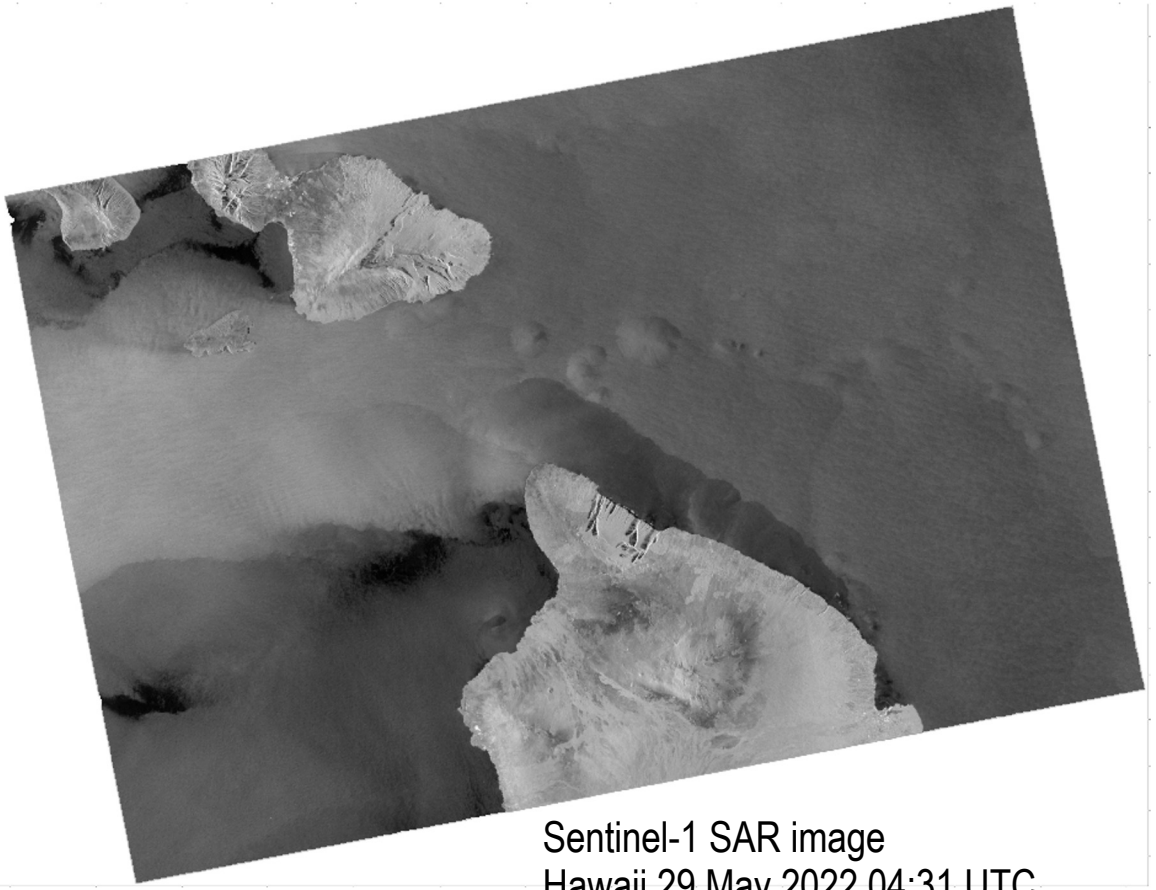
How Various Oceanic and Atmospheric Phenomena Appear in SAR Imagery

Module 3: Synthetic Aperture Radar Series

NOAA CoastWatch Satellite Courses



Sentinel-1 SAR image
Hawaii 29 May 2022 04:31 UTC

Last Updated: 12/10/2024

coastwatch.info@noaa.gov

The CoastWatch Synthetic Aperture Radar instructional series

The CoastWatch Synthetic Aperture Radar (SAR) instructional series consists of three (3) training modules:

Module 1: An overview of SAR

Module 2: Descriptions of available SAR products and where to find them

Module 3: Examples of how various phenomena appear in SAR imagery (this module)

What can be detected by SAR?

Oceanic

Surface Waves

- Significant Wave Height
- Wave Spectra

Surfactants (Biogenic Slicks, Oil Seeps)

Sea Ice

Internal Waves

Currents and Fronts

Eddies

Upwelling

Underwater Topography

Atmospheric

Surface Wind

Convection Cells / Rolls

Storm Systems

Vortex Streets

Gravity Waves

Rain Cells / Thunderstorms

Anthropogenic

Hard Targets (Ships/Oil Platforms)

Ship Wakes

Pollution (Oil Spills)

Coastal / Land

Flooding and Inundation

Shorelines

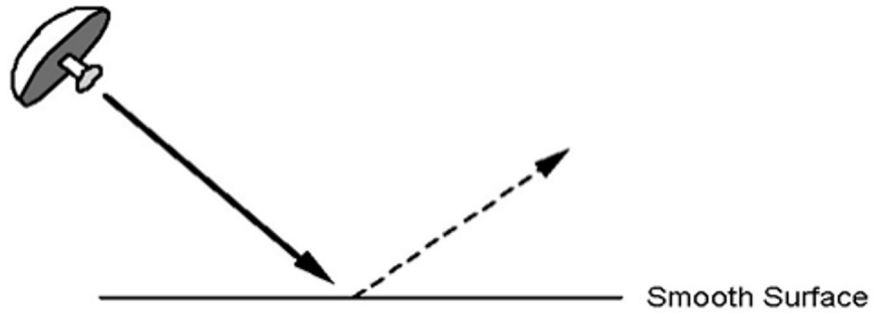
Land Use

Land Deformation (interferometry)

Burn Scar Identification

…there are many other applications

A radar measures the portion of the transmitter radar energy that is backscattered to the antenna



Smooth surfaces scatter most of the radar energy away from the radar, so less signal is backscattered to the SAR antenna.

These SAR images appear black.

Rough surfaces backscatter more the radar energy back to the SAR antenna.

These SAR images appear brighter

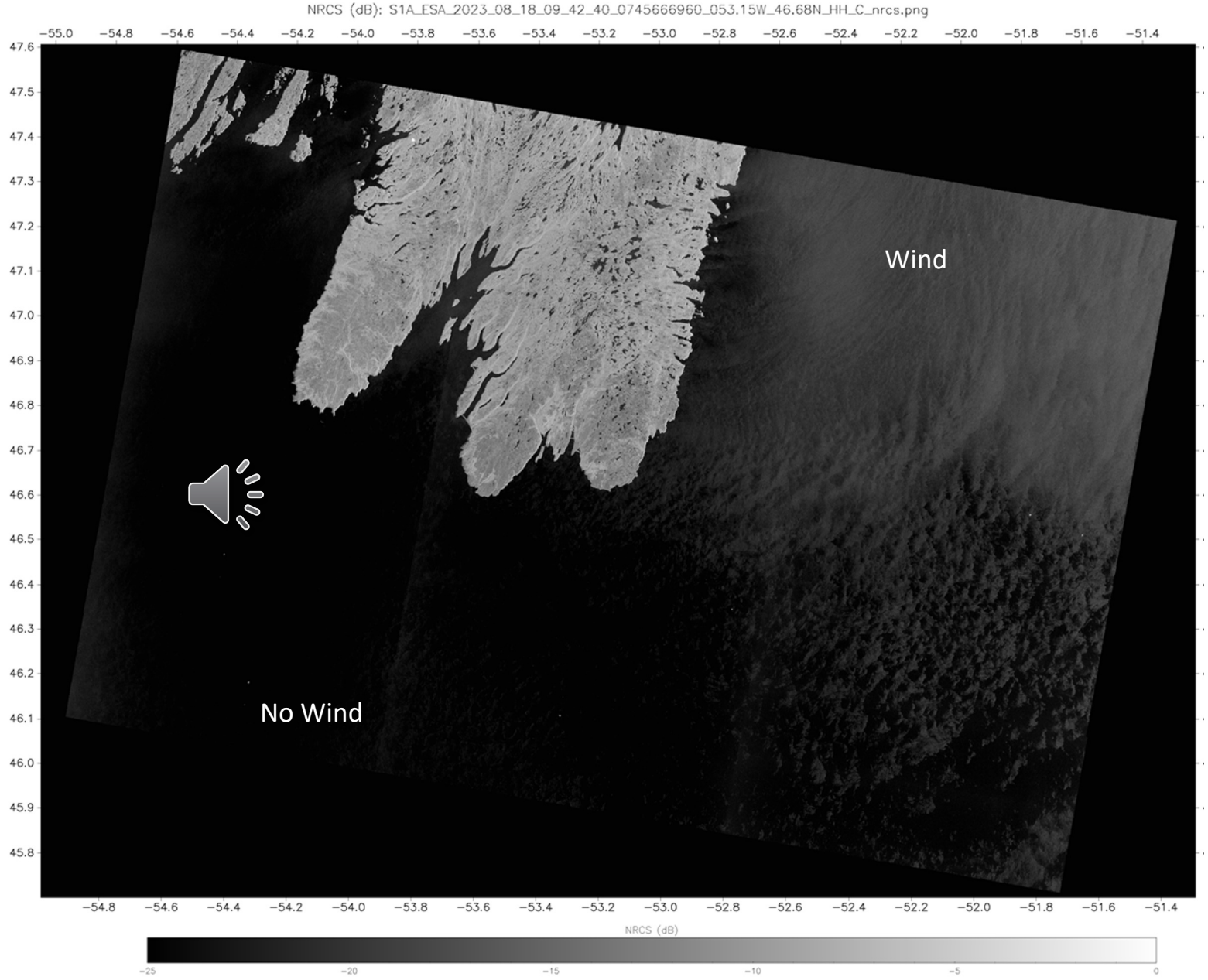
Normalized Radar Cross Section (NRCS) is the measure of radar backscatter

Images from https://appliedsciences.nasa.gov/join-mission/training/english/arset-introduction-synthetic-aperture-radar

The effect of wind…

Sentinel 1A SAR Co-Pol HH NRCS
18 August 2023 09:42 UTC

- As the surface wind over the ocean increases, the radar backscatter increases
  - Bright = Rough
  - Dark = Smooth



https://www.star.nesdis.noaa.gov/socd/mecb/sar/AKDEMO_products/APL_winds/wind_images2/2023-08/S1A_ESA_2023_08_18_09_42_40_0745666960_053.15W_46.68N_HH_C_nrcs.png

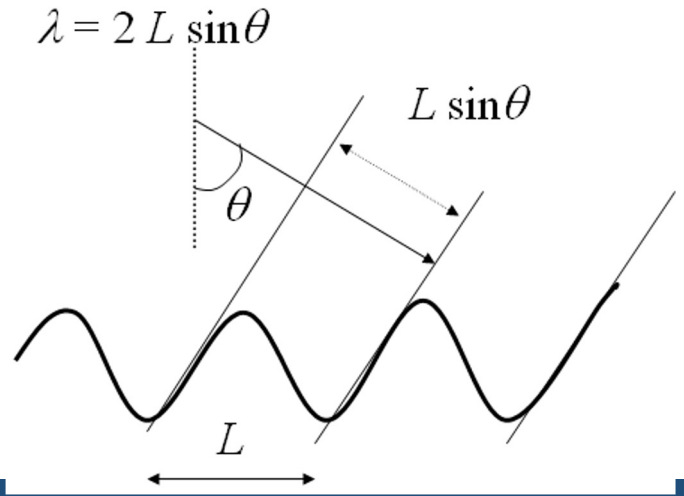
Components of ocean surface roughness contributing to backscatter

Wind is the principle source of ocean surface roughness for active microwave instruments

The wind generates short waves (capillary to short gravity waves) that have wavelengths from a few centimeters to tens of centimeters and periods < 1 second

As the wind over the ocean surface increases, the radar backscatter from the wind-driven short (cm scale) waves increases due to interaction between the incident radar wave and the short surface waves through a Bragg-like resonance.

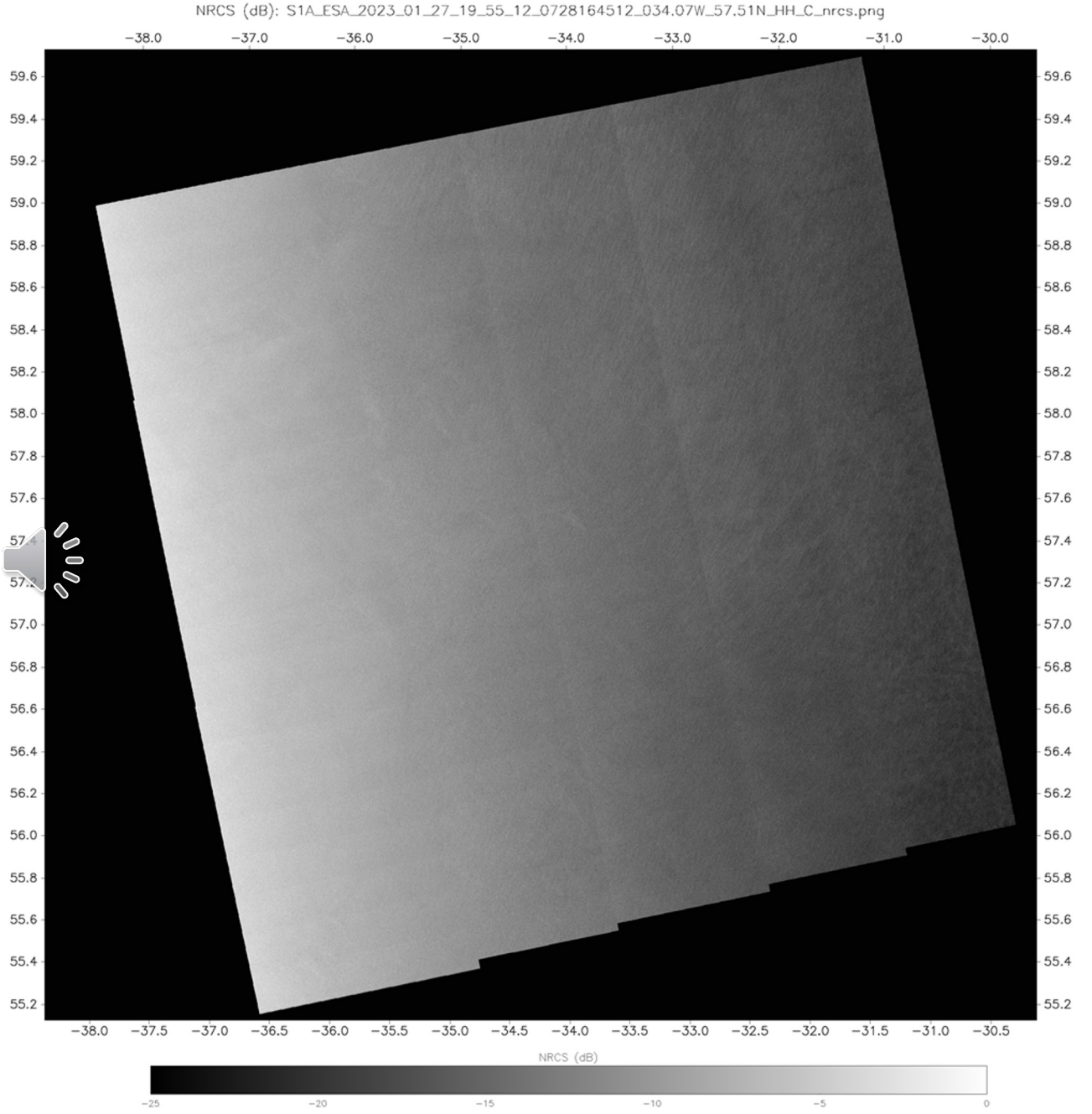
All other atmospheric and oceanic phenomena visible on the ocean surface in a SAR image are the result of modifiying the pattern of the wind-generated short waves.



Information Content

Sentinel 1A SAR Co-Pol HH NRCS
27 January 2023 19:55 UTC

Even “non-descript” images…..



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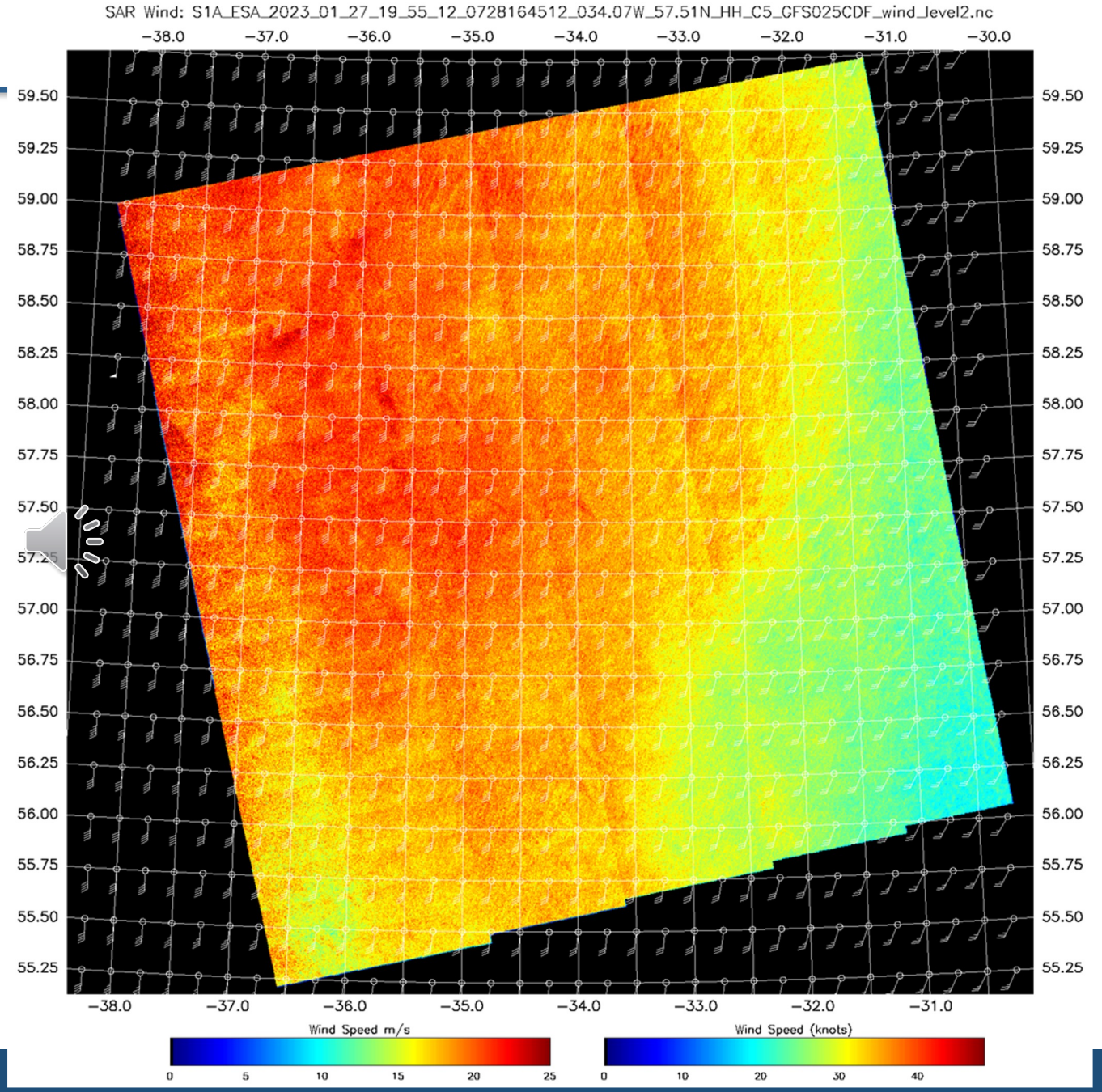
SAR Derived Wind Speed

Sentinel 1A SAR Co-Pol HH NRCS
27 January 2023 19:55 UTC

Even “non-descript” images…..

… can contain useful information

Ocean surface Normalized Radar Cross Section converted to wind speed using the CMOD4 Geophysical Model Function



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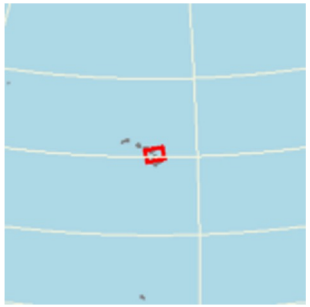
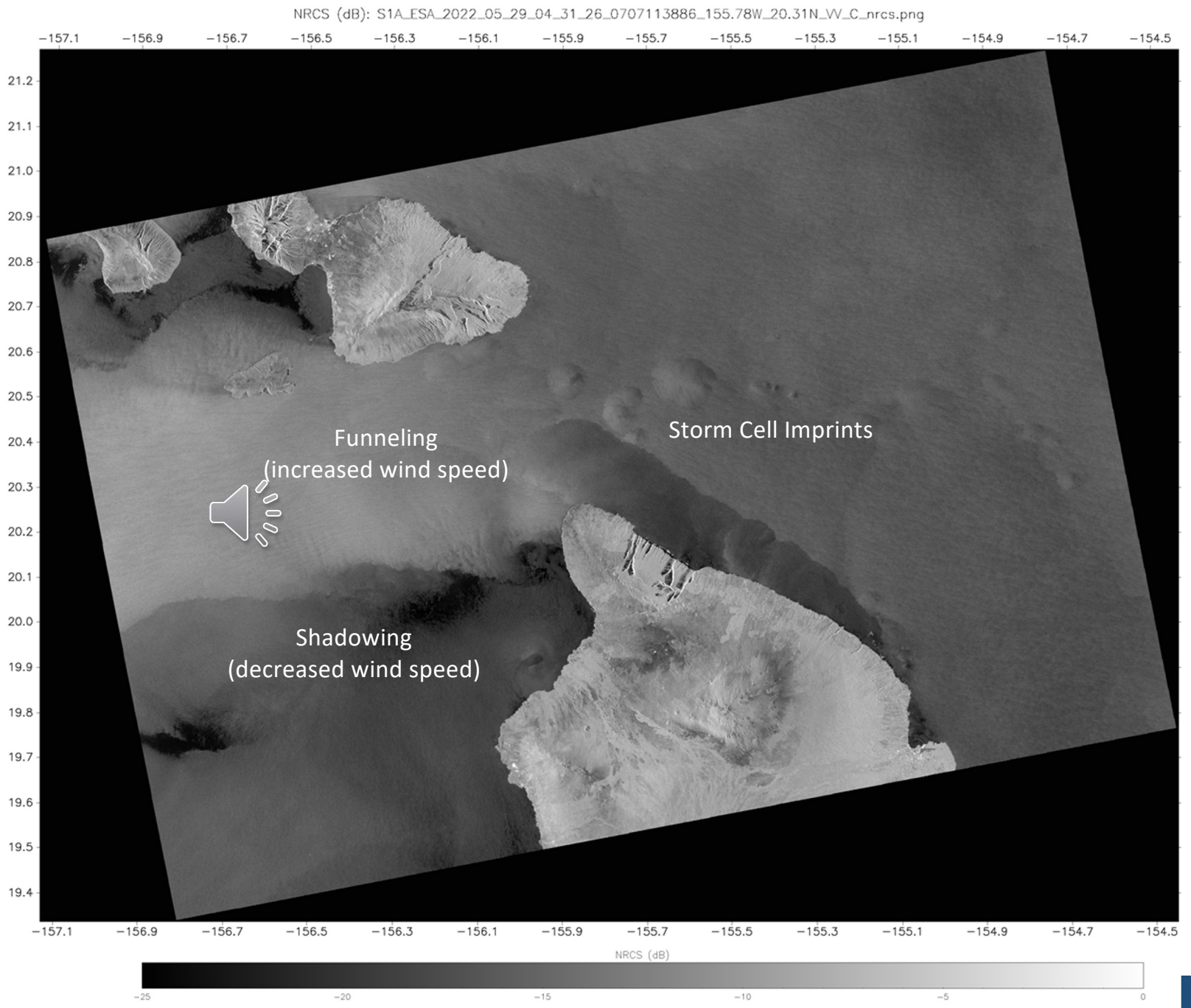
Atmosphere

Sentinel 1A SAR Co-Pol VV NRCS
29 May 2022 04:31 UTC



- Moderate (15 kt) winds out of the east are influenced by the island topography producing regions of increased and reduced wind speed

- Storm cell imprints (cold pools)
  A cold pool is a pocket of dense air that forms when rain evaporates during intense precipitation. A surface-based cold pool is a region of relatively stable air.

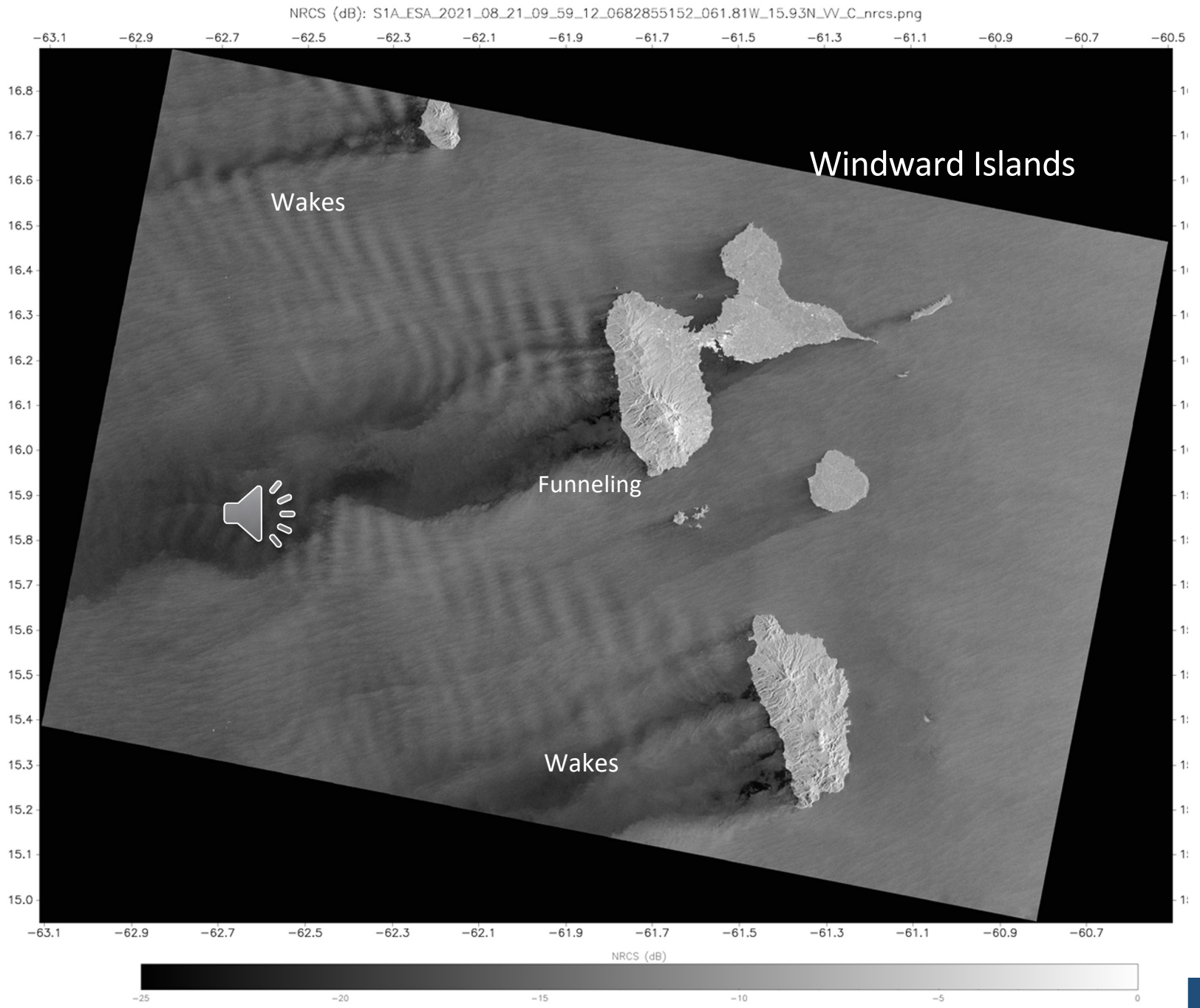


https://www.star.nesdis.noaa.gov/socd/mecb/sar/AKDEMO_products/APL_winds/wind_images2/2022-05/S1A_ESA_2022_05_29_04_31_26_0707113886_155.78W_20.31N_VV_C_nrcs.png

Atmosphere

Sentinel 1A SAR Co-Pol Winds
21 August 2021 09:59 UTC

- Wind (from the east) interacting with the Windward Islands produce the signatures of wind funneling, island wakes.
- Island wakes / shadowing can extend 100s of km behind an island



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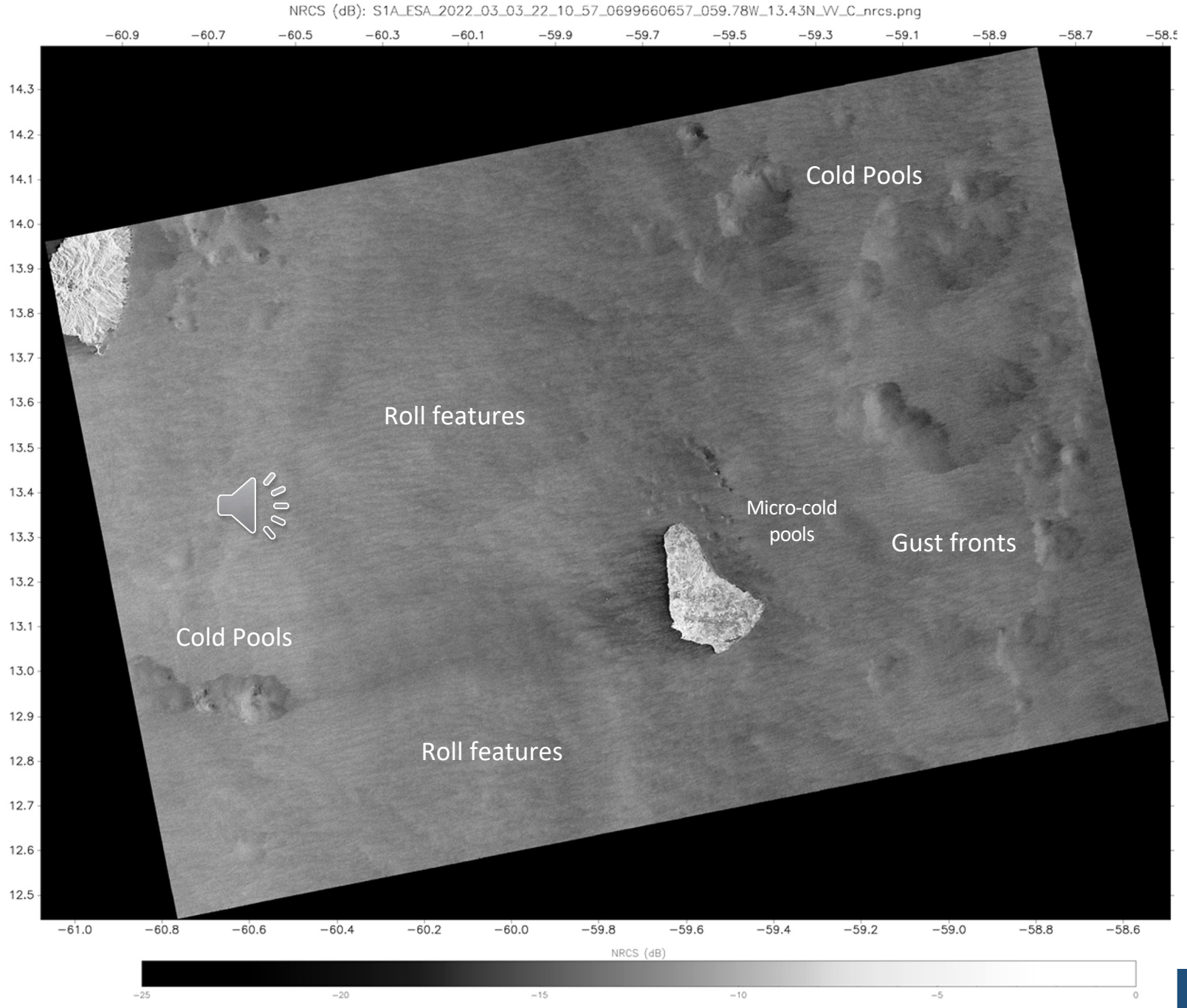
Atmosphere

Sentinel 1A SAR Co-Pol Winds
03 March 2022 22:11 UTC

- Atmospheric signatures include a gust front, cold pools, micro-cold pools and fine scale atmospheric boundary layer rolls (BLR)
- BLRs are counterrotating vortical rolls along a horizontal axis that is approximately aligned with the mean wind direction.

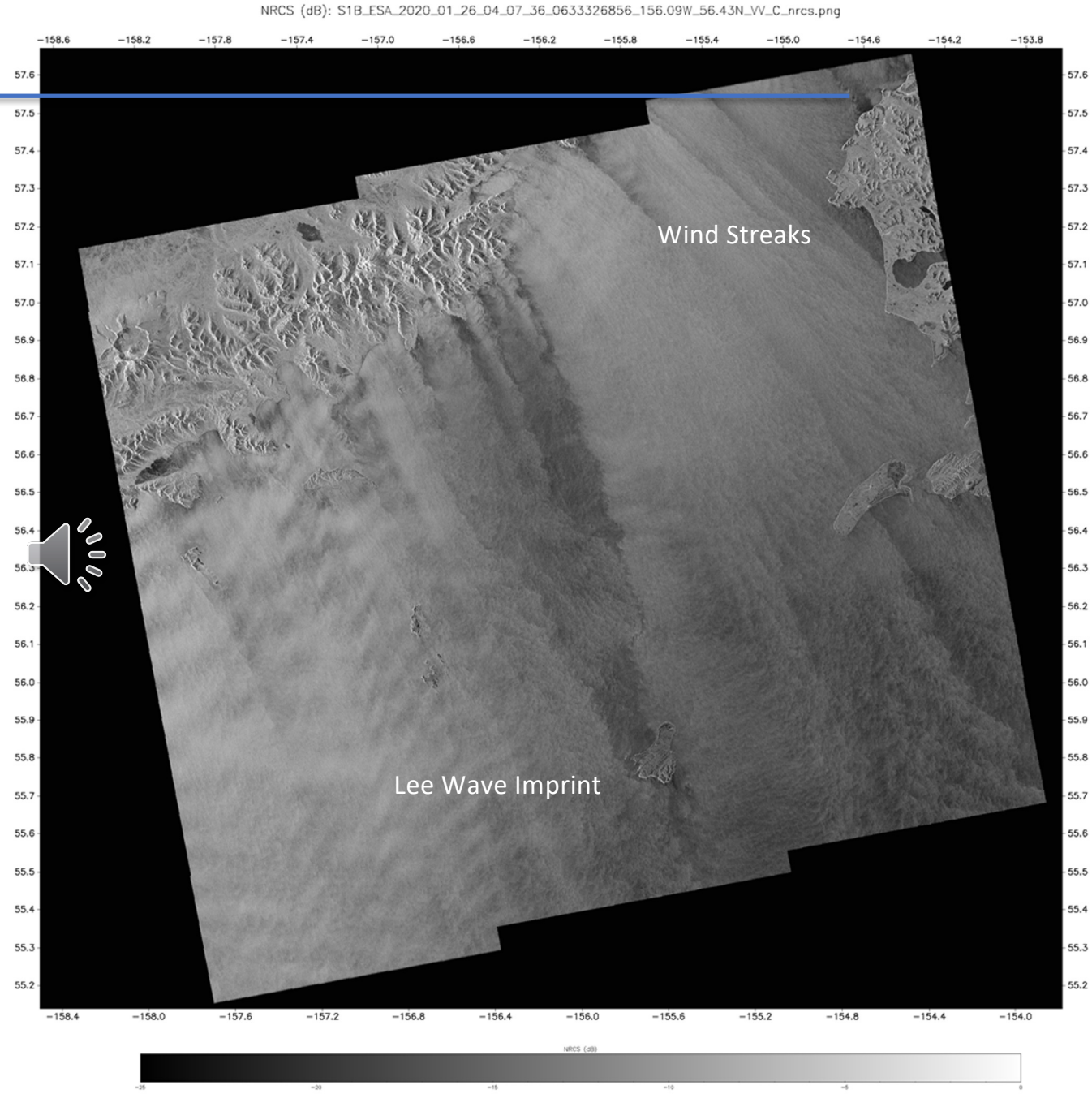


https://www.star.nesdis.noaa.gov/socd/mecb/sar/AKDEMO_products/APL_winds/wind_images2/2022-03/S1A_ESA_2022_03_03_22_10_57_0699660657_059.78W_13.43N_VV_C_nrcs.png

Atmosphere - Wind

Sentinel 1A SAR Co Pol VV NRCS
26 January 2020 04:07 UTC

- 15 to 20 kt winds out of the northwest are accelerated by gaps in the topography resulting in gap flows.
- The flows produce “wind streaks” long linear features aligned with the wind direction
- The topography has also induced lee waves (which appear as alternating light/dark bands parallel with the topography)



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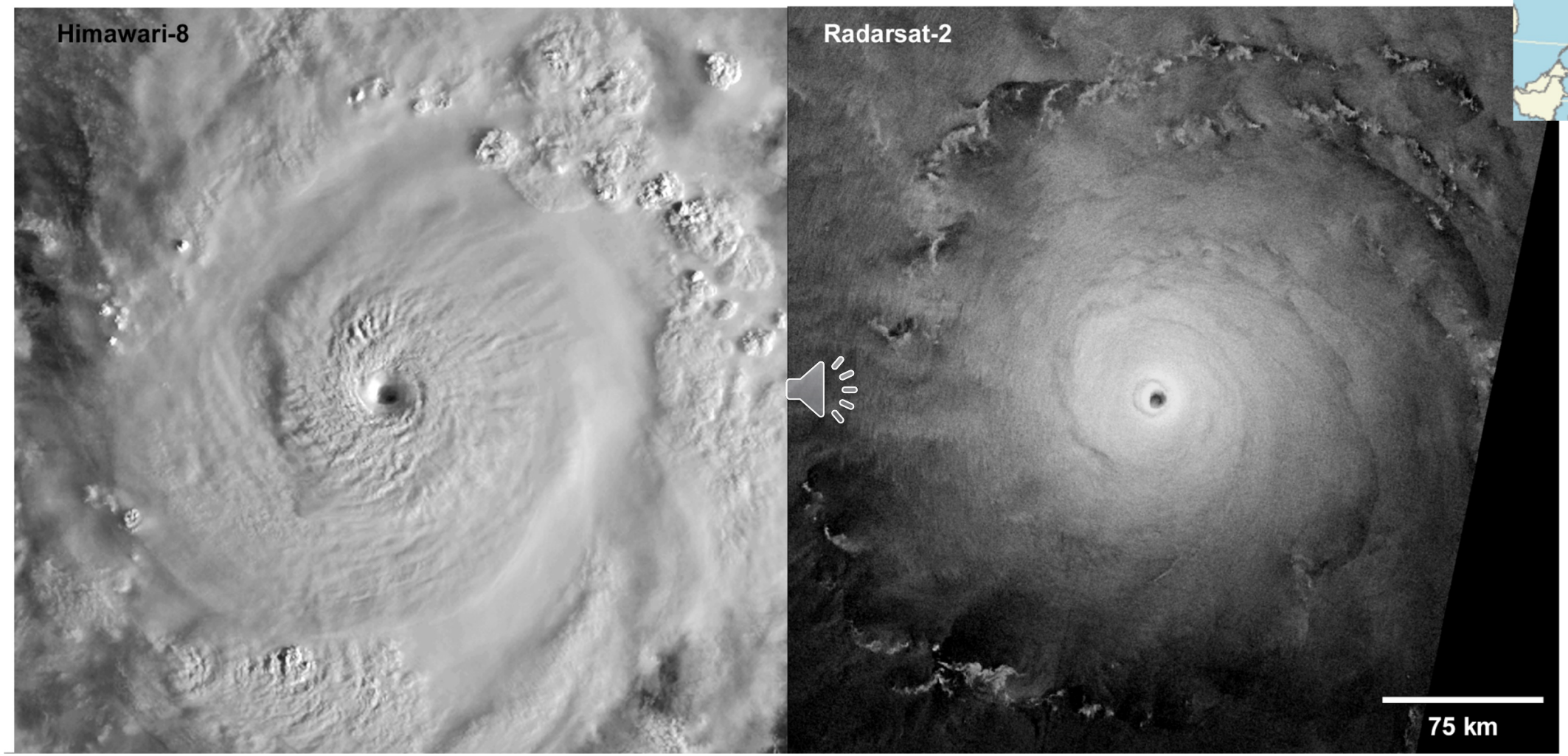
https://www.star.nesdis.noaa.gov/socd/mecb/sar/AKDEMO_products/APL_winds/wind_images2/2020-01/S1B_ESA_2020_01_26_04_07_36_0633326856_156.09W_56.43N_VV_C5_GFS05CDF_wind.png

Super Typhoon Goni – 30 Oct 2020

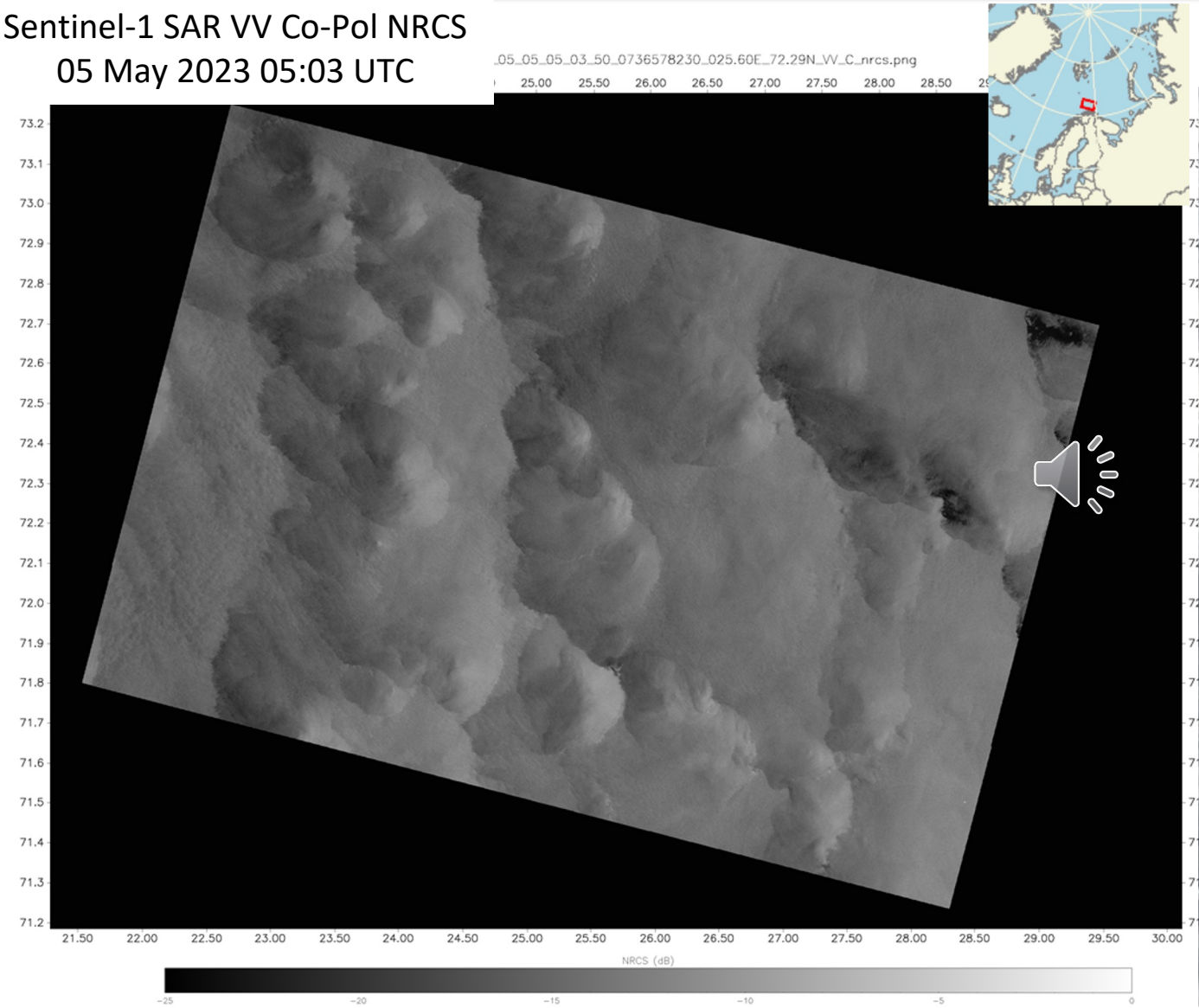


Himawari-8 22:17 UTC Visible Band
(Cloud Top)

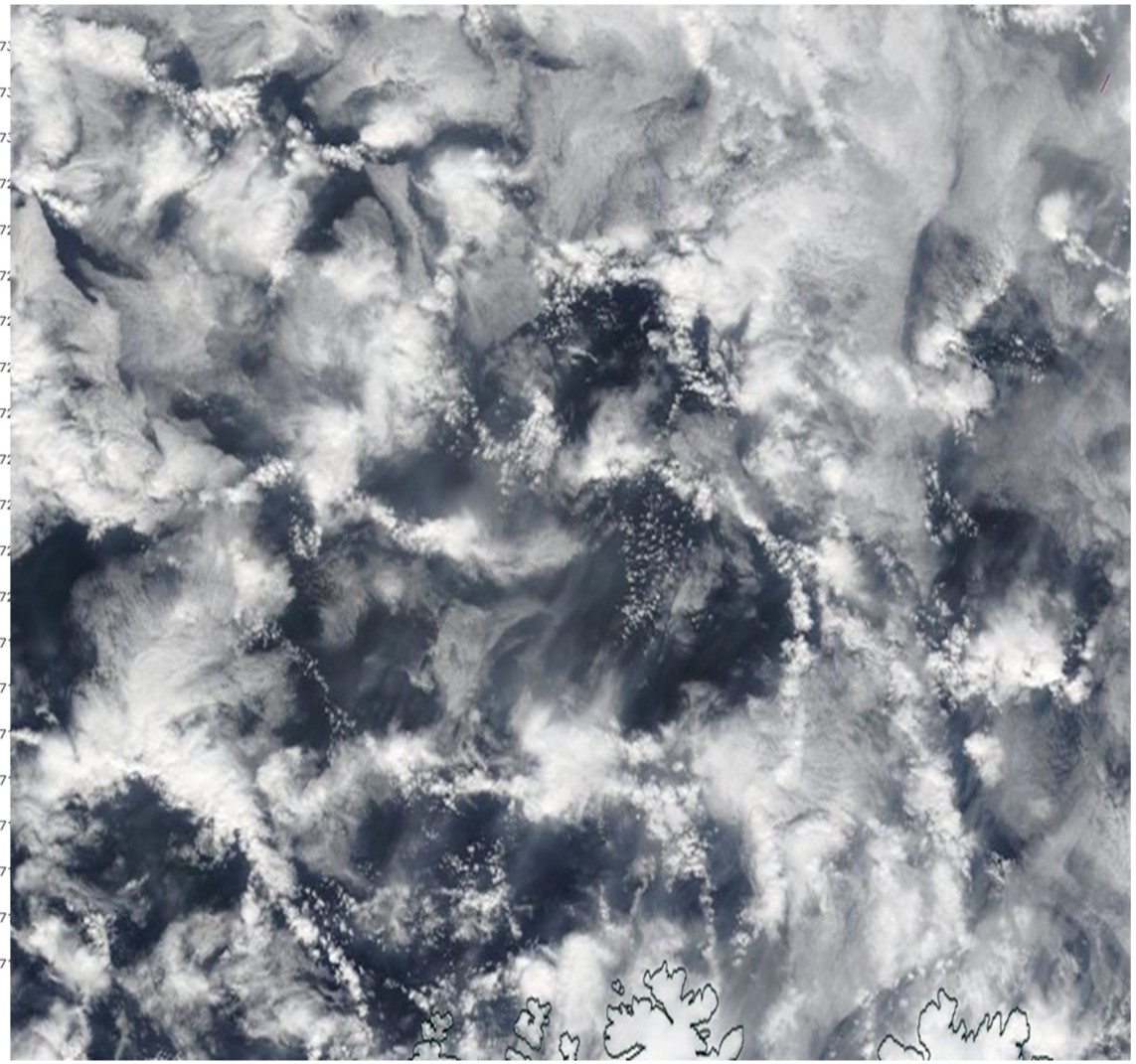
Radarsat-2 21:16 UTC Cross-Polarization (VH)
(Ocean Surface)

Atmosphere - Open Cell Clouds

Sentinel-1 SAR VV Co-Pol NRCS
05 May 2023 05:03 UTC



MODIS True Color
05 May 2023 04:45 UTC



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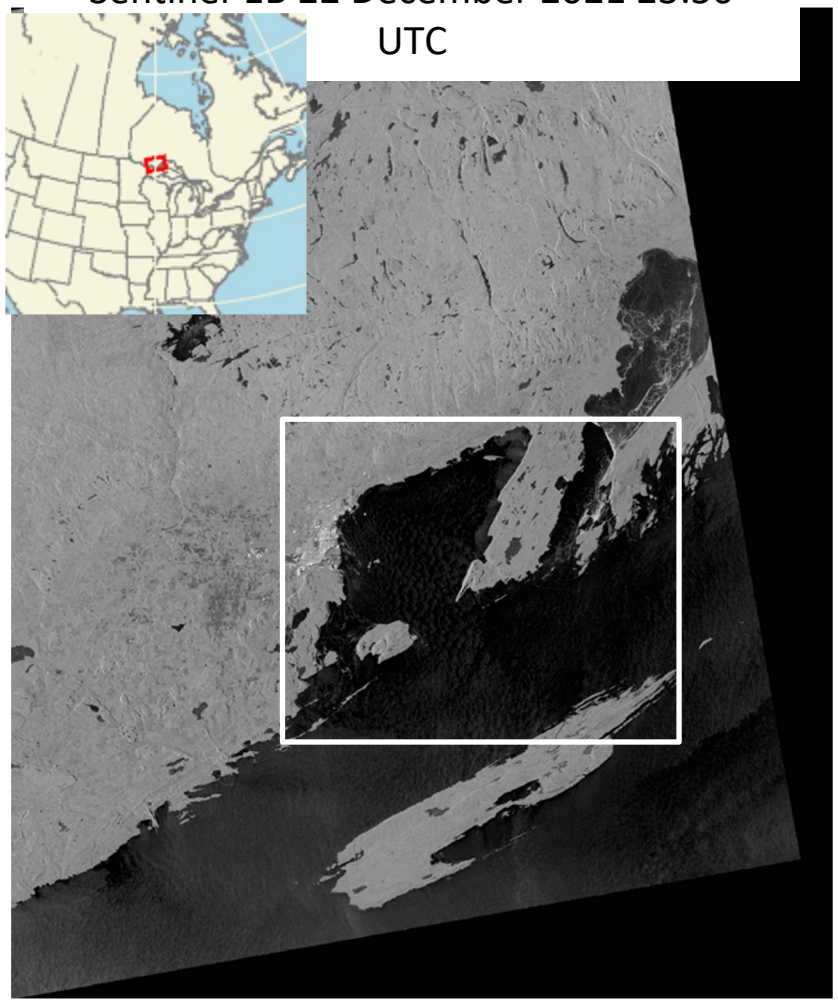
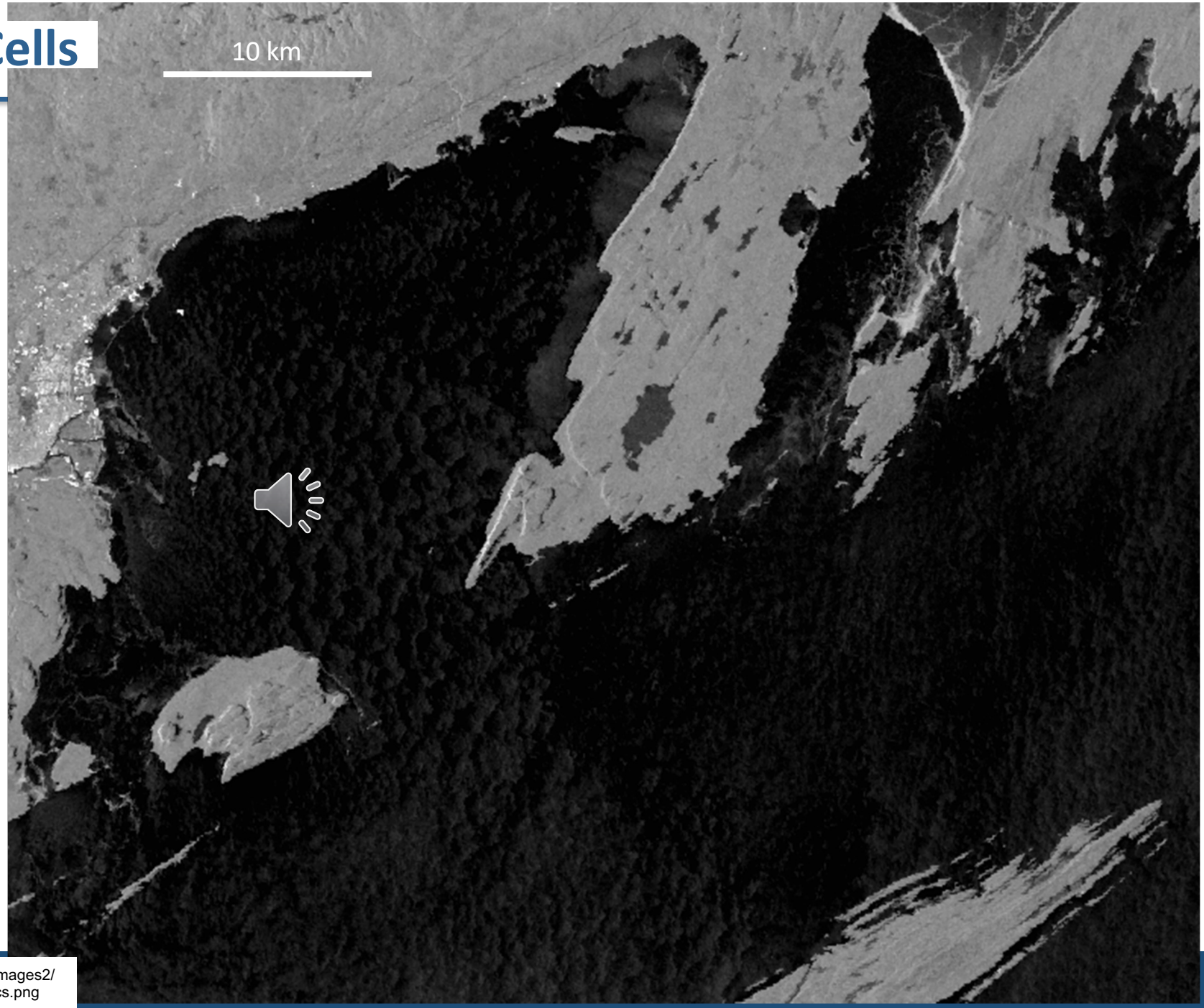
Atmosphere - Convection Cells

Thunder Bay – Lake Superior
Sentinel-1B 22 December 2021 23:50 UTC



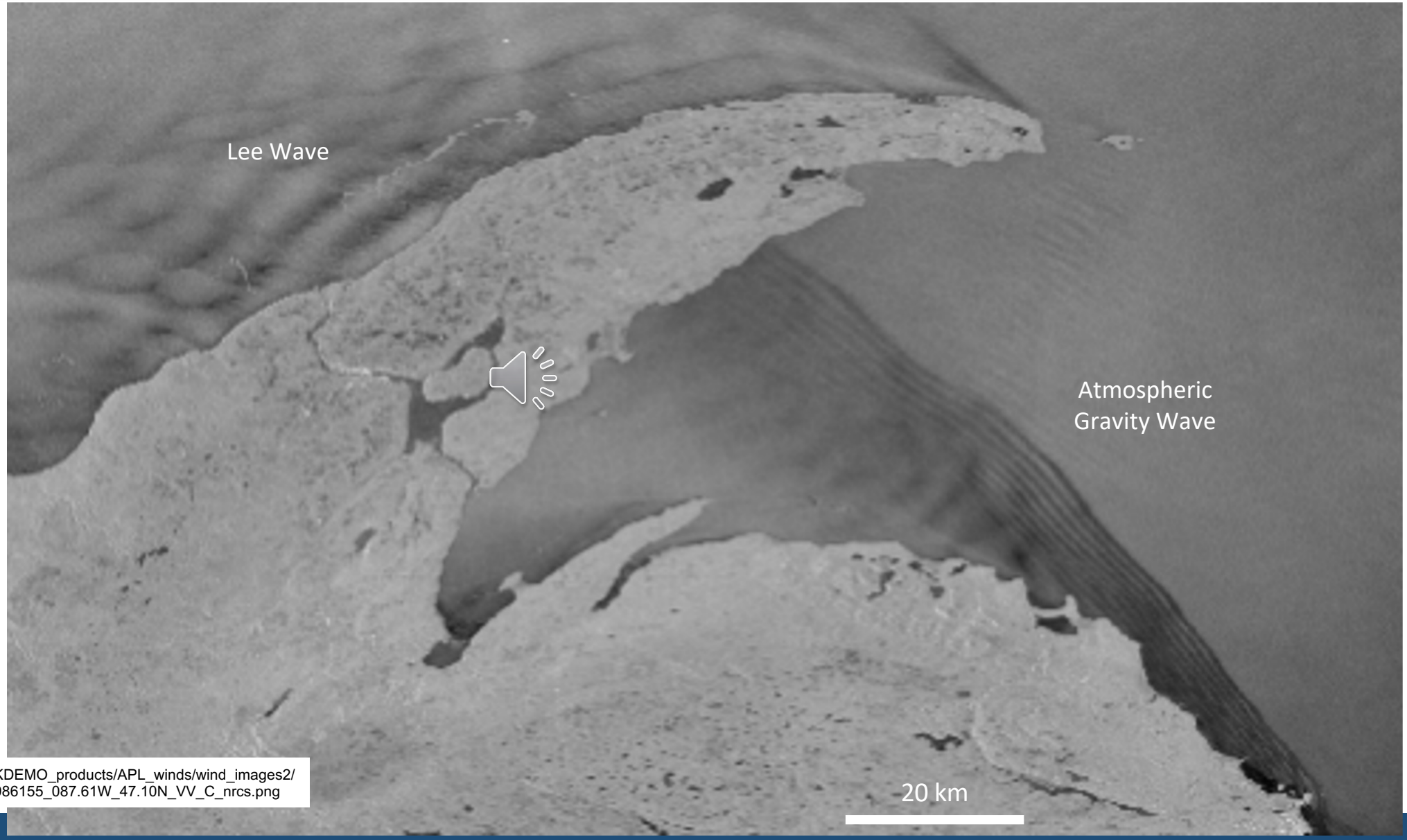


https://www.star.nesdis.noaa.gov/socd/mecb/sar/AKDEMO_products/APL_winds/wind_images2/2021-12/S1B_ESA_2021_12_22_23_50_30_0693532230_089.95W_48.46N_VV_C_nrcs.png

Atmosphere – Lee waves and Atmospheric Gravity Waves

Sentinel-1 SAR
VV Co-Pol NRCS
22 April 2022 23:42 UTC

Lee waves and atmospheric gravity waves



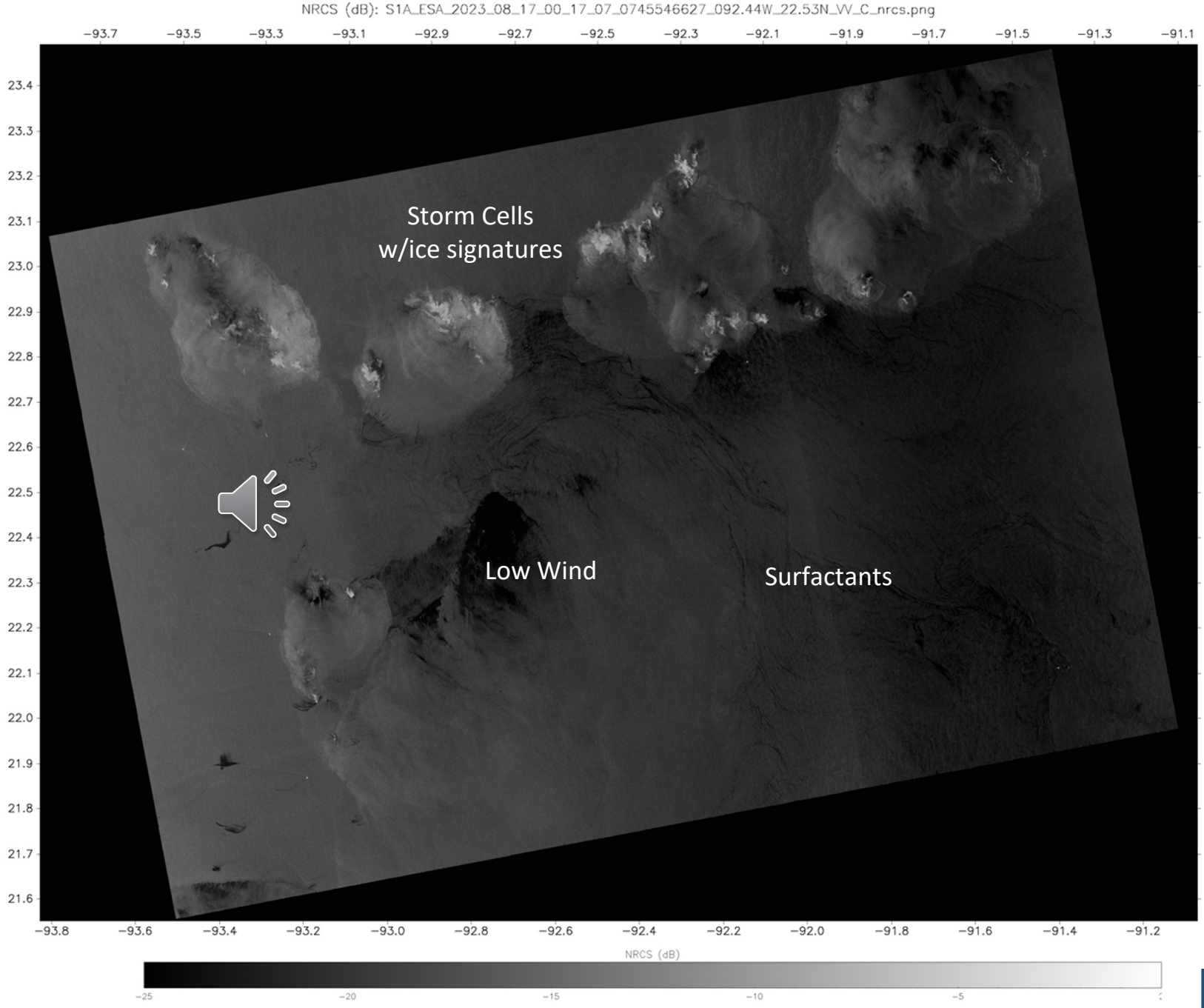
https://www.star.nesdis.noaa.gov/socd/mecb/sar/AKDEMO_products/APL_winds/wind_images2/2022-04/S1A_ESA_2022_04_22_23_42_35_0703986155_087.61W_47.10N_VV_C_nrcs.png

Atmosphere and Ocean

Sentinel 1A SAR Co-Pol Winds
17 August 2023 00:17 UTC

- Atmospheric signatures include storm cells with high NRCS returns from atmospheric ice.
- Low NRCS features are regions of low wind and natural surfactants (oil)

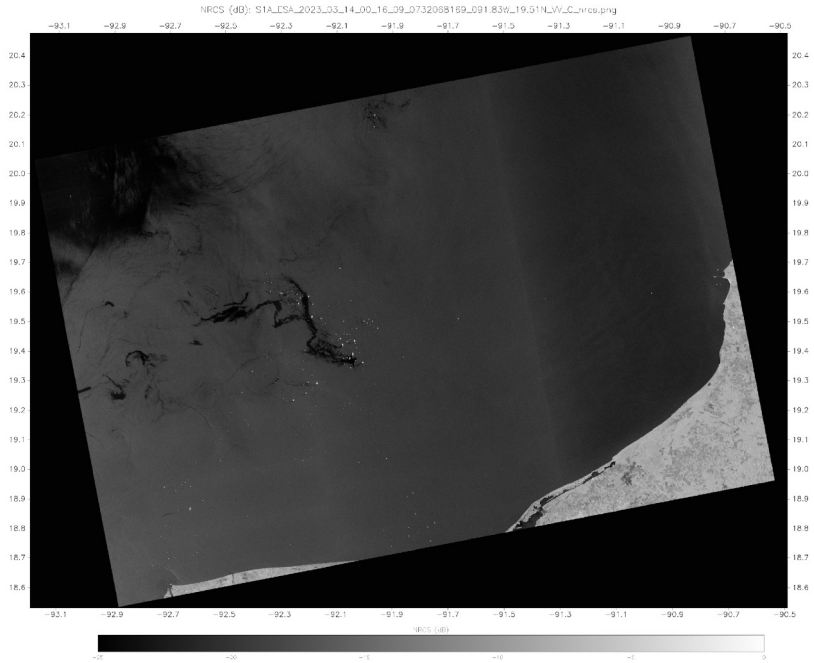
https://www.star.nesdis.noaa.gov/socd/mecb/sar/AKDEMO_products/APL_winds/wind_images2/2023-08/S1A_ESA_2023_08_17_00_17_07_0745546627_092.44W_22.53N_VV_C_nrcs.png

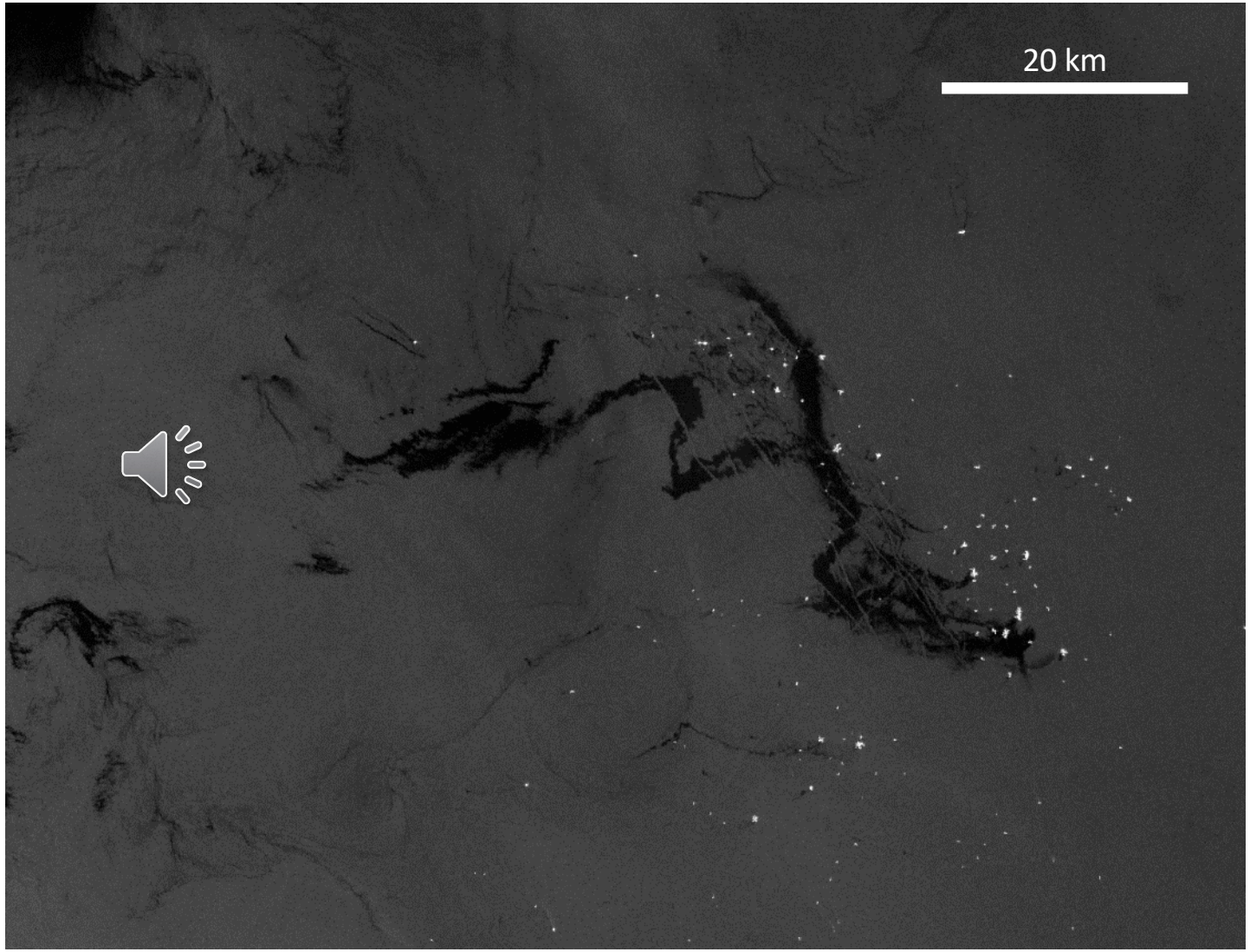


Ocean – Oil

Sentinel-1 SAR VV Co-Pol NRCS
14 March 2023 00:16 UTC

Ships and Oil Platforms (high backscatter)
Oil spill and surfactants (low backscatter)





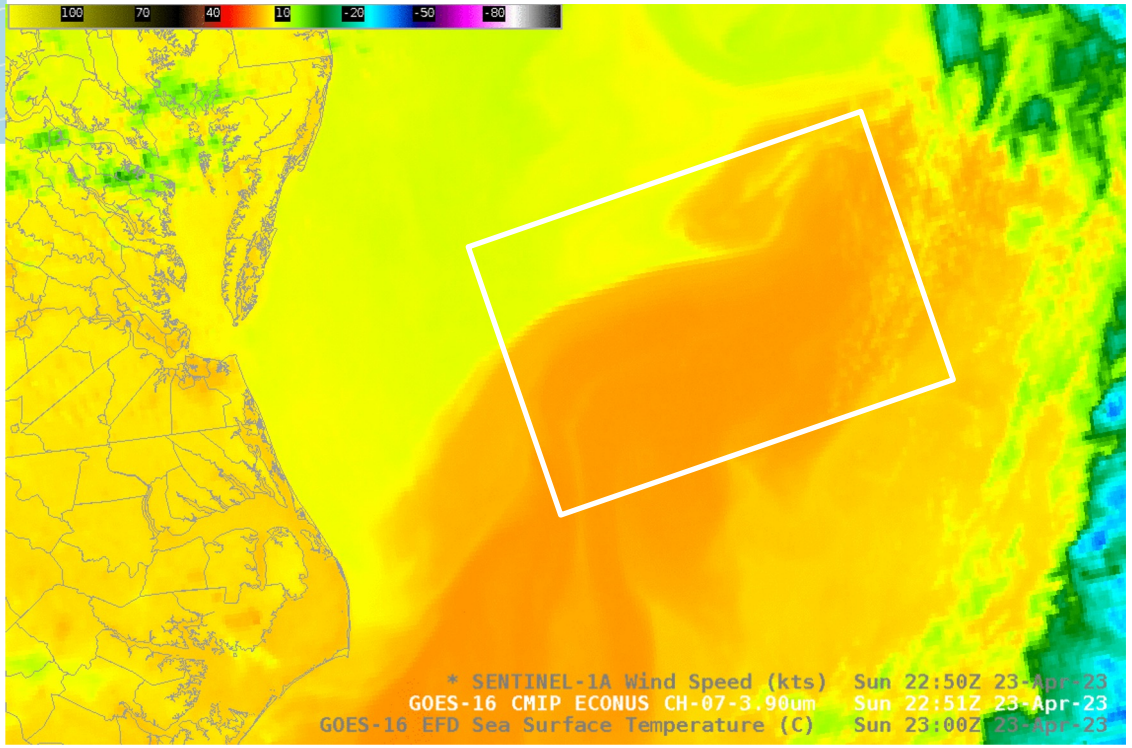
https://www.star.nesdis.noaa.gov/socd/mecb/sar/AKDEMO_products/APL_winds/wind_images2/2023-03/S1A_ESA_2023_03_14_00_16_09_0732068169_091.83W_19.51N_VV_C_nrcs.png

Ocean – Sea Surface Temperature (SST) on SAR Backscatter

Sentinel-1 SAR VV Co-Pol NRCS
23 April 2023 22:50 UTC

https://www.star.nesdis.noaa.gov/socd/mecb/sar/AKDEMO_products/APL_winds/wind_images2/2023-04/S1A_ESA_2023_04_23_22_50_25_0735605425_072.79W_36.69N_VV_C_nrcs.png

SAR data views of the North Wall of the Gulf Stream by Scott Lindstrom
https://cimss.ssec.wisc.edu/satellite-blog/archives/51902

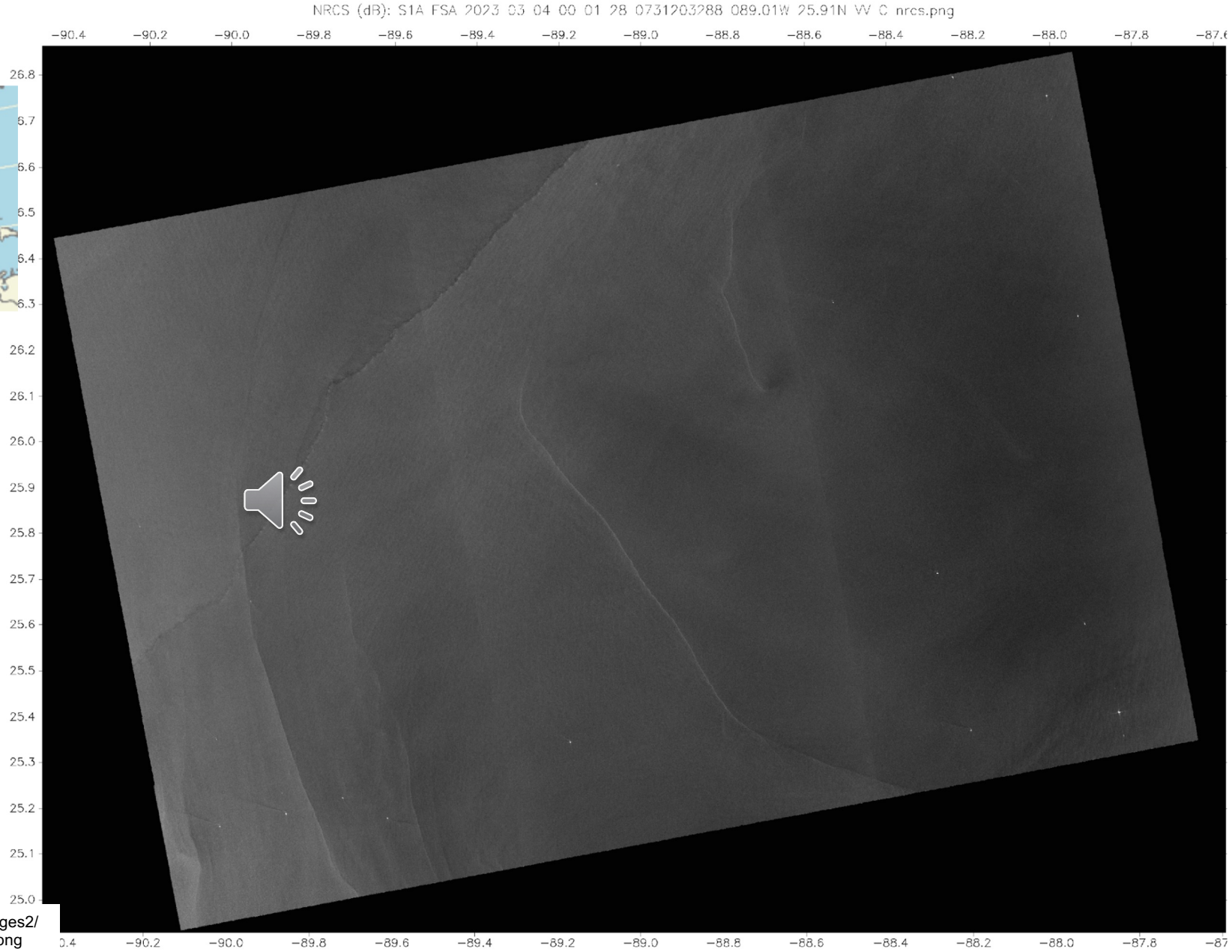


Water temperature affects water surface tension, which influences the formation of wind driven capillary waves. Differences in the capillary wave field show up as difference in backscatter

Ocean – Current / Suloy

Sentinel-1 SAR VV Co-Pol NRCS
4 March 2023 00:01 UTC

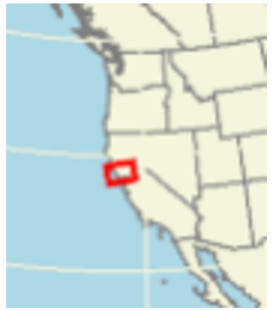
- A Suloy is a line indicating an interface between two ocean currents.
- At the interface, there is usually a slight upwelling altering the surface roughness



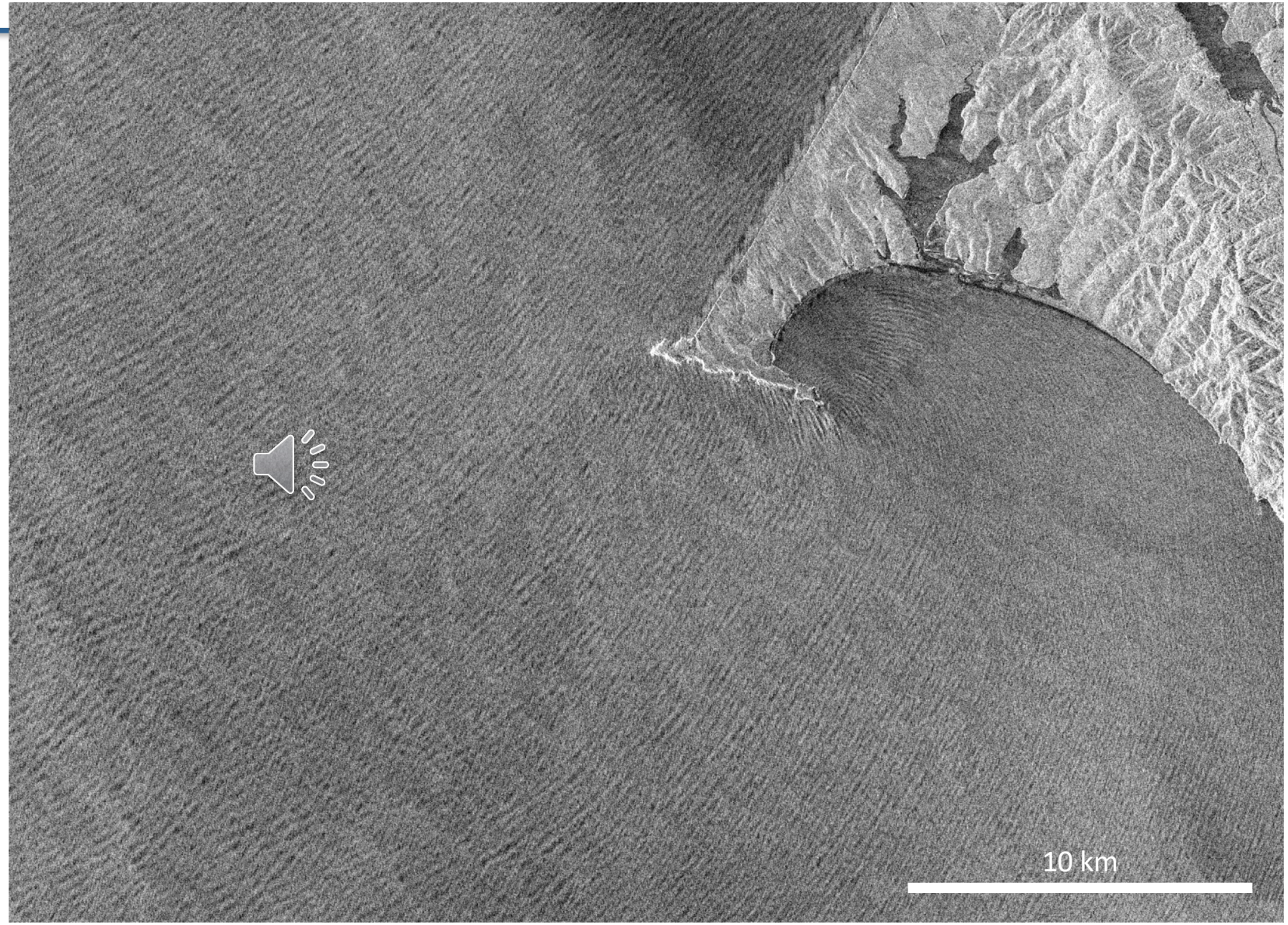
https://www.star.nesdis.noaa.gov/socd/mecb/sar/AKDEMO_products/APL_winds/wind_images2/2023-03/S1A_ESA_2023_03_04_00_01_28_0731203288_089.01W_25.91N_VV_C_nrcs.png

Ocean – Swell Waves

Sentinel-1 SAR VV Co-Pol NRCS
23 February 2023 02:08 UTC



- Swell waves (wavelength ~400 m – 1km) are produced by consistent wind forcing.
- The swell can be seen refracting around Point Reyes (California)

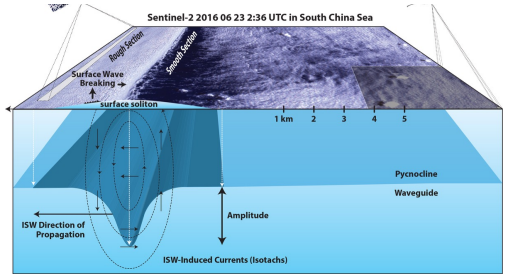


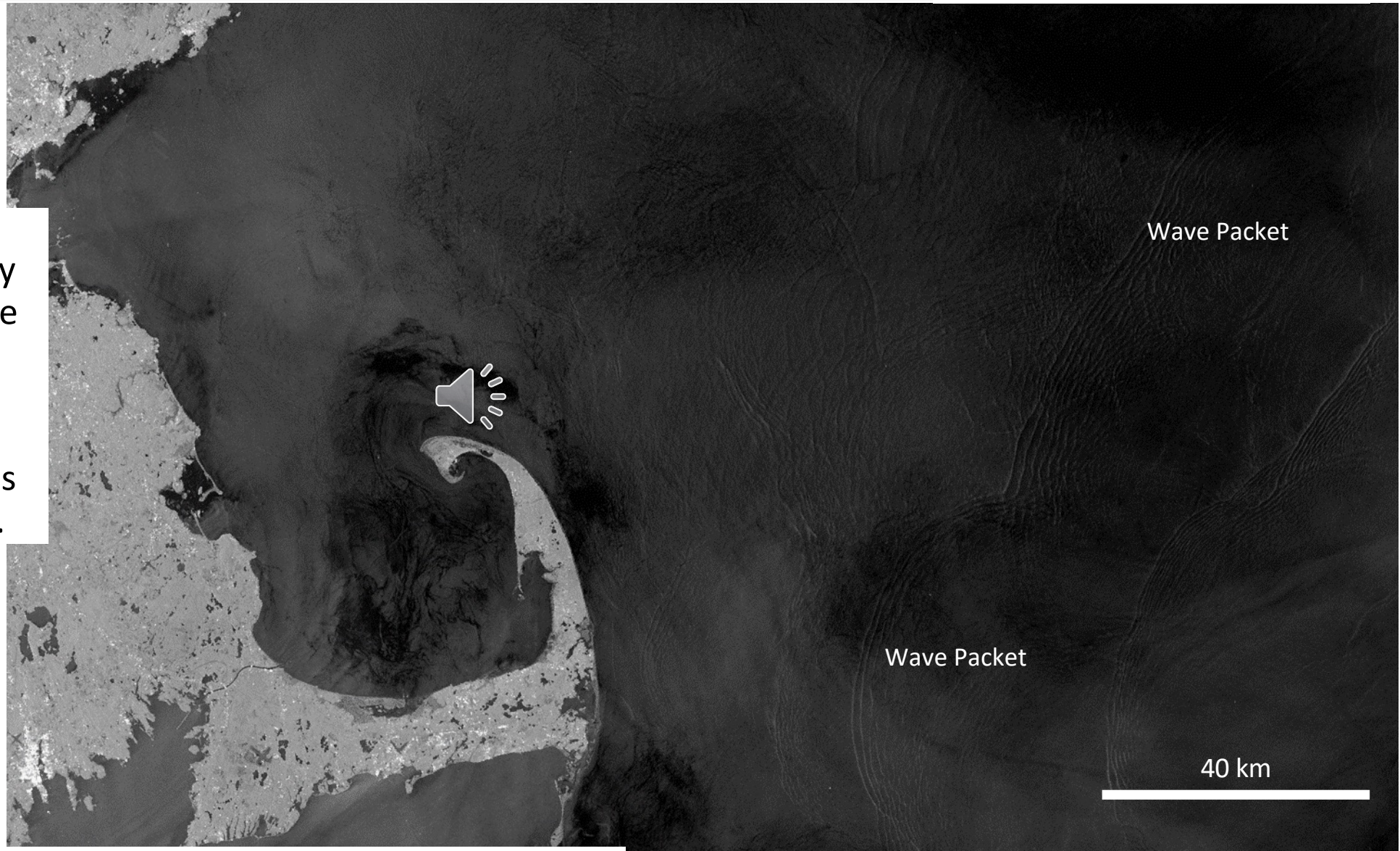
https://www.star.nesdis.noaa.gov/socd/mecb/sar/AKDEMO_products/APL_winds/wind_images2/2023-02/S1A_ESA_2023_02_23_02_08_23_0730433303_122.55W_38.56N_VV_C_nrcs.png

Ocean – Nonlinear Internal Waves

Sentinel-1 SAR VV Co-Pol NRCS
5 August 2024 22:35 UTC

A nonlinear internal wave propagates along a density interface (pycnoline) in the water column. It induces convergent and divergent currents on the surface which alters the roughness allowing it to be detected.

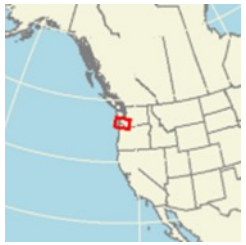




Magalhães, J.M., W. Alpers, A.M. Santos-Ferreira, and J.C.B. da Silva. 2021. Surface wave breaking caused by internal solitary waves: Effects on radar backscattering measured by SAR and radar altimeter. Oceanography 34(2):166–176, https://doi.org/10.5670/ oceanog.2021.203.

https://www.star.nesdis.noaa.gov/socd/mecb/sar/AKDEMO_products/APL_winds/wind_images2/2024-08/S1A_ESA_2024_08_05_22_35_29_0776212529_069.87W_42.03N_VV_C_nrcs.png

Ocean – River Plume and Wave Breaking



Pulses of warmer less dense water from river outflows create sharp boundary with ocean and have a reduced surface tension (and thus increased surface roughness)

Breaking waves affect (randomize) the phase of the radar pulses causing the resulting image to be “blurry”

Sentinel-1 SAR VV Co-Pol NRCS
15 July 2023 14:22 UTC

River Plume

Internal Wave Packet

10 km

Sentinel-1 SAR VV Co-Pol NRCS
6 December 2023 14:22 UTC

Breaking Waves

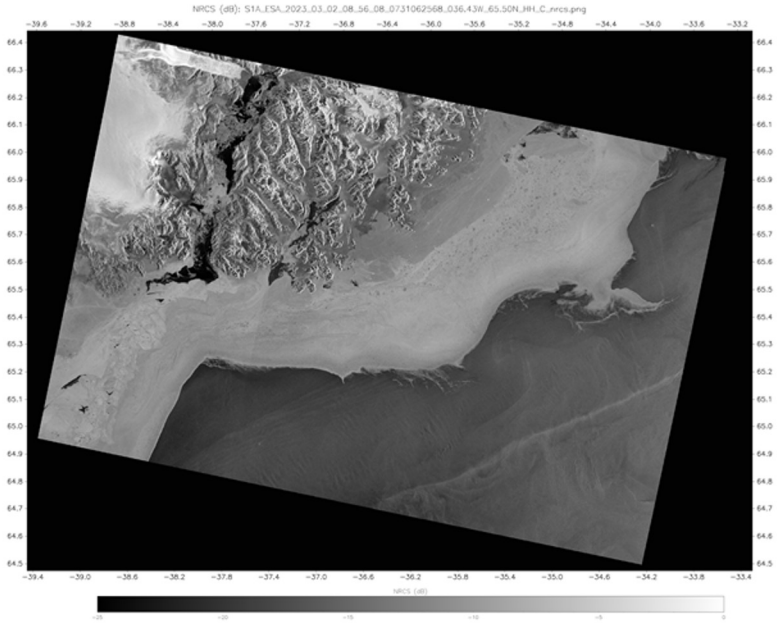
Breaking Waves

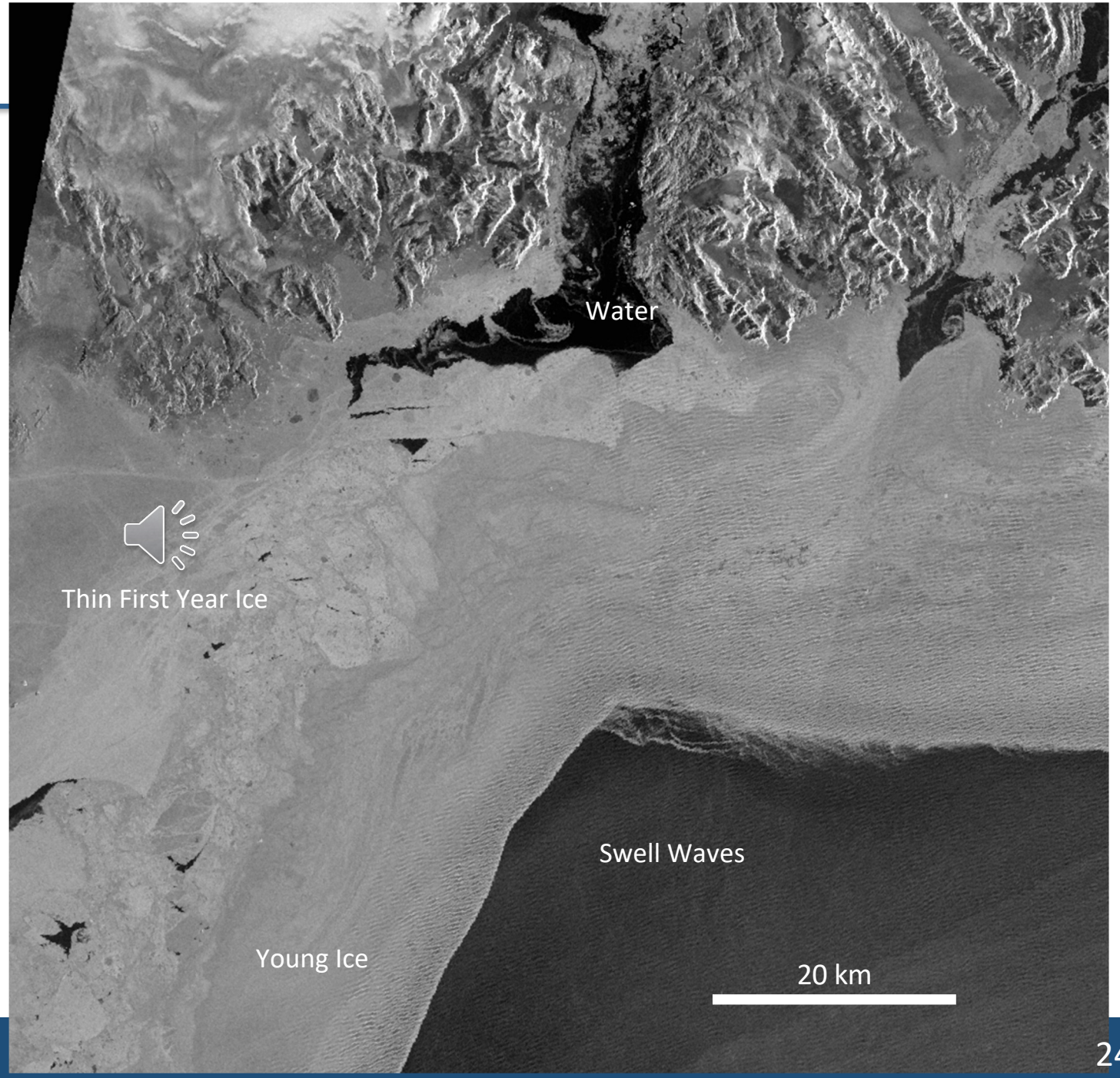
Swell

Ocean - Waves and Sea Ice

Sentinel-1 SAR HH Co-Pol NRCS
02 April 2023 22:50 UTC

Young sea ice is thin enough to be influenced by oceanic currents and waves. Here it contains the imprint of the swell wave field propagating shoreward





https://www.star.nesdis.noaa.gov/socd/mecb/sar/AKDEMO_products/APL_winds/wind_images2/2023-03/S1A_ESA_2023_03_02_08_56_08_0731062568_036.43W_65.50N_HH_C_nrcs.png

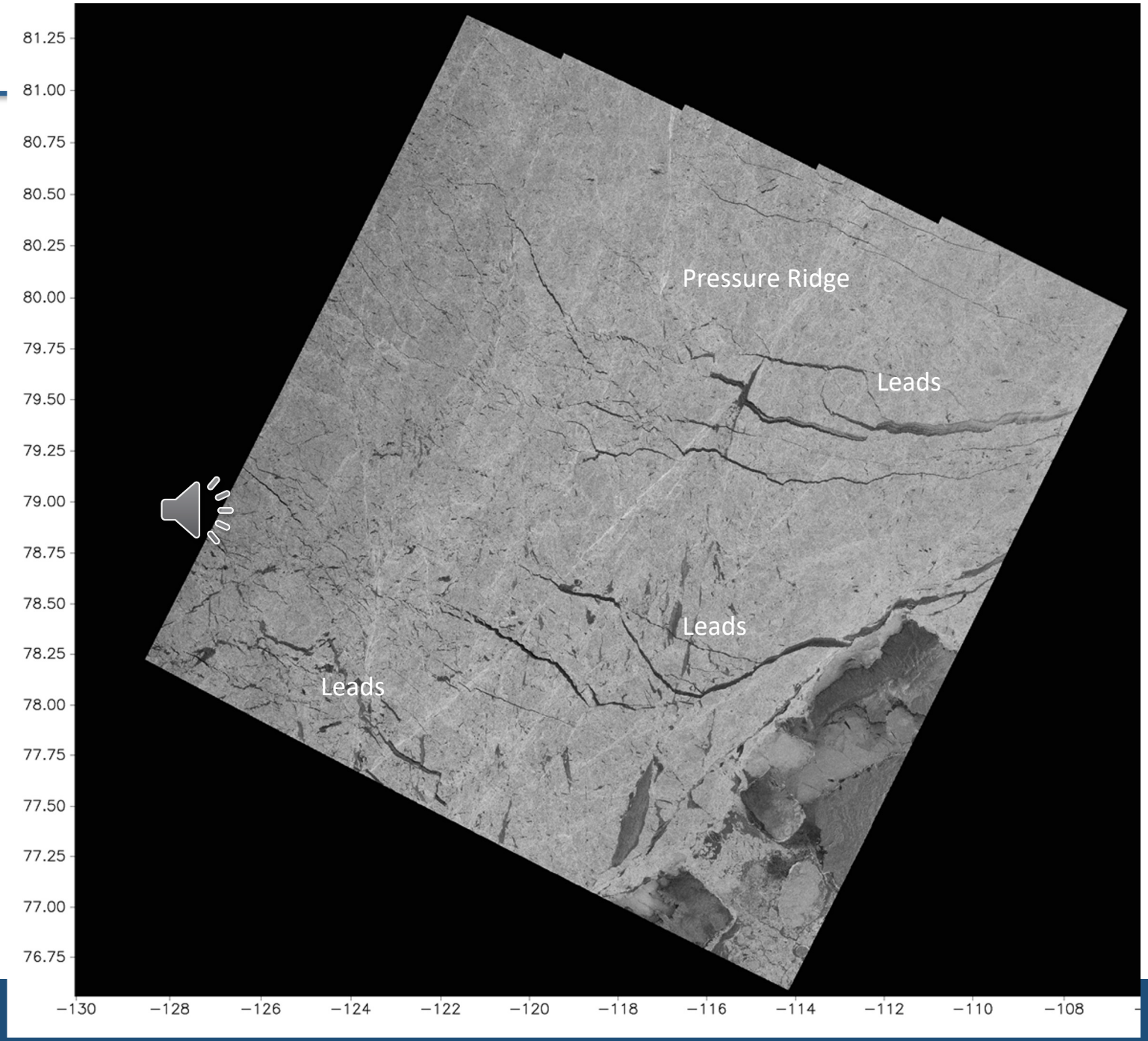
Ocean – Sea Ice

Sentinel-1 SAR HH Co-Pol NRCS
02 March 2023 15:27 UTC

- Multi-year ice pack ice off the Canadian Archipelago contains leads (breaks in the ice motion that exposes water) and pressure ridges (areas of sea ice compression).

- Multi-year ice in winter is rough appearing bright, water is less rough (darker) and ridges have enhanced roughness (brighter)

https://www.star.nesdis.noaa.gov/socd/mecb/sar/AKDEMO_products/APL_winds/wind_images2/2023-03/S1A_ESA_2023_03_02_15_27_02_0731086022_117.75W_79.51N_HH_C_nrcs.png

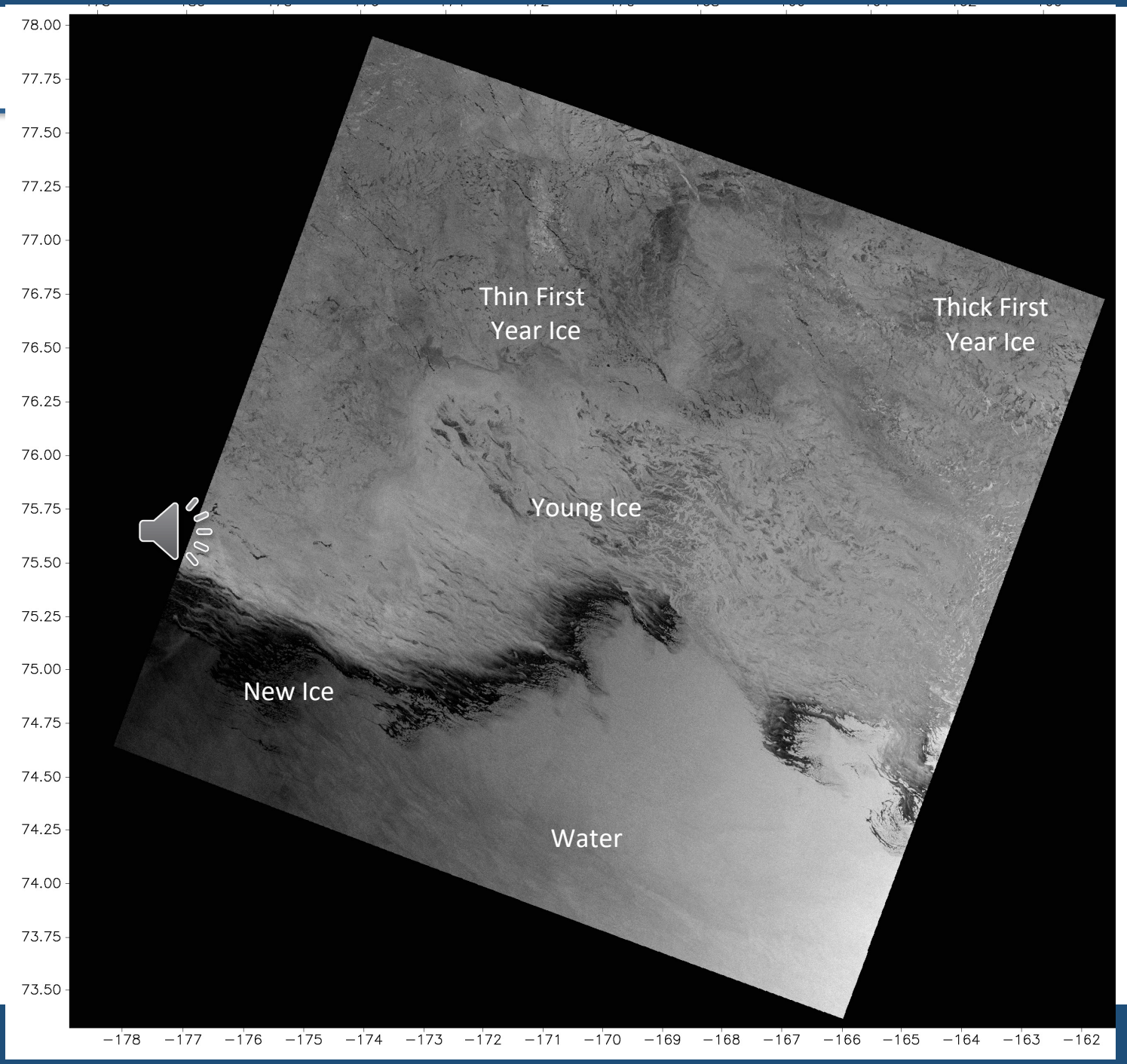


Ocean – Sea Ice

Sentinel-1 SAR HH Co-Pol NRCS
23 October 2022 18:29 UTC

- This image shows a variety of ice types in the Western Beaufort Sea as the sea ice begins to form and expand in the fall.
- New ice is smooth and appears black
- Young ice is influenced by the ocean currents
- First year ice is riddled with breaks and leads.

https://www.star.nesdis.noaa.gov/socd/mecb/sar/AKDEMO_products/APL_winds/wind_images2/2022-10/S1A_ESA_2022_10_23_18_29_12_0719864952_169.95W_75.93N_HH_C_nrcs.png

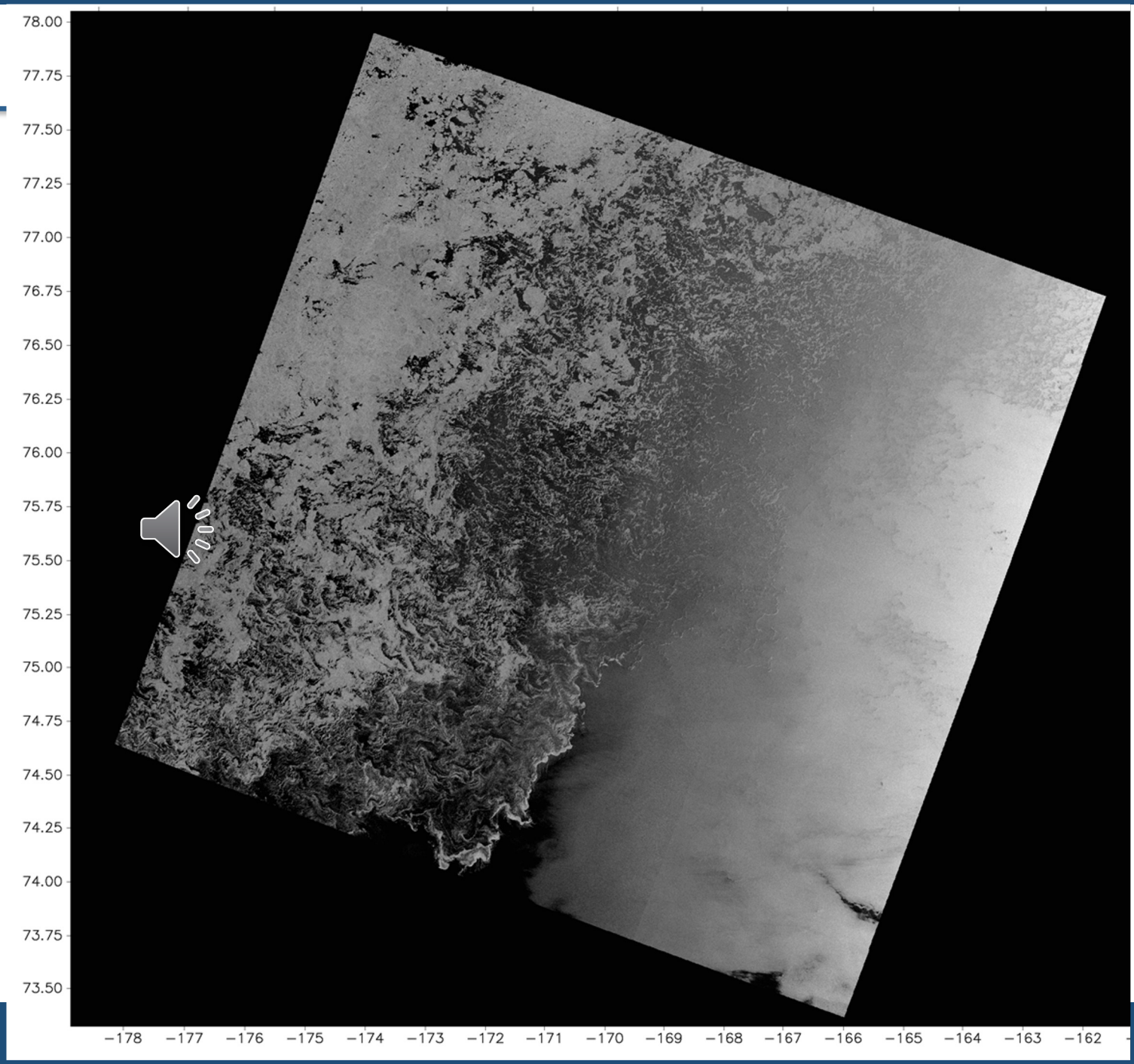


Ocean – Sea Ice

Sentinel-1 SAR HH Co-Pol NRCS
24 August 2022 18:29 UTC

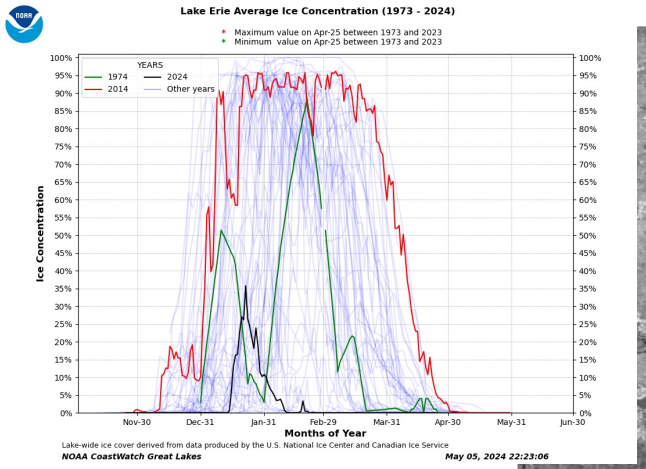
The sea ice edge in the Beaufort Sea looks very different after experiencing summer melt

https://www.star.nesdis.noaa.gov/socd/mecb/sar/AKDEMO_products/APL_winds/wind_images2/2022-08/S1A_ESA_2022_08_24_18_29_10_0714680950_169.96W_75.93N_HH_C_nrcs.png



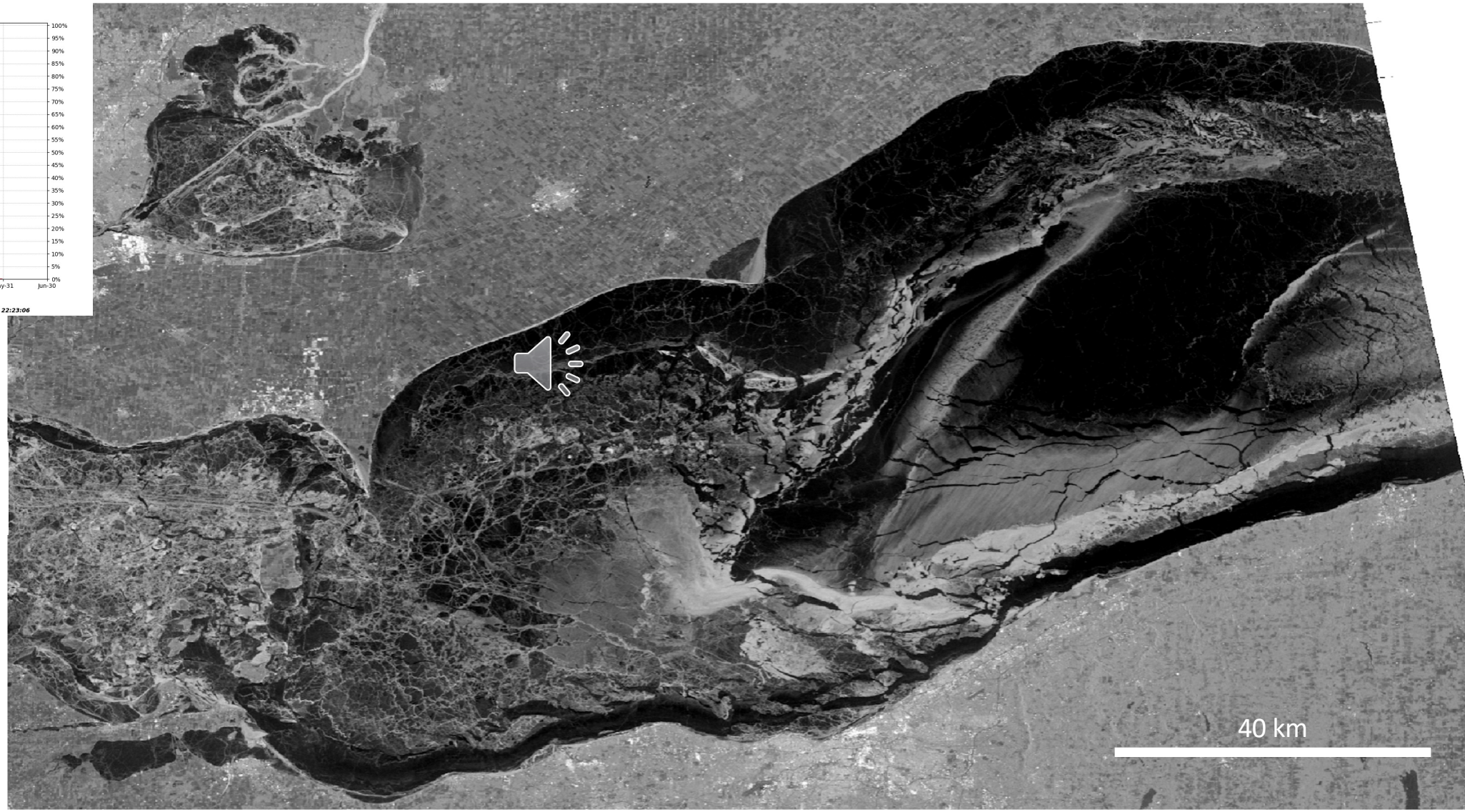
Ocean - Lake Ice

See a True Color MODIS image from 31 Jan 2022
https://worldview.earthdata.nasa.gov/?v=-84.02631447225245,40.866,
-79.04768552774756,43.24900000000001&l=MODIS_Aqua_CorrectedReflectance_TrueColor&lg=true&t=2022-01-31-T22%3A37%3A51Z



Ice covering Lake Erie

Sentinel-1 SAR VV Co-Pol NRCS
30 January 2022 23:23 UTC



https://www.star.nesdis.noaa.gov/socd/mecb/sar/AKDEMO_products/APL_winds/wind_images2/2022-01/S1A_ESA_2022_01_30_23_24_38_0696900278_082.18W_41.77N_VV_C_nrcs.png

Ocean - Lake Ice

See a True Color MODIS image from 31 Jan 2022
https://worldview.earthdata.nasa.gov/?v=-84.02631447225245,40.866,
-79.04768552774756,43.24900000000001&l=MODIS_Aqua_CorrectedReflectance_TrueColor&lg=true&t=2022-01-31-T22%3A37%3A51Z

Ice covering Lake Erie

Sentinel-1 SAR VV Co-Pol NRCS
30 January 2022 23:23 UTC

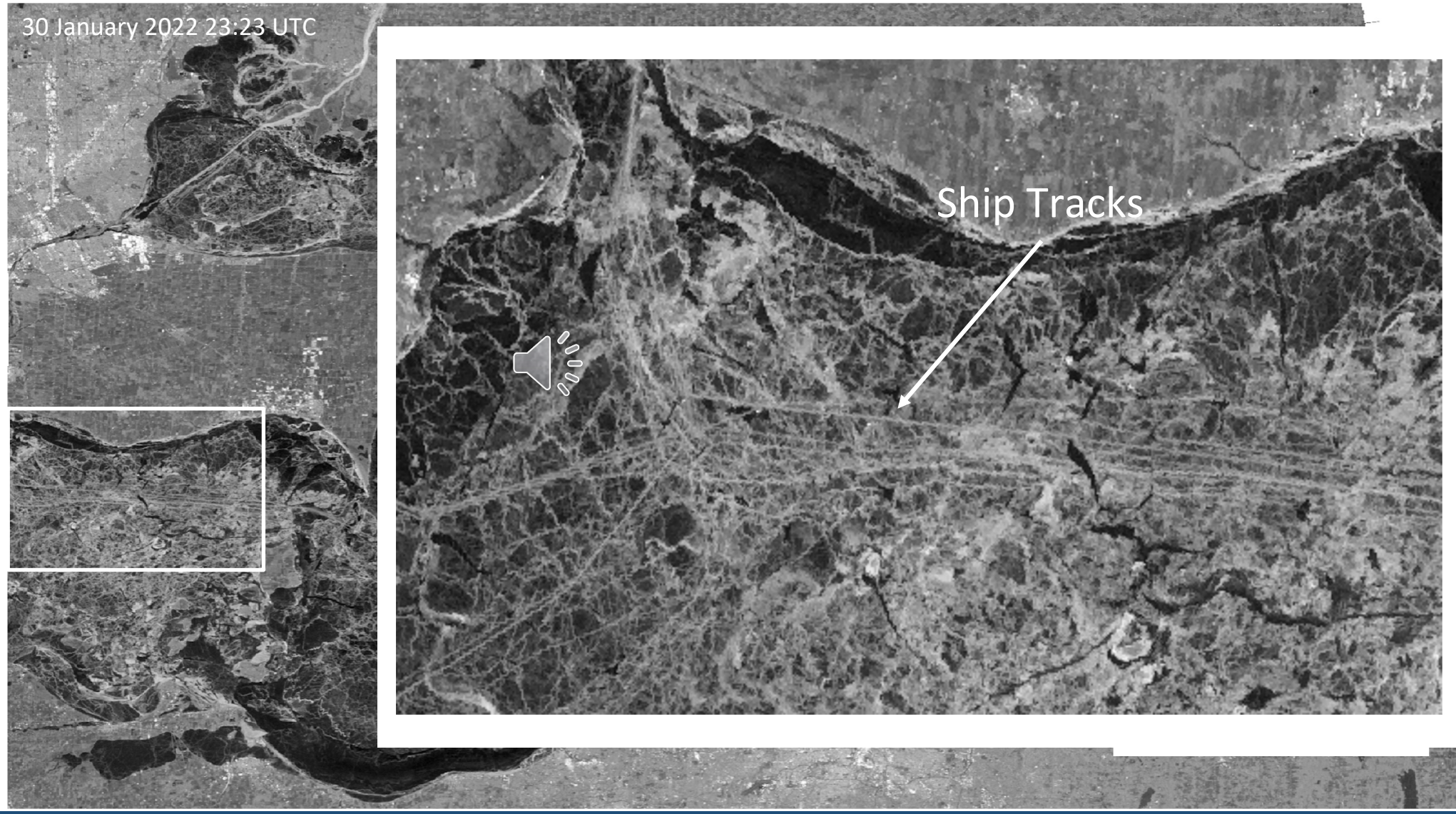
https://www.star.nesdis.noaa.gov/socd/mecb/sar/AKDEMO_products/APL_winds/wind_images2/2022-01/S1A_ESA_2022_01_30_23_24_38_0696900278_082.18W_41.77N_VV_C_nrcs.png

Ocean - Lake Ice 30 January 2022

https://www.star.nesdis.noaa.gov/socd/mecb/sar/AKDEMO_products/APL_winds/wind_images2/2022-01/S1A_ESA_2022_01_30_23_24_38_0696900278_082.18W_41.77N_VV_C_nrcs.png

Sentinel-1 SAR VV Co-Pol NRCS
30 January 2022 23:23 UTC

Ice covering Lake Erie



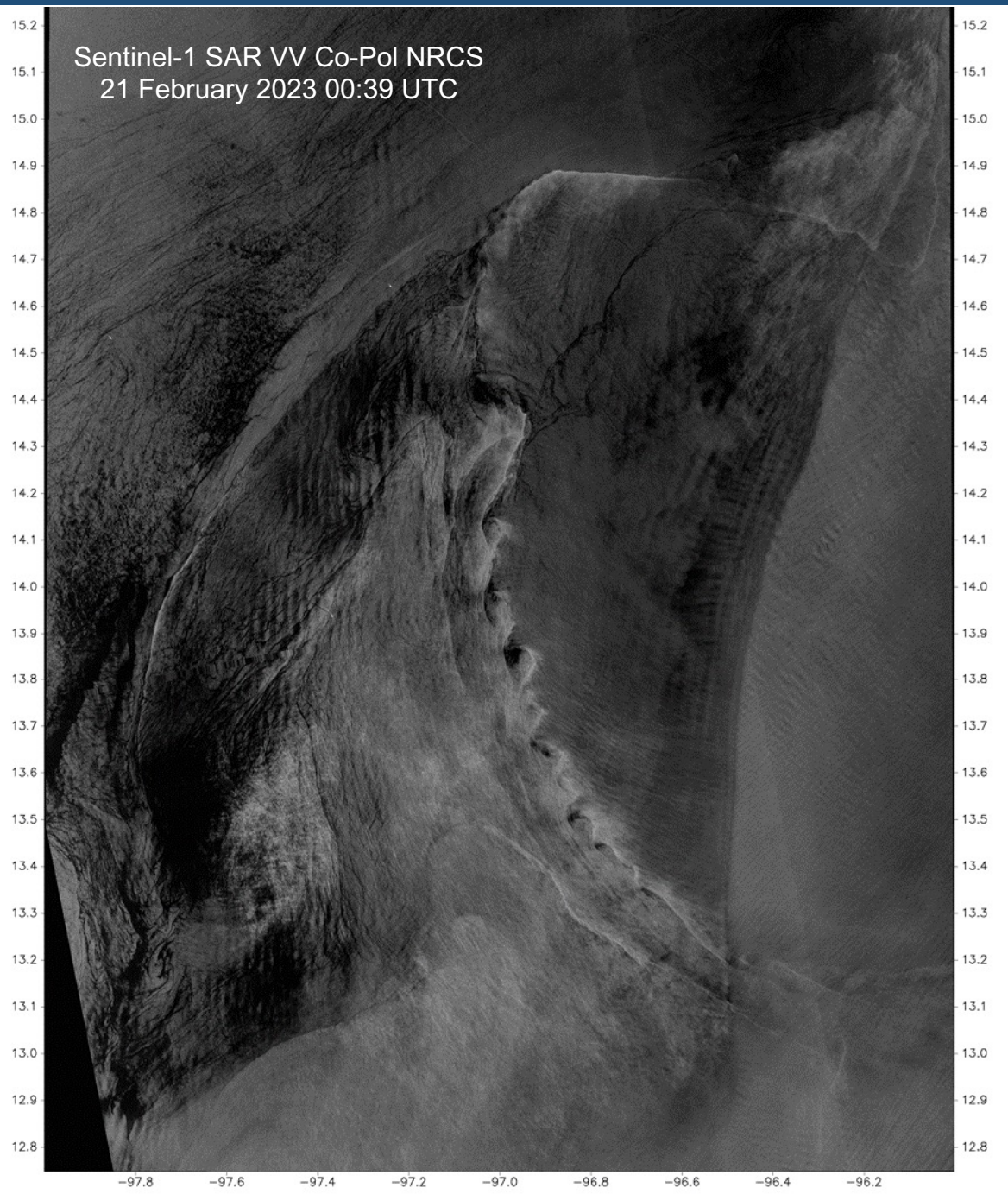
Ocean and Atmosphere

And sometimes the image contain really complex collection of signatures…..

- Current Boundaries
- Atmospheric Front
- Atmospheric Gravity Waves
- Swell
- Internal Waves
- Surfactants
- Ocean Vortices

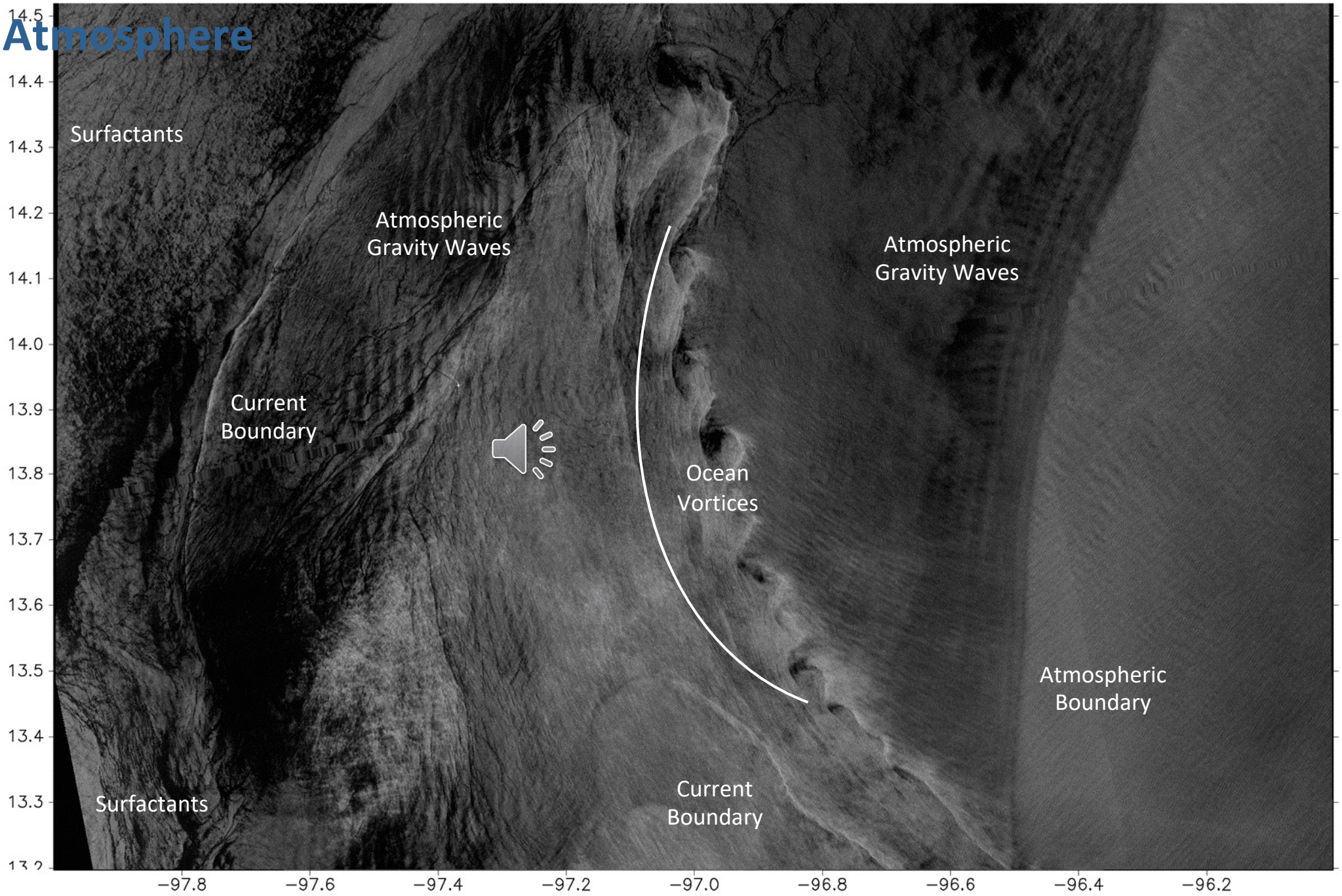
These signatures are the result of interactions between surface winds, sea surface temperature, and ocean currents

https://www.star.nesdis.noaa.gov/socd/mecb/sar/AKDEMO_products/APL_winds/wind_images2/2023-02/S1A_ESA_2023_02_21_00_39_31_0730255171_097.04W_14.72N_VV_C_nrcs.png
https://www.star.nesdis.noaa.gov/socd/mecb/sar/AKDEMO_products/APL_winds/wind_images2/2023-02/S1A_ESA_2023_02_21_00_39_04_0730255144_096.71W_13.09N_VV_C_nrcs.png

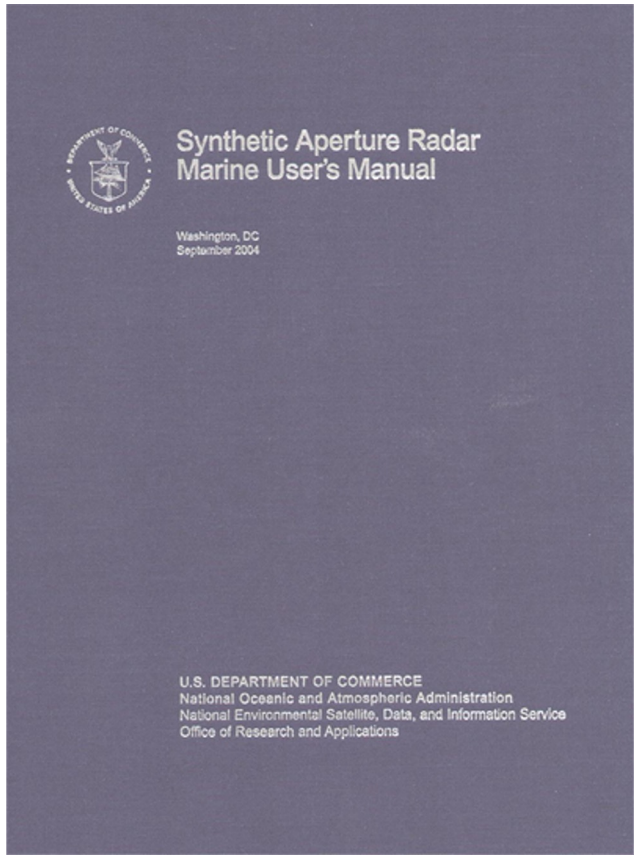


Ocean and Atmosphere

Sentinel-1 SAR
VV Co-Pol NRCS
21 February 2023
00:39 UTC



References and other online sites for imagery and information



NOAA STAR SAR Ocean Surface Winds
Sentinel-1:
https://www.star.nesdis.noaa.gov/socd/mecb/sar/sarwinds_s1.php
Radarsat-2 and Radarsat Constellation Mission (RCM):
https://www.star.nesdis.noaa.gov/socd/mecb/sar/sarwinds_rcm_rs2.php

SAR Marine Users Manual (https://www.sarusersmanual.com)
Part I. Background
Part II. Oceanic Measurements
Part III. Atmospheric Boundary Layer Measurements
Part IV. Sea Ice Observations

ESA Ocean Virtual Laboratory (Sentinel-1)
https://ovl.oceandatalab.com

Cooperative Institute for Meteorological Satellite Studies (CIMSS) Satellite Blog
https://cimss.ssec.wisc.edu/satellite-blog/

CoastWatch Data Portal

- Contains Sentinel-1 100m NRCS PNG/NetCDF files since October 2018. The data are principally over the US EEZ (including Alaska and Hawaii) but also extend over the Caribbean and North Atlantic
- Most of the imagery presented should be available.
- Search L1/L2->S1A NRCS or S1B NRCS

https://coastwatch.noaa.gov/cw_html/cwViewer.html