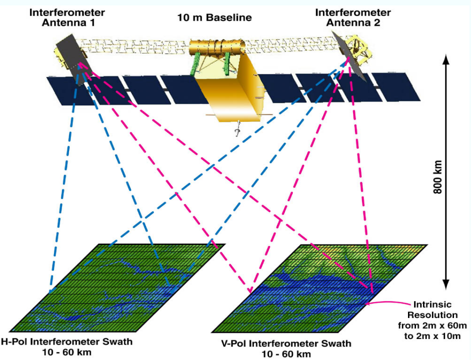
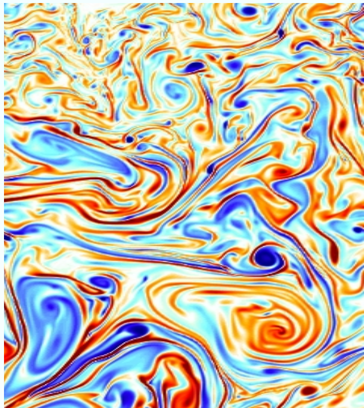
”Ocean Turbulence from SPACE”

Patrice Klein (Caltech/JPL/Ifremer)

(I) Introduction





Reading list :

Satellite Oceanography :

- The Future of Oceanography from Space. 2010. Special Issue of « Oceanography », Vol 23, No.4
- Le Traon P.Y.. (2013). From satellite altimetry to Argo and operational oceanography: Three revolutions in oceanography. Ocean Sci., 9, 901–915.

2-D Turbulence :

- Provenzale, A.. (1999) Transport by Coherent Barotropic Vortices. Ann. Rev. Fluid Mech. . 31 :55-93.
- Rhines PB. 1983. Lectures in geophysical fluid dynamics. Lect. Appl. Math. 20:3–58.
- McWilliams JC. 1991. Geostrophic vortices. In Nonlinear Topics in Ocean Physics, Proceedings of the International School of Physics, "Enrico Fermi" Course CIX. ed. A.R. Osborne. Amsterdam: IOS Press
- McWilliams, J. (1984) : The Emergence of isolated coherent vortices in Turbulent Flow. J. Fluid Mech., 146, 21-43.
-

3-D (QG) turbulence :

- Salmon RS. 1980. Baroclinic instability and geostrophic turbulence. Geophys. Astrophys. Fluid Dyn. 15:167–211
- Smith KS, Vallis GK. 2001. The scales and equilibration of midocean eddies: freely evolving flow. J. Phys. Oceanogr. 31:554–71
- Hua et al. (1998): Lagrangian Accelerations in Geostrophic Turbulence. *J. Fluid Mech.*, 35, 1-22.
- Charney J. 1971. Geostrophic turbulence. J. Atmos. Sci. 28:1087–95
- Capet et al. 2008. Surface density transfer in surface quasigeostrophic flows. *J. Fluid Mech.*, 604, 165-174.

Submesoscales :

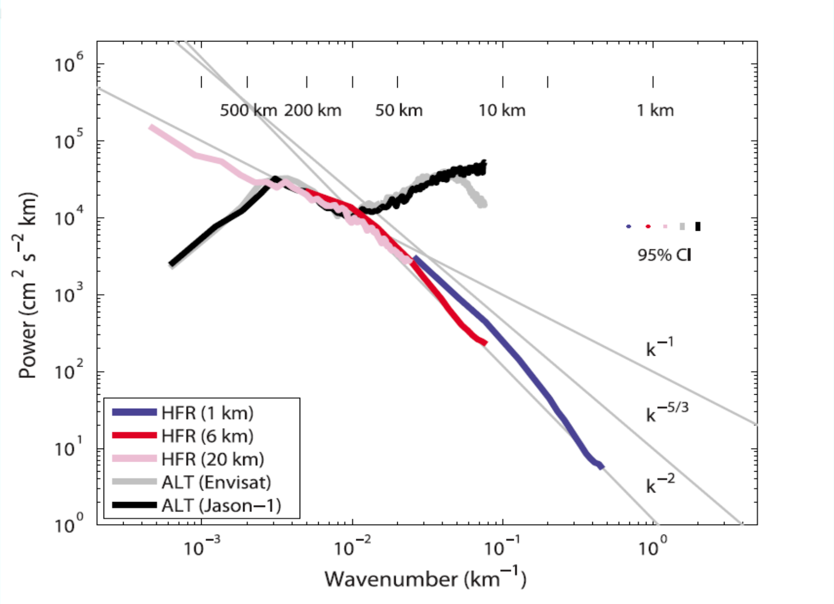
- Stone, P. H., 1971: Baroclinic instability under non-hydrostatic conditions. J. Fluid Mech., 45, 659–671.
- Munk et al. (2000) : Spirals on the Sea. Proc. R. Soc. London A. 456, 1217-1280.
- Marshall, J., C. N. Hill, L. Perelman, and A. Adcroft, 1997a: Hydrostatic, quasi-hydrostatic and non-hydrostatic ocean modeling. J. Geophys. Res., 102, 5733–5752.
- Boccaletti et al. 2007. Mixed-layer instabilities and restratification. J. Phys. Ocean., 37, 2228-2250.

Textbooks :

- All classical textbooks +
- Vallis G. (2006) : Atmospheric and Oceanic Fluid Dynamics. Cambridge University Press.
- Seelye M. (2014) : An Introduction to Ocean Remote Sensing. Cambridge University Press.

Ocean Turbulence spans a large range of scales …

… from 10000 km to 1 m, even smaller ...



From Kim et al. JGR'11

Because of the strong development of satellite oceanography over the last few decades (and the help of in-situ measurements), we have a better vision on this ocean turbulence and on the interactions between the different scales involved.

As an introduction:

A brief illustration of the large range of scales observed and diagnosed from space … just to emphasize the strong potential of satellite oceanography

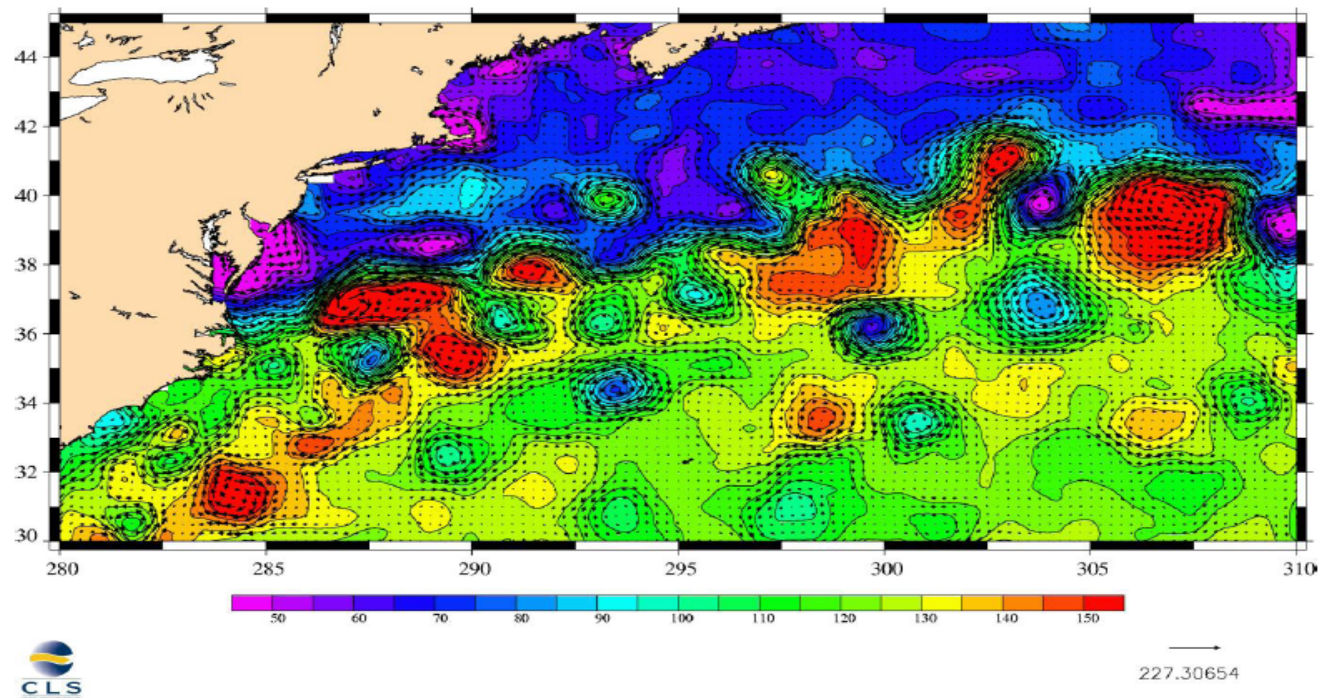
Satellite oceanography involves different sensors …

Satellite altimeters (100 km – 10000 km):

- One of the most important satellite technics for oceanography.
- It provides, **global, real-time, all weather** Sea Surface Height measurements (or SSH).
- Using the geostrophic approximation, these measurements allow to recover surface motions.

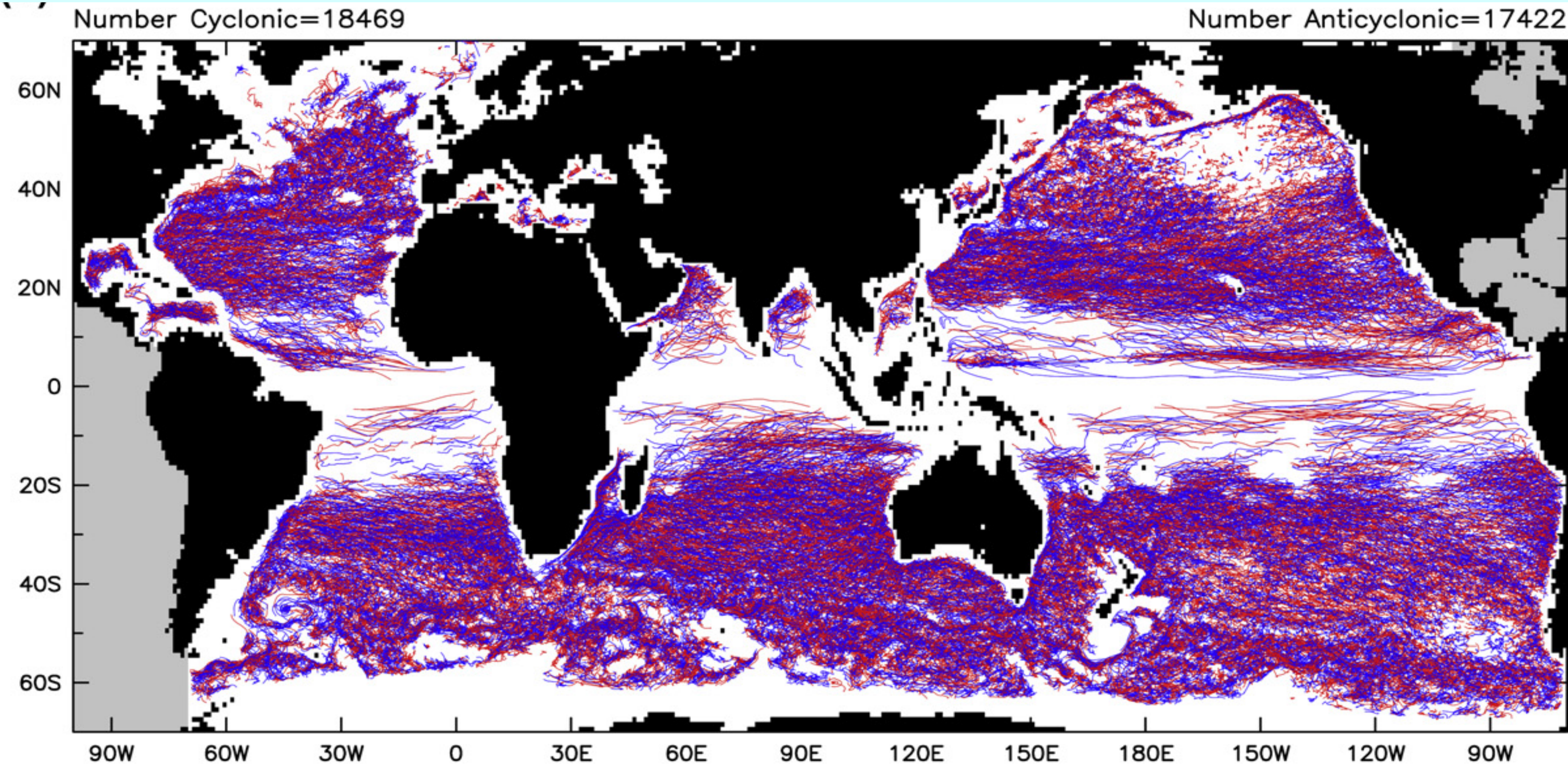
Some applications …

Surface motions diagnosed from the SSH (estimated from the merging of three altimeters) using the geostrophic approximation



High resolution description from the real time merging of Jason-1, ERS-2 and GFO

20 years of altimeter data have revealed the ubiquituous existence of mesoscale eddies (100 km – 300 km). They are estimated to represent about 80% of the total kinetic energy of the oceans !



The trajectories of cyclonic (blue lines) and anticyclonic (red lines) eddies over the 16-year period October 1992–December 2008 for (a) lifetimes >16 weeks. The numbers of eddies of each polarity are labeled at the top of each panel. From D. Chelton et al., Prog. Ocean. 2011

Altimeter data cannot capture scales smaller than 100 km …

But satellite images, such as SST, Ocean Color and SAR images have a much higher resolution. They reveal not only mesoscale eddies (100-200km) but also smaller scales (5 km-40 km) called submesoscales.

From these images, not only mesoscales but also submesoscales are ubiquitous in the World Ocean!

Different physics:

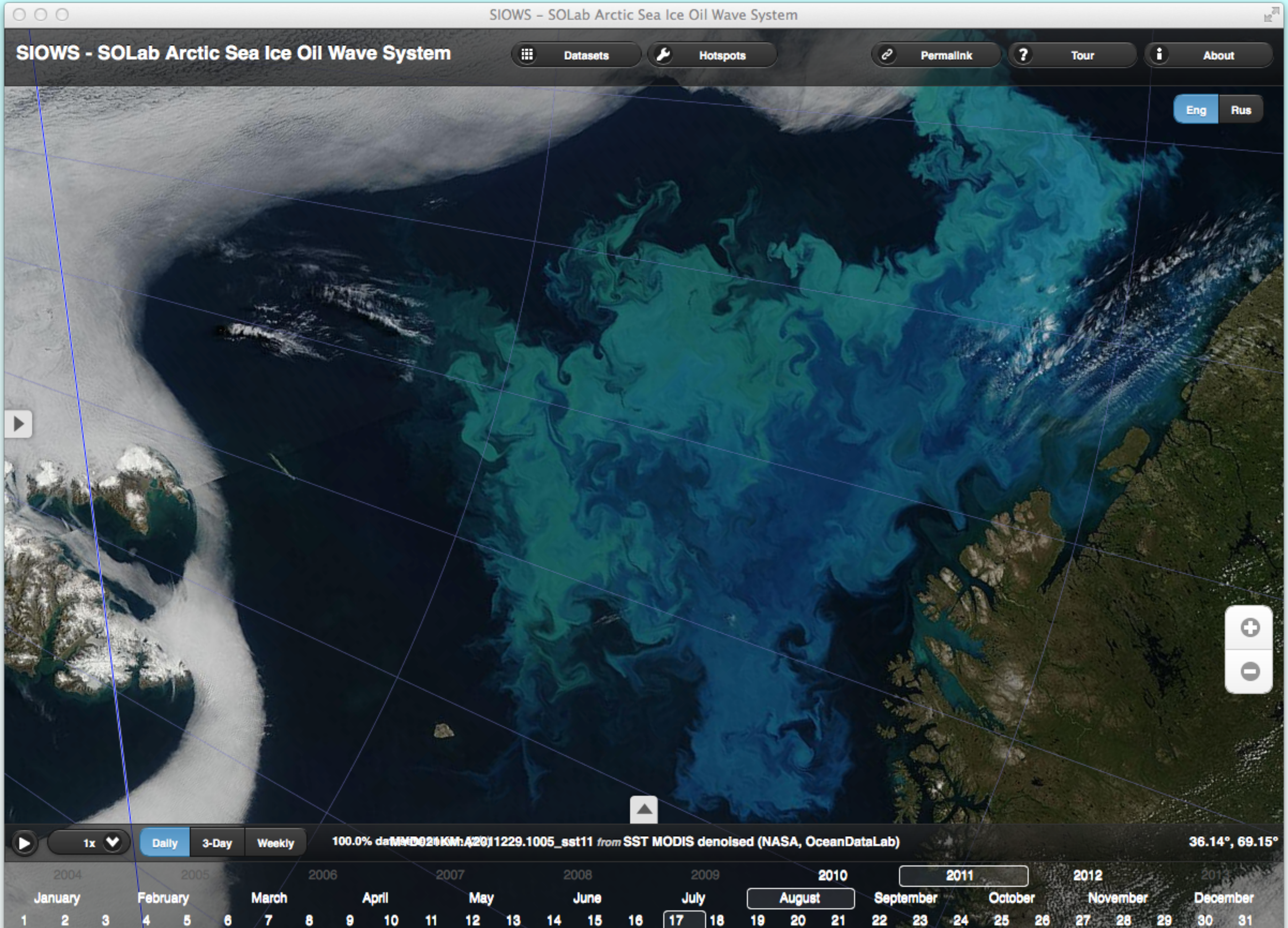
- **Infrared images (1km): Sea Surface Temperature**
- **Ocean color images (1 km): Chlorophyll**
- **Synthetic Aperture Radar images (100 m): roughness due to the interaction between surface waves and currents.**

Comparing SST, Ocean Color and SAR images reveals a very strong coherence in particular at meso and submesoscales, which suggests that submesoscales are associated with energetic 3-D dynamics.

The following satellite images can be found in:

http://www.labexmer.eu/en/research/ocean-at-high-resolution/workshop-2dto3d-ocean-dynamics-from-space/downloads

See the presentation by Fabrice Collard (Ocean Data Lab)


SIOWS – SOLab Arctic Sea Ice Oil Wave System
SIOWS - SOLab Arctic Sea Ice Oil Wave System
Datasets
Hotspots
Permalink
Tour
About
Eng
Rus
1x
Daily
3-Day
Weekly
MOD021KM.A2011229.1005_sst11 from SST MODIS denoised (NASA, OceanDataLab)
36.14°, 69.15°
2004
2005
2006
2007
2008
2009
2010
2011
2012
January
February
March
April
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October
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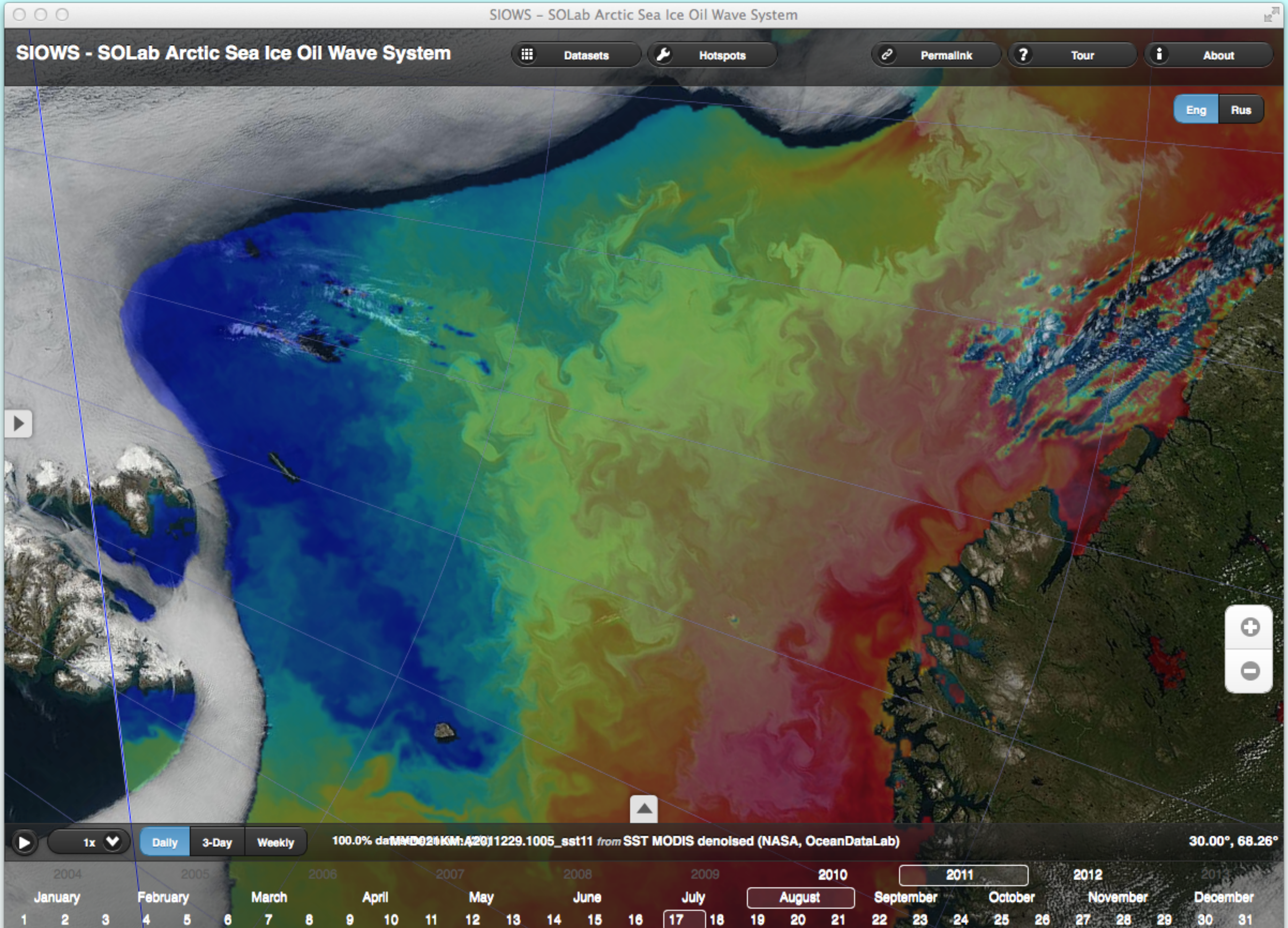
December
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31


SIOWS – SOLab Arctic Sea Ice Oil Wave System
SIOWS - SOLab Arctic Sea Ice Oil Wave System
Datasets
Hotspots
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Tour
About
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1x
Daily
3-Day
Weekly
SST MODIS denoised (NASA, OceanDataLab)
30.00°, 68.26°
2004
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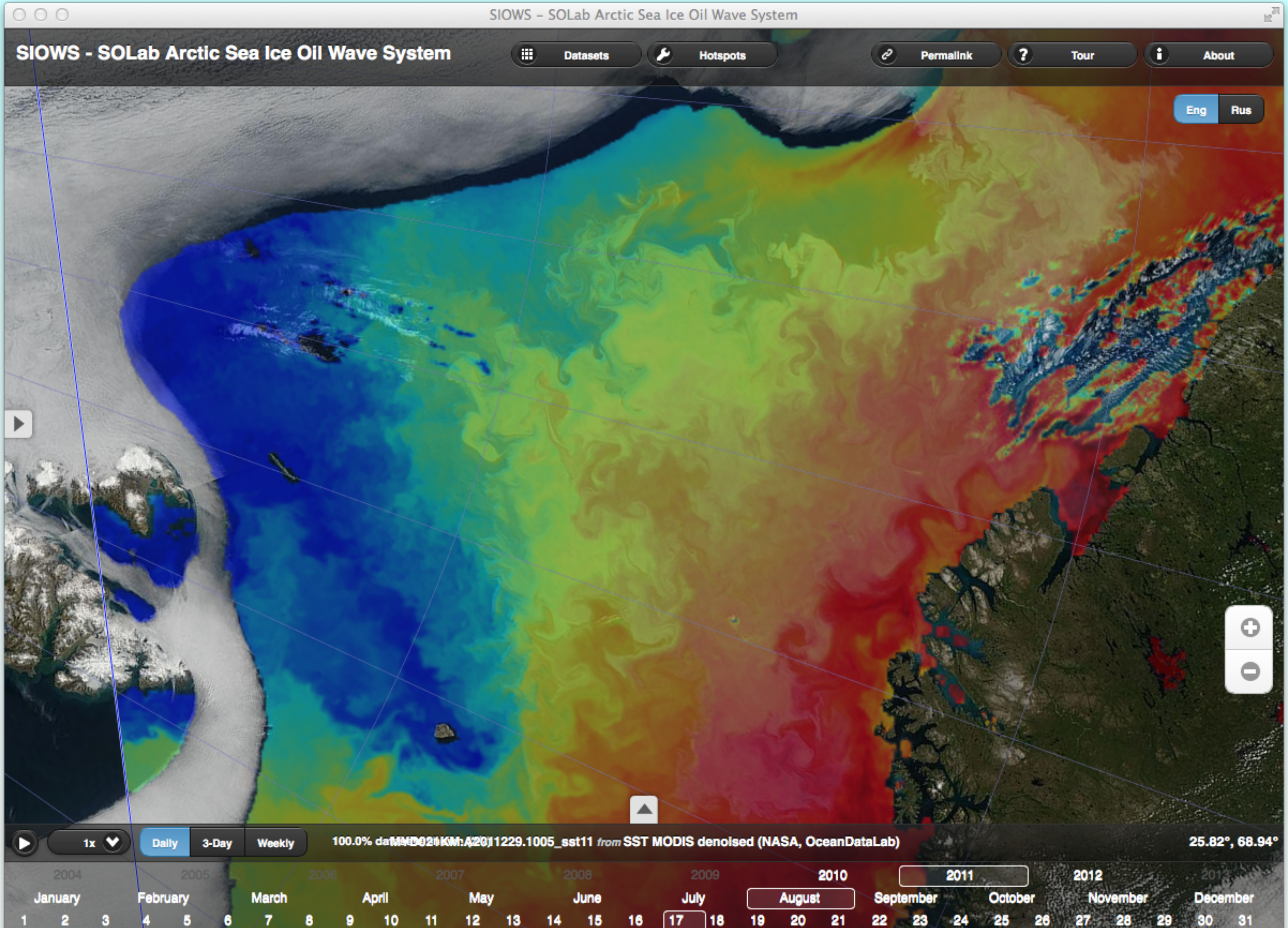

SIOWS – SOLab Arctic Sea Ice Oil Wave System
SIOWS - SOLab Arctic Sea Ice Oil Wave System
Datasets
Hotspots
Permalink
Tour
About
Eng
Rus
1x
Daily
3-Day
Weekly
SST MODIS denoised (NASA, OceanDataLab)
25.82°, 68.94°
2004
2005
2006
2007
2008
2009
2010
2011
2012
January
February
March
April
May
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July
August
September
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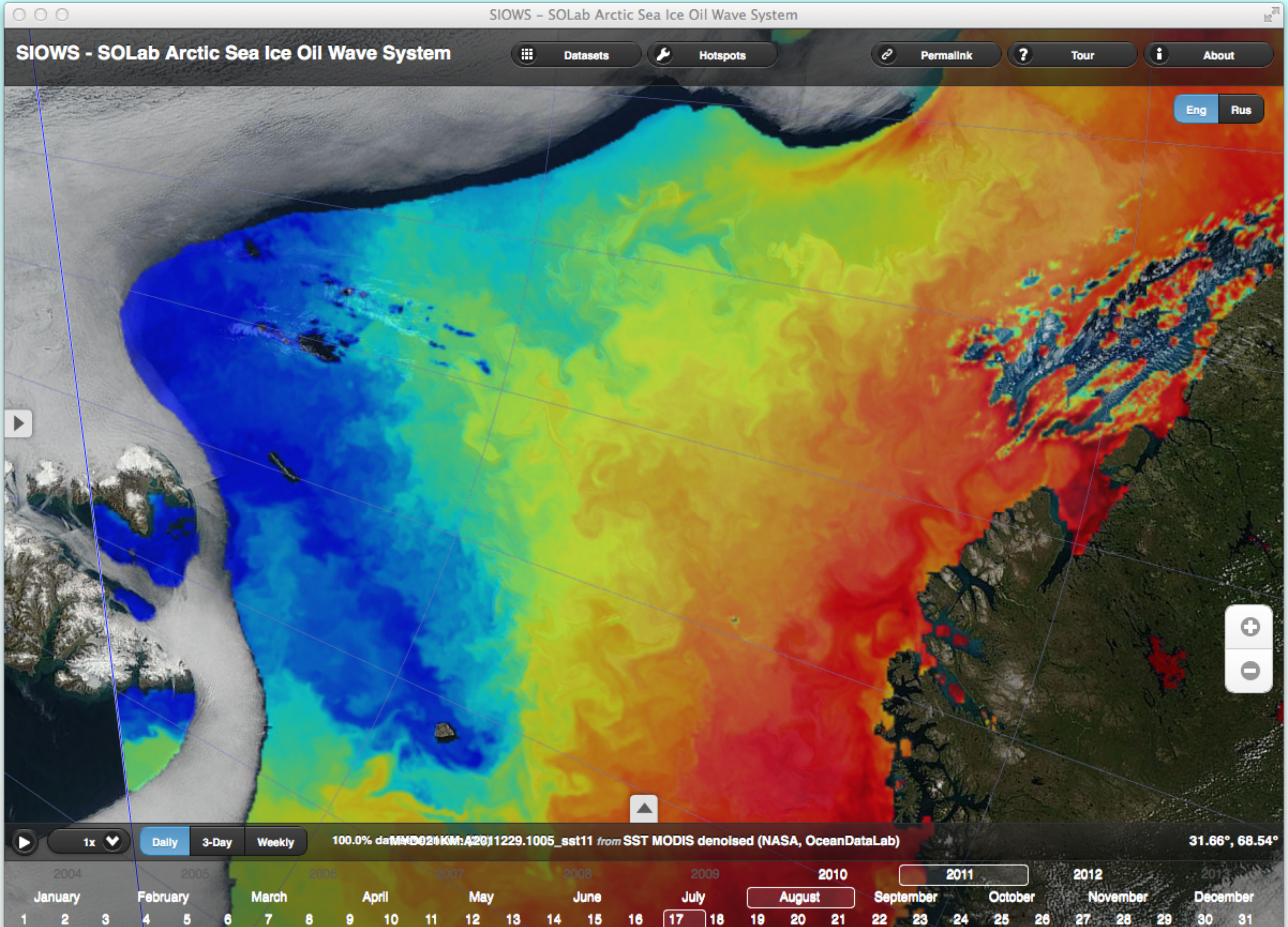
November
December
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31


SIOWS – SOLab Arctic Sea Ice Oil Wave System
SIOWS - SOLab Arctic Sea Ice Oil Wave System
Datasets
Hotspots
Permalink
Tour
About
Eng
Rus
1x
Daily
3-Day
Weekly
MYD021KM.A2011229.1005_sst11 from SST MODIS denoised (NASA, OceanDataLab)
31.66°, 68.54°
2010
2011
2012
January
February
March
April
May
June
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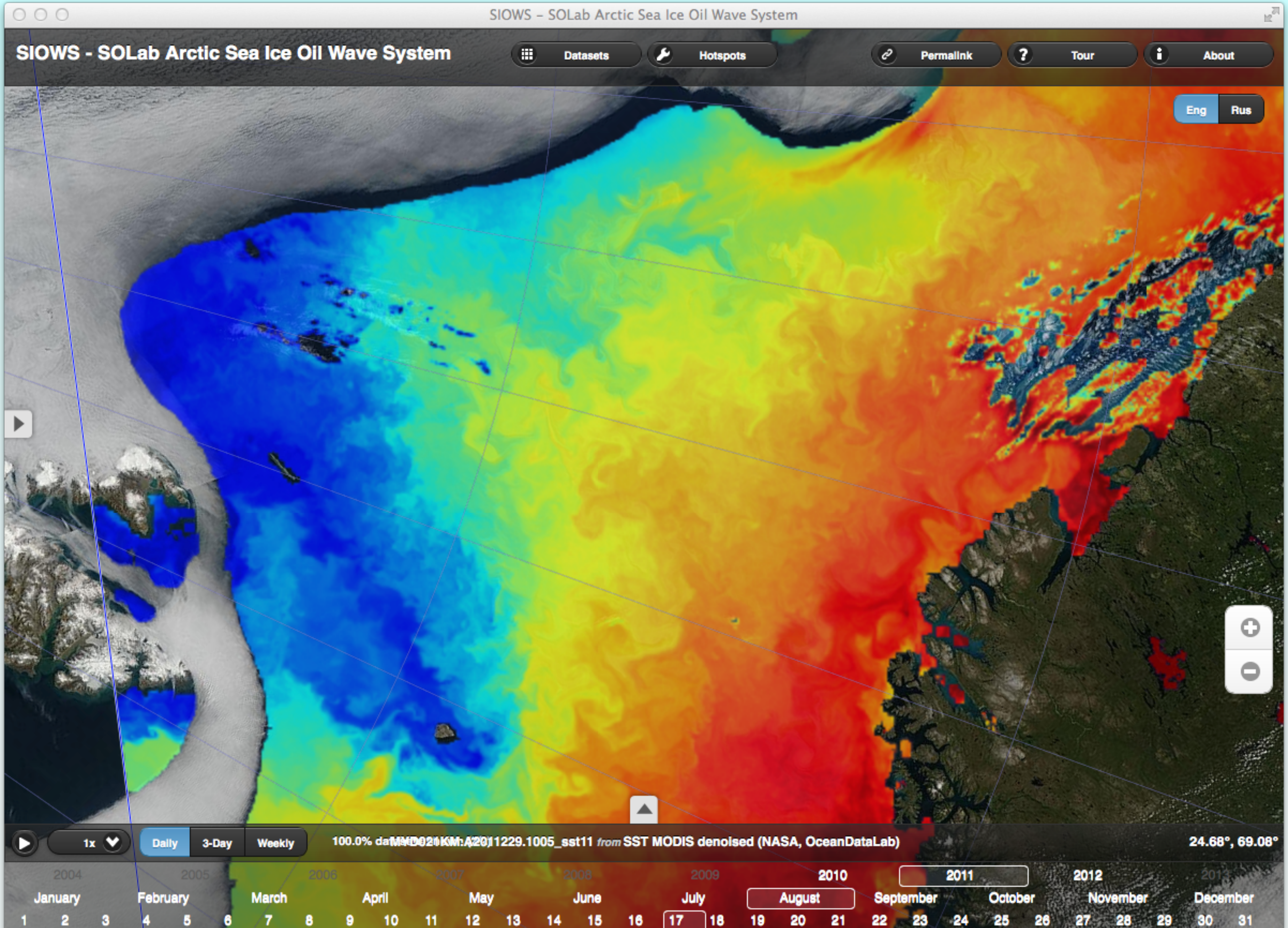
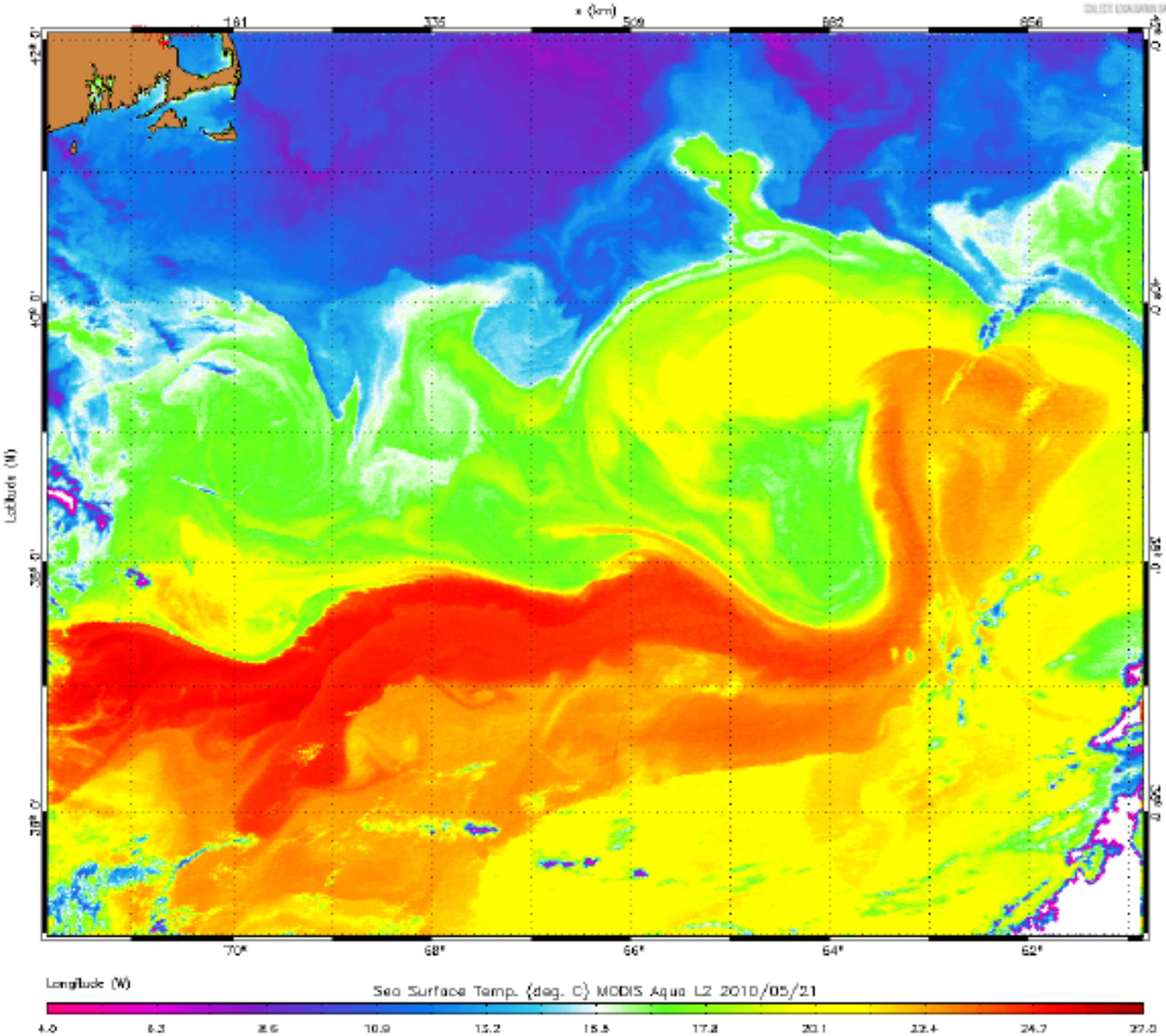
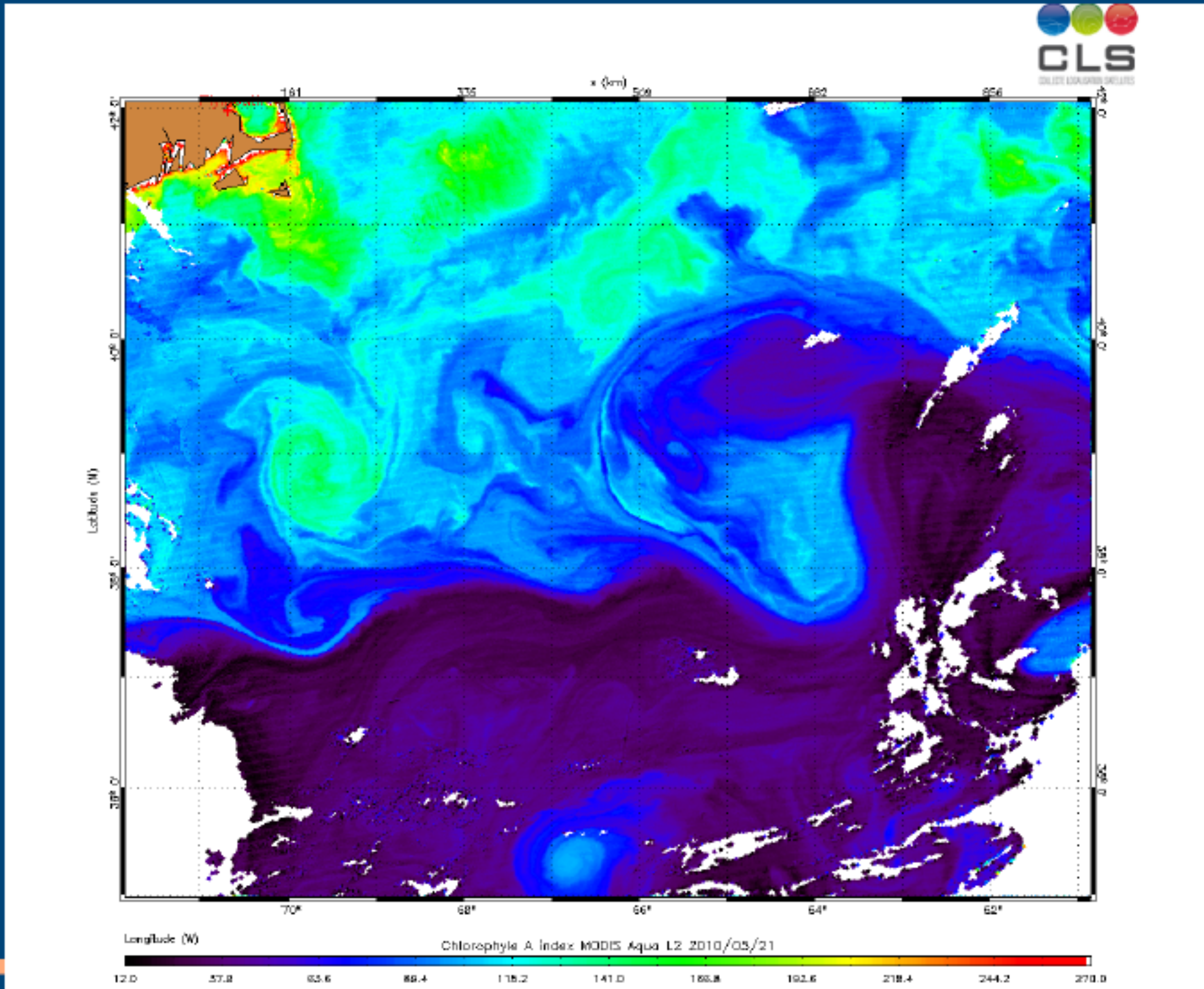
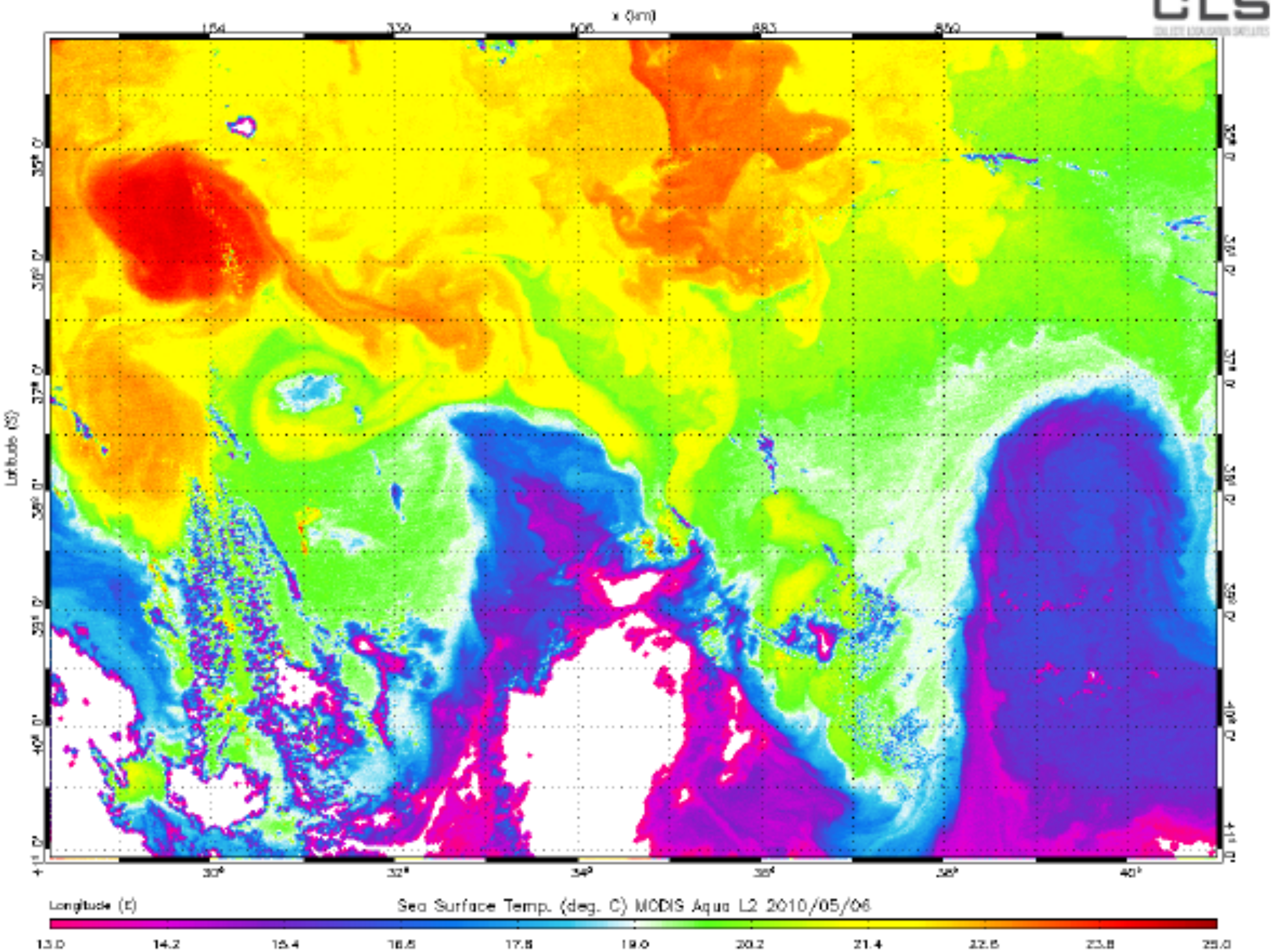
October
November
December
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31


SIOWS – SOLab Arctic Sea Ice Oil Wave System
SIOWS - SOLab Arctic Sea Ice Oil Wave System
Datasets
Hotspots
Permalink
Tour
About
Eng
Rus
1x
Daily
3-Day
Weekly
MYD021KM.A2011229.1005_sst11 from SST MODIS denoised (NASA, OceanDataLab)
24.68°, 69.08°
2010
2011
2012
January
February
March
April
May
June
July
August
September
October
November
December
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31

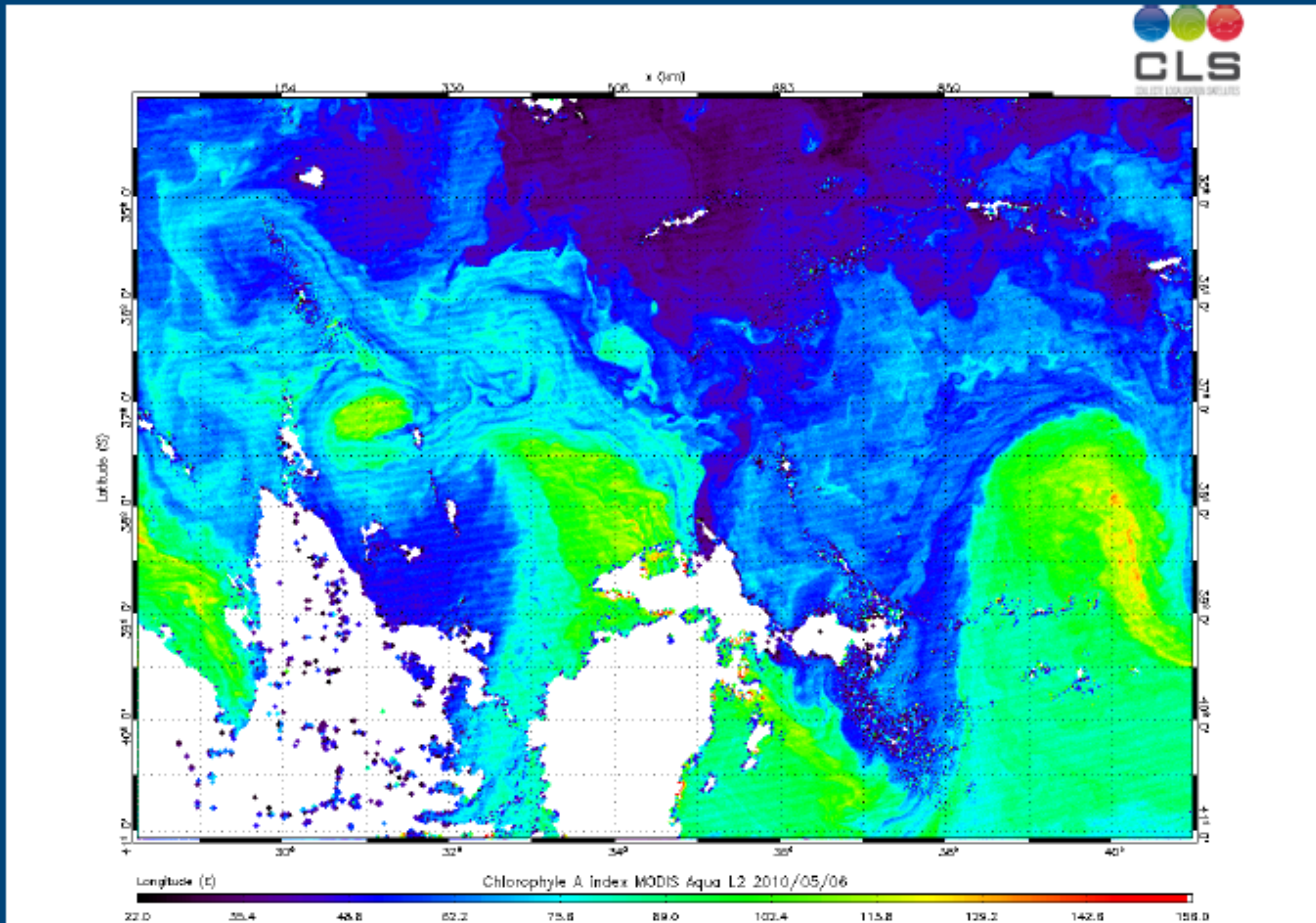
Numerous contemporaneous MODIS Brightness temperature and Ocean Colour surface signatures

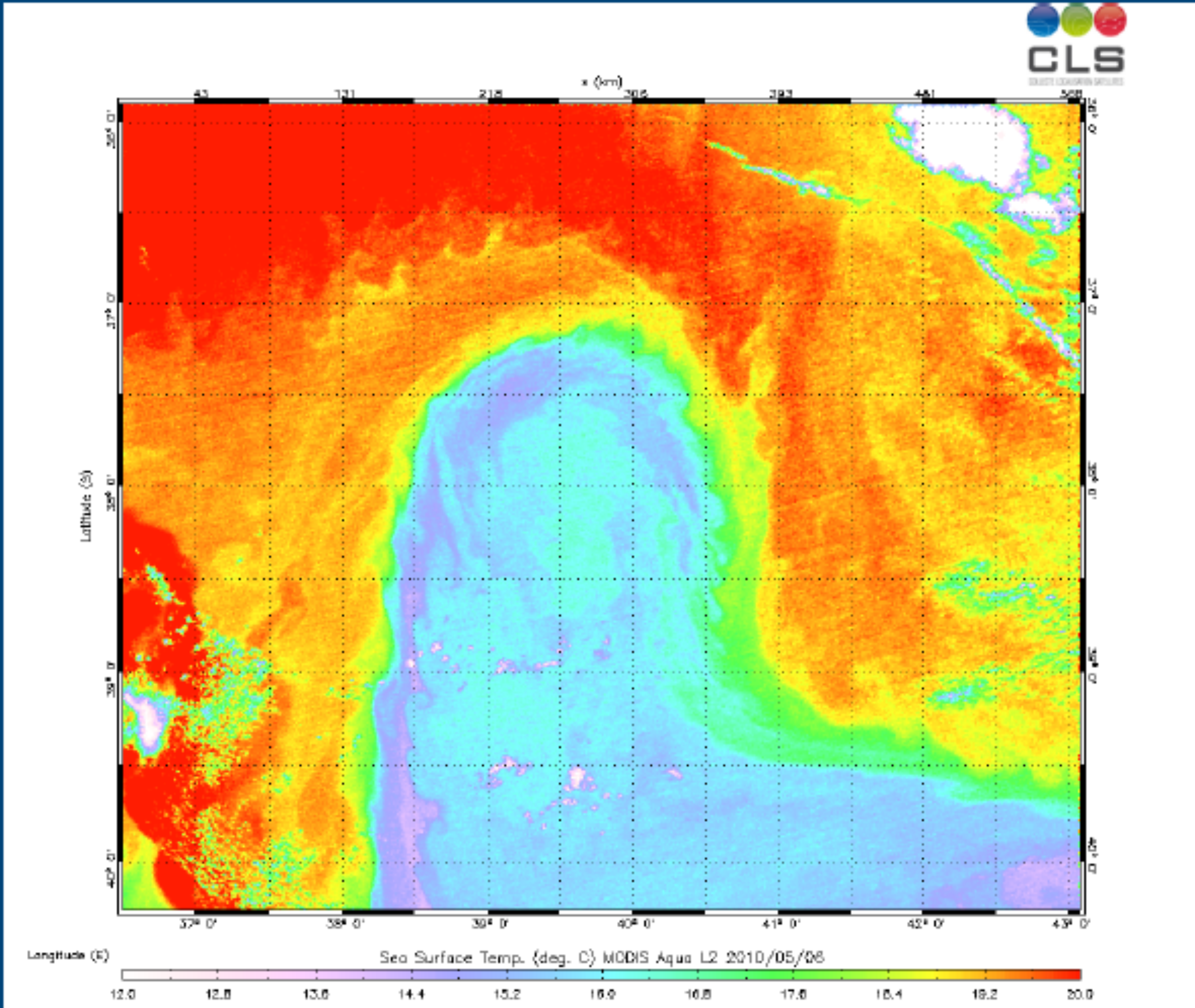



CLS
x (km)
Latitude (N)
70°
68°
66°
64°
62°
Longitude (W)
Chlorophyle A index MODIS Aqua L2 2010/05/21
12.0
37.8
63.6
89.4
115.2
141.0
166.8
192.6
218.4
244.2
270.0

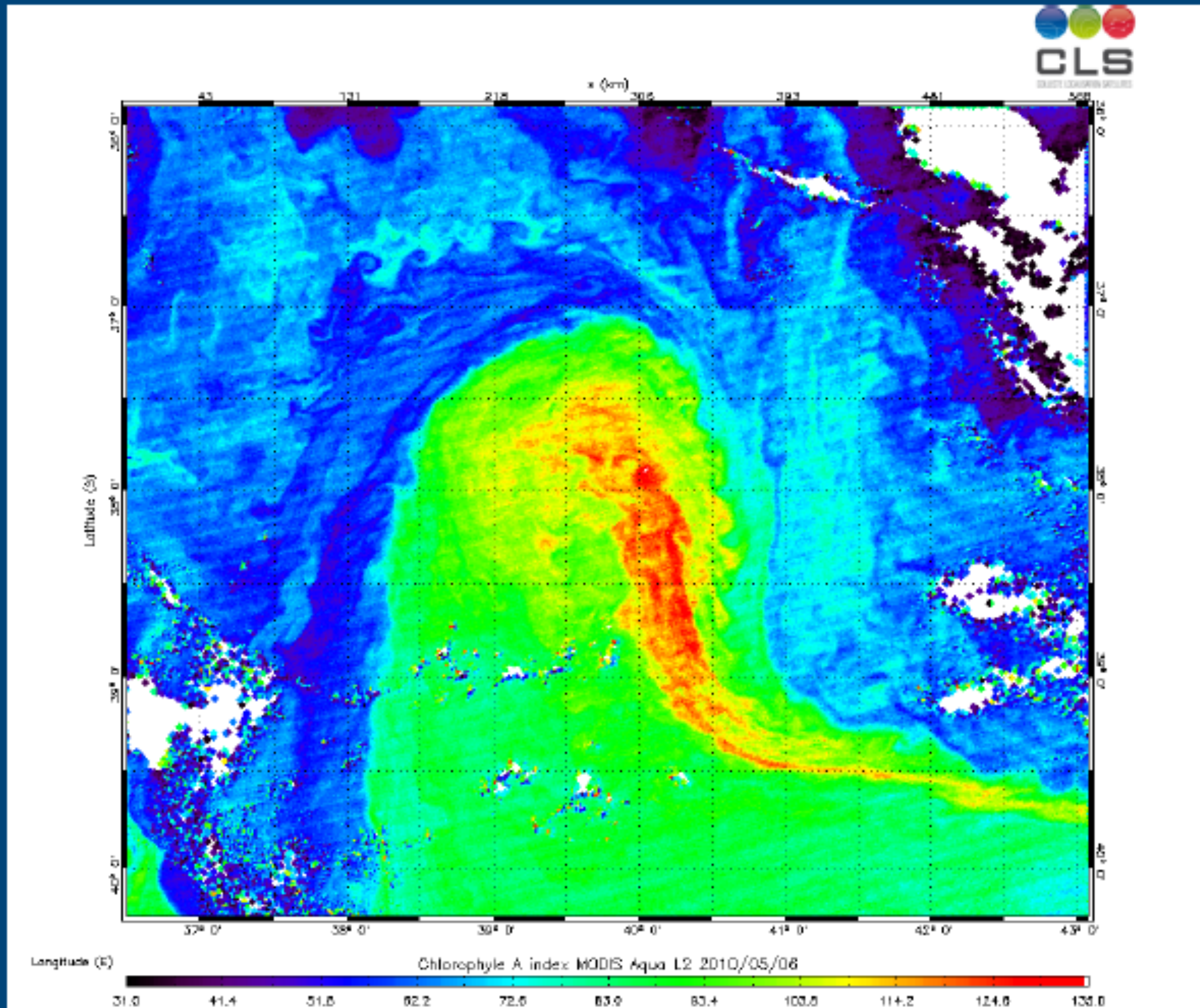


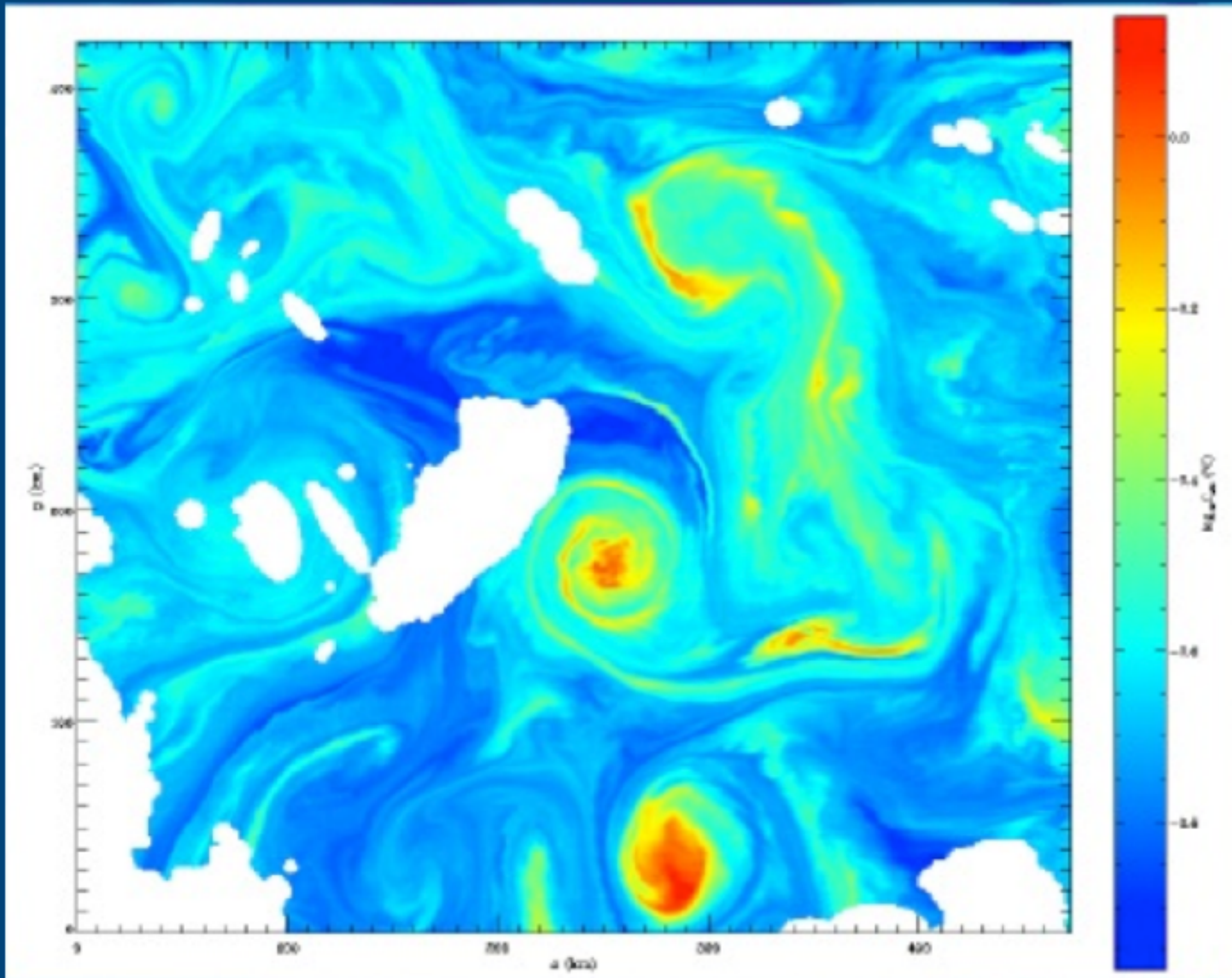
x (km)
154
330
506
683
859
Latitude (S)
30°
32°
34°
36°
38°
40°
Longitude (E)
Sea Surface Temp. (deg. C) MODIS Aqua L2 2010/05/06
13.0
14.2
15.4
16.6
17.8
19.0
20.2
21.4
22.6
23.8
25.0

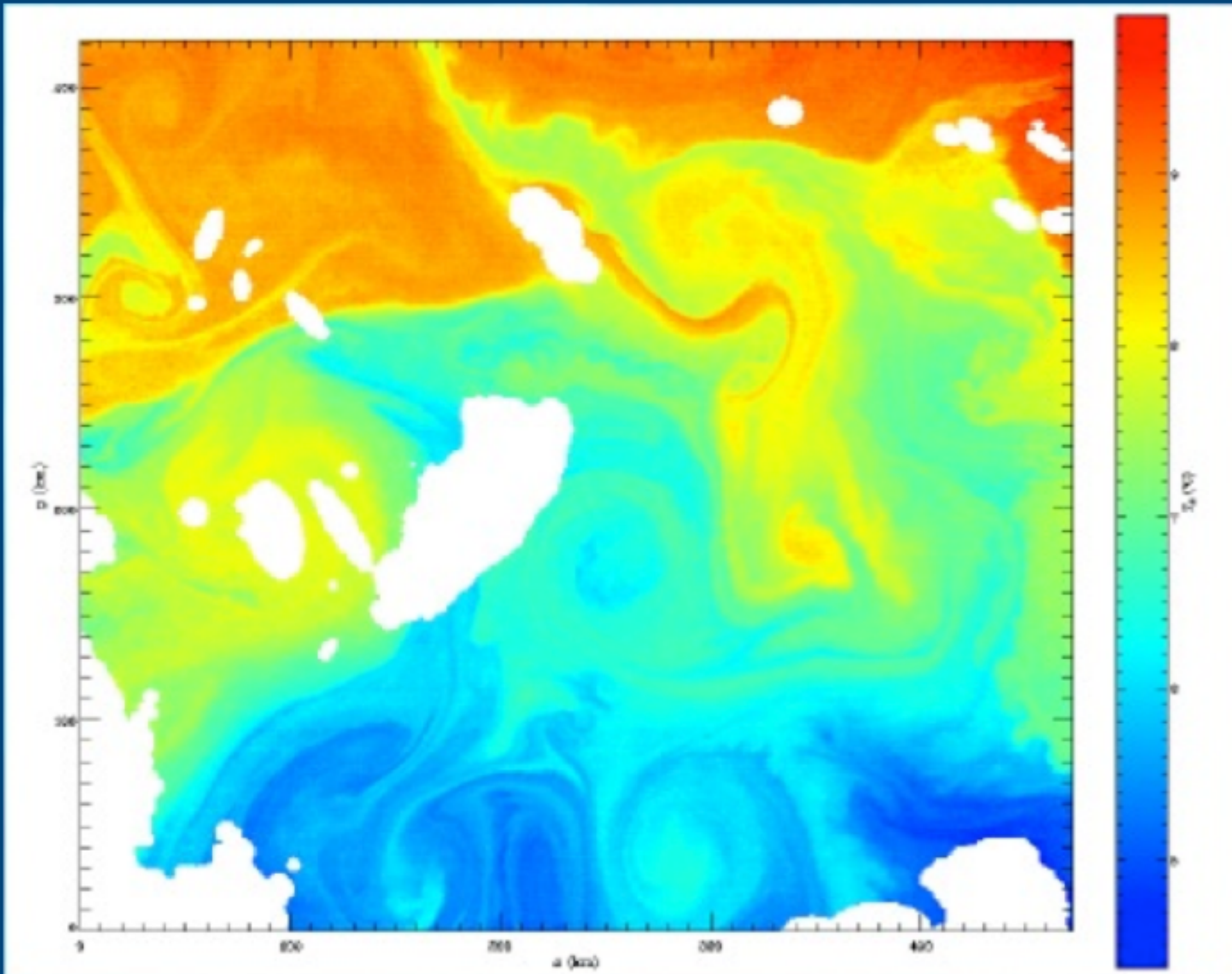

x (km)
154
330
506
683
859
Latitude (S)
30°
32°
34°
36°
38°
40°
Longitude (E)
Chlorophyle A index MODIS Aqua L2 2010/05/06
22.0
35.4
48.8
62.2
75.6
89.0
102.4
115.8
129.2
142.6
156.0

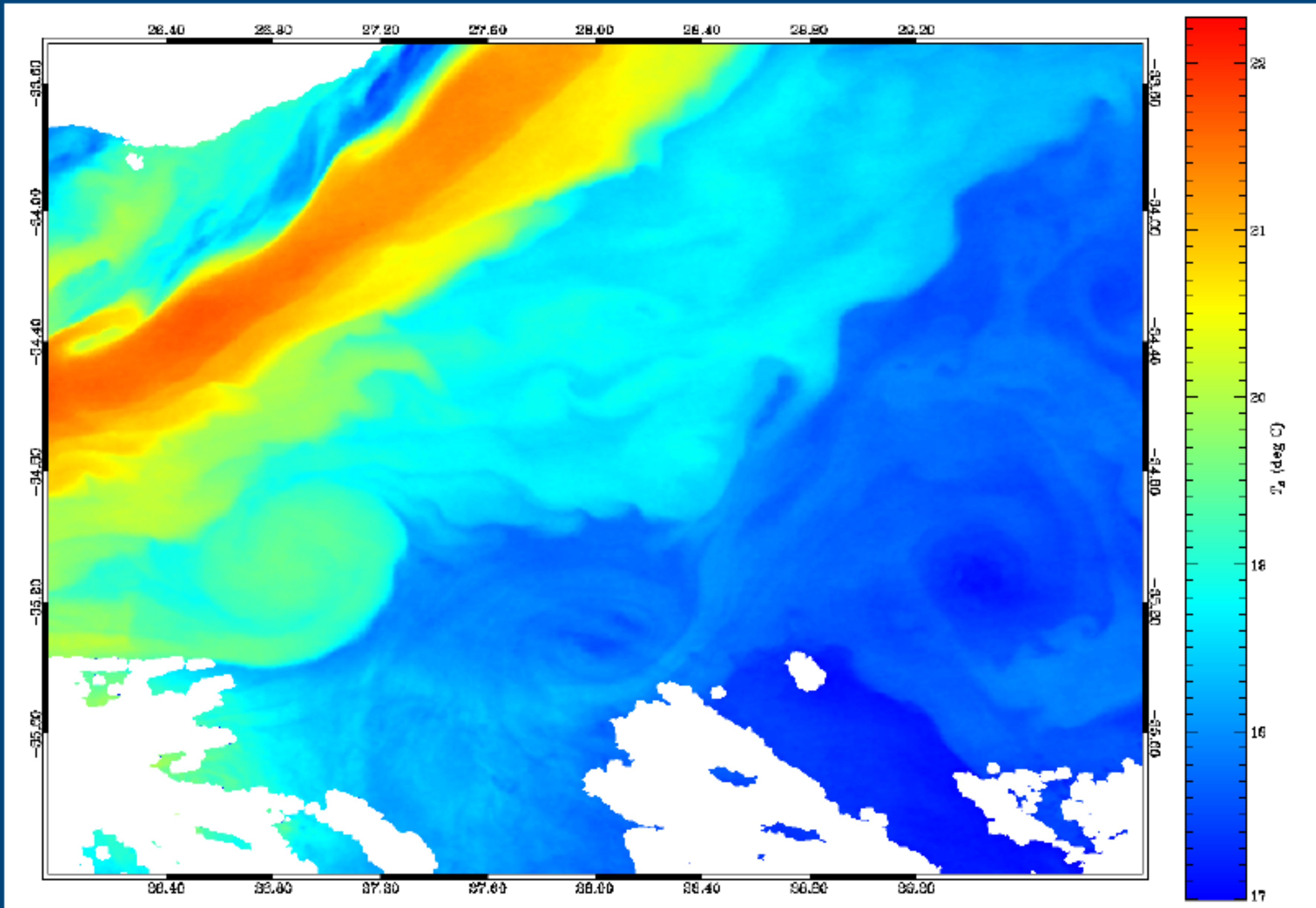


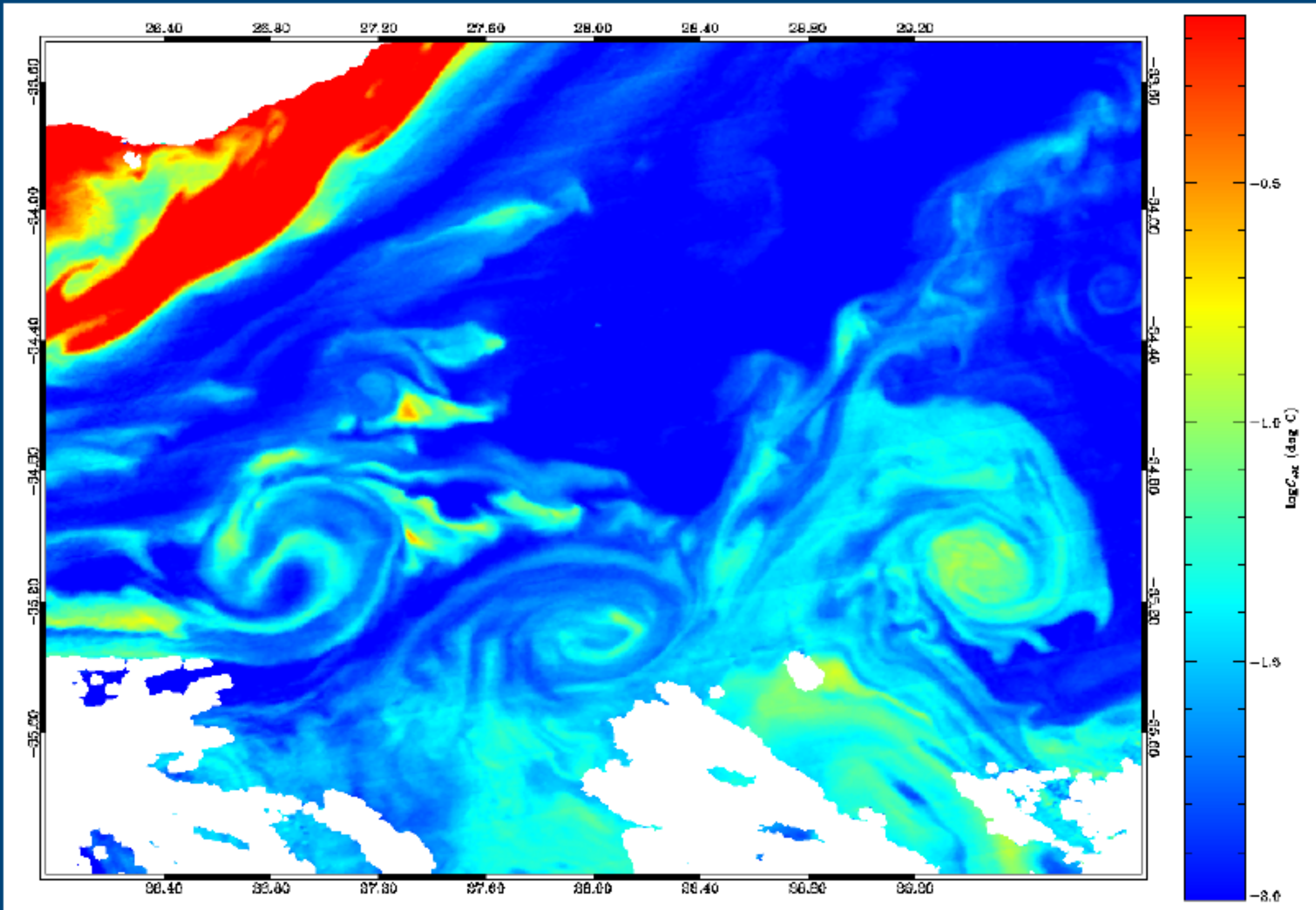
x (km)
43
131
218
306
393
481
568
Latitude (S)
36° 0'
37° 0'
38° 0'
39° 0'
40° 0'
37° 0'
38° 0'
39° 0'
40° 0'
41° 0'
42° 0'
43° 0'
Longitude (E)
Sea Surface Temp. (deg. C) MODIS Aqua L2 2010/05/08
12.0
12.8
13.6
14.4
15.2
16.0
16.8
17.6
18.4
19.2
20.0


CLS
x (km)
43
131
218
306
393
481
568
Latitude (S)
37° 0'
38° 0'
39° 0'
40° 0'
41° 0'
42° 0'
43° 0'
Longitude (E)
Chlorophyle A index MODIS Aqua L2 2010/05/06
31.0
41.4
51.8
62.2
72.6
83.0
93.4
103.8
114.2
124.6
135.0






27.20
27.60
28.00
28.40
22
21
20
17


26.40
26.80
27.20
27.60
28.00
28.40
28.80
29.20
-0.5
-1.0
-1.5
-2.0

Synthetic Aperture Radar (SAR) images show the roughness at the ocean surface due to the wind-driven surface waves.
Their spatial resolution is of the order of 100m.

Roughness varies when surface waves are affected by surface currents.
SAR images allow to detect **strong convergence and divergence regions.**

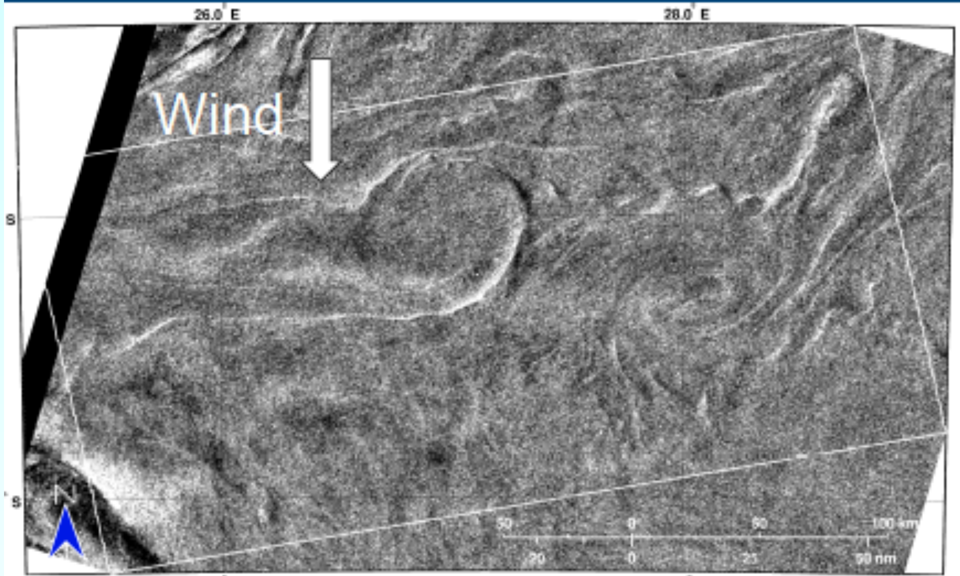
But mesoscale and submesoscale patterns are observed on these images only when the wind speed is moderate!

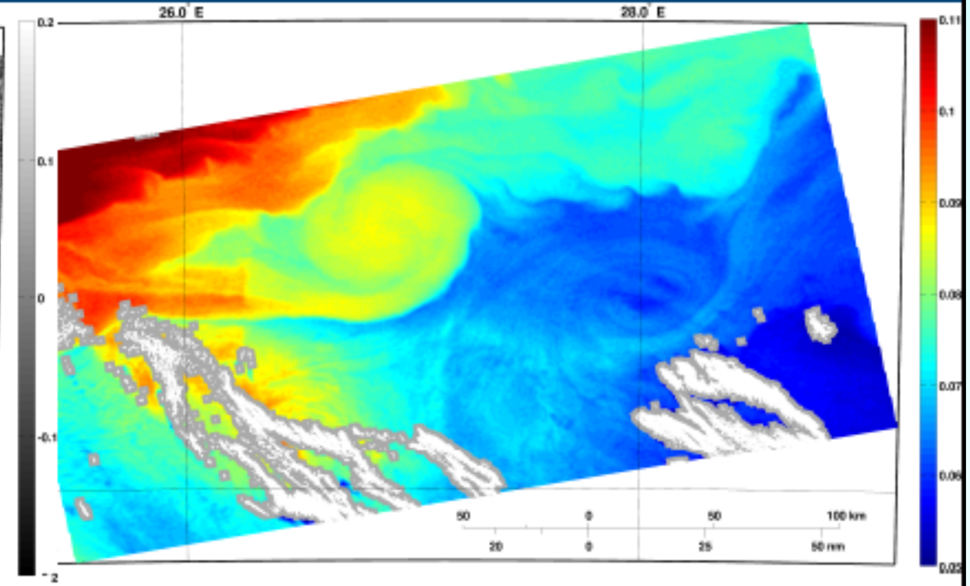
Visit:

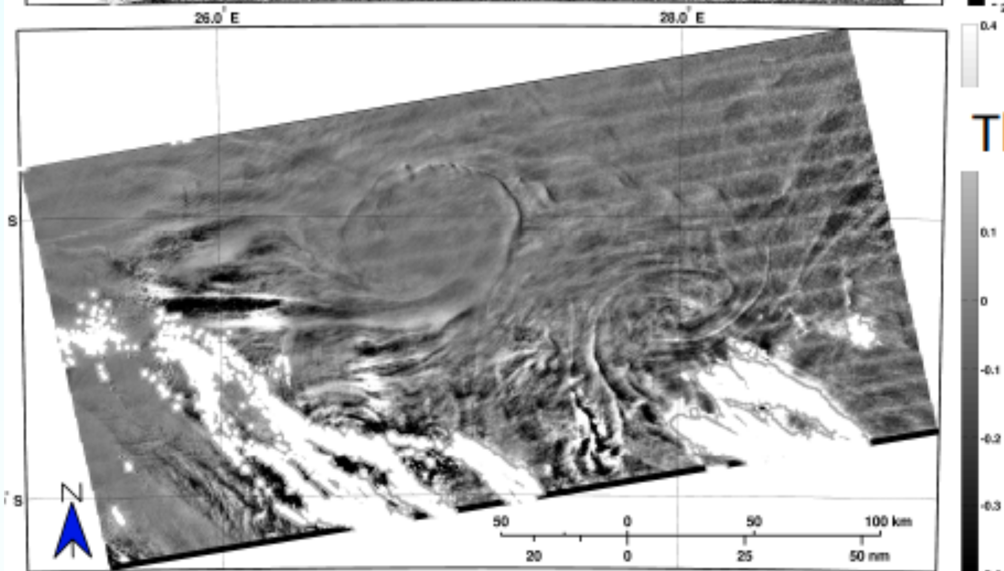
http://www.labexmer.eu/en/research/ocean-at-high-resolution/workshop-2dto3d-ocean-dynamics-from-space/downloads

See the presentation by Fabrice Collard (Ocean Data Lab)

Synergies with surface roughness







$V = U + \bar{u} + \tilde{u}$

The divergence of the total flow, $\nabla \cdot V$

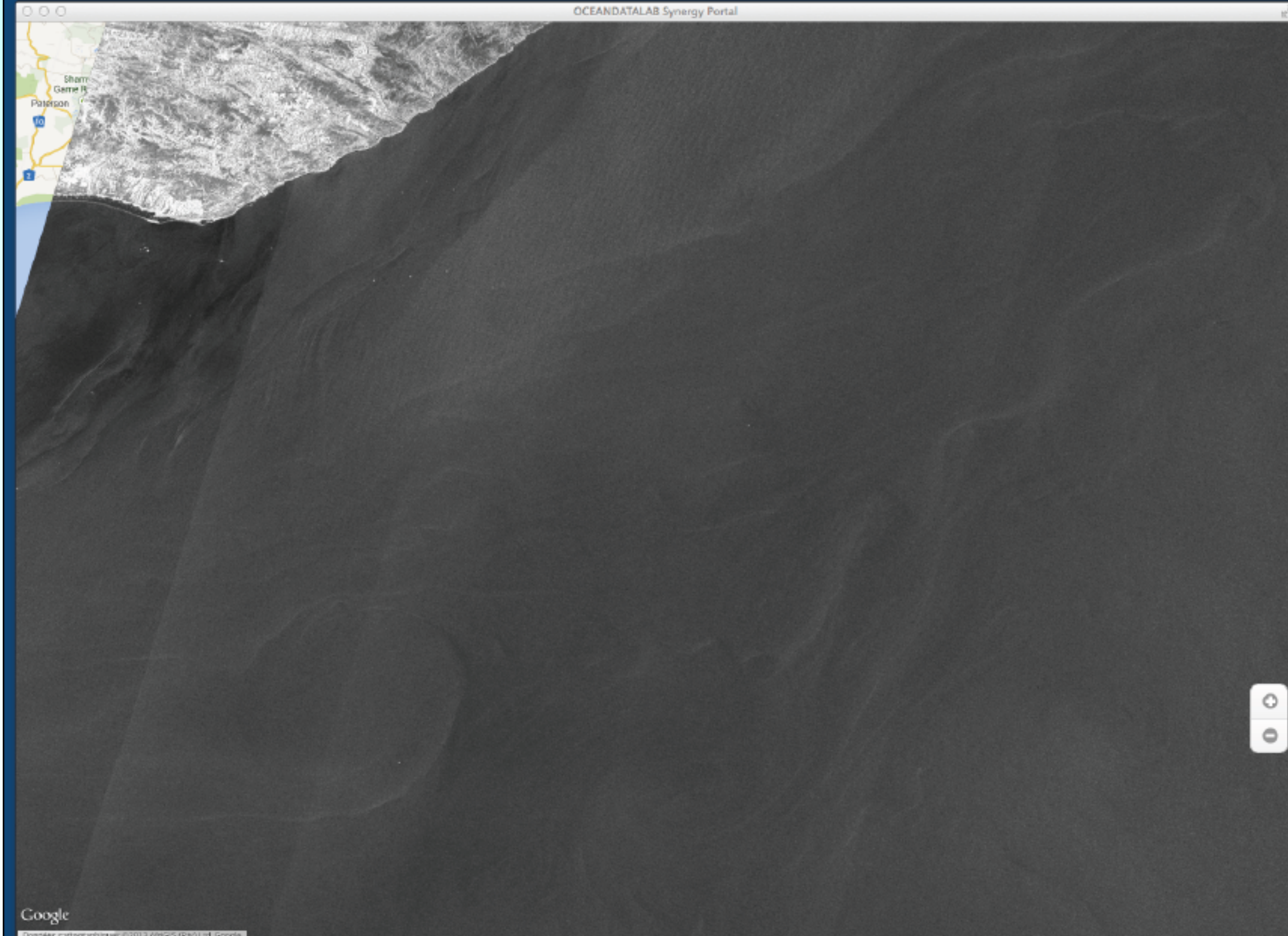
is governed by the secondary ageostrophic flow $\tilde{u}$

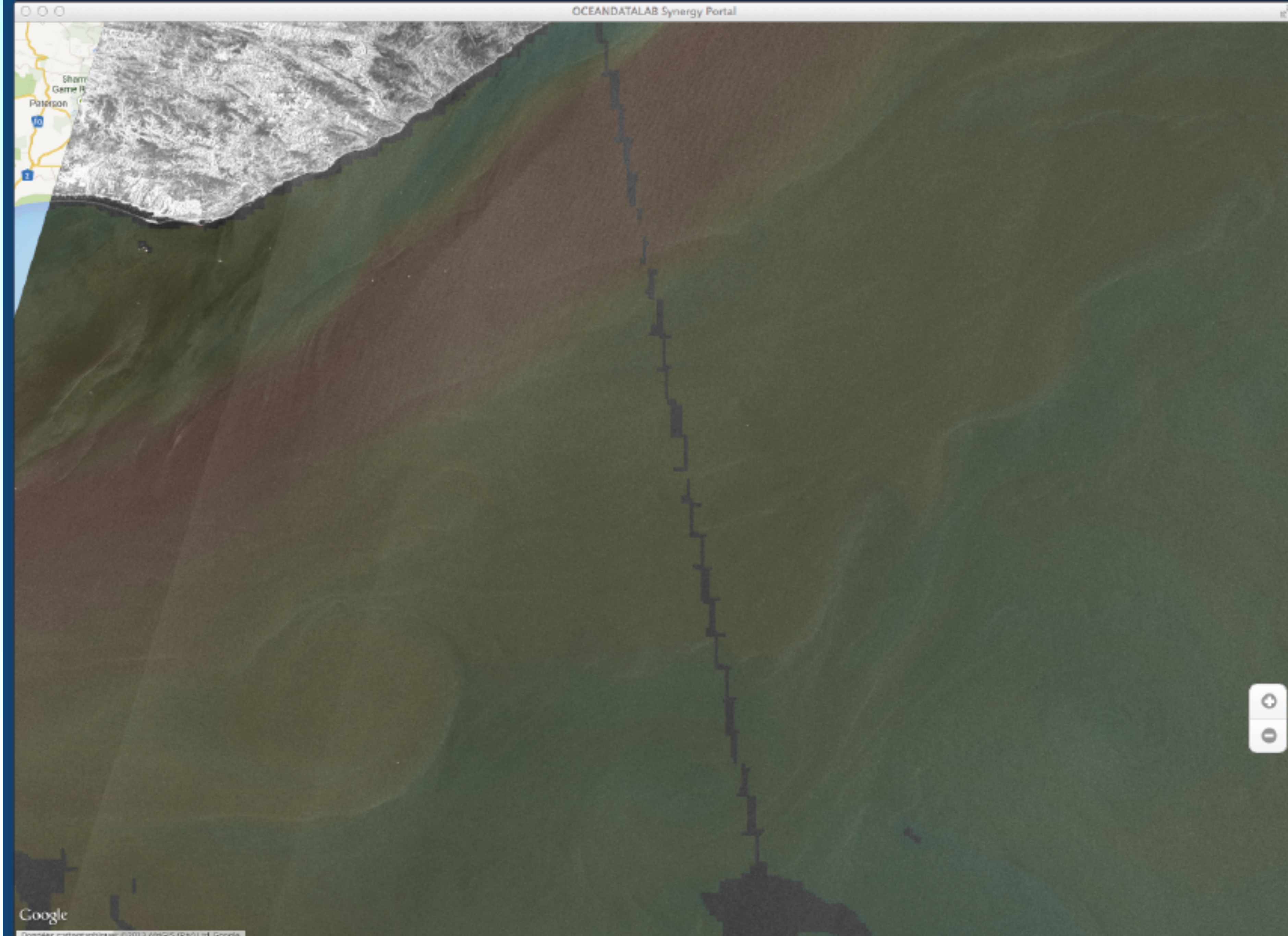
and reads $\nabla \cdot V = -f^{-1}\bar{u}_j \dfrac{\partial}{\partial x_j}\Omega_z$

where

$$\Omega_z = \partial U_1 / \partial x_2 - \partial U_2 / \partial x_1 \equiv \Delta\psi$$

is the vorticity of the QG currents


OCEANDATALAB Synergy Portal
Paterson
Google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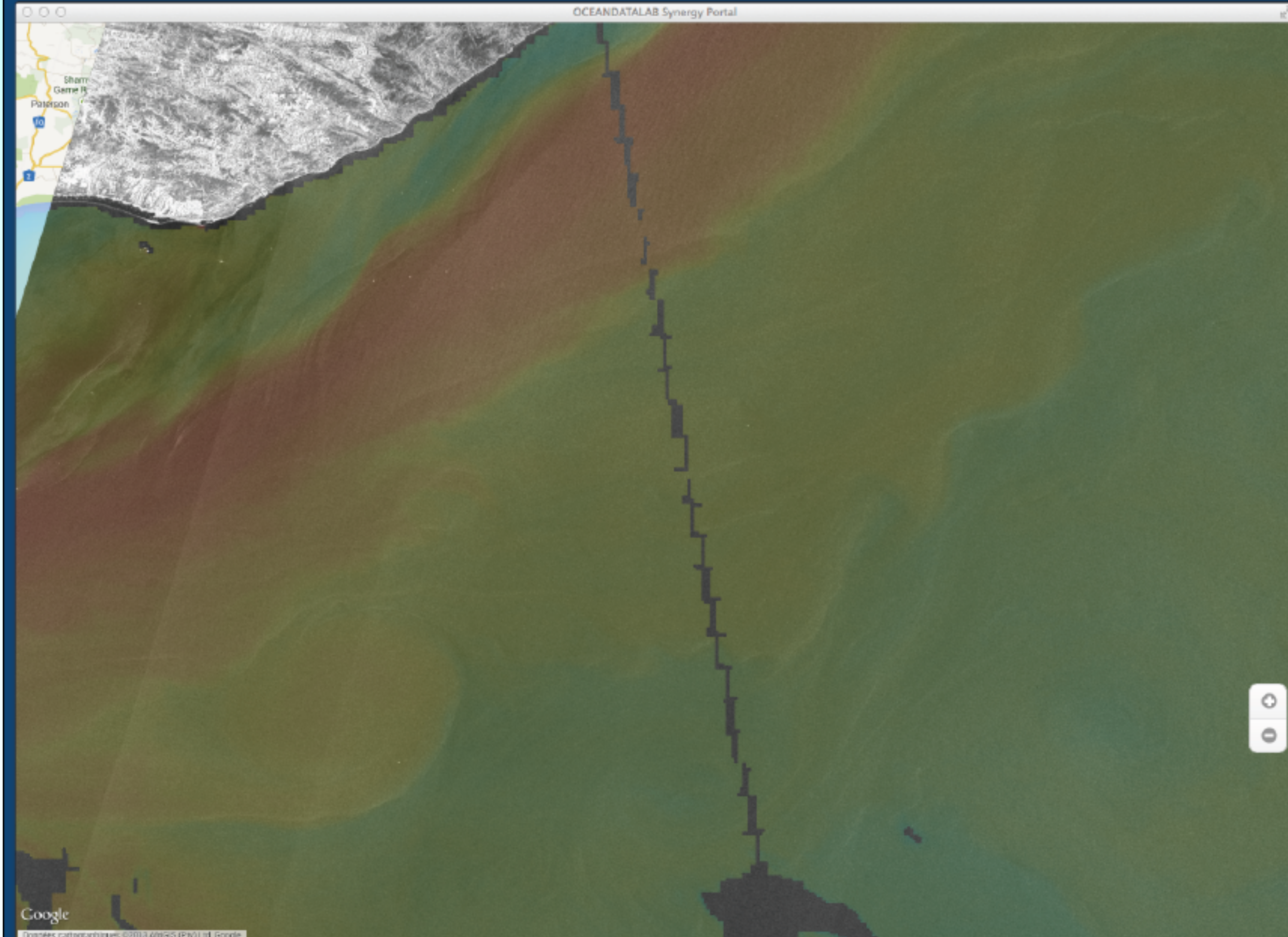
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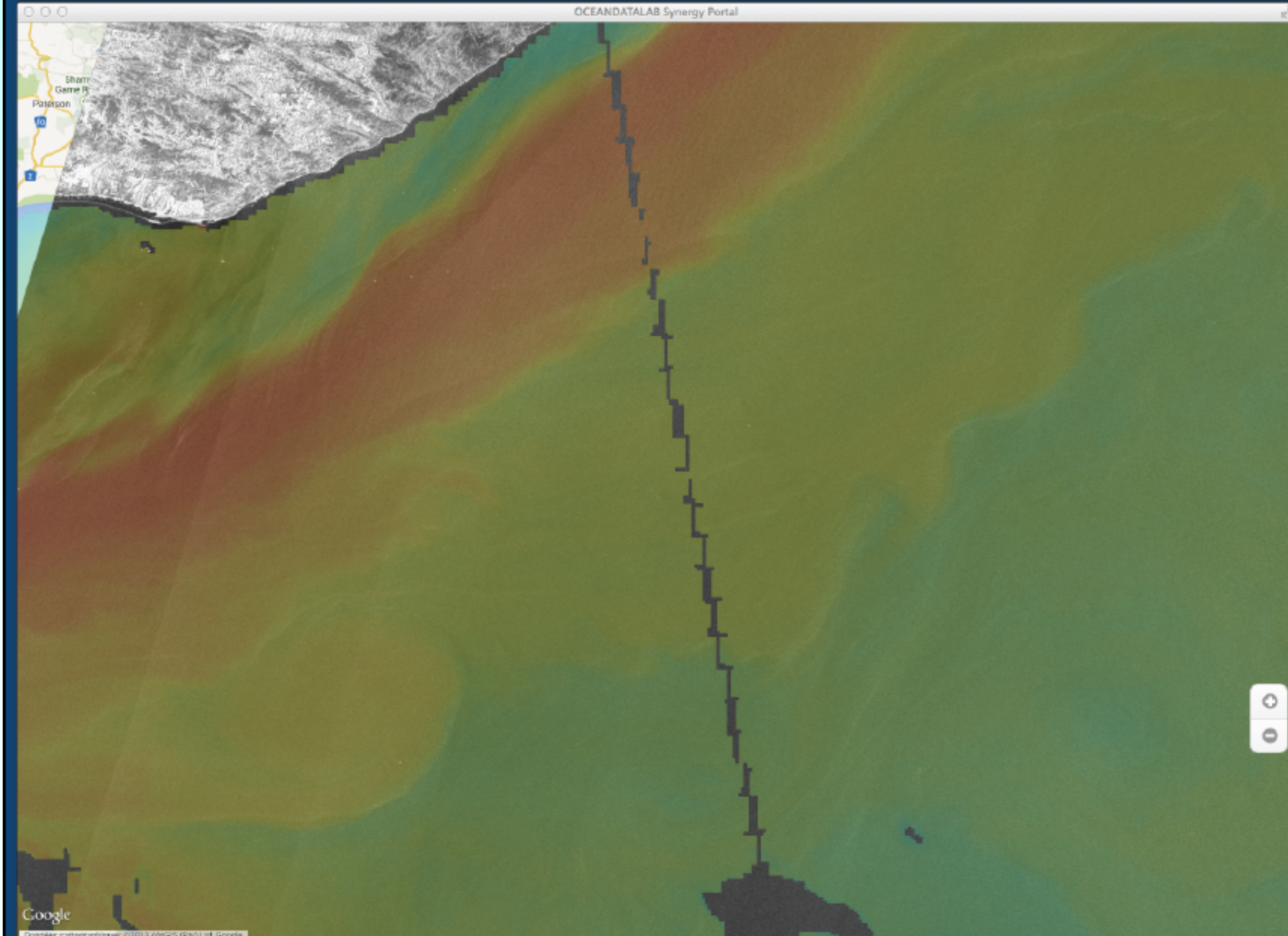
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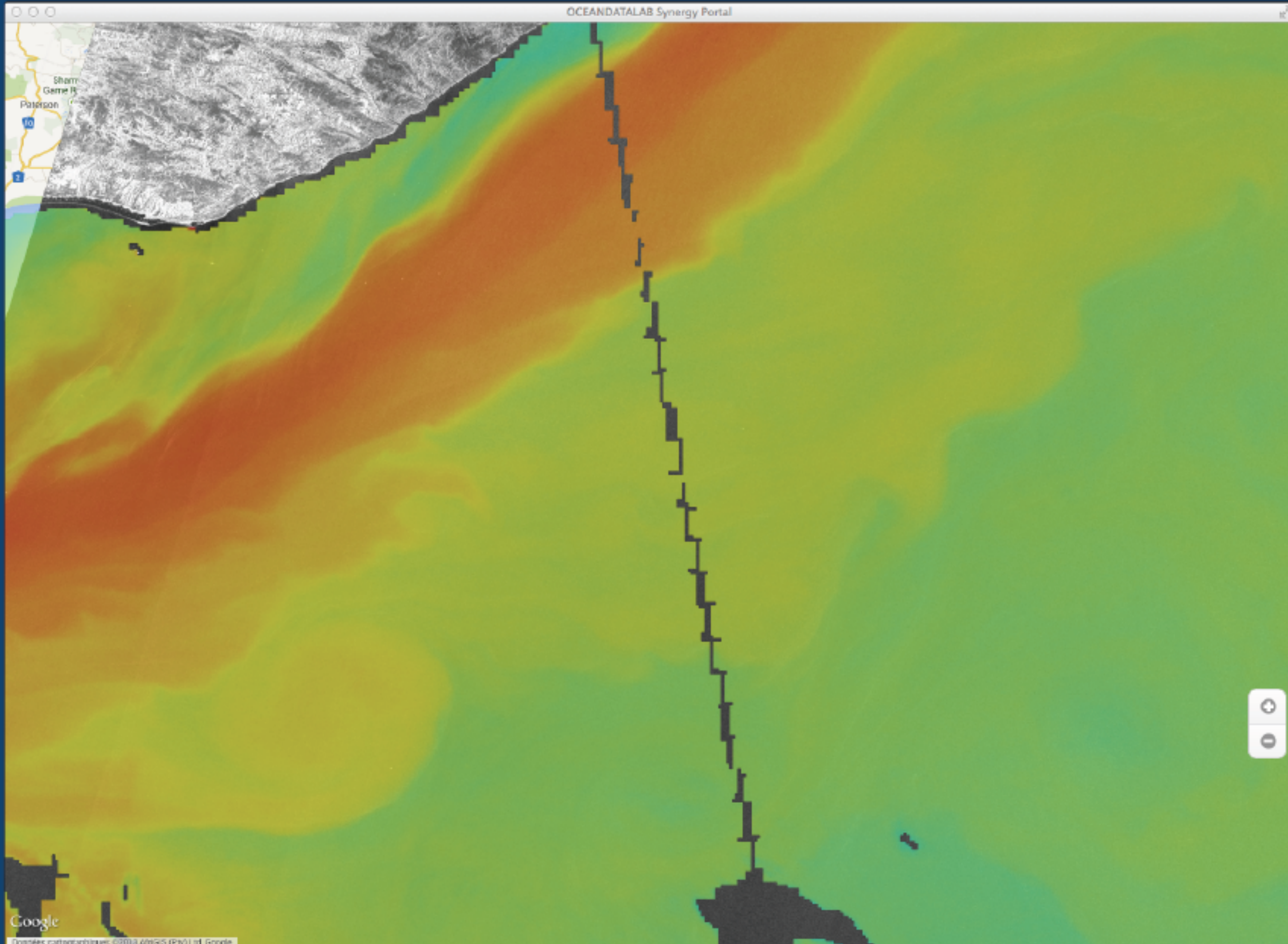
Données cartographiques ©2013 AfriGIS (Pty) Ltd, Google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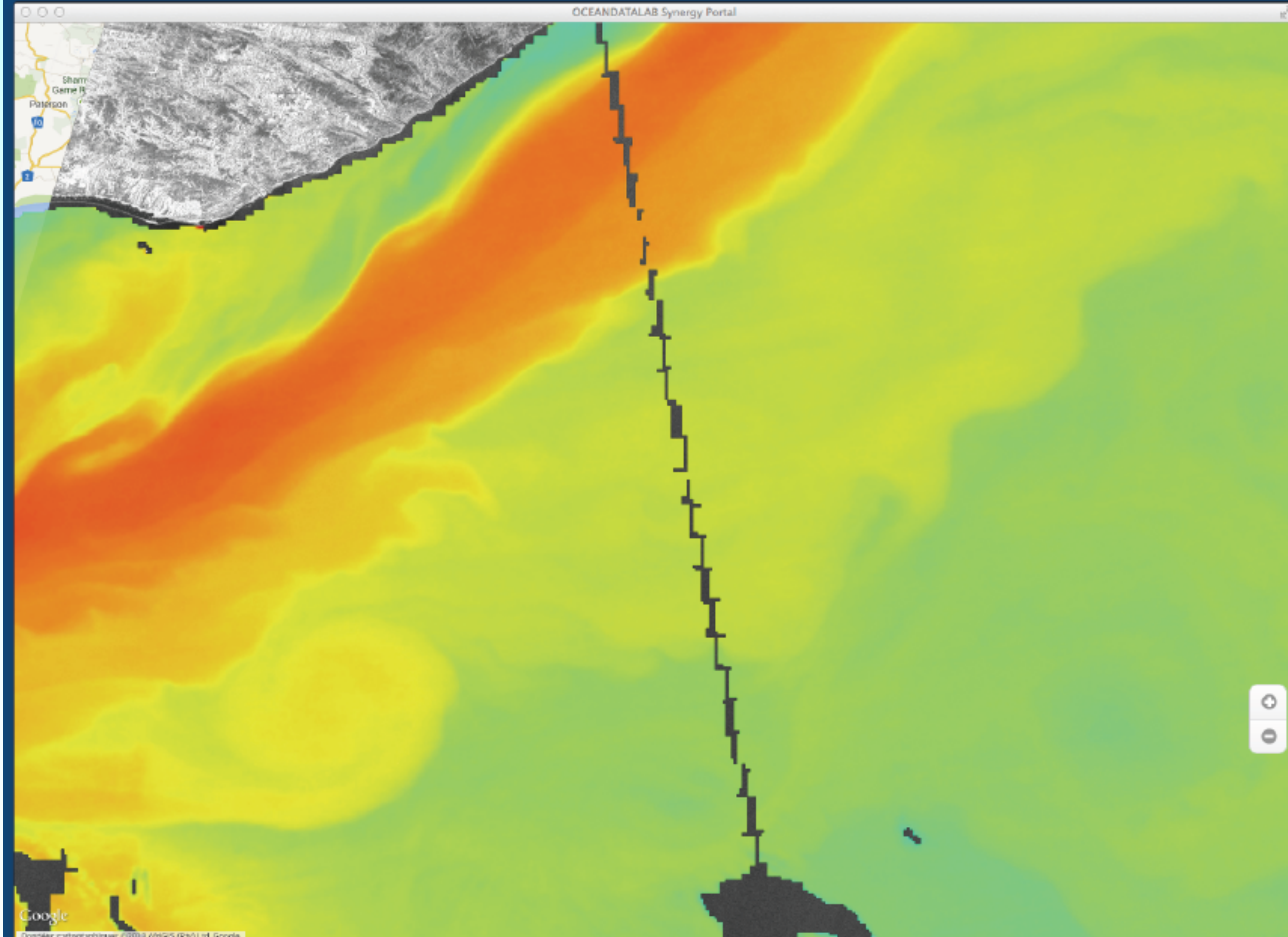
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Sunglitter images: resolution of 50 to 20 m.

Spiral eddies (10-25 km) were first seen in the sunglitter on the Apollo mission 45 years ago! (see Munk et al., 2000)

From Munk et al. (2000)

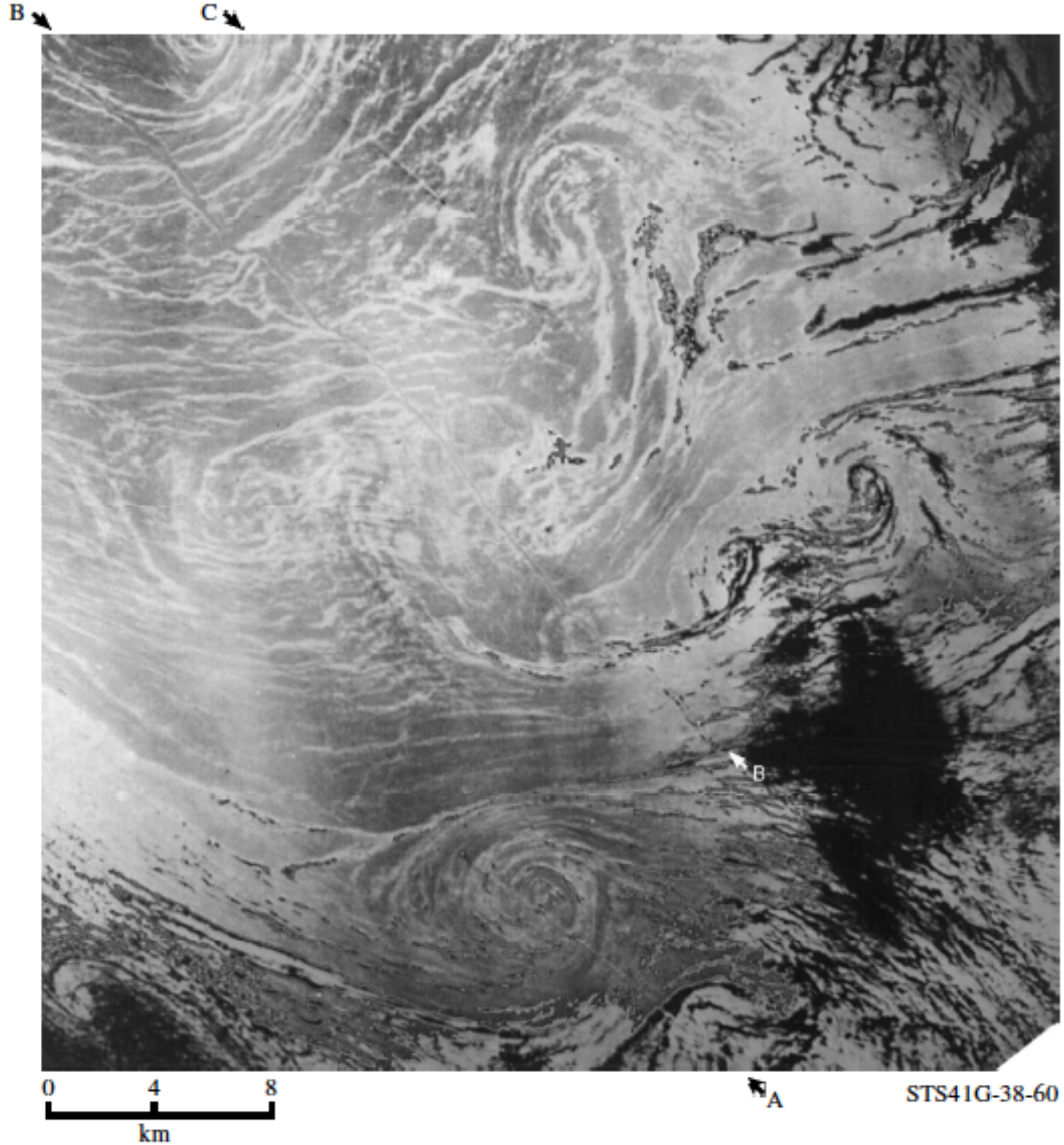
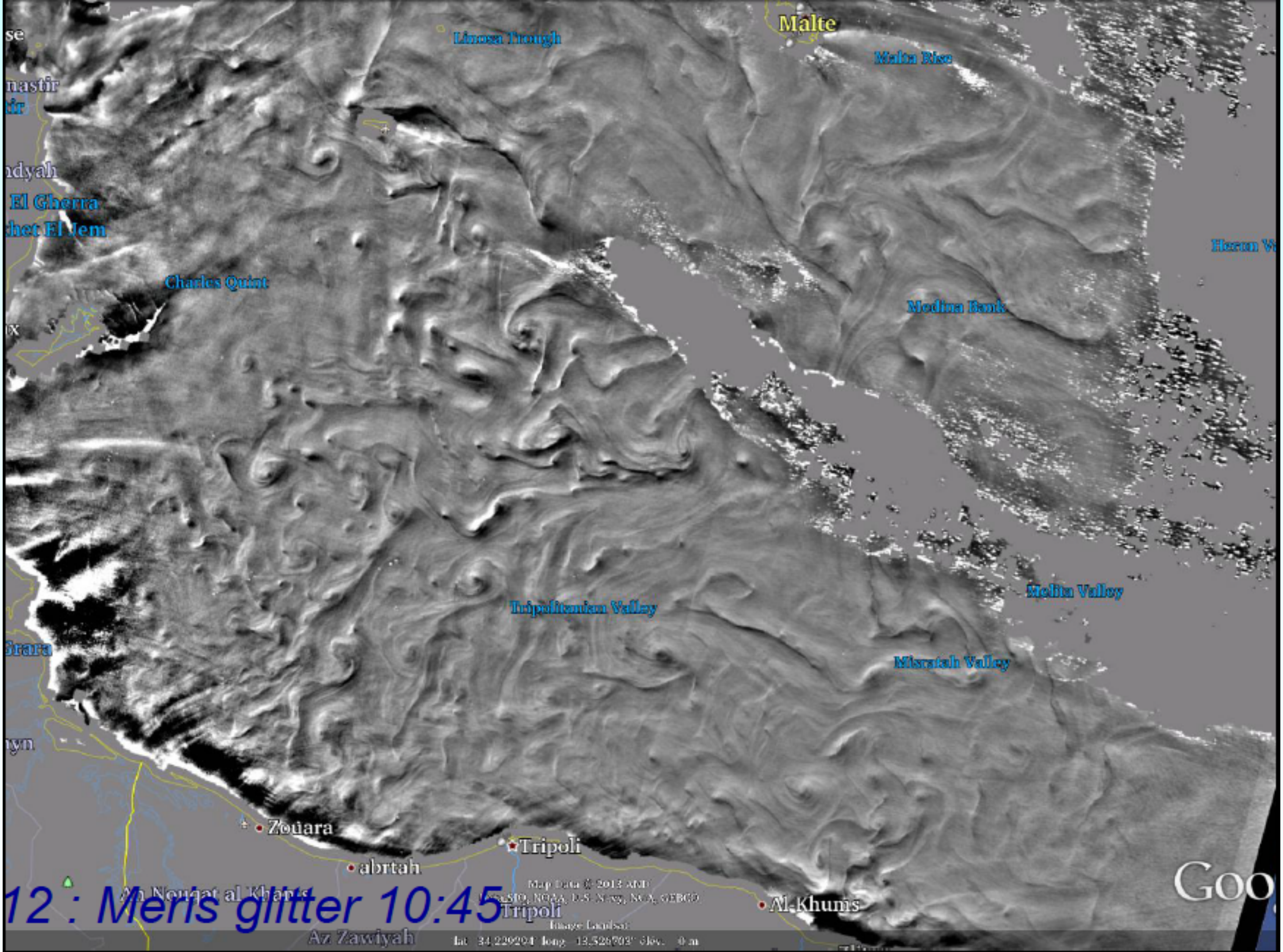
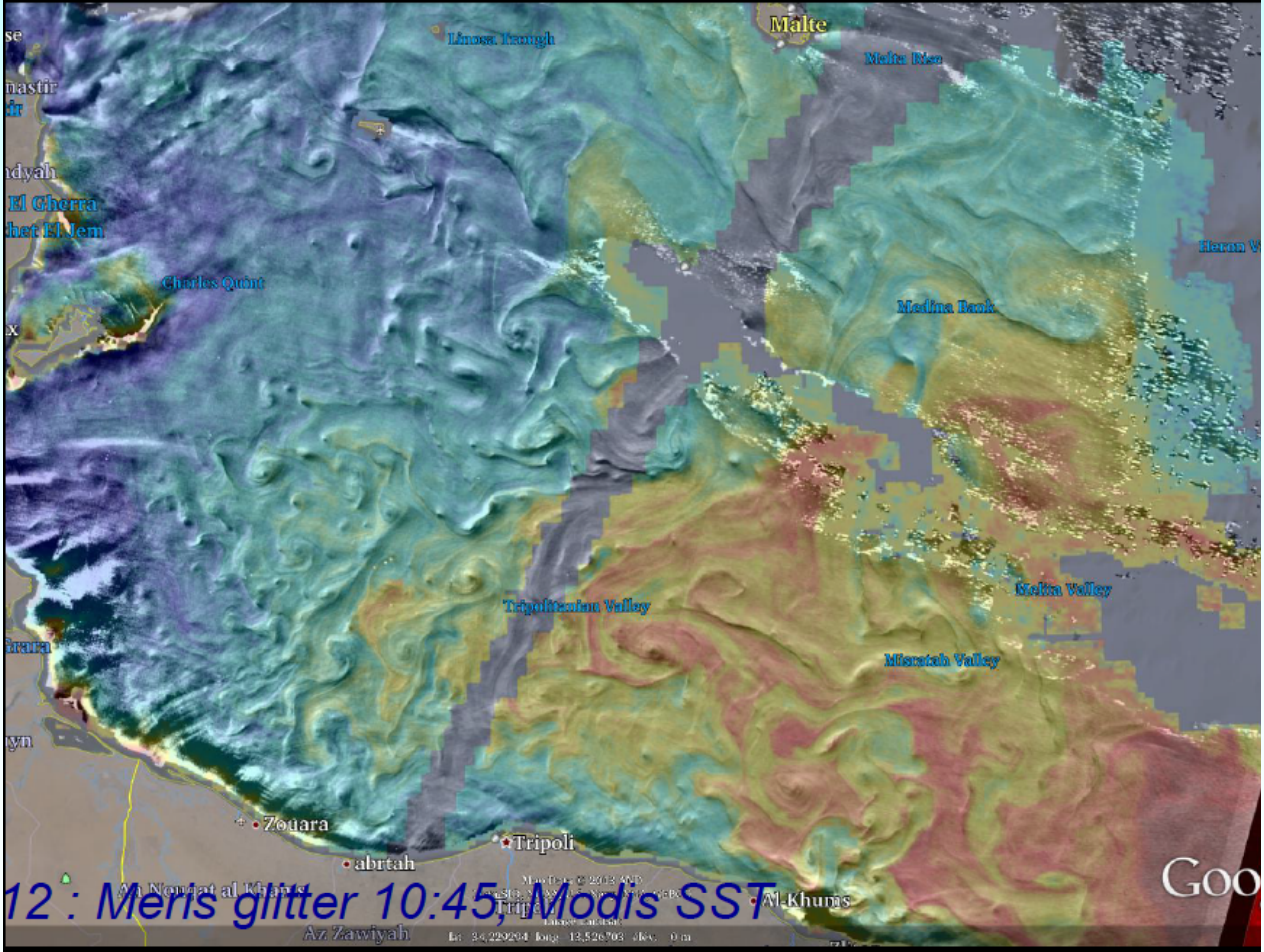


Figure 7. Ship tracks in the Ionian Sea. Tracks A and C are young with the ships visible. Track A shows minor distortion during passage through the developing core, the centre of which is *ca.* 3 km aft of the ship. Ship track B is old and shows significant offsets at cyclonic sharp fronts coincident with streaks. The rendition of the streaks changes from light in the inner sunglitter to the upper left, to dark in the outer sunglitter in the lower and right hand portion of the image.

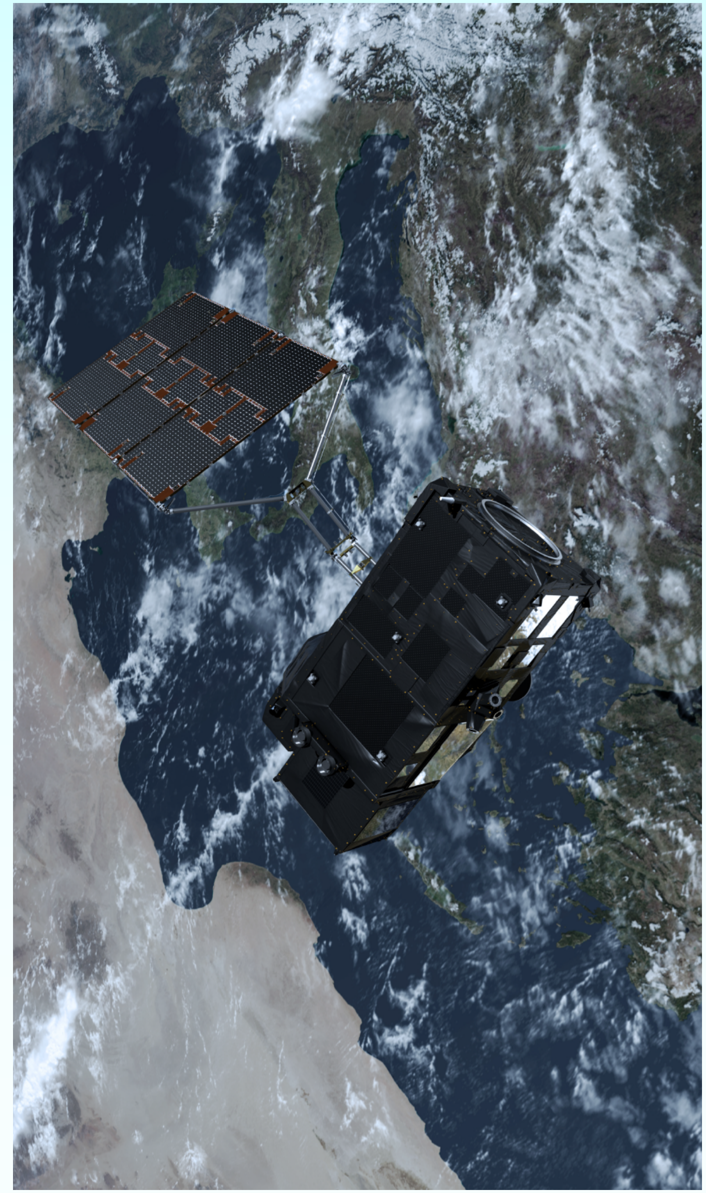


12 : Meris glitter 10:45

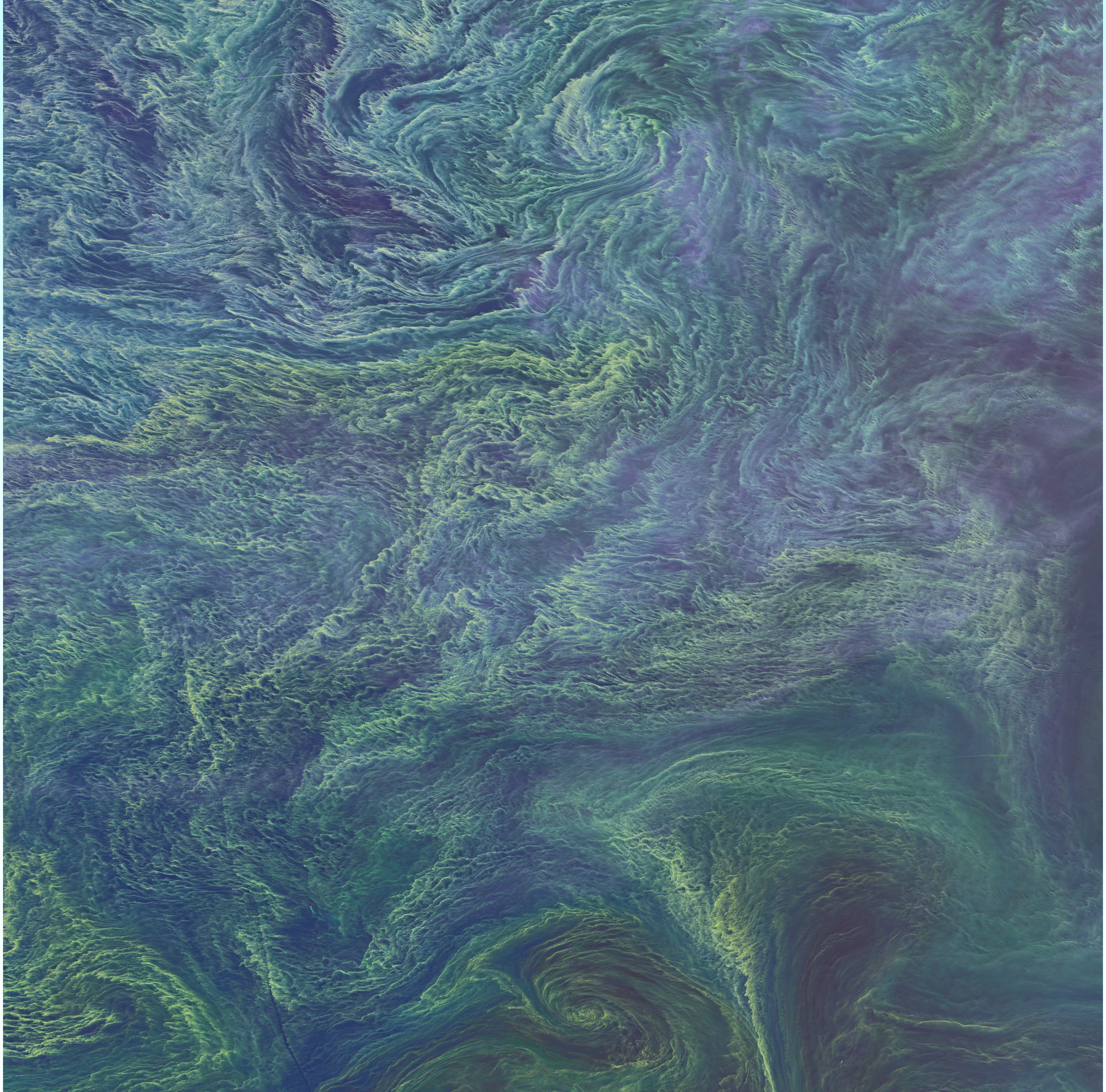


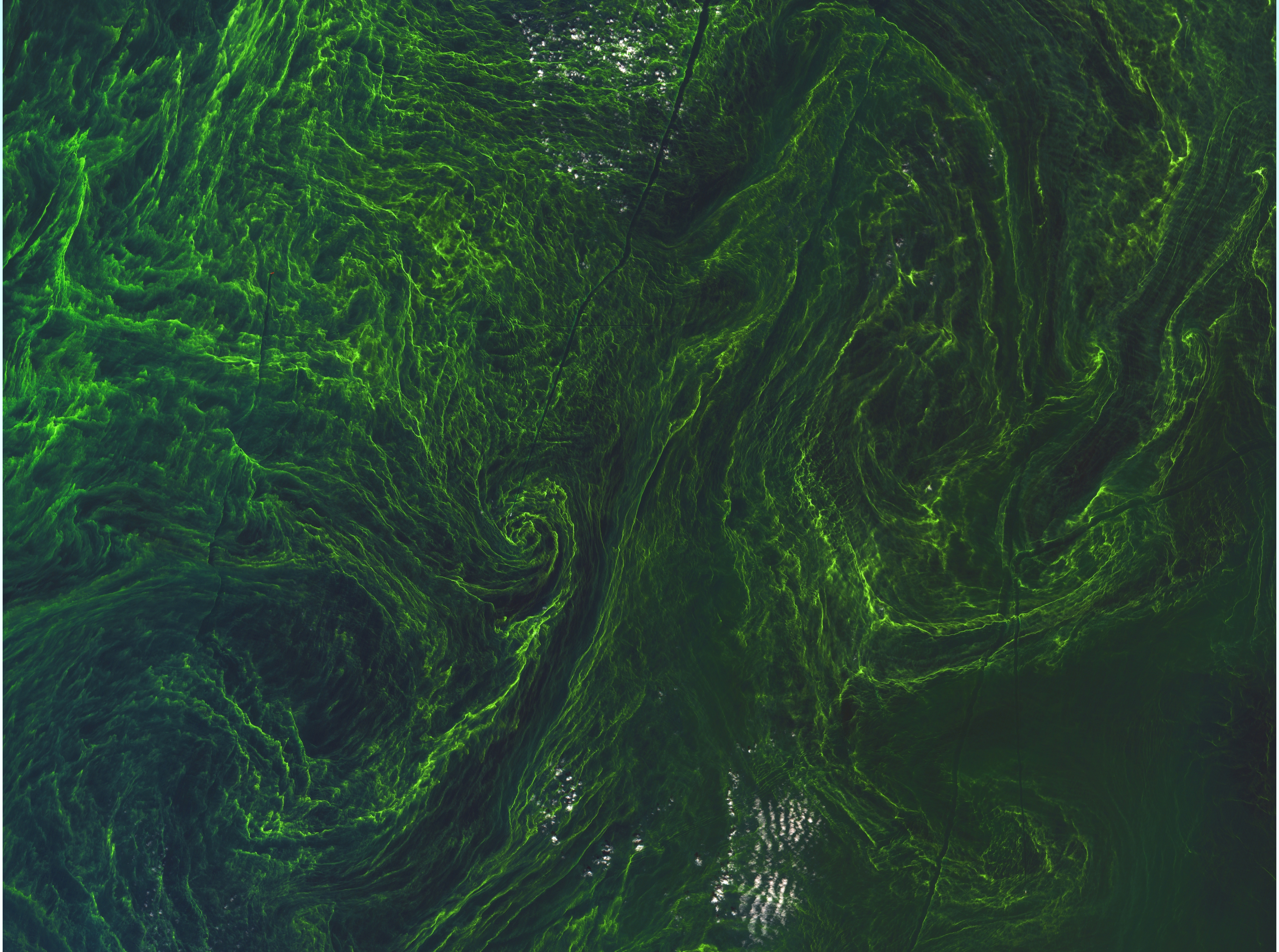
12 : Meris glitter 10:45, Modis SST

Optical imagery with a resolution of 10 m !
from Sentinel mission (ESA)



See next slide:
Algal bloom in the Baltic Sea
(7 august 2015)





Satellite oceanography reveals a large range of scales in all regions of the World Ocean from mesoscale eddies (100–300 km) to submesoscales (5–40 km) and even smaller scales

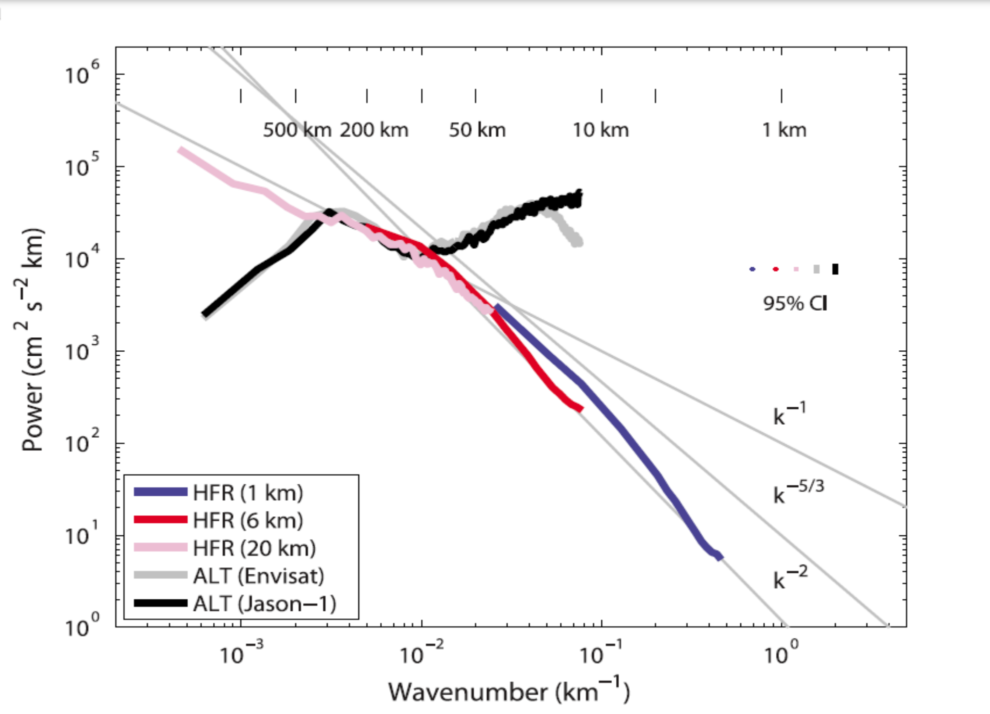
These scales are strongly interacting as indicated by the spatial patterns displayed by the SST images. But small scales are not just passively advected by horizontal motions. SAR and Ocean Color images suggest that they are associated with an energetic vertical velocity field.

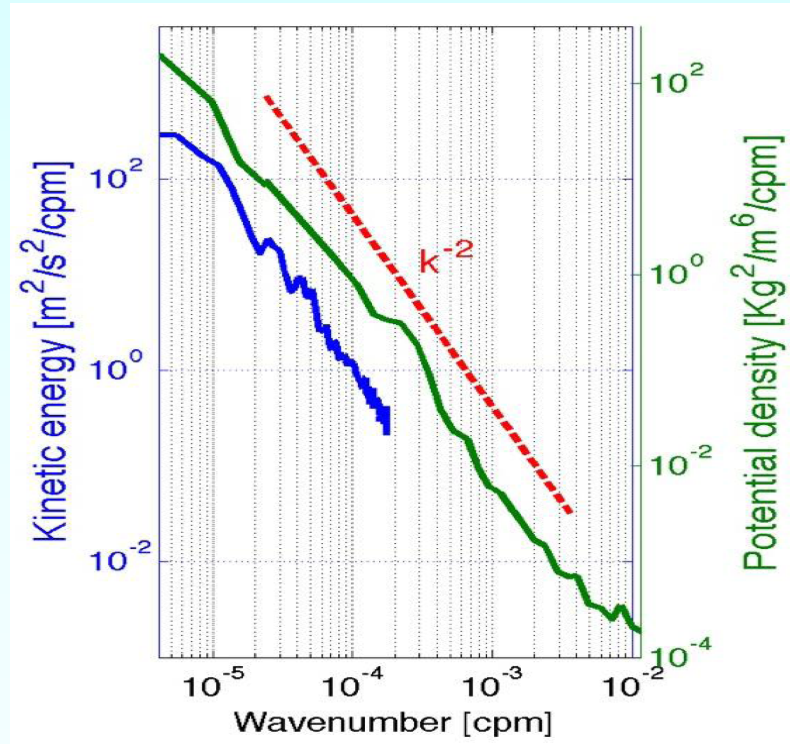
These ocean scale interactions appear to be confirmed by some in-situ

experiments ...

Kim et al.,'11, using **HF radar observations,** indicate that the velocity spectrum (NE Pacific) is in $\mathbf{k}^{-2}$, in particular in the range of submesoscales

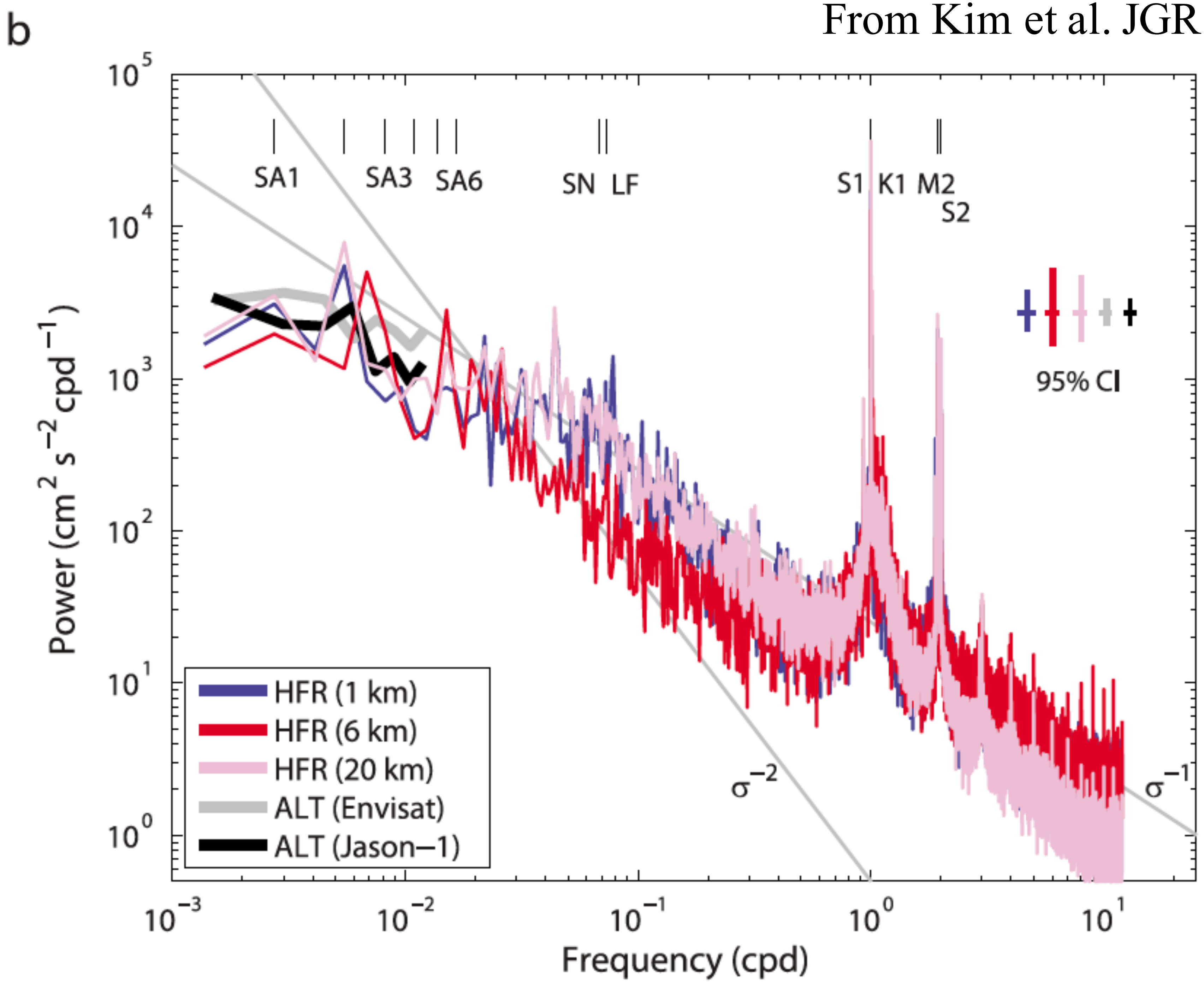
Observations: from Ferrari & Rudnick, 2000: both velocity and density spectra in $\mathbf{k}^{-2}$





These high-resolution observations reveal that submesoscales are more energetic than previously thought: velocity and density spectra have a shallower slope (**k^{-2} instead of k^{-3}** near the surface)

From Kim et al. JGR'11



These continuous spectra indicate that the different scales are strongly interacting with the consequences that: **significant energy transfers (due to the nonlinear interactions) can occur from large to smaller or small to larger scales!**

Characteristics of these nonlinear interactions may differ from one region to the others.

Satellite oceanography (and in particular the future satellite missions) should help to better understand these characteristics how they differ in the World Ocean.

But we need a dynamical framework to analyse these satellite data (in connection with in-situ data) that goes beyond the geostrophic approximation in order to take into account these nonlinearities.

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This dynamical framework is the purpose of this course.

Focus on scales from 10 km to 10000 km

This concerns turbulence in rotating and stratified flows

Properties of this turbulence are well known.

Using these properties can help to define a dynamical framework to better analyse existing and future satellite data and also to analyse results from realistic simulations performed at high resolution.

Synopsis of the course:

1 - Satellite altimetry: major breakthroughs and existing limitations. Expectations from future altimeter missions and need for a better dynamical framework.

2 – Basic properties of 2-D turbulence: impacts of nonlinear interactions

3 – Basic properties of 3-D mesoscale turbulence

4 - Submesoscales and their interactions with mesoscale eddies

5 – Scattering of internal waves by mesoscale and submesoscale structures

6 – Potential of a dynamical framework to diagnose 3-D ocean dynamics from satellite data at high resolution and in-situ data at much higher resolution (ARGO float dataset)