Remote sensing of highly concentrated phytoplankton blooms

IOCCG SLS 2026

Pierre GERNEZ

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What causes a bloom? (open ocean)

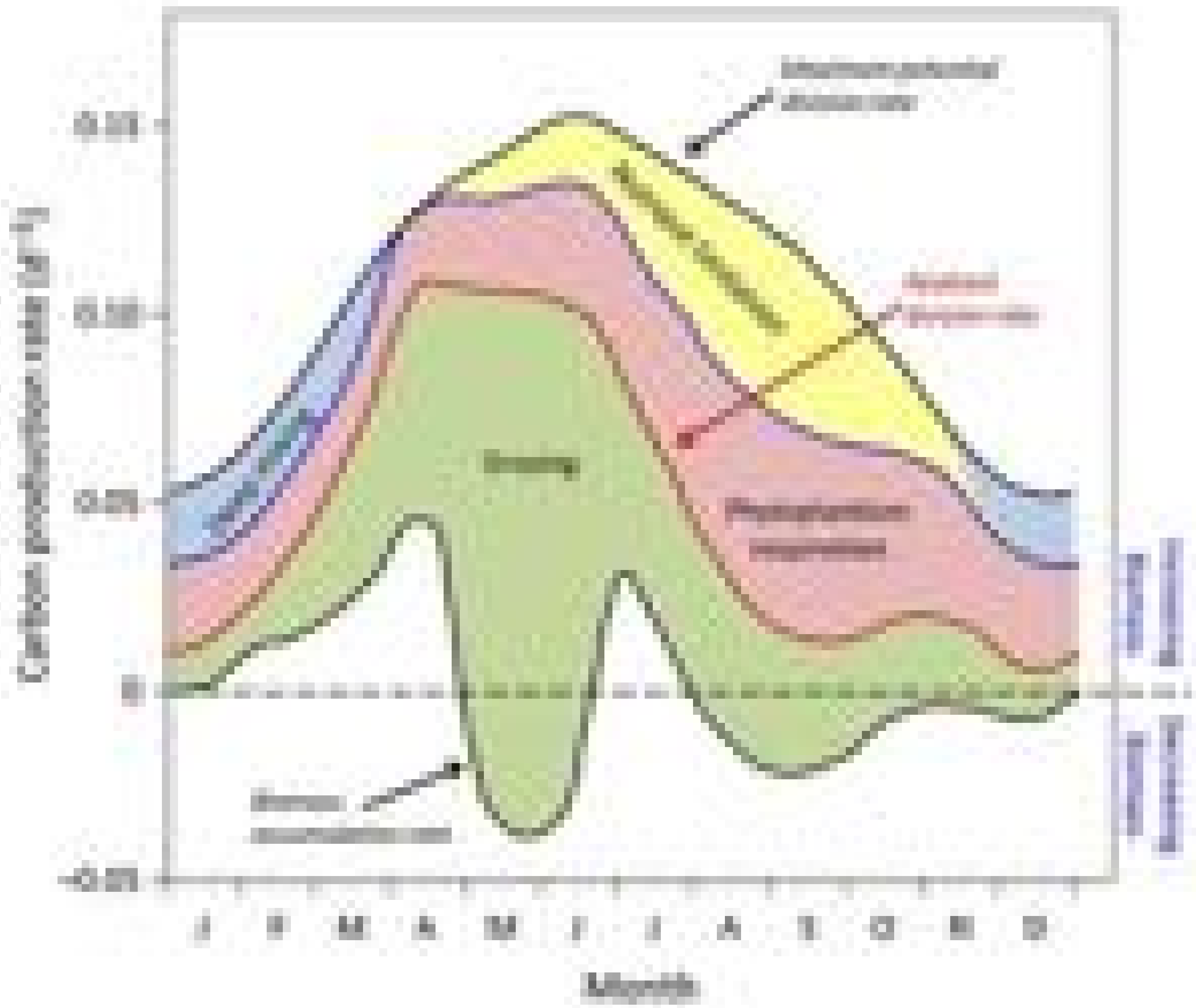
Global Change Biology

INVITED REVIEW | Open Access

Student's tutorial on bloom hypotheses in the context of phytoplankton annual cycles

Michael J. Behrenfeld, Emmanuel S. Boss

First published: 08 August 2017 | https://doi.org/10.



What is a bloom? (coastal waters)

LIMNOLOGY AND OCEANOGRAPHY

ASLO
Association for the Sciences of Limnology and Oceanography

Article | Free to Read

What is a bloom? A commentary

Theodore J. Smayda

First published: 22 December 2003

Abstract

There are at least eight different modes and mechanisms by which harmful phytoplankton species can cause mortality, physiological impairment, or other negative in situ effects. Their distinction from nonharmful phytoplankton taxa is clearly warranted. Increasing use of bloom descriptors such as "exceptional," "unusual," "nuisance," and subjective reference to specific occurrences as blooms reveal widespread confusion concerning: what is a bloom?, how is it to be defined?, what is harmful?, and what distinguishes a harmful bloom from other blooms? Such efforts have been influenced by comparison with perceived spring diatom bloom characteristics. Examples, selected from among harmful bloom events, are presented to support the view that the classical focus on the spring diatom bloom has significant conceptual and operational biases as to what constitutes a bloom. This and the inexact criteria used to define a bloom compromise

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Highly concentrated phytoplankton blooms aka red tides

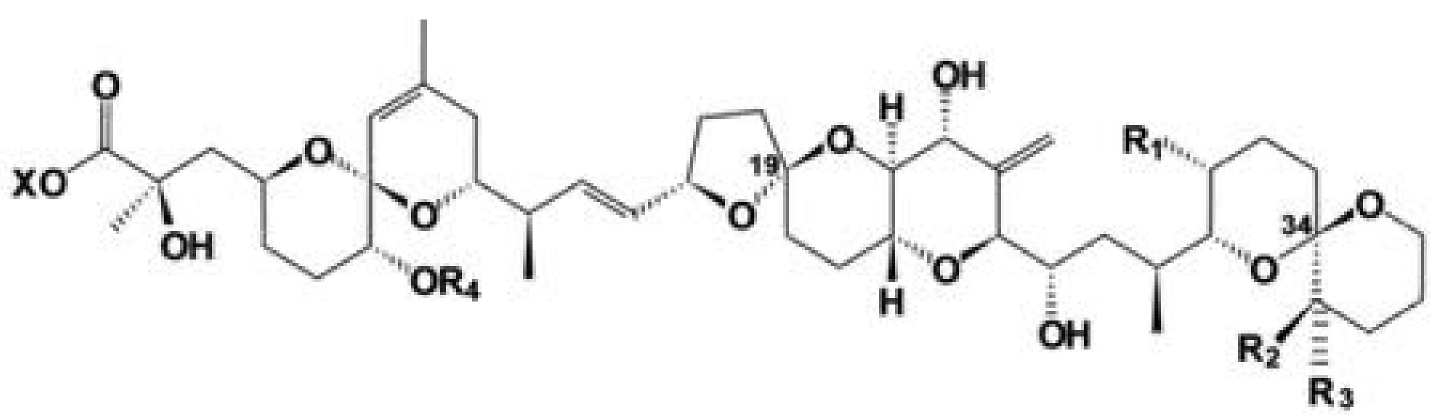
sometimes: harmful algal blooms (HABs)

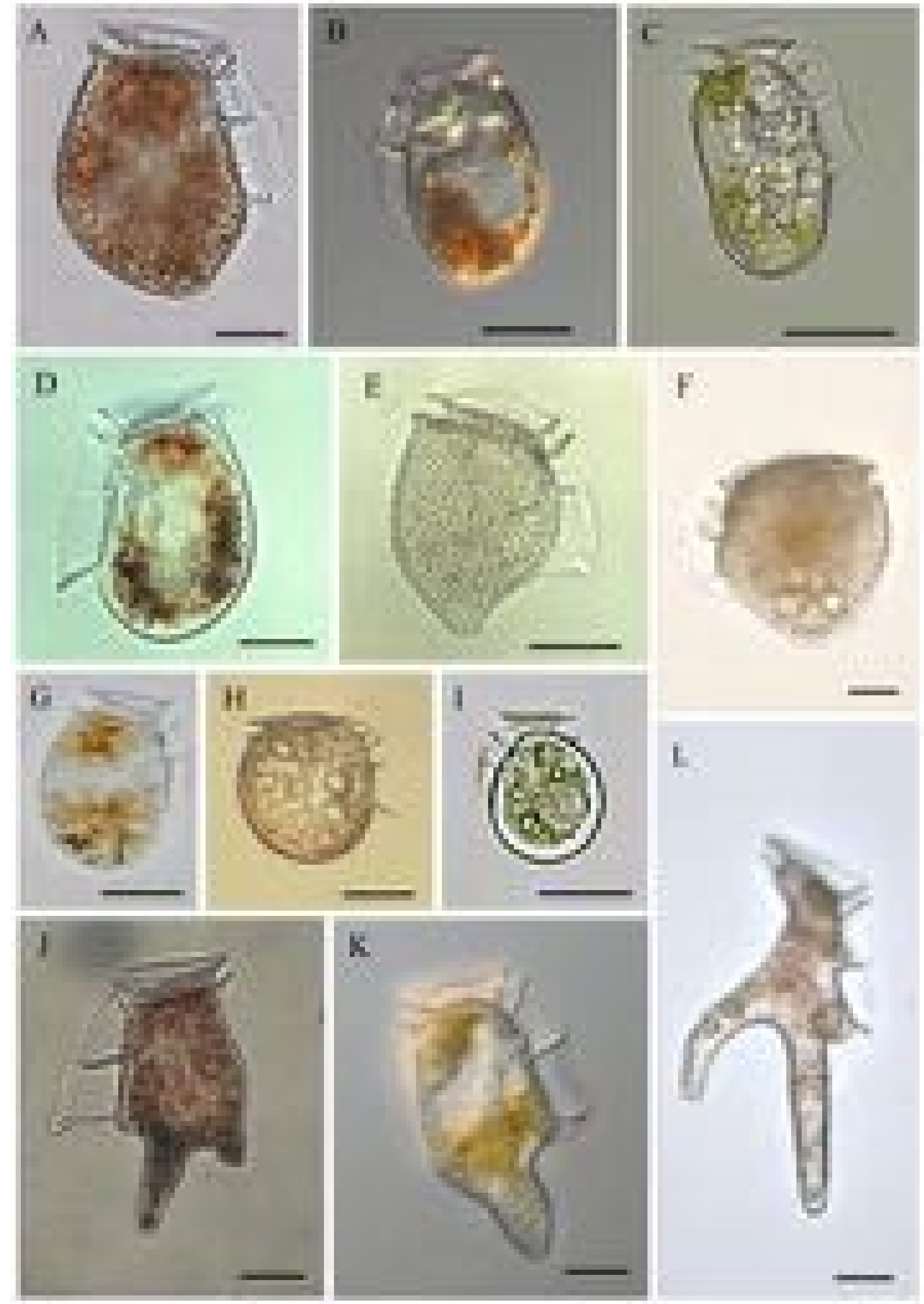
- Directly toxic
- Oxygen depletion during bloom decay
- Accumulation of ammonium inside cells

Low-concentration HABs

Some species can produce high amount of toxins at low cell abundance

***Dinophysis* sp.** (~ 100 cells / L)
Diarrheic Shellfish Poisoning (DSP) toxins
Okadaic acids (Reguera et al., 2014)





Several species of the *Dinophysis* genera are toxic

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Reguera, B., Riobó, P., Rodríguez, F., Díaz, P. A., Pizarro, G., Paz, B., ... & Blanco, J. (2014). *Dinophysis* toxins: Causative organisms, distribution and fate in shellfish. Marine drugs, 12, 394-461.

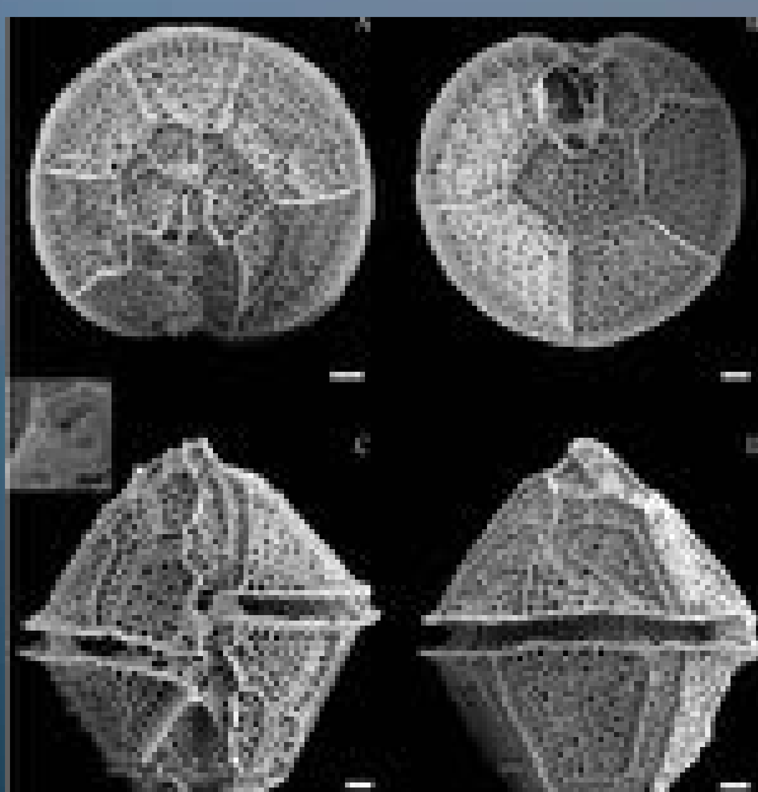
Example of yessotoxins (YTX) producers

Main YTX producers

Lingulodinium polyedra

Protoceratium reticulatum

Gonyaulax spinifera



Mertens et al., (2023)
L. polyedra cell concentration up to 3,600,000 cells/L…
… but no toxicity recorded in shellfish

YTX were produced by *P. ceratium* (low cell concentration)

Mertens, K. N., Retho, M., Manach, S., Zoffoli, M. L., Doner, A., Schapira, M., ... & Gernez, P. (2023). An unprecedented bloom of *Lingulodinium polyedra* on the French Atlantic coast during summer 2021. Harmful Algae, 125, 102426.

269 known harmful phytoplankton species

214 known toxic and 55 non-toxic (but still harmful) species

- 55% dinoflagellates
- 20% diatoms
- 16% cyanobacteria

Be careful with taxonomy…

WoRMS
World Register of Marine Species

Lingulodinium polyedra ? Not any more! ***Lingulaulax polyedra***

★ *Lingulodinium polyedra* (F.Stein) J.D.Dodge, 1989

AphiaID	233592 (urn:lsid:marinespecies.org:taxname:233592)
Classification	Biota > ★ Chromista (Kingdom) > ★ Harosa (Subkingdom) > ★ Alveolata (Infrakingdom) > ★ Myzozoa (Phylum) > ☆ Dinozoa (Subphylum) > ☆ Dinoflagellata (Infraphylum) > ★ Dinophyceae (Class) > ★ Peridiniphycidae (Subclass) > ★ Gonyaulacales (Order) > ★ Lingulodiniaceae (Family) > ★ *Lingulodinium* (Genus) > ★ *Lingulodinium polyedra* (Species)
Status	✖ unaccepted > superseded combination
Accepted name	★ *Lingulaulax polyedra* (F.Stein) M.J.Head, K.N.Mertens & R.A.Fensome, 2024

★ *Lingulaulax polyedra* (F.Stein) M.J.Head, K.N.Mertens & R.A.Fensome, 2024

AphiaID	1778370 (urn:lsid:marinespecies.org:taxname:1778370)
Classification	Biota > ★ Chromista (Kingdom) > ★ Harosa (Subkingdom) > ★ Alveolata (Infrakingdom) > ★ Myzozoa (Phylum) > ☆ Dinozoa (Subphylum) > ☆ Dinoflagellata (Infraphylum) > ★ Dinophyceae (Class) > ★ Peridiniphycidae (Subclass) > ★ Gonyaulacales (Order) > ★ Lingulodiniaceae (Family) > ★ *Lingulaulax* (Genus) > ★ *Lingulaulax polyedra* (Species)
Status	accepted
Rank	Species
Type taxon of	★ *Lingulaulax* M.J.Head, K.N.Mertens & R.A.Fensome, 2024
Parent	★ *Lingulaulax* M.J.Head, K.N.Mertens & R.A.Fensome, 2024
Original name	★ *Gonyaulax polyedra* F.Stein, 1883
Synonymised names	★ *Gonyaulax polyedra* F.Stein, 1883 · unaccepted > superseded combination ★ *Hystrichosphaeridium machaerophorum* Deflandre & Cookson, 1955 † · unaccepted > junior subjective synonym ★ *Lingulodinium polyedra* (F.Stein) J.D.Dodge, 1989 · unaccepted > superseded combination

Thank you Kenneth…

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Red tides

not always red

not always harmful

always extremely concentrated

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Pitcher, G. C., & Jacinto, G. S. (2019). Ocean deoxygenation links to harmful algal blooms. Ocean Deoxygenation: Everyone's problem-causes, impacts, consequences and solutions, 153-170.

Simplified IOP model

Optical variability dominated by phyto

$$\boldsymbol{a}(\lambda) \sim \boldsymbol{a}_{\mathbf{w}}(\lambda) + \boldsymbol{a}_{\mathbf{phy}}(\lambda) + a_{\mathrm{cdom}}(\lambda) + a_{\mathrm{nap}}(\lambda)$$

Phytoplankton dominated by 1-2 species

$$\boldsymbol{a}_{\mathbf{phy}}(\lambda) \sim \boldsymbol{a}_{\mathbf{phy,1}}(\lambda) + a_{\mathrm{phy,2}}(\lambda) + a_{\mathrm{phy,3}}(\lambda) + a_{\mathrm{phy,4}}(\lambda) + a_{\mathrm{phy,5}}(\lambda) + \ldots$$

Reductionist approach

Stramski et al., (2001)

$$
\begin{aligned}
a(\lambda) &= a_w(\lambda) + \sum_{i=1}^{18} a_{\mathrm{pla},i}(\lambda + a_{\mathrm{det}}(\lambda) + a_{\mathrm{min}}(\lambda) + a_{\mathrm{CDOM}}(\lambda) \\
&= a_w(\lambda) + \sum_{i=1}^{18} N_{\mathrm{pla},i}\sigma_{a,\mathrm{pla},i}(\lambda) + N_{\mathrm{det}}\sigma_{a,\mathrm{det}}(\lambda) \\
&\quad + N_{\mathrm{min}}\sigma_{a,\mathrm{min}}(\lambda) + a_{\mathrm{CDOM}}(\lambda), \qquad (1)
\end{aligned}
$$

Table 1. Summary of Planktonic Components

Label	Planktonic Component	D (µm)	n 500 nm	$a^* \times 10^2$ 440 nm	$a^* \times 10^2$ 675 nm	$\mathrm{Chl}_{\mathrm{cell}}$ (pg)	Ref.
VIRU	Viruses	0.07	1.050	0	0	0	25
HBAC	Heterotrophic bacteria	0.55	1.055	0.509	0.857	0	24
PROC	Generic *Prochlorophyte*, the average of	0.66	1.053	19.54	10.30	1.486×10^{-3}	
	Prochlorococcus strain MED	0.58	1.055	23.35	15.77	1.435×10^{-3}	27
	average of *Prochlorococcus* strains NATL and SARG	0.73	1.048	15.76	4.841	1.499×10^{-3}	27
SYNE	Generic *Synechococcus*, the average of	1.05	1.053	5.067	2.930	2.053×10^{-2}	
	Synechococcus strain MAX41 (Cyanophyceae)	0.92	1.047	3.415	2.995	1.573×10^{-2}	27
	Synechococcus strain MAX01 (Cyanophyceae)	0.94	1.049	4.305	2.547	1.521×10^{-2}	27
	Synechococcus strain ROS04 (Cyanophyceae)	1.09	1.049	4.636	2.254	1.260×10^{-2}	27
	Synechococcus strain DC2 (Cyanophyceae)	1.14	1.050	4.248	2.373	1.490×10^{-2}	27
	Synechococcus strain WH8103 (Cyanophyceae)	1.14	1.062	9.251	4.868	4.026×10^{-2}	20
SYMA	Generic phycocyanin-rich picophytoplankton, the average of	1.41	1.055	6.495	2.737	4.437×10^{-2}	
	Synechocystis (Cyanophyceae)	1.39	1.059	4.038	1.805	3.044×10^{-2}	26
	Anacystis marina (Cyanophyceae)	1.43	1.060	8.808	3.662	5.250×10^{-2}	26
PING	*Pavlova pinguis* (Haptophyceae)	2.87	1.046	4.177	2.708	1.536×10^{-1}	22
PSEU	*Thalassiosira pseudonana* (Bacillariophyceae)	2.99	1.065	9.231	7.207	3.081×10^{-1}	24
LUTH	*Pavlova lutheri* (Haptophyceae)	4.28	1.045	5.767	2.493	1.092×10^{-1}	22
GALB	*Isochrysis galbana* (Haptophyceae)	4.43	1.056	7.673	5.591	5.259×10^{-1}	26
HUXL	*Emiliania huxleyi* (Haptophyceae)	4.93	1.050	3.022	2.558	2.397×10^{-1}	28
CRUE	*Porphyridium cruentum* (Rhodophyceae)	5.23	1.053	3.053	2.643	2.861×10^{-1}	22
FRAG	*Chroomonas fragarioides* (Cryptophyceae)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	26
PARV	*Prymnesium parvum* (Haptophyceae)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	31
BIOC	*Dunaliella bioculata* (Chlorophyceae)	[illegible]	1.055	[illegible]	[illegible]	2.275	29
TERT	*Dunaliella tertiolecta* (Chlorophyceae)	7.58	1.063	4.269	3.976	1.795	29
CURV	*Chaetoceros curvisetum* (Bacillariophyceae)	7.71	1.034	3.077	1.488	3.314×10^{-1}	22
ELON	*Hymenomonas elongata* (Haptophyceae)	11.77	1.046	13.67	7.591	9.394	26
MICA	*Prorocentrum micans* (Dinophyceae)	27.64	1.045	2.486	1.719	25.39	26

depending on the main bloom-forming species!

Two main challenges

To what extent is it possible to identify the main bloom-forming species from space <u>in the absence of *in situ* observations</u>?

Do we know the optical properties of all bloom-forming species?

Spectral libraries

USGS
science for a changing world

SCIENCE PRODUCTS

GEOLOGY, GEOPHYSICS, AND GEOCHEMISTRY SCIENCE CENTER | SCIENCE

USGS High Resolution Spectral Library

By Geology, Geophysics, and Geochemistry Science Center April 6, 2018

The USGS Spectral Library contains reflectance spectra, including samples of minerals, rocks, soils, physically constructed as well as mathematically computed mixtures, plants, vegetation communities, microorganisms, and man-made materials. The samples and spectra collected were assembled for the purpose of using spectral features for the remote detection of these and similar materials. The latest version is an update to the previously published version (2007) that is the leading database used by the global scientific community to identity materials by their "spectral fingerprints." The library is fundamental for Mineral Resources Program projects to characterize mineral resources with imaging spectrometer data.

National Spectral Database

Page last updated: 18 June 2024

Australian Government

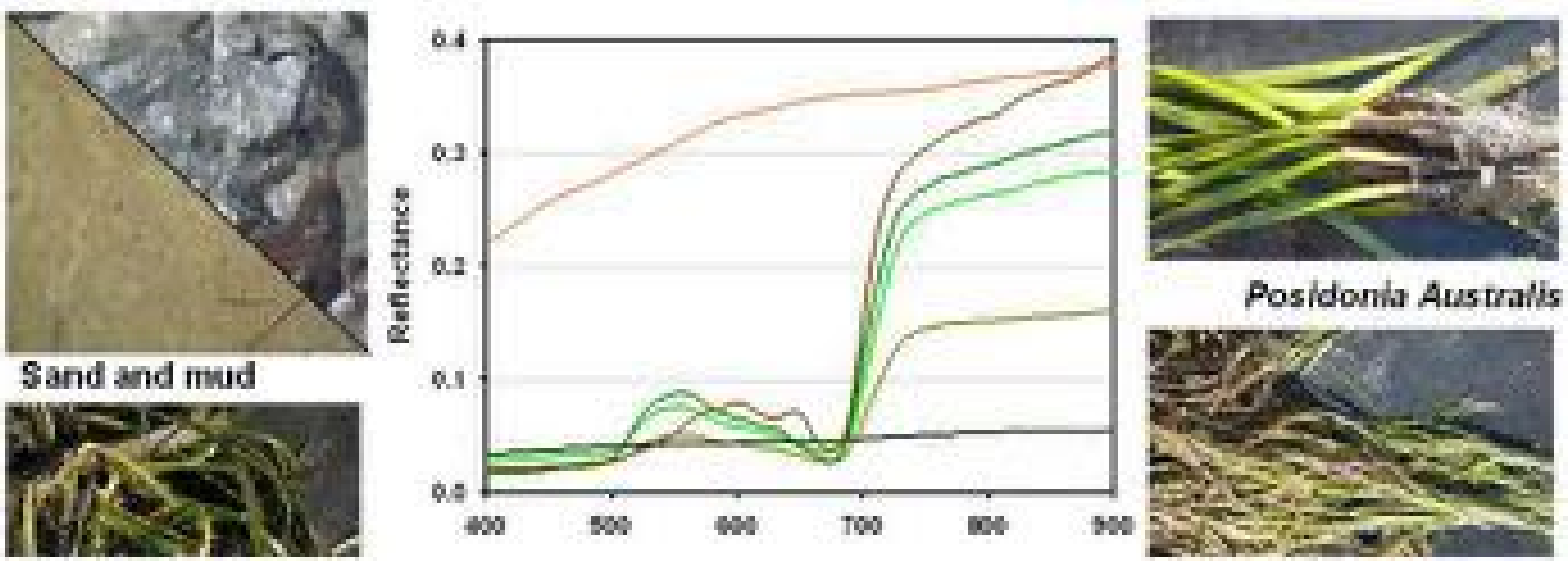
Geoscience Australia

The National Spectral Database (NSD) houses best-practice spectral data collected by Australian remote sensing scientists from multiple locations and institutions across the country. As the collection grows the NSD will service continental scale research for the Earth observation community and support application such as the validation of satellite-based measurements of surface reflectance.

The National Spectral Database targets as diverse as soils, vegetation, waterbodies, coral, macro to micro algae, seagrasses and land surfaces.

Spectral libraries for shallow water RS

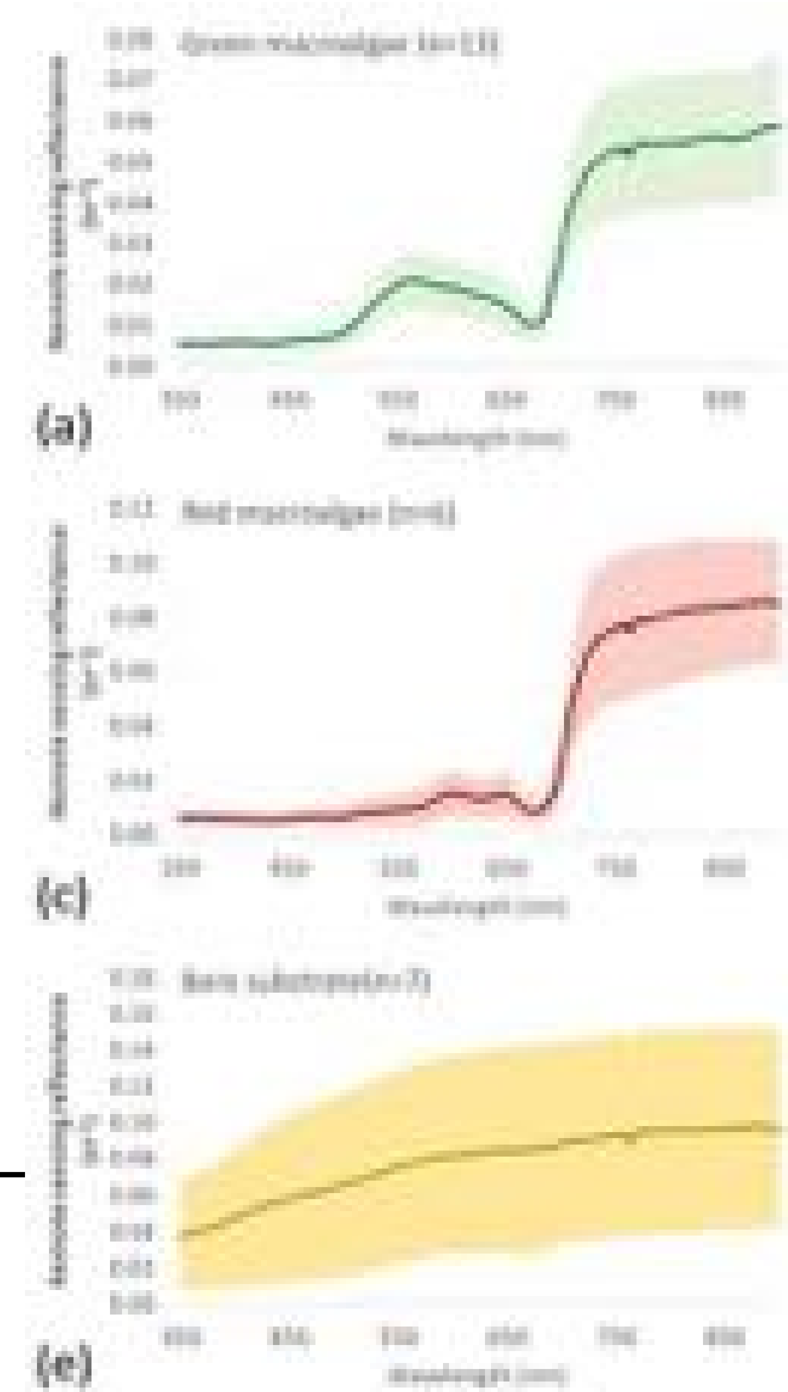
Roelfsema, Christiaan M; Phinn, Stuart R; Joyce, Karen (2016): Spectral reflectance library of algal, seagrass and substrate types in Moreton Bay, Australia [dataset]. *PANGAEA*, https://doi.org/10.1594/PANGAEA.864310



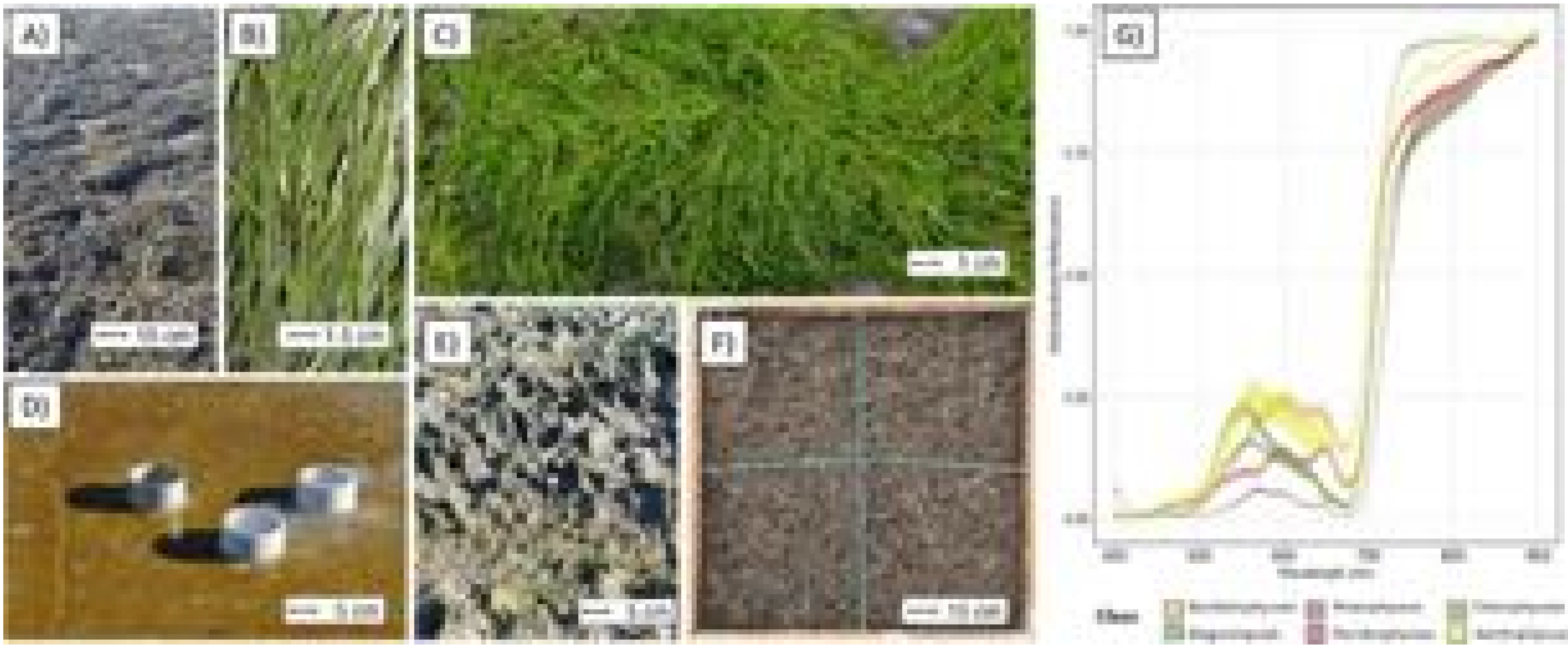
Earth System Science Data

Hyperspectral library of submerged aquatic vegetation and benthic substrates in the Baltic Sea

Ele Vahtmäe, Laura Argus, Kaire Toming, Martin Ligi, and Tiit Kutser



Spectral library for intertidal vegetation



Davies et al., (2023) and Davies et al., (under review)

Davies, B. F. R., Gernez, P., Geraud, A., Oiry, S., Rosa, P., Zoffoli, M. L., & Barillé, L. (2023). Multi-and hyperspectral classification of soft-bottom intertidal vegetation using a spectral library for coastal biodiversity remote sensing. Remote Sensing of Environment, 290, 113554.

Phytoplankton spectral library??

Very complex as it requires to

- document the IOPs and AOPs of many phytoplankton species
- take into account the effects of changes in phytoplankton concentration
- take into account all the other optical constituents

Several approaches

- lab measurements of IOPs using cultures, combined with $R_{rs}(\lambda)$ simulations
- in situ measurements of IOPs and AOPs during very intense blooms
- satellite measurements of $R_{rs}(\lambda)$ during very intense blooms

In situ measurements of phytoplankton bio-optical properties during red tides

Very challenging to sample

Unpredictable events, difficult to anticipate

Patchy events, short duration

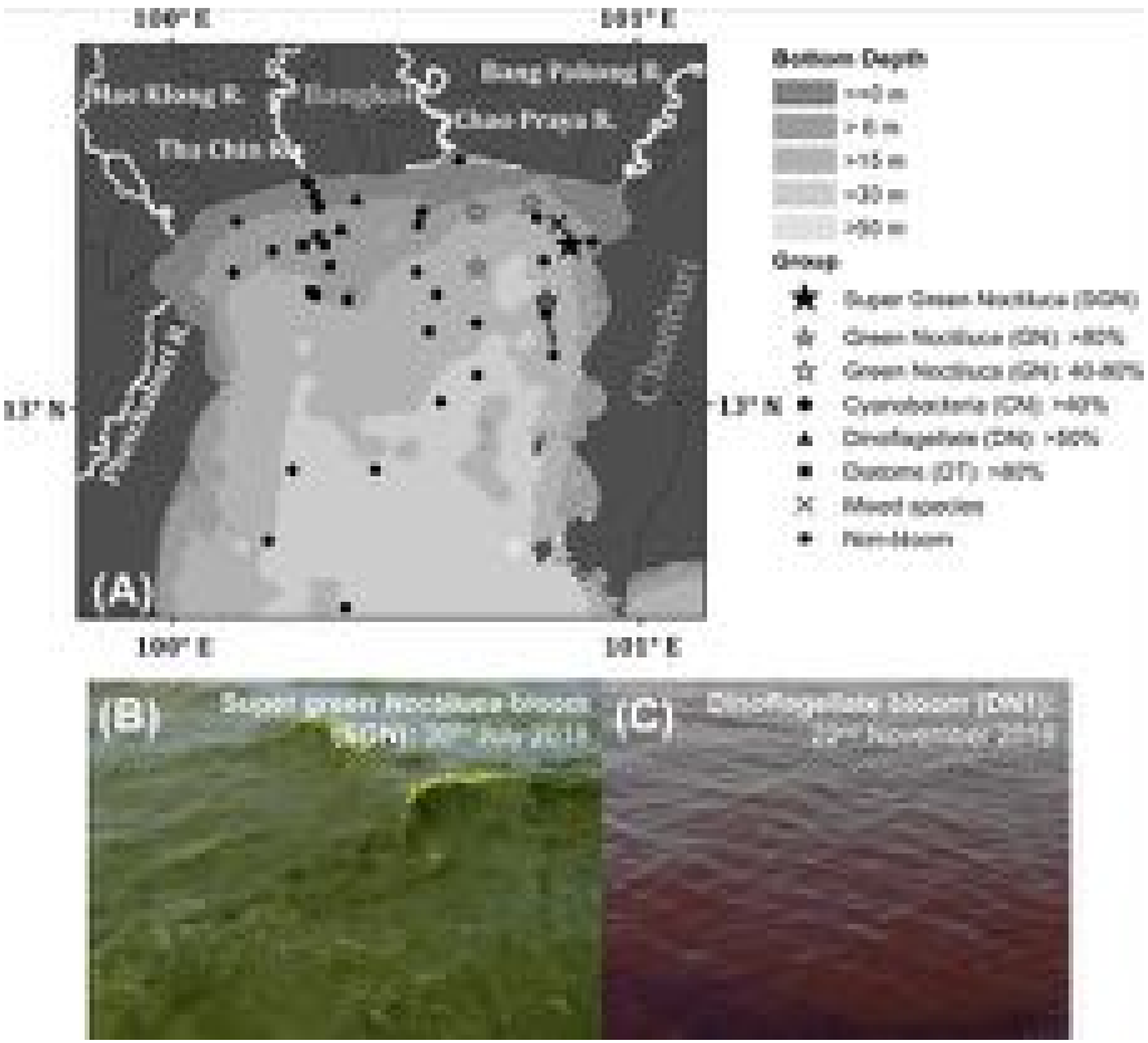
Large ships not ideal to sample relatively small patches

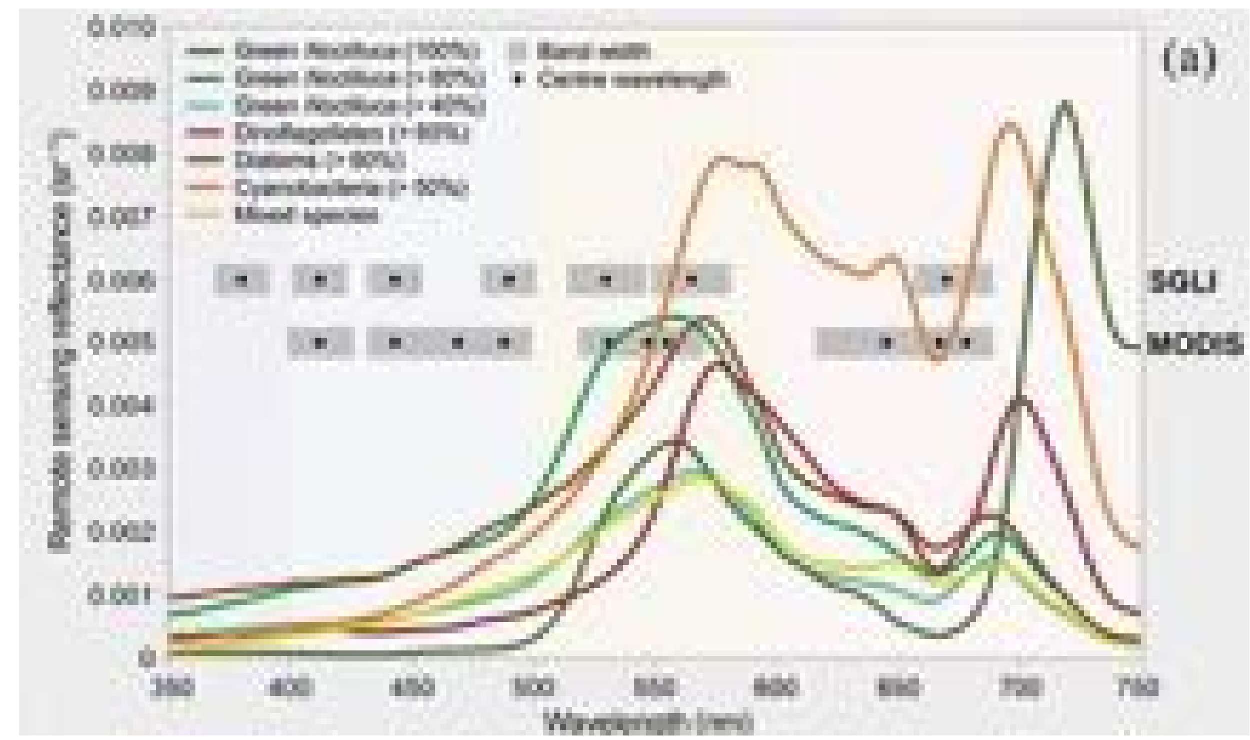
More in situ data needed!

IOPs and AOPs

pigments, cytometry, microscope observations and DNA (taxonomy)

Luang-on et al., (2023, 2024)





GLObal Reflectance community dataset for Imaging and optical (GLORIA)

Excellent database

7,572 hyperspectral $R_{rs}(\lambda)$

chl-a, SPM, a_{cdom}, Secchi

GLORIA for HABs?

Red tide events?

Pigments?

Taxonomic data?


scientific **data**

GLORIA - A globally representative hyperspectral *in situ* dataset for optical sensing of water quality

Satellite approaches

In search of floating algae and other organisms in global oceans and lakes

Lin Qi [a b c], Chuanmin Hu [c], Karlis Mikelsons [d e], Menghua Wang [d], Veronica Lance [d f], Shaojie Sun [a b c], Brian B. Barnes [c], Jun Zhao [a b], Dimitry Van der Zande [g]

Floating algae observed with VIIRS and S3/OLCI

- Macroalgae: several *Sargassum* and *Ulva* species
- Cyanobacteria scums: *Trichodesmium*, *Microcystis*, *Nodularia*
- Microalgae: red and green *Noctiluca*
- Other floating stuff: pumice raft, oil slick, jellyfish blooms?, shrimp eggs?

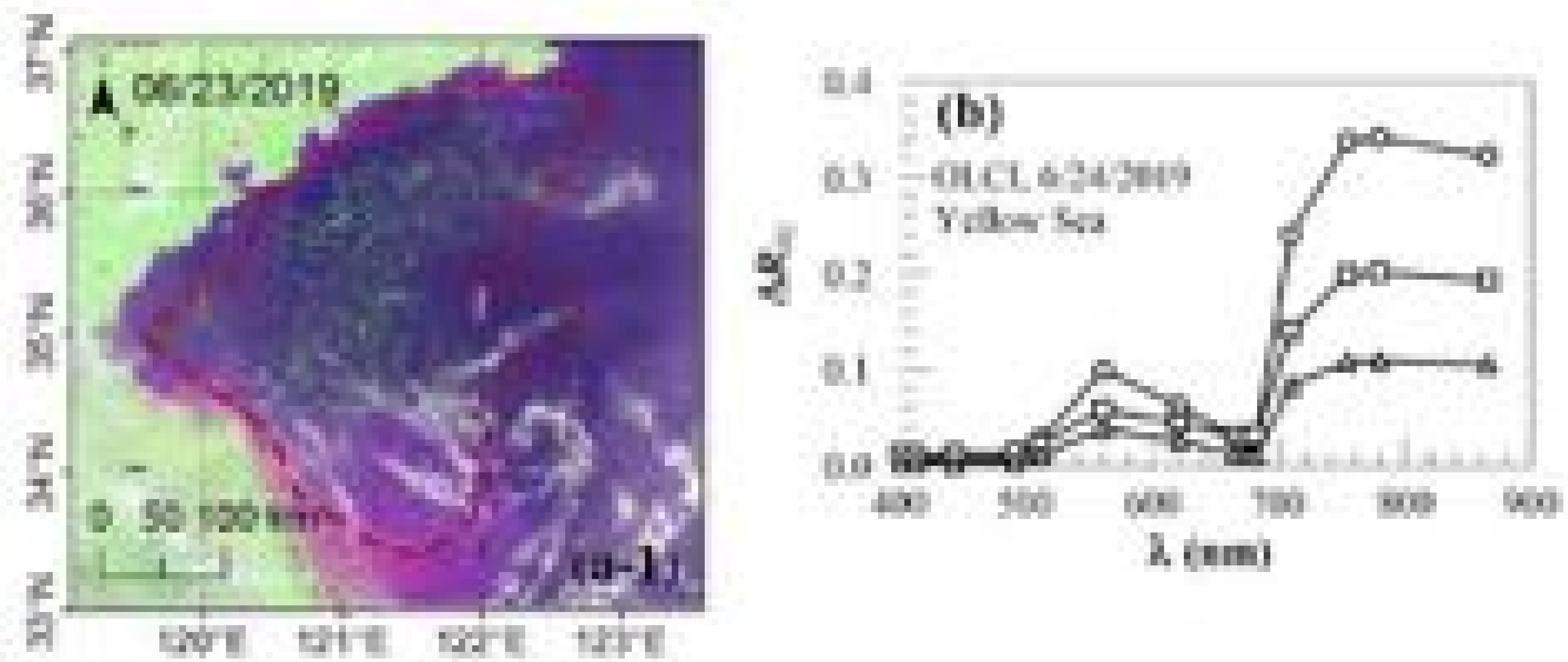
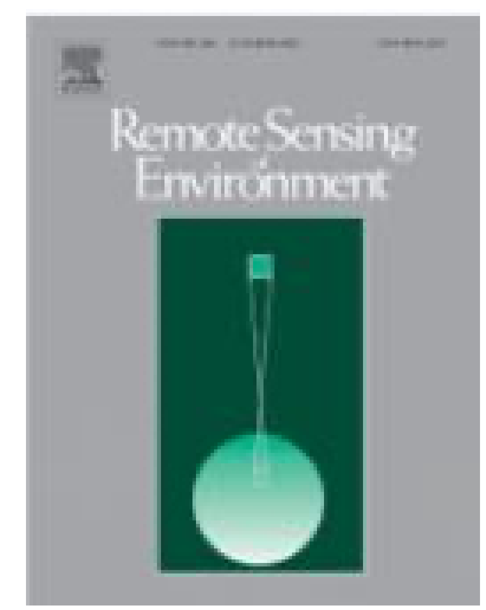


Fig. 3. (a) VIIRS FRGB image shows an *Ulva* bloom in the western Yellow Sea (Box 3 in Fig. 1 & Table 2). (b) Typical OLCI $\Delta R_{rc}(\lambda)$ of several pixels selected from the greenish image features.



High spatial resolution required

If too coarse spatial resolution

→ *bloom "diluted" with non-bloom pixels*

→ *optical fingerprint is not "pure"*

- ✓ Sentinel-2
- ✓ Landsat-8/9
- ✓ PRISMA
- ✓ EnMAP

- × Sentinel-3
- × MODIS
- × VIIRS
- × PACE

S2 spectral library

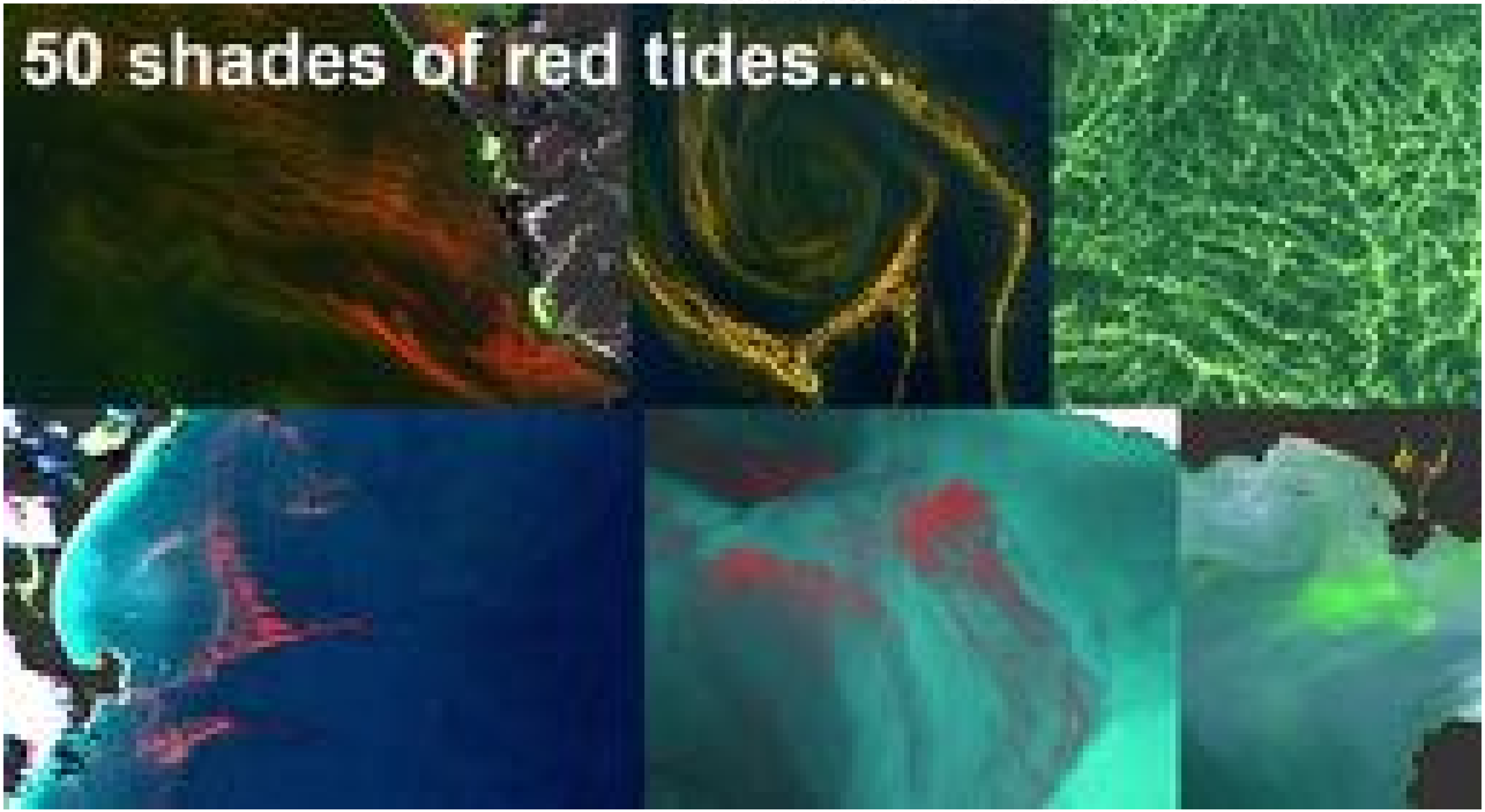

Contents lists available at ScienceDirect

Remote Sensing of Environment

journal homepage: www.elsevier.com/locate/rse

The many shades of red tides: Sentinel-2 optical types of highly-concentrated harmful algal blooms

Pierre Gernez, Maria Laura Zoffoli, Thomas Lacour, Tania Hernández Fariñas, Gabriel Navarro, Isabel Caballero, Tristan Harmel



IN SITU PHYTOPLANKTON DATA

Searched bloom events in harmful algae event database (**HAEDAT**) from 2015 – 2021 (304 blooms with known causative species)

Also searched in French phytoplankton and phycotoxin monitoring network (**REPHY**)

Criterion: > 10^5 cells / L of a single dominant genus / species (> 85% diversity)

Additional reports: scientific **literature**, regional **monitoring reports**, citizen science

Selection of events documented in situ,
synchronous to cloud free S2 acquisition,
with conspicuous seawater discoloration

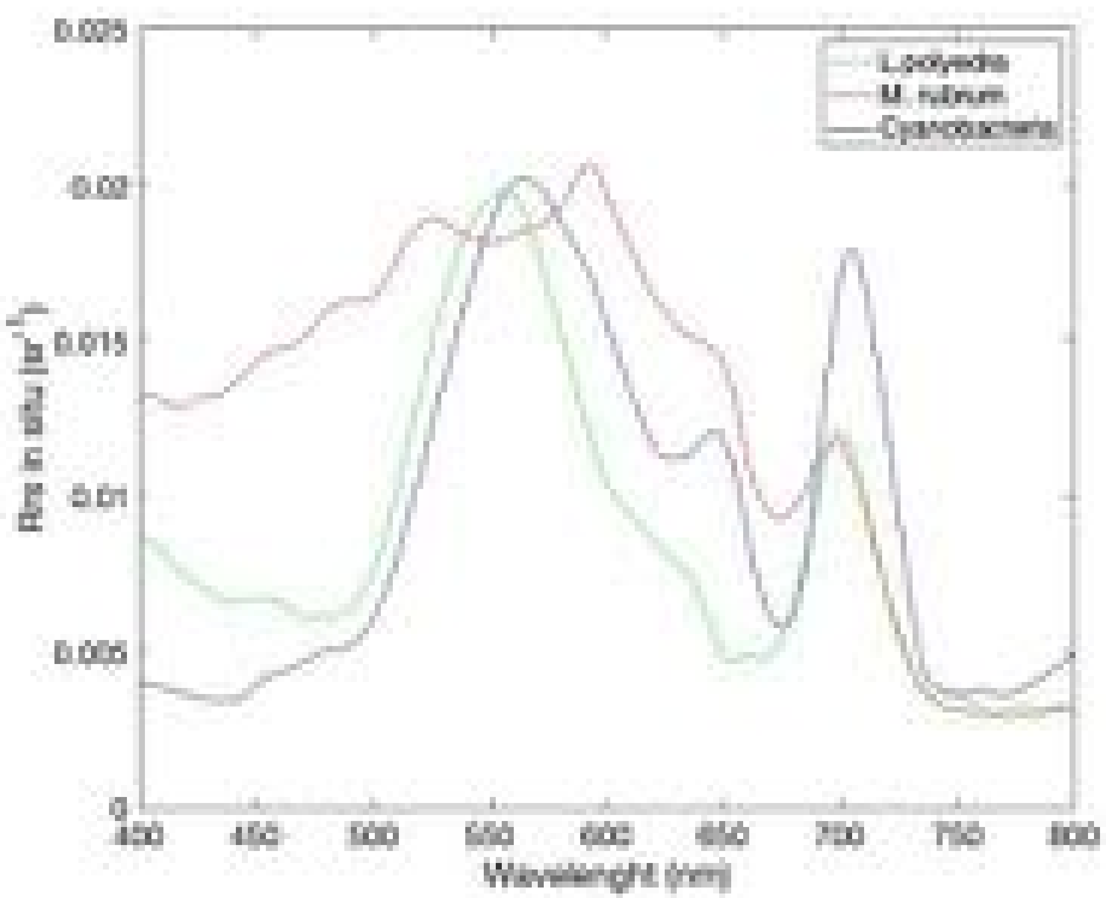
Remote-sensing reflectance $R_{rs}(\lambda)$ re-sampled at 20 m

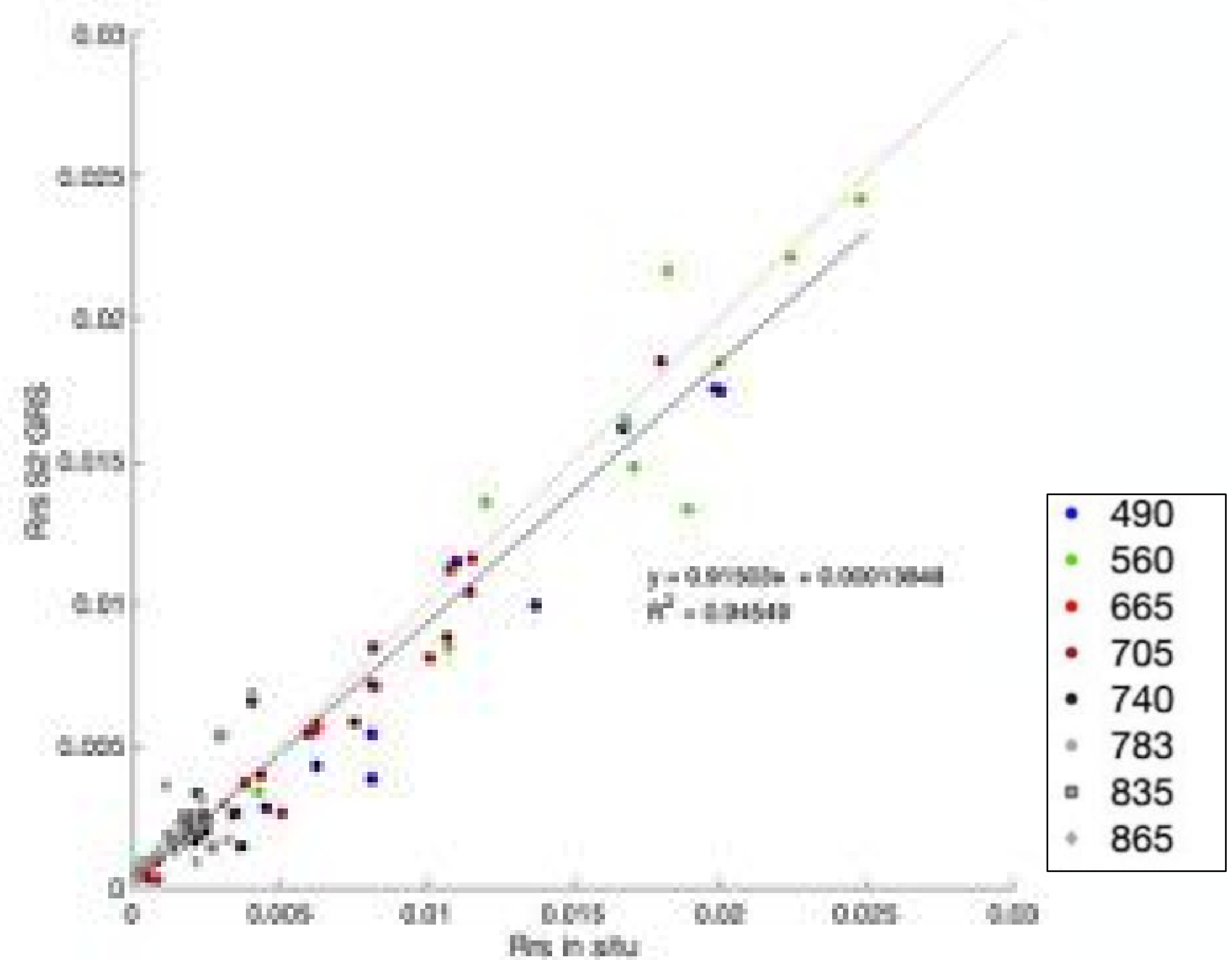
Atmospheric and sunglint correction

(GRS, Harmel et al. 2018)

Evaluation of AC & deglint performance

(N = 24, r^2 = 0.95, slope = 0.92, intercept = 0)

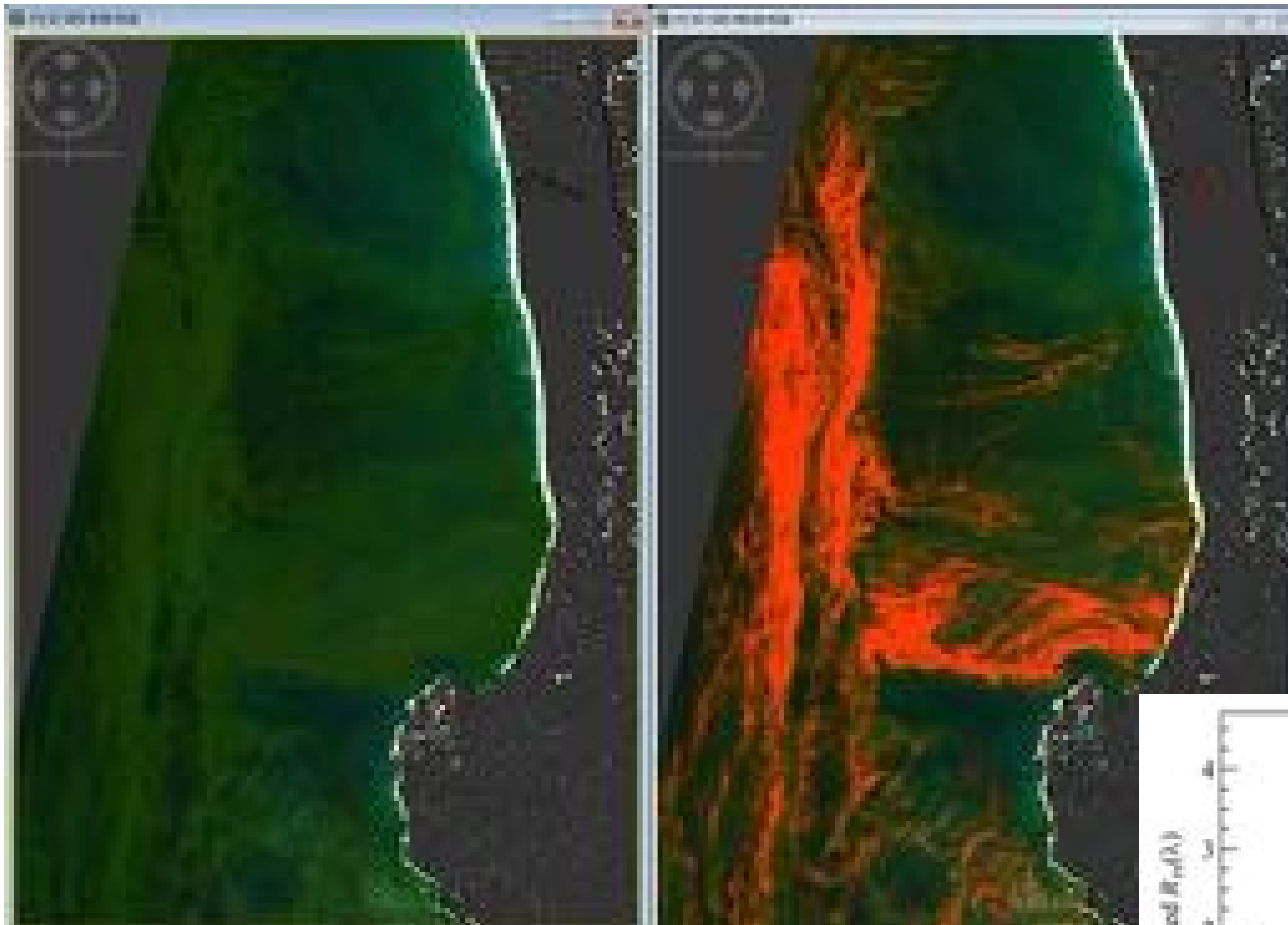




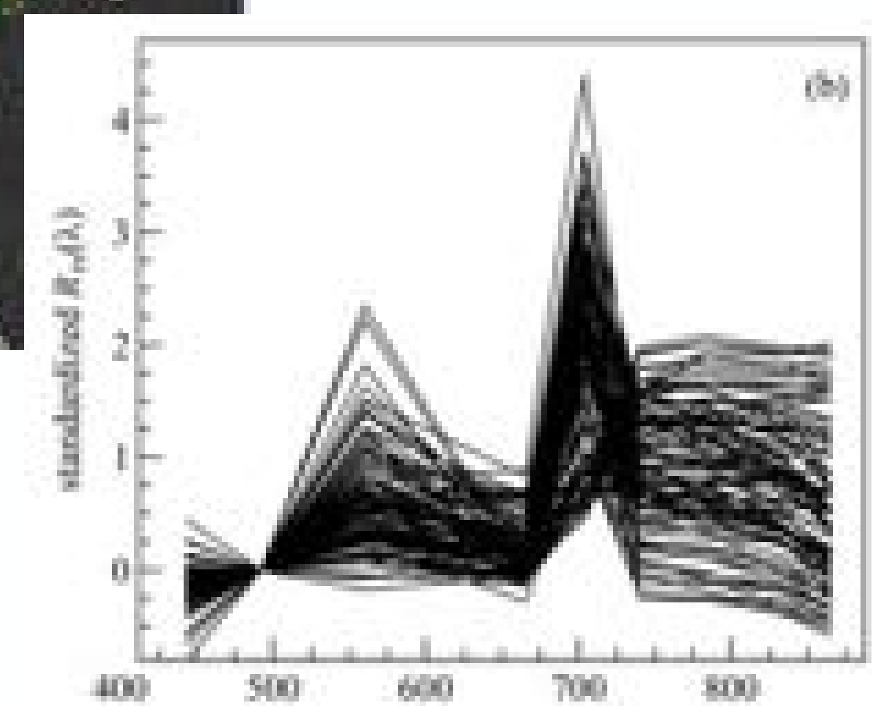
In situ R_{rs} matchups, high phytoplankton

Red-edge Green Blue colour composite (REGB)

RGB
665 nm
560 nm
490 nm



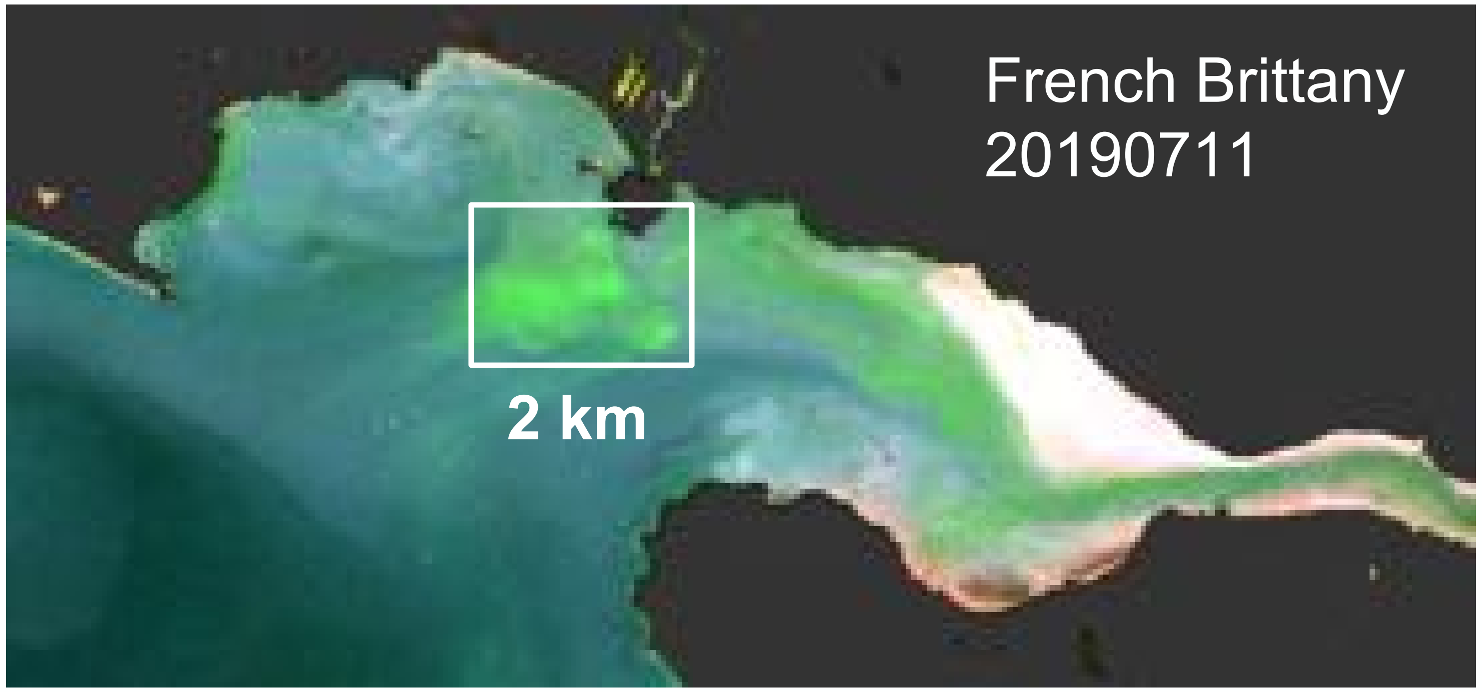
REGB
705 nm
560 nm
490 nm



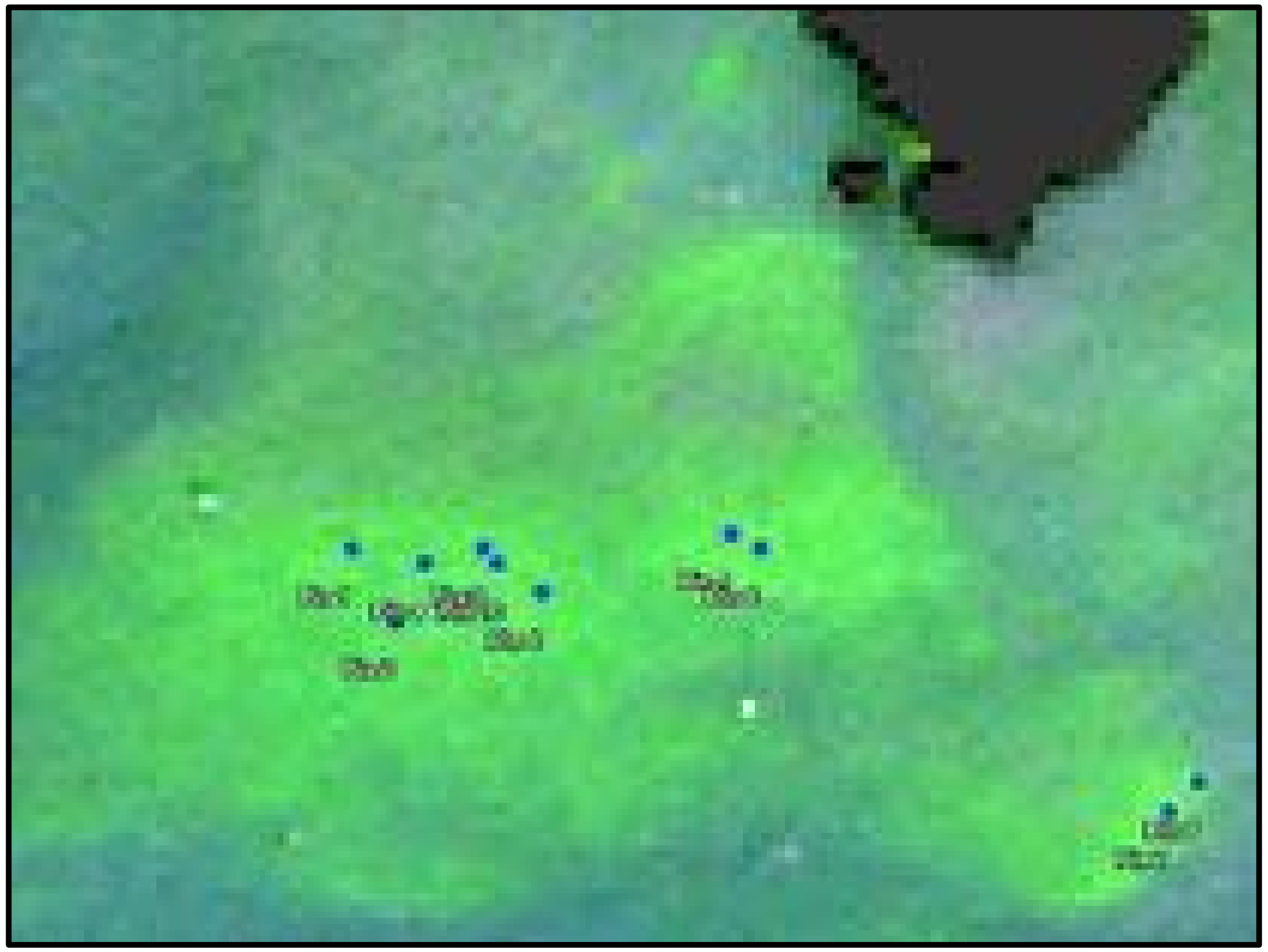
For each bloom event, selected & averaged 10 pixels in the area of maximum biomass

S2 high resolution → low spectral mixing

(limit influence of CDOM, NAP, other phyto)



Bloom dominated by *Lepidodinium chlorophorum*
(> 95% total microphytoplankton; N > 10^6 cells / L)



STATISTICAL ANALYSES

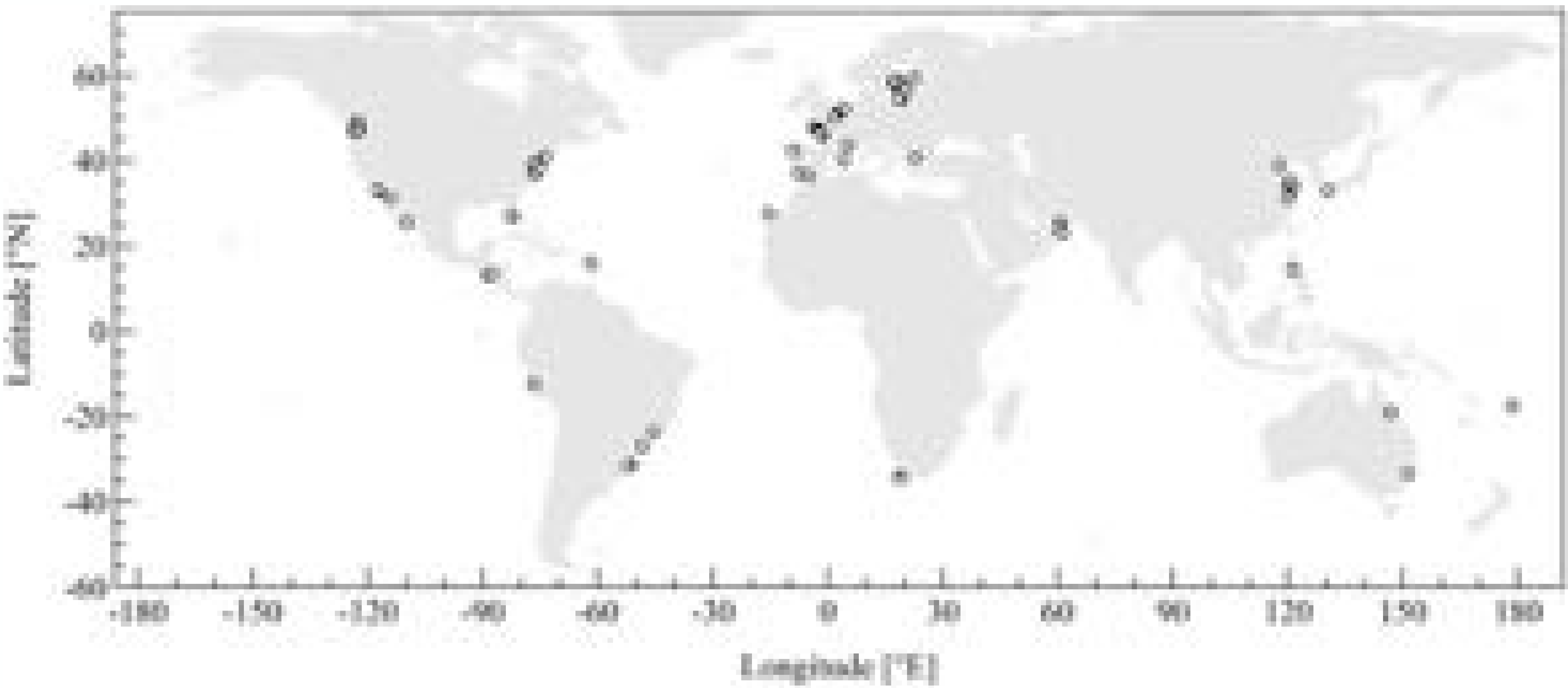
Computed averaged $R_{rs}(\lambda)$ when

- several blooms of same species in different regions → geographical robustness
- Several species from same genus →reduce interspecific variability

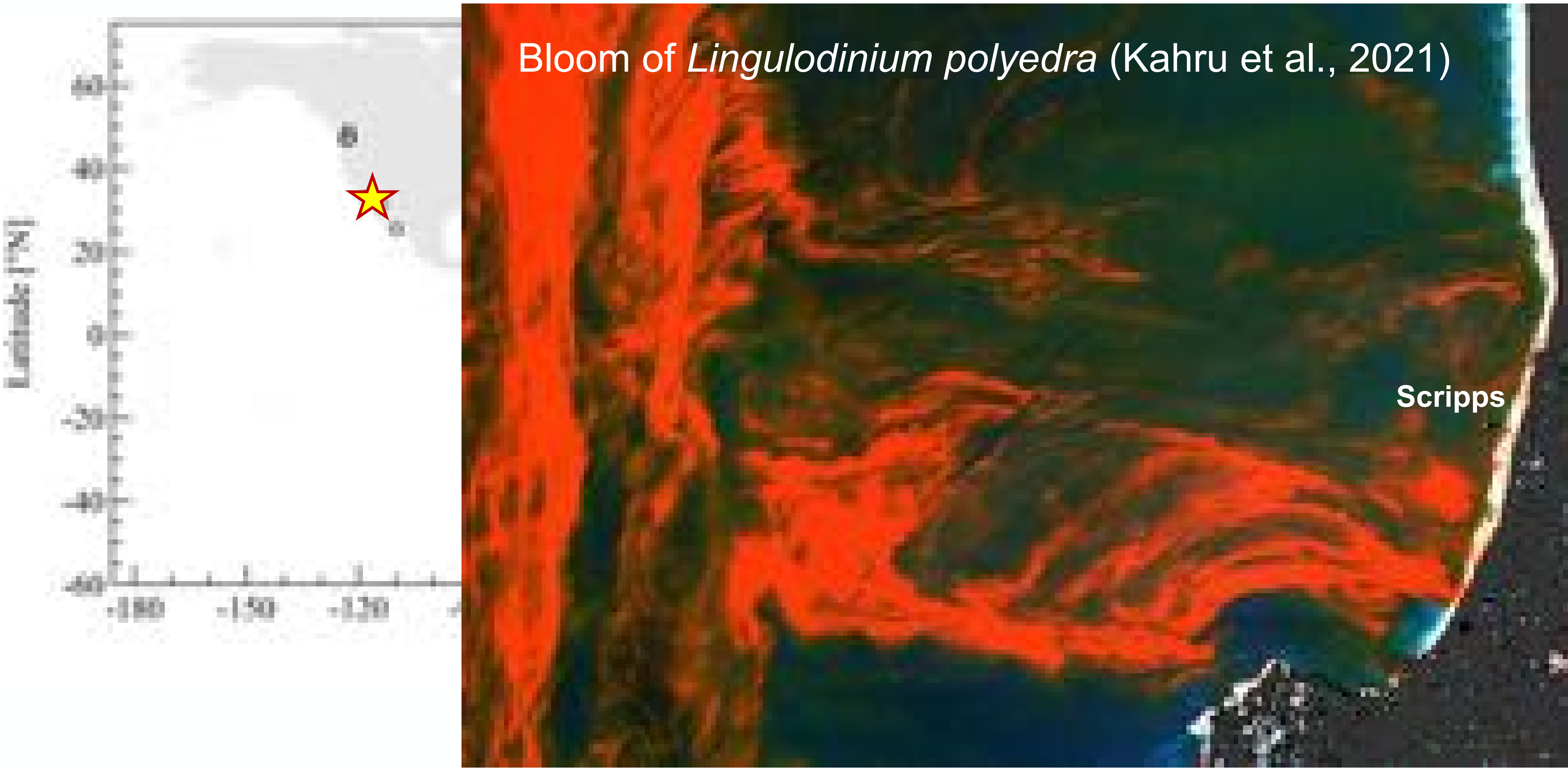
Standardized $R_{rs}(\lambda)$ to focus on spectral shape variability (Spyrakos et al., 2018)

Optical Bloom Types identified using Hierarchical Cluster Analysis (HCA) with cosine distance (Millie et al., 1997, Torrecilla et al., 2011)

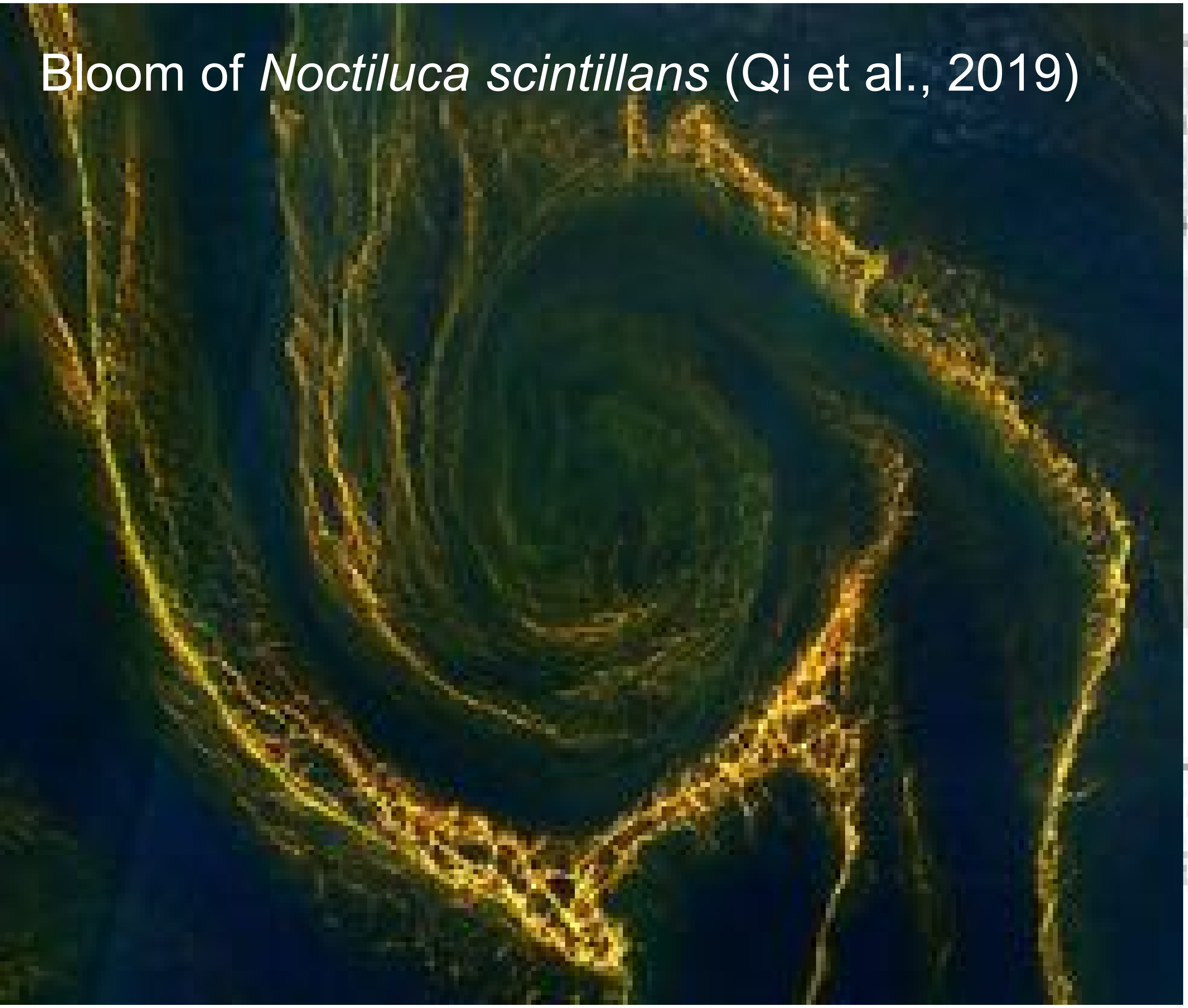
S2 RED TIDE DATABASE = 108 bloom events worldwide

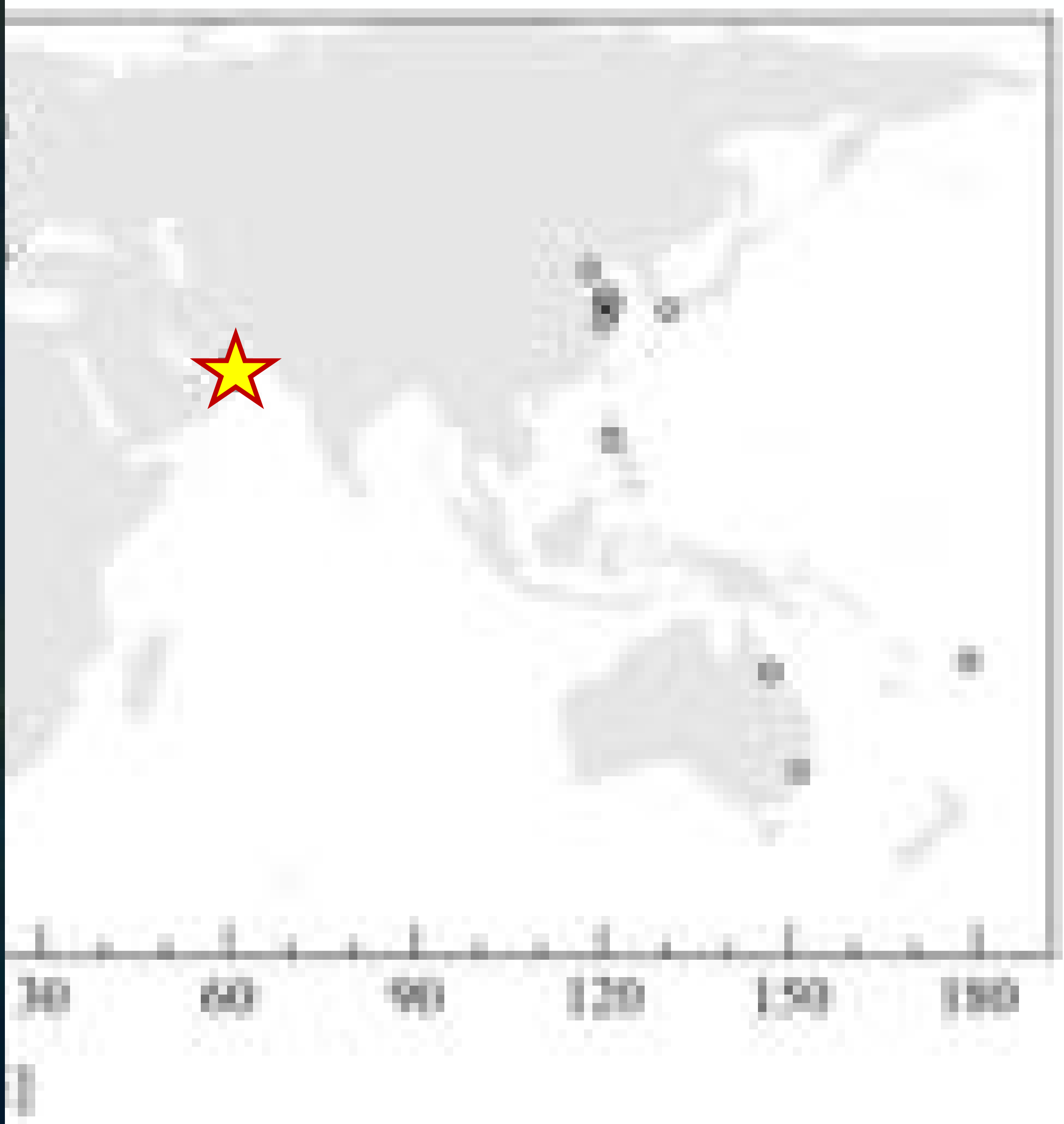


S2 RED TIDE DATABASE = 108 bloom events worldwide



S2 RED TIDE DATABASE = 108 bloom events worldwide





TAXONOMIC DIVERSITY OF S2 RED TIDE DATABASE

27 species

20 genera

5 classes

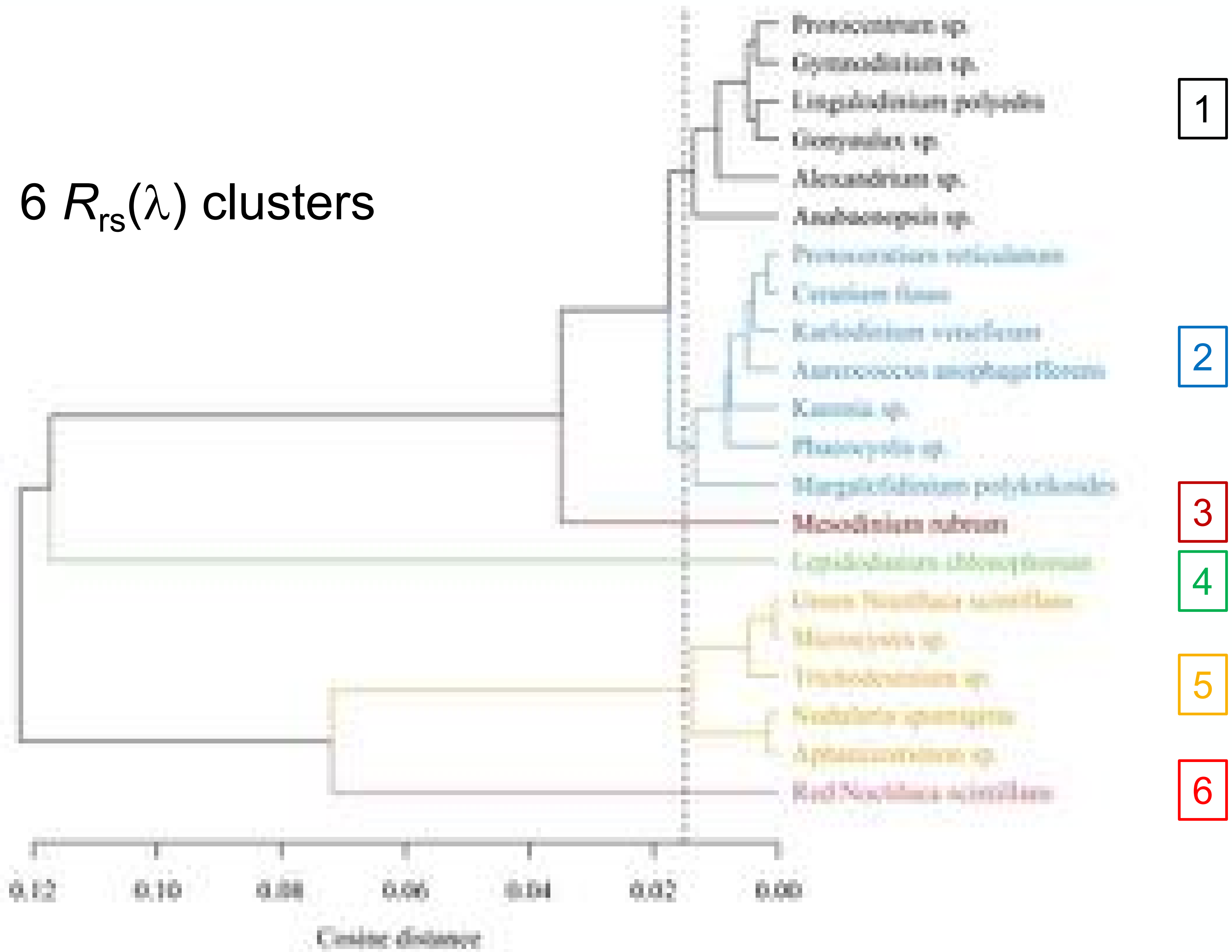
- Many dinoflagellates (55%)
- Many cyanobacteria (30%)
- *M. rubrum* (Ciliate, 7%)
- *Phaeocystis* (Haptophyte, 5%)
- *Aureococcus* (Pelagophyte, 3%)

→ **21 avg $R_{rs}(\lambda)$ spectra**

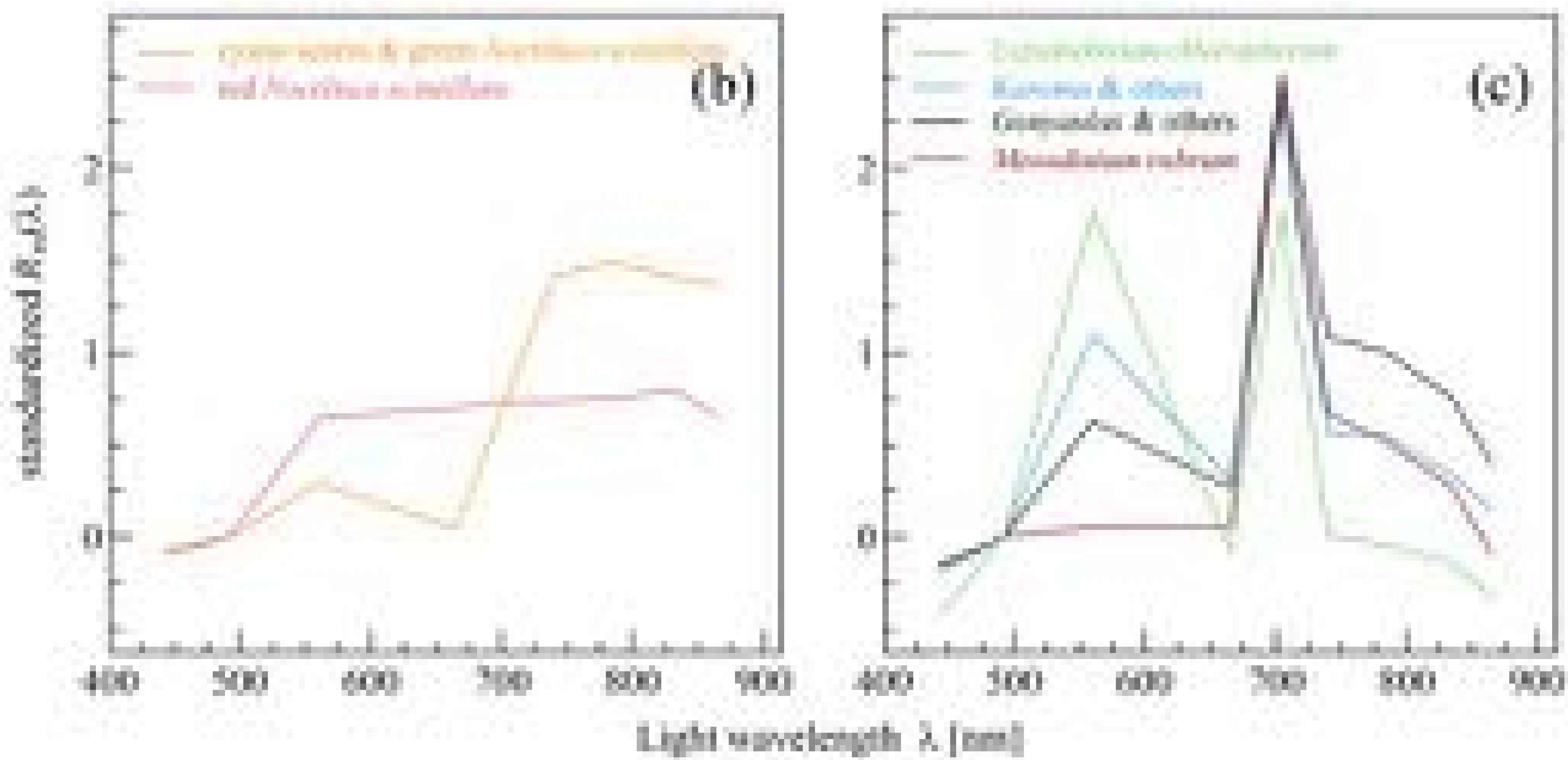
Class	Genus	Species	Bloom number
Dinophyceae	*Alexandrium*	*monilatum, or ostenfeldii*	5
	Ceratium	*furca*	3
	Gonyaulax	*digitale, polygramma, or spinifera*	6
	Gymnodinium	*aureolum, catenatum, or impudicum*	5
	Karenia	*brevis or mikimotoi*	5
	Karlodinium	*veneficum*	2
	Lepidodinium	*chlorophorum*	5
	Lingulodinium	*polyedra*	8
	Margalefidinium	*polykrikoides*	5
	Noctiluca	*scintillans* (green form)	7
	Noctiluca	*scintillans* (red form)	6
	Prorocentrum	*micans, or minimum*	5
	Protoceratium	*reticulatum*	3
Cyanophyceae	*Anabaenopsis*	*sp.*	5
	Aphanizomenon	*flosaquae, or spp.*	8
	Microcystis	*sp.*	8
	Nodularia	*spumigena*	6
	Trichodesmium	*sp.*	7
Litostomatea	*Mesodinium*	*rubrum*	8
Prymnesiophyceae	*Phaeocystis*	*sp.*	6
Pelagophyceae	*Aureococcus*	*anophagefferens*	2

BLOOM OPTICAL TYPES

6 $R_{rs}(\lambda)$ clusters



Optical Bloom Types with Sentinel-2



Gernez, P., Zoffoli, M. L., Lacour, T., Fariñas, T. H., Navarro, G., Caballero, I., & Harmel, T. (2023). The many shades of red tides: Sentinel-2 optical types of highly-concentrated harmful algal blooms. Remote Sensing of Environment, 287, 113486.

High NIR $R_{rs}(\lambda)$

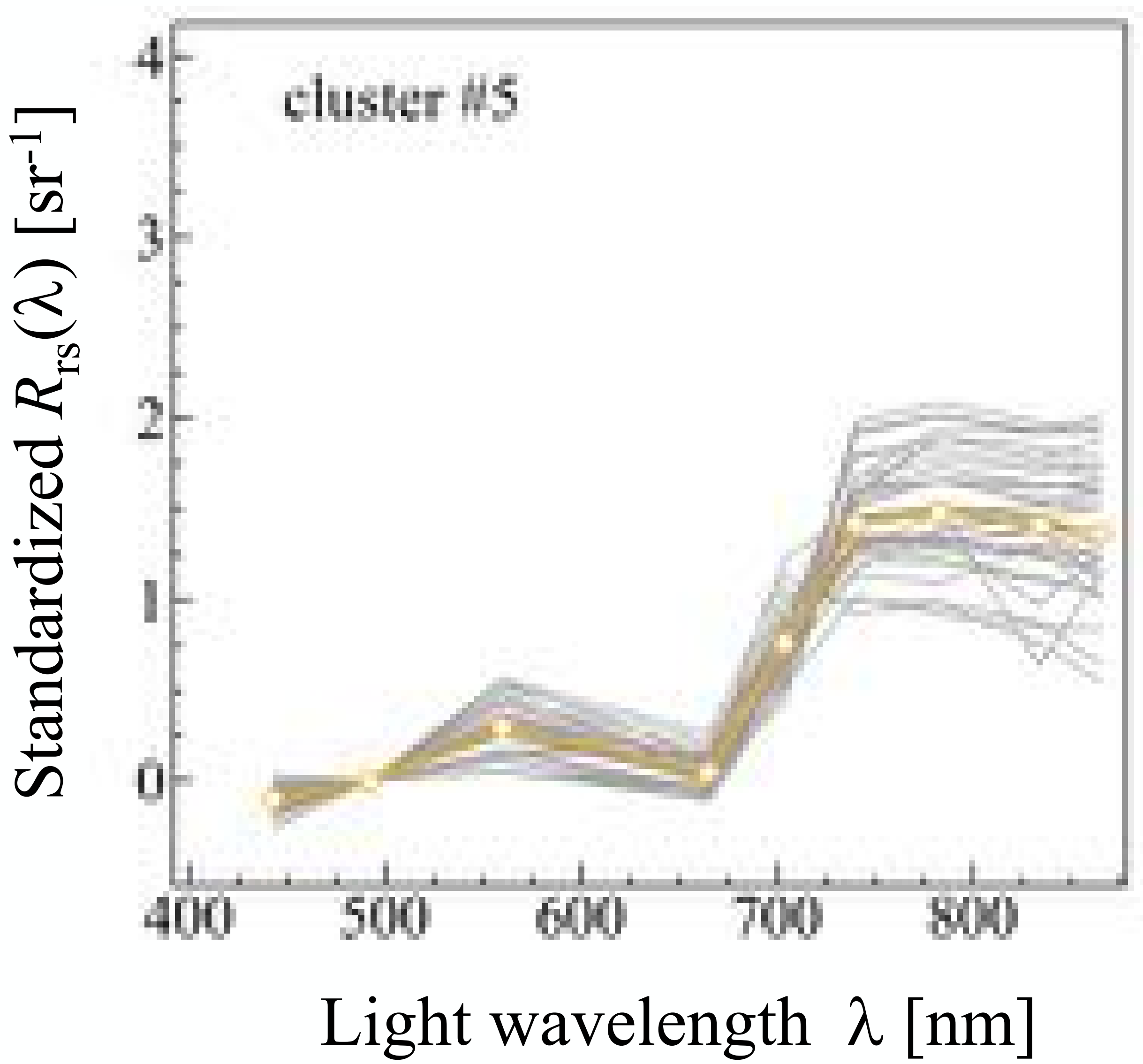
Buoyant cyanobacteria & dinoflagellate

- *Aphanizomenon sp.*
- *Nodularia spumigena*
- *Trichodesmium sp.* **
- *Microcystis sp.* **
- *Noctiluca scintillans* (green form)

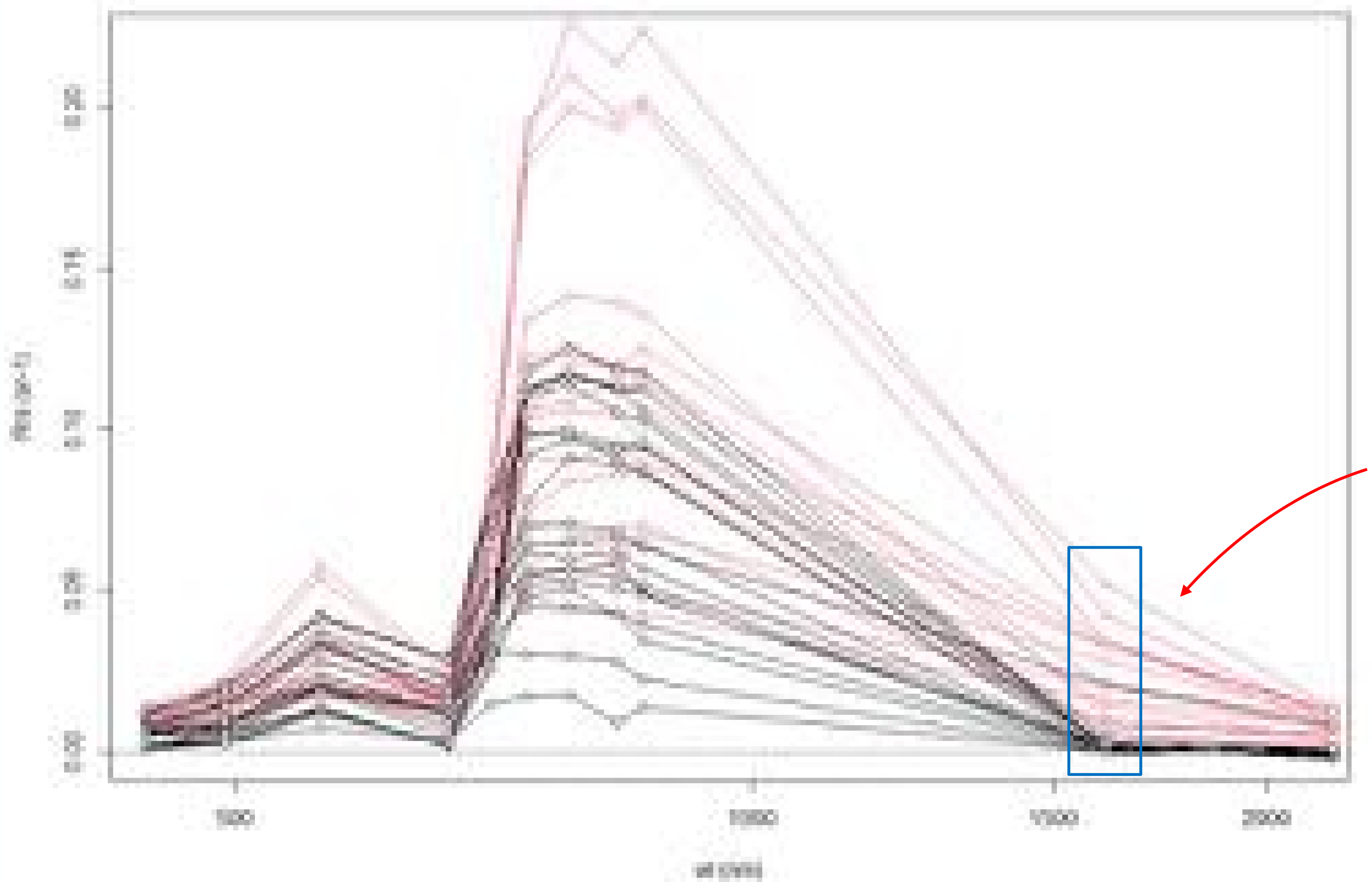
Spectral shape: surface accumulation [Chl-*a*]

Two species with high SWIR

R_{rs}(1610 nm) > 0 (next slide)



Appendix: cyanoHABs with high SWIR



Microcystis
Trichodesmium
$R_{rs}(1610) > 0$

Green *Noctiluca*,
Nodularia
Aphanizomenon

Flat $R_{rs}(\lambda)$ from 560 – 865 nm

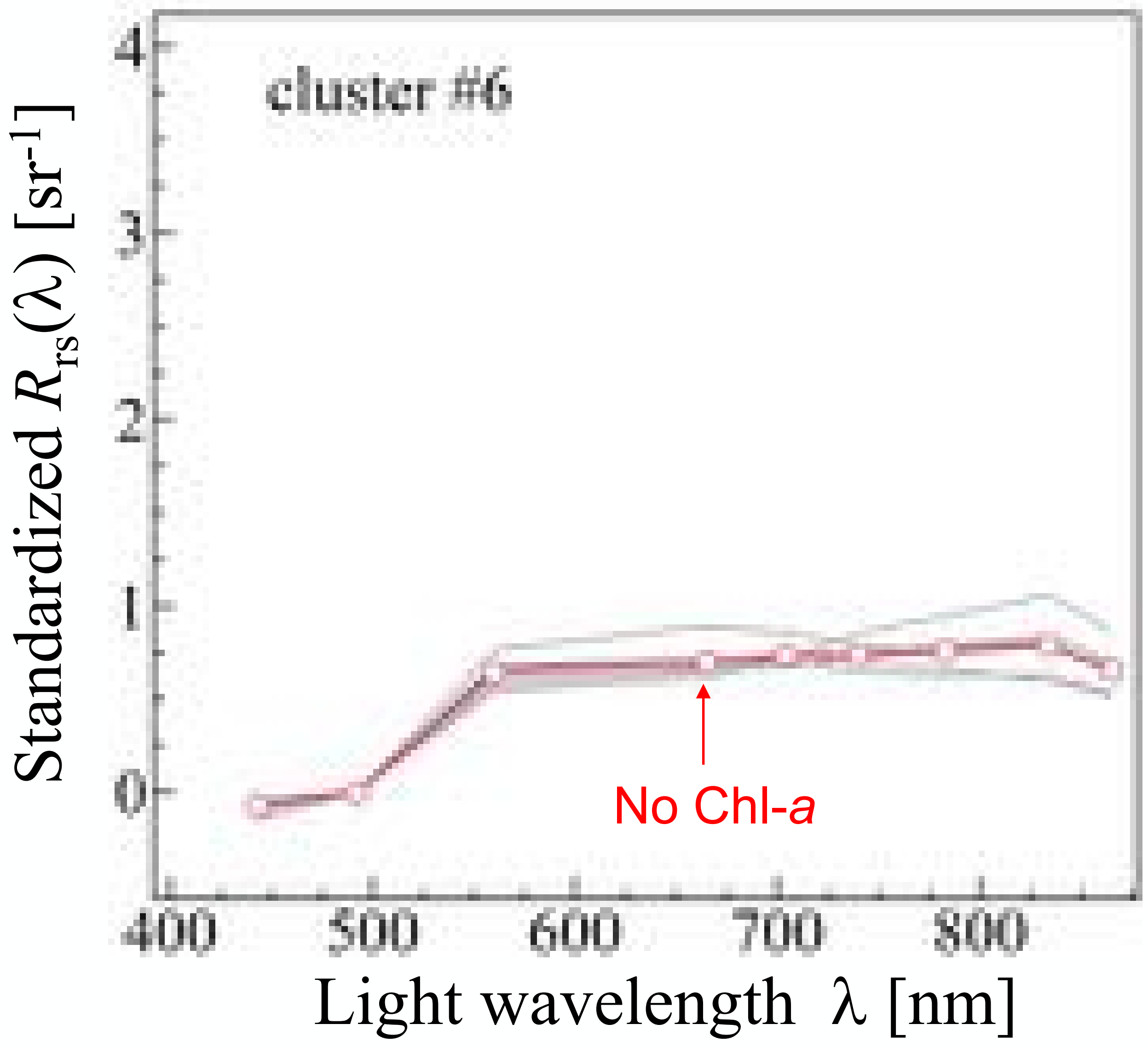
Monospecific cluster

Low $R_{rs}(\lambda)$ variability (6 blooms / 5 countries)

High biomass, **Chl-*a* absent**

(pure heterotroph with carotenoids)

Distinct from green *Noctiluca* (contains Chl-*a* due to photosynthetic symbiont)



Low $R_{rs}(\lambda)$ in VIS, 1 peak at 705 nm

Monospecific cluster

Low $R_{rs}(\lambda)$ variability (8 blooms / 5 countries)

Particular pigment composition

Phycoerythrin-545, Alloxanthin, Chl-*c*2

~ *pigment type 5 in Zapata et al., 2012*

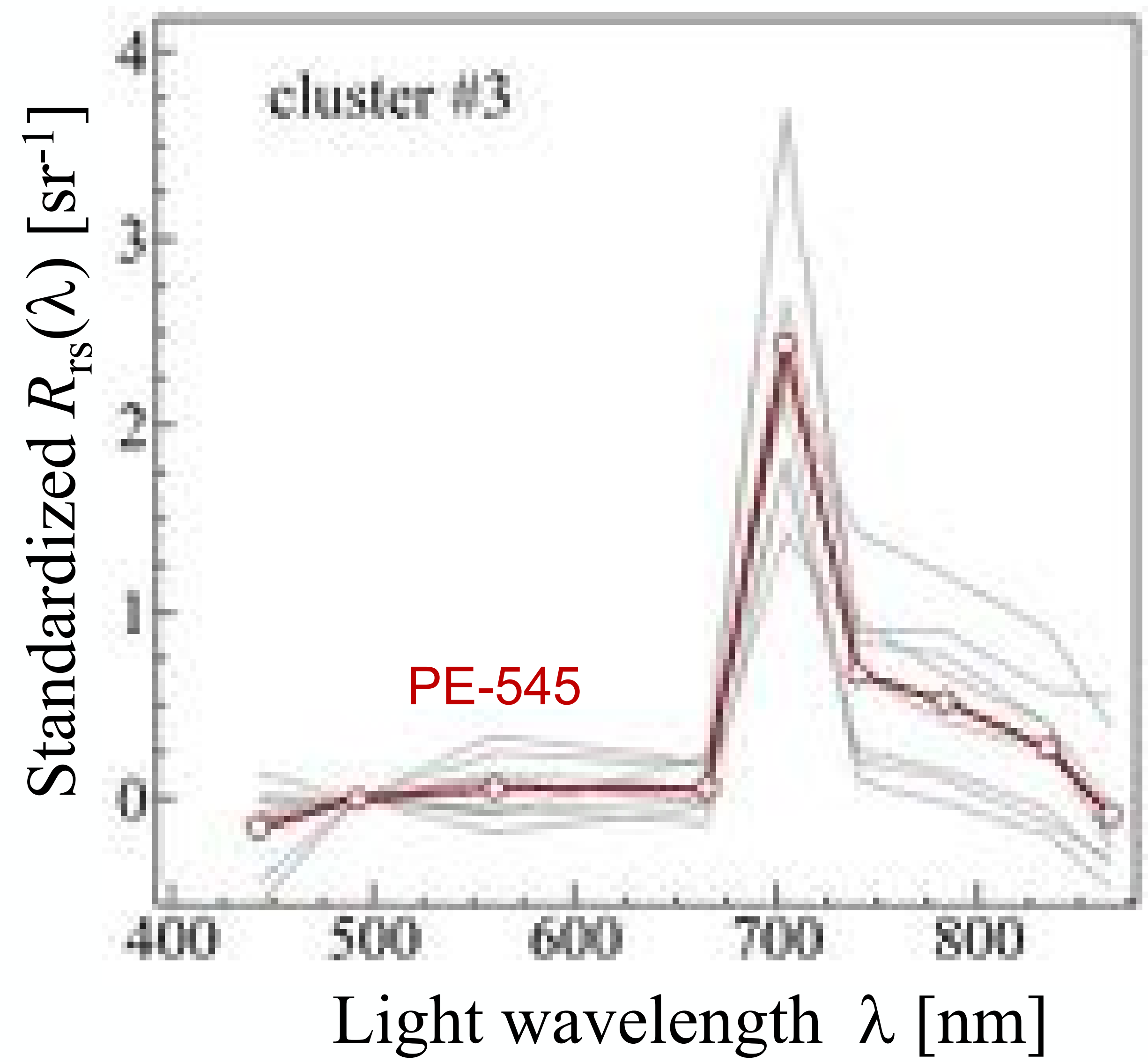
Vol. 465: 33–52, 2012
doi: 10.3354/meps09879

MARINE ECOLOGY PROGRESS SERIES
Mar Ecol Prog Ser

Published September 28

Pigment-based chloroplast types in dinoflagellates

Manuel Zapata[1,†], Santiago Fraga[2], Francisco Rodríguez[2,*], José L. Garrido[1]



LEPIDODINIUM CHLOROPHORUM

Two $R_{rs}(\lambda)$ peaks at 560 and 705 nm

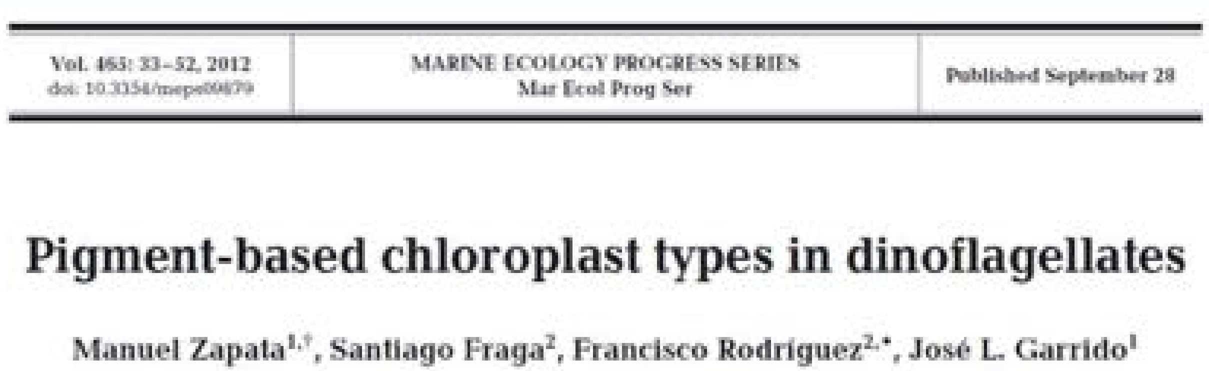
Monospecific cluster

Low $R_{rs}(\lambda)$ variability (5 blooms / France)

Particular pigment composition

Chl-*b*, no Peridinin, no Fucoxanthin

~ *pigment type 6 in Zapata et al., 2012*



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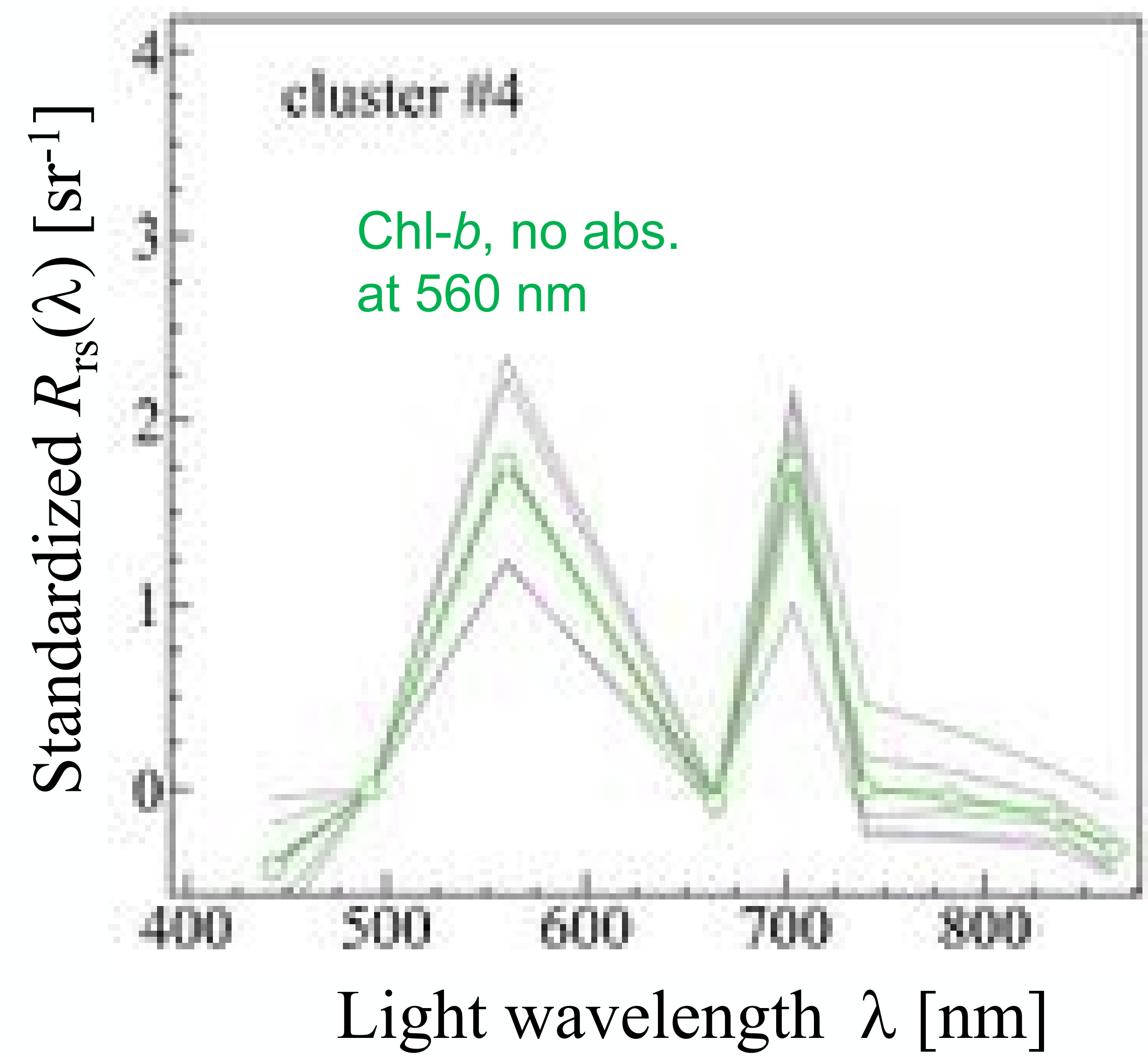

DINOFLAGELLATES… with Peridinin?

Dominated by dinos (5/6 genera)

all them bearing Peridinin

- *Prorocentrum*
- *Gymnodinium*
- *Lingulodinium polyedra*
- *Gonyaulax*
- *Alexandrium*

~ pigment type 1 in Zapata et al., 2012

Vol. 465: 33–52, 2012
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MARINE ECOLOGY PROGRESS SERIES
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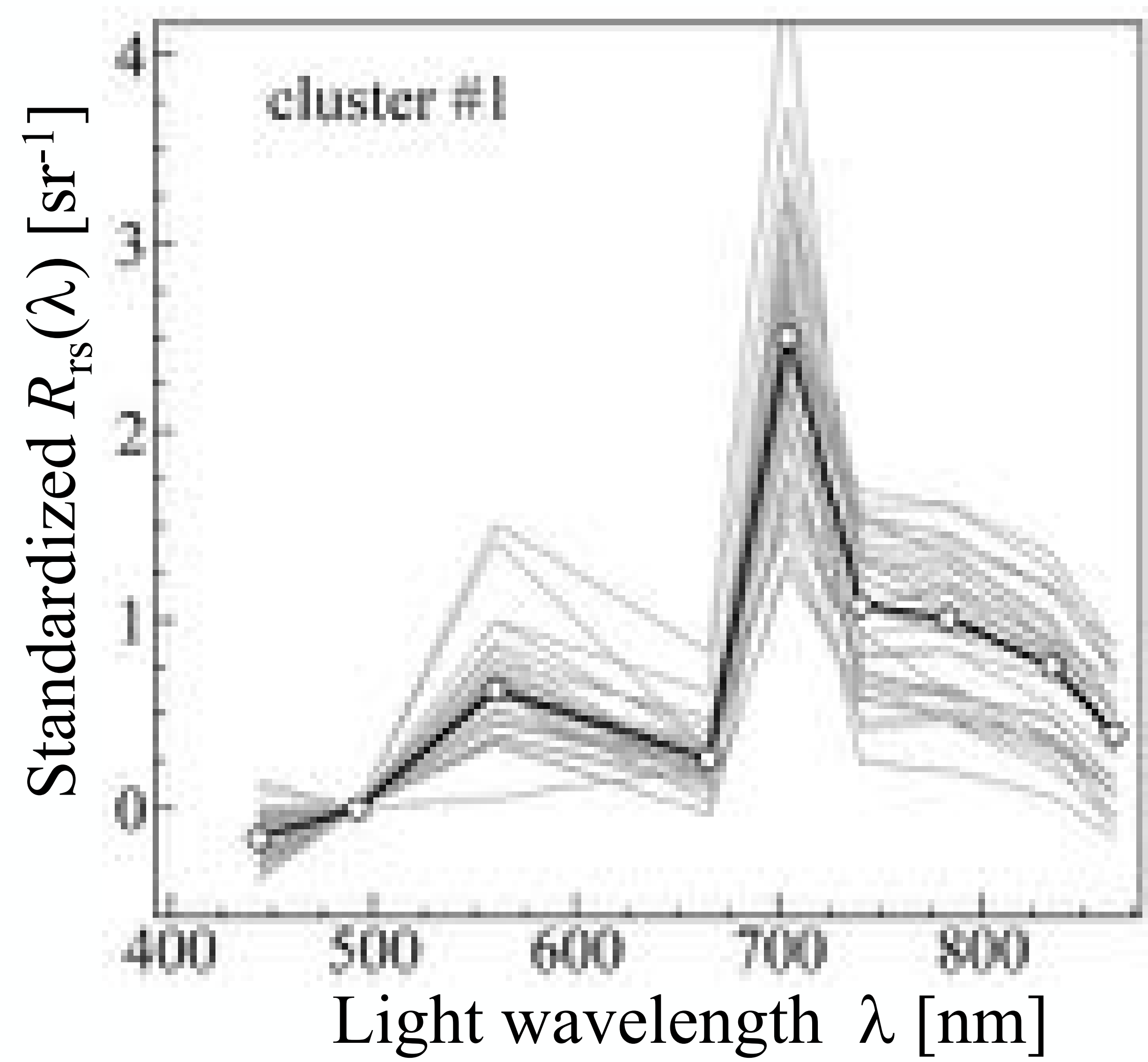


DINOFLAGELLATES…with Fucoxanthin?

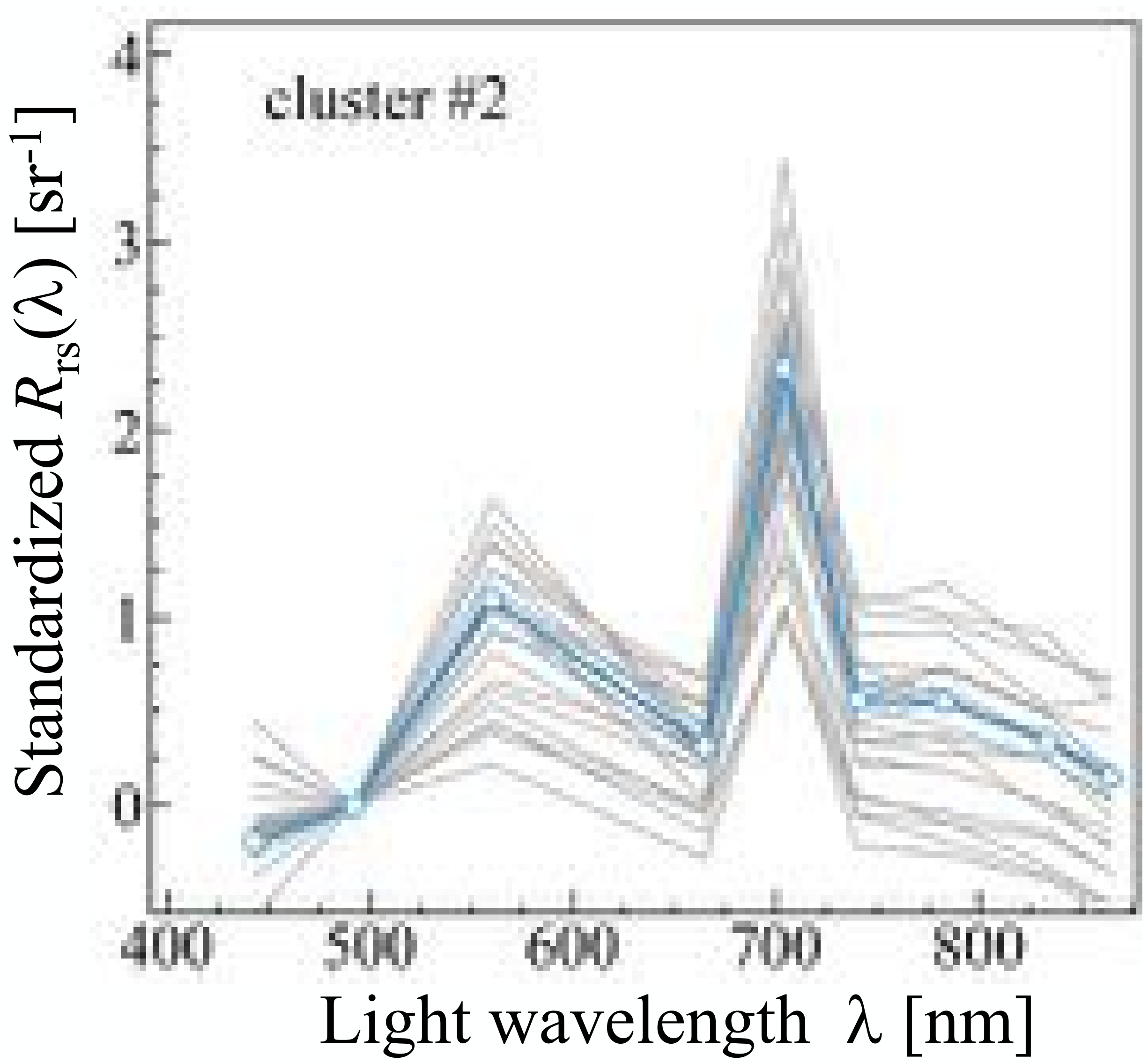
Dominated by dinos (5/7 genera),

- *Protoceratium reticulatum*
- *Ceratium fusus*
- *Karlodinium veneficum* *
- *Karenia sp.* *
- *Margalefidinium polykrikoides*

Also contains 2 other classes

- *Phaeocystis sp.* *
- *Aureococcus anophagefferens* *

Fucoxanthin-bearing species (4/7)



CONCLUSION

Three species had unique $R_{rs}(\lambda)$ fingerprint (specific pigment composition)

- *Lepidodinium chlorophorum* (Chl-*b*), *Mesodinium rubrum* (PE-545), Red *Noctiluca scintillans* (absence of Chl-*a*)

Floating cyanoHABs (+ green *Noctiluca*) could be discriminated (high NIR & SWIR)

Clusters dominated by Dinoflagellates: very diverse, risk of confusion (e.g. *Phaeocystis*), discrimination between Peridin- vs. Fucoxanthin-bearing species?

Blooms of Diatoms (absent of the database) should be further investigated

TAKE HOME MESSAGE

Sentinel-2 is relevant for HAB monitoring (in synergy with field observations)

In the absence of in situ measurement, S2 could identify a few optical bloom types

S2-HABs database could be use for algorithms development and validation

“Spectral library approach” could be improved using hyperspectral sensors

5 min break


HYDRATION BREAK
MBAPPE GIVES HIS OPINION ON ~~HYDRATION BREAKS~~
PHYTO ABSORPTION

Hyperspectral approaches

Pigments line height

Spectral derivatives

Similarity index

Optical water type (OWT) classification

Many others: see lectures by Jeremy Werdell and Ivona Cetinić

Pigments line height

$$\mathrm{LH} = 100^{*}[R_{rs}(\lambda_1) + \tau \bullet (R_{rs}(\lambda_3) - R_{rs}(\lambda_1)) - R_{rs}(\lambda_2)]$$

$$\tau = \frac{\lambda_2 - \lambda_1}{\lambda_3 - \lambda_1}$$

Contents lists available at ScienceDirect

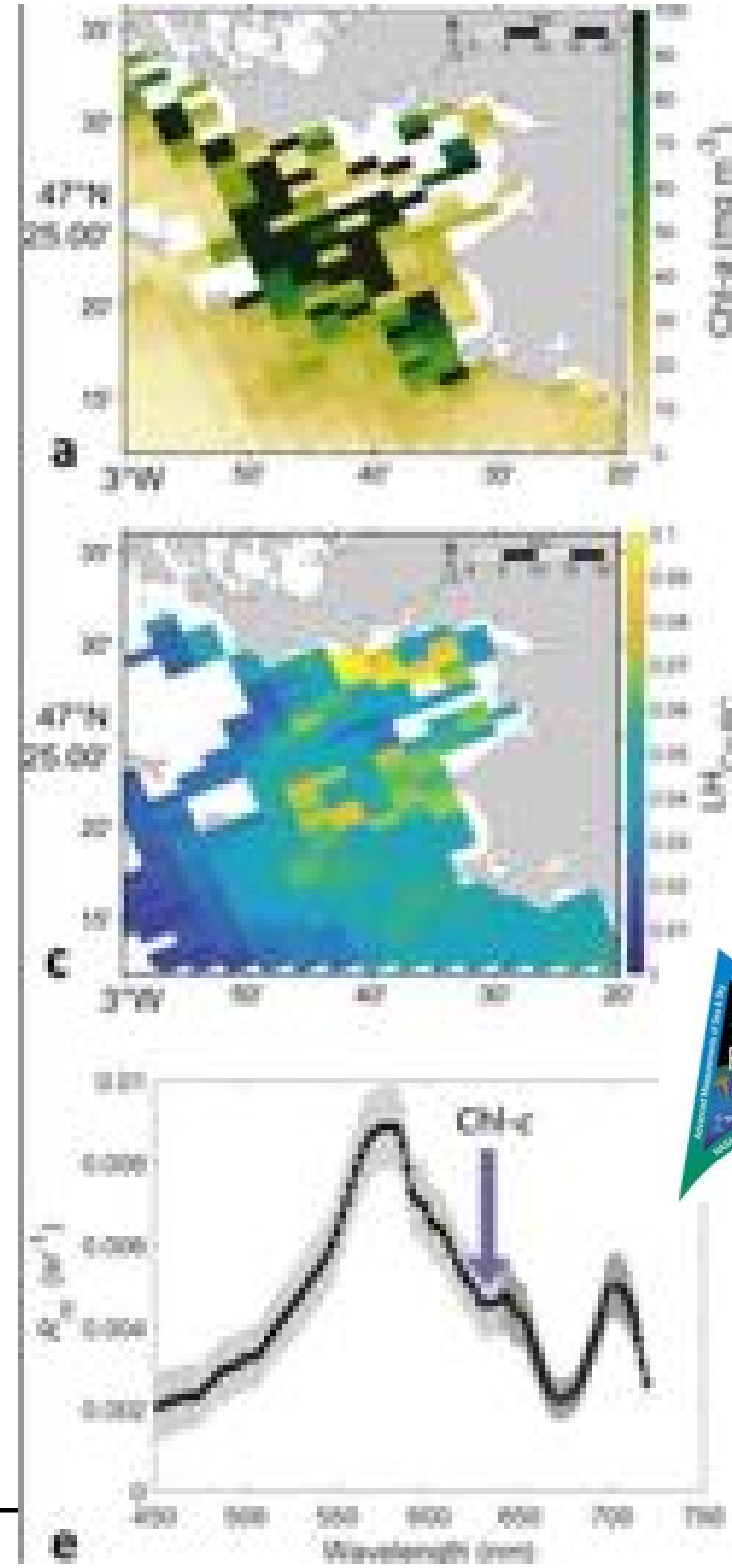
Remote Sensing of Environment

journal homepage: www.elsevier.com/locate/rse

ELSEVIER

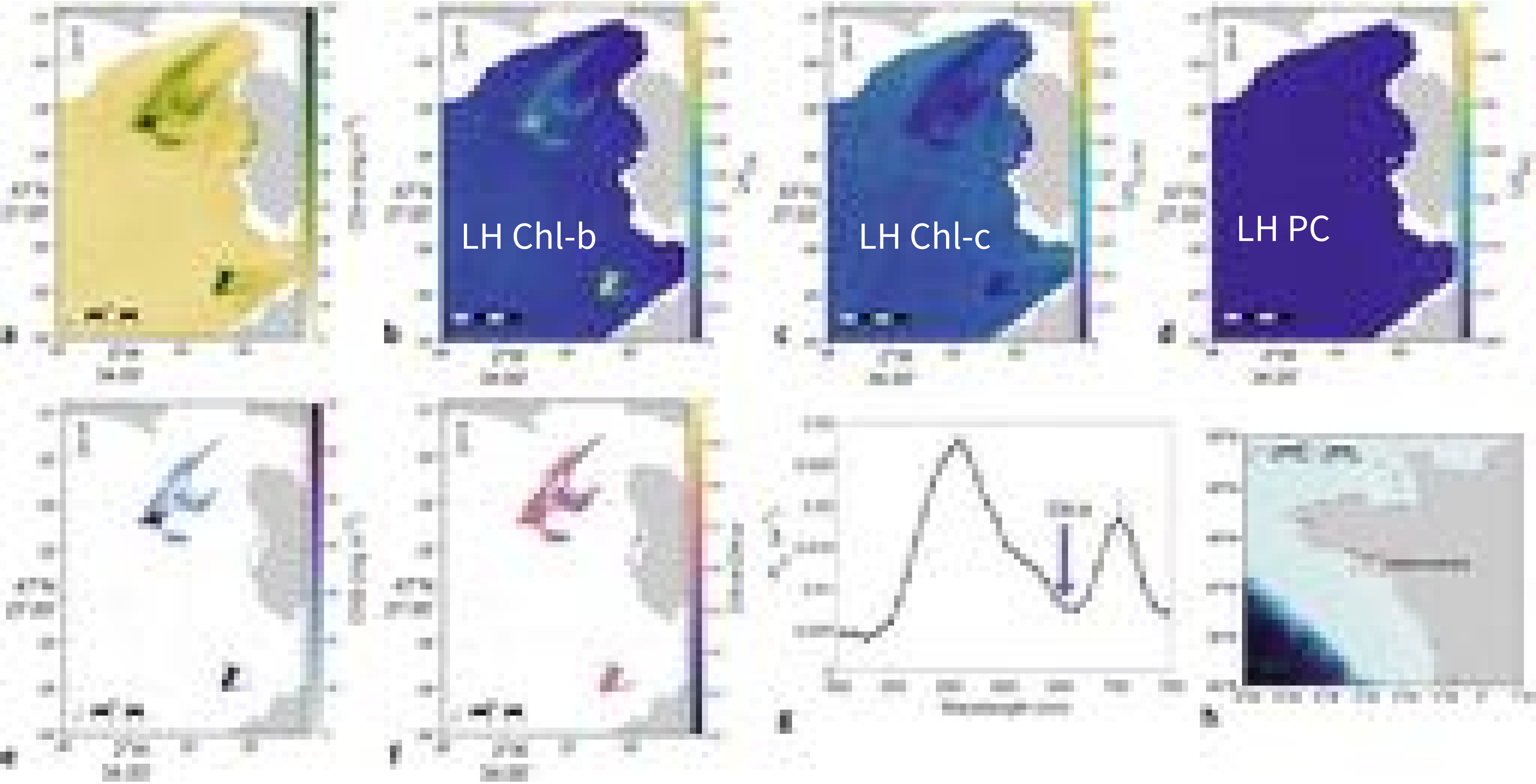
Toward elucidating accessory pigments in intense phytoplankton blooms using hyperspectral satellite remote sensing in support of harmful algal bloom (HAB) monitoring

Maria Laura Zoffoli, Victor Pochic, Mariano Bresciani, Federica Braga, Thomas Lacour, Michaël Retho, Soazig Manach, Rüdiger Röttgers, Amália Maria Sacilotto Detoni, Tristan Harmel, Simon Oiry, Pierre Gernez



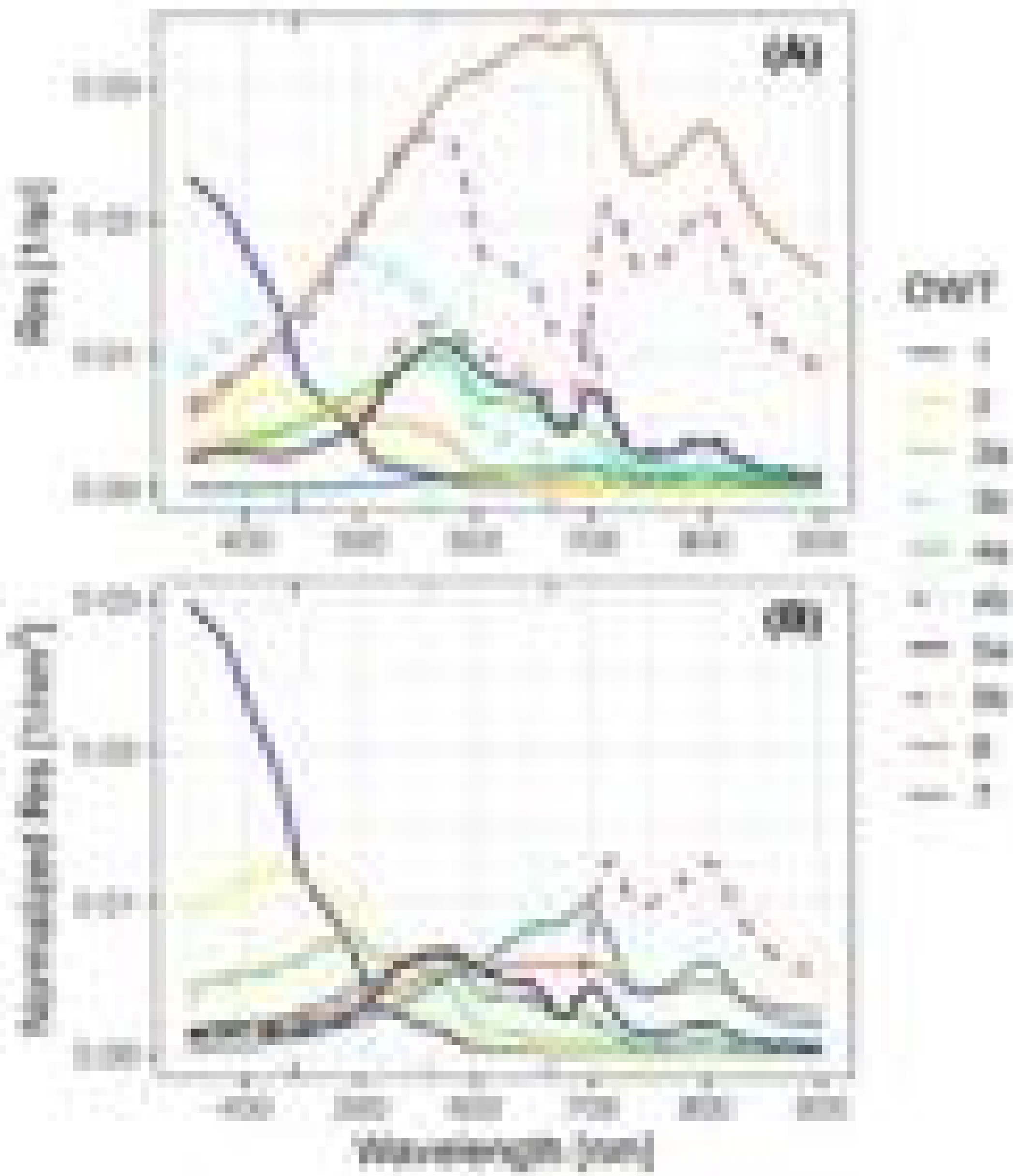
Zoffoli et al., (2026)

Chl-*b* line height
(absorption max ~ 650 nm)



Zoffoli et al., (2026)

Optical water types (OWTs)



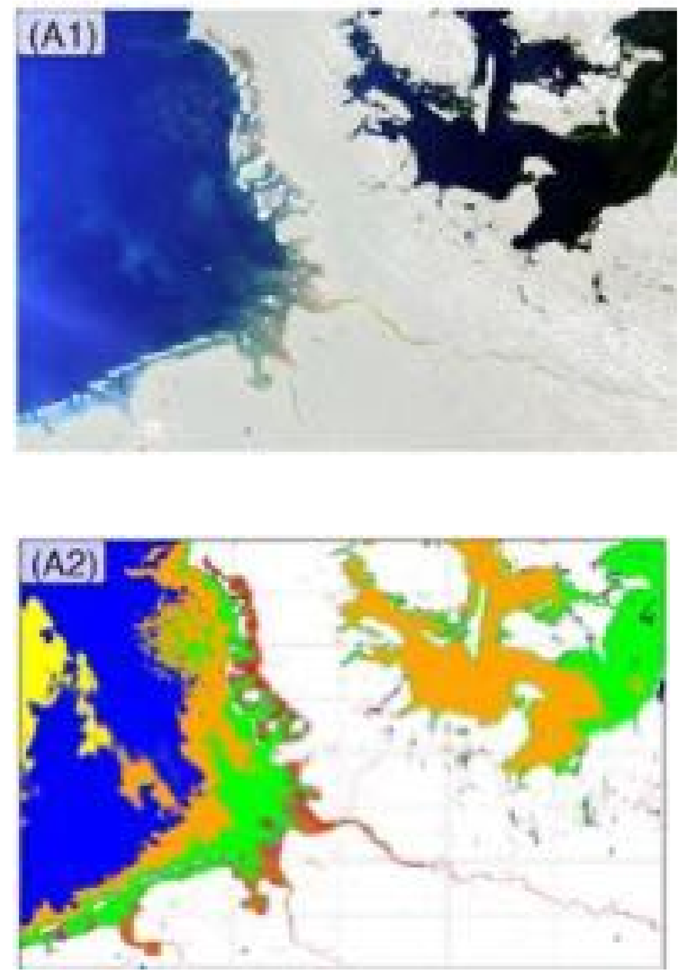


Table 1. Conceptual description of optical water types.

OWT	Description
1	Extremely clear and oligotrophic indigo-blue waters with high reflectance in the short visible wavelengths.
2	Blue waters with similar biomass level as OWT 1 but with slightly higher detritus and CDOM content.
3a	Turquoise waters with slightly higher phytoplankton, detritus, and CDOM compared to the first two types.
3b	A special case of OWT 3a with similar detritus and CDOM distribution but with strong scattering and little absorbing particles like in the case of Coccolithophore blooms. This type usually appears brighter and exhibits a remarkable ~490 nm reflectance peak.
4a	Greenish water found in coastal and inland environments, with higher biomass compared to the previous water types. Reflectance in short wavelengths is usually depressed by the absorption of particles and CDOM.
4b	A special case of OWT 4a, sharing similar detritus and CDOM distribution, exhibiting phytoplankton blooms with higher scattering coefficients, e.g., Coccolithophore bloom. The color of this type shows a very bright green.
5a	Green eutrophic water, with significantly higher phytoplankton biomass, exhibiting a bimodal reflectance shape with typical peaks at ~560 and ~709 nm.
5b	Green hyper-eutrophic water, with even higher biomass than that of OWT 5a (over several orders of magnitude), displaying a reflectance plateau in the Near Infrared Region, NIR (vegetation-like spectrum).
6	Bright brown water with high detritus concentrations, which has a high reflectance determined by scattering.
7	Dark brown to black water with very high CDOM concentration, which has low reflectance in the entire visible range and is dominated by absorption.

LIMNOLOGY
and
OCEANOGRAPHY

ASLO

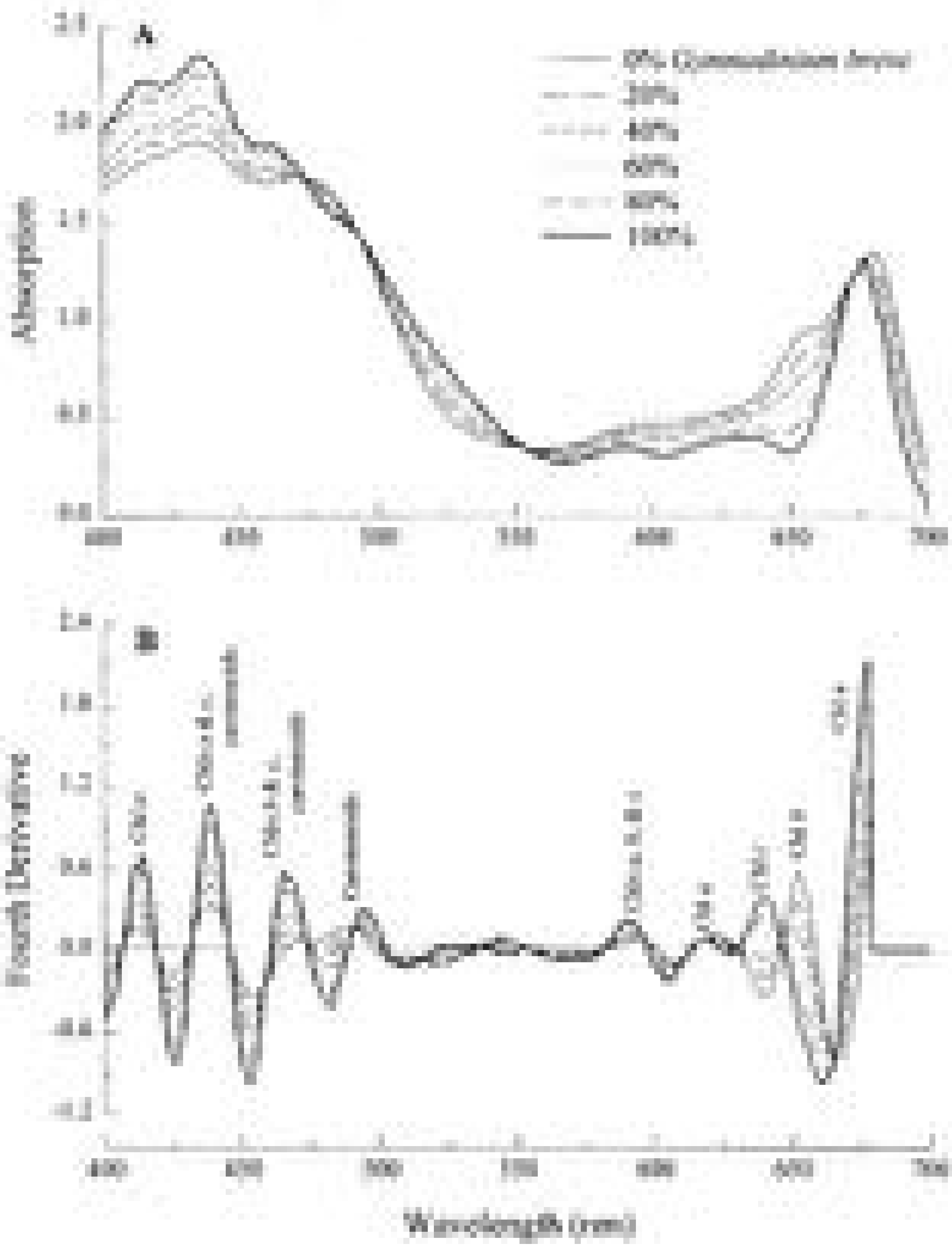
Limnol. Oceanogr. 69, 2024, 1547–1561

doi: 10.1002/lno.12606

Holistic optical water type classification for ocean, coastal, and inland waters

Shun Bi,* Martin Hieronymi
Institute of Carbon Cycles, Helmholtz-Zentrum Hereon, Geesthacht, Germany

Spectral derivative (using absorption)



LIMNOLOGY AND OCEANOGRAPHY

ASLO

Article · Free to Read

Detection of harmful algal blooms using photopigments and absorption signatures: A case study of the Florida red tide dinoflagellate, *Gymnodinium breve*

David F. Millie, Oscar M. Schofield, Gary J. Kirkpatrick, Geir Johnsen, Patricia A. Tester, Bryan T. Vinyard

Millie et al., (1997)

Spectral derivative (using reflectance)

Applied Optics Vol. 45, Issue 21, pp. 5414-5425 (2006) • https://doi.org/10.1364/AO.45.005414

OPTICA PUBLISHING GROUP

Use of hyperspectral remote sensing reflectance for detection and assessment of the harmful alga, *Karenia brevis*

Susanne E. Craig, Steven E. Lohrenz, Zhongping Lee, Kevin L. Mahoney, Gary J. Kirkpatrick, Oscar M. Schofield, and Robert G. Steward

Abstract

We applied two numerical methods to *in situ* hyperspectral measurements of remote sensing reflectance R_{rs} to assess the feasibility of remote detection and monitoring of the toxic dinoflagellate, *Karenia brevis*, which has been shown to exhibit unique absorption properties. First, an existing quasi-analytical algorithm was used to invert remote sensing reflectance spectra, $R_{rs}(\lambda)$, to derive phytoplankton absorption spectra, $a_\varphi^{Rrs}(\lambda)$. Second, the fourth derivatives of the $a_\varphi^{Rrs}(\lambda)$ spectra were compared to the fourth derivative of a reference *K. brevis* absorption spectrum by means of a similarity index (SI) analysis. Comparison of reflectance-derived a_φ with

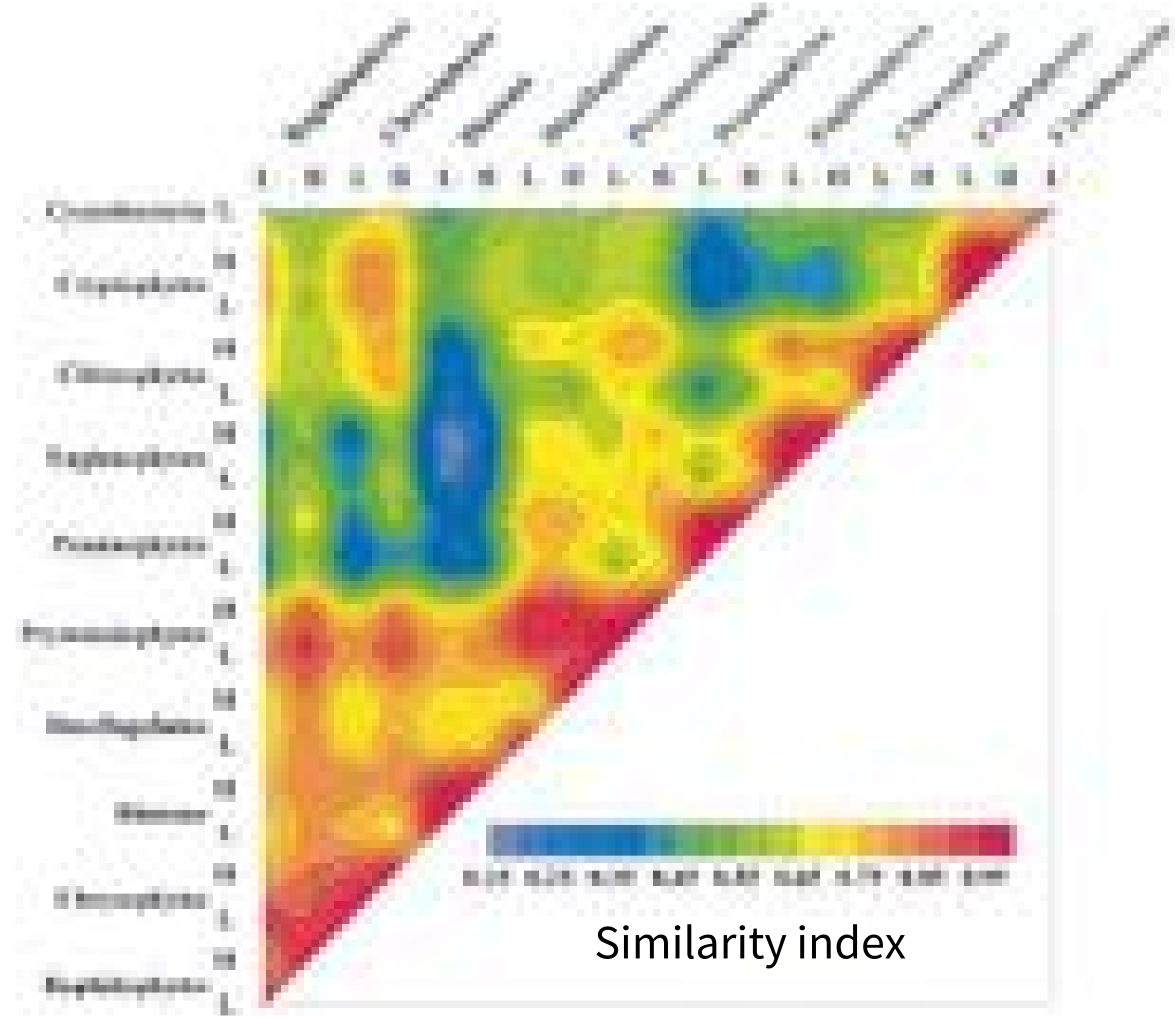
Craig et al., (2006)

Similarity index (2 spectra are similar if SI = 1) aka spectral angle mapper (SAM)

Within each comparison, the degree of similarity between spectra then was computed using an index (SI) algorithm:

$$SI = \frac{2}{\pi}\ \text{arccosine}\ \frac{(S_1 \bullet S_2)}{|S_1| \times |S_2|}$$

where $\frac{(S_1 \bullet S_2)}{|S_1| \times |S_2|}$ is the cosine of the angle between two vectors, S_1 is the vector of fourth-derivative spectrum values $S_1(\lambda_1), S_1(\lambda_2), S_1(\lambda_3), \ldots, S_1(\lambda_n)$ for the first spectrum, and, similarly, S_2 is the vector of the fourth-derivative spectrum values for the second absorbance or



Using absorbance and fluorescence spectra to discriminate microalgae

Published online by Cambridge University Press: **08 October 2002**

DAVID F. MILLIE, OSCAR M. E. SCHOFIELD, GARY J. KIRKPATRICK, GEIR JOHNSEN and TERENCE J. EVENS

Millie et al., (2002)

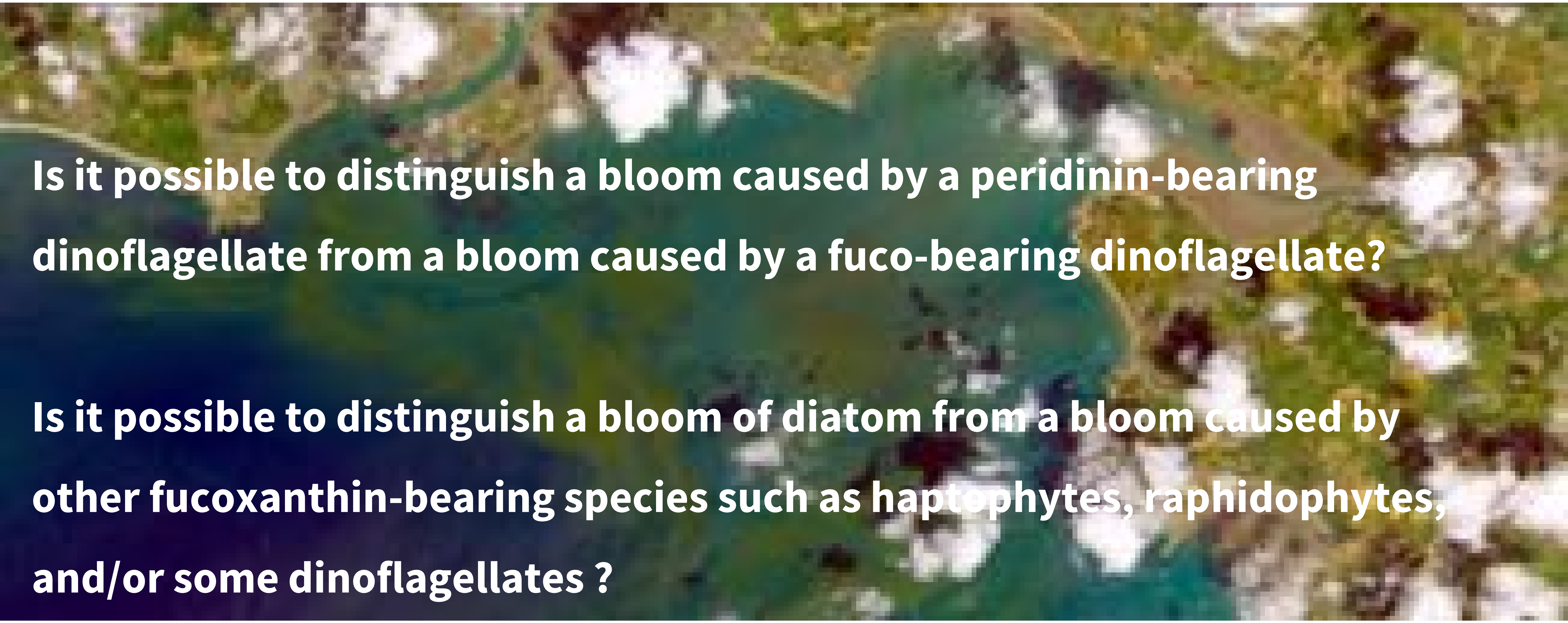
MARINE ECOLOGY PROGRESS SERIES
Mar. Ecol. Prog. Ser.

***In vivo* absorption characteristics in 10 classes of bloom-forming phytoplankton: taxonomic characteristics and responses to photoadaptation by means of discriminant and HPLC analysis**

Geir Johnsen[1], Oddgeir Samset[1], Lois Granskog[1], Egil Sakshaug[1]

Johnsen et al., (1994)

Assessing potential of hyperspectral RS



Is it possible to distinguish a bloom caused by a peridinin-bearing dinoflagellate from a bloom caused by a fuco-bearing dinoflagellate?

Is it possible to distinguish a bloom of diatom from a bloom caused by other fucoxanthin-bearing species such as haptophytes, raphidophytes, and/or some dinoflagellates ?

Material & Methods

Particulate absorption coefficient $a_p(\lambda)$ measured on monospecific algal cultures using filter pads (inside sphere) or cells suspension (inside PSICAM).

Spectral library of 60 bloom-forming phytoplankton species

164 hyperspectral spectra covering 8 taxonomic classes compiled from Xi et al. (2015), Lomas et al. (2024), and a new IOP library of bloom-forming species.

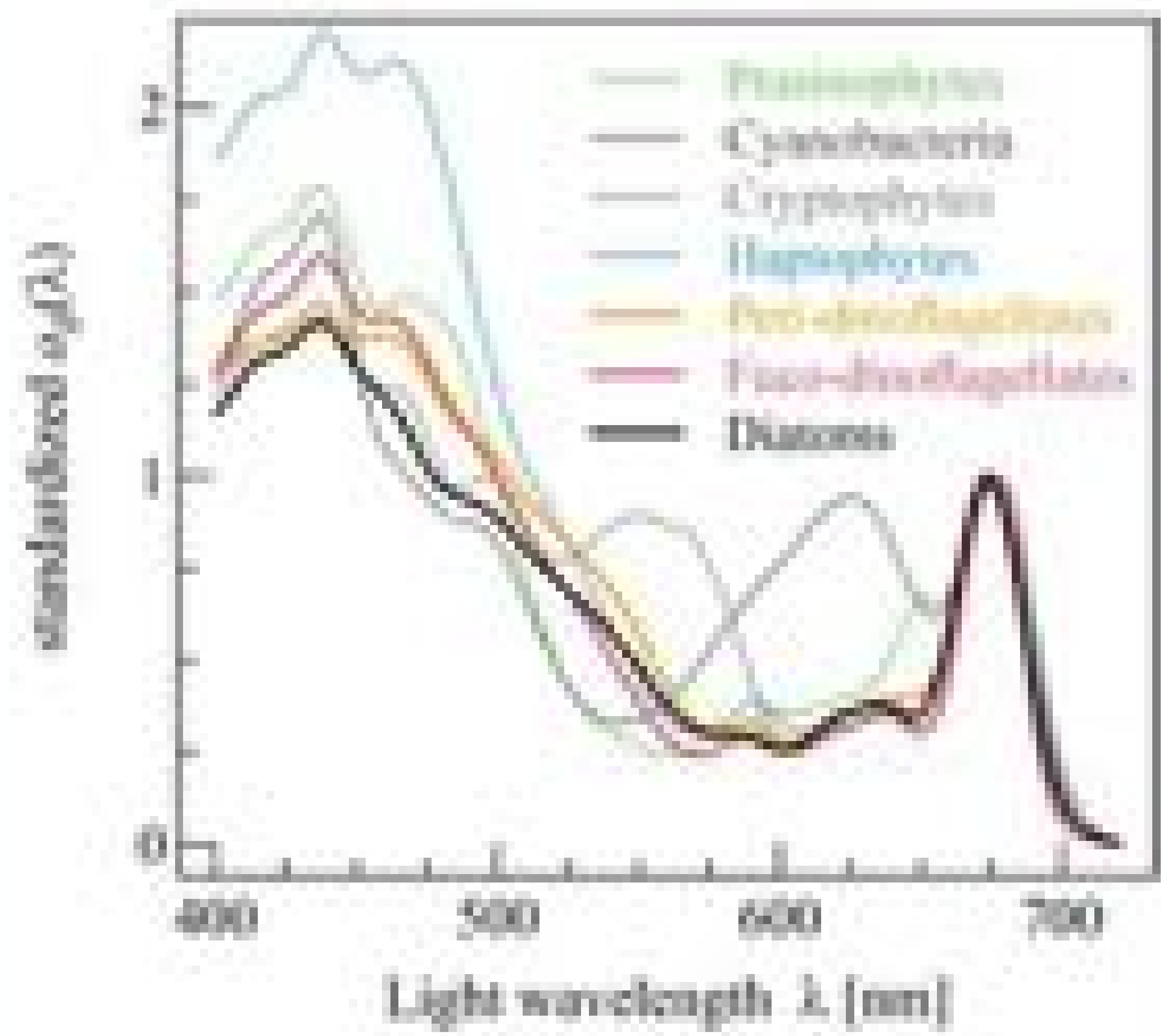
Simple classification method of $a_p(\lambda)$ spectra

Spectra were smoothed (9nm moving average), and 2nd derivative computed.

Hierarchical cluster analysis was performed using a similarity index distance.

Absorption diversity: 7 clusters at class level

Class-averaged absorption of 7 optical clusters



Prasinophytes

Cyanobacteria

Cryptophytes

Easy due to unique pigments and absorption signature

Haptophytes

Peridinin-bearing dinoflagellates

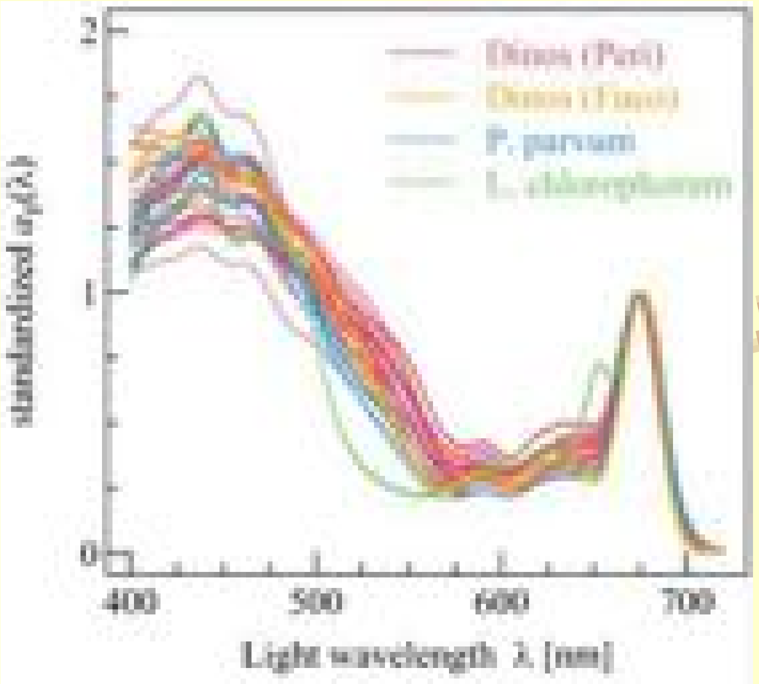
Fucoxanthin-bearing dinoflagellates

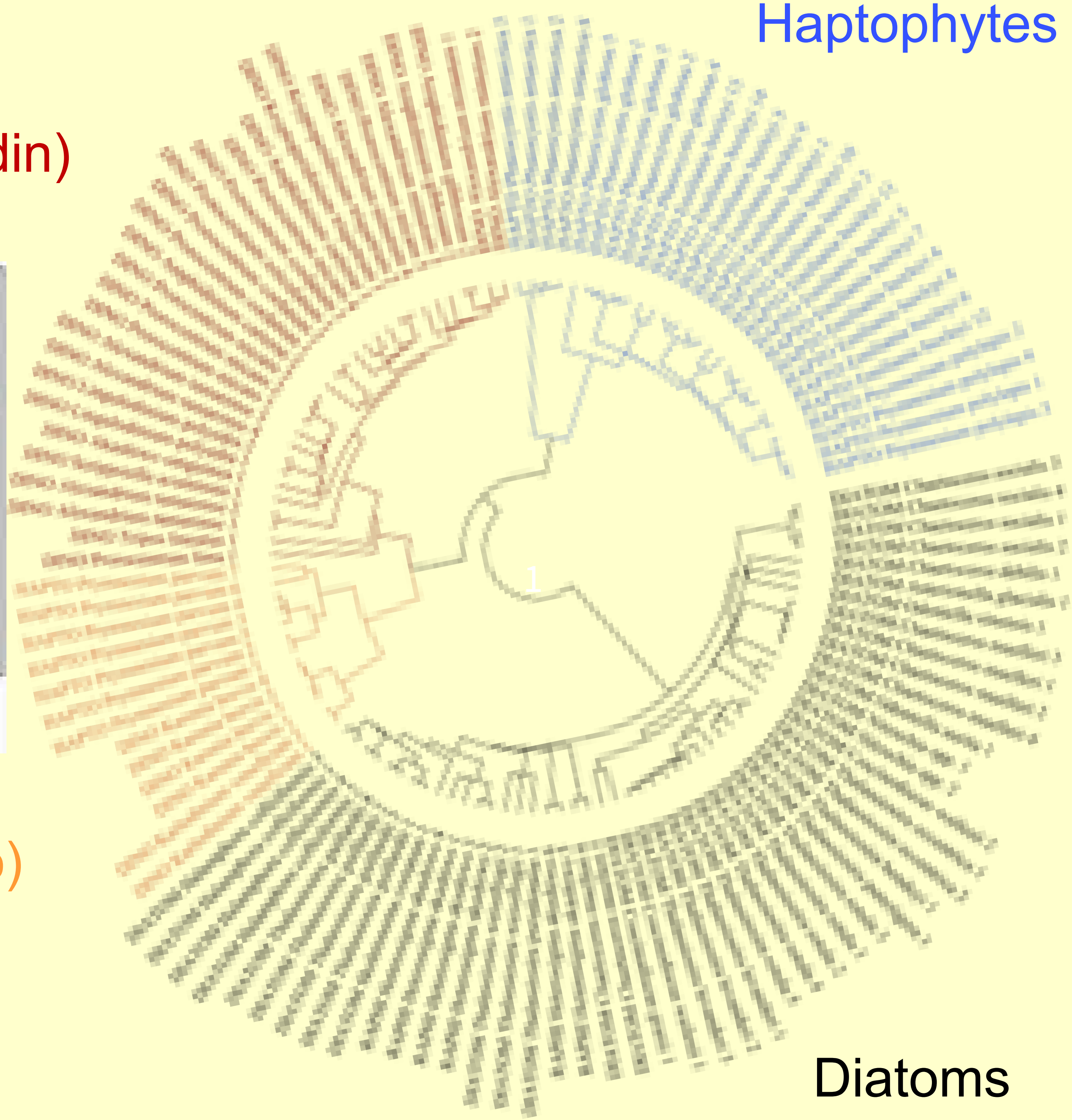
Diatoms and/or raphidophytes

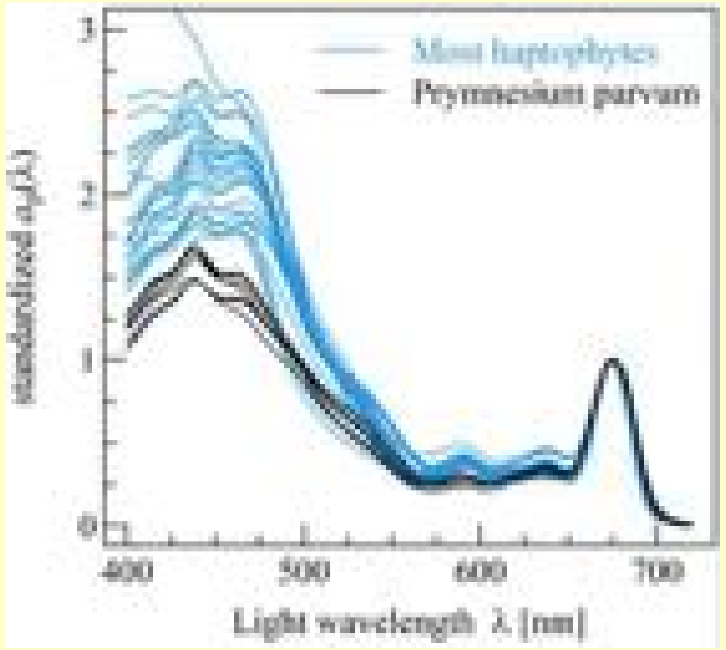
more challenging (next slide)

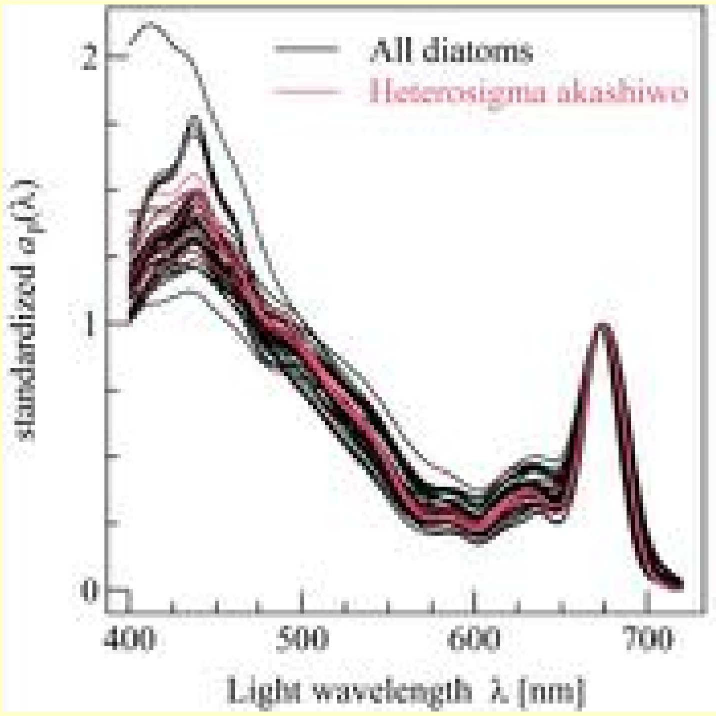
Haptophytes

Dinoflagellates (Peridin)









Dinoflagellates (Fuco)

Diatoms

Scattering coef. of phytoplankton cultures

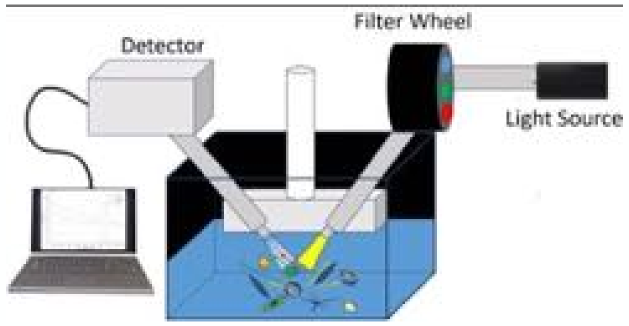
HABLAB: full characterization of phytoplankton scattering using advanced instruments

Attenuation $c_p(\lambda)$ and scattering $b_p(\lambda)$ coefficients (ac-s)

Angular scattering at 515 nm $\beta_p(\theta)$

Hyperspectral backscattering coefficient $b_{bp}(\lambda)$

LISST-VSF: directional scattering at 515 nm (phase function + polarization terms)



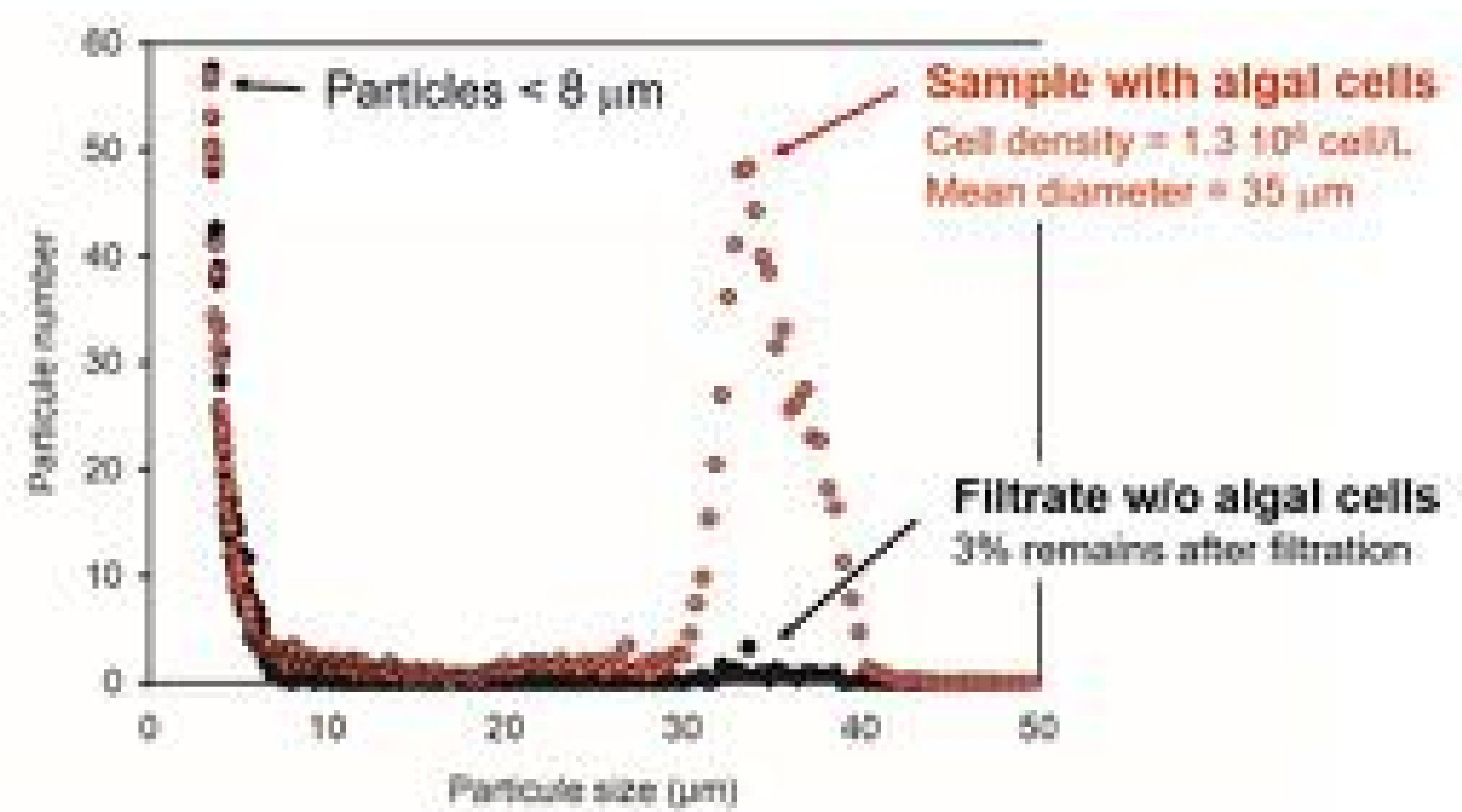
Hyfi-bb: hyperspectral backscattering through mono-directional VSF measurement (*Novak et. al, 2024*)

https://doi.org/10.1364/OE.529061

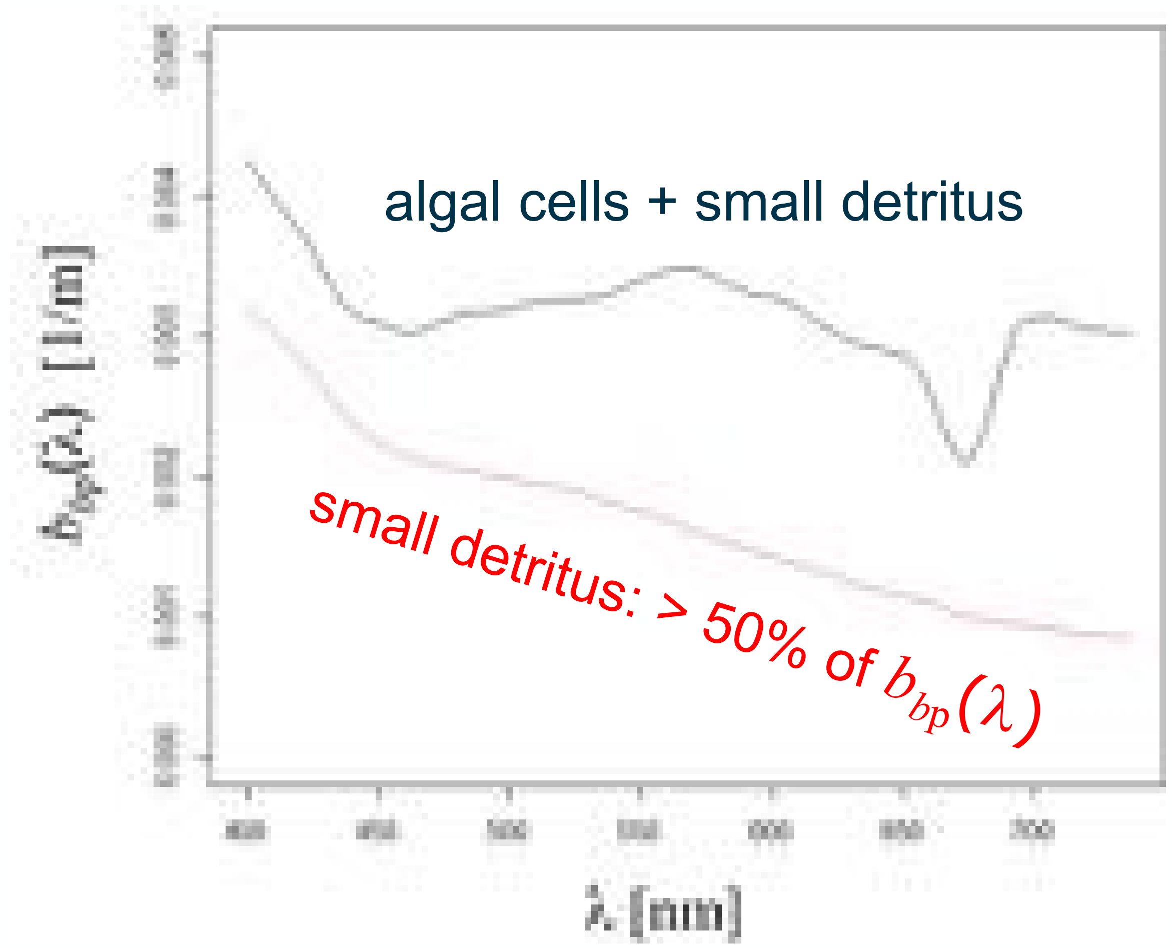
Removing background particles in cultures

Removing small detritus using nucleopore filters

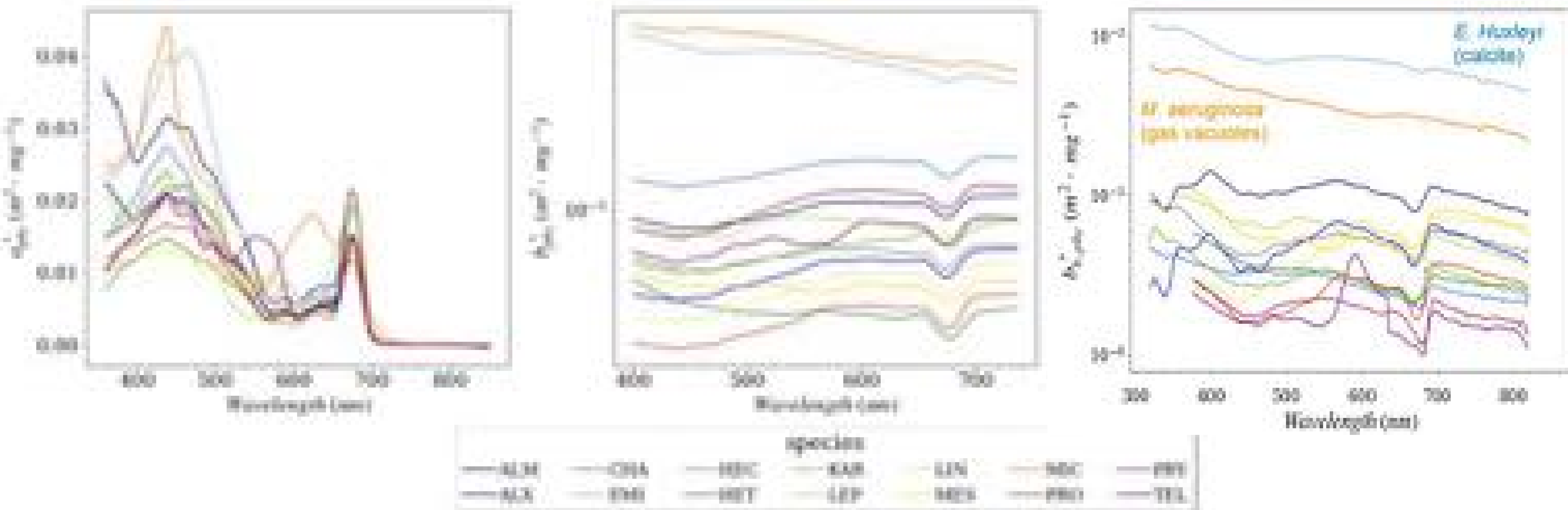
Required to measure microalgae scattering without bias



Coulter counter measurements



HABLAB results



ALM & ALX = *Alexandrium minutum*, CHA = *Chaetoceros muelleri*, HEC = *Heterocapsa triquetra*, KAR = *Karlodinium veneficum*, LIN = *Lingulaulax polyedra*, MIC = *Microcystis aeruginosa*, PRY = *Prymnesium parvum*, EMI = *Emiliania huxleyi*, HET = *Heterosigma akashiwo*, LEP = *Lepidodinium chlorophorum*, MES = *Mesodinium rubrum*, PRO = *Prorocentrum micans*, TEL = *Teleaulax amphioxeia*

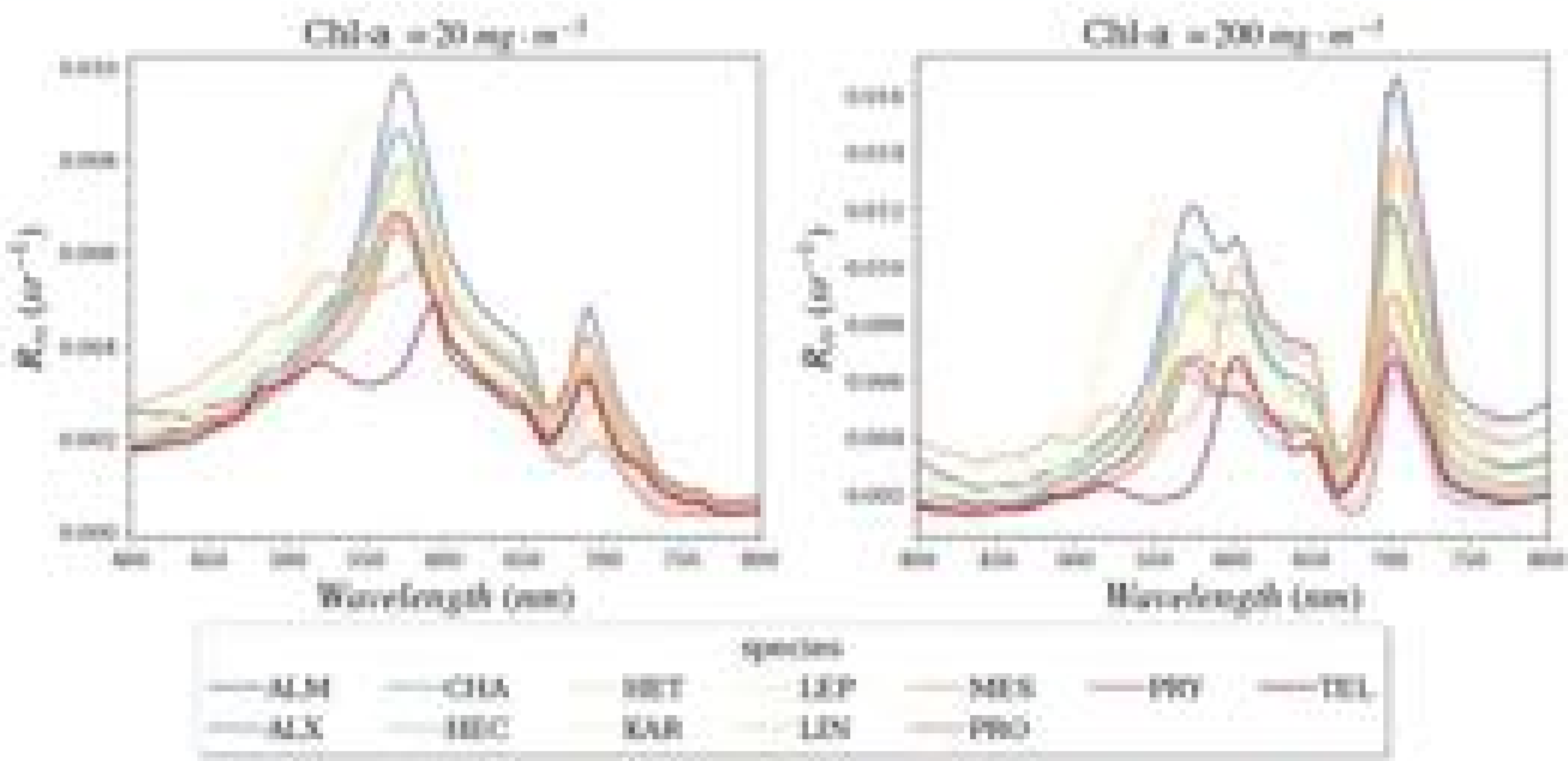
Radiative transfer simulations

RT model from Harmel et al., (in prep.)

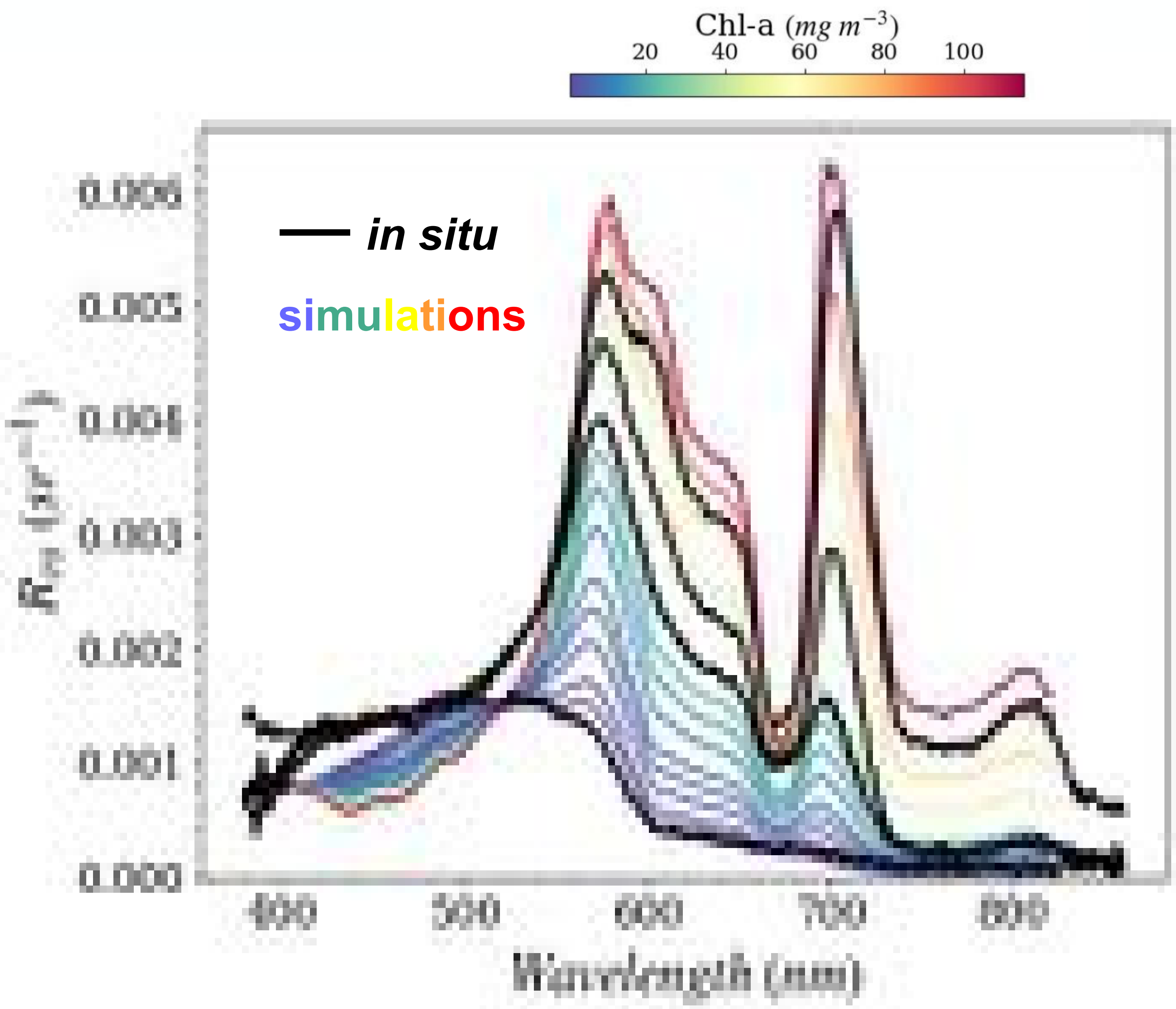
$$R_{rs}\left(\lambda,\theta_s,\theta_v,\Delta\phi\right) = f\left(\frac{b_b(\lambda)}{a(\lambda)},\theta_s,\theta_v,\Delta\phi\right)$$

IOP model parameterized using lab data

$$\begin{cases} a(\lambda) = a_w(\lambda) + a_{cdom}(\lambda) + [\text{Chl-a}]\, \boldsymbol{a^*_{phy}(\lambda)} + a_{others}(\lambda) \\ b_b(\lambda) = b_{b,w}(\lambda) + [\text{Chl-a}]\, \boldsymbol{b^*_{b,phy}(\lambda)} + b_{b,others}(\lambda) \end{cases}$$

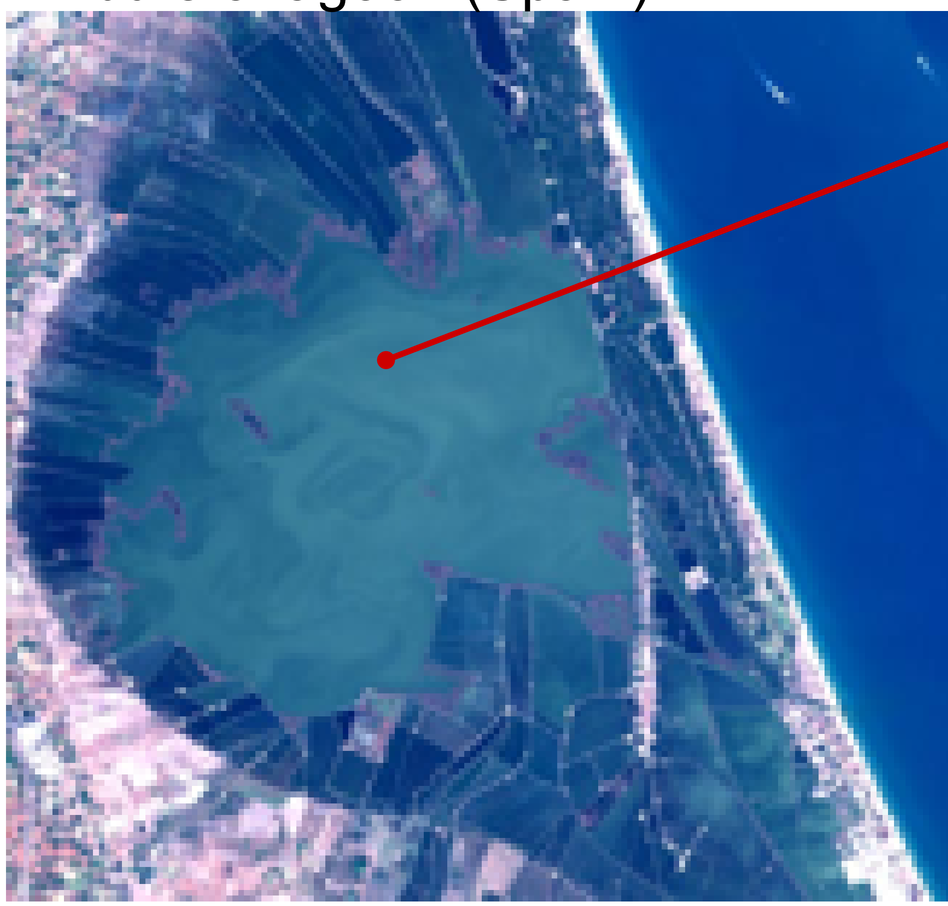


Applications to HAB monitoring: *in situ* $R_{rs}(\lambda)$

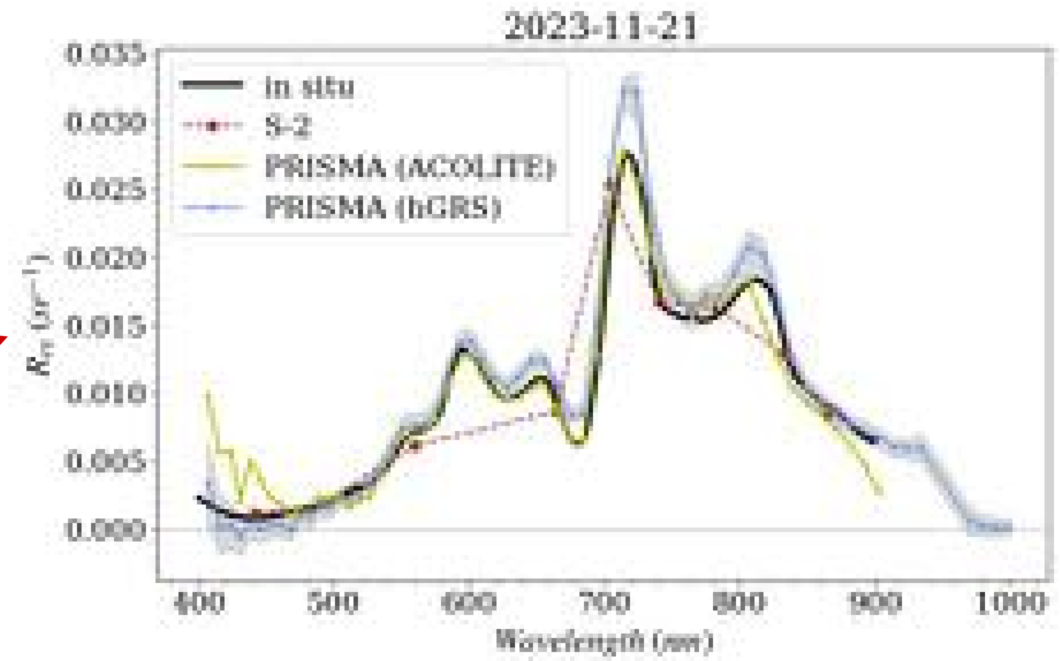


Application to PRISMA

Albufera lagoon (Spain)



Bloom dominated by tiny reddish bacteria (likely *Raphidiopsis* or *Leptolyngbya*)

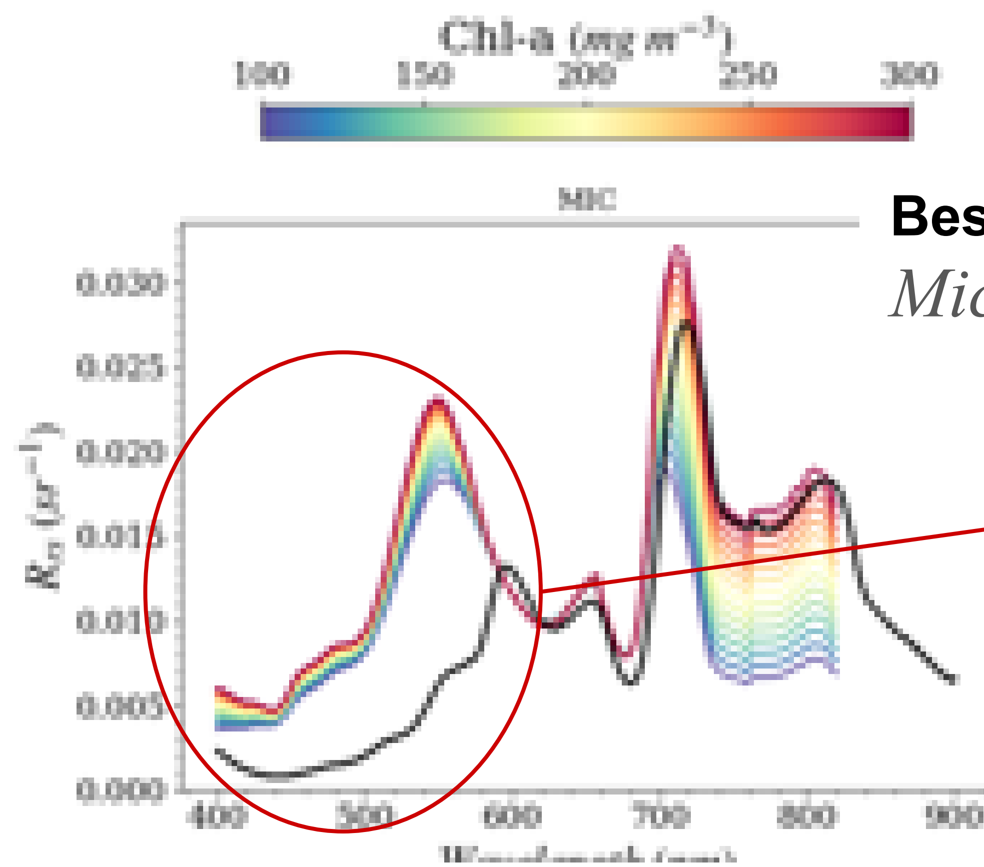


In situ data from
Antonio Ruiz Verdú et al.

Chl-*a*: 230.0 µg/l

CDOM (a_400): 2.78 m^{-1}

SPM : 28.57 mg/L



Best fit with cyanobacteria
Microcystis aeruginosa

discrepancies in blue-green

Need to expand IOPs dataset with more cyanobacteria species

Conclusions

Detailed characterization of phytoplankton IOPs for bloom-forming species

Laboratory measurements of volume scattering function, absorption and backscattering coefficients

Lab data used to feed forward & inverse RT model

Preliminary application to HAB monitoring using in situ and PRISMA

Next steps

Expand IOP database to include more cyanobacteria

How many Optical Bloom Types could be identified using hyperspectral satellites?

Validate approach for HAB monitoring and phytoplankton bloom studies

General framework for red tides RS

1. Identify & classify main bloom-forming species

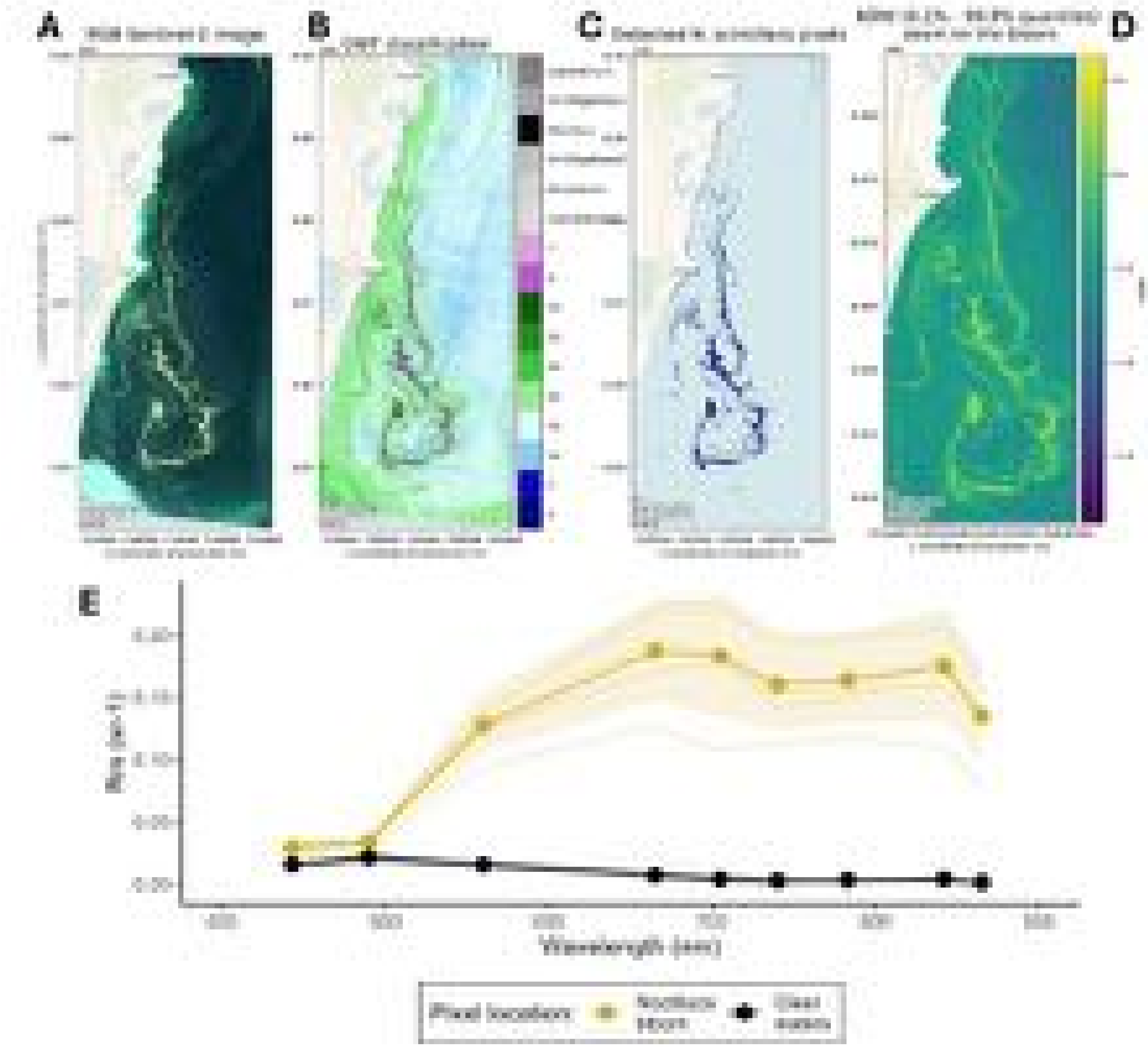
(using i.e. OWT/OBT, spectral derivative, SI, pigments LH, pigments fluorescence, …)

2. Select most relevant IOP model

3. Inverse IOP, pigments concentration and/or cell abundance

Example using Sentinel-2

results from Victor Pochic and Zoé Besnard



1. OWT & OBT classification

→ *Noctiluca*

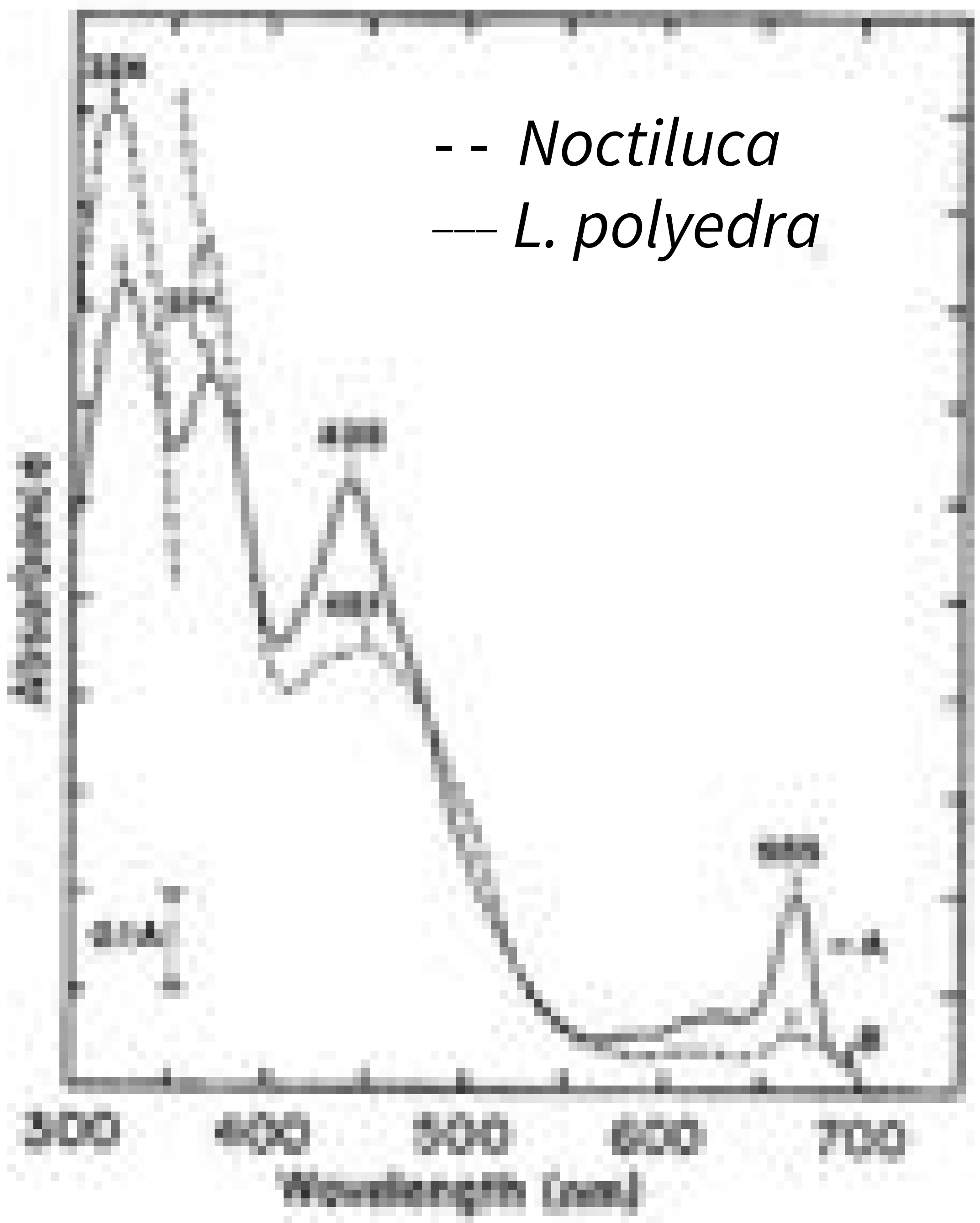
2. Specific algorithm

NDNI (Detoni et al., 2023)

Mafra et al., submitted

New research avenues

UV-absorption as signature of dinoflagellates?



Balch & Haxo (1984)

Home › Marine Biology › Article

Release of ultraviolet-absorbing compounds by the red-tide dinoflagellate *Lingulodinium polyedra*

Published: March 1996

Volume 127, pages 35–44 (1996) Cite this article

Save article

M. Vernet & K. Whitehead

These results indicate that UV-absorbing compounds synthesized by phytoplankton, such as certain dinoflagellates, may be a component of the DOM pool in surface waters of the ocean and contribute to the attenuation of UV radiation in the water column.

ultraviolet-absorbing compounds:
known as **mycosporine-like amino acids (MAAs)**

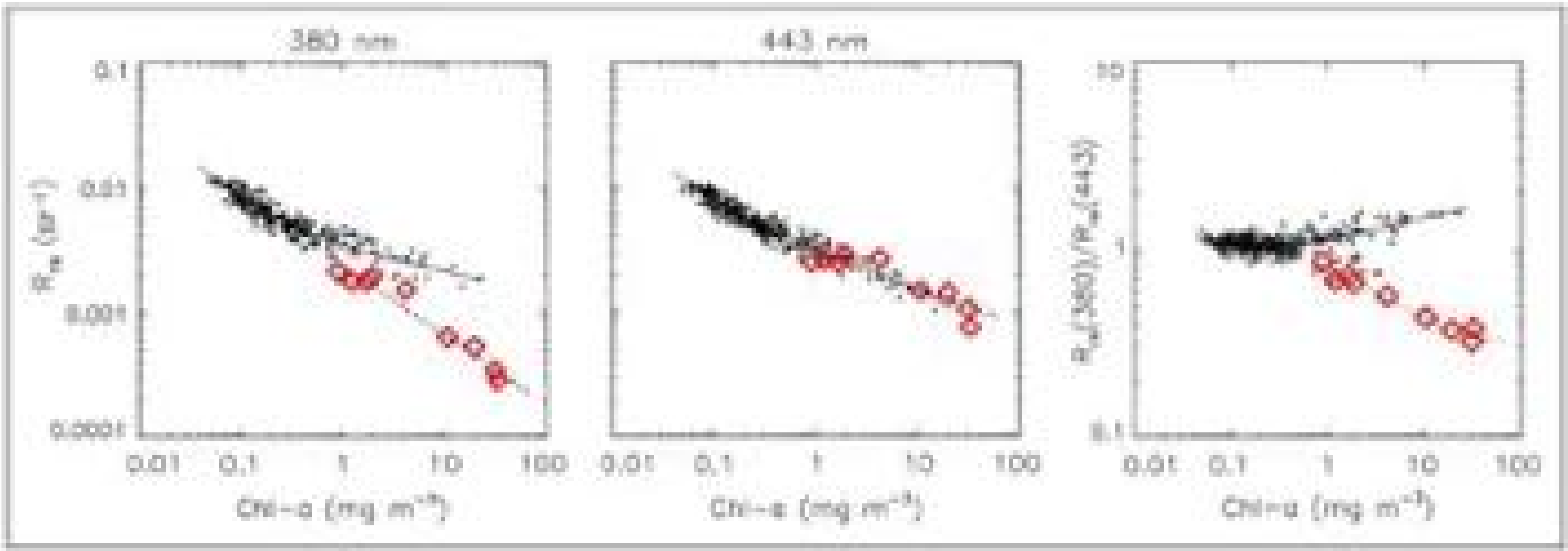
Vernet & Whitehead (1996)

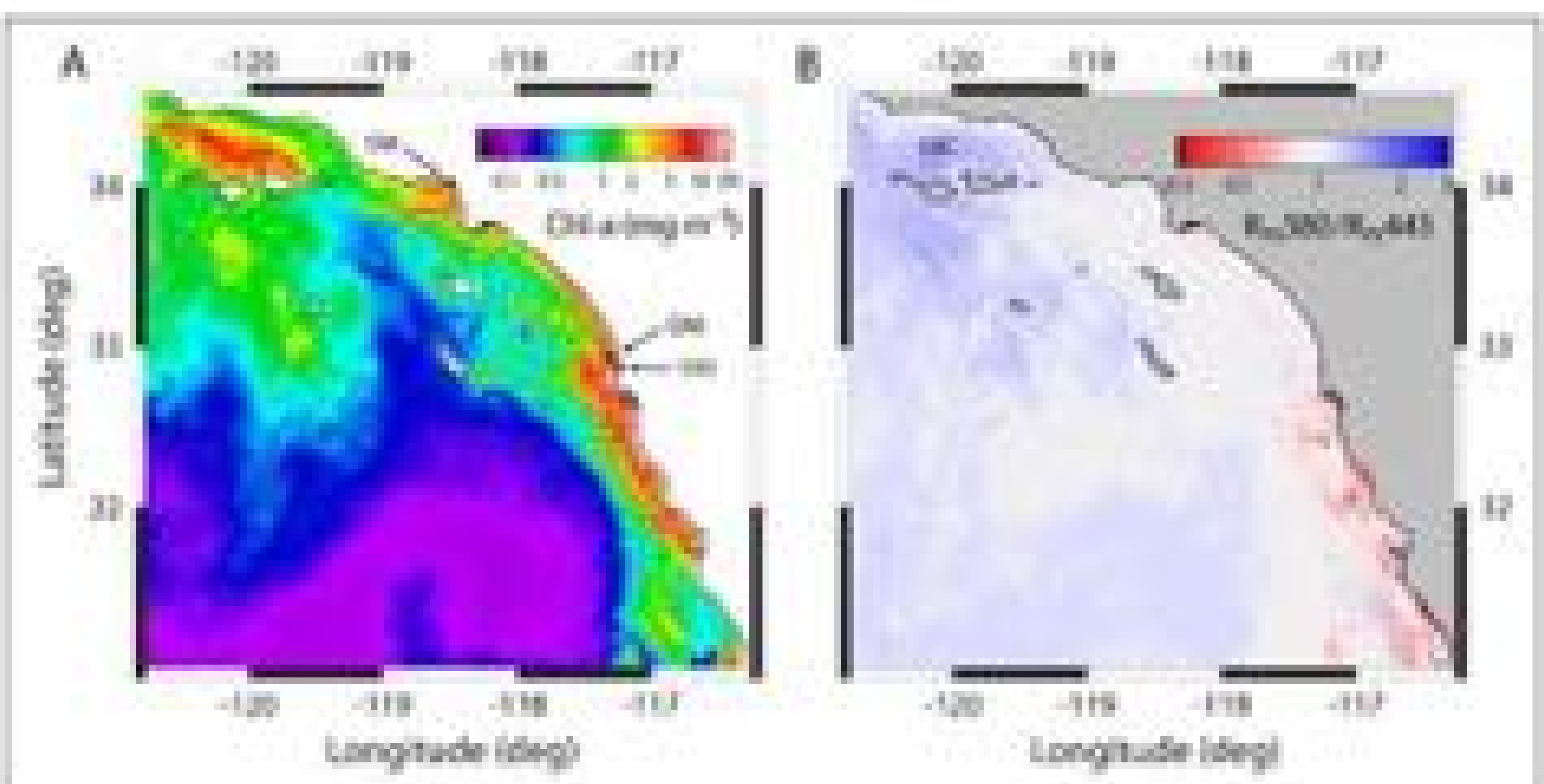
Application to HAB remote sensing

RESEARCH ARTICLE

Satellite detection of dinoflagellate blooms off California by UV reflectance ratios

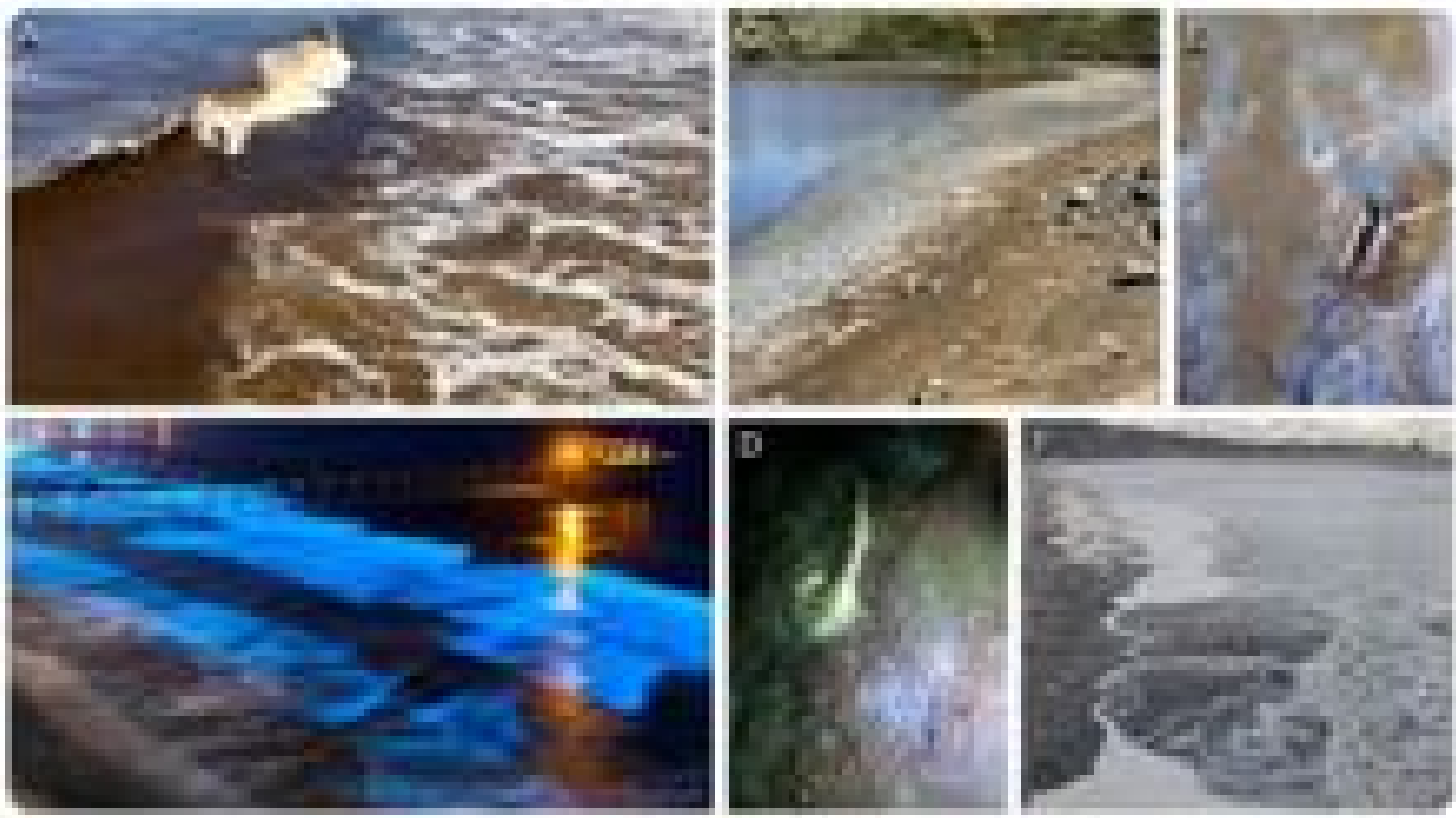
Mati Kahru[1,*], Clarissa Anderson[2], Andrew D. Barton[1,3], Melissa L. Carter[1], Dylan Catlett[4], Uwe Send[1], Heidi M. Sosik[5], Elliot L. Weiss[1], and B. Greg Mitchell[1]





Karhu et al., (2021)

Remote sensing of bioluminescence?

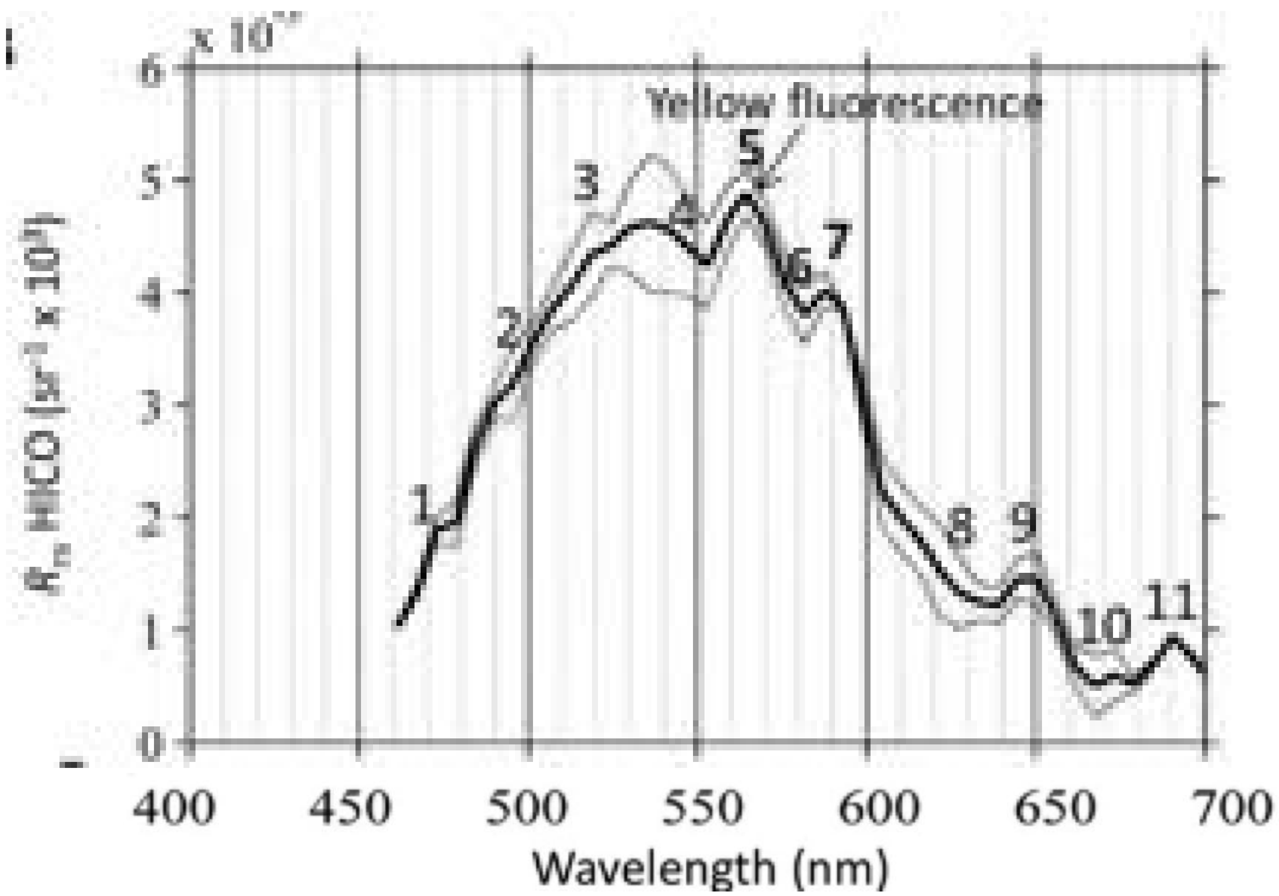


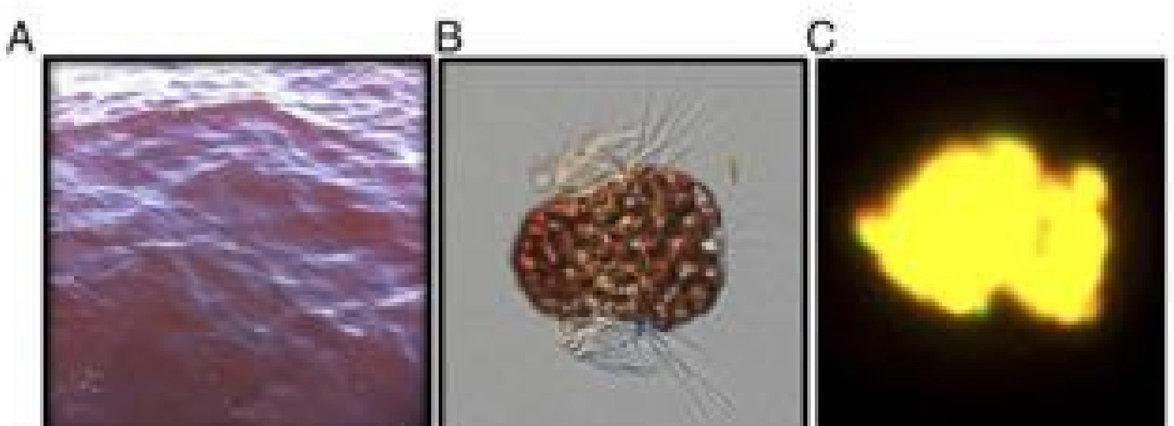
A photo compilation showing aspects of the 2020 *L. polyedra* red tide.

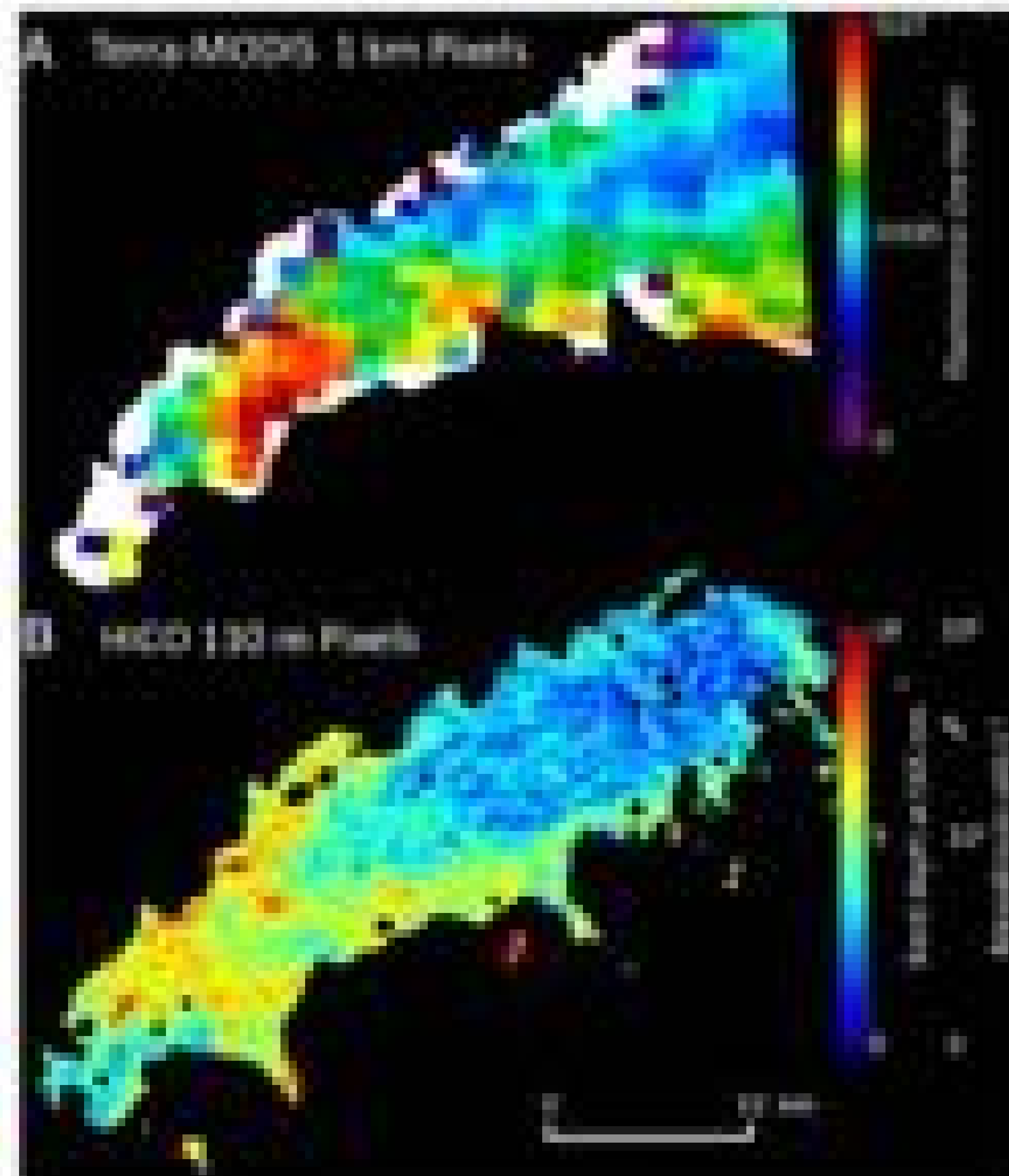
Fluorescence of bio-marker pigments?

Space station image captures a red tide ciliate bloom at high spectral and spatial resolution

Heidi Dierssen[a,1], George B. McManus[a], Adam Chlus[a], Dajun Qiu[a,b], Bo-Cai Gao[c], and Senjie Lin[a]

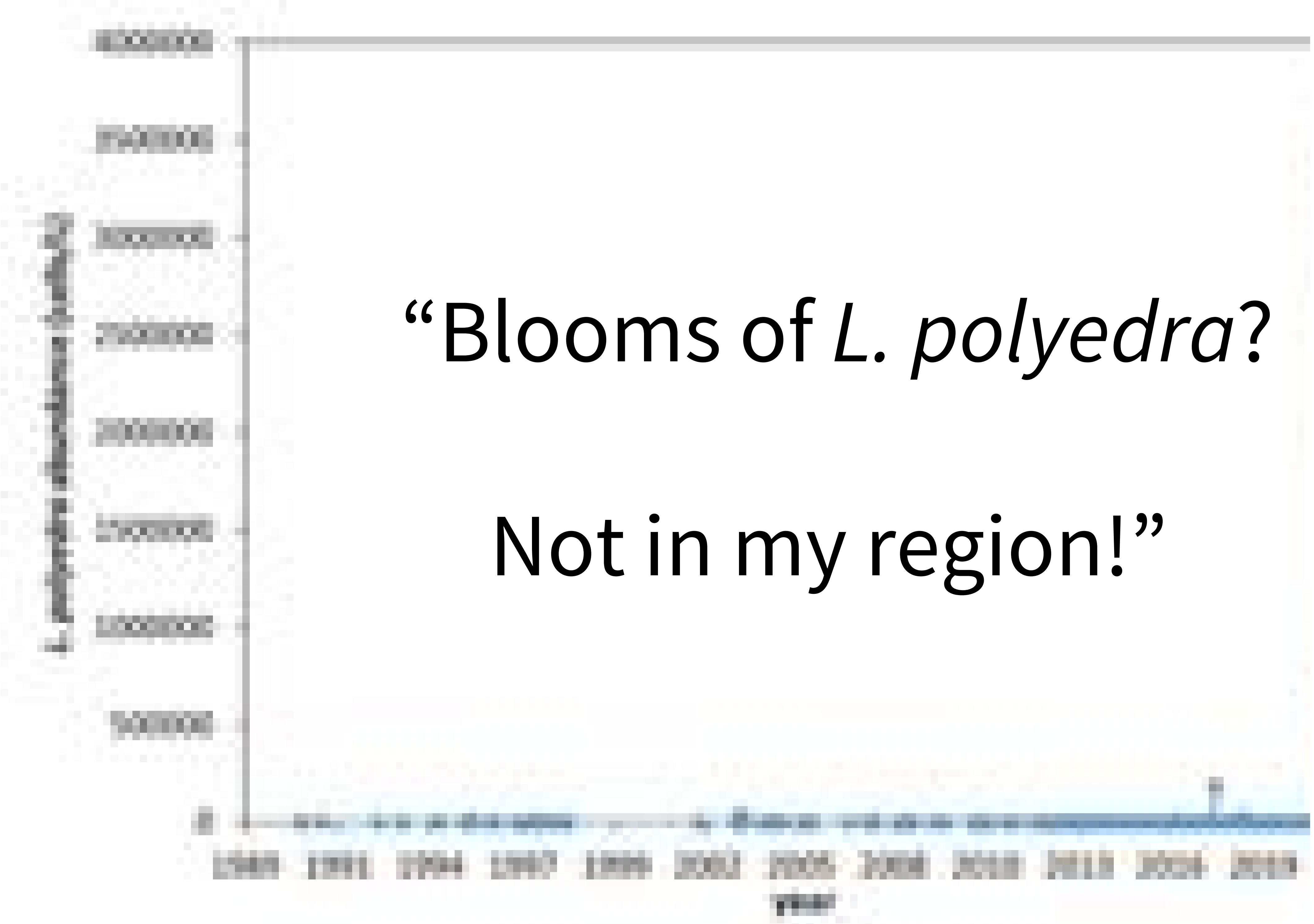






Dierssen et al., (2015)

Do not trust empirical knowledge too much

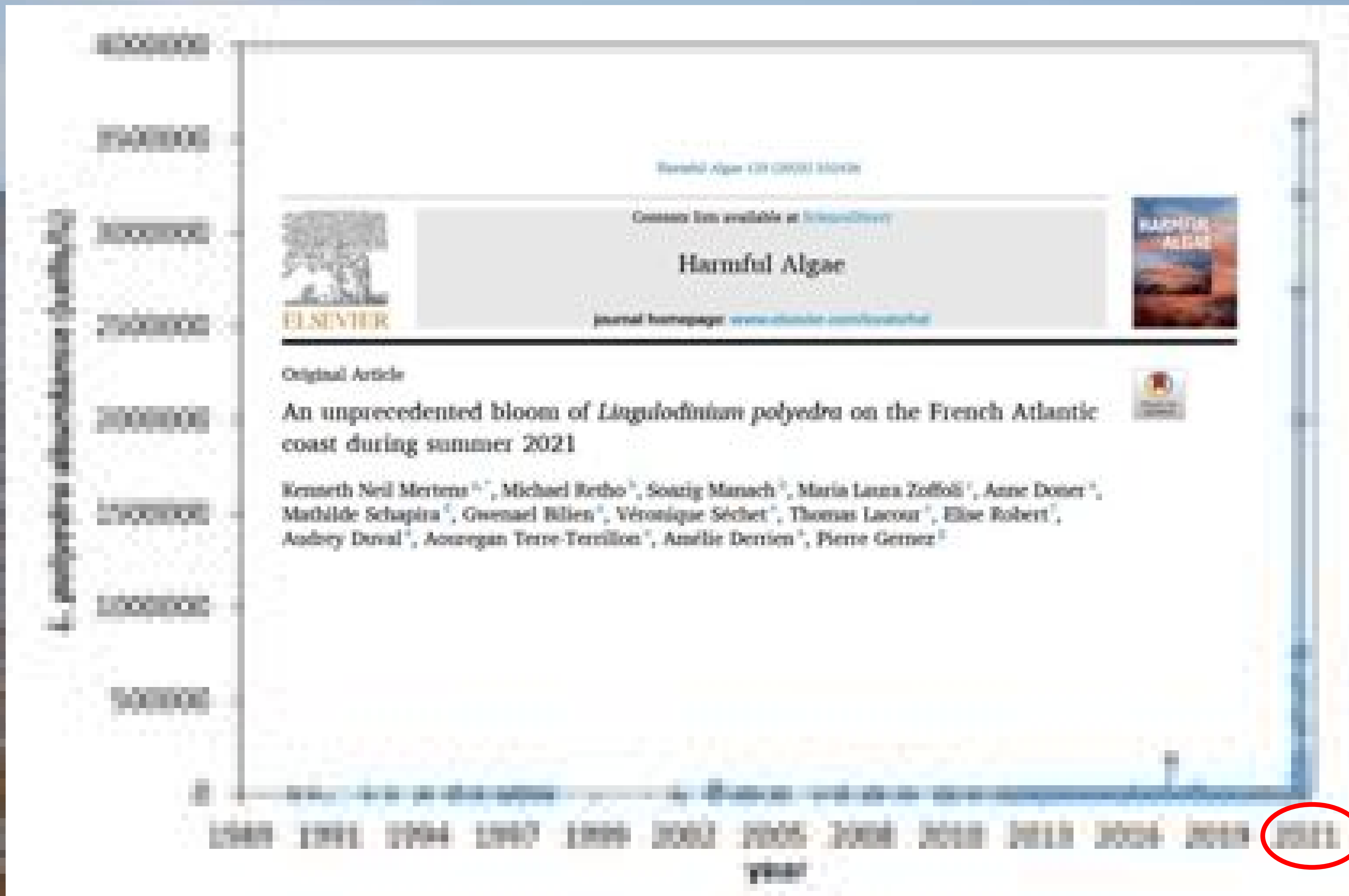


“Blooms of *L. polyedra*?

Not in my region!”

Mertens et al., (2023)

Surprise!



Mertens et al., (2023)

Emerging HABs

“These findings reveal a BTX-producing Karenia that causes substantial detrimental marine ecosystem impacts, representing an emerging international threat with unknown consequences given changing ocean conditions”

nature ecology & evolution

A catastrophic marine mortality event caused by a complex algal bloom including the brevetoxin producer *Karenia cristata*


Thank you for your attention!