IOCCG Summer Lecture Series

Applications of LiDAR to Ocean Color science

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Ocean optics course

16 July 2026

Summary

- Introduction
  - Passive and active measurements

- OC Lidar history
  - Late 1960s – 1970s: Early days
  - Late 1970s – 1980s: Transition to quantitative retrievals
  - Late 1980s–1990s: Toward modern bio-optical applications

- OC Lidar applications
  - Shipborne
  - Airborne
  - Satellite

- Current and Future OC Lidar initiatives
  - EarthCARE
  - LUCE
  - Toward a network of in-situ lidar?

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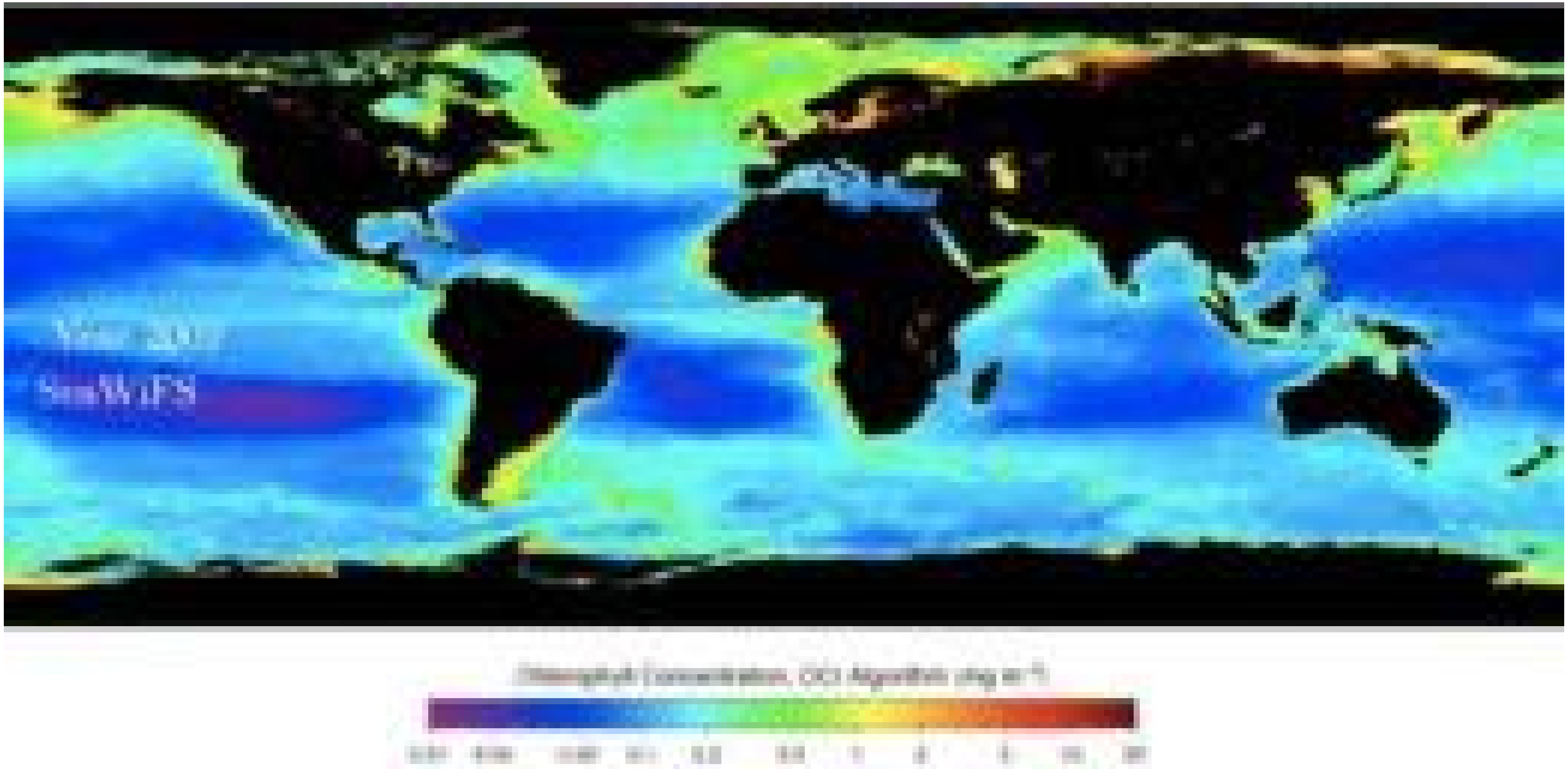
Istituto di Scienze Marine

Introduction – OC remote sensing

Space-borne observations of ocean color are the only tools to monitor at high spatial and temporal resolutions the bio-optical and biogeochemical parameters of the ocean



Introduction – OC remote sensing

Passive vs Active OC observations

Passive Ocean Color Sensors

✅ Strengths:
•Large spatial coverage
•Long-term data records
•Multi-spectral capabilities

❌ Weaknesses:
•Dependent on sunlight
•Surface-limited (no profiling)
•Atmospheric corrections required

Lidar Ocean Color Sensors

✅ Strengths:
•Works day and night (independent of sunlight)
•Subsurface profiling
•High spatial and vertical resolution
•Measurements through thin clouds, between holes in broken clouds, aerosol layers

❌ Weaknesses
•Limited spatial coverage
•One or two wavelengths
•Low repetitivity for spaceborne lidars

Active/Passive observations are highly complementary

Introduction – OC Lidar

Late 1960s – 1970s: Early days

1969 — Airborne laser applied to bathymetry (Hickman and Hogg, 1969).

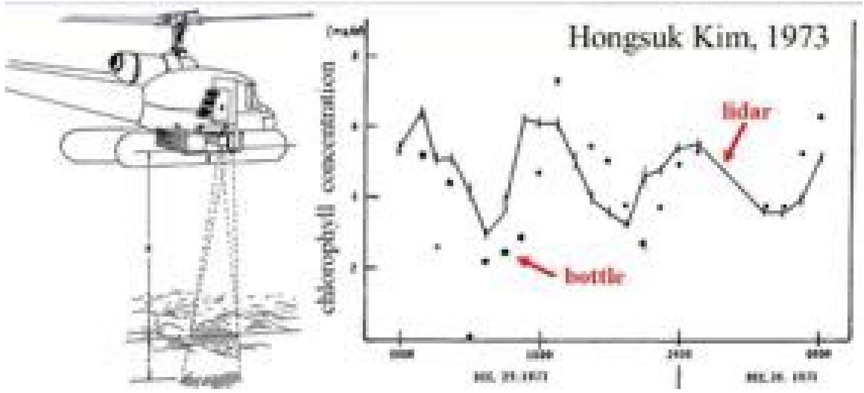
- Not yet targeting color or biology, demonstration of the feasibility of laser probing of the water column from aircraft

1973 — First airborne lidar mapping of chlorophyll (Kim, 1973)

- Development of an airborne laser fluorosensor to detect chlorophyll-a fluorescence (~685 nm) using dye laser excitation (~590 nm).

1977 — Development of airborne oceanographic lidar (AOL, Bressel et al., 1977)

- First integrated airborne lidar system explicitly designed for oceanographic (bio-optical) applications. Emission: 532 nm; Detection: spectrometer 350–800 nm

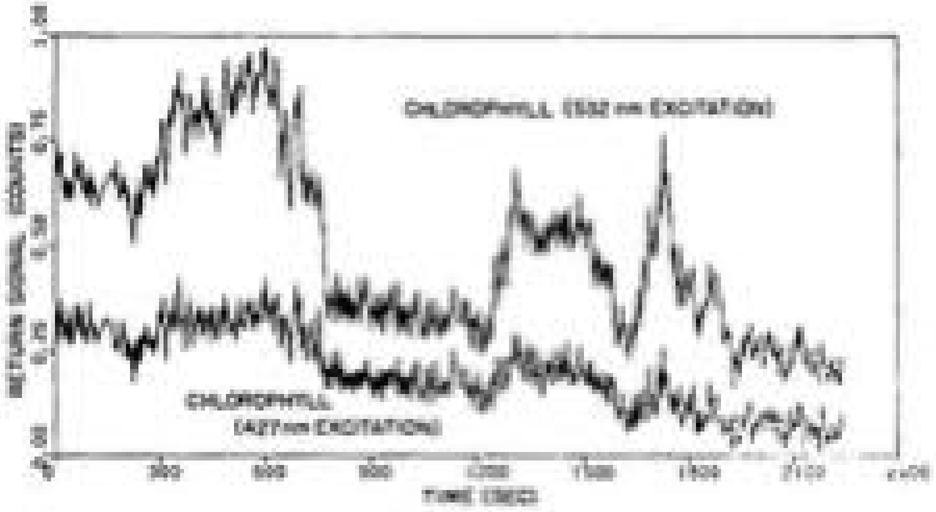


Introduction – OC Lidar

Late 1970s – 1980s: Transition to quantitative retrievals

1981 — Raman-corrected chlorophyll retrievals (Bristow et al., 1981)

- First operational Raman-based correction of attenuation effects, enabling quantitative airborne estimation of chlorophyll. Emission: 337 nm; Detection: Raman 381 nm; Chl-a 685 nm



1983 — Dual-laser excitation and pigment discrimination (Hoge and Swift, 1983)

- First use of dual-laser excitation to discriminate pigment types (e.g., chlorophyll vs phycoerythrin) and study water masses. Emission: 532 + 425 nm; Detection: Raman 645 nm; Chl-a 685 nm; PE 580 nm

1986 — Integrated active–passive ocean color measurements (Hoge et al., 1986)

- First combined active-passive ocean color system.

Since 2001 AOL:

Emission: 355 and 532 nm

Detection: 404–405 nm; 450-460 nm;

570–590 nm; 645–650 nm; 685 nm

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Introduction – OC Lidar

Late 1980s–1990s: Toward modern bio-optical applications

1993 — LIF lidar applications (Babichenko et al., 1993)

- Use of LIF lidar to measure phytoplankton abundaces

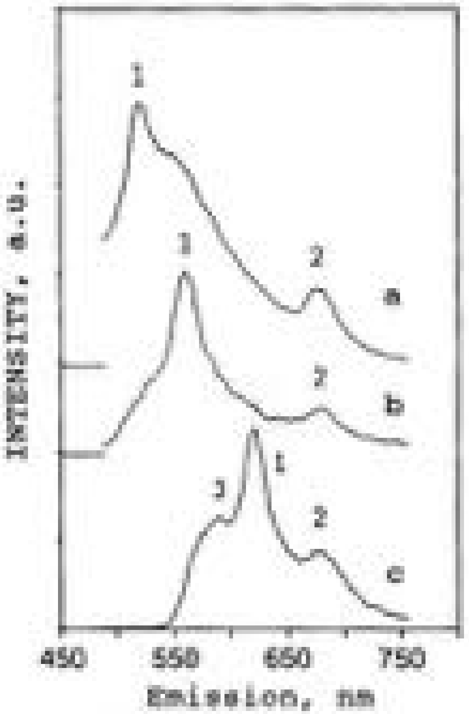


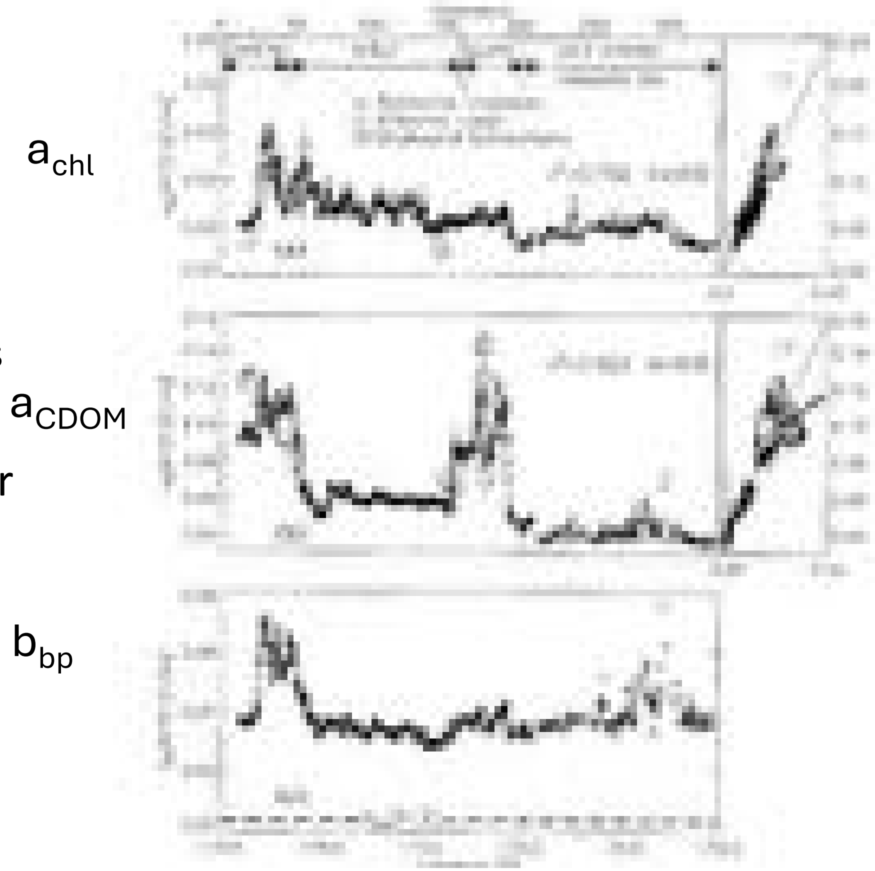
Figure 2. Laser-induced fluorescence spectra of surface water obtained during underway measurements at a) 445 nm, b) 490 nm, and c) 515 nm excitation wavelengths: 1 - Raman scattering band, 2 - fluorescence of Chlorophyll a, 3 - fluorescence of phycoerythrin.

1995 — Retrieval of CDOM and inherent optical properties (Hoge et al., 1995)

- Shift toward retrieval of inherent optical properties (IOPs) beyond chlorophyll

1999 — Integration with satellite-era ocean color (Hoge, 1999)

- Lidar becomes a bridge between in situ measurements and global satellite ocean color retrievals



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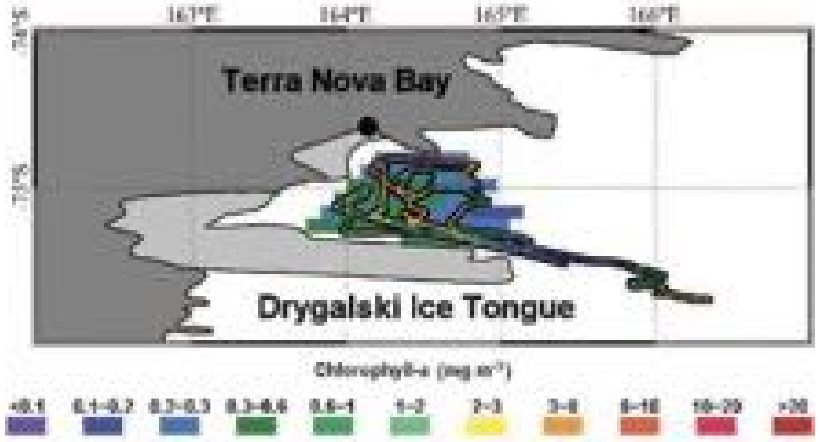
OC lidar – Applications

Shipborne lidar

Barbini et al., 2002

Fluorescence Lidar



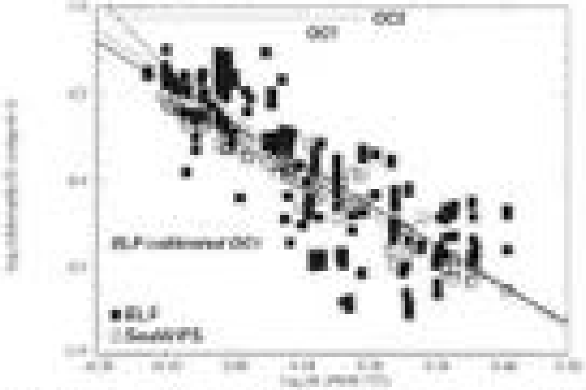


Table 2. Specifications of ELF during a typical operation in oceanographic campaigns.

Transmitter	Laser	Nd:YAG
	Wavelength	355 nm
	Pulse energy	3 mJ
	Pulse duration	10 ns
	Pulse repetition rate	10 Hz
Receiver	Telescope	Cassegrain
	Clear aperture	0.4 m
	Focal length	1.65 m
	Centre wavelengths	404, 450, 650, 680 nm
	Bandwidths	5 nm FWHM
Electronics	Detectors	Photomultipliers
	Gate width	100 ns
	Dynamic range	15 bit
	Bus	ISA-VME mixed
	Central Processing Unit	VME embedded 486 (100 MHz)

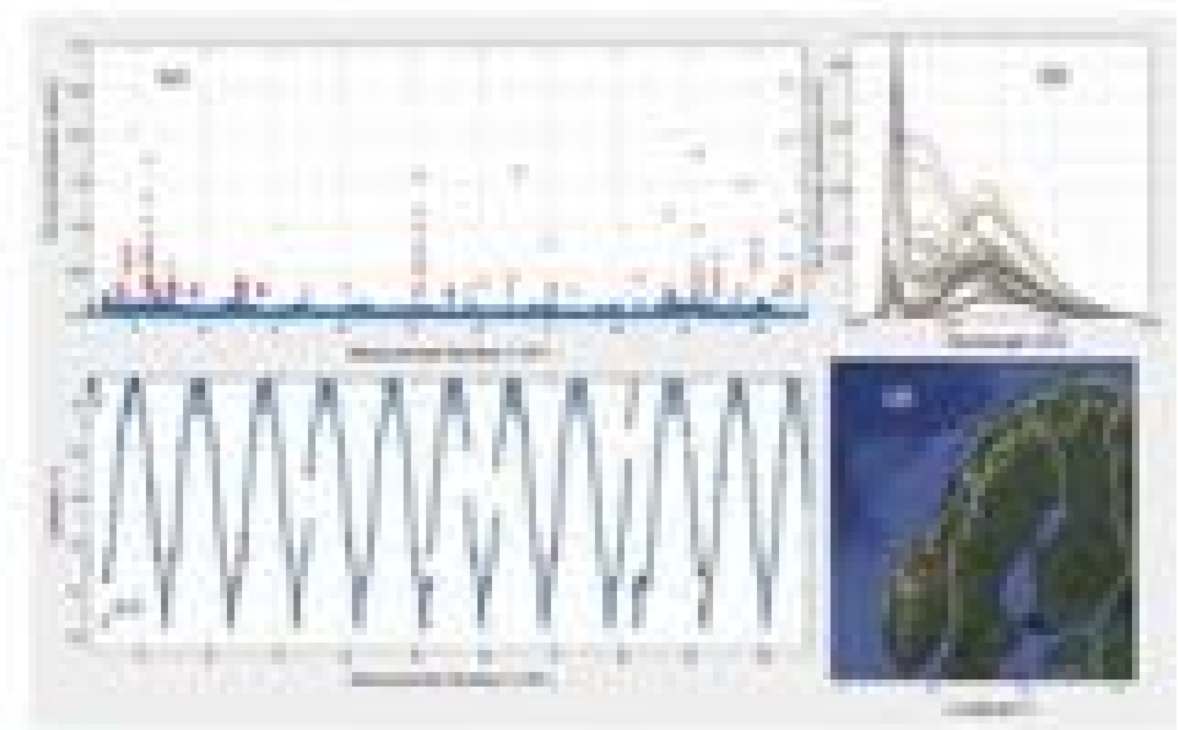
- ❑ Lidar chlorophyll-a compared with SeaWiFS chlorophyll products for algorithm assessment/calibration.
- ❑ Largest discrepancies occurred in coastal waters; offshore waters showed lower discrepancy and were suitable for calibration.

Demonstrates the value of active fluorescence lidar for satellite ocean-colour validation in Southern Ocean waters.

OC lidar – Applications

Shipborne lidar

Babichenko et al., 2016



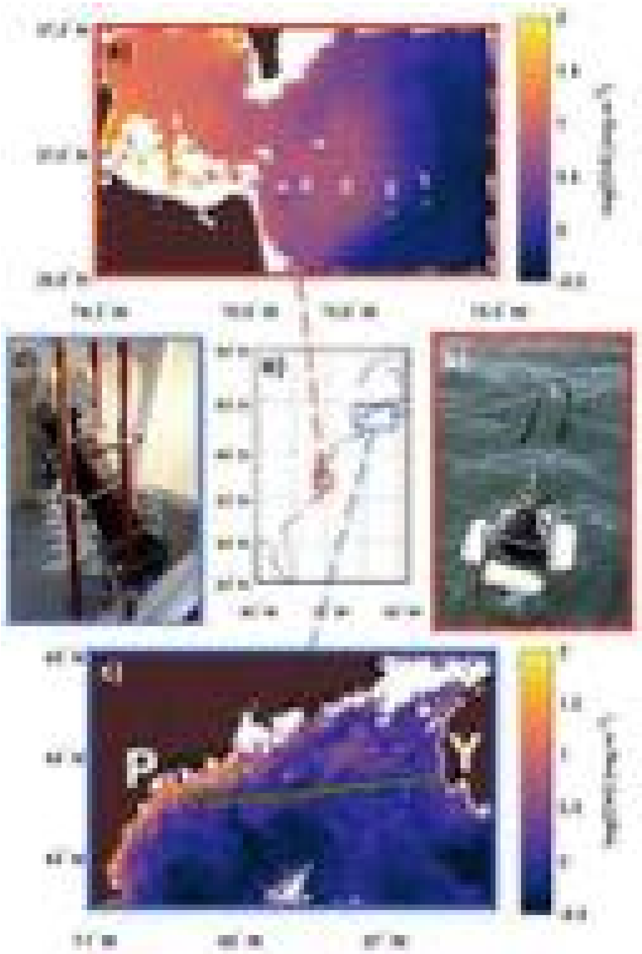
- Compact Hyperspectral Laser-Induced Fluorescence (HLIF) LiDAR for real-time marine monitoring.
- Detection and characterization of oil-in-water pollution using intrinsic fluorescence signatures.

From research prototypes to compact, operational, unattended fluorescence-lidar monitoring.

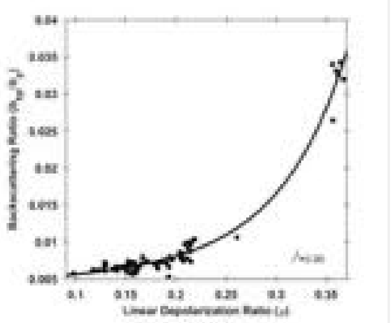
OC lidar – Applications

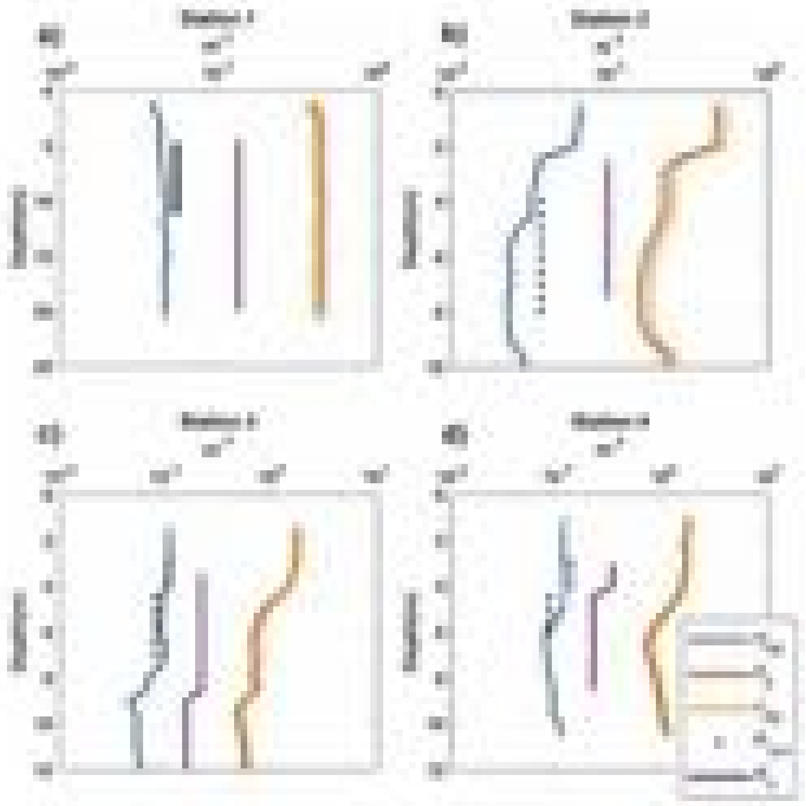
Shipborne lidar

Collister et al., 2018



- ❑ Constructed and deployed a ship-based lidar to profile laser backscatter and linear depolarization in the upper ocean
- ❑ Linear depolarization ratio was strongly related to particulate backscattering ratio bbp/bp, supporting particle characterization



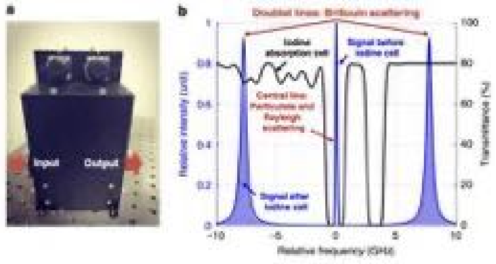


Shipboard lidar complements passive ocean colour by resolving vertical particle and optical-property distributions

OC lidar – Applications

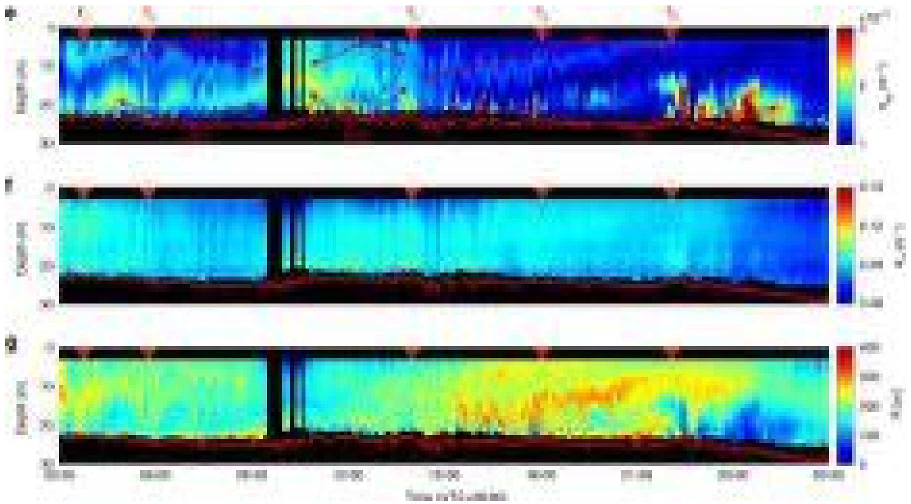
Shipborne lidar

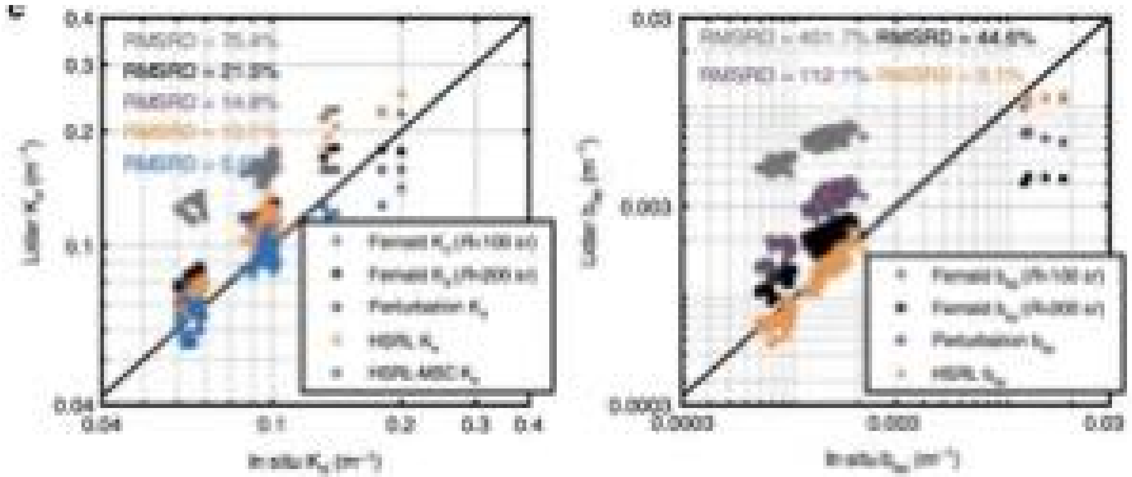
Zhou et al., 2022

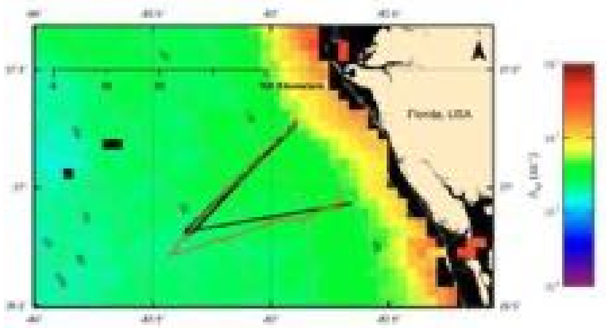


- ❑ Shipborne oceanic High-Spectral-Resolution LiDAR (HSRL) for depth-resolved optical-property retrievals (Kd and bbp at 532 nm)
- ❑ Combines HSRL separation with a multiple-scattering correction to address elastic-lidar retrieval limitations.

HSRL represents a major accuracy leap toward 3D, day/night mapping of upper-ocean optical structure.







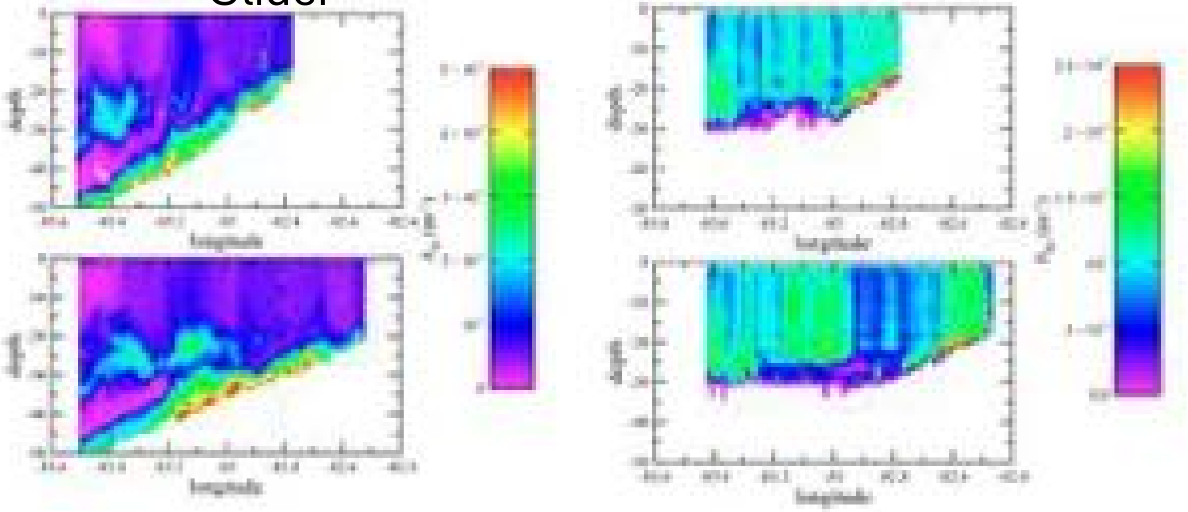
OC lidar – Applications

Airborne lidar

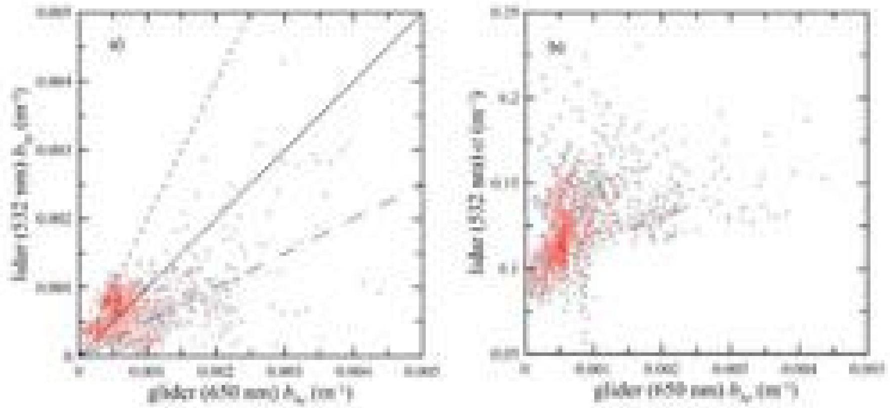
Churnside and MarchBanks, 2017

Glider

Lidar



- Airborne elastic lidar estimates ocean particulate backscatter profiles from range-resolved 532 nm returns
- Compared lidar-derived optical backscattering with underwater-glider measurements
- Moderate but significant correlation with mismatch due to sampling offsets, particle composition and lidar retrieval errors



Elastic airborne lidar can deliver dense vertical bbp-like information, but validation depends strongly on matchup geometry and particle composition.

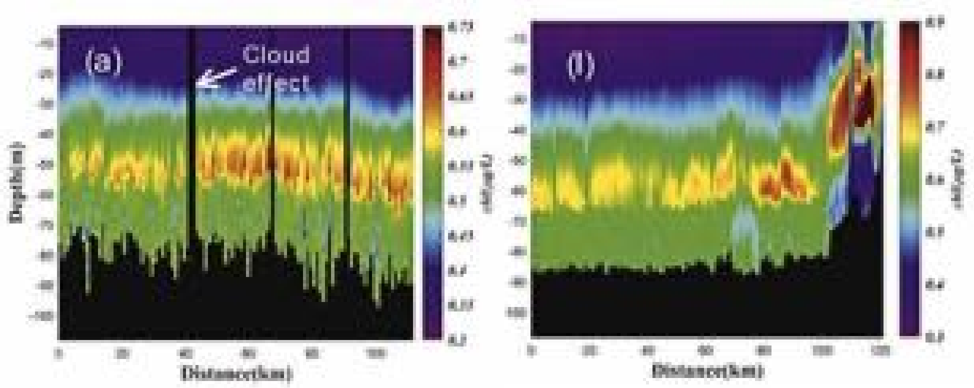
OC lidar – Applications

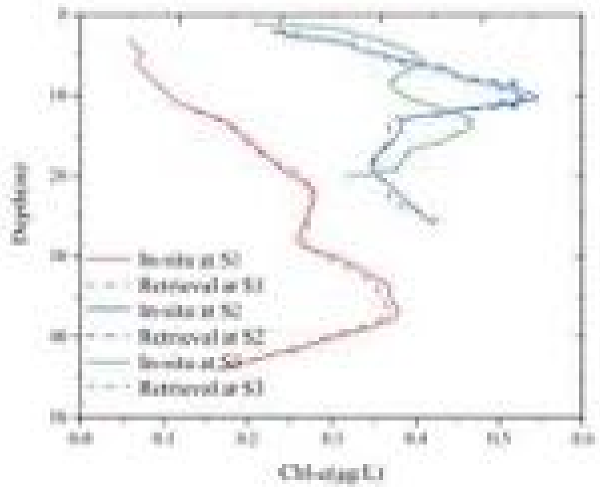
Airborne lidar

Chen et al., 2021

- ❑ Airborne dual elastic polarized lidar (532 and 486 nm)
- ❑ First quantitative airborne-lidar measurements of the subsurface phytoplankton layer (SPL) vertical distribution in the South China Sea.
- ❑ Lidar-retrieved chlorophyll-a agreed with in situ profiles ($R^2 > 0.8$; mean absolute percentage error < 15%).

Airborne lidar directly fills the passive ocean-colour blind spot: the vertical architecture of subsurface phytoplankton biomass.





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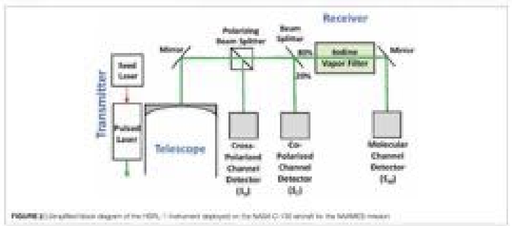
OC lidar – Applications

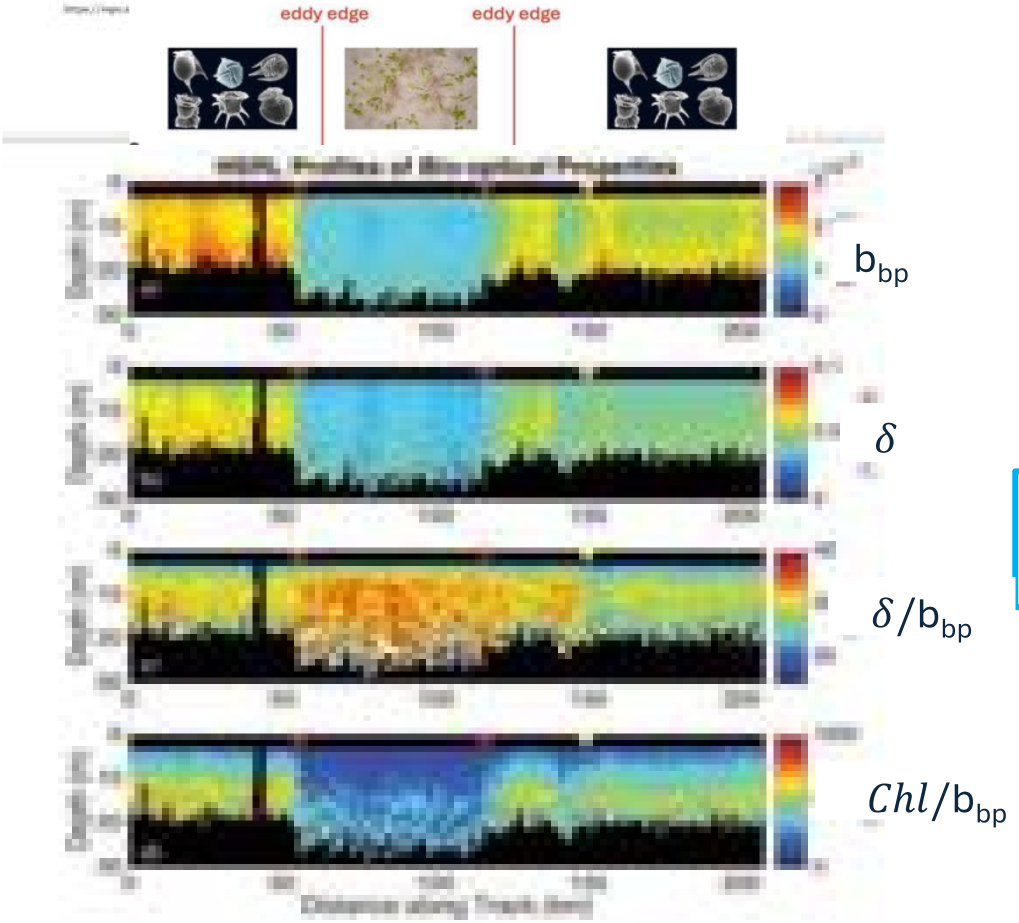
NASA HSRL-2

Airborne lidar

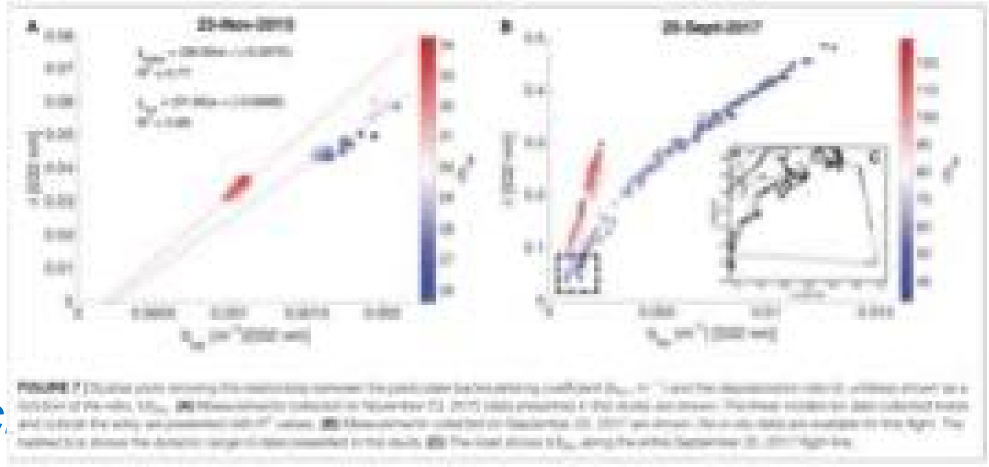


Schulien et al., 2020

- ❑ Airborne HSRL measurements of scattering, depolarization and attenuation coincided with shifts in phytoplankton community composition across an anticyclonic eddy.
- ❑ Chl:bbp decreased by more than a factor of two inside the eddy, supporting interpretation of community-composition change.
- ❑ Demonstrates HSRL sensitivity not only to particle amount, but also to particle morphology / ecosystem structure.



HSRL + depolarization moves airborne ocean lidar from biomass mapping toward community-structure diagnostics

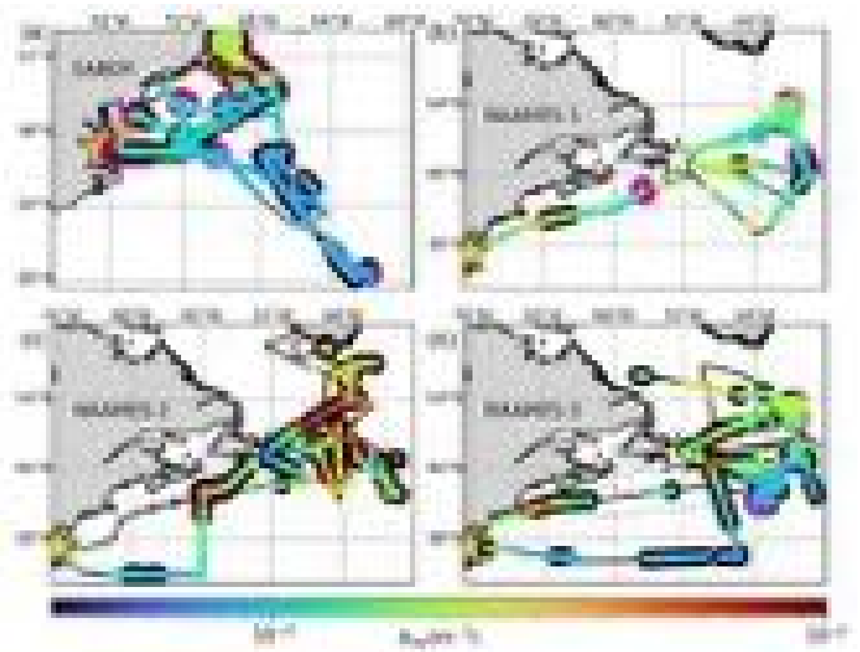


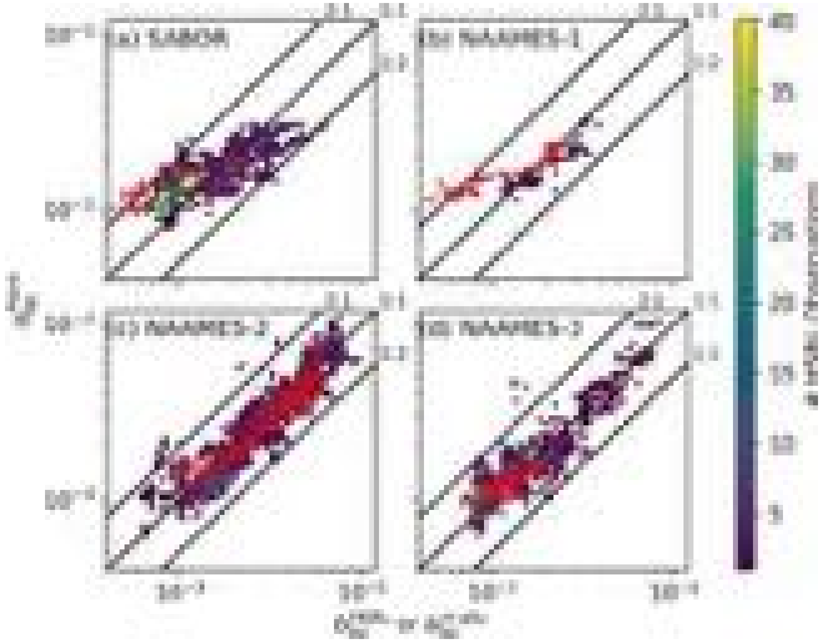
OC lidar – Applications

Airborne lidar

Collister et al., 2024

- Comparison of b_{bp} derived from airborne HSRL, satellite ocean color, and *in situ* measurements across a diversity of optical domains
- Identified regional/seasonal dependencies in satellite ocean-colour bbp retrievals, consistent with algorithm-domain limitations.



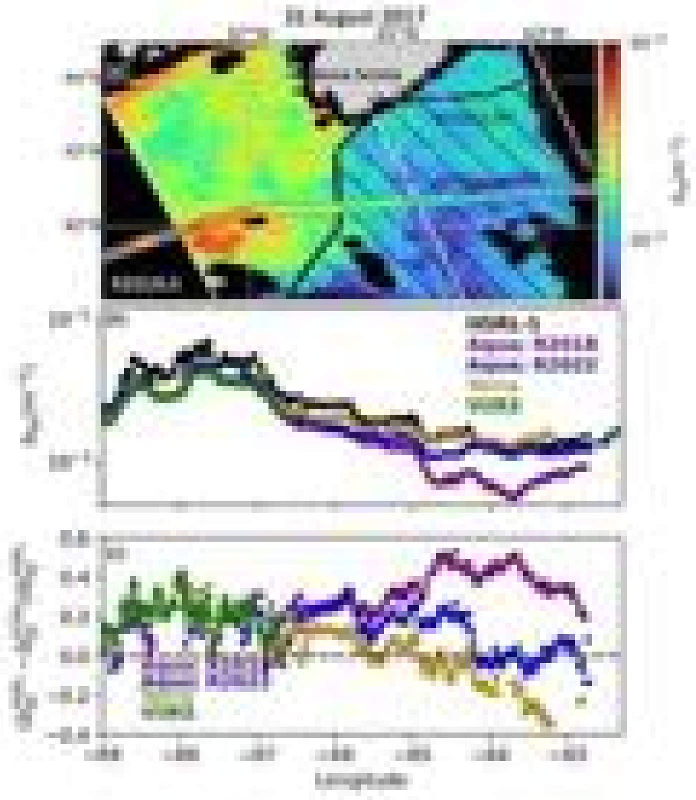


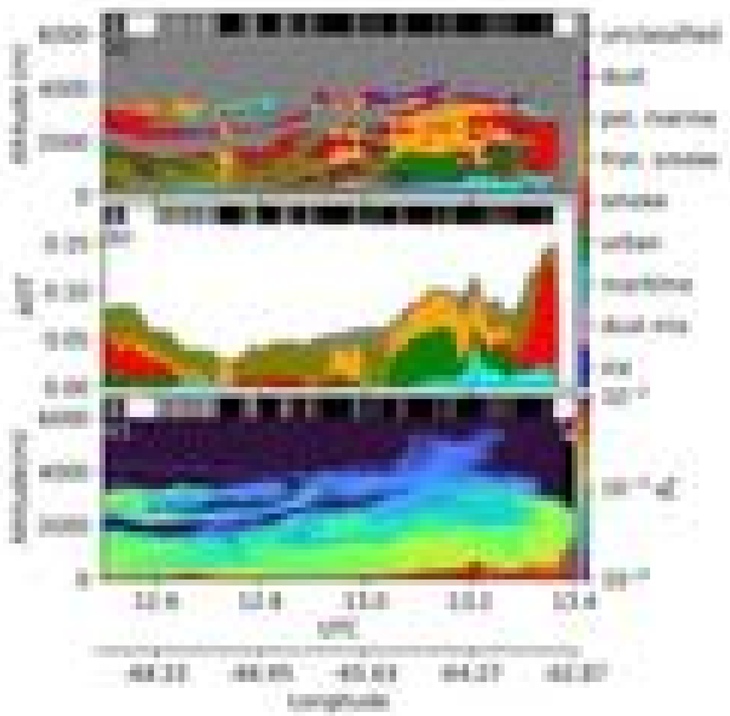
OC lidar – Applications

Collister et al., 2024

Airborne lidar

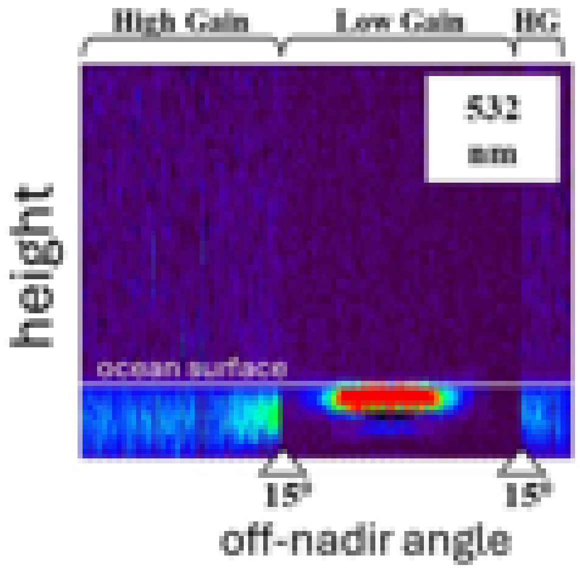
- Case studies showed how HSRL atmospheric + ocean information can diagnose inadequate atmospheric correction in passive products





Airborne HSRL as a benchmark tool for evaluating both in-water IOP retrievals and atmospheric correction in passive ocean colour

OC lidar – Applications

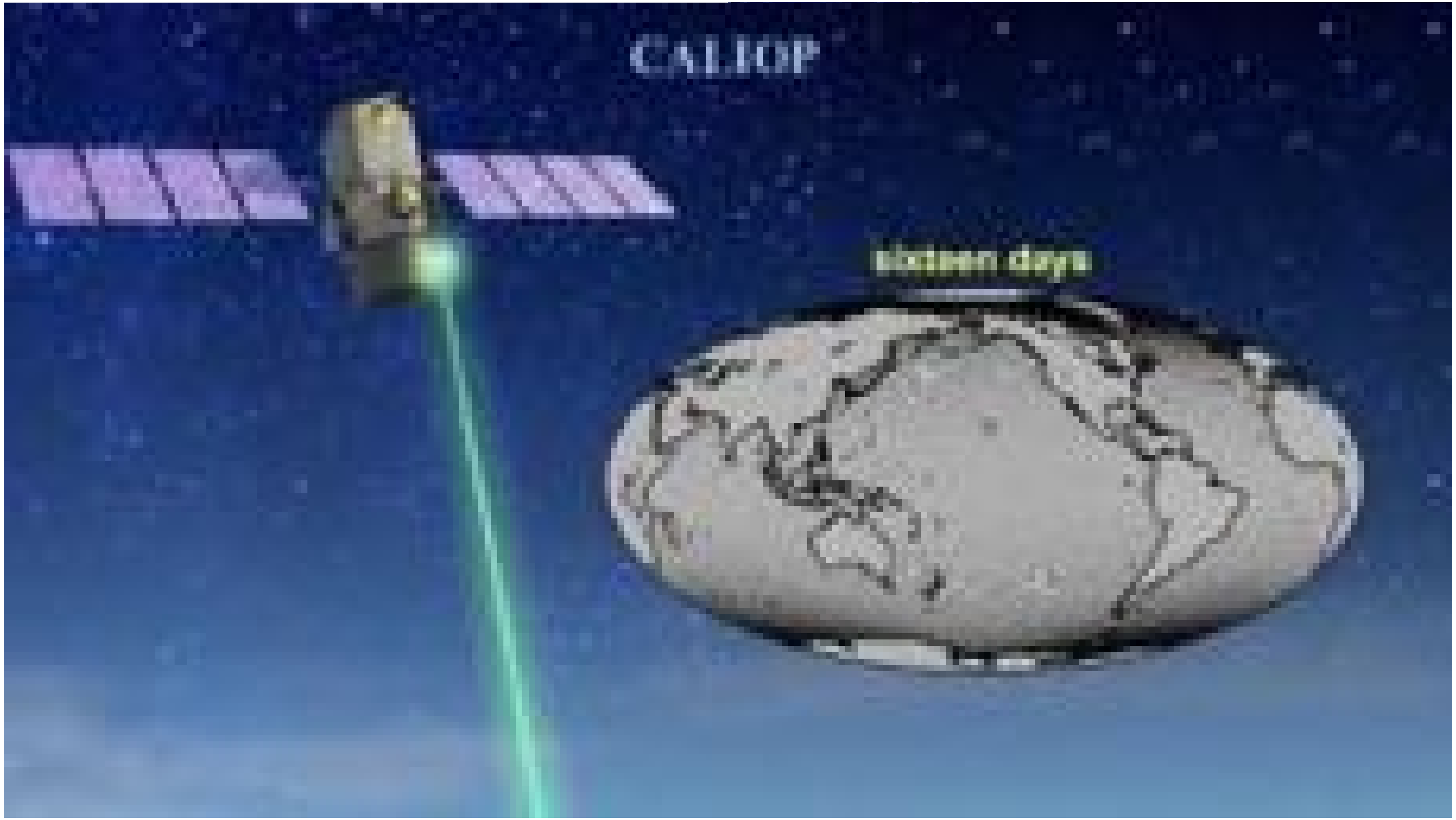


OC lidar – Applications

Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP)

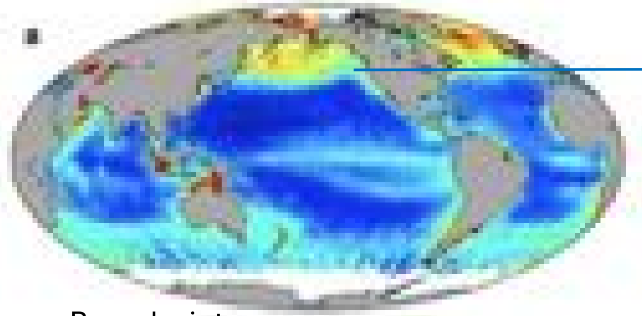
- NASA-CNES partnership (2006 – 2023)
- Designed for atmospheric (**NOT** ocean) science
- 2-wavelength Nd:Yg laser (532, 1064 nm)
- 3-channel (532||, 532 ⊥ , 1064 nm)
- 30 m air / 23 m water vertical resolution
- polar orbiting, 16 day repeat cycle

OC lidar – Applications

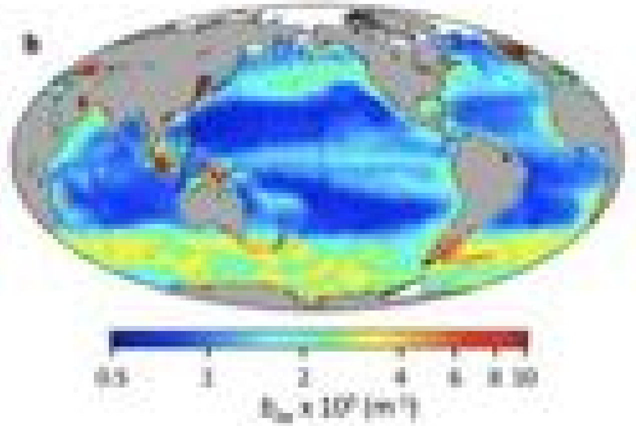


OC lidar – Applications

Boreal summer



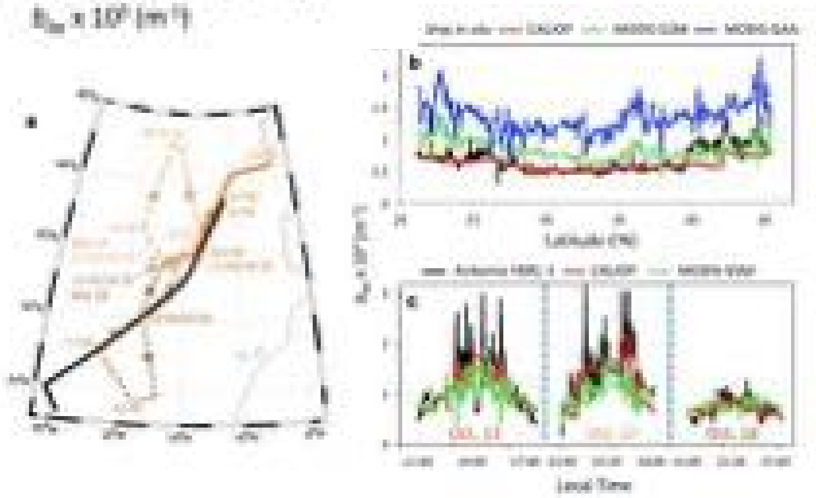
Boreal winter



Satellite lidar

Behrenfeld et al., 2013

- First demonstration that CALIOP can retrieve ocean particulate backscatter and use it to estimate global phytoplankton carbon biomass and particulate organic carbon stocks.
- The seasonal and spatial patterns consistent with known ocean plankton ecology



Beginning of satellite lidar as a quantitative tool for global ocean biogeochemistry.

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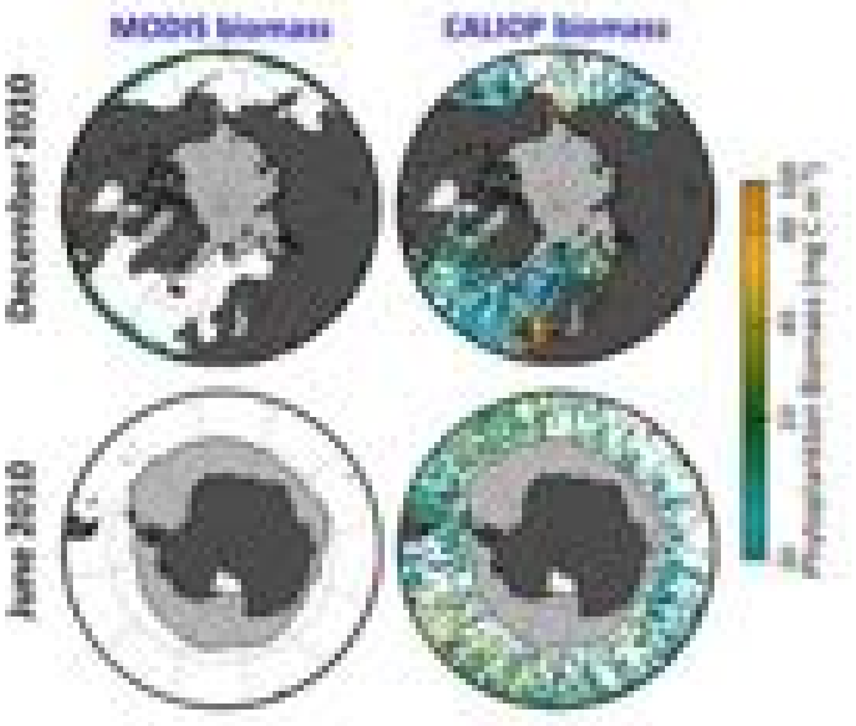
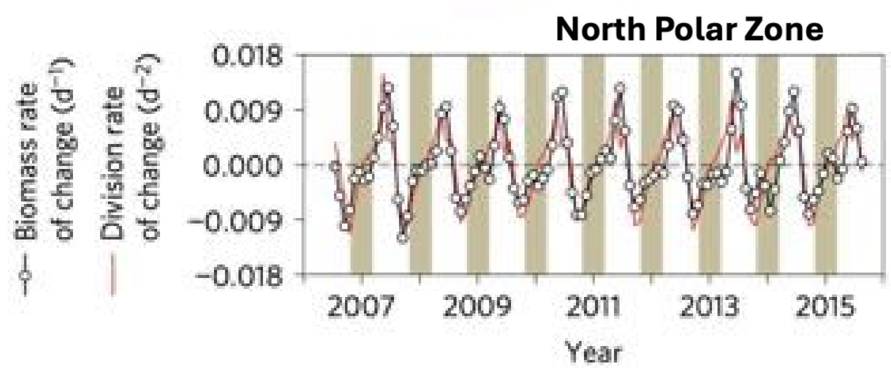
OC lidar – Applications



Satellite lidar

Behrenfeld et al., 2016

- ❑ Passive ocean color severely limited in polar regions by persistent cloud cover, polar darkness and low solar elevations.
- ❑ CALIOP observations from 2006–2015 enabled a decade of polar phytoplankton biomass cycles
- ❑ First unbroken record of polar plankton blooms:
  - Annual boom–bust cycles in polar phytoplankton biomass, linked to predator–prey imbalances and environmental forcing
  - Antarctic variability strongly influenced by changes in sea-ice cover, Arctic variability more strongly associated with ecological processes.
- ❑ Blooms support huge animal populations
- ❑ Polar regions exhibiting amplified responses to climate warming

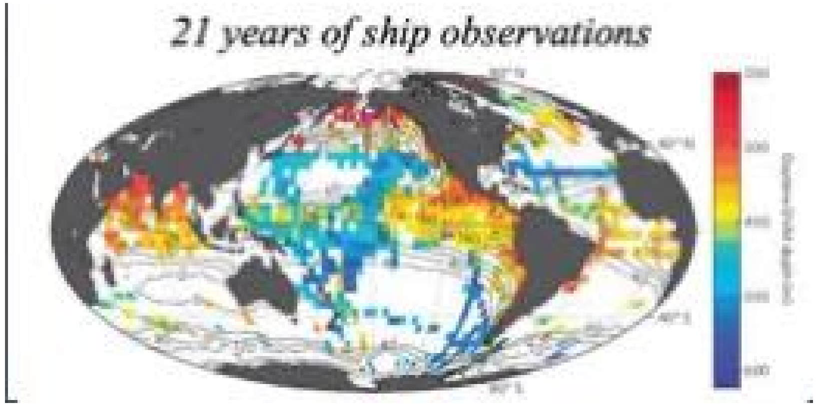


Spaceborne lidar opens a polar observing window that passive ocean color cannot fully provide

OC lidar – Applications

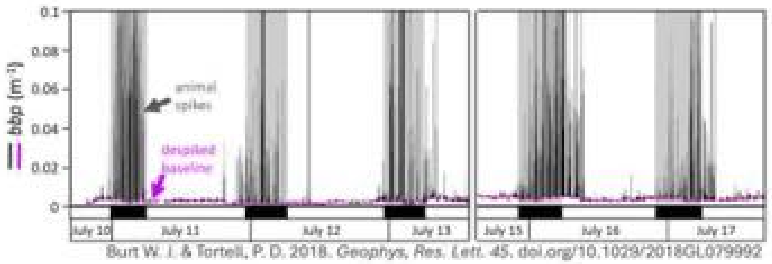
Satellite lidar

Behrenfeld et al., 2019



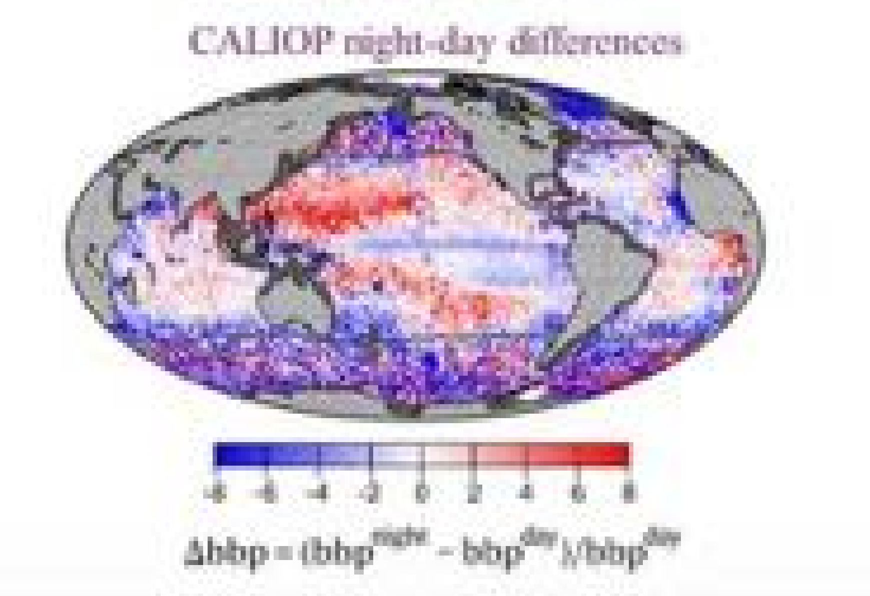
Diel Vertical Migration: 'DVM'

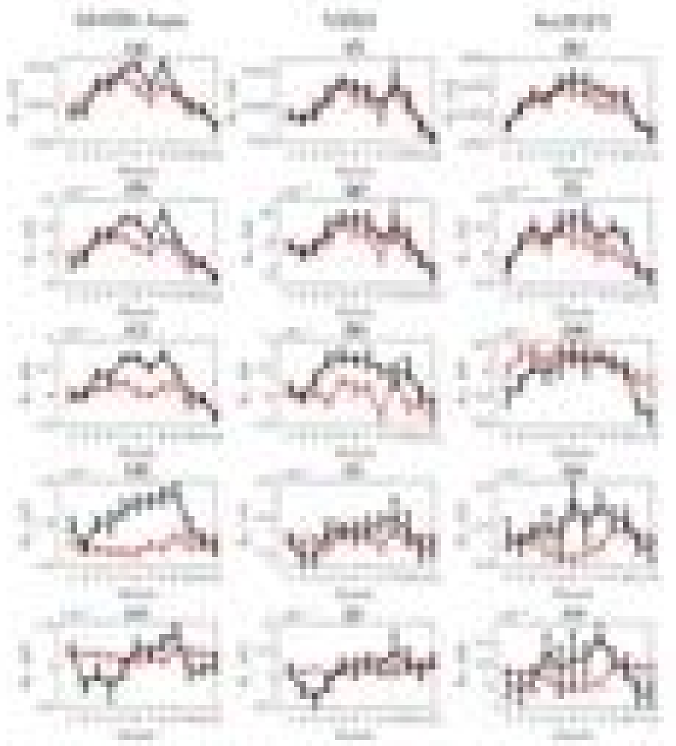
- ❑ Largest animal migration on Earth
- ❑ Major carbon sequestration
- ❑ Target for large scale extraction
- ❑ Ocean color provides NO information



Caliop observation

- ❑ First space-based observations of the migration
- ❑ Monthly coverage dwarfs field data
- ❑ Application: Fisheries (i.e., food stocks)
- ❑ Carbon sequestration assessments
- ❑ Changing stocks (natural, climate-related, fisheries related)

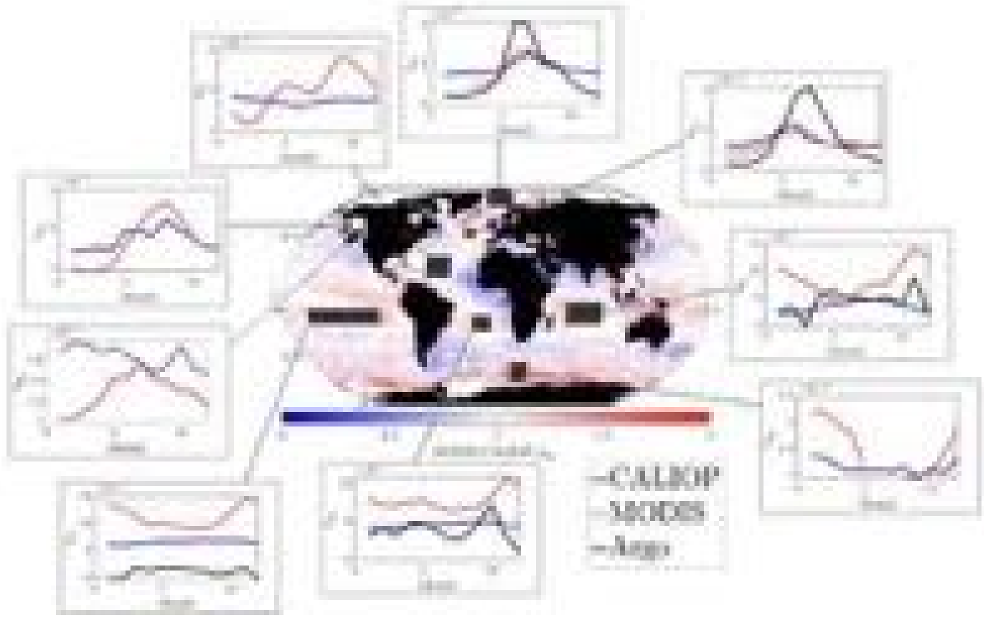




Satellite lidar

Bisson et al., 2021

- Identification of a seasonal bias in satellite-derived $R\_rs\ (\lambda)$, present to different degrees in VIIRS, SeaWiFS and MODIS observations. This bias affected particulate backscattering, chlorophyll and absorption estimates
- CALIOP data, together with Argo floats and MOBY measurements, helped confirm the propagation of the bias from local validation to regional and global scales
- Bias evident in low-biomass regions (e.g. subtropical gyres), less obvious in high-biomass waters

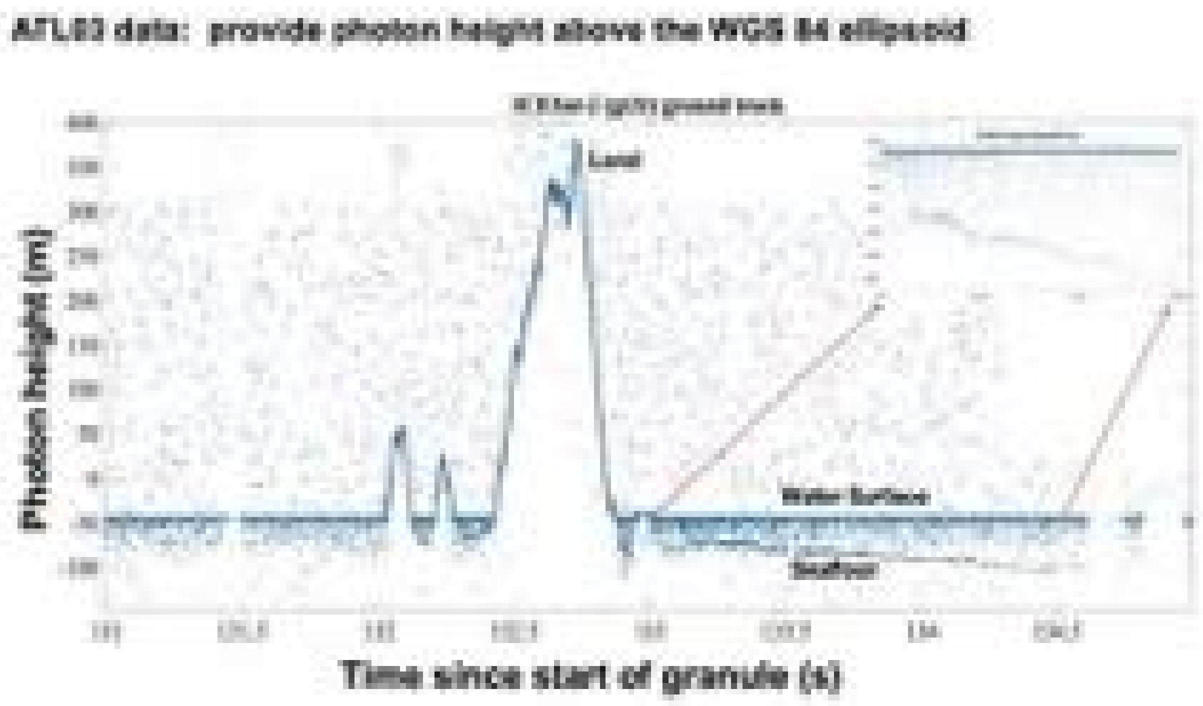


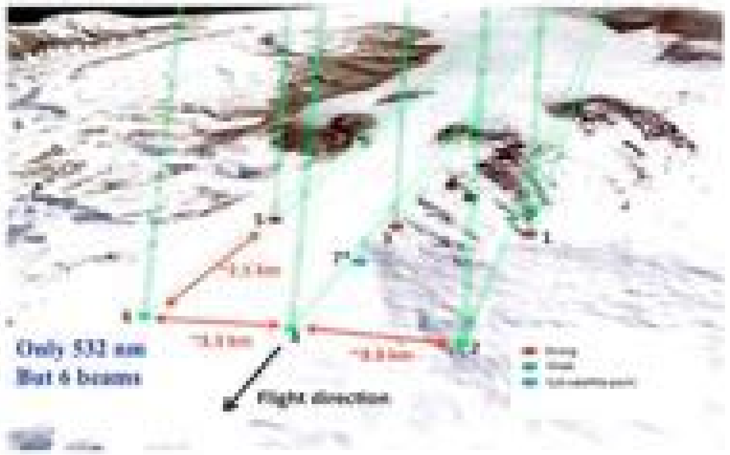
CALIOP data enabled discovery of a seasonal bias in the ~30 yr ocean color record

OC lidar – Applications

Satellite lidar

ATLAS (Advanced Topographic Laser Altimeter System) aboard the ICESat-2 (Ice, Cloud, and land Elevation Satellite 2) has the objective to measure ice sheet elevation, sea ice thickness, land topography, vegetation characteristics, and clouds.



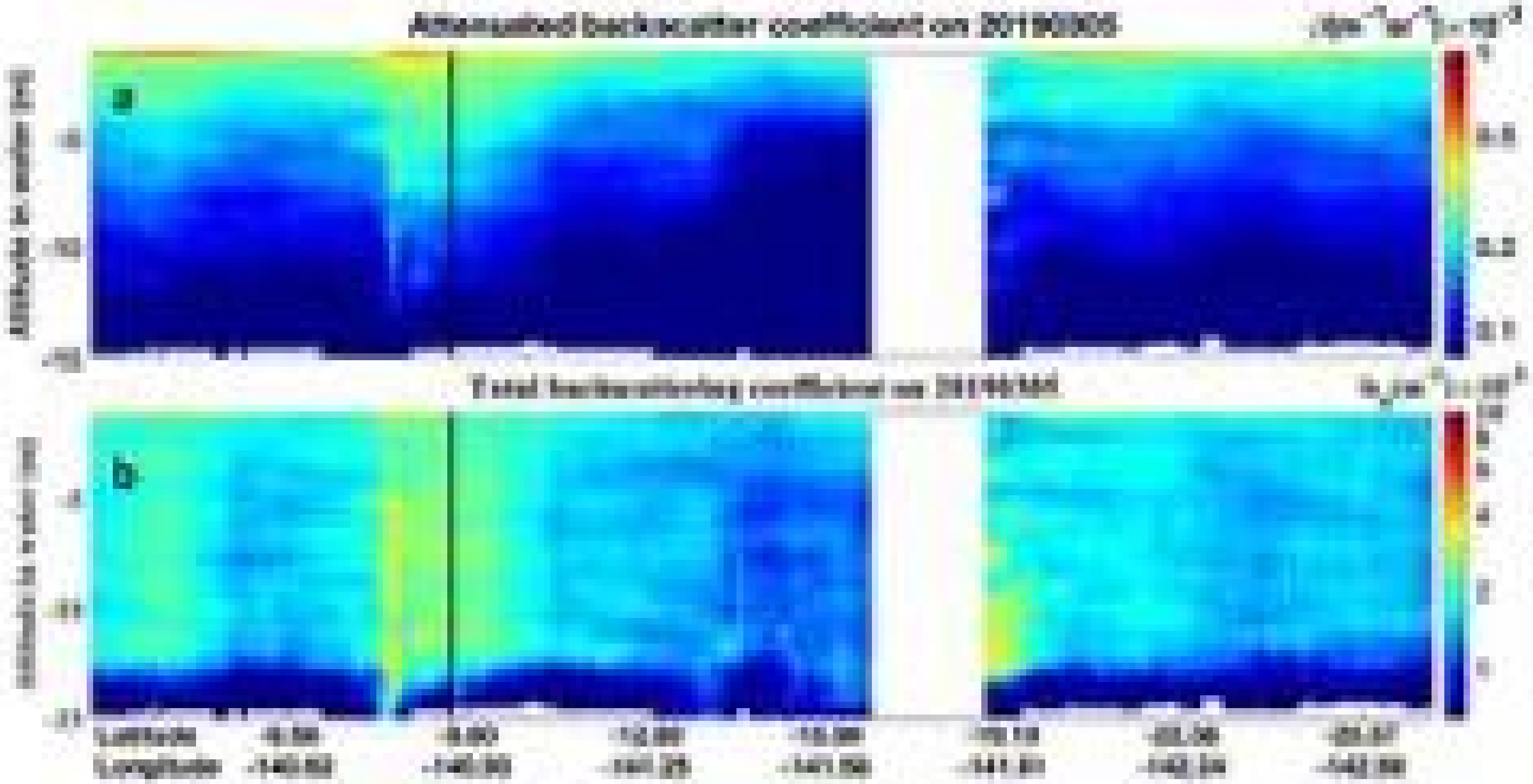


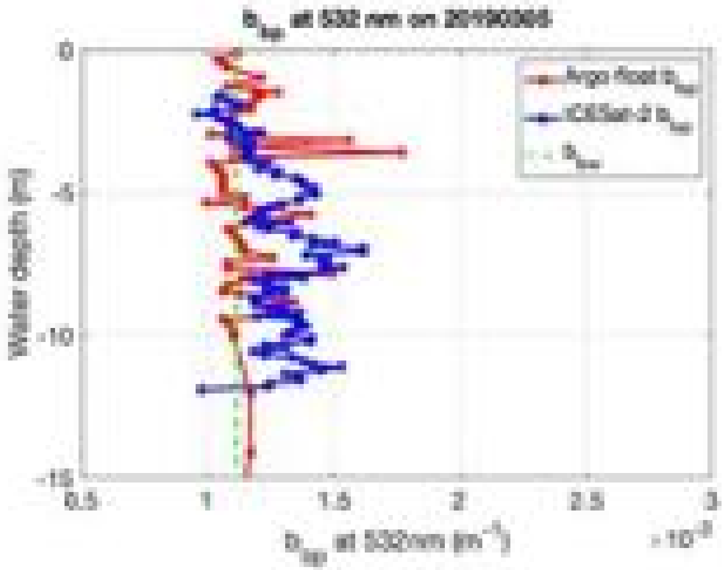
- Launched on September 15, 2018
- laser pulse split into 6 beams
- 92°-inclined orbit, 480 km

OC lidar – Applications

Satellite lidar

Lu et al., 2021





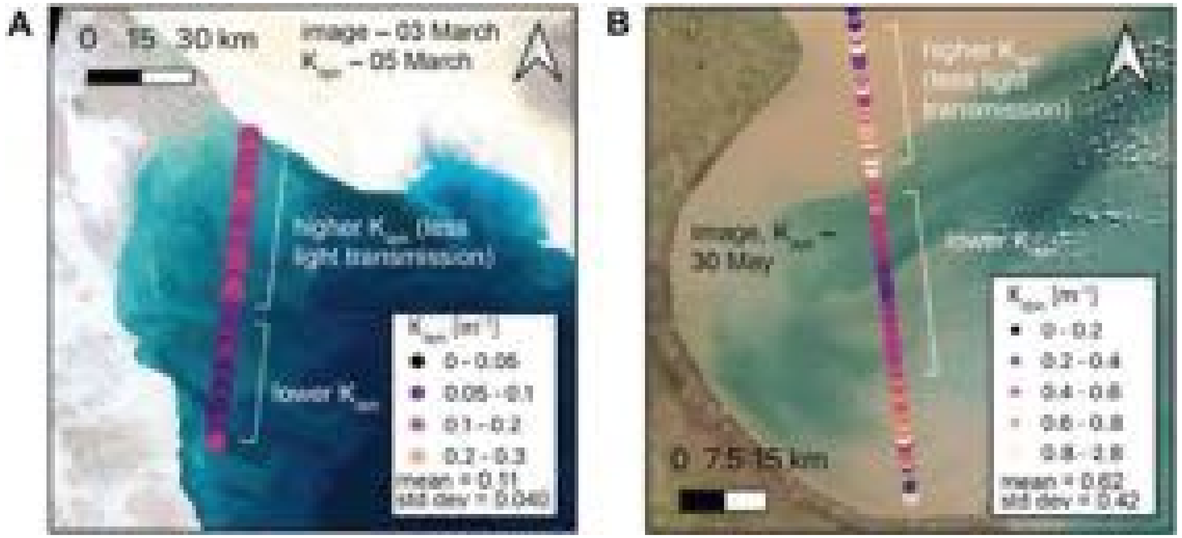
ICESat-2/ATLAS provides a new opportunity to study ocean biology globally, adding nighttime observations and a vertical dimension with high horizontal and vertical resolution

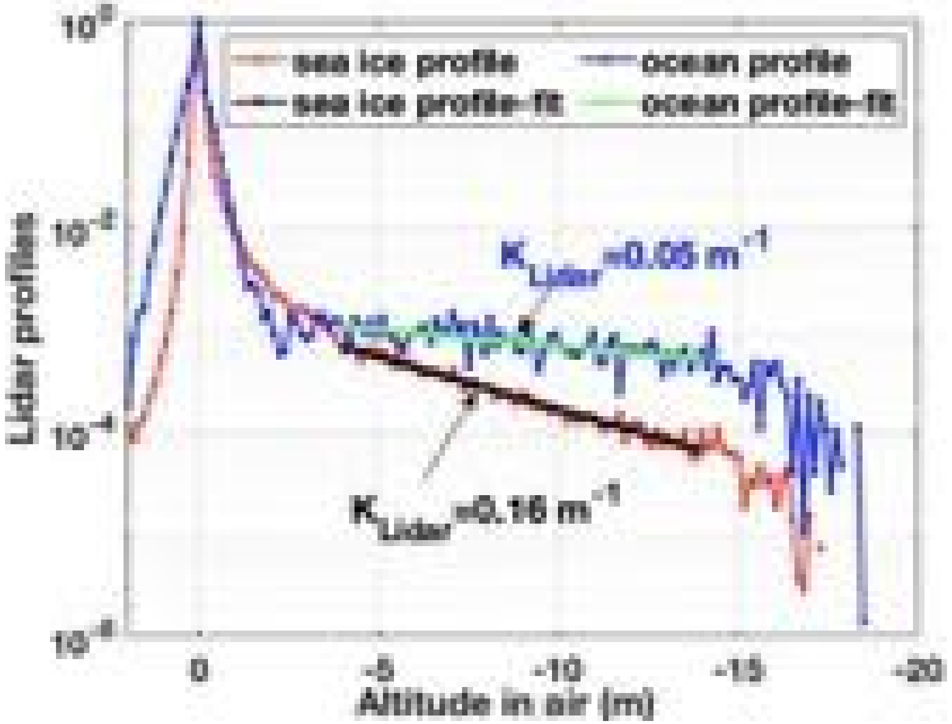
OC lidar – Applications

Satellite lidar

Eidam et al., 2024

Lu et al., 2023





- ❑ Comparison between Icesat2 vs Sentinel-3 K_d (integrated parameter)
- ❑ First K_d profiles obtained from spaceborne lidar

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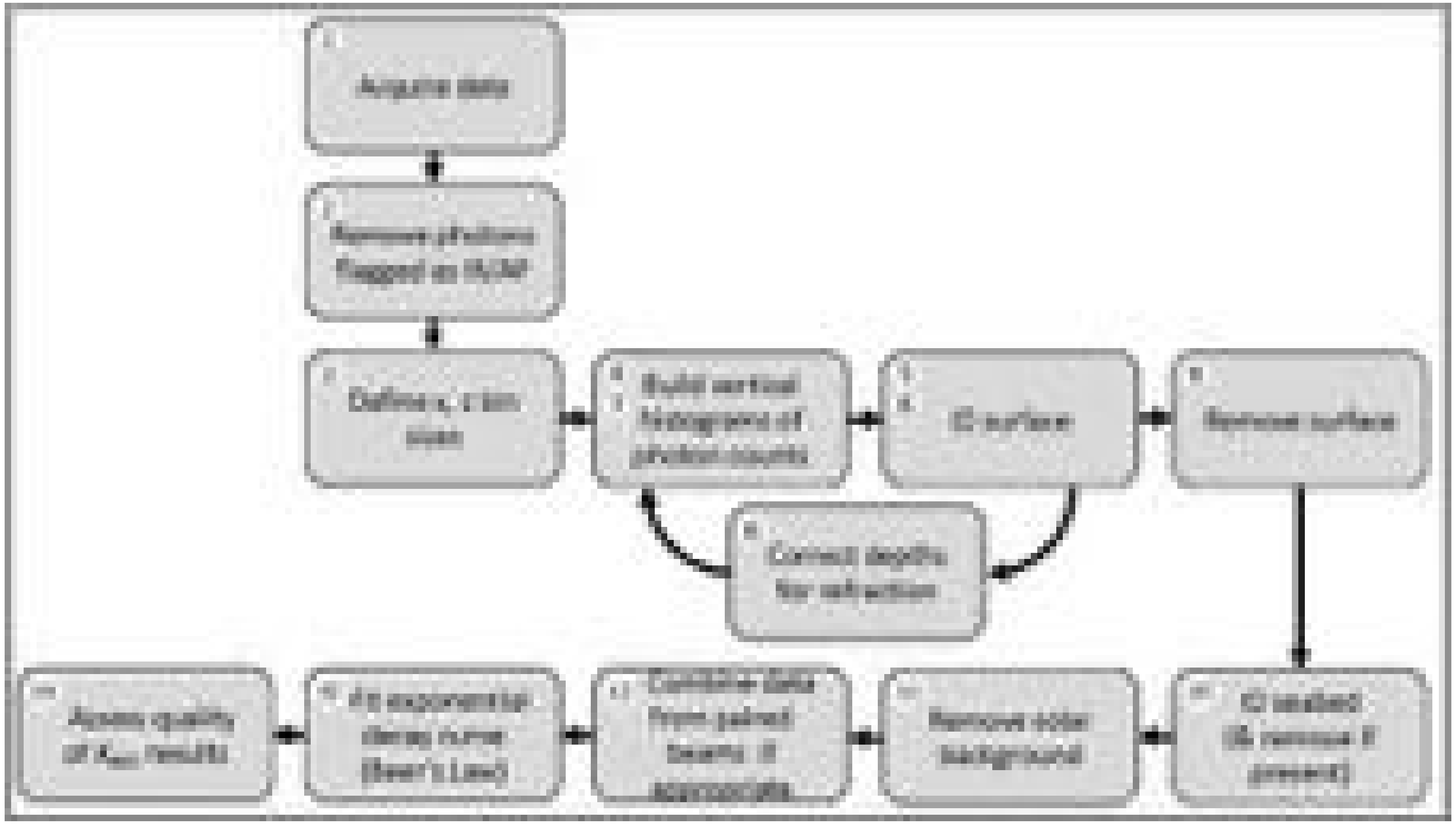
OC lidar – Applications

Satellite lidar

Eidam et al., 2024

Workflow for calculating K_{dph} from ATL03 data



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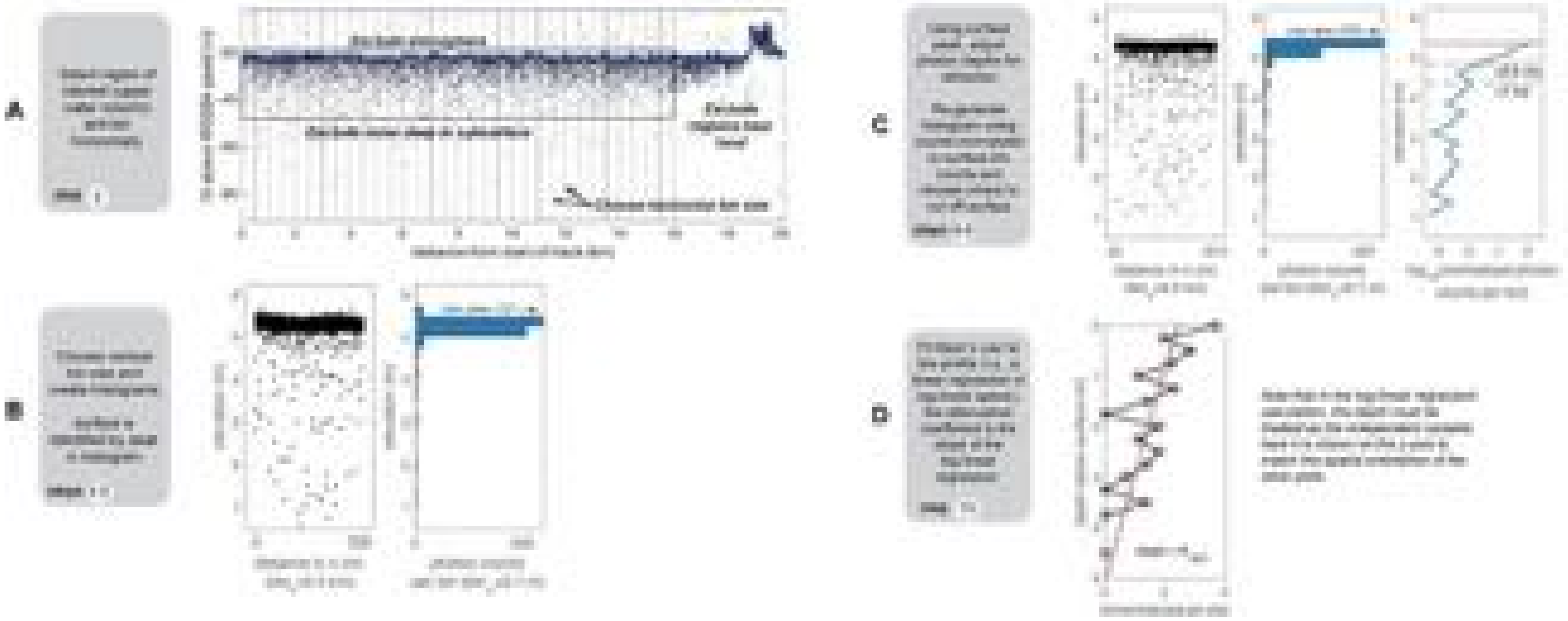
OC lidar – Applications

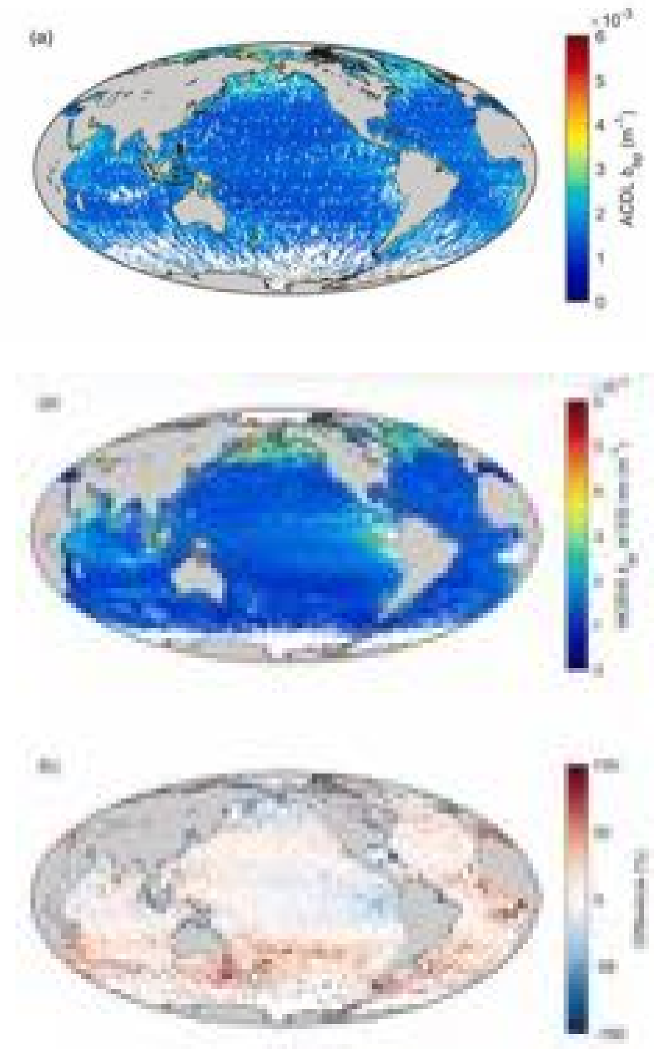
Satellite lidar

Workflow for calculating K_{dph} from ATL03 data

Eidam et al., 2024 (supplementary material)

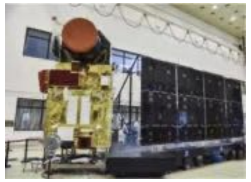


OC lidar – Applications



Satellite lidar

Yang et al., 2024



ACDL (Spaceborne Aerosol and Carbon dioxide Detection Lidar) onboard the Chinese DQ-1 satellite is a spaceborne HSRL originally designed for aerosol and cloud observations.

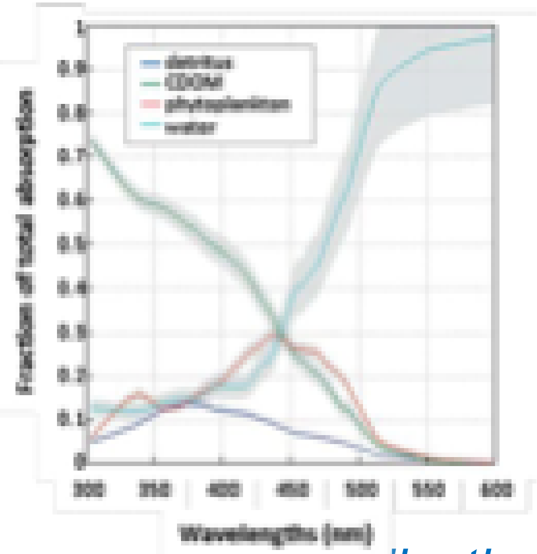
- A novel algorithm to retrieve the particulate backscatter coefficient b_{bp} in the global ocean.
- ACDL-derived b_{bp} agrees well with MODIS-derived b_{bp}
- ACDL b_{bp} also shows high correlation with Argo float in situ data under different spatial and temporal matching windows.

ACDL/DQ-1 moves satellite ocean lidar from elastic-lidar feasibility toward HSRL-based global ocean optical-property retrievals.

OC lidar – Applications

Satellite lidar

Dionisi et al., 2024



ALADIN (Atmospheric LAser Doppler Instrument) aboard Aeolus mission acquired:

- ❑ For the first time wind profiles on a global scale.
- ❑ Atmospheric backscatter and extinction coefficient profiles at 355 nm.

AEOLUS gives the opportunity to investigate the signal backscattered by the ocean sub-surface:

- ❑ First orbiting HSRL lidar
- ❑ Ocean subsurface information content in the UV
- ❑ The line-of-sight (LOS) points 35º from nadir

Lack of the UV information of past and current Ocean Color sensors

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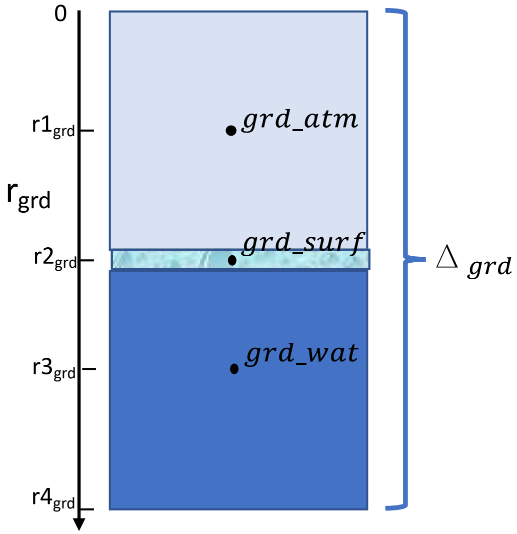
OC lidar – Applications

Satellite lidar

Dionisi et al., 2024

COLOR (CDOM-proxy retrieval from aeOLus ObseRvations) ESA funded project explored the feasibility of deriving an in-water AEOLUS product through the analysis of data acquired by the ground bin.



$$S_X(grd) = M_X \left[\frac{A}{\left(r_{atm} + \frac{\Delta r_{atm}}{n} \right)^2} \right] B_{grd} T_A^2(r_{atm}) + S_{bkd}$$

X= $Ray_{A,B}$
X= Mie

$$B_{grd} = B_{atm} + B_{srf} + B_{wat}(K_L, \beta_{wat}^{par}, \beta_{wat}^{mol})$$

$$B_{wat} = \int_0^{r_{wat}} \beta_{wat}(\pi, r'_{wat})\, exp \left[-2 \int_0^{r'_{wat}} K_{LID}(r''_{wat}) dr''_{wat} \right] dr'_{wat}$$

This characterization is based on:

a) **Radiative transfer numerical modelling**
b) **AEOLUS data analysis**

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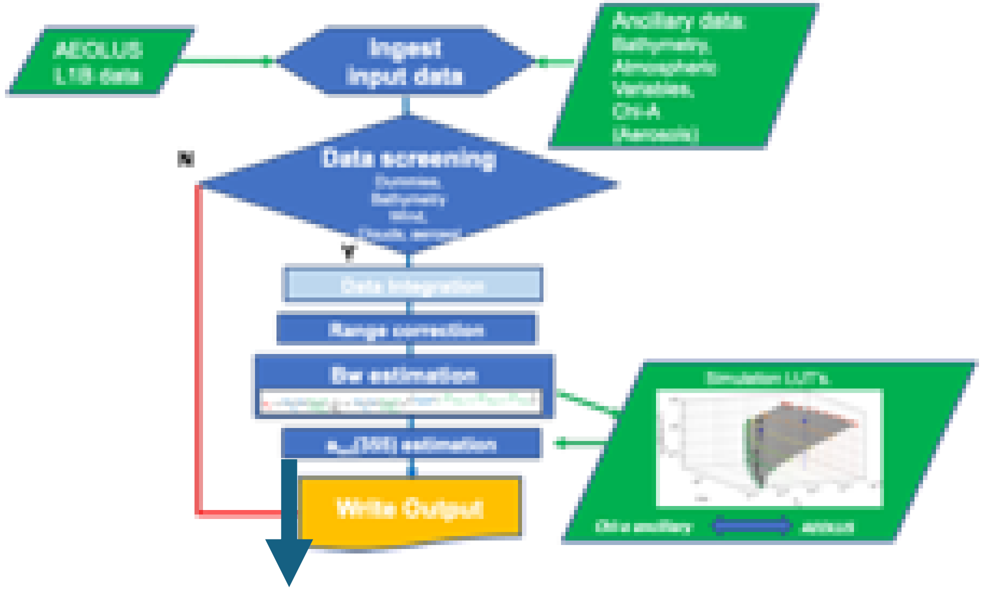
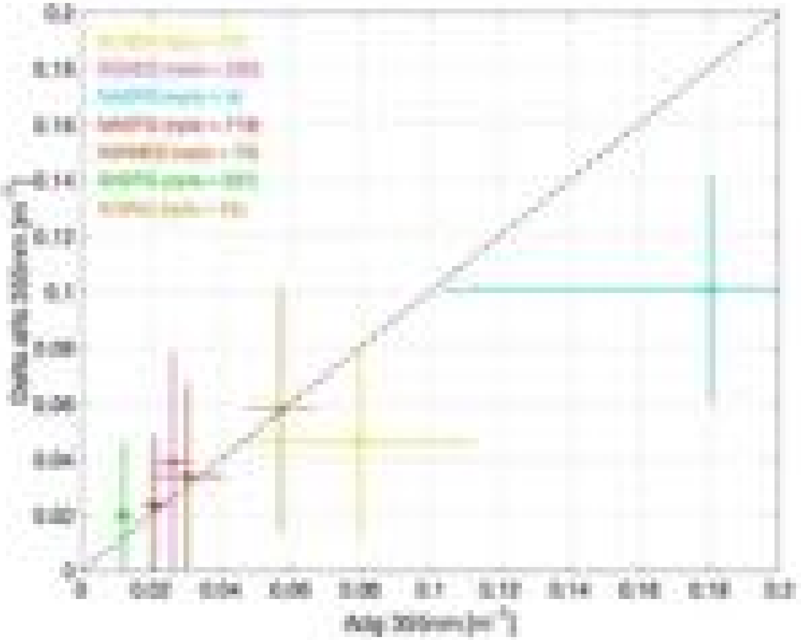
OC lidar – Applications

Satellite lidar

Dionisi et al., 2024



ALADIN



ESA-OC-CCI

$$\boldsymbol{\Delta a(355)} = a_{CDOM}(355) + a_{NAP}(355) \approx \boldsymbol{a_{CDOM}(355)}$$

- ☑ Δa parameter vs a_{cdm} showed that CDOM measurements can be derived by Aeolus measurements

- ✗ Limited spatial and temporal coverage
- ✗ Low maturity level of the AEOLUS OC prototype product (e.g. HSRL not exploited, partial associated uncertainties, *home-made* cloud detections and aerosol corrections)

Summary

- Introduction
  - Passive and active measurements

- OC Lidar history
  - Late 1960s – 1970s: Early days
  - Late 1970s – 1980s: Transition to quantitative retrievals
  - Late 1980s–1990s: Toward modern bio-optical applications

- OC Lidar applications
  - Shipborne
  - Airborne
  - Satellite

- Current and Future OC Lidar initiatives
  - EarthCARE
  - LUCE
  - Toward a network of in-situ lidar?

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Ocean Lidar Applications

Satellite lidar: present

First investigations on **CALIOP subsurface bins** (Shi and Wang, 2008)

CALIOP Integrated **subsurface backscatter vs chlorophyll-a concentration** (Lu et al., 2014)

Going beyond standard ocean color observation: Lidar and Polarimetry (Jamet et al., 2019)

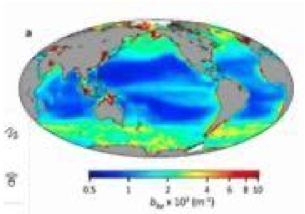
Demonstrated opportunity for future OC applications (IOCS, 2019)

Assessment of the oceanic surface layer's optical properties through CALIOP (2020-2022)

EarthCARE

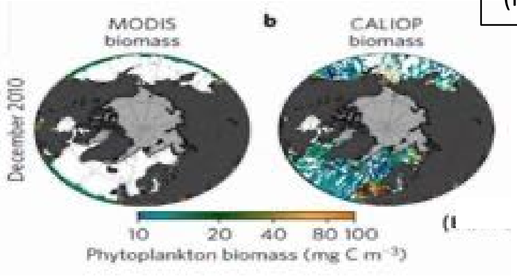
2008 2010 2012 2014 2016 2018 2020 2022 2024

Ocean particulate backscatter from Caliop



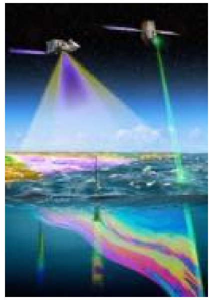
Behrenfeld et al., 2013

Annual cycle of polar phytoplankton **biomass**



Behrenfeld et al., 2017

New ***lidar era*** in satellite oceanography (Hostetler et al., 2018)



Ocean subsurface observations through ICEsat-2 (Lu et., 2019)

CALIOP δ_T used as an oceanic variable for the ocean particulate optical properties (Dionisi et al., 2020)

GUANLAN mission for space oceanography (S. Wu, Aeolus cal/val meeting, 2020)

Vertical distribution of phytoplankton optical properties through CALIOP and ICEsat-2 measurements (Lu et al., 2021)

AEOLUS OC prototype product (Dionisi et al., 2024)

'New lidar era in satellite oceanography (Hostetler et al., 2018)'

OC lidar – Applications

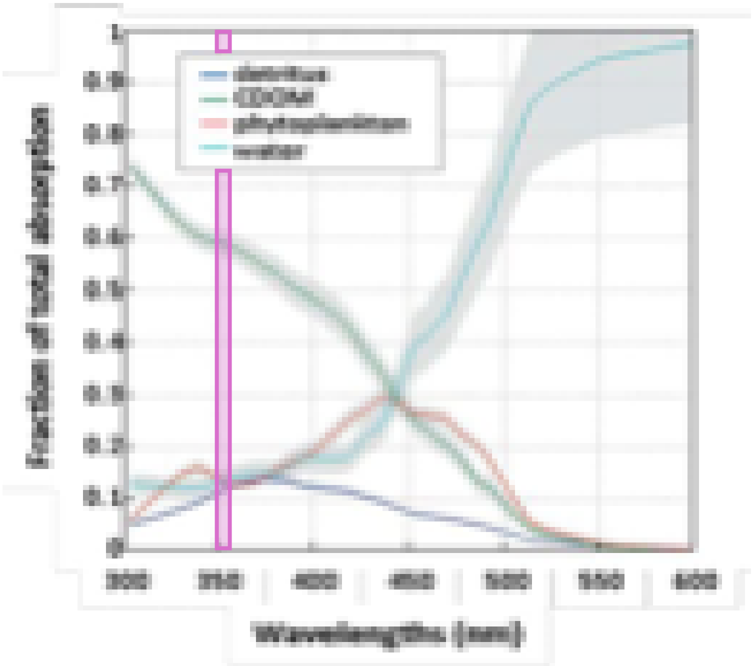
EarthCARE

OCEAN: Ocean Color EarthCARE Analysis

24 months feasibility study approved by **ESA** within *the EARTHCARE+ INNOVATION - EXPRO+ Innovation program* (ESA 4000147849/25/I-AG)

OCEAN proposes to evaluate and document the feasibility of deriving in-water EarthCARE products:

- Lidar parameters:
  - Attenuation coefficient (**K_L**)
  - Backscatter coefficient (β^{par}_{wat})
- Ocean Colour parameters:
  - Diffuse attenuation for downwelling irradiance (**K_d**)
  - Hemispheric particulate backscatter coefficient (**b_{bp}**)
- Bio-geochemical parameter:
  - Chromophoric Dissolved Organic Matter (**CDOM**)



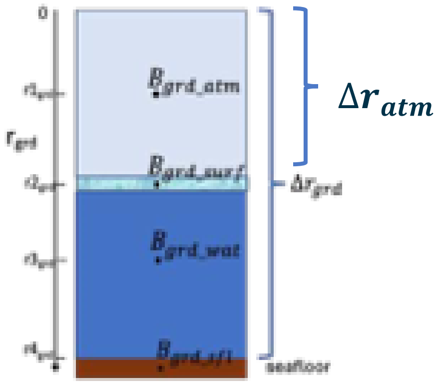
*In the UV, **CDOM** is the most relevant contributor to the light absorption → **K_d** is used as a proxy of CDOM light absorption.*

OC lidar – Applications

***OCEAN:* Ocean Color EarthCARE Analysis**

ATLID integrated attenuated backscatter:

ATLID attenuated backscatter summed over 3 bins around the assumed surface (11% vertical crosstalk, *do Carmo et al. 2021*) and multiplied by the bin thickness Δr_{grd}



Mie (M)

$$A_M(r_{grd}) = \{B_{atmM} + B_{srfM} + B_{watM}\}\, T_A^2(r_{atm})$$

Rayleigh (R)

$$A_R(r_{grd}) = \{B_{atmR} + B_{srfR} + B_{watR}\}\, T_A^2(r_{atm})$$

Cross (X)

$$A_X(r_{grd}) = \{B_{atmX} + B_{srfX} + B_{watX}\}\, T_A^2(r_{atm})$$

- ❑ $T_A^2(r_{atm})$ estimated with L2 ATLID products
- ❑ B_{atmY} estimated using the information in the bins above the ground bin and multiplied by Δr_{atm}
- ❑ No seafloor contribution
- ❑ $B_{srfM} = \frac{\rho}{4\pi\sigma^2\cos^4\theta}\exp\left(-\frac{\tan^2\theta}{\sigma^2}\right)$ $\quad B_{srfR} = 0$ $\quad B_{srfX} = 0$

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OC lidar – Applications

OCEAN: Ocean Color EarthCARE Analysis

Rayleigh (R)

$$B_{watR} = f \cdot \frac{T_{srf}^{dn} T_{srf}^{up}}{n^2} \cdot \int_0^\infty \beta_{wat}^{mol} \cdot T_{wat}^2(r)dr \Rightarrow K_L = f \cdot \frac{T_{srf}^2}{n^2} \cdot \frac{\beta_{wat}^{mol}}{2B_{watR}}$$

- ❑ Assuming complete extinction of the signal in the bin
- ❑ $T_{wat}^2(r) = e^{-2K_L r}$ vertically homogenous extinction
- ❑ $T_{srf}^{dn} = T_{srf}^{up} = T_{srf}(\phi, \theta, u, v)$ from wind and surface modelling
- ❑ Pure seawater backscatter coefficient β_{wat}^{mol} known
- ❑ Negligible depolarization from molecular (Brillouin) scattering
- ❑ Refractive index $n(T, S)$ known
- ❑ spectral response function ratio $f \approx 1$
  (G-J. van Zadelhoff and J. Smith, personal communication)

Mie (M)

$$B_{watM} = \frac{T_{srf}^{dn} T_{srf}^{up}}{n^2} \cdot \int_0^\infty f_C(r) \cdot \beta_{wat}^{par}(r) \cdot T_{wat}^2(r)dr \Rightarrow \beta_{wat}^{par} = B_{watM} \cdot \frac{n^2}{T_{srf}^2} \cdot 2K_L(1+\delta)$$

$$f_X(r) = 1 - f_C(r) \qquad \delta = \frac{f_X}{f_C}$$

⚠ Signal dominated by the high surface reflectance

OC lidar – Applications

OCEAN: Ocean Color EarthCARE Analysis

Cross (X)

$$B_{watX} = \frac{T_{srf}^{dn} T_{srf}^{up}}{n^2} \cdot \int_0^\infty \left[f_X(r)\beta_{wat}^{par}(r) + 2\left(f_C(r)\beta_{wat}^{par}(r) + \beta_{wat}^{mol}\right) \int_0^r \gamma(r')dr' \right] \cdot T_{wat}^2(r)dr$$

depolarization by forward multiple scattering

Assuming $\gamma(r')$ vertically homogeneous: $\int_0^r \gamma(r')dr' = \gamma r$

$$\Rightarrow B_{watX} = \frac{T_{srf}^2}{n^2} \cdot \left[\frac{\delta}{1+\delta} \frac{\beta_{wat}^{par}}{2K_L} + \frac{(\beta_{wat}^{par}/(1+\delta) + \beta_{wat}^{mol})\gamma}{2K_L{}^2} \right]$$

γ from literature or derived through MC

If all three signals have sufficient SNR, K_L, β_{wat}^{par}, and δ can be retrieved.

The high intensity of the surface reflection prevents the use of Mie channel
→ additional assumptions are necessary

$$\delta = \begin{cases} 2K_d(532) & \text{if } K_d(532) < 0.15 \text{ m}^{-1} \\ 0.3 & \text{otherwise} \end{cases}$$

Behrenfeld et al. 2013

$$\frac{\delta}{(1+\delta)} \approx 1.6K_d$$

Behrenfeld et al. 2022

OC lidar – Applications

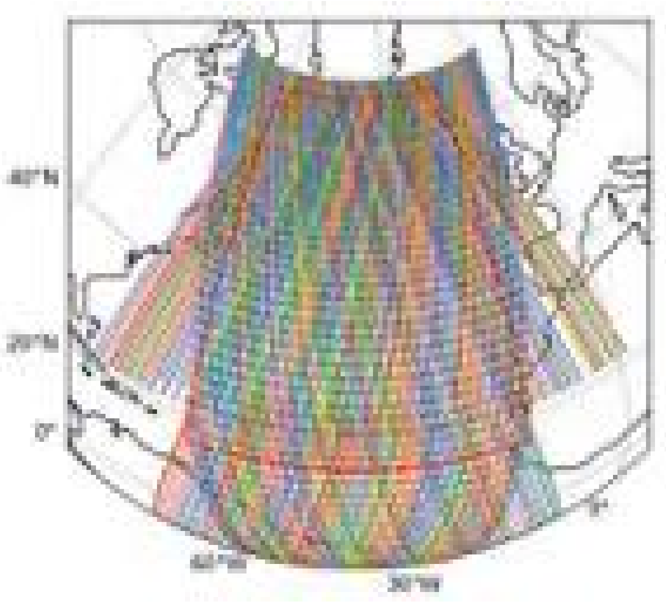
OCEAN: Ocean Color EarthCARE Analysis

- ❑ Ground bin selected with FM `featuremask`
- ❑ Data selected using the following flags and masks:
  - No bad retrievals / fully Rayleigh attenuated bins
  - No clouds or thick aerosol in the bin above surface
  - Ocean
  - Ice-free conditions
  - Signal-based surface detection
- ❑ Signal integrated over 100 measurements (including non-selected)
- ❑ In-water signal calculated as:

$$B_{watR} = \frac{A_R(r_{grd})}{T_A^2} - B_{atmR}$$

- ❑ T_A^2 and B_{atmR} calculated using:
  - FM: `surface_rayleigh_tau`
  - EBD: `particle_optical_depth_355nm` (high resolution)
  - EBD: `rayleigh_backscatter_355nm_model`

Test on baseline BA for April and September 2025



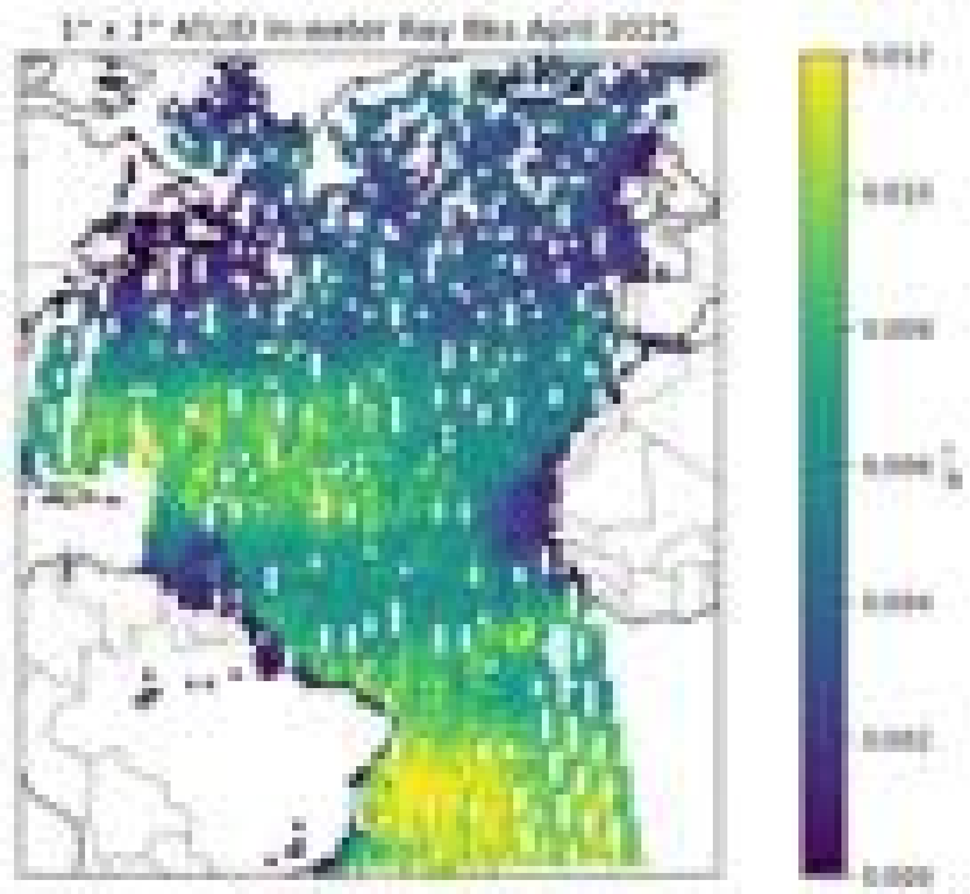
$$K_L = f \cdot \frac{T_{srf}^2}{n^2} \cdot \frac{\beta_{wat}^{mol}}{2B_{watR}} \quad \rightarrow \quad K_L \sim K_d \quad \rightarrow \quad K_d = 0.0239 + 0.149 \cdot \mathrm{Chl{-}a}^{0.767}$$

Case 1 waters, Morel and Maritorena 2001

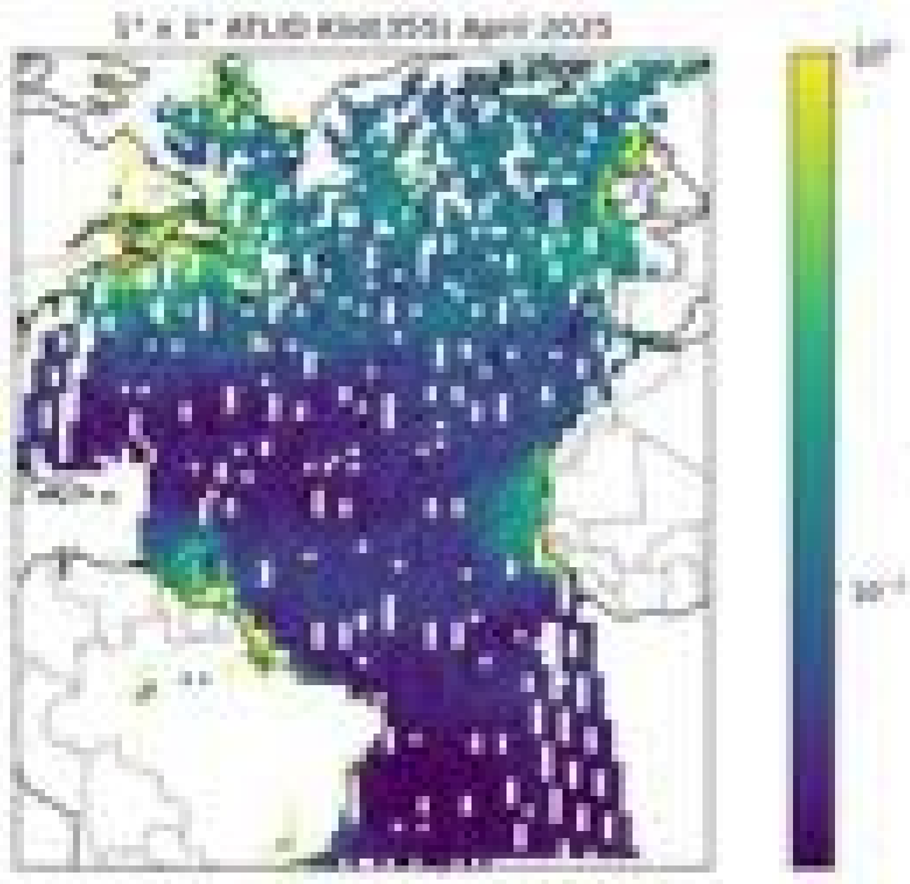
OC lidar – Applications

***OCEAN:* Ocean Color EarthCARE Analysis**

B_{watR}



K_L



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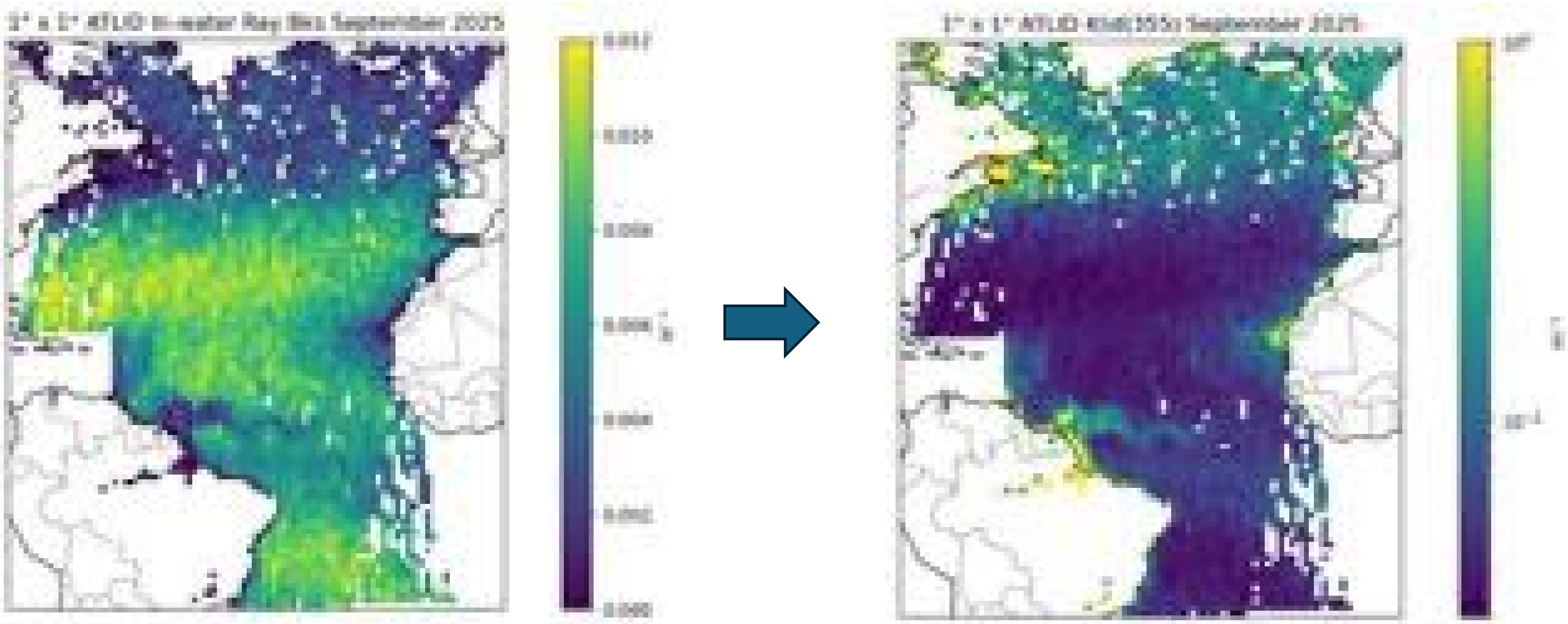
OC lidar – Applications

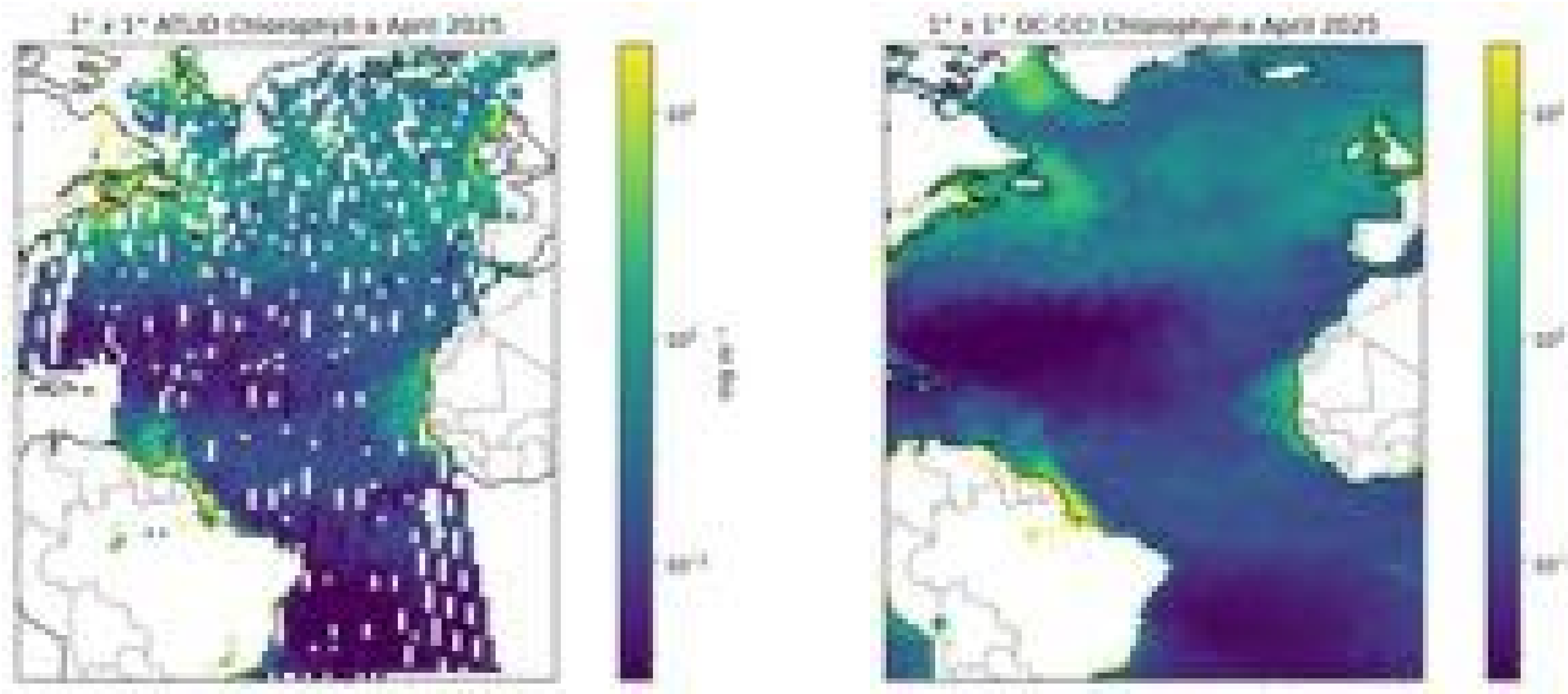
OCEAN: **O**cean **C**olor **E**arthCARE **An**alysis

B_{watR} K_L



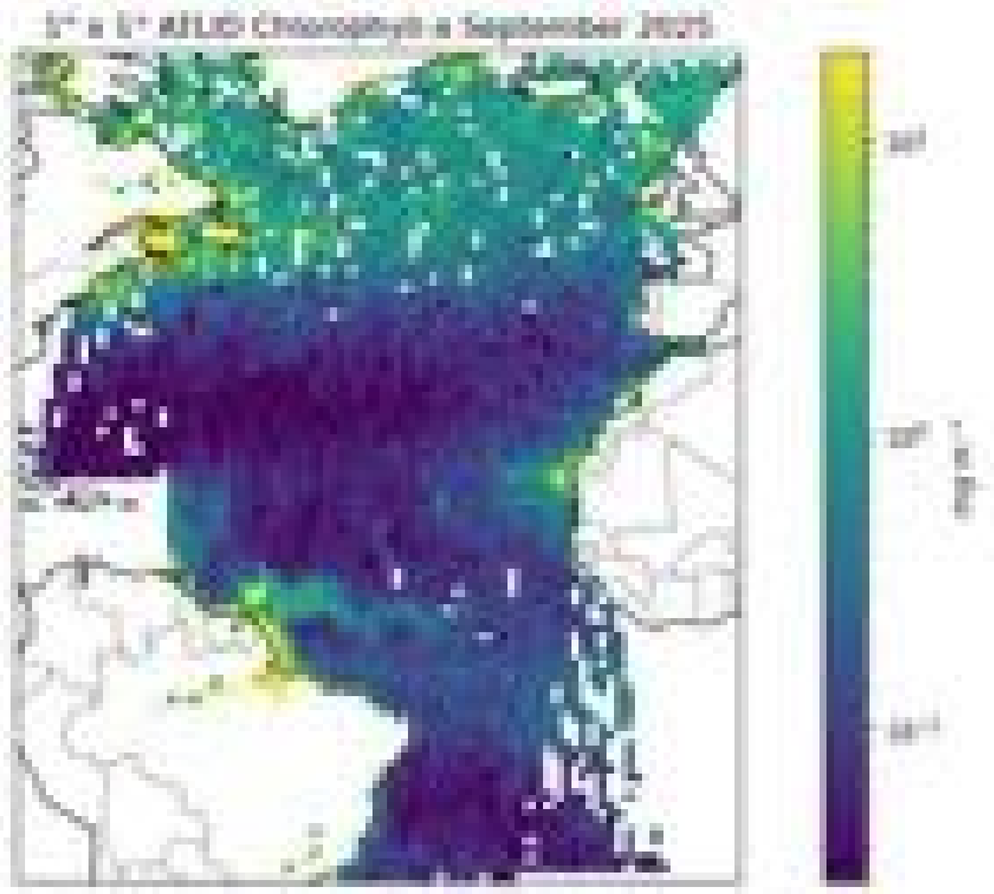
OC lidar – Applications

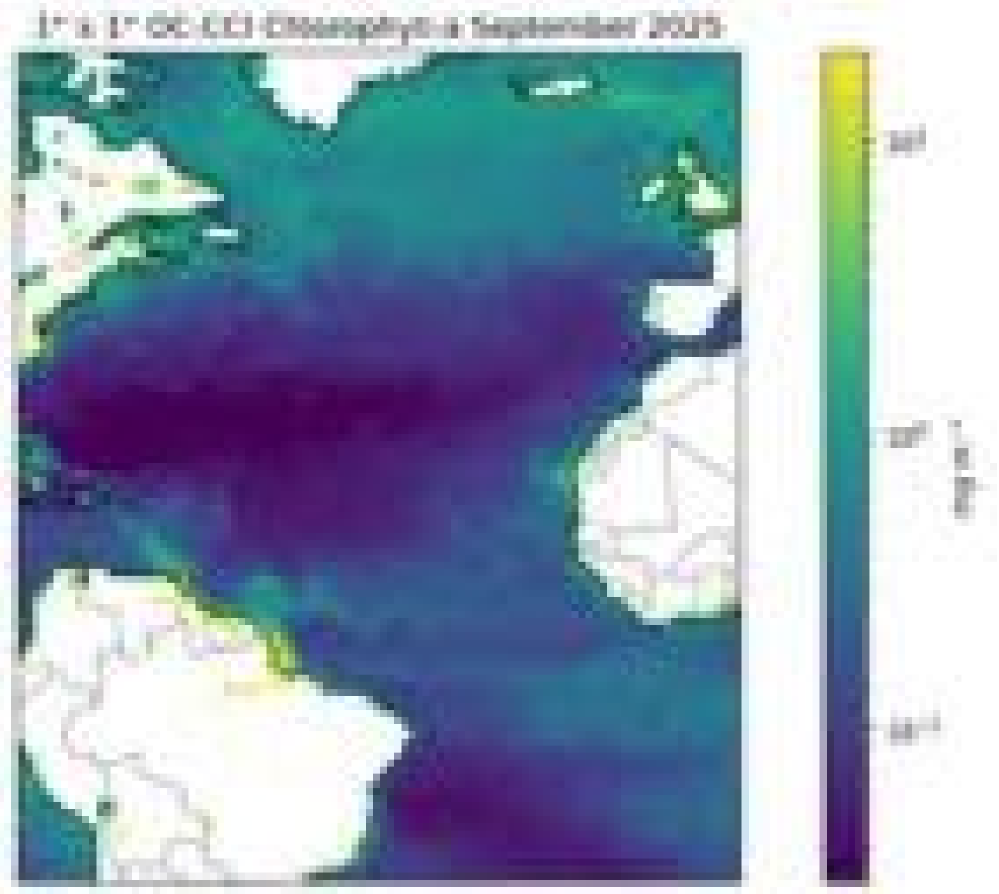
***OCEAN:* Ocean Color EarthCARE Analysis**



OC lidar – Applications

***OCEAN:* O**cean **C**olor **E**arthCARE **An**alysis





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OC lidar – Applications

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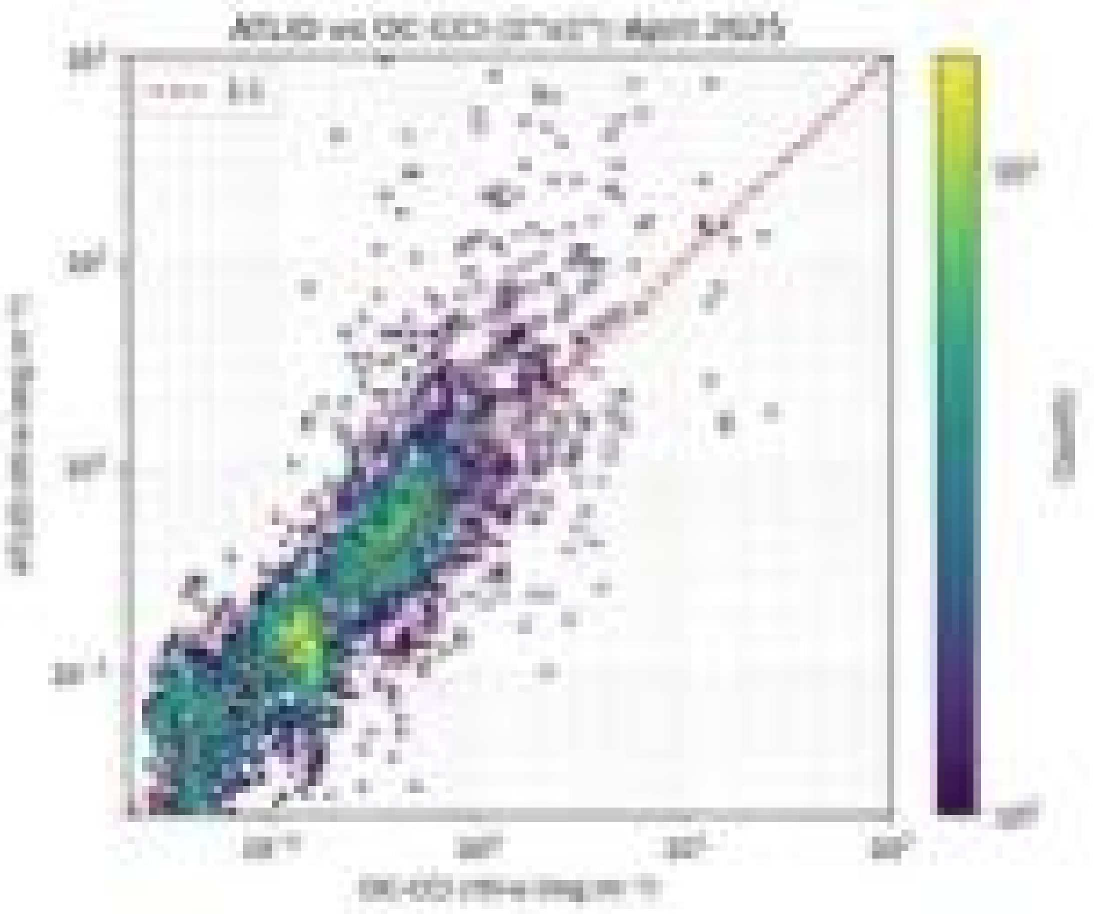

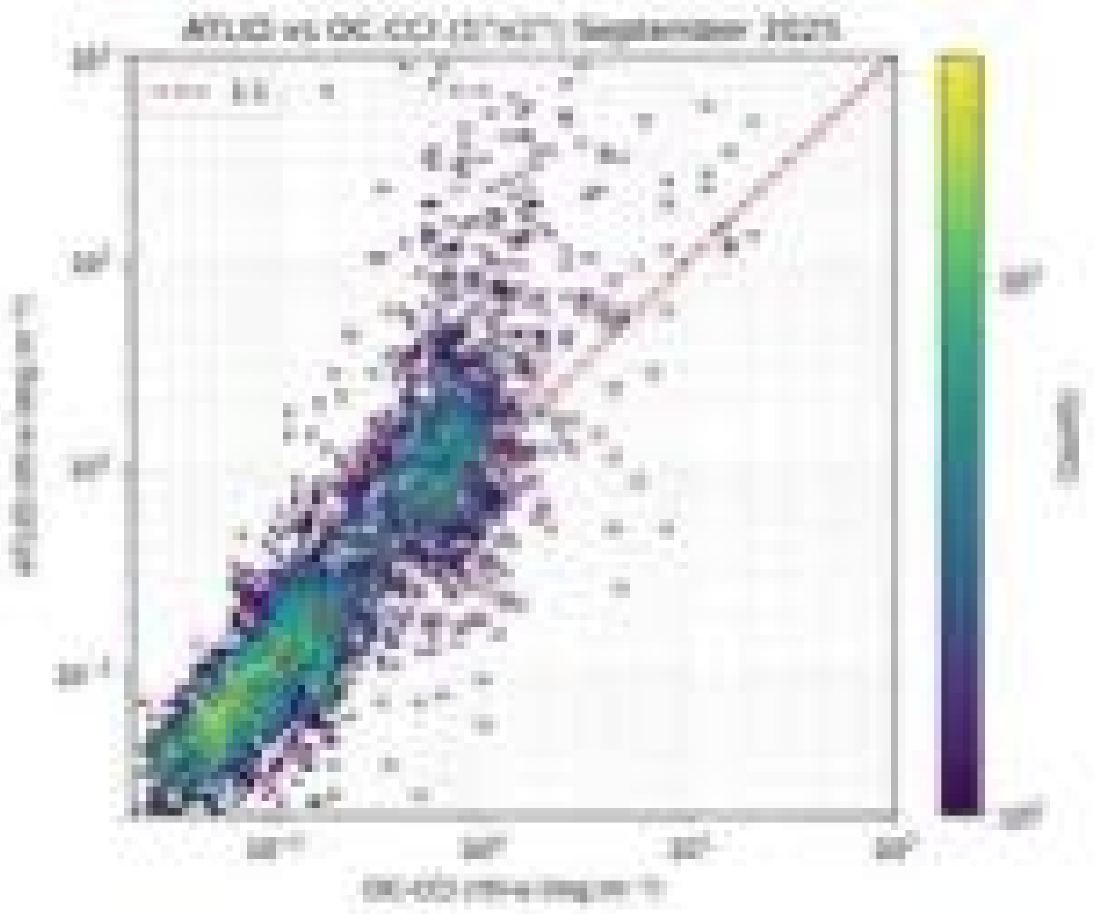

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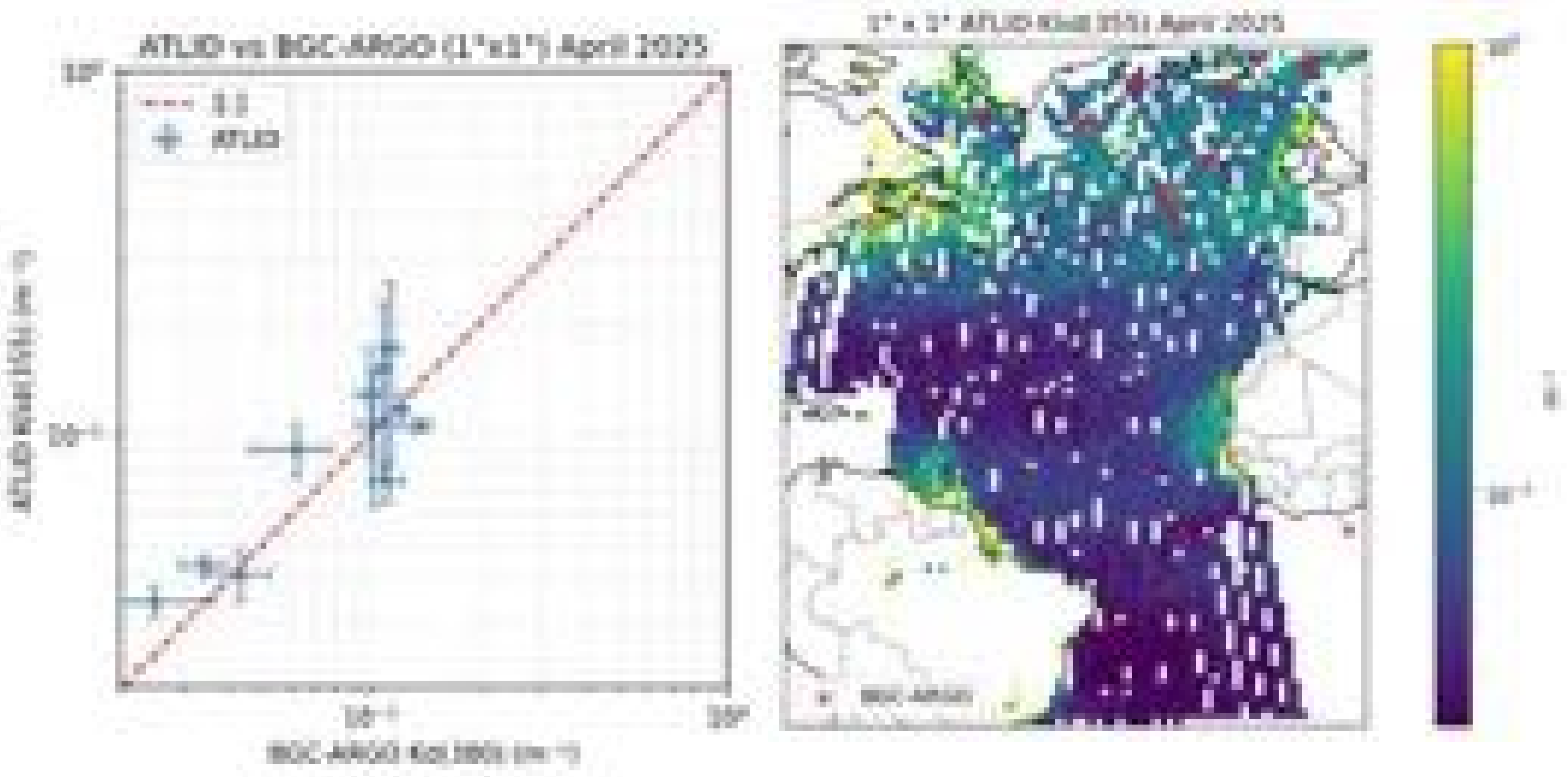
OC lidar – Applications

***OCEAN:* Ocean Color EarthCARE Analysis**

April 2025 (monthly averages vs point measurements)

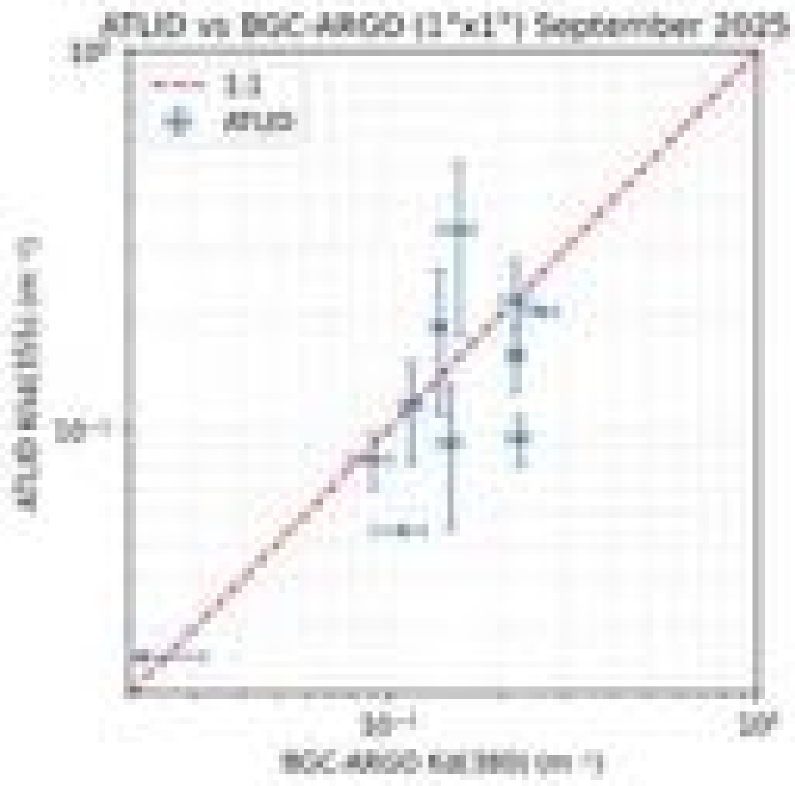


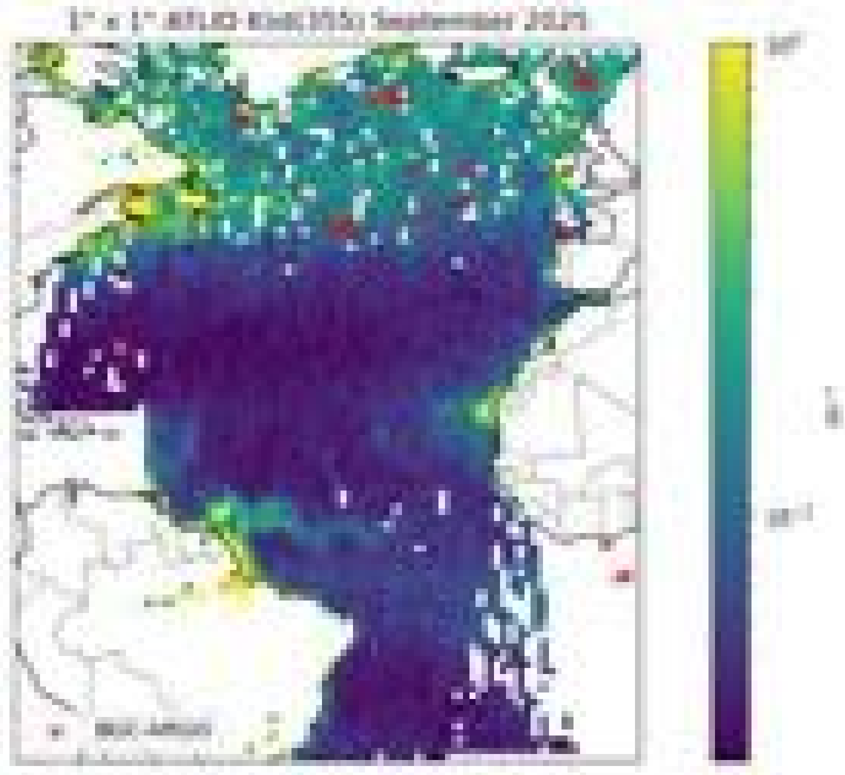
biogeochemical Argo

OC lidar – Applications

OCEAN: Ocean Color EarthCARE Analysis

September 2025 (monthly averages vs point measurements)





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OC lidar – Applications

OCEAN: **O**cean **C**olor **E**arthCARE **An**alysis

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- T_A^2 and B_{atmX} calculated using:
  - FM: `surface_rayleigh_tau`
  - EBD: `particle_optical_depth_355nm` (high resolution)
  - NOM: `crosspolar_attenuated_backscatter` 2 bins over the surface

$$\beta_{wat}^{par} = 2K_L \frac{(1+\delta)}{\delta + \frac{\gamma}{K_L}} \left(\frac{n^2}{T_{srf}^2} B_{watX} - \frac{\gamma \beta_{wat}^{mol}}{2K_L^2} \right)$$

preliminary assumptions

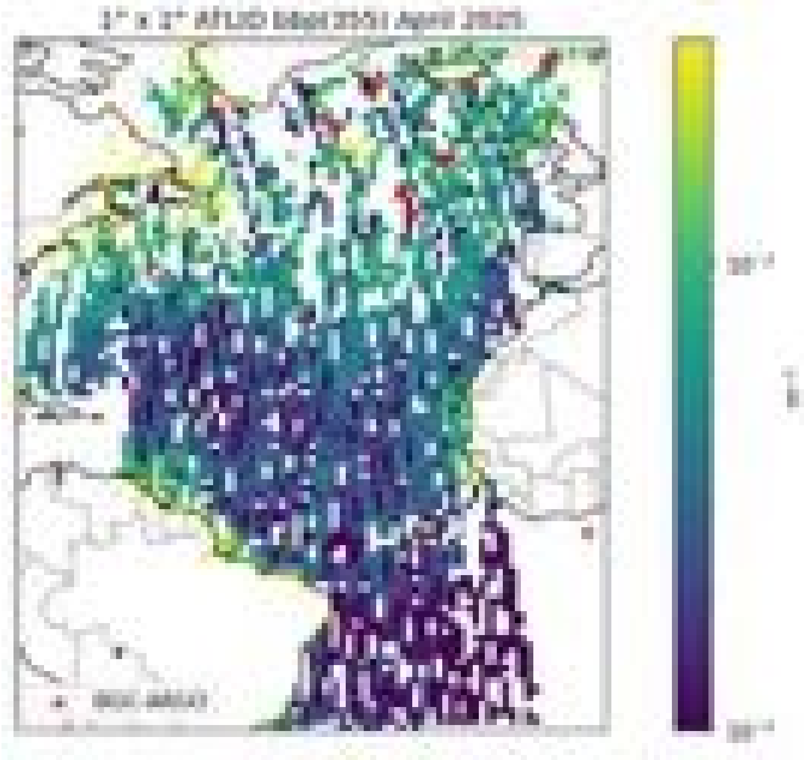
$\frac{\delta}{1+\delta} \approx 1.6K_d(532)$	*Behrenfeld et al. 2022*
$K_d(532) = \frac{K_L(355)}{4} + 0.05$	355 → 490 nm: linear fit 490 → 532 nm: *Lu et al. 2016*
$\gamma = 2 \cdot 10^{-3}$ m^{-1}	*Churnside 2008* *Behrenfeld et al. 2022*
$\chi = 0.5$	*Lacour et al. 2020*

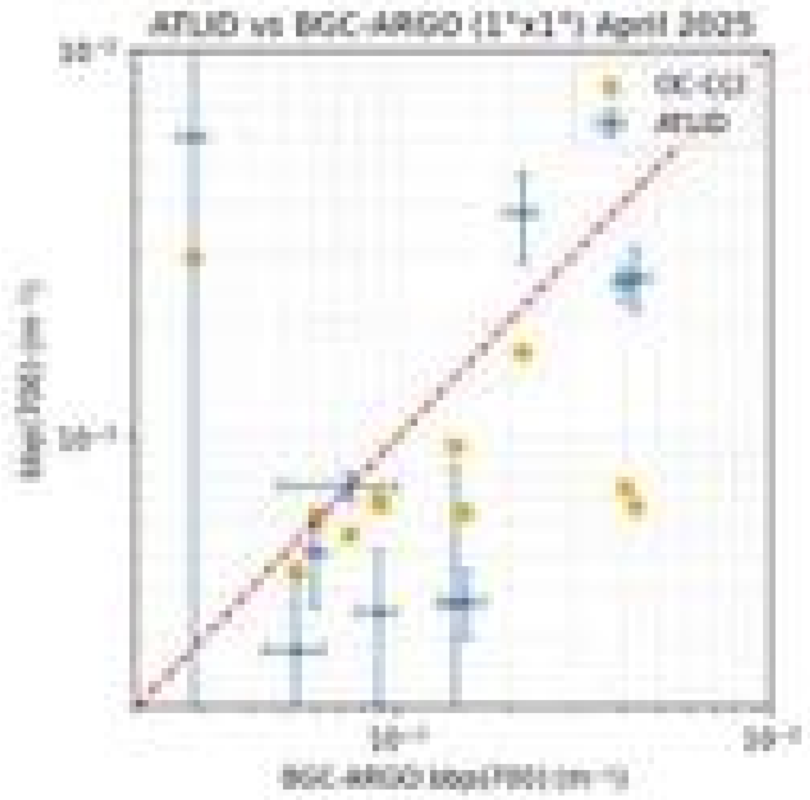
$$b_{bp} = 2\pi\chi\beta_{wat}^{par}$$

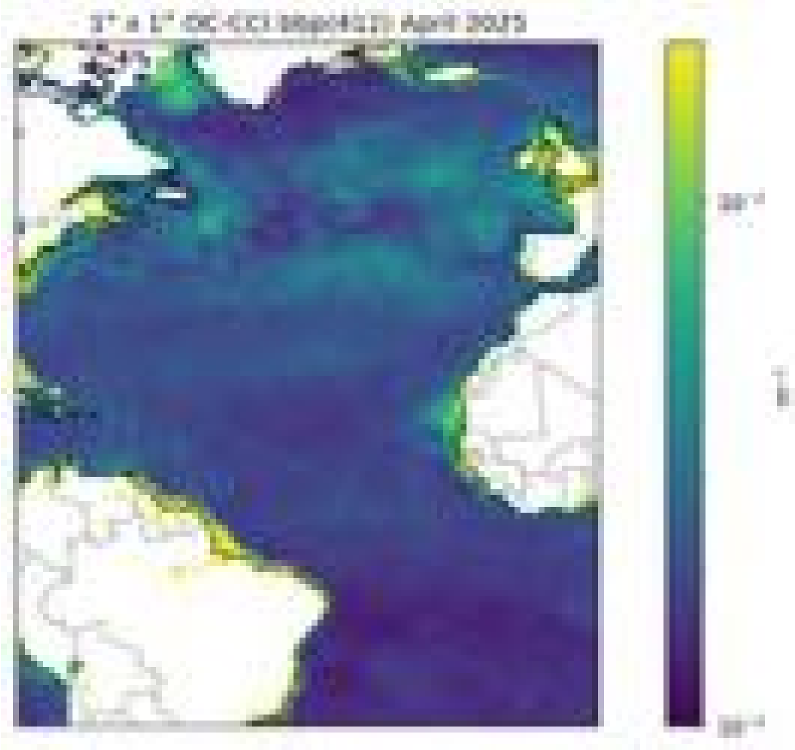
OC lidar – Applications

OCEAN: **O**cean **C**olor **E**arthCARE **An**alysis

$$b_{bp}(\lambda) = b_{bp}(355)\left(\frac{355}{\lambda}\right)^{\eta}$$ with η from OC-CCI

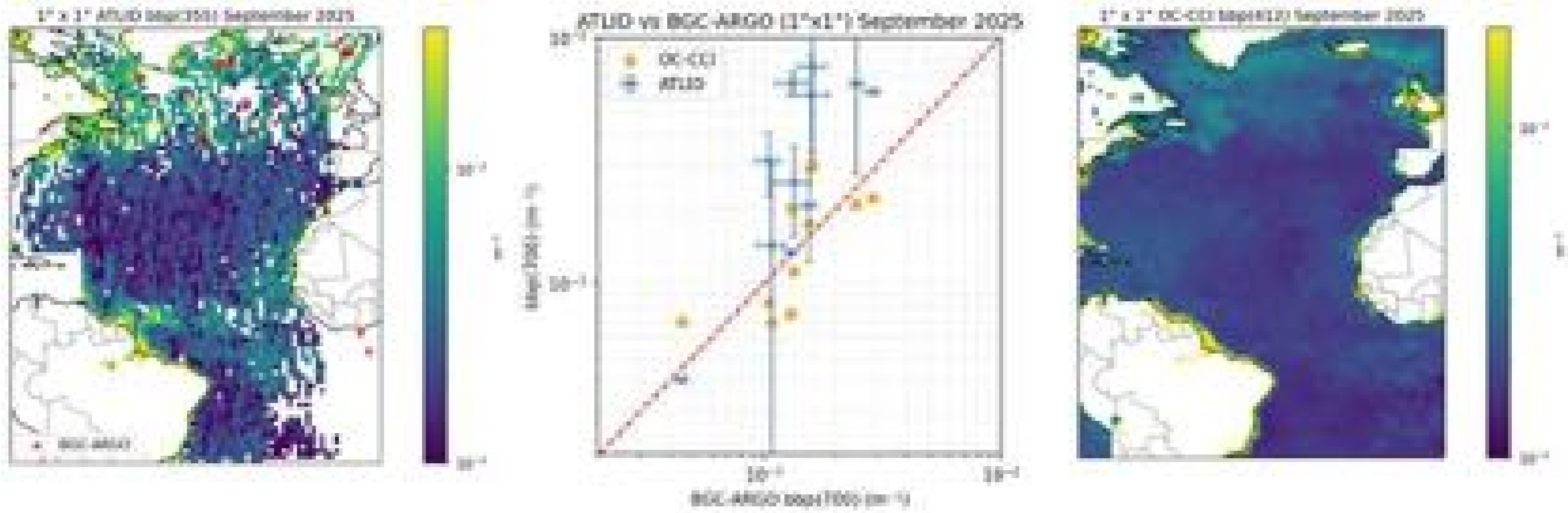






OC lidar – Applications

***OCEAN:* Ocean Color EarthCARE Analysis**

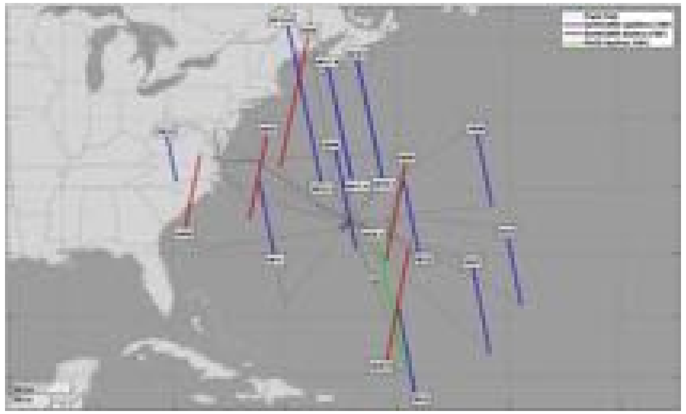


OC lidar – Applications

***OCEAN:* Ocean Color EarthCARE Analysis**

Next

- Extend the analysis on a 12 month global dataset (BA baseline)
- Application of a K_L correction based on RTM results
- Exploitation of Cross polar and Mie channels using RTM results
- Statistical (specific ROIs) and global validation with BGC-ARGO float dataset
- Comparison between ATLID OCEAN products and NASA HSRL-2 measurements (NightBLUE campaign, September 2025)
- Analysis of the diurnal cycle



Ocean Lidar Applications

Satellite lidar: future

2008 — 2010 — 2012 — 2014 — 2016 — 2018 — 2020 — 2022 — 2024

First investigations on **CALIOP subsurface bins** (Shi and Wang, 2008)

CALIOP Integrated **subsurface backscatter vs chlorophyll-a concentration** (Lu et al., 2014)

Going beyond standard ocean color observation: Lidar and Polarimetry (Jamet et al., 2019)

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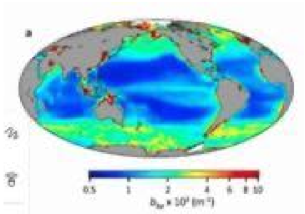
earthcare

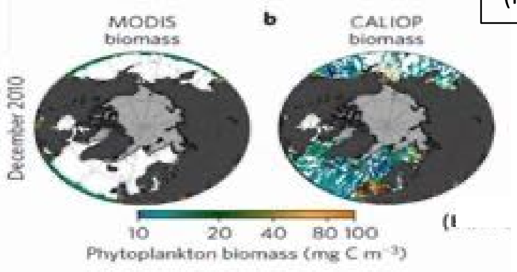
LUCE

Ocean particulate backscatter from Caliop



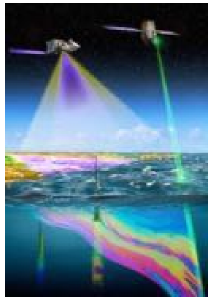
Behrenfeld et al., 2013

Annual cycle of polar phytoplankton **biomass**



Behrenfeld et al., 2017

New ***lidar era*** in satellite oceanography (Hostetler et al., 2018)



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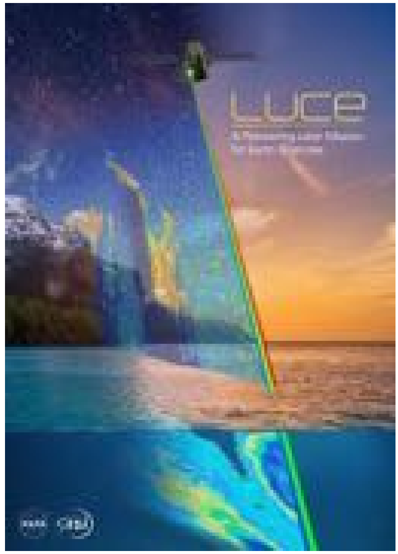
AEOLUS OC prototype product (Dionisi et al., 2024)

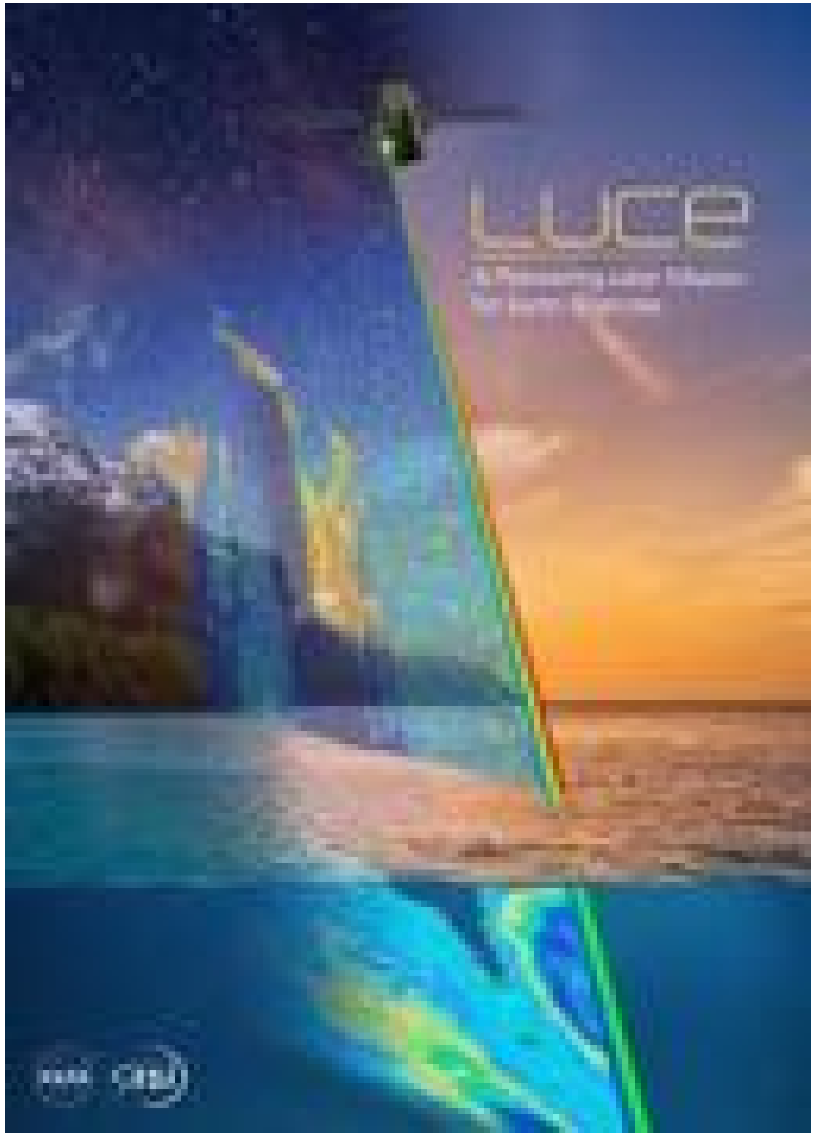


Ocean Lidar Applications

LUCE: What is this mission?

Luce is an **interdisciplinary Earth Sciences mission** significantly advancing global knowledge on the coupled atmosphere-ocean-land system.

- **First spaceborne Raman-elastic-fluorescence lidar** enabled through a partnership between ASI and NASA.
- Provides **multi-wavelength vertical profile measurements** of atmospheric particles (aerosols) and clouds to better understand their roles in air quality, weather, and climate.
- Provides the **depth-resolved near-surface observations of the world's oceans** revealing unprecedented insights on the health and productivity of phytoplankton and zooplankton, their impact on fisheries, and role in Earth's carbon cycle.
- Offers **new land measurement capabilities** on natural and agricultural plant health and refined estimates of snow depth and snow water content.



Luce: Multidisciplinary Earth Science

Atmosphere

Improved vertical profile measurements of aerosols and clouds to better understand their roles in climate, weather, and air quality

Land/Cryosphere

New global information on natural and agricultural plant health and estimates of snow depth and snow water content

Ocean

First profiles observations of the world's oceans revealing unprecedented insights on the health and productivity of phytoplankton and zooplankton, their impact on fisheries, and role in Earth's carbon cycle

Ocean Lidar Applications

LUCE concept

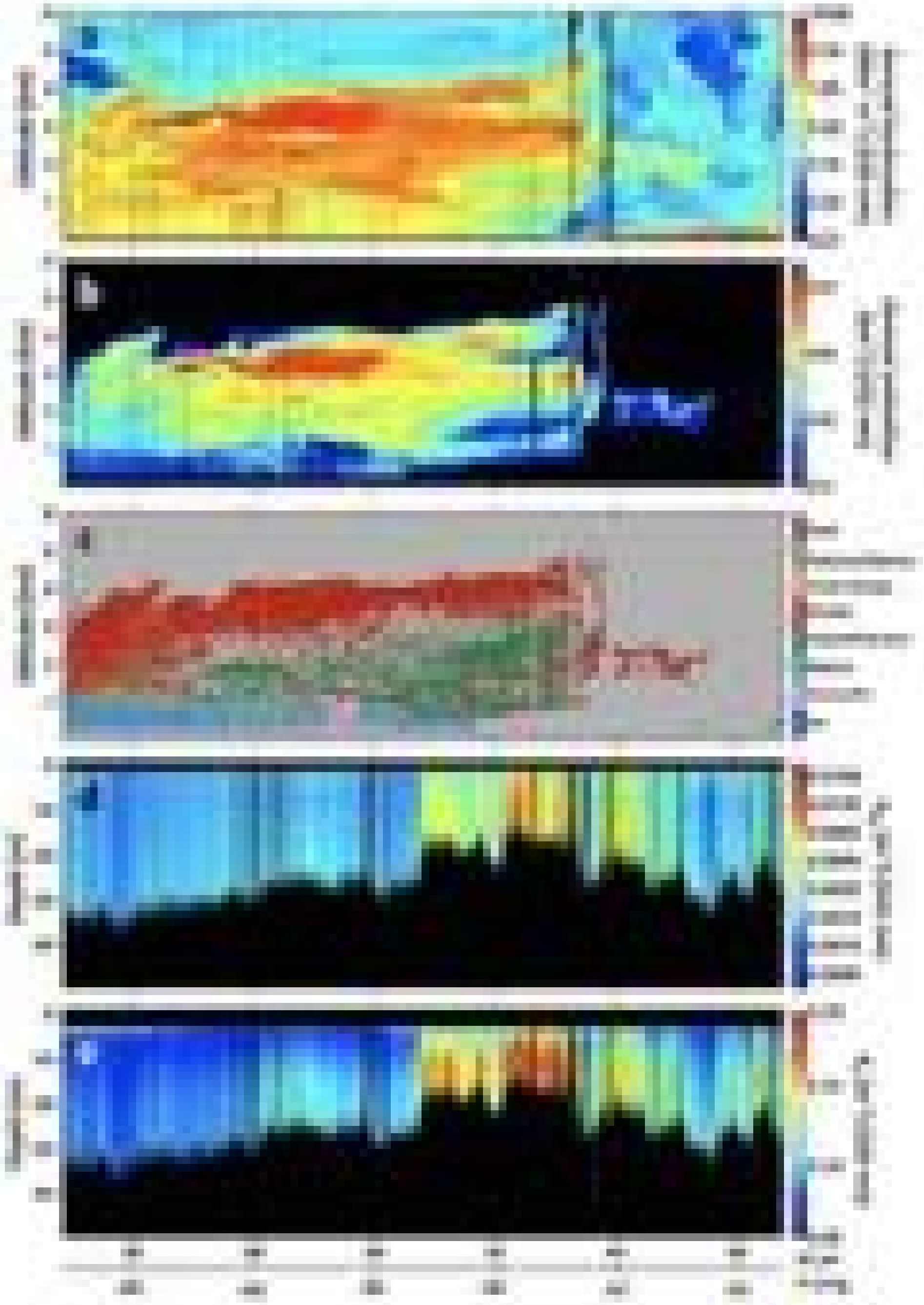
Atmosphere

Simultaneous acquisition of vertically resolved profiles of atmospheric and ocean scattering excited by laser pulses

LUCE mission would enable vertically resolved on a global scale atmospheric aerosol and cloud properties and ocean parameters (phytoplankton biomass, POC, and net primary productivity).

Ocean

Neukermans et al. 2018



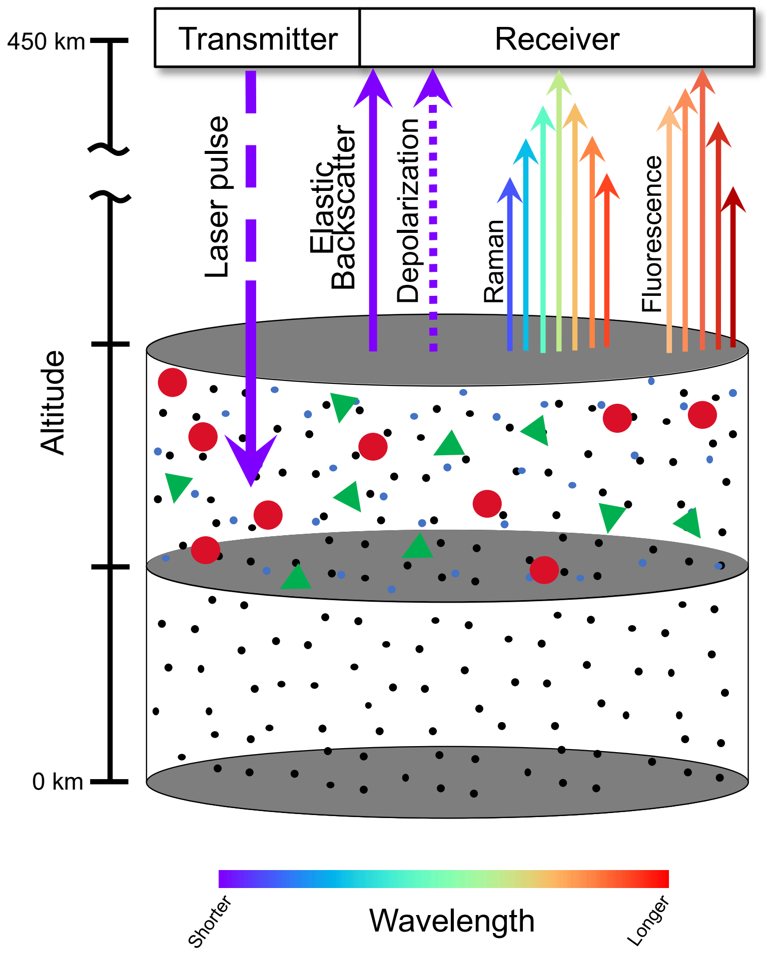
Physics Exploited by the Luce Lidar

Elastic scattering: change in light's direction

Depolarization: change in light's polarization state

Raman scattering: change in light's direction *and* an exchange of energy

Fluorescence: emission of light that has been absorbed



Elastic scattering: proportional to the attenuation of the laser beam and the amount scatters in the volume (molecules, particles)

Depolarization: size, shape of particles (liquid water vs ice, dust)

Raman scattering: **unique fingerprint**

- Allows one to collect backscatter from a specific species of interest

Fluorescence: **unique fingerprint**

- Identifier of the type particle in the volume

Ocean Lidar Applications

8 receiver channels

- Multiple channels often used to derive a single geophysical quantity

3 wavelength laser

Transmitted wavelengths	Receiver Wavelengths [nm]: Parallel elastic backscatter	Perpendicular elastic backscatter	N_2+O_2 rotational Raman backscatter	H_2O rotational-vibrational Raman backscatter	Fluorescence
355 nm	355 nm A O L C	355 nm A O L C	353.95 nm + 355.7 nm A	405 nm A O L C	685 nm A O L
532 nm	532 nm A O L	532 nm A O L			
1064 nm	1064 nm A L				

Channel Usage:
Atmosphere
Ocean Land
Cryosphere

Elastic backscatter with polarization sensitivity
Foundational to nearly all types of retrievals

Raman backscatter
Atmosphere (N_2+O_2) & ocean (H_2O) calibration
Water vapor and snow density retrievals

Fluorescence
Indicator of chlorophyll

Heritage measurements
CALIOP on CALIPSO (2006 – 2023)
ATLID on EarthCARE (2024 – 2027+)

Luce's first-ever measurements
Relatively weak signals, stimulated more effectively by shorter wavelengths (i.e. 355nm)

Ocean Lidar Applications

LUCE lidar characteristics

- Transmitted wavelengths: 355, 532, 1064 nm
- Pulse energy: 157, 47, 144 mJ
- Pulse repetition rate: 51 Hz, ~140 m between shots
- Vertical sampling: 1.25 m, native (on-board vertical averaging)
- 8 detector channels Raman, elastic and fluorescence
- Telescope diameter: 1 m
- Field of view: 30 µrad, ~14 m at surface
- Off-nadir pointing angle: ~10 deg
- Mean orbit altitude: ~450-500 km (trade study)
- Equatorial crossing time: 13:30 (descending node)
- Data volume ~4 Tbits/day
- Data access NASA and ASI data facilities
- Launch 2034

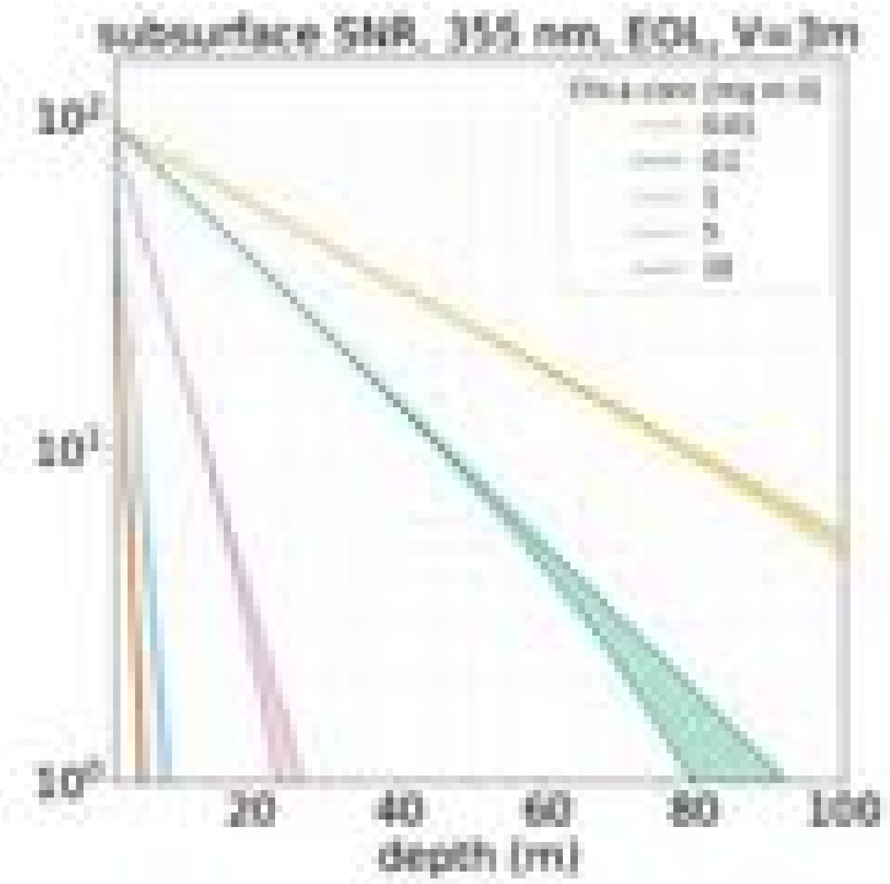
Ocean Lidar Applications

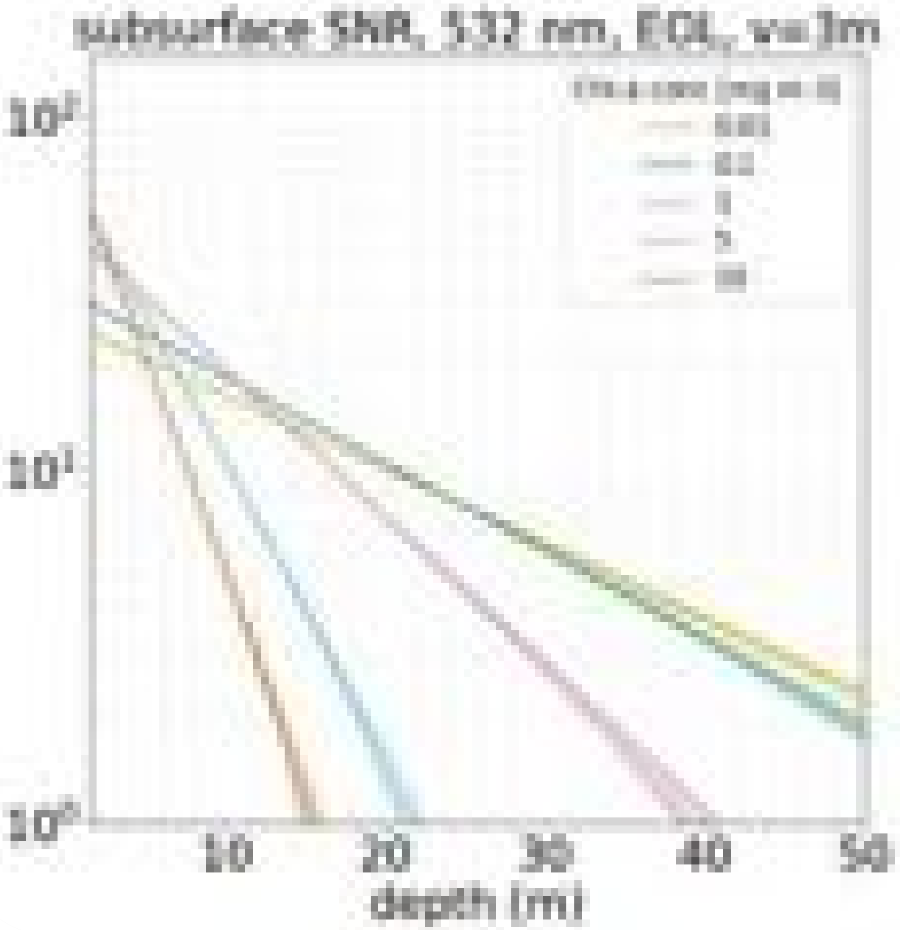
Native Vertical Resolutions around 7m

Atmosphere and ocean: same lidar echoes, different temporal portions with different vertical resolution

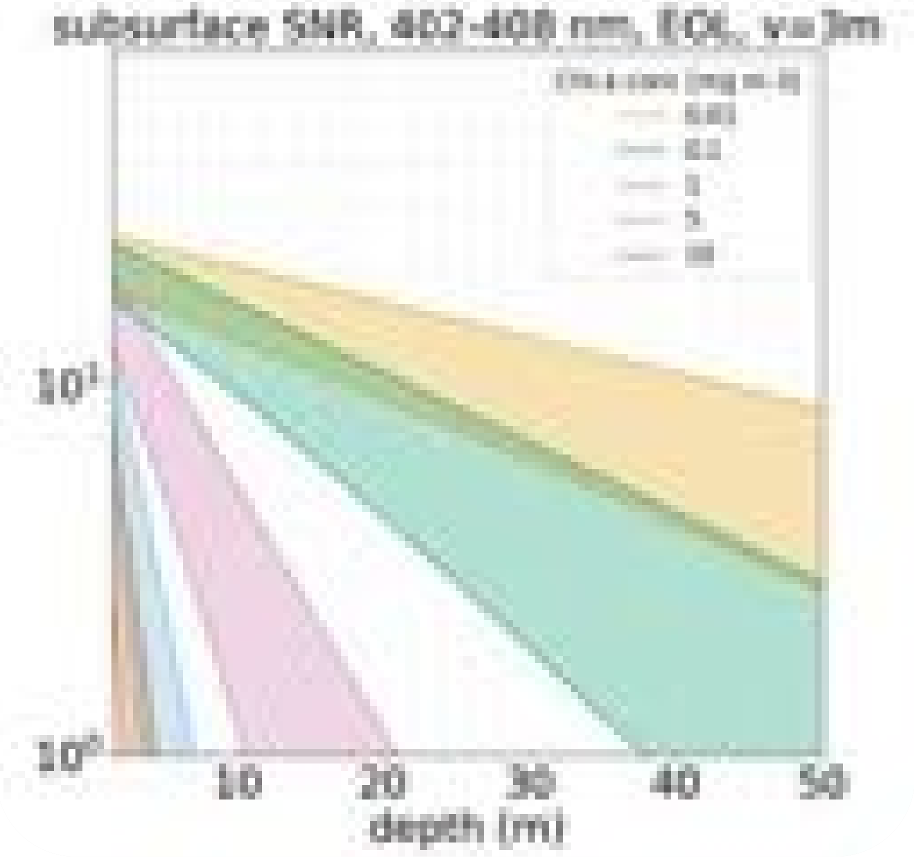
Reference	Range (km)		Description	Vertical resolution (in air) [m]					
	Upper	Lower		Para-Perp 355nm	Para-Perp 532nm	Total 1064nm	Rotational Raman	Water Raman	Fluore-scence
MSL	90	45	Stratosphere & mesosphere	360					
	45	32	Elastic calibration	180	180				
	32	20	Stratosphere	90	90	180	180	360	
	20	8	Troposphere	30	30	30	30	120	120
	8	5	Liquid clouds, coarse resolution	7.5	30	30	30	120	120
	5	0.20	Liquid clouds, fine resolution	3.75	30	30	30	120	120
	0.20	-0.25	Ocean & ocean surface	1.25	1.25	30	1.25	1.25	1.25
	-0.25	-0.50	Atmosphere below MSL	30	30	30	30	120	120
AGL	0.20	-0.05	Snow & vegetation (land-only)	1.25				1.25	1.25

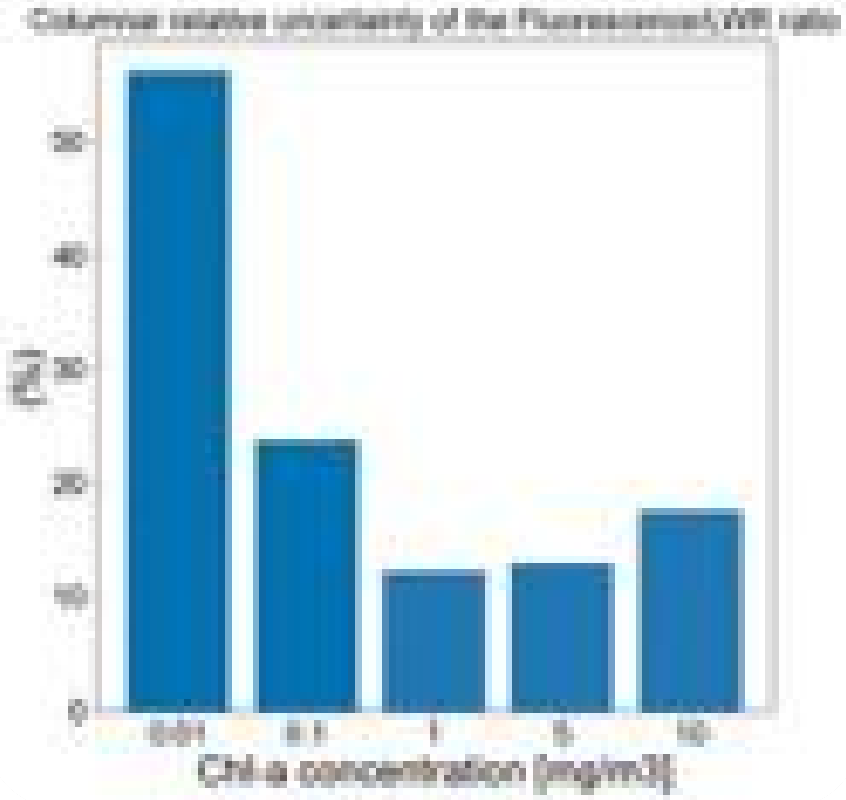
LUCE oceanic signals





LUCE oceanic signals





Ocean Lidar Applications

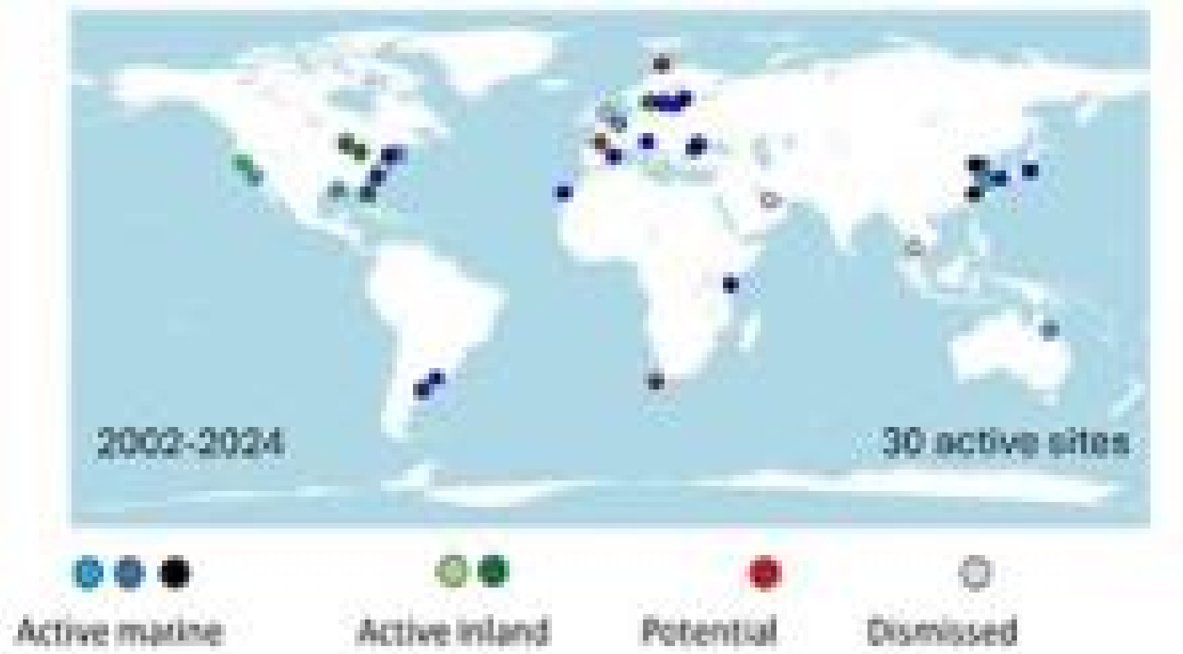
Towards a network of in-situ lidar?

Atmospheric Lidar networks

EARLINET (European Aerosol Research Lidar Network)

- ✓ Well established internationally
- ✓ Mature technology
- ✓ Consolidated QA procedures
- ✓ Common retrieval software

OC network



AERONET - OC (Aerosol Robotic Network Ocean Color)

Towards a network of in-situ lidar?

INTERNATIONAL SPACE SCIENCE INSTITUTE

ISSI FORUM on network of Oceanic Lidars

Attendees from diverse scientific and technological fields:
- atmospheric Lidar
- ocean color
- Lidar manufacturers

Aim: to discuss the opportunity to develop a network of in-situ observations using the Lidar technique.

Specific objectives:
- ❑ Identification of scientific and technological requirements
- ❑ White paper
- ❑ Expanding the Oceanic Lidar community

20-22 May 2025

Towards a network of in-situ lidar?

Challenges

Need for different platforms (stationary vs mobile) results in different approaches to setting up measurements

Fixed stations

- Restricted to coastal and inland waters
- 24/7 operation, possible scanning, eye-safety
- Easily connected to other networks stations, e.g. atmospheric lidar profiling (EARLINET, MPLNET), passive atmospheric/ocean color sites (AERONET)

Ship-based

- possible for open water, coastal areas and inland waters
- relying on the research vessels for complex experiments
- if oceanic lidar of simple, durable, user friendly, plug-in design can be used on commercial and opportunity vessels

Air-borne

- mainly for open water and coastal areas
- research aircrafts only
- extreme time/space coverage
- highest operational costs
- Not really feasible to operate on network-basis

Towards a network of in-situ lidar?

Outcomes

- Shipborne and fixed stations as preferable sites
- Miminum Lidar configuration: emission wavelength at 532 nm, 3 receiving channels (elastic co and cross polarization, water Raman), vertical resolution of 50 cm
- Day and night operation
- B_{bp}, K_d, Chl-a as primary geophysical products
- Evaluation and selection of different retrieval algorithms
- Initiating different activities to expand the community

Towards a network of in-situ lidar?

On-going studies

Atmo-Access ALIO TNA

October 2024
ULAS Scanning Mobile Lidar
Żywiec Lake, Poland

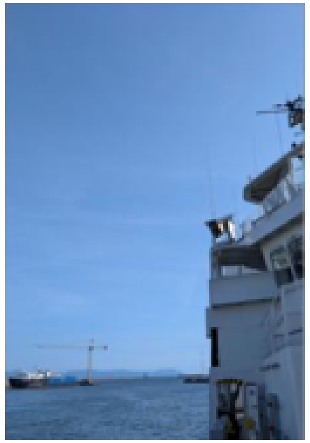
Aim: Assessing the feasibility of using Lidar designed for atmospheric purpose to study the optical properties of water.

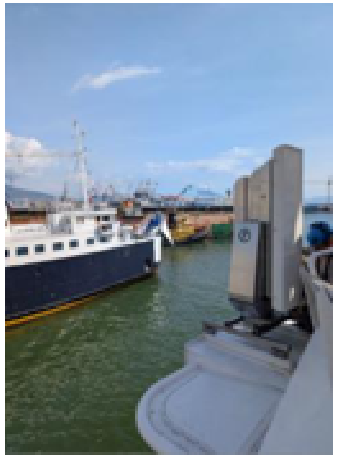
Ocean Lidar Applications

ITINERIS

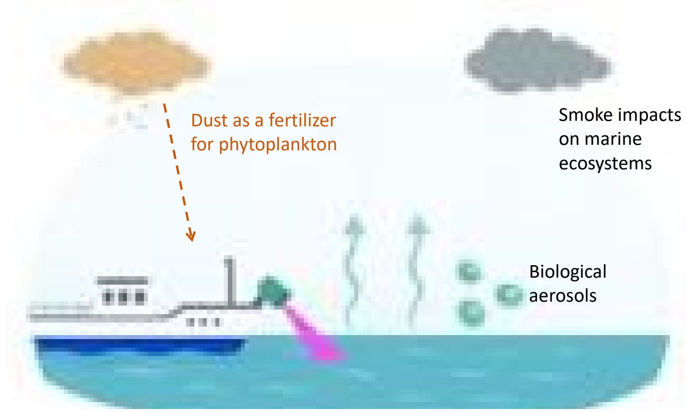
Towards a network of in-situ lidar?

Gaia Blu – AAOT
3D Scanning Marine Lidar





On-going studies



First commercial Lidar system combining atmospheric and ocean measurements. Synergetic use with automatic photometer on board.

Aim: Study of marine aerosols and processes at the air-sea interface.

Giuliano et al., 2026, Optics Letters,in review

Contact us if you wish to **join** our research group in Rome!

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National Research Council of Italy

ROME - TOR VERGATA

"9-eyes" RMR LIDAR