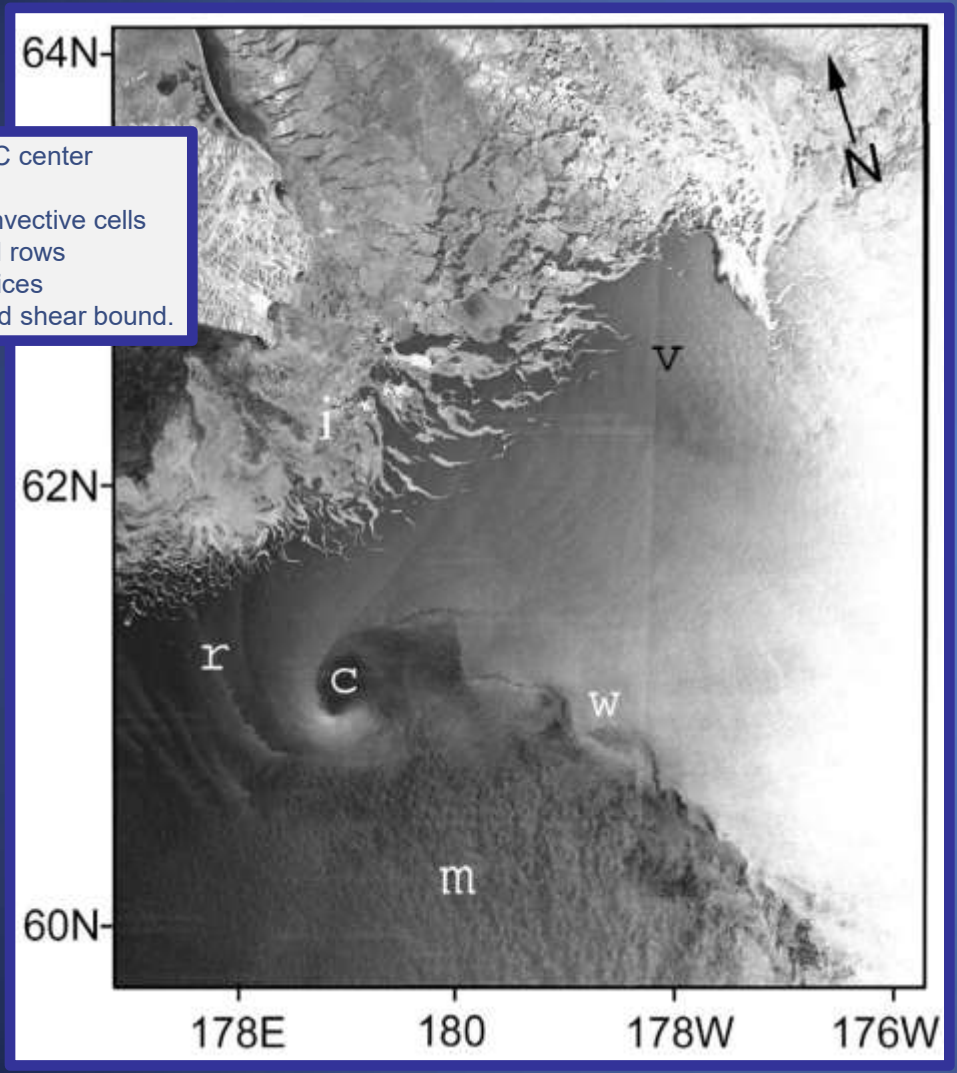
SAR Wind Fields
Take-Home Messages

High-resolution wind fields
(Sub-) Mesoscale atmospheric dynamics
Convective cells, roll vortices, lee waves

Storms, Tropical Cyclones

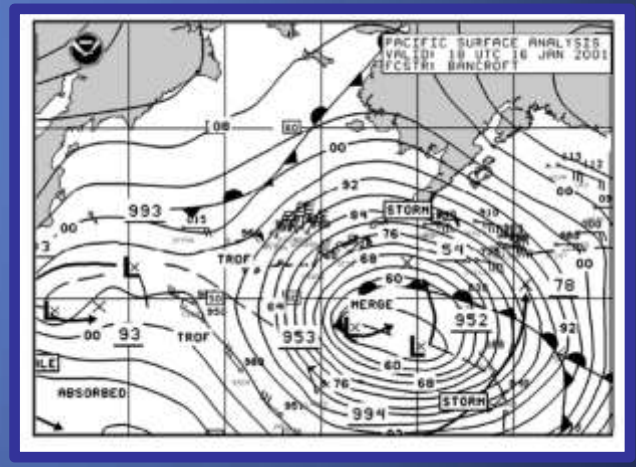
Storms & Tropical Cyclones

c: PMC center
i: ice
m: convective cells
r: wind rows
v: vortices
w: wind shear bound.



Polar mesoscale cyclone

Pacific Surface Analysis
16 Jan 2001 1800 UTC
(NOAA National Weather Service)

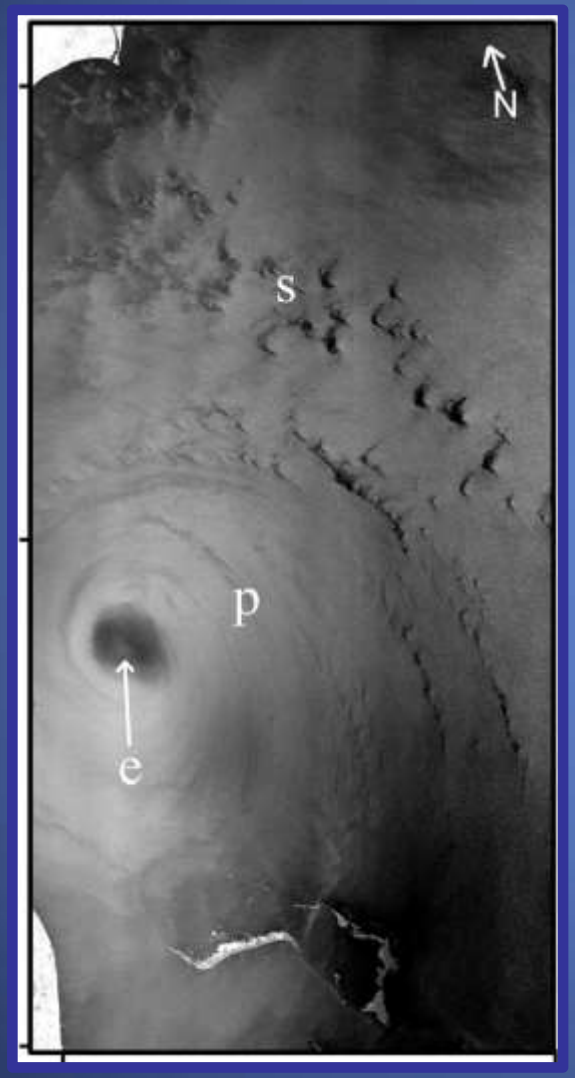


[Jackson & Apel, 2004]

Radarsat-1 ScanSAR Image (C-HH, 500 km × 600 km) - Bering Sea (16 January 2001, 18:21 UTC, © CSA)

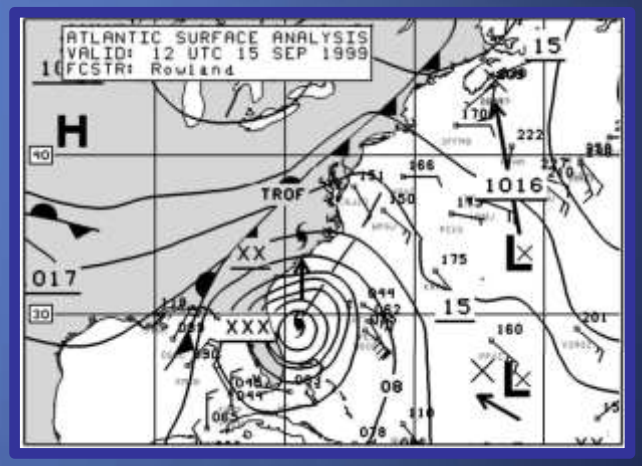
Storms & Tropical Cyclones

e: eye
p: precipitation
s: convective cells



Hurricane *Floyd*

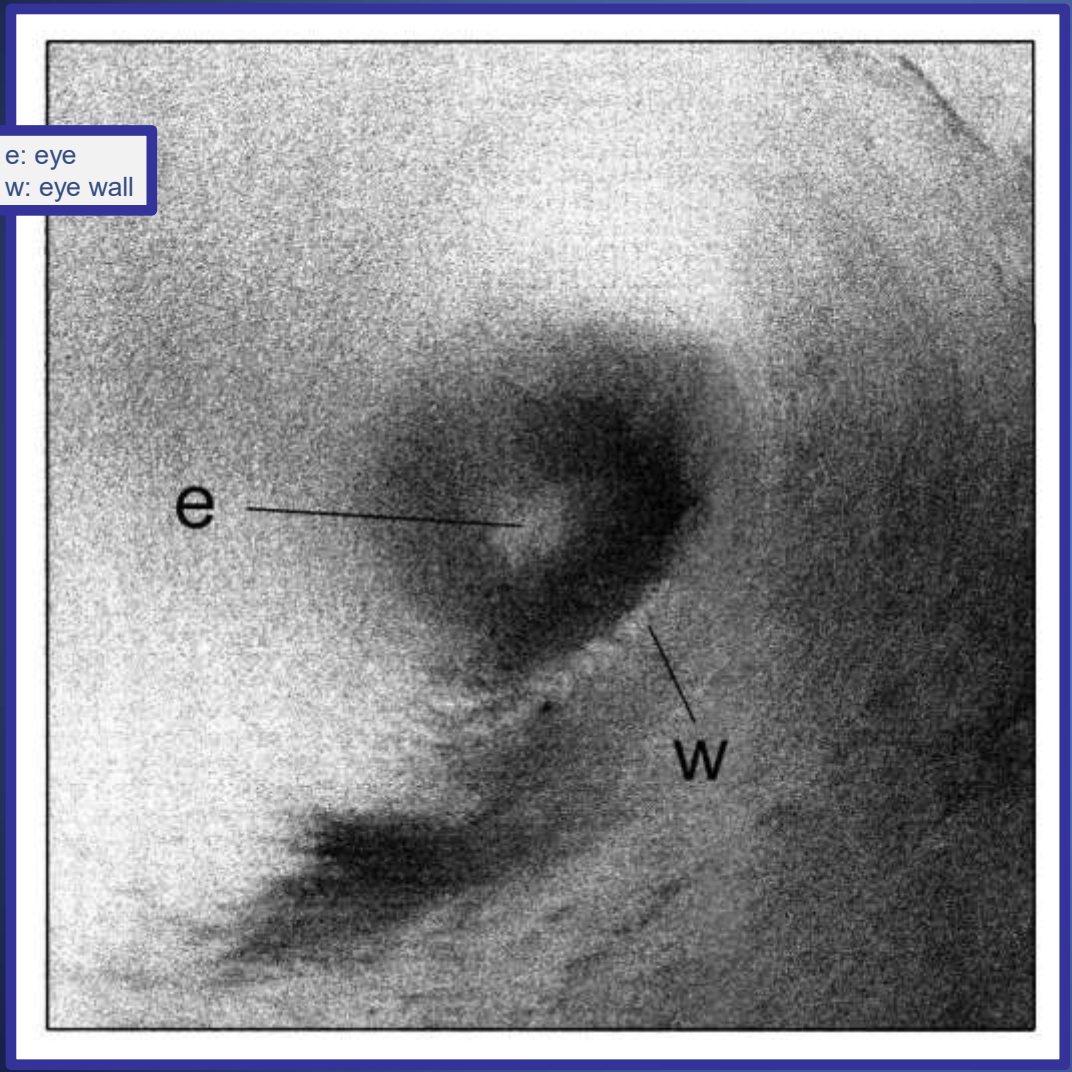
Atlantic Surface Analysis
15 Sep 1999 1200 UTC
(NOAA National Weather Service)



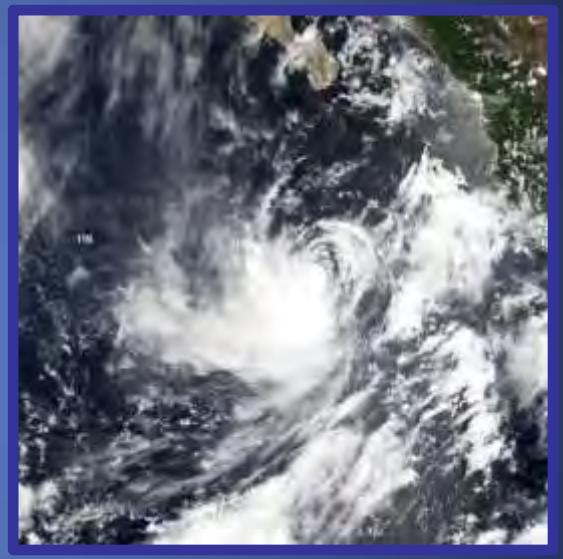
[Jackson & Apel, 2004]

Radarsat-1 ScanSAR Image (C-HH, 500 km × 1000 km)
East of Florida
(15 September 1999, 11:08 UTC, © CSA)

Storms & Tropical Cyclones



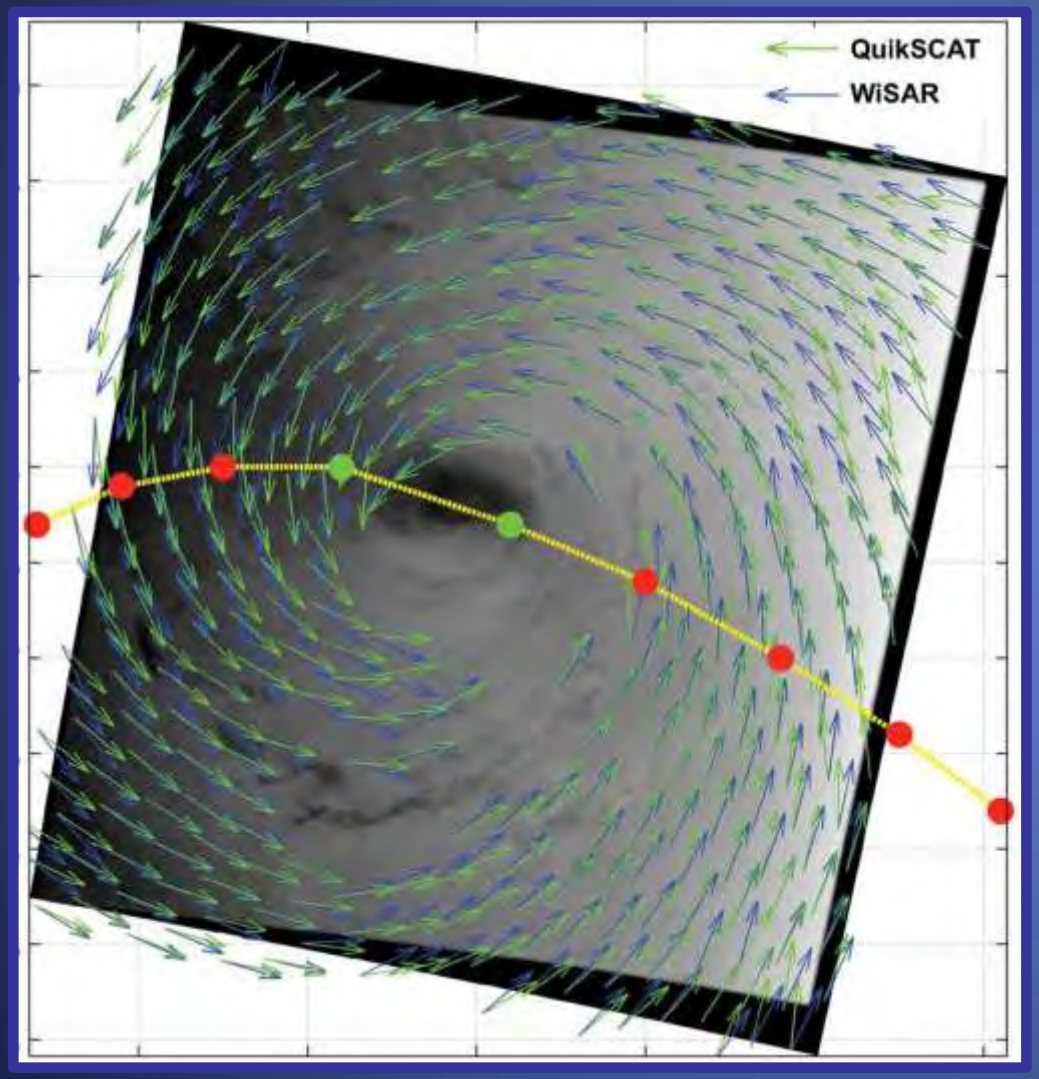
Hurricane *Dalila*



Radarsat-1 ScanSAR Image (C-HH, 100 km × 100 km) - Pacific (26 July 2001, 01:24 UTC, © CSA)

[Jackson & Apel, 2004]

Storms & Tropical Cyclones



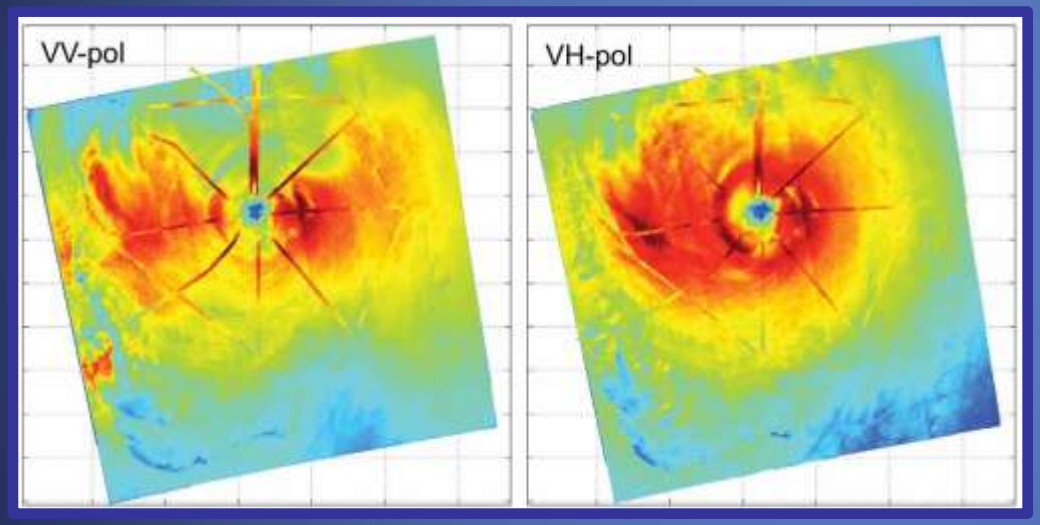
Typhoon *Fitow*

Radarsat-1 ScanSAR Image (C-HH)
Pacific
(31 August 2007, 19:43 UTC, © CSA)

[Horstmann et al., 2013]

Storms & Tropical Cyclones

Hurricane *Earl*



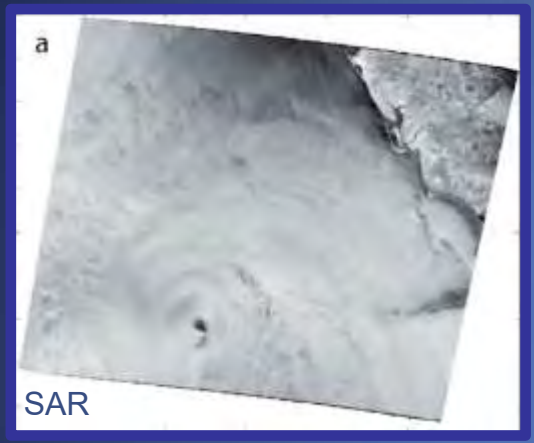
[Horstmann et al., 2013]

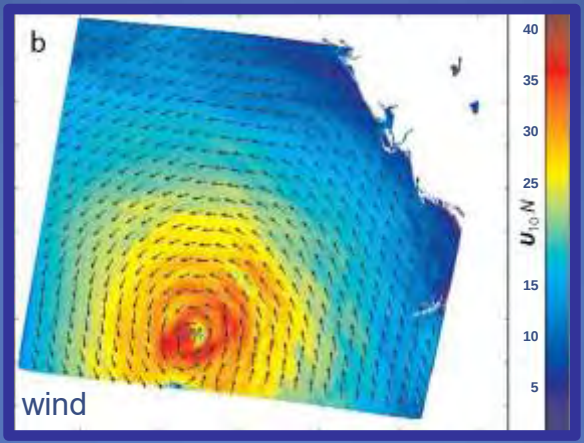
Tracks: Stepped Frequency Microwave Radiometer (SFMR)

Data basis:
Radarsat-2 ScanSAR Image (C-VV/VH)
Bermuda
(2 September 2010, 22:59 UTC)

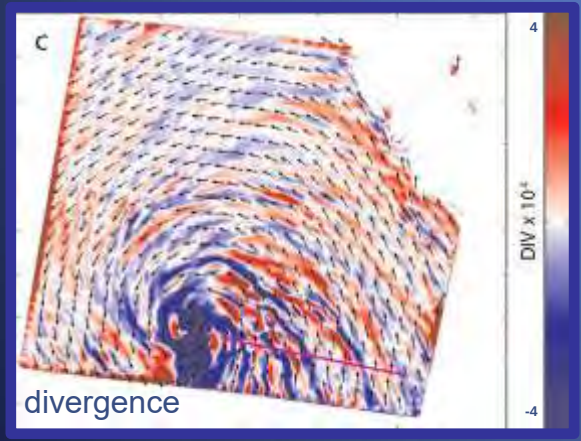
Storms & Tropical Cyclones

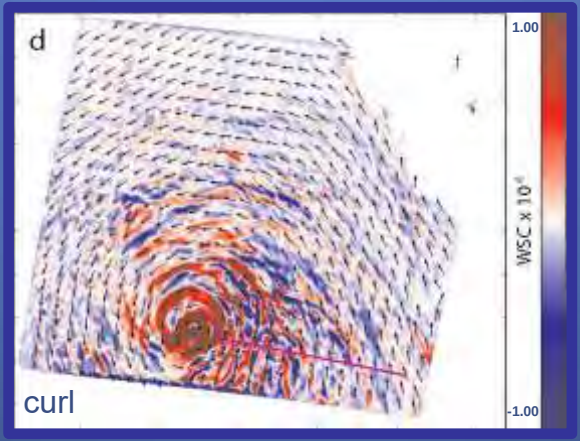
Hurricane *Katrina*





NOAA Weather Radar





[Foster, 2013]

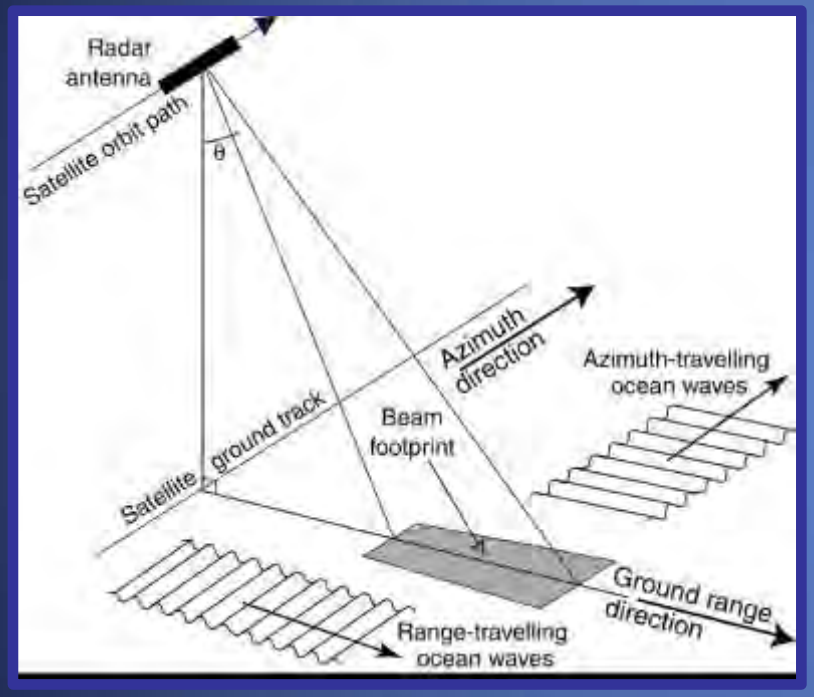
Radarsat-1 ScanSAR Image (C-HH)
Gulf of Mexico
(27 August 2005, 11:38 UTC, © CSA)

Storms, Tropical Cyclones
Take-Home Messages

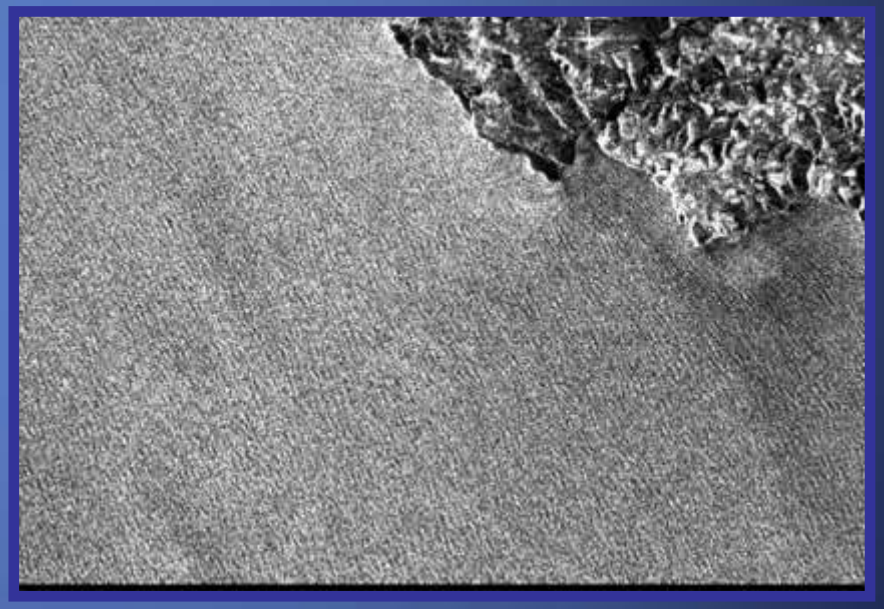
Detailed studies/observation of spatial wind distribution in storms/cyclones

Ocean Surface Waves

SAR Imaging of Ocean Surface Waves



[Robinson, 2010]



ERS-1 SAR Image (C-VV, 25 km × 17 km)
English Channel

Propagation direction of the ocean waves is important!

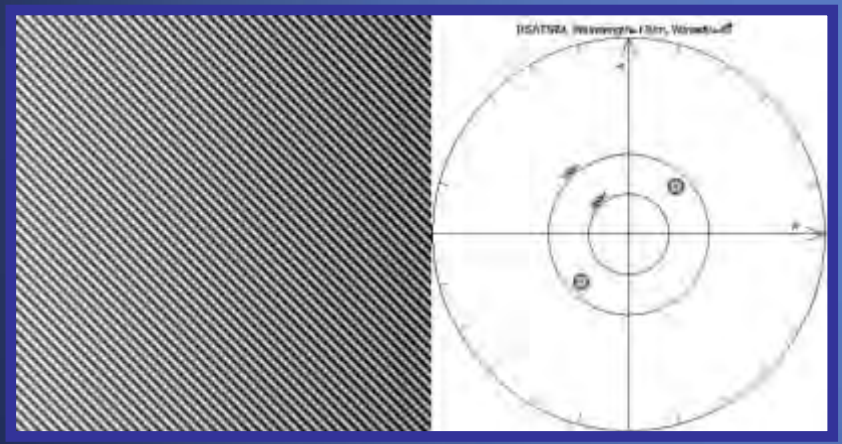
SAR Imaging of Ocean Surface Waves

SAR Image Spectra

$$S_I(\vec{k}) \sim \Psi(\vec{k}) \; ?$$

Image spectrum

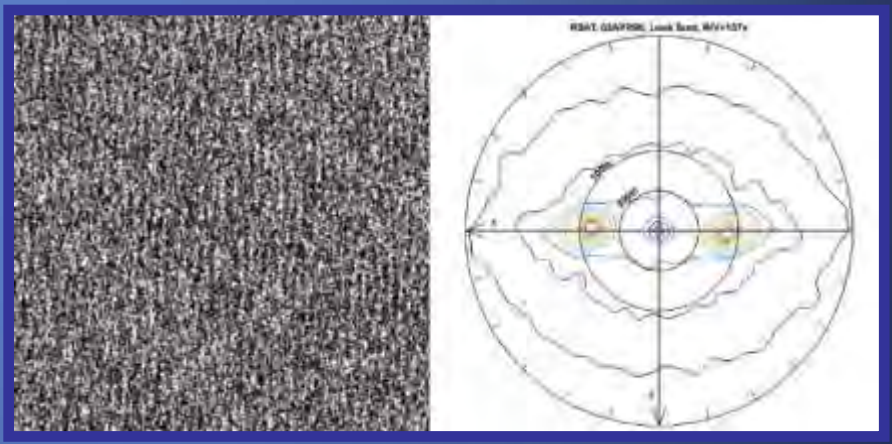
ocean wave spectrum



Simulated Image

Image Spectrum

6.4 km × 6.4 km, sinusoidal waves (120 m, 45°)



Radarsat-1 SAR Image

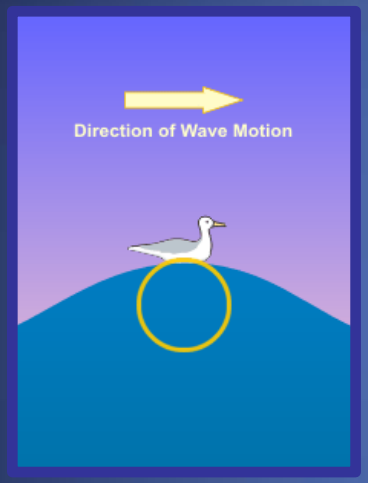
SAR Image Spectrum

6.4 km × 6.4 km, ocean waves (≈ 120 m, 0°)

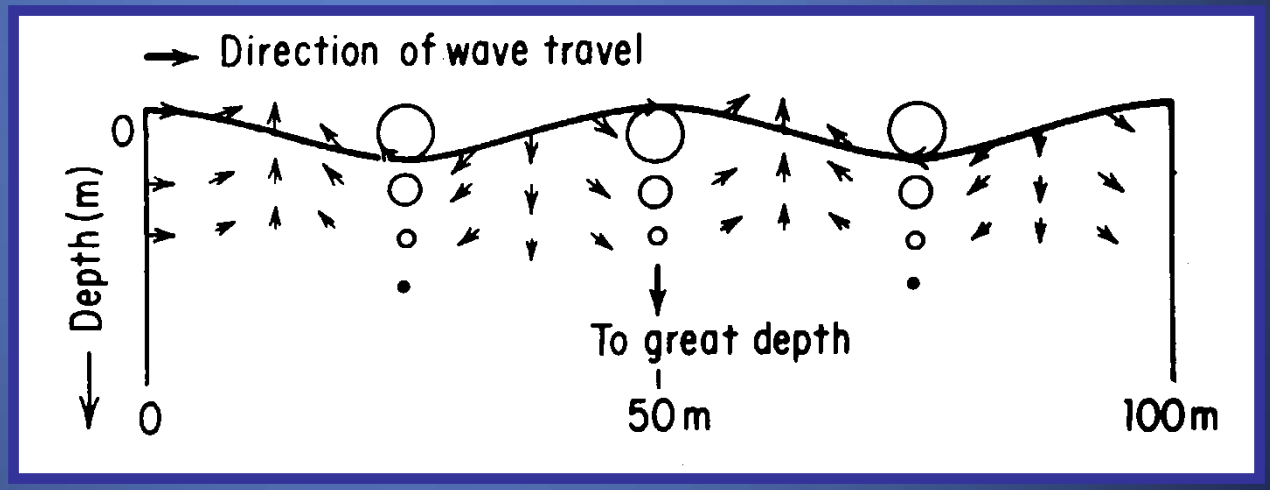
[Jackson & Apel, 2004]

Ocean Waves

Orbital motion of long ocean waves



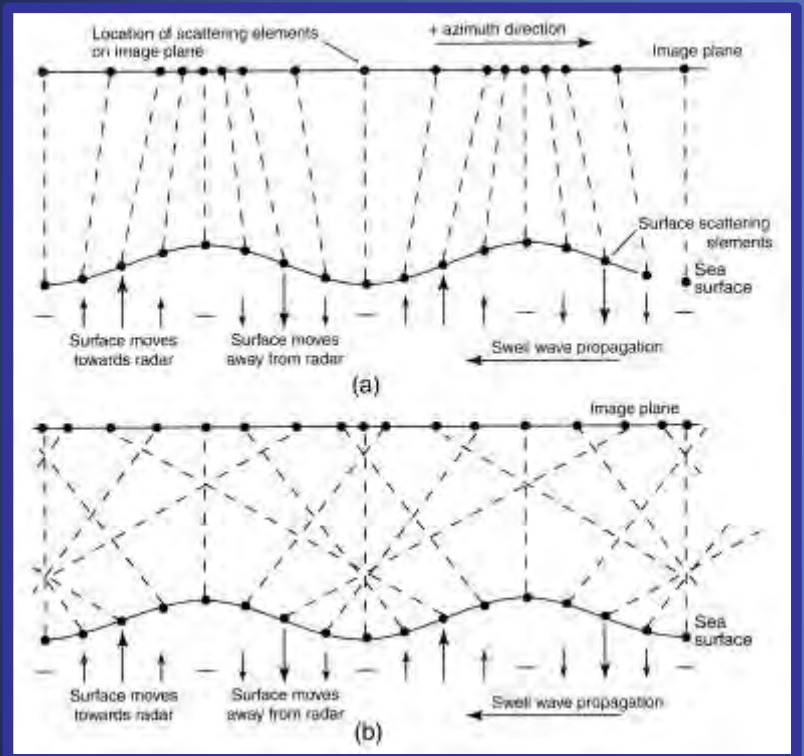
[NOAA]



[Jackson & Apel, 2004]

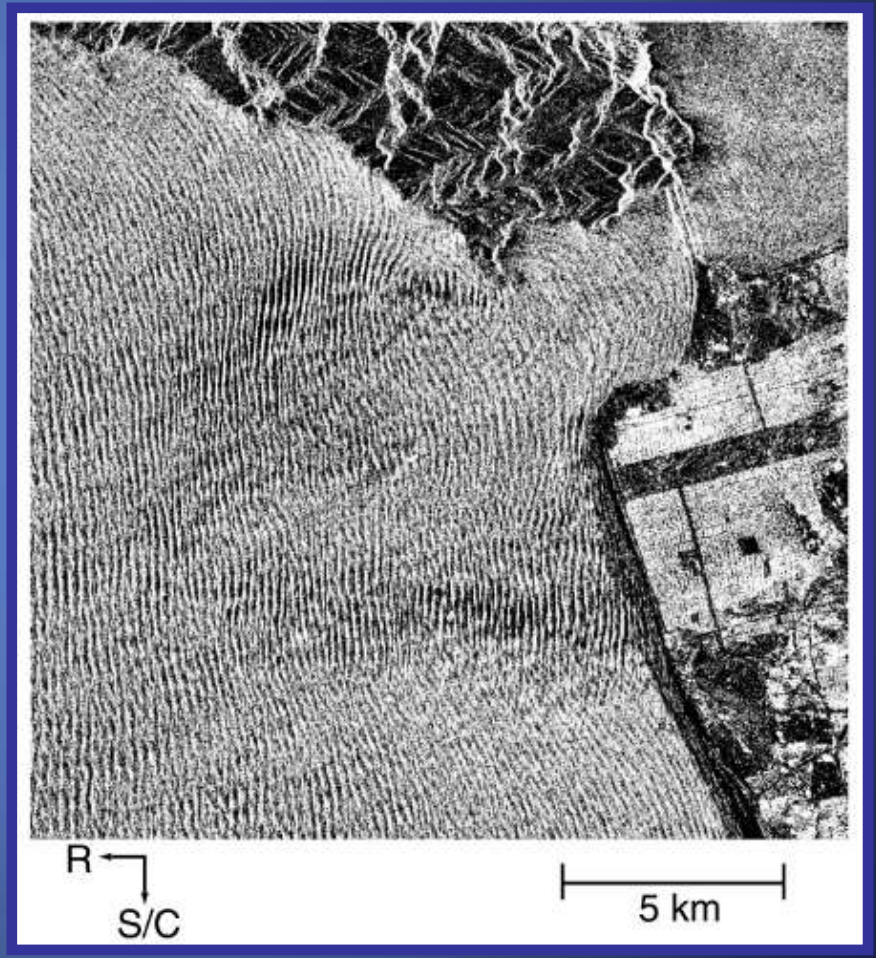
SAR Imaging of Ocean Surface Waves

Velocity bunching



[Robinson, 2003]

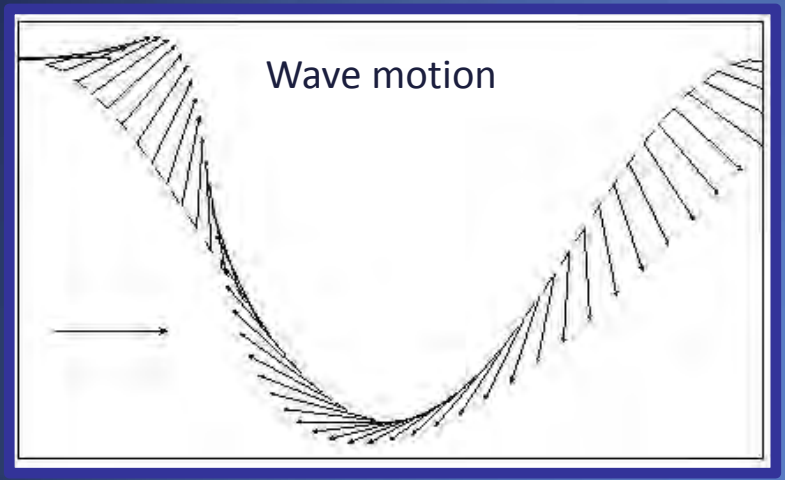
Propagation direction of the ocean waves is important!

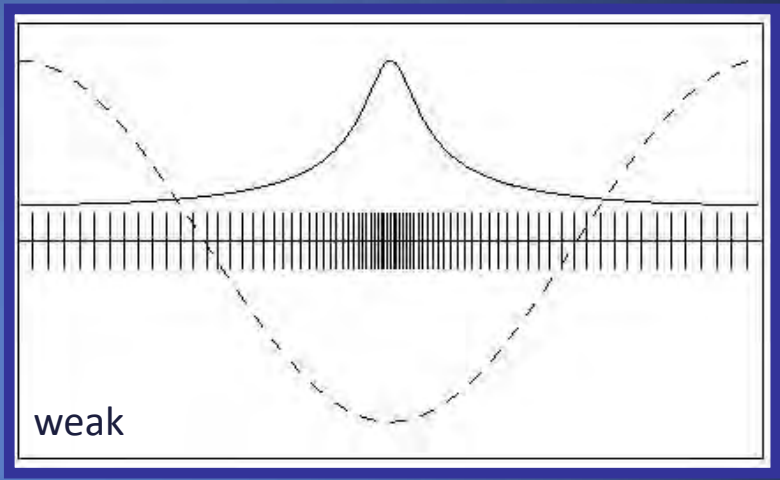


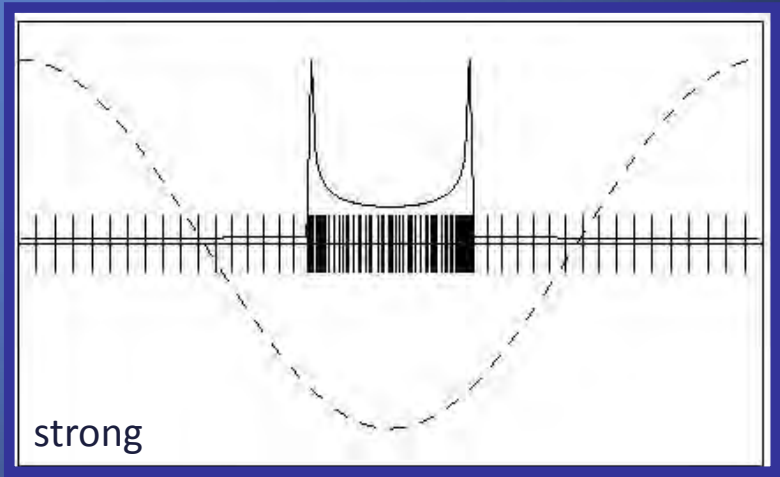
[Jackson and Apel, 2004]

SAR Imaging of Ocean Surface Waves

Velocity bunching







Azimuthal cutt-off:

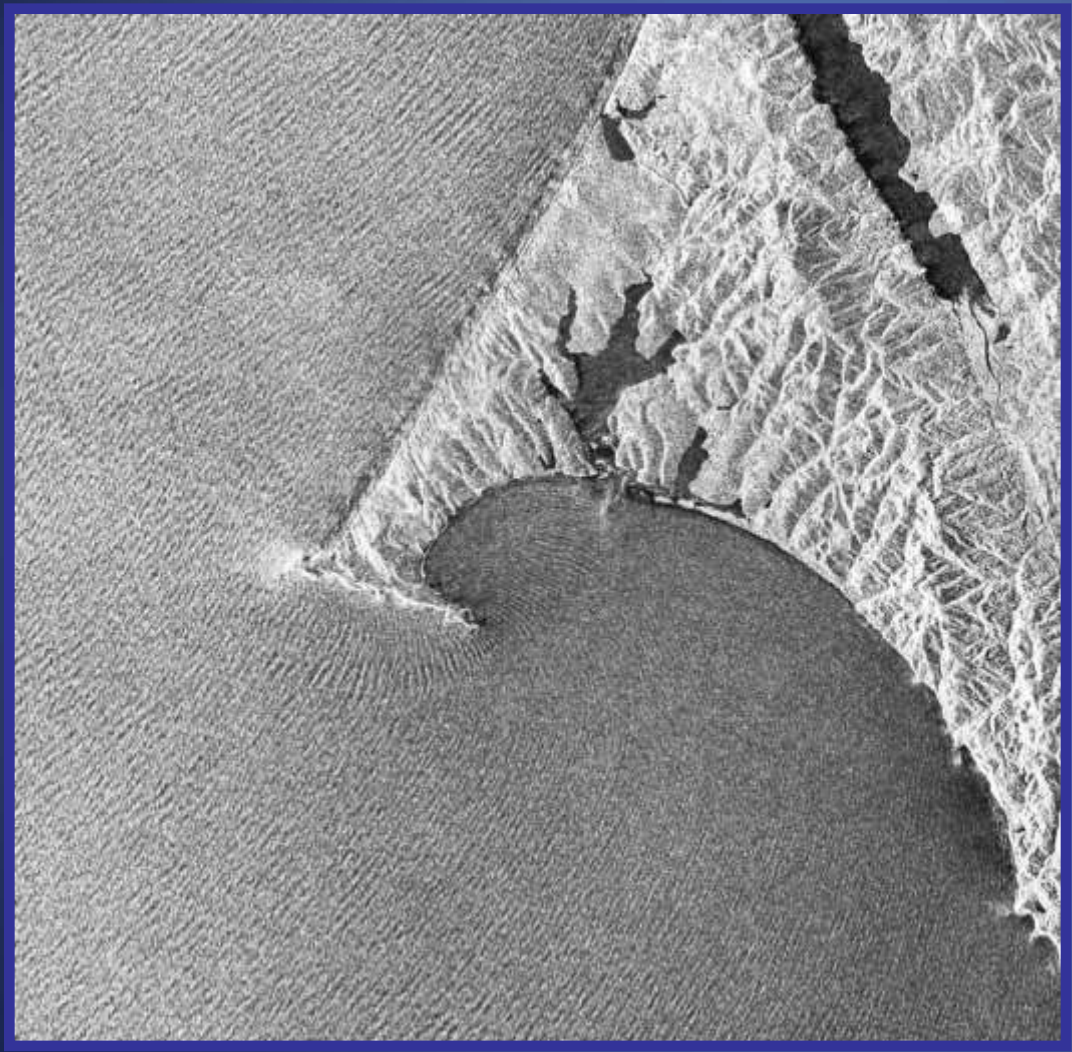
$$\lambda_{min} \cong \frac{R}{V}\sqrt{H_s}$$

with
- R: range (distance)
- V: platform velocity
- H_s: significant wave height

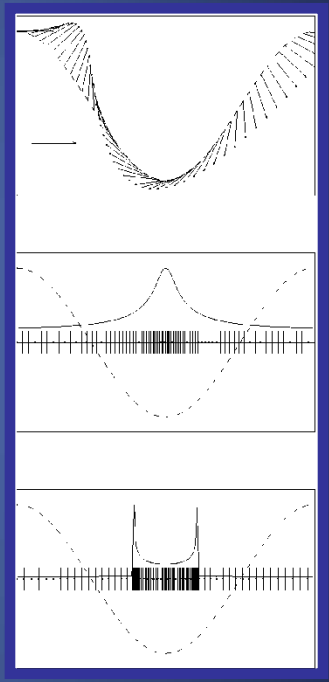
E.g., R = 800km, V = 7km/s, H_s = 2m: $\lambda_{min} \approx$ 162m

[Jackson and Apel, 2004]

SAR Imaging of Ocean Surface Waves



Wave refraction



[Jackson & Apel, 2004]

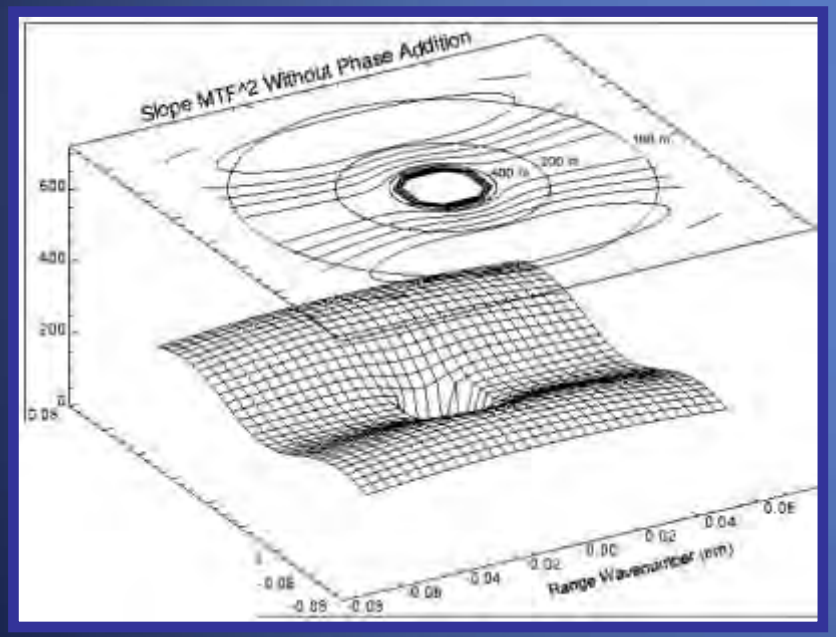
Radarsat-1 SAR Image (C-HH, 29 km × 28 km) Point Reyes (22 November 2001, 22:39 UTC, © CSA)

SAR Imaging of Ocean Surface Waves

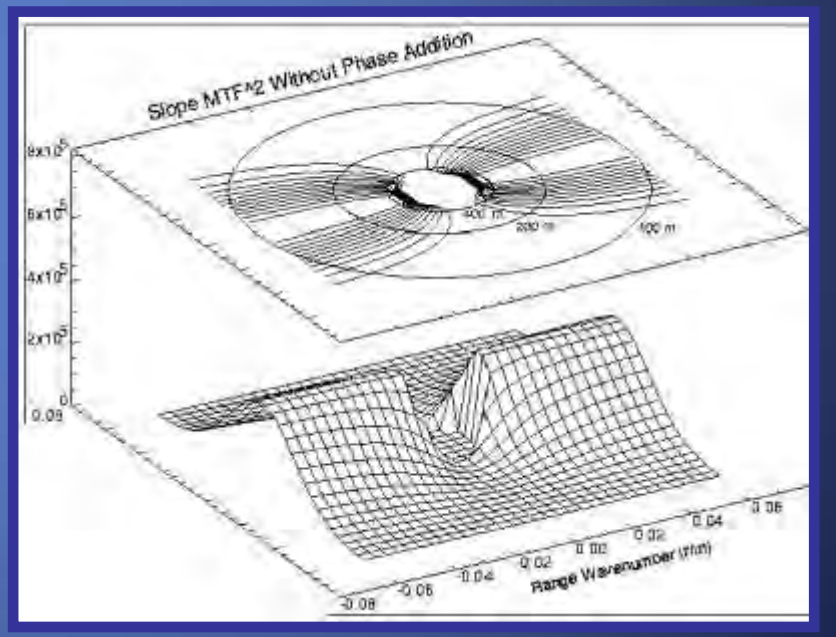
Dependence of SAR Image and Ocean Wave Spectrum

$$S_I(\vec{k}) = [H_D(\vec{k})\ T(\vec{k})\ \Psi(\vec{k}) + S_N(\vec{k})]$$

- $S_I(\vec{k})$: Image spectrum
- $H_D(\vec{k})$: dynamic response function
- $T(\vec{k})$: modulation transfer function
- $\Psi(\vec{k})$: ocean wave spectrum
- $S_N(\vec{k})$: noise spectrum



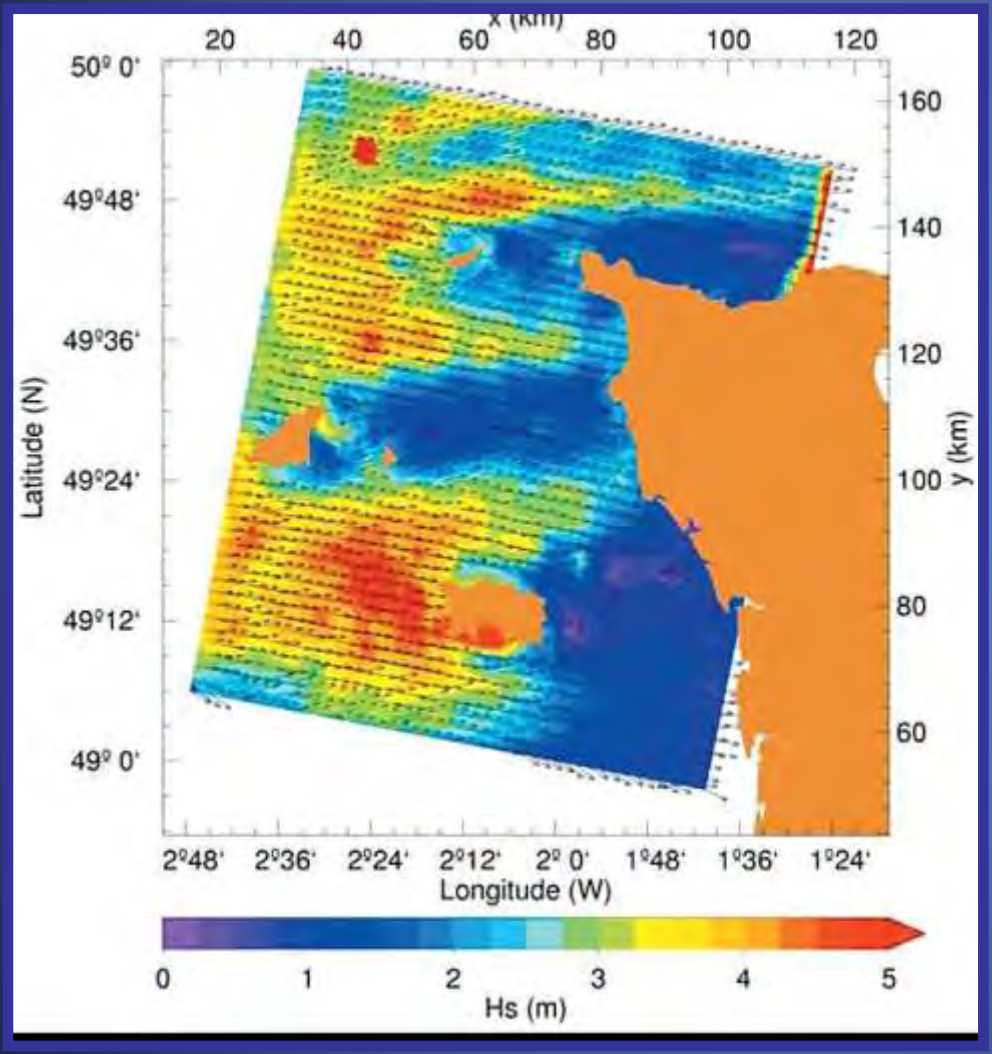
θ = 25°, (R/V) = 30 s, H_s = 1 m



θ = 25°, (R/V) = 120 s, H_s = 1.6 m

[Jackson & Apel, 2004]

SAR Imaging of Ocean Surface Waves



Wave field (height + direction)

basis:
ENVISAT ASAR image (C-VV, SLC)
Gulf of St. Malo, English Channel
9 March 2003, 10:22 UTC

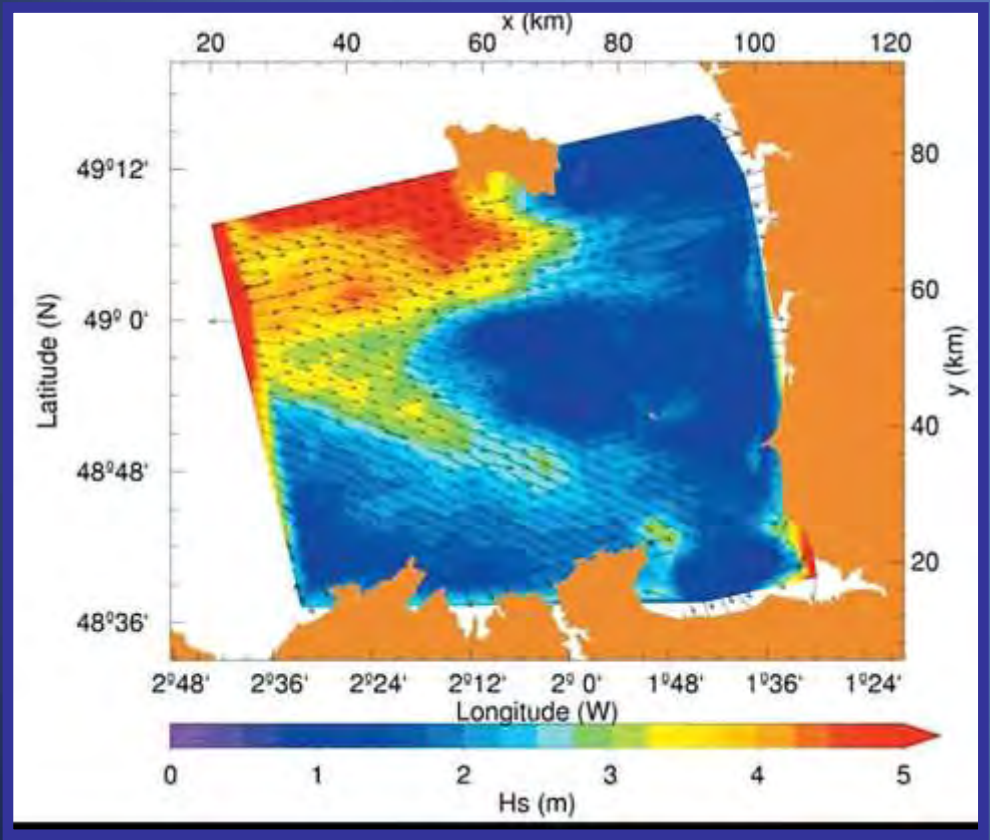
ENVISAT ASAR
wave-mode imagette
(C-VV, SLC, 5 km × 6.7 km)

[Robinson, 2010]

SAR Imaging of Ocean Surface Waves

Wave field (height + direction)

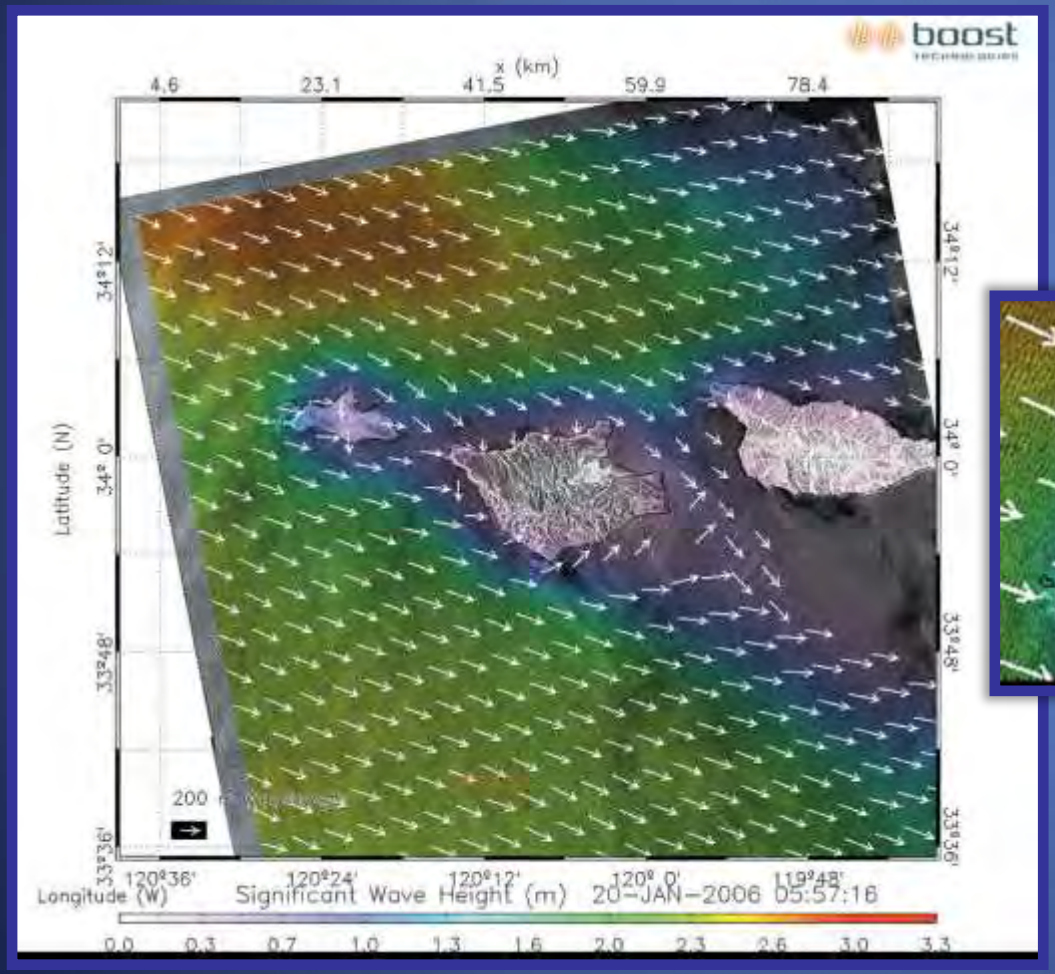
basis:
ENVISAT ASAR image (C-VV, SLC)
Gulf of St. Malo, English Channel
9 March 2003, 21:44 UTC



ENVISAT ASAR
wave-mode imagette
(C-VV, SLC, 5 km × 6.7 km)

[Robinson, 2010]

SAR Imaging of Ocean Surface Waves



Wave field (height + direction)

basis:
ENVISAT ASAR image (C-VV, SLC)
Channel Islands, CA, USA
20 January 2006, 05:57 UTC

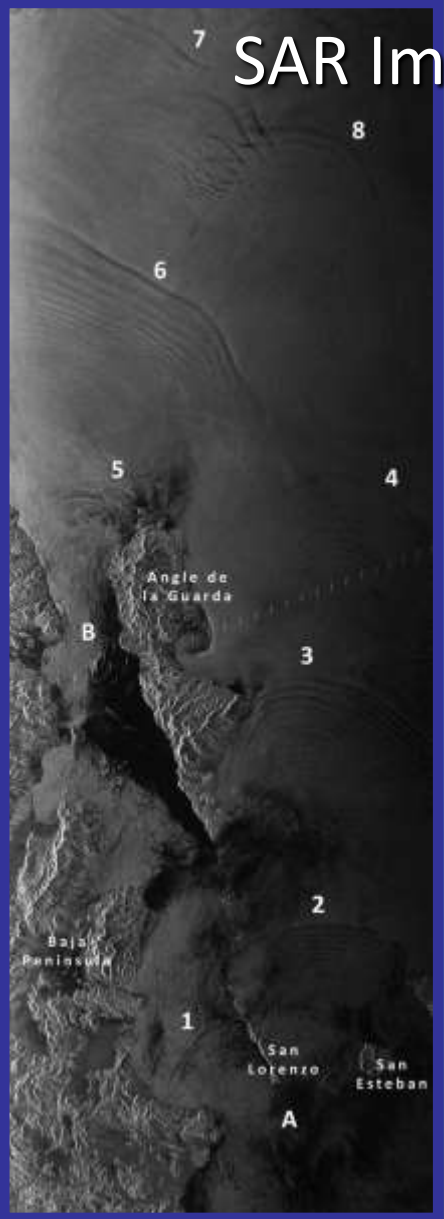
[Robinson, 2010]

Ocean Surface Waves
Take-Home Messages

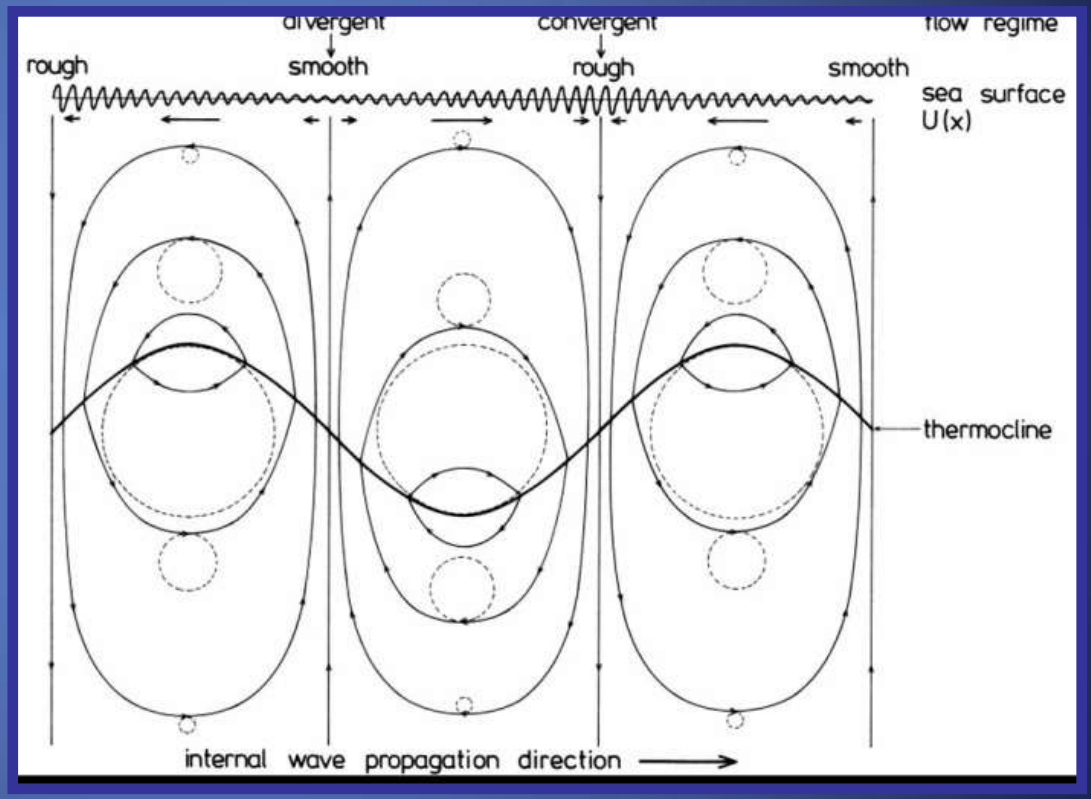
Wave orbital motion: velocity bunching
Non-linearity: azimuthal cut-off
Operational wave fields

Oceanic Internal Waves

SAR Imaging of Oceanic Internal Waves



Seasat: First SAR Imaging of Internal waves

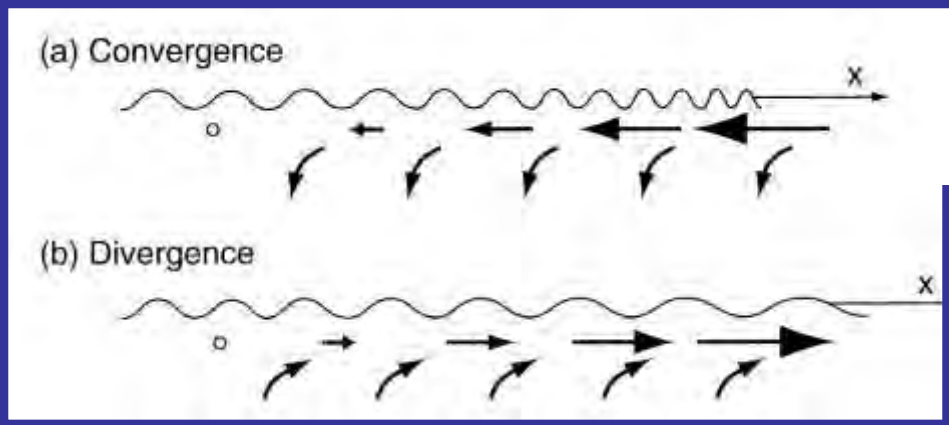


[Robinson, 2010]

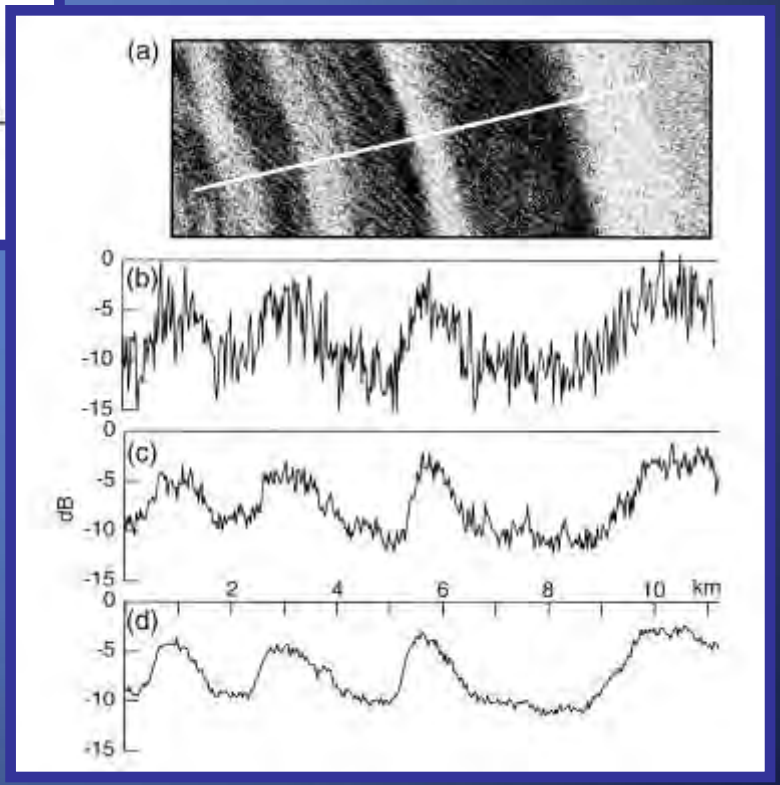
Seasat SAR Image (L-HH, 100 km × 270 km)
Gulf of California
(29 September 1978, 18:11 UTC, © NASA)

Hydrodynamic Processes at the Sea Surface

Imaging by SAR

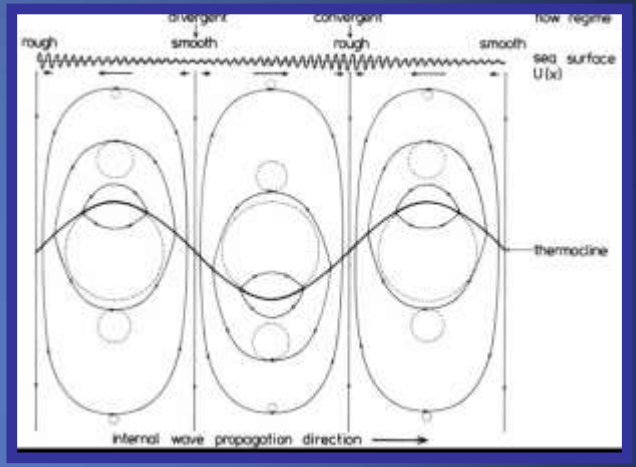


[Robinson, 2003]



SAR Imaging of Oceanic Internal Waves

Internal waves



[Robinson, 2010]

ERS SAR Image (C-VV, 100 km × 100 km)
Strait of Gibraltar
(1 January 1993, 22:39 UTC, © ESA)

SAR Imaging of Oceanic Internal Waves

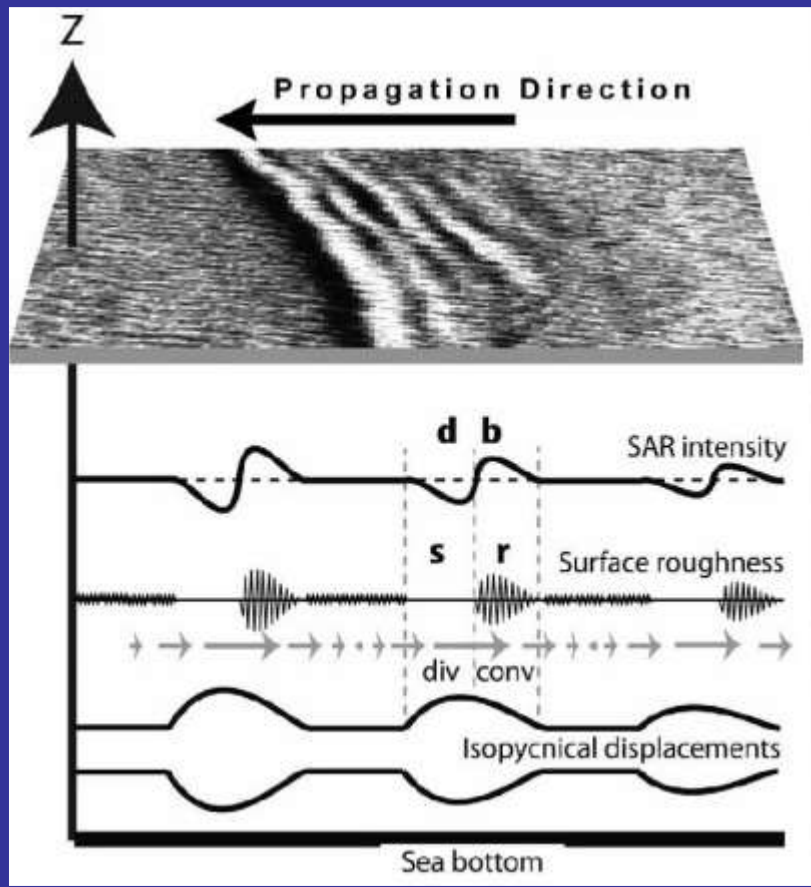
ERS SAR Image (C-VV, 30 km × 30 km)
Cape Cod
(21 August 1994, 15:26 UTC, © ESA)

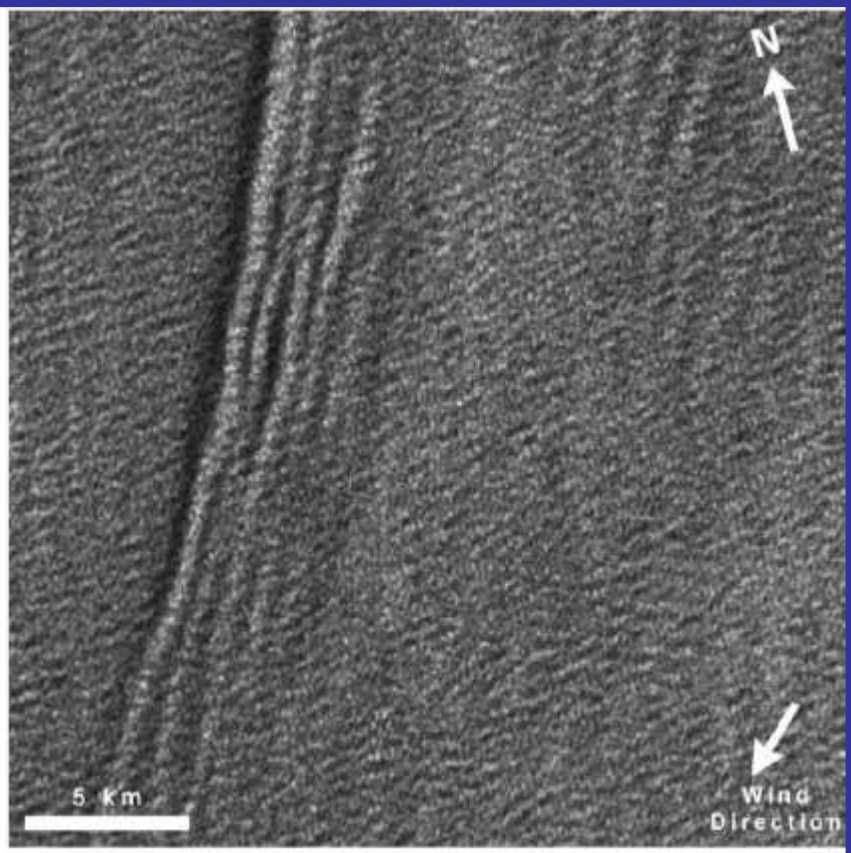
Roughness variations

[Robinson, 2010]

SAR Imaging of Oceanic Internal Waves

Roughness variations

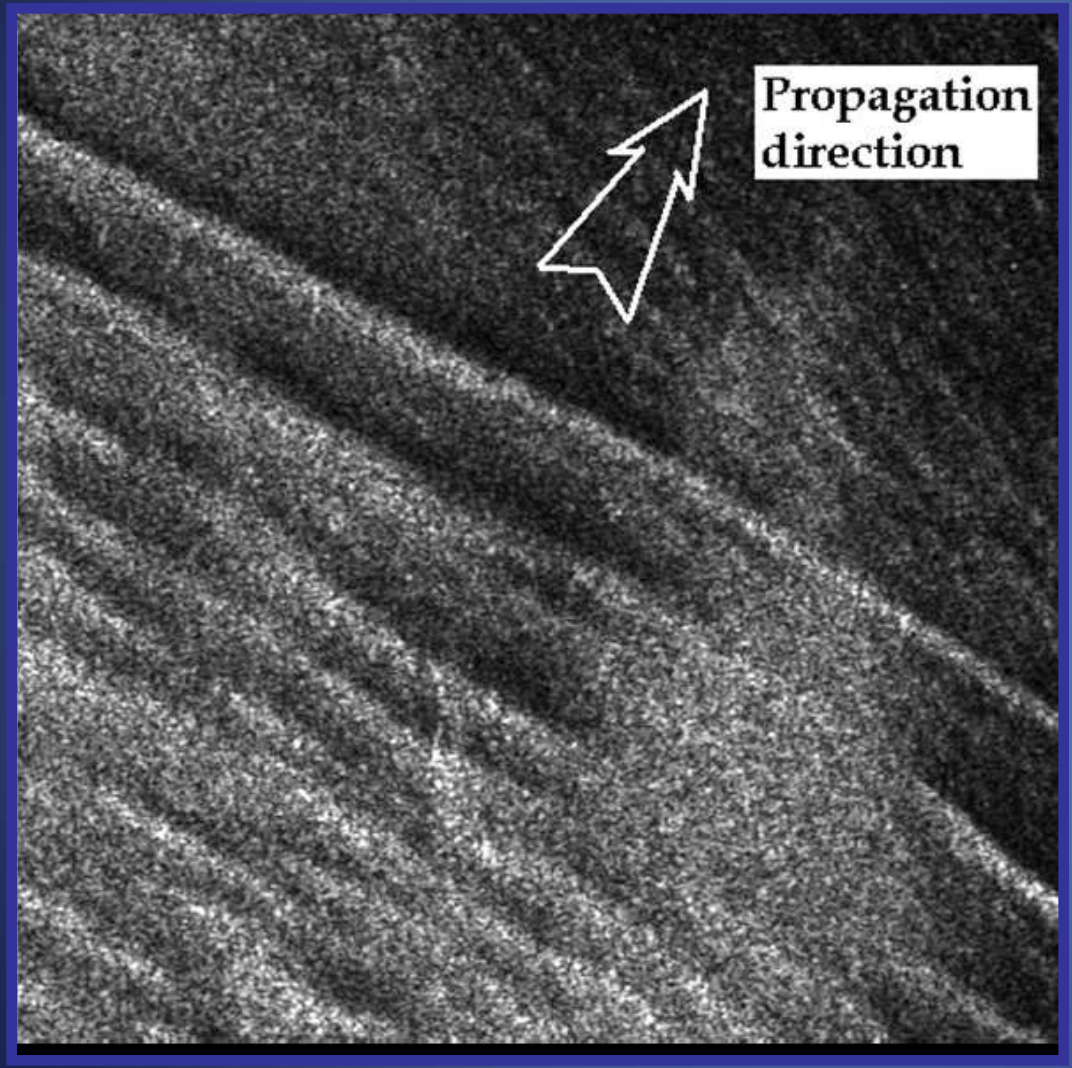




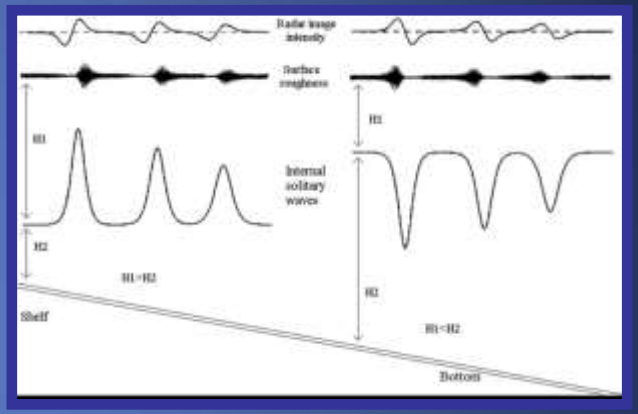
[Jackson et al., 2013]

ERS-2 SAR Image (C-VV, 25 km × 25 km)
Mozambique Channel
(24 September 2001, 07:39 UTC, © ESA)

SAR Imaging of Oceanic Internal Waves



Roughness variations

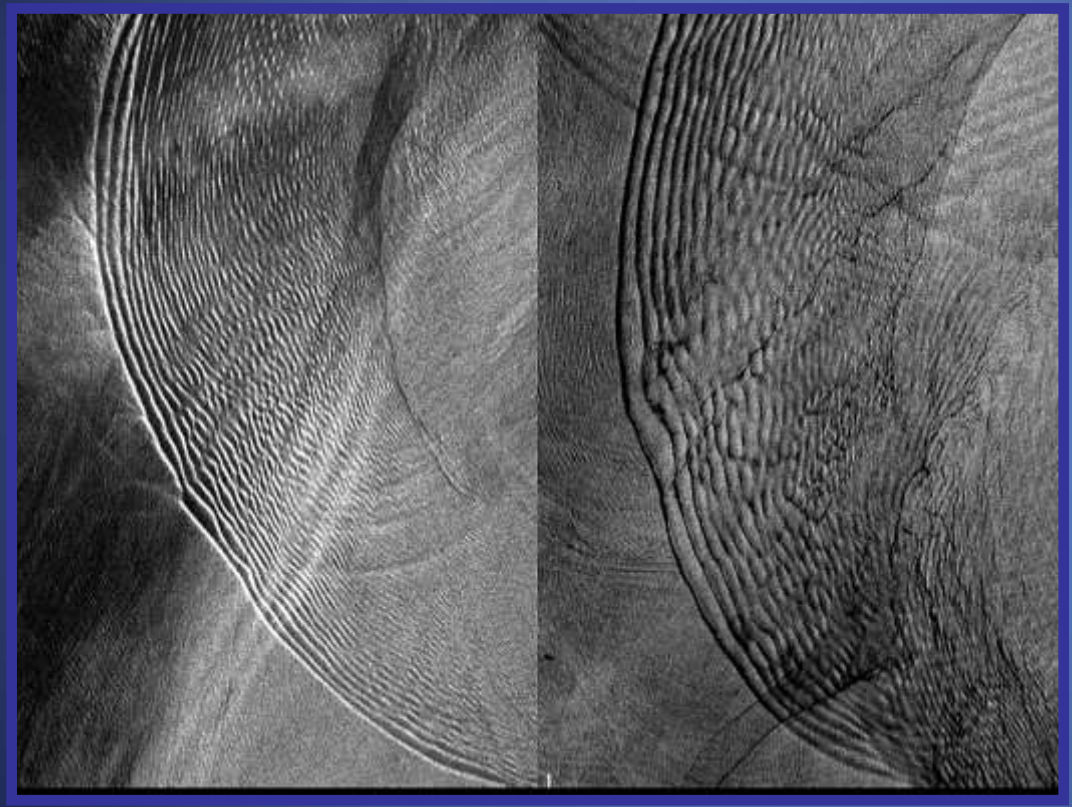


[Robinson, 2010]

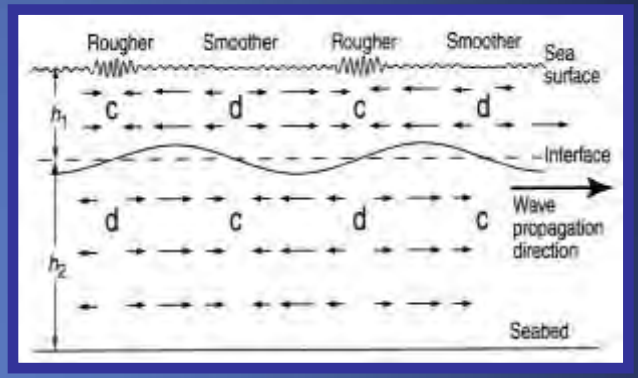
ERS-2 SAR Image (C-VV, 15 km × 15 km)
Gulf of Cadiz
(23 July 1998, 11:10 UTC, © ESA)

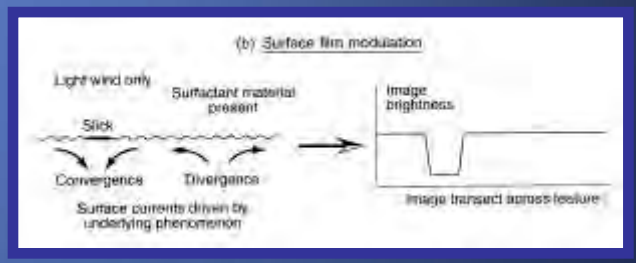
SAR Imaging of Oceanic Internal Waves

Roughness variations



[Robinson, 2010]



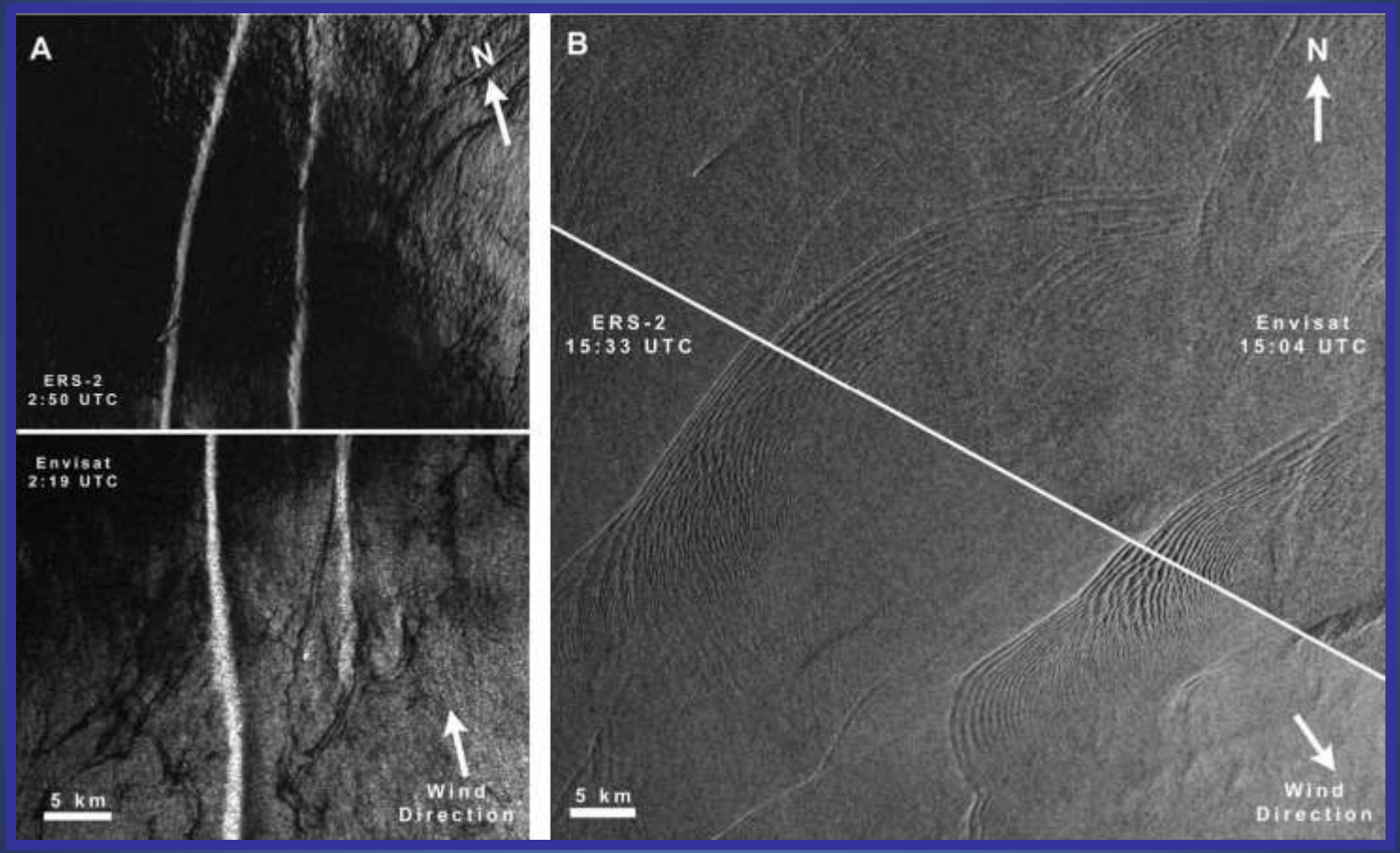


[Robinson, 2003]

TerraSAR-X Images (X-VV, 11 km × 17 km)
U.S. East Coast
(23 June 2008, 22:26 UTC, 4 July 2008, 22:26 UTC, © DLR)

SAR Imaging of Oceanic Internal Waves

Propagation speed from pairs of ERS / ENVISAT images



[Jackson et al., 2013]

ERS-2 SAR / ENVISAT ASAR Images
(C-VV, 35 km × 30 km) South China Sea
(28 March 2009, 02:19 / 02:50 UTC, © ESA)

ERS-2 SAR / ENVISAT ASAR Images
(C-VV, 65 km × 65 km) U.S. East Coast
(8 August 2006, 15:04 / 15:33 UTC, © ESA)

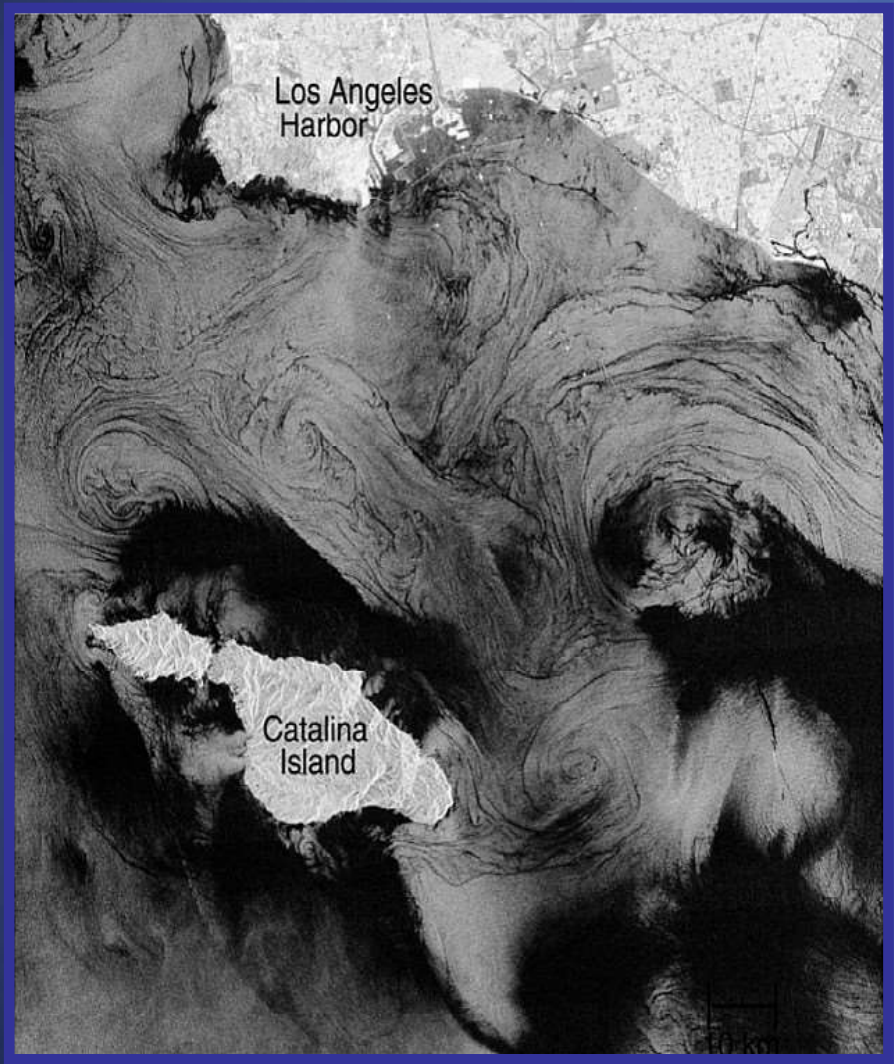
Oceanic Internal Waves
Take-Home Messages

IWs at two-layer interface (pycnocline, thermocline): mixing processes

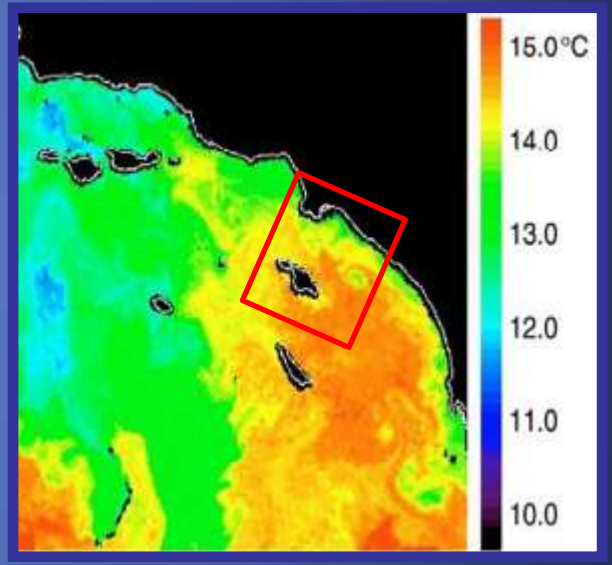
Surface roughness variations

Marine Surface Films

Marine Surface Films



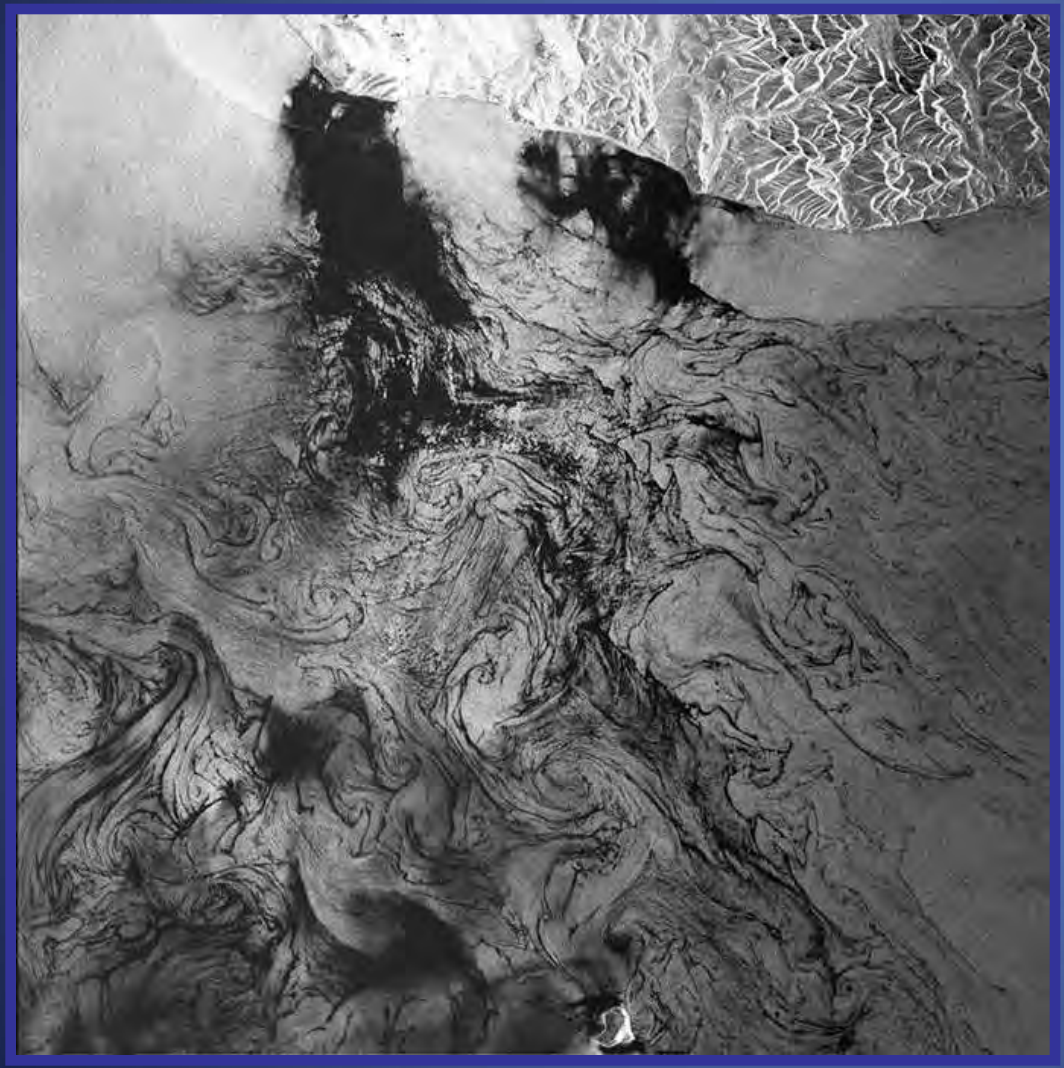
Slicks & eddies



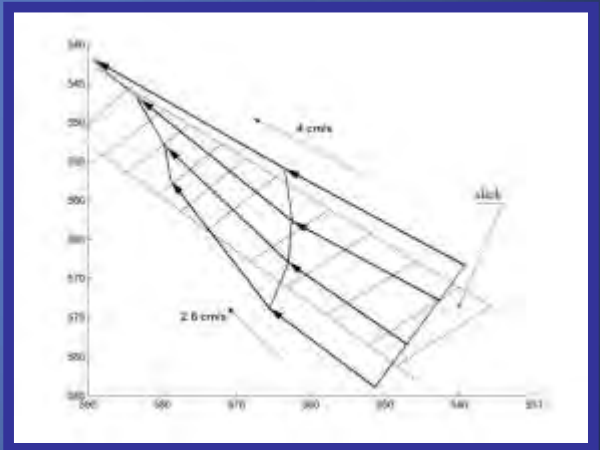
[Jackson & Apel, 2004]

Radarsat-1 SAR Image (C-HH)
Catalina Channel
(26 December 1998, © CSA)

Marine Surface Films



Slicks & eddies

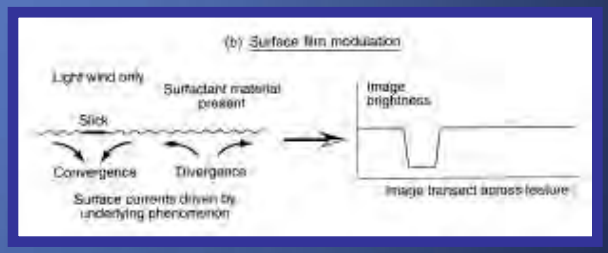


[Gade et al., 2014]

ERS SAR Image (C-VV; 70 km × 70 km)
Bering Strait
(24 June 1997, 22:30 UTC, © ESA)

Marine Surface Films

Slicks & eddies



[Robinson, 2003]

ERS SAR Image (C-VV; 100 km × 100 km)
Caspian Sea
(12 October 1993, © ESA)

Monomolecular Surface Films

palmitic acid methyl ester (PME)

oleyl alcohol (OLA)

triolein (TOLG)

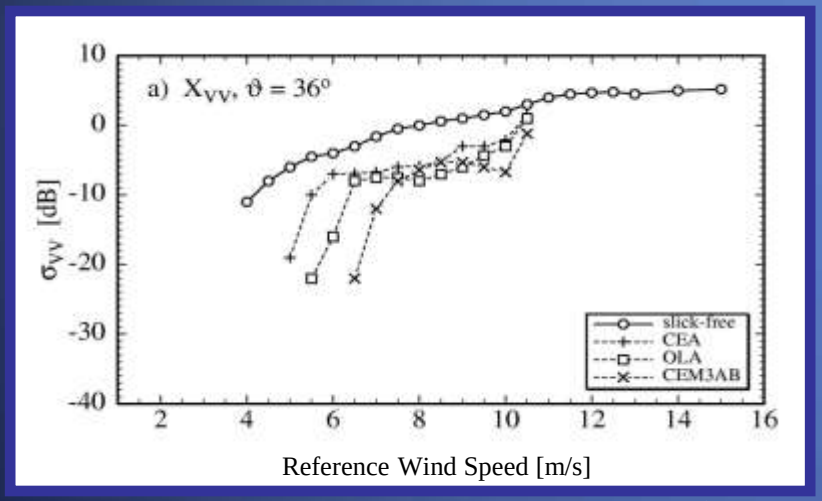
Model Substances represent main components of natural marine surface films

Hydrophobic part (long alcyl chain) – Hydrophilic head group

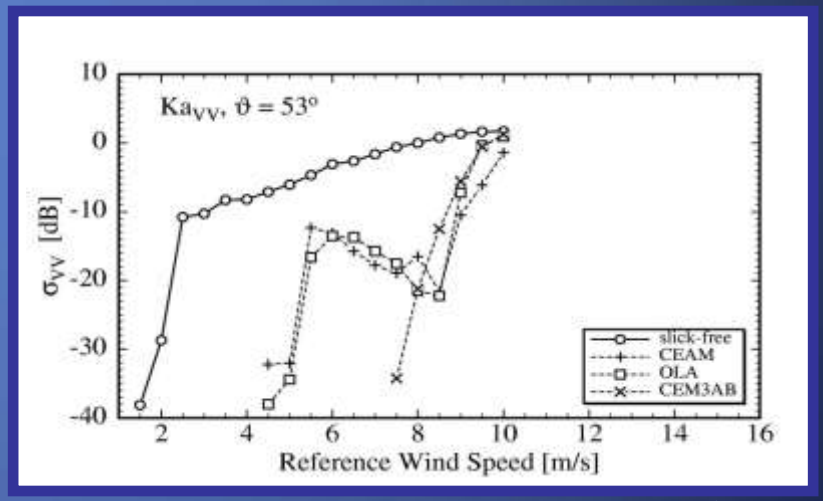
Substances accumulate at the water surface as monomolecular film

Monomolecular Surface Films

Monomolecular Surface Films



[Gade, 1998]

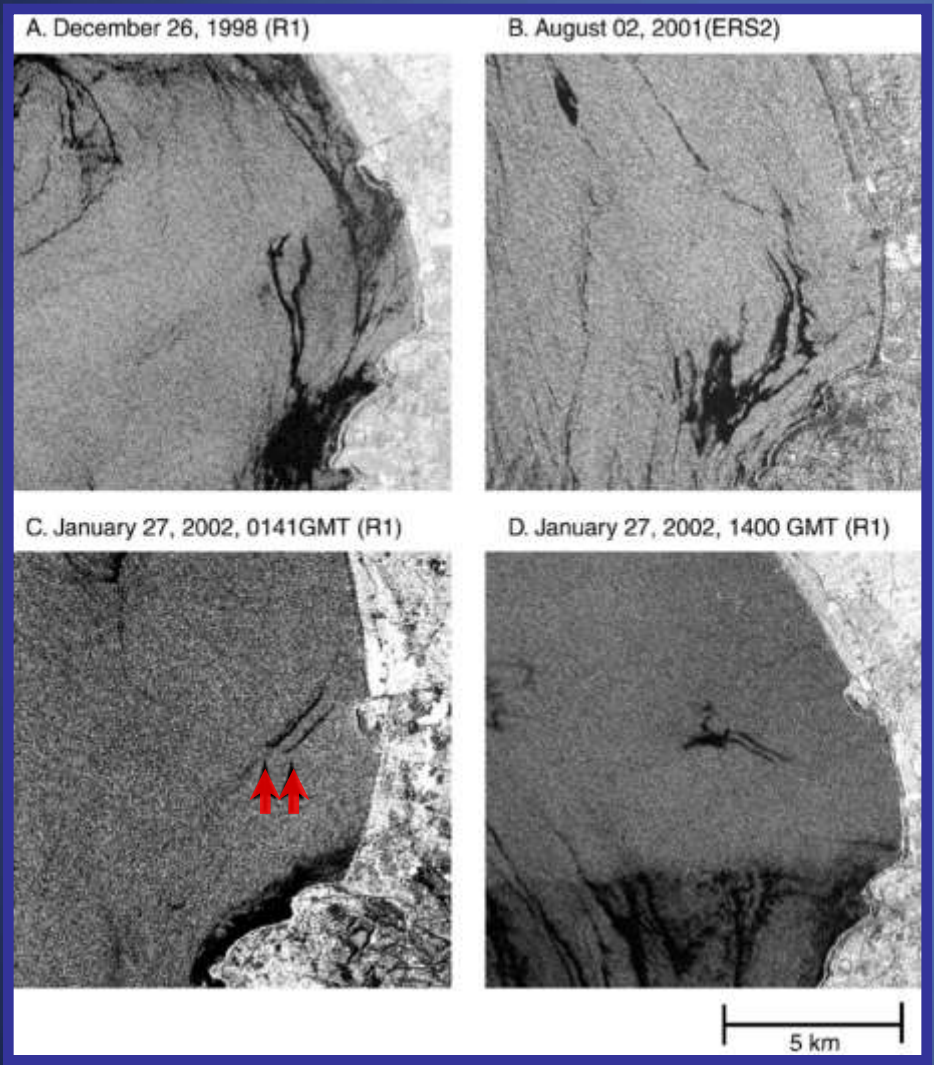


[Gade, 1998]

Measured radar contrast

left: X band (9.8 GHz, λ_B = 3 cm) right: Ka band (37 GHz, λ_B = 0.8 cm)

Marine Surface Films

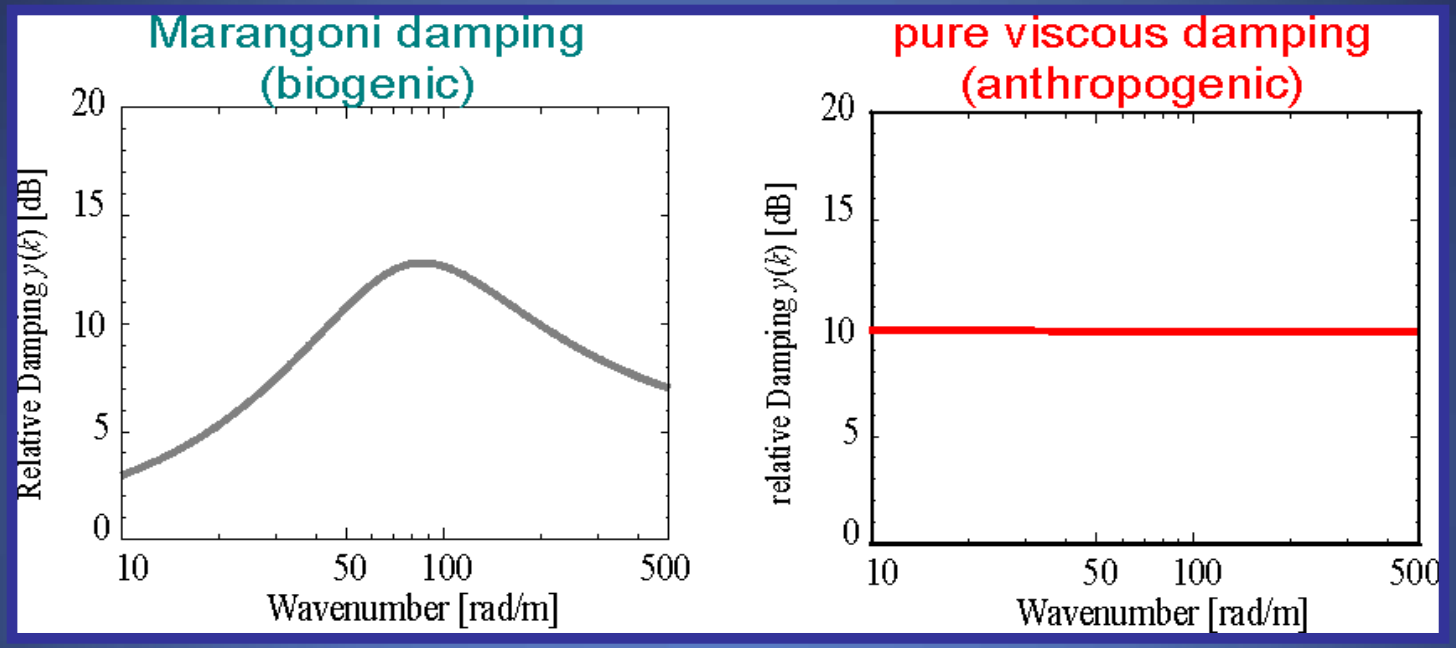


Natural oil seeps

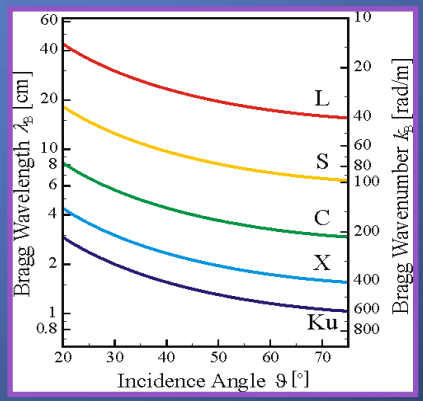
Radarsat-1 SAR Images (C-HH; 12.5 km × 12.5 km)
ERS-2 SAR Image (C-VV; 12.5 km × 12.5 km)
Redondo Beach, CA
(© CSA, ESA)

[Jackson & Apel, 2004]

Wave Damping by Surface Films



Use multi-frequency radar techniques to discriminate between biogenic and anthropogenic surface films

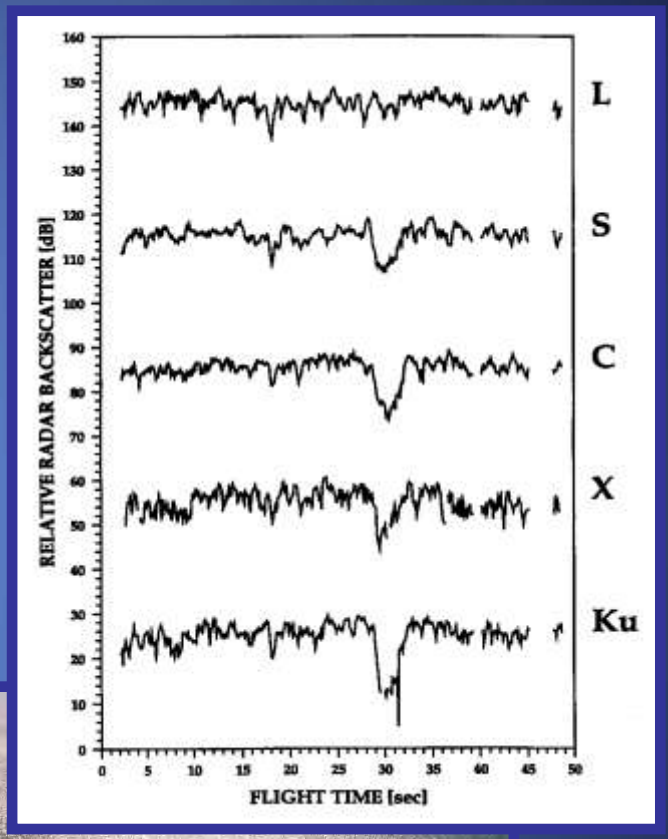


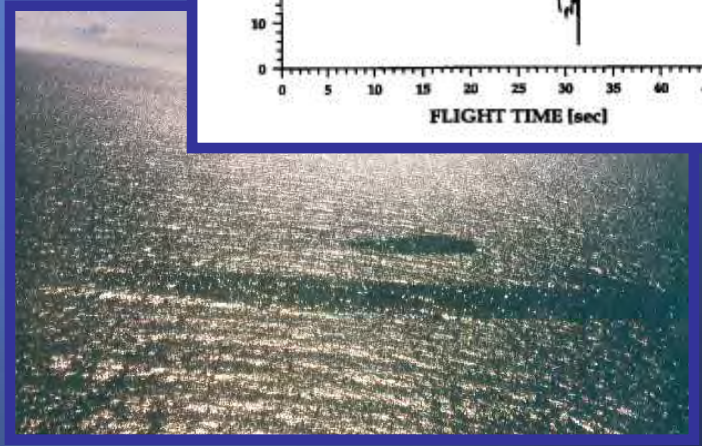
Scatterometer Experiments

MULTI³SCAT of Uni Hamburg

- flown on BO 105
- 5 frequencies: (L, S, C, X, Ku band)
- 4 polarisations (HH, HV, VV, VH)
- incidence angle: 23° ... 65°
- nominal flight height: 150 m
- Ø footprint: 1.6 m ... 128.9 m
- transmit power: 10 mW ... 150 mW

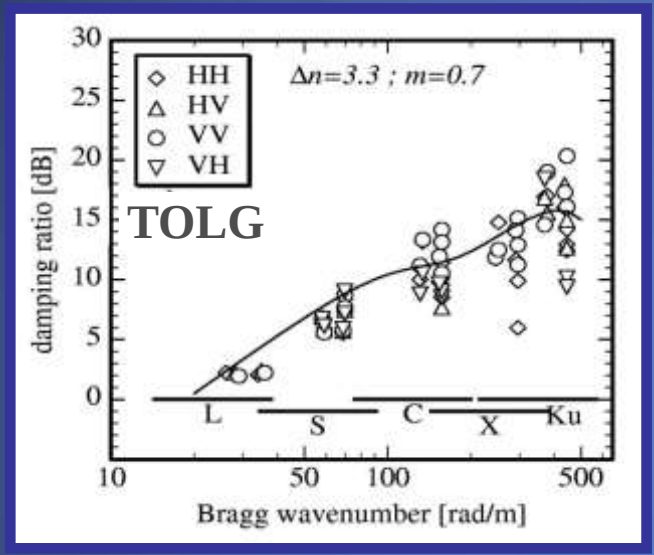
Marine Surface Films

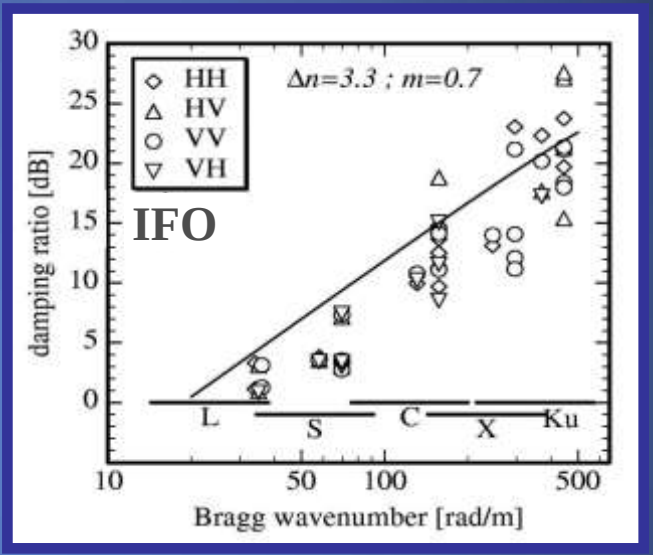




Marine Surface Films

Modeling damping ratios at high wind speeds





[Gade, 1996]

$$\frac{\sigma^{(0)}}{\sigma^{(s)}} = \frac{\Psi_0(k)}{\Psi_s(k)} \approx \frac{\beta_s - 2\Delta_s c_g}{\beta_0 - 2\Delta_0 c_g} \cdot m^{\Delta n - 4} \left(2u_* \sqrt{\frac{|\cos\varphi| k}{g}} \right)^{\Delta n}$$

m : parameter describing reduction of friction velocity
Δn : parameter describing reduction of wave breaking

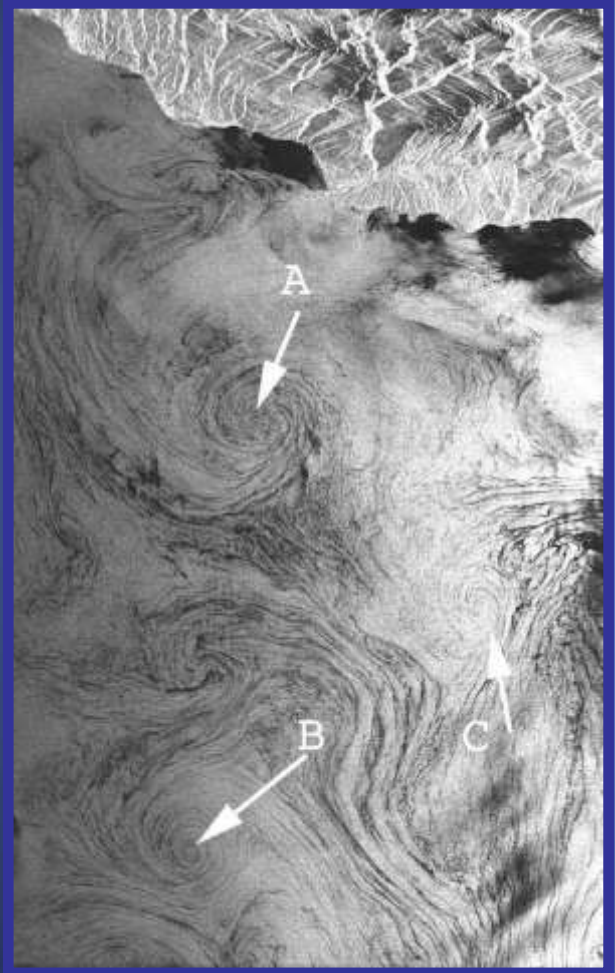
Model can explain

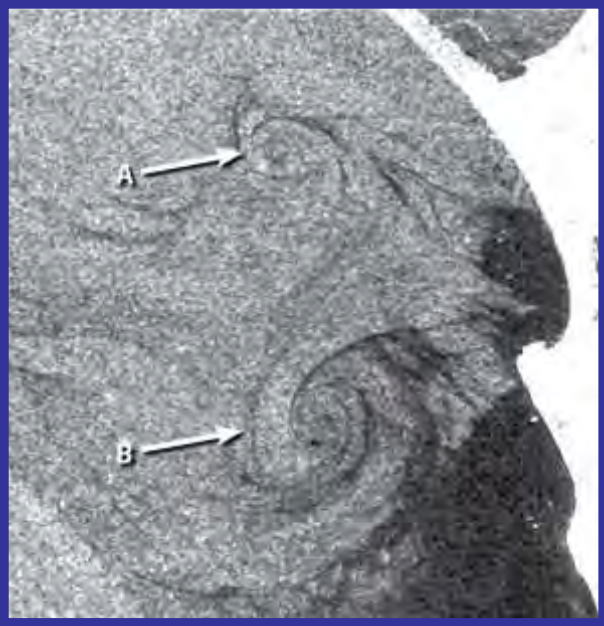
monotonous increase of damping curves (no Marangoni maximum!)

similar damping behavior of biogenic and anthropogenic films

Marine Surface Films

Detecting and tracking of sub-mesoscale oceanic eddies





ENVISAT ASAR WS Image (C-VV; 25 km × 25 km)
NE Black Sea
(15 August 2006, 19:18 UTC, © ESA)

ENVISAT ASAR WS Image (C-VV; 120 km × 200 km)
NE Black Sea
(10 May 2007, 07:37 UTC, © ESA)

[Gade et al., 2013]

Marine Surface Films

High-resolution surface current fields from pairs of Sar images

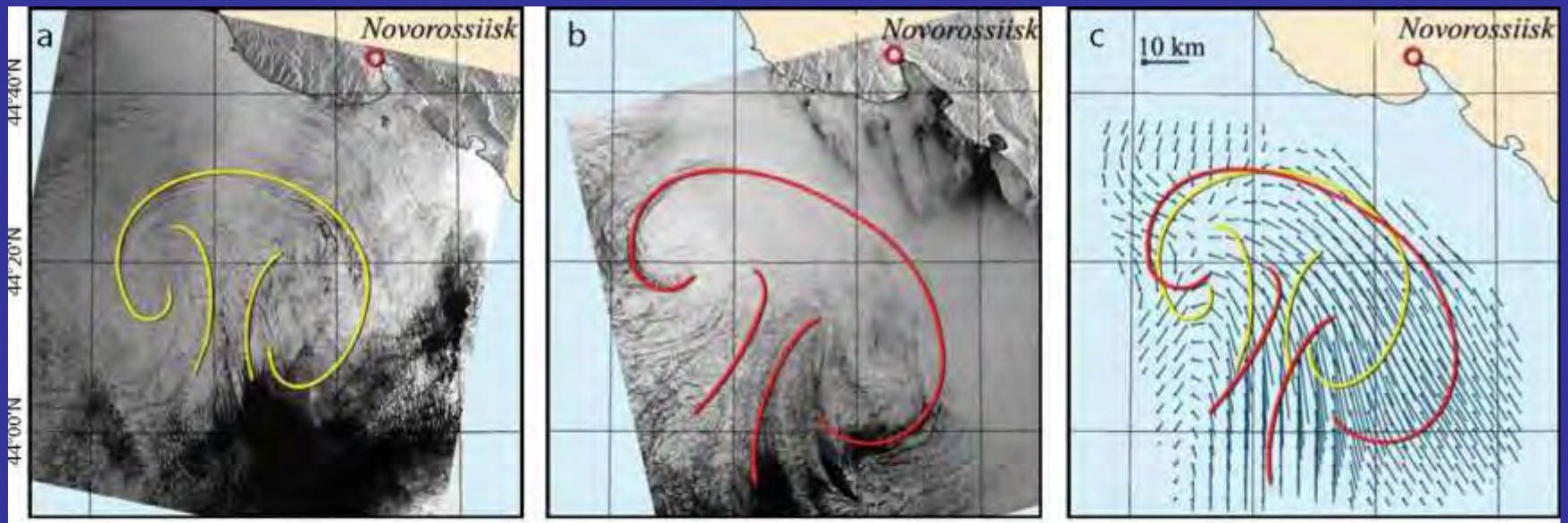


Figure 11. (a) Envisat ASAR image obtained June 19, 2006, at 07:52 GMT showing a nascent dipole eddy. Dimensions are about 66 km x 62 km. © ESA, 2006 (b) Envisat ASAR image of a 92 km x 78 km dipole eddy obtained June 19, 2006, at 19:10 GMT © ESA, 2006 (c) Reconstruction of the local velocity field from analysis of images a and b.

[Gade et al., 2013]

Marine Surface Films

Eddy statistics for the northeastern Black Sea

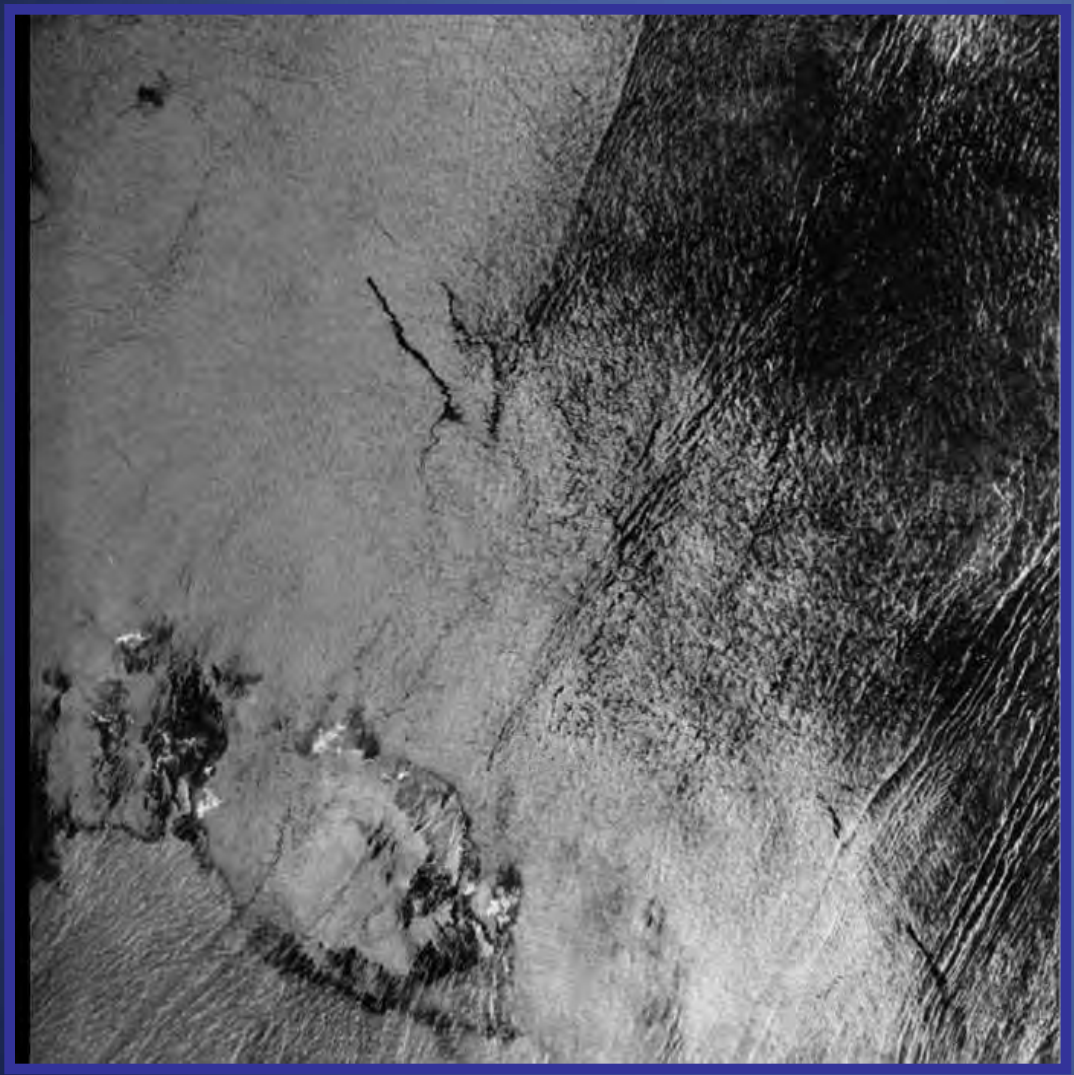
[Gade et al., 2013]

Marine Surface Films
Take-Home Messages

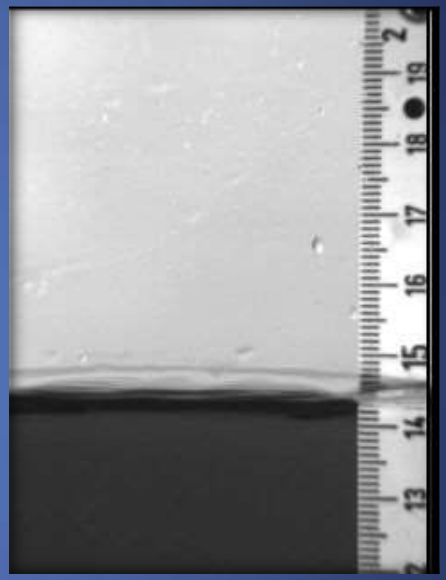
Monomolecular surface films
Strong wave damping
Tracers for turbulent features/processes in upper water layer

Rain

Heavy Rain

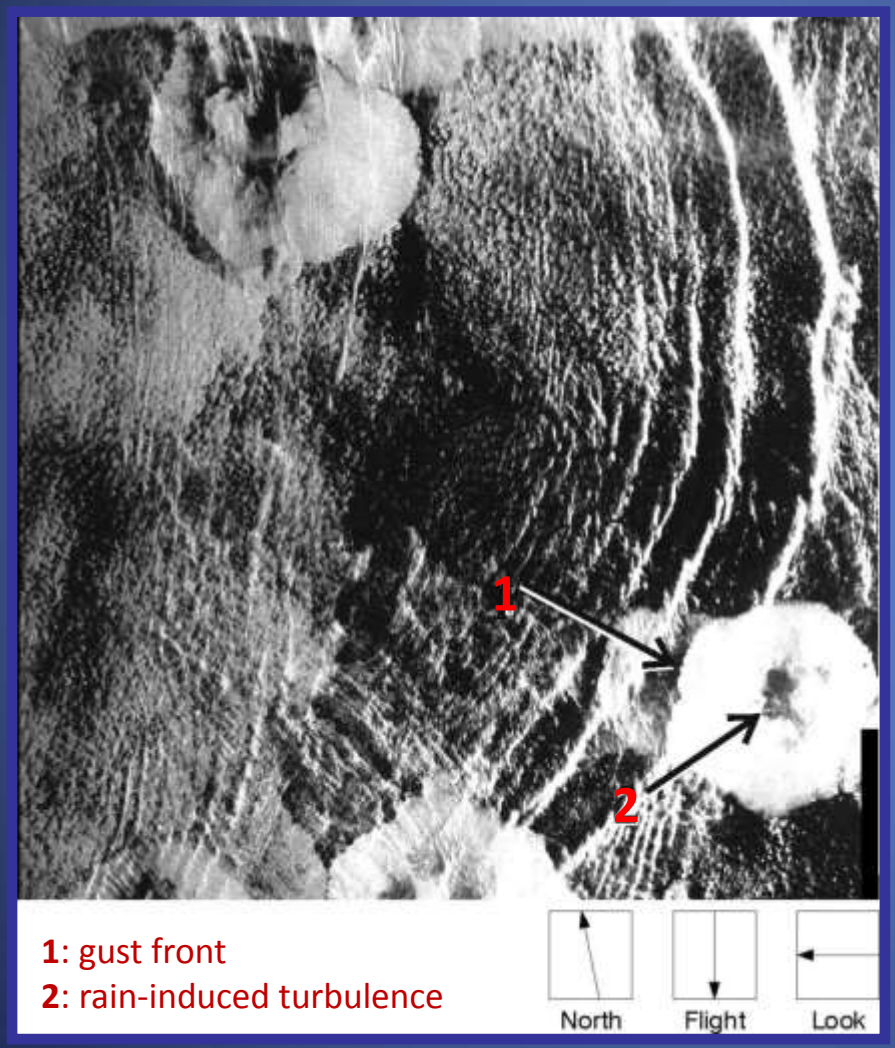


Impinging rain drop



ERS SAR Image (100 km × 100 km)
South Chinese Sea
(14 May 1998, 02:52 UTC, © ESA)

Heavy Rain

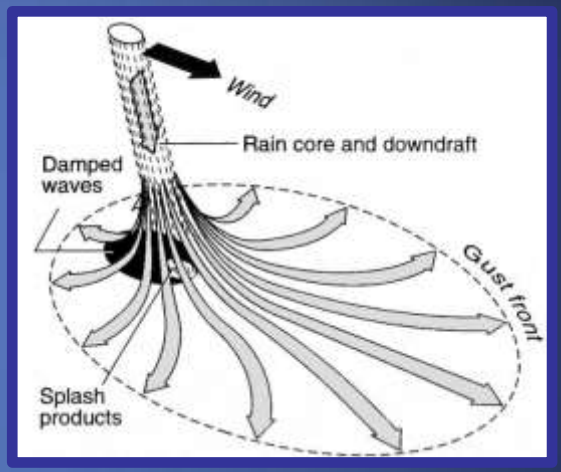


1: gust front
2: rain-induced turbulence

ERS-1 SAR Image (100 km × 100 km)
Andaman Sea
(3 April 1996, 12:34 UTC, © ESA)

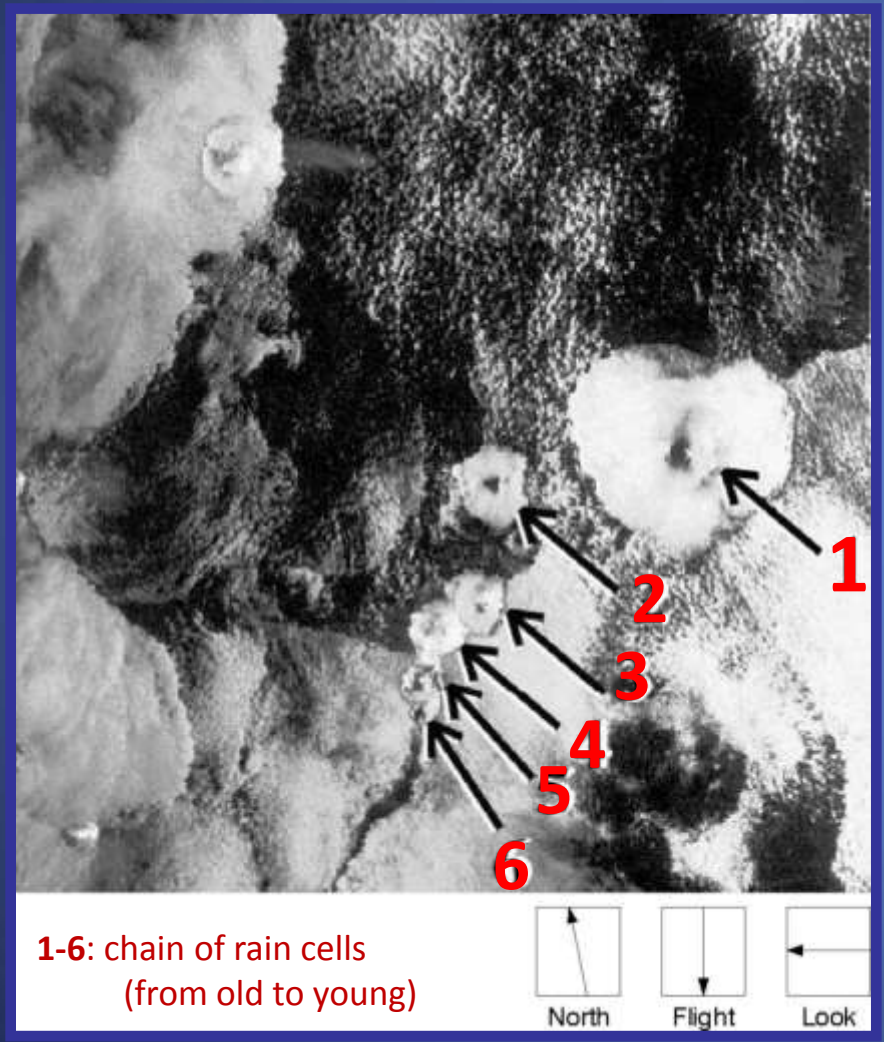
[Jackson & Apel, 2004]

Downdraft

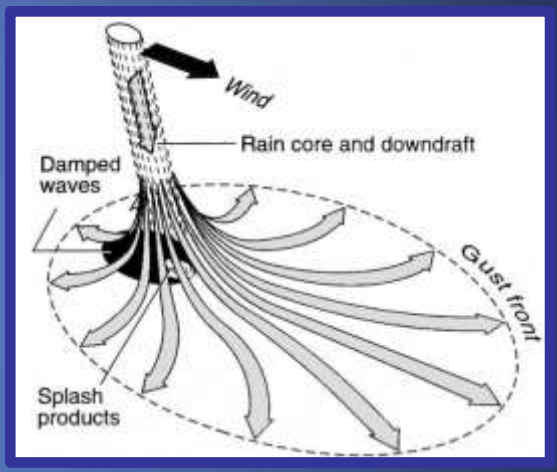


[Jackson & Apel, 2004]

Heavy Rain



Downdraft

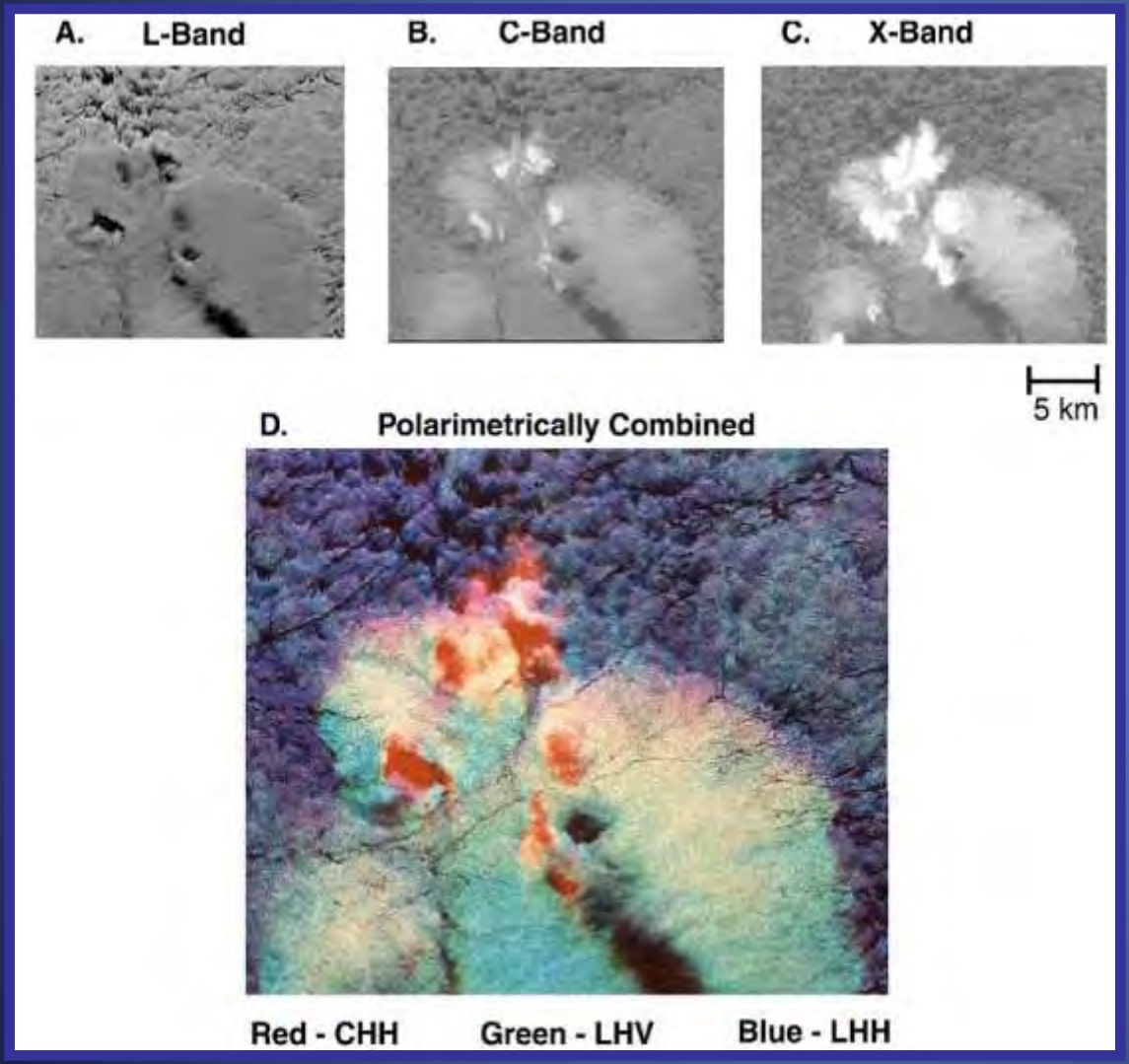


[Jackson & Apel, 2004]

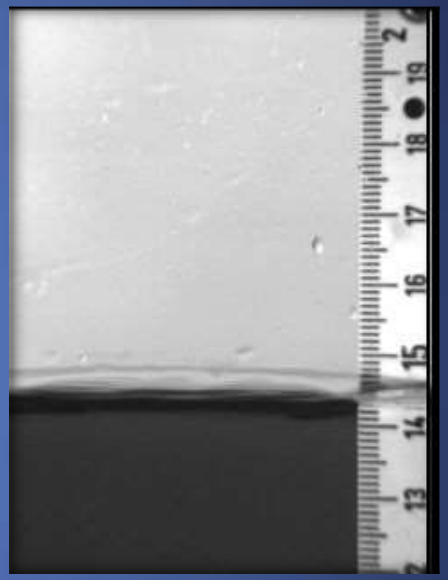
ERS-1 SAR Image (100 km × 100 km)
Gulf of Thailand
(18 April 1994, 03:42 UTC, © ESA)

[Jackson & Apel, 2004]

Heavy Rain



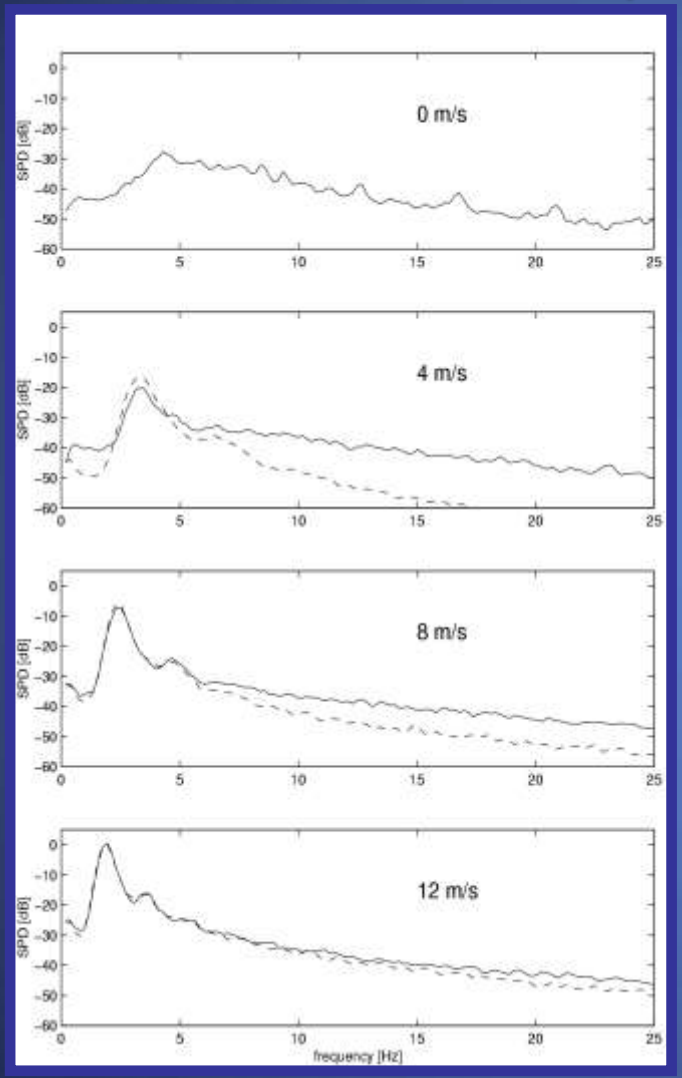
Impinging rain drop



SIR-C/X-SAR Images (5 km × 4 km)
Solomon Islands
(10 April 1994)

[Jackson & Apel, 2004]

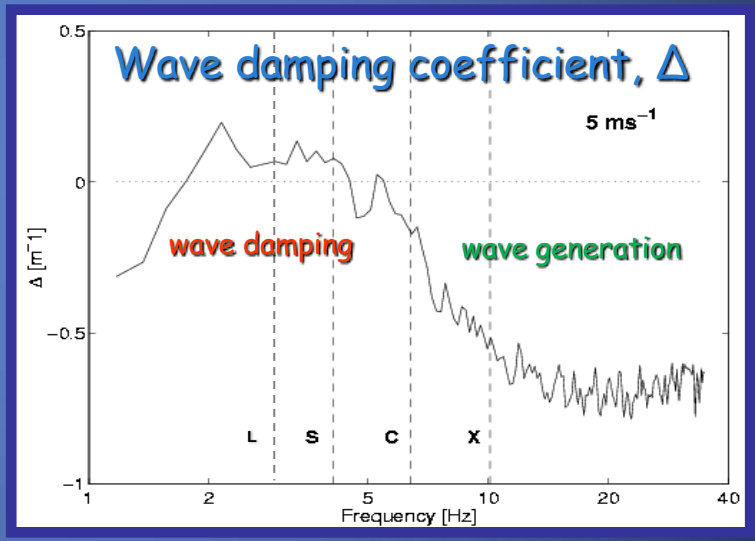
The Action of Heavy Rain on the Water Surface



[Braun, 2002]

wind only

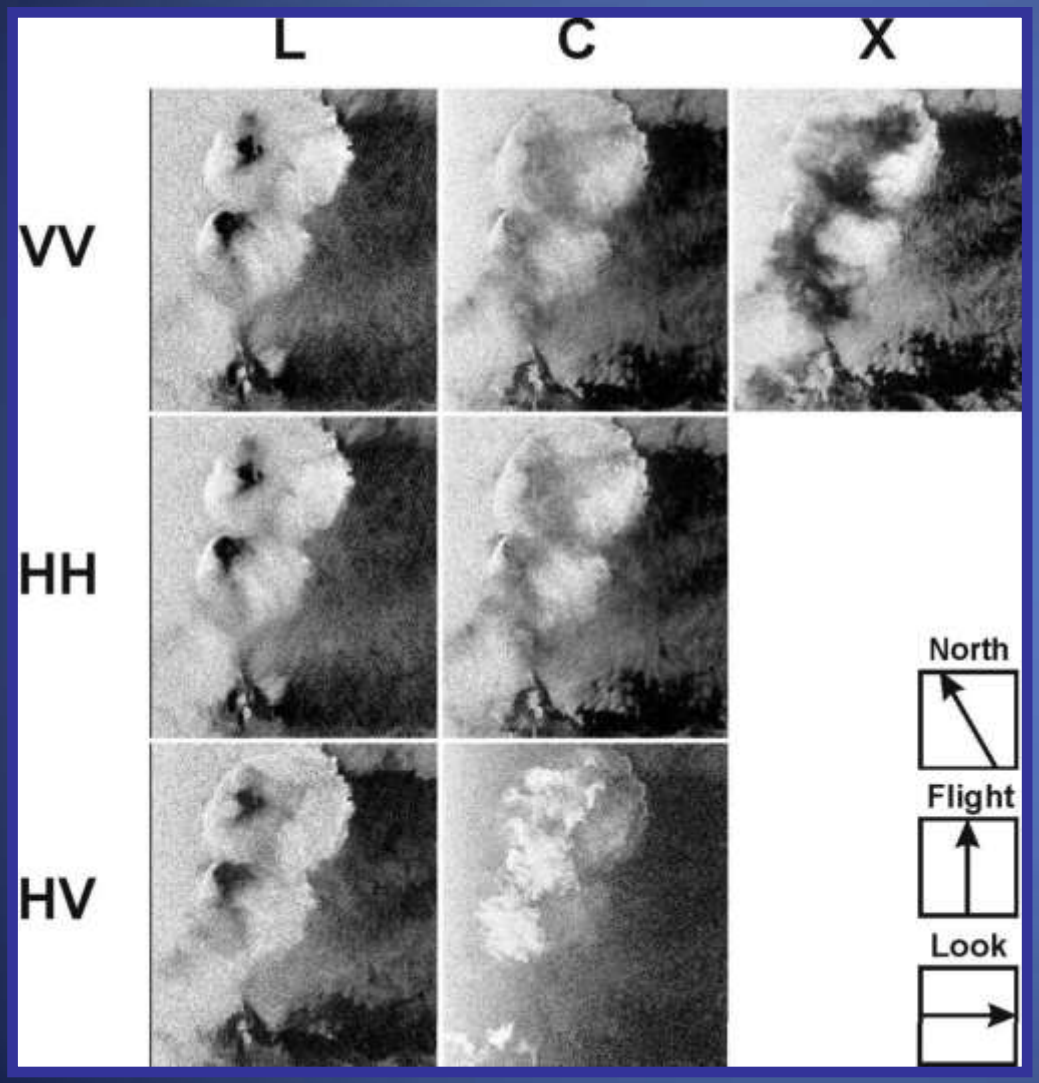
wind and rain



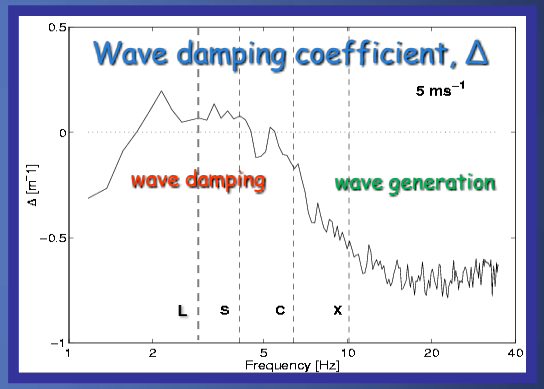
Damping of long waves (f < 5 Hz)

Generation of short waves (f > 5 Hz)

Heavy Rain



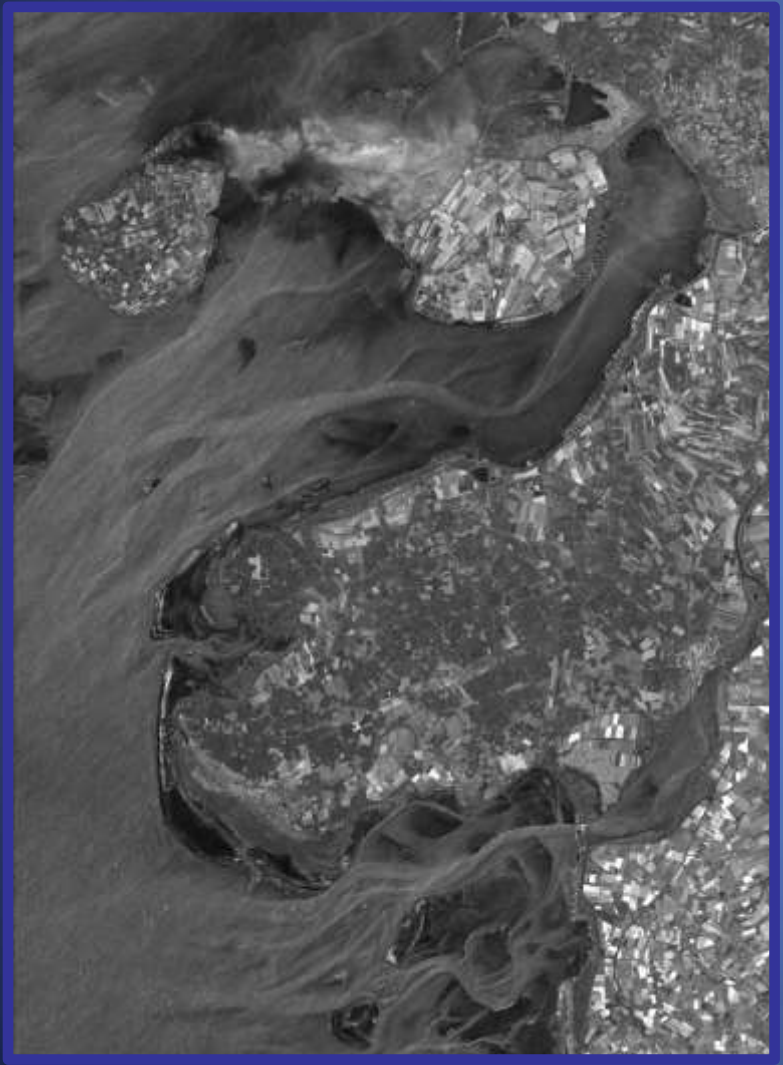
SAR Imaging at different radar frequencies and radar polarizations



SIR-C/X-SAR Images (16 km × 18 km)
Northern Straits of Malacca
(17 April 1994, 18:47 UTC)

[Jackson & Apel, 2004]

Comparison of SAR Imagery and Weather Radar



TerraSAR-X Image (X-VV, 30 km × 40 km)
German Bight
21 August 2008, 05:50 UTC, © DLR

Rain
Take-Home Messages

Heavy rain visible (surface & atmosphere)
Turbulence: wave damping
Splash products: roughness generation

"There've been reports of an increase in chatter among the women."

to be continued…