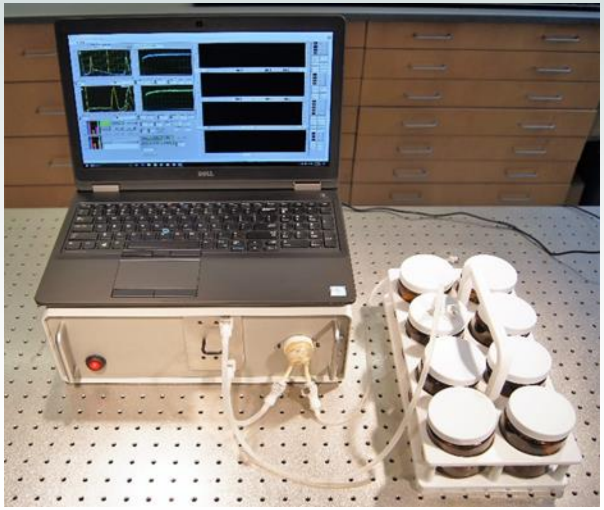
Advanced Laser Fluorometry for Characterization of Natural Aquatic Environments

Alexander Chekalyuk

Lamont Doherty Earth Observatory of Columbia University

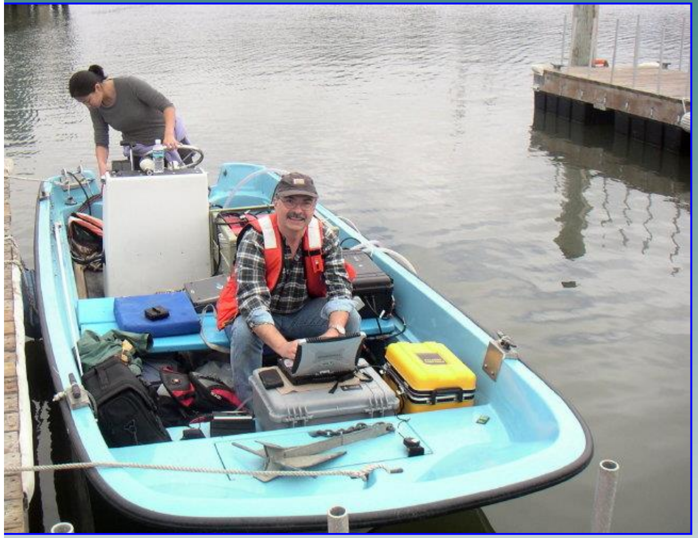
www.linkedin.com/in/alexanderchekalyuk
www.researchgate.net/profile/Alexander_Chekalyuk
achekalyuk@gmail.com, chekaluk@ldeo.columbia.edu



EG&G

LAMONT-DOHERTY EARTH OBSERVATORY
THE EARTH INSTITUTE AT COLUMBIA UNIVERSITY

Laser Fluorescence Analysis: **What We Can Do**



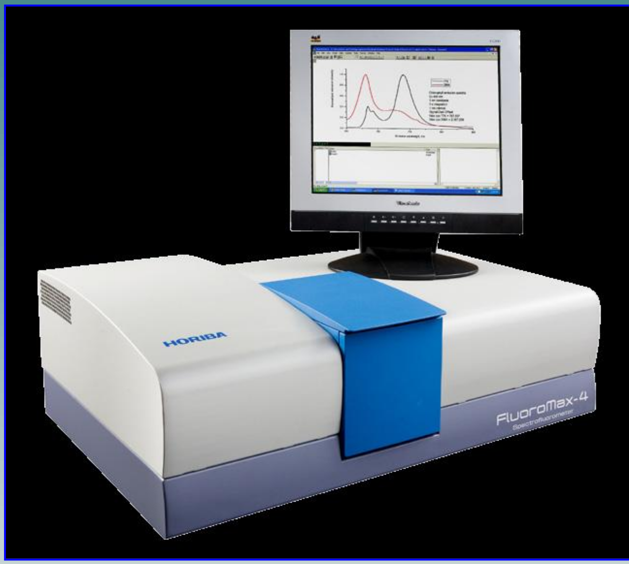
- ❑ **Fluorescent constituents in natural waters**:
  - Phytoplankton and bacteria
  - Chromophoric organic matter (COM = CDOM + CPOM)
  - Oil (poly-aromatic hydrocarbons (PAHs))

- ❑ **Information** that can be obtained:
  - P<u>hytoplankton</u>: pigments, biomass, phytoplankton composition, photo-physiology, and photosynthetic rates.

  - <u>CDOM and oil/PAHs</u>: qualitative characterization and content assessment.

Chekalyuk and Hafez, Limnol. Oceanogr. Methods 2008, 6:591-609

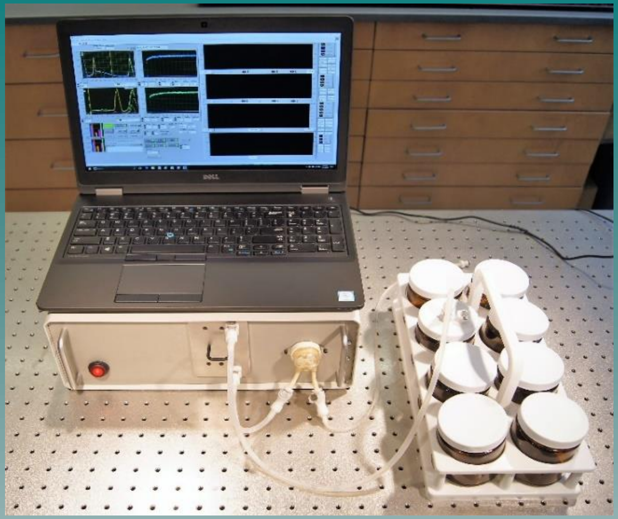
Advanced Laser Fluorometry (ALF): Filling the **Gap** between **Laboratory** and **Field** Instrumentation



Scanning fluorometers: provide ***informative*** and ***data-rich*** Excitation-Emission Matrix (EEM) measurements, *but they are* ***bulky***, ***slow***, *and* ***not sensitive enough*** for marine applications.

ALF – ***portable, field-deployable***, provides ***data-rich*** and ***accurate*** characterization of natural waters.

Field fluorometers: *compact*, *fast*, *deployable*, but *low informative* and (often) *inaccurate*.



Advanced Laser Fluorometry (ALF): Motivation and Approach

<u>Motivation</u>:

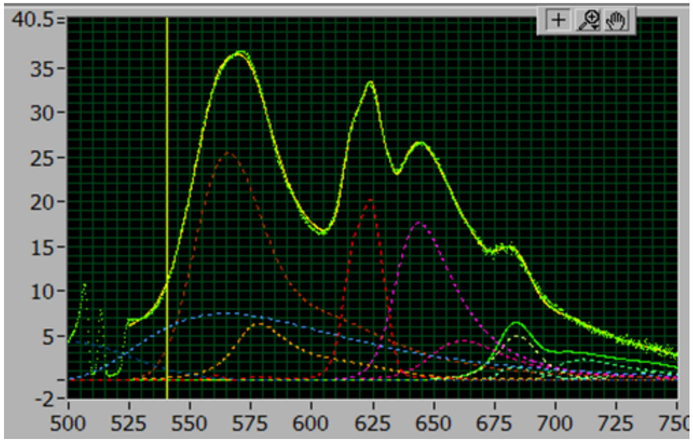
The need for *affordable*, *deployable* yet *informative* analytical *instruments* and *methods* for characterization of natural waters.

<u>Key solution</u>:

Concurrent *SPECTRAL* and *TEMPORAL* measurements of *LASER*-stimulated emission.

Spectral AND **Temporal Laser** Fluorescence: Why?

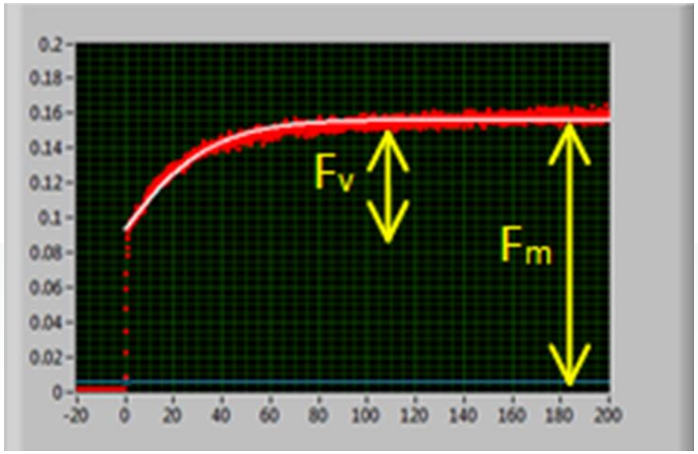
- ***Why "laser" excitation?***
  - High SENSITIVITY, SELECTIVITY, and better SPECTRAL DISCRIMINATION



- ***Why "spectral" measurements?*** - Emission bands of aquatic fluorescence constituents are spectrally BROAD and OVERLAPPED

=> To address the **spectral complexity of natural waters,** we need:
  - BROADBAND spectral measurements;
  - Spectral DECONVOLUTION of fluorescence signatures.
  - \+ Fluorescence normalization to water Raman also helps!

- ***Why "temporal" measurements?***
  - To **assess** phytoplankton PHOTO-PHYSIOLOGY (Fv/Fm) and **improve** assessments of CHLOROPHYLL



- ***Why "spectral AND temporal"?*** - It helps BOTH ways…

Chekalyuk and Hafez, Limnol. Oceanogr. Methods 2008, 6:591-609

ALF: Spectral Components for SDC Analysis

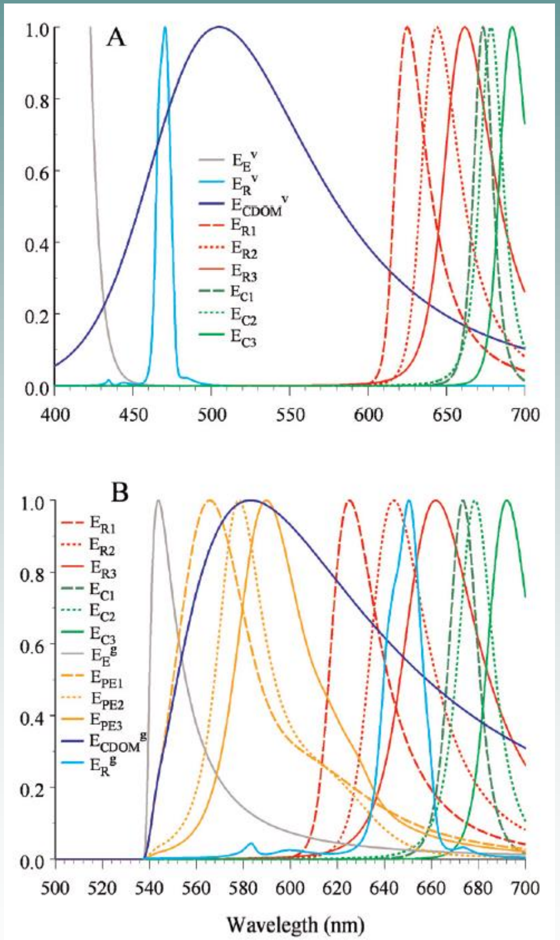
Limnol. Oceanogr.: Methods 6, 2008

Advanced laser fluorometry of natural aquatic environments

Alexander Chekalyuk[1] and Mark Hafez[2]*
[1]Lamont Doherty Earth Observatory of Columbia University, Marine Biology 4a, 61 Rt. 9W, Palisades, NY 10964
[2]EG&G Services Inc., NASA Wallops Flight Facility, Bldg. N159, Wallops Island, VA

$$y=\frac{a_0\left[1+\frac{\left(x-\frac{a_2a_4}{2a_3}-a_1\right)^2}{a_2^{\,2}}\right]^{-a_3}\exp\left[-a_4\left(\tan^{-1}\left(\frac{x-\frac{a_2a_4}{2a_3}-a_1}{a_2}\right)+\tan^{-1}\left(\frac{a_4}{2a_3}\right)\right)\right]}{\left(1+\frac{a_4^{\,2}}{4a_3^{\,2}}\right)^{-a_3}}$$

Here, a_0, a_1, a_2, a_3, and a_4 are parameters that define the amplitude, center, width, shape$_1$, and shape$_2$, respectively, of the Pearson's IV band.



A and **B**: SDC component sets for analysis of spectra measured with 405 and 532 nm excitation, respectively

Table 1. SDC spectral components*

	Spectral component	Abbreviation	Emission peak, nm
1	Elastic scattering	E_E^v	405
2	CDOM fluorescence	E_{CDOM}^v	508
3	Water Raman scattering, 1660, 2200, and 3440 cm^{-1}	E_R^v	434, 445, 471
4	Elastic scattering	E_E^g	532
5	CDOM fluorescence	E_{CDOM}^g	587
6	Water Raman scattering, 1660, 2200, 3440 cm^{-1}	E_R^g	583, 602, 651
7	Red emission 1	E_{R1}	625
8	Red emission 2	E_{R2}	644
9	Red emission 3	E_{R3}	662
10	Chl *a* fluorescence	E_{C1}	673
11	Chl *a* fluorescence	E_{C2}	679
12	Chl *a* fluorescence	E_{C3}	693
13	PE fluorescence 1	E_{PE1}	565
14	PE fluorescence 2	E_{PE2}	578
15	PE fluorescence 3	E_{PE3}	589

*Three bands of the water Raman scattering with the Raman shifts ν_{max} = 1660, 2200, and 3440 cm^{-1}, respectively, are integrated into one SDC component representing the Raman scattering in the LSE spectra. Spectral location of the individual Raman peak can be calculated as $\lambda_{max} = (\lambda_{exc}^{-1} - \nu_{max})^{-1}$; here, λ_{max} and λ_{exc} are the wavelengths of the Raman scattering peak and excitation, respectively.

ALF: SDC Analysis of Emission Spectra, 532 nm excitation

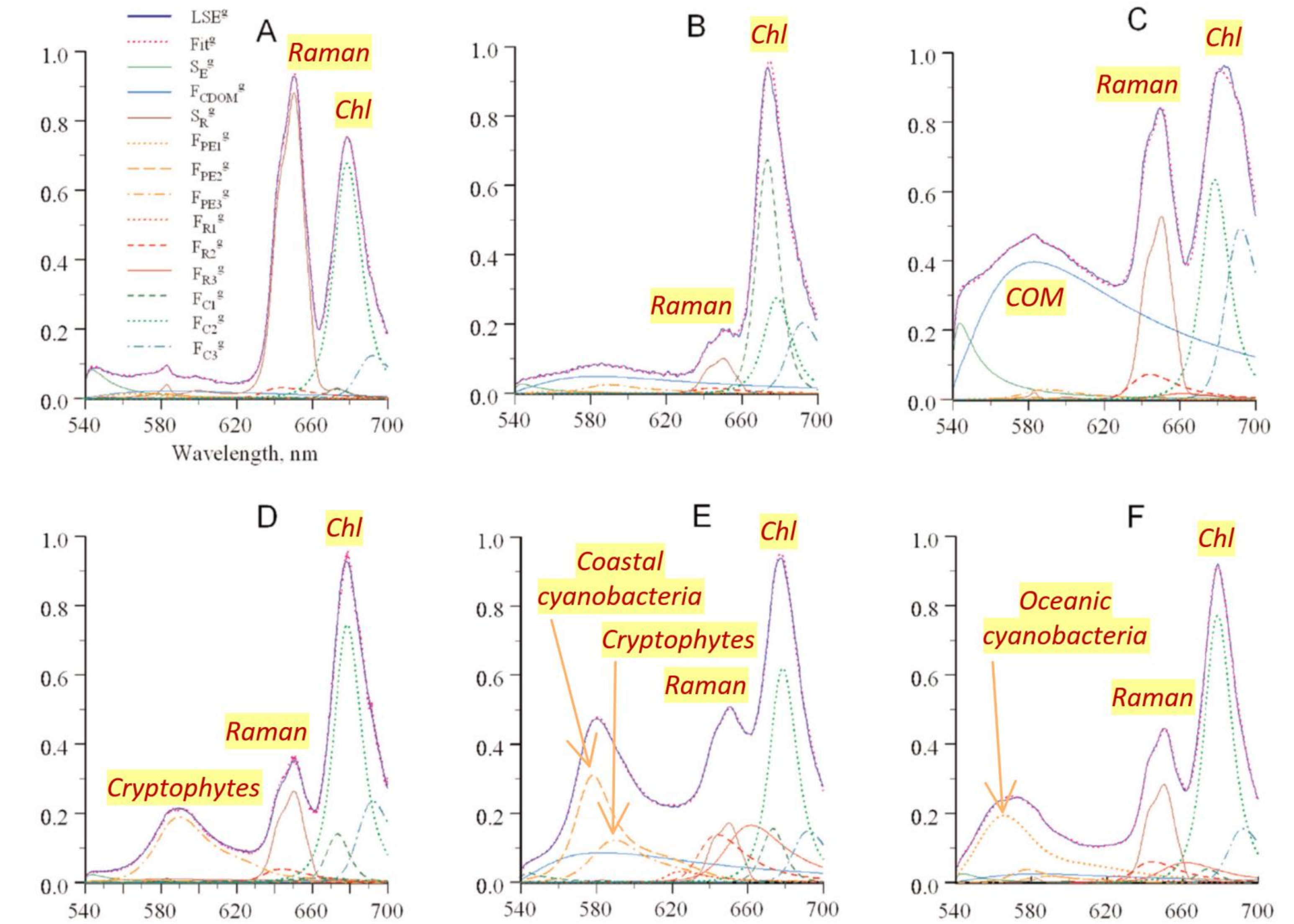
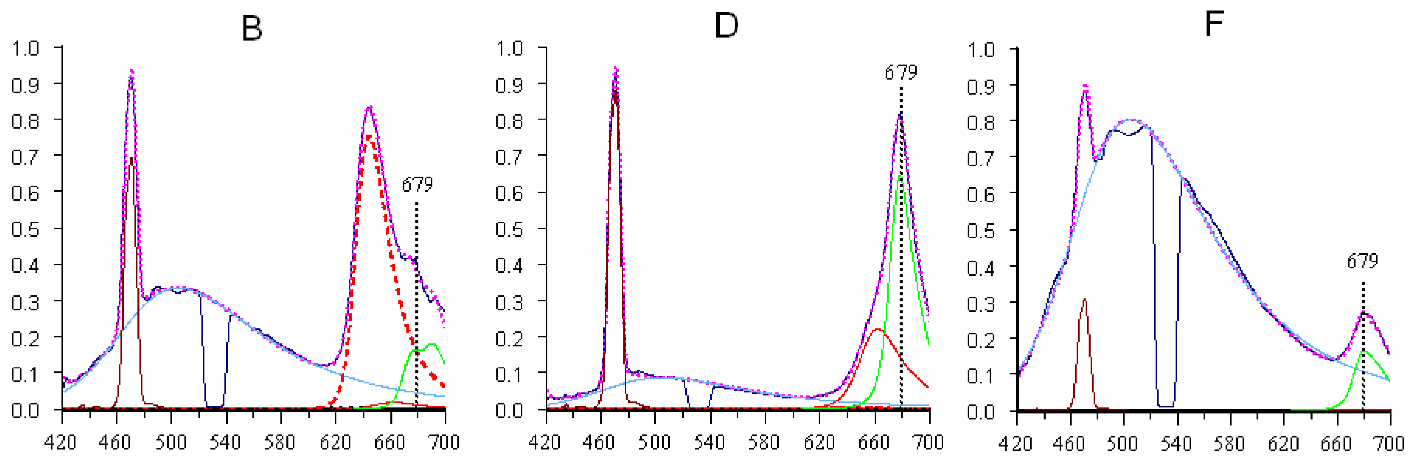
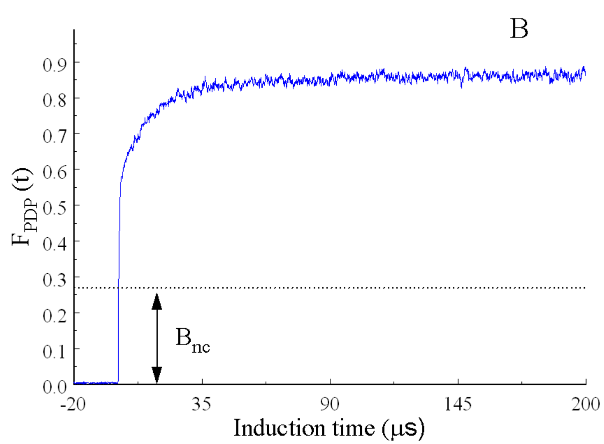


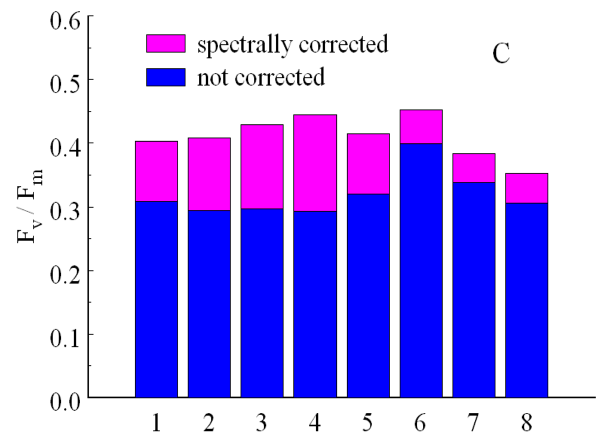
Fig. 6. Variability in the LSE^g spectra measured in diverse surface waters with excitation at 532 nm. (A): Southern California Bight, April 2007. (B): Moss Landing Harbor (California), September 2006. (C): Delaware River, June 2006. (D): Coastal zone of the Southern California Bight near Point Conception, April 2007. (E): Lower Chesapeake Bay, June 2005. (F): Middle Atlantic Bight, vicinity of the Delaware Bay mouth, June 2006.

Chekalyuk and Hafez, Limnol. Oceanogr. Methods 2008, 6:591-609

ALF: SPECTRAL measurements can help to improve TEMPORAL measurements of variable fluorescence, F_v/F_m







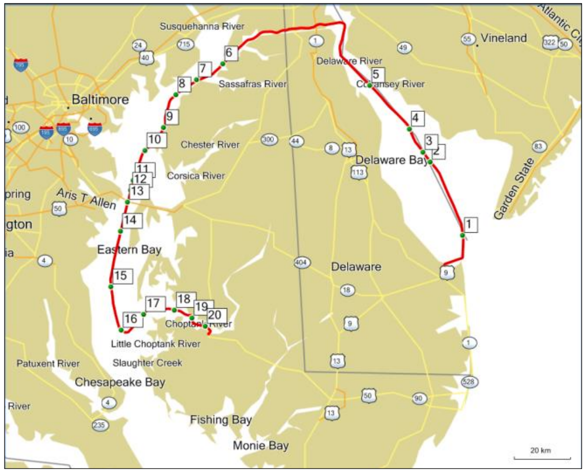
<u>Upper panels</u>: **Non-Chl fluorescence** in the spectral area of Chl-a fluorescence peak **may be significant**.

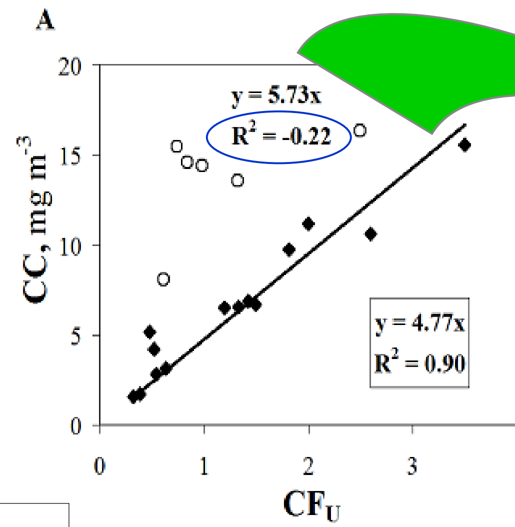
<u>Lower panels</u>: **subtraction of none-Chl fluorescence** background, $\mathbf{B_{nc}}$, from fluorescence induction measurements **improves the accuracy of phytoplankton photophysiological assessments,** $\mathbf{F_v/F_m}$**.**

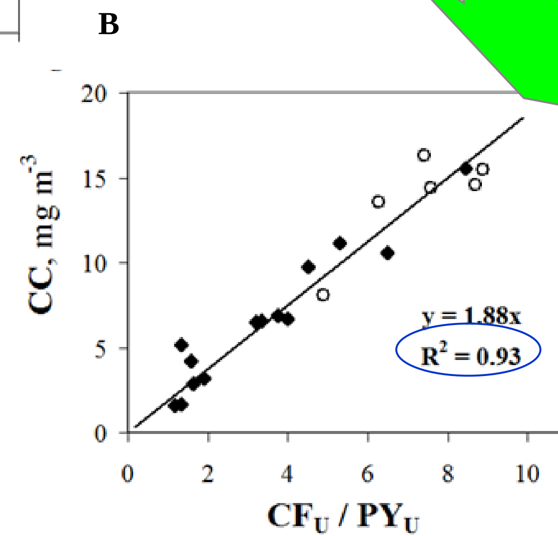
Chekalyuk and Hafez, Limnol. Oceanogr. Methods 2008, 6:591-609

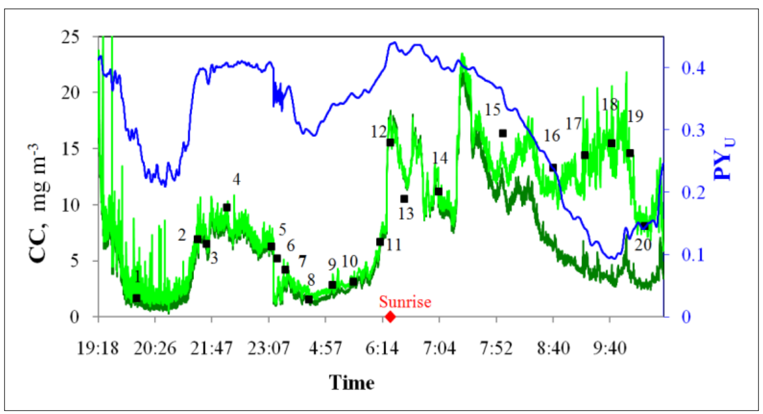
ALF: TEMPORAL Fv/Fm measurements can help to improve SPECTRAL Chl assessments

Chekalyuk, A. and M. Hafez. Optics Express. 19(23): 22643–22658 (2011)





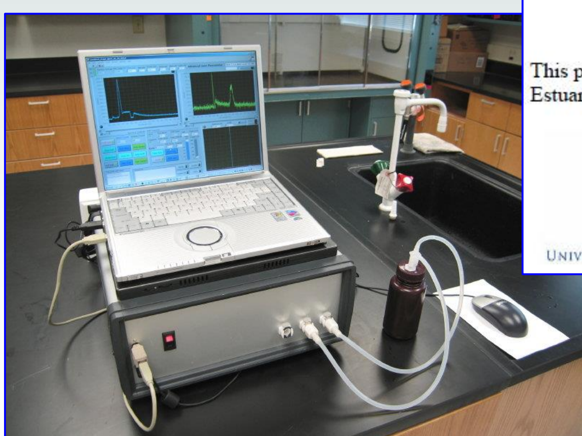




(A): Correlation between the HPLC measurements of Chl concentration (**CC**) and the underway Chl fluorescence measurements (**CF_U**); the **night fluorescence measurements** (black diamonds) show **high correlation with CC** (R^2=0.9), while the morning, **NPQ-affected** fluorescence data (white circles) **do not correlate with CC** (R^2= -0.22).

(B): normalizing CF_U to the concurrent measurements of variable fluorescence, **PY_U**, can be used to eliminate the NPQ effect to **improve the accuracy of Chl fluorescence assessments**.

Initial ALF Development: NOAA/CICEET Project (2003-2006)



Advanced Laser Fluorescence (ALF) Technology for Estuarine and Coastal Environmental Biomonitoring

A Final Report Submitted to

The NOAA/UNH Cooperative Institute for Coastal and Estuarine Environmental Technology (CICEET)

Submitted by

Dr. Alexander M. Chekalyuk
Center for Atmospheric Sciences, Hampton University
Hampton, VA 23668

Dr. Kenneth A. Moore
Virginia Institute of Marine Science, College of William and Mary
1208 Greate Road, Gloucester Point, VA 23062

Dr. David L. White
Baruch Institute, University of South Carolina, Georgetown, SC 29442

Dr. Dwayne E. Porter
Norman J. Arnold School of Public Health, University of South Carolina
1233 Washington Street, Columbia, SC 29201

March 31, 2006

CICEET

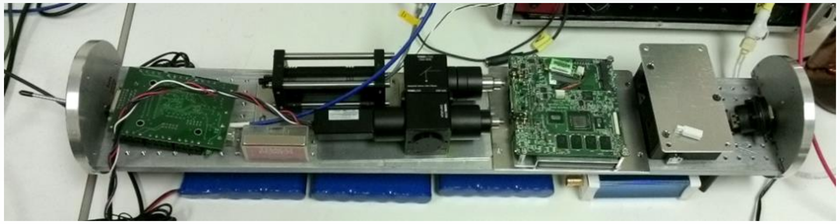
This project was funded by a grant from NOAA/UNH Cooperative Institute for Coastal and Estuarine Environmental Technology, NOAA Grant Number(s) NA03NOS4190195

University of New Hampshire

NOAA

ALF: Instruments and Platforms

Aquatic Laser Fluorescence Analyzer (ALFA): 1st Commercial ALF Instrument (LDEO/WET Labs)



First commercial ALF instrument (ALFA) was developed by LDEO/WET Labs in 2010-2013 (sponsored by the National Oceanographic Partnership Program (NOPP))

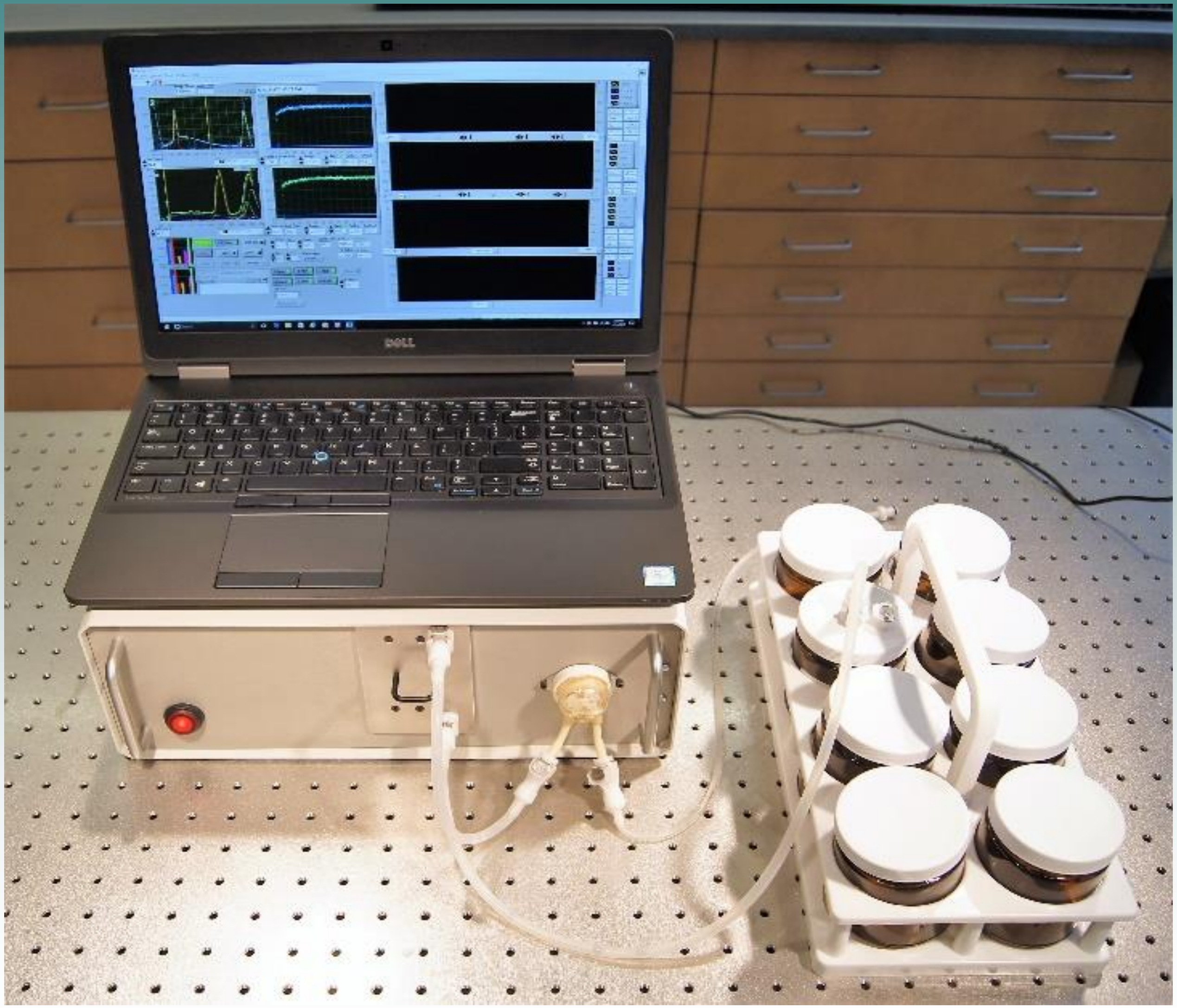
ALFA: 405 and 514 nm laser excitation

- dual laser excitation (405 and 514 nm)
- **Chlorophyll** (0.01 – 100 mg m^{-3})
- **PBP pigments** for characterization of oceanic/coastal **cyanobacteria** and eukaryotic **cryptophytes**
- **COM** (CDOM + CPOM)
- Phytoplankton photochemical efficiency, **Fv/Fm**

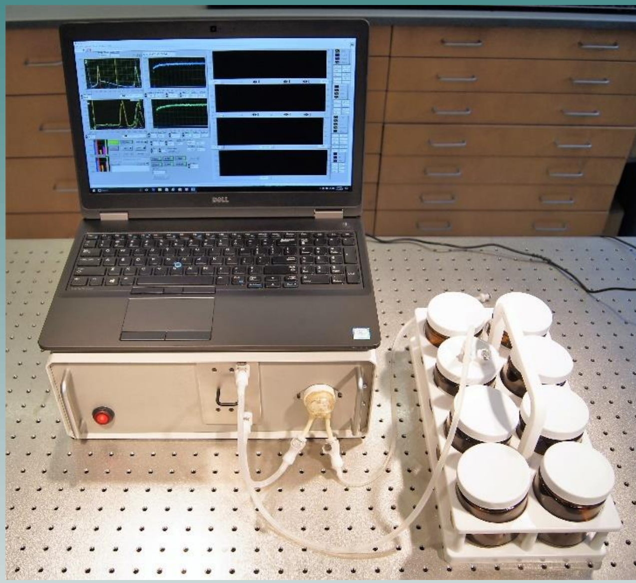
ALF In Situ (ALFIS) prototype: 514 nm laser excitation

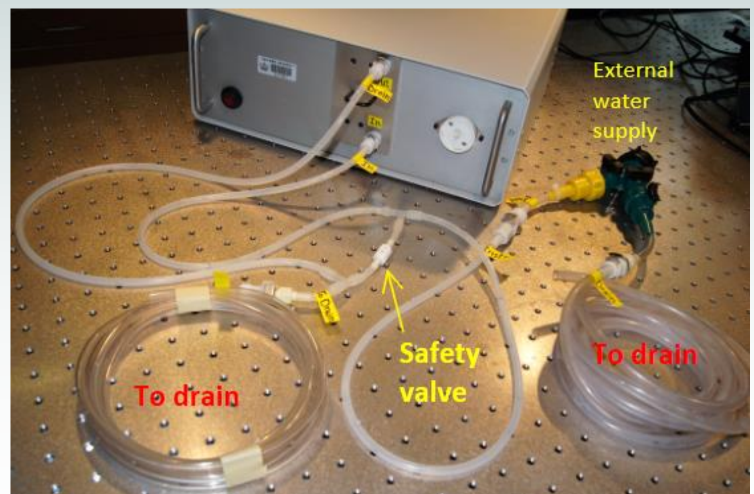
- **Chl** and **PBP pigments** for characterization of **blue/green-water cyanobacteria** and eukaryotic **cryptophytes, Fv/Fm**, and **CDOM** (coastal/estuarine/fresh waters)

Next Generation ALF:
Custom Laser Analytical Spectroscopic System (CLASS)



Next Generation ALF:
Custom Laser Analytical Spectroscopic Systems (CLASS)





ALF Methods and Instrument Designs: Two Broad US Patents (2015 & 2017)

(12) **United States Patent**
Chekalyuk

(10) **Patent No.:** **US 8,970,841 B2**
(45) **Date of Patent:** **Mar. 3, 2015**

(54) **SPECTRAL AND TEMPORAL LASER FLUORESCENCE ANALYSIS SUCH AS FOR NATURAL AQUATIC ENVIRONMENTS**

(75) Inventor: **Alexander Chekalyuk**, Bridgewater, NJ (US)

(73) Assignee: **The Trustees of Columbia University in the City of New York**, New York, NY (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 141 days.

(21) Appl. No.: **13/513,786**

(22) PCT Filed: **Dec. 3, 2010**

(86) PCT No.: **PCT/US2010/058891**

§ 371 (c)(1), (2), (4) Date: **Sep. 11, 2012**

(87) PCT Pub. No.: **WO2011/069067**

PCT Pub. Date: **Jun. 9, 2011**

(65) **Prior Publication Data**

US 2012/0324986 A1 Dec. 27, 2012

Related U.S. Application Data

(60) Provisional application No. 61/266,756, filed on Dec. 4, 2009.

(51) **Int. Cl.**
G01J 3/30 (2006.01)
G01J 3/28 (2006.01)
(Continued)

(52) **U.S. Cl.**
CPC ***G01N 21/6408*** (2013.01); ***G01J 3/02*** (2013.01); ***G01J 3/0264*** (2013.01); ***G01J 3/4406*** (2013.01);
(Continued)

(58) **Field of Classification Search**
None
See application file for complete search history.

(56) **References Cited**

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"CICEET Progress Report for the period Sep. 15, 2004 Through Mar. 15, 2005; dvanced Laser Fluorescence (ALF) Technology for Estuarine and Coastal Environmental Biomonitoring", http://ciceet.unh.edu/progressreports/2005/3_2005/chekalyuk2003/, 6 pgs.
(Continued)

Primary Examiner — Kara E Geisel
Assistant Examiner — Hina F Ayub
(74) *Attorney, Agent, or Firm* — Schwegman Lundberg & Woessner, P.A.

(57) **ABSTRACT**

An Advanced Laser Fluorometer (ALF) can combine spectrally and temporally resolved measurements of laser-stimulated emission (LSE) for characterization of dissolved and particulate matter, including fluorescence constituents, in liquids. Spectral deconvolution (SDC) analysis of LSE spectral measurements can accurately retrieve information about individual fluorescent bands, such as can be attributed to chlorophyll-a (Chl-a), phycobiliprotein (PBP) pigments, or chromophoric dissolved organic matter (CDOM), among others. Improved physiological assessments of photosynthesizing organisms can use SDC analysis and temporal LSE measurements to assess variable fluorescence corrected for SDC-retrieved background fluorescence. Fluorescence assessments of Chl-a concentration based on LSE spectral measurements can be improved using photo-physiological information from temporal measurements. Quantitative assessments of PBP pigments, CDOM, and other fluorescent constituents, as well as basic structural characterizations of photosynthesizing populations, can be performed using SDC analysis of LSE spectral measurements.

25 Claims, 23 Drawing Sheets

(12) **United States Patent**
Chekalyuk

(10) **Patent No.:** **US 9,618,449 B2**
(45) **Date of Patent:** **Apr. 11, 2017**

(54) **OPTICAL ANALYSIS OF EMISSIONS FROM STIMULATED LIQUIDS**

(71) Applicant: **The Trustees of Columbia University in the City of New York**, New York, NY (US)

(72) Inventor: **Alexander Chekalyuk**, Bridgewater, NJ (US)

(73) Assignee: **The Trustees of Columbia University in the City of New York**, New York, NY (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 120 days.

(21) Appl. No.: **14/376,297**

(22) PCT Filed: **Feb. 1, 2013**

(86) PCT No.: **PCT/US2013/024484**

§ 371 (c)(1), (2) Date: **Aug. 1, 2014**

(87) PCT Pub. No.: **WO2013/116760**

PCT Pub. Date: **Aug. 8, 2013**

(65) **Prior Publication Data**

US 2015/0000384 A1 Jan. 1, 2015

Related U.S. Application Data

(60) Provisional application No. 61/594,778, filed on Feb. 3, 2012, provisional application No. 61/677,318, filed on Jul. 30, 2012.

(51) **Int. Cl.**
G01N 21/00 (2006.01)
G01N 21/64 (2006.01)
(Continued)

(52) **U.S. Cl.**
CPC ***G01N 21/6402*** (2013.01); ***G01J 3/021*** (2013.01); ***G01J 3/0208*** (2013.01);
(Continued)

(58) **Field of Classification Search**
CPC .. G02B 26/0833; G02B 26/08; G02B 26/085; G02B 26/0875; G02B 26/10;
(Continued)

(56) **References Cited**

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WO WO-2013116760 A1 8/2013

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"International Application Serial No. PCT/US2013/024484, International Search Report mailed Apr. 22, 2013", 3 pgs.
(Continued)

Primary Examiner — Michael P Stafira
(74) *Attorney, Agent, or Firm* — Schwegman, Lundberg & Woessner, P.A.

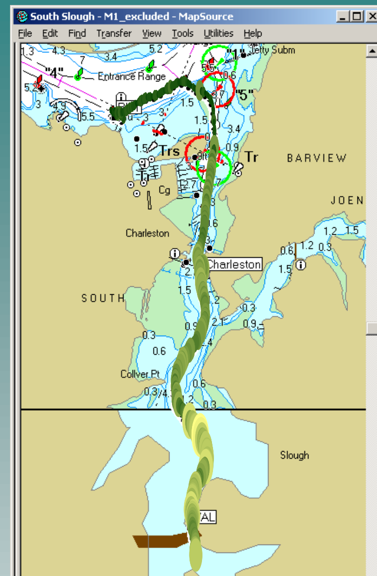
(57) **ABSTRACT**

Modular systems can be used for optical analysis, including in-situ analysis, of stimulated liquids. An excitation module can include a radiation sources, e.g., a laser, LED, lamp, etc. A detection module can include one or more detectors configured to receive spectral and/or temporal information from a stimulated liquid. Such systems can be used to identify or measure optical emissions including fluorescence or scattering. The efficient excitation of liquid samples and collection of emissions from the samples provides substantial, up to four-fold increase in the emission signal over prior systems. In an example, emission measurements can be
(Continued)

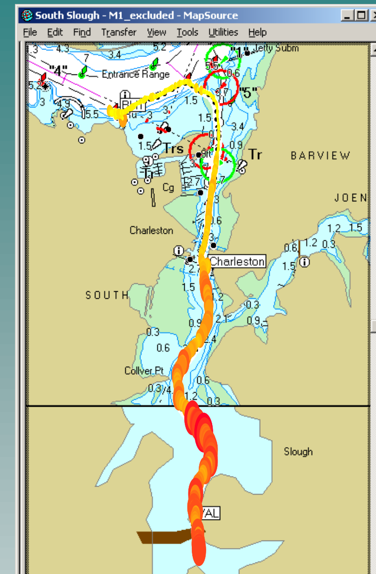
Chekalyuk, A.M. "Spectral and Temporal Laser Fluorescence Analysis such as for Natural Aquatic Environments", **US Patent 8970841**.

Chekalyuk, A.M. "Optical Analysis of Emissions from Stimulated Liquids", **US Patent 9618449**.

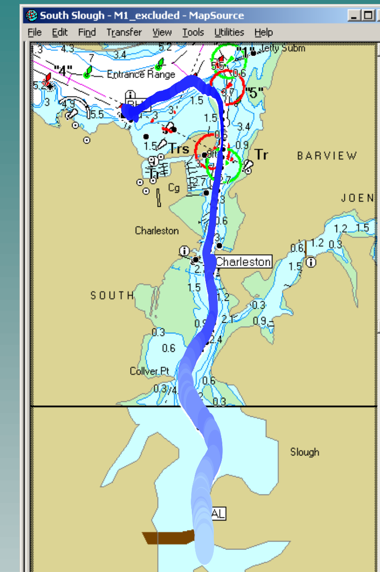
ALF: Motorboat underway survey at Sough Slow NERR (OR, 2005)



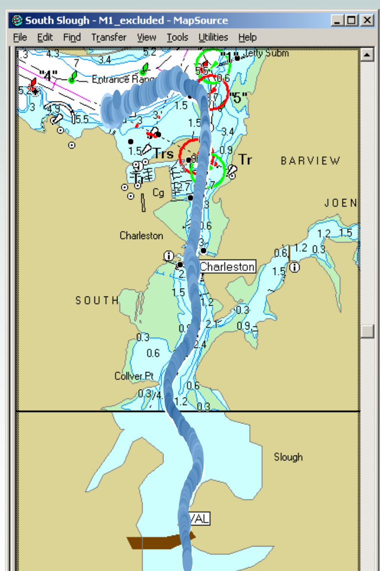
Chlorophyll



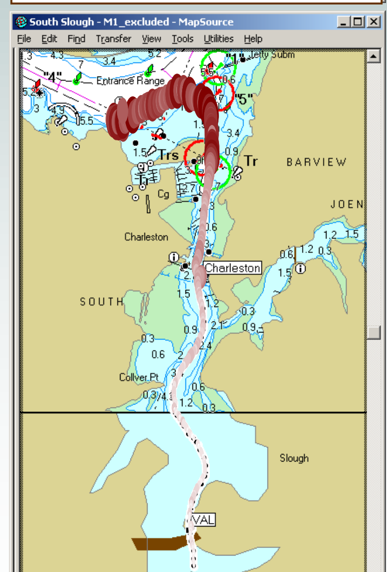
Phycoerythrin



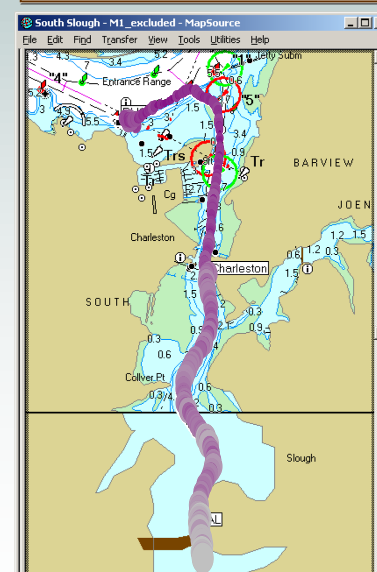
CDOM concentration



Variable fluor., Fv/Fm

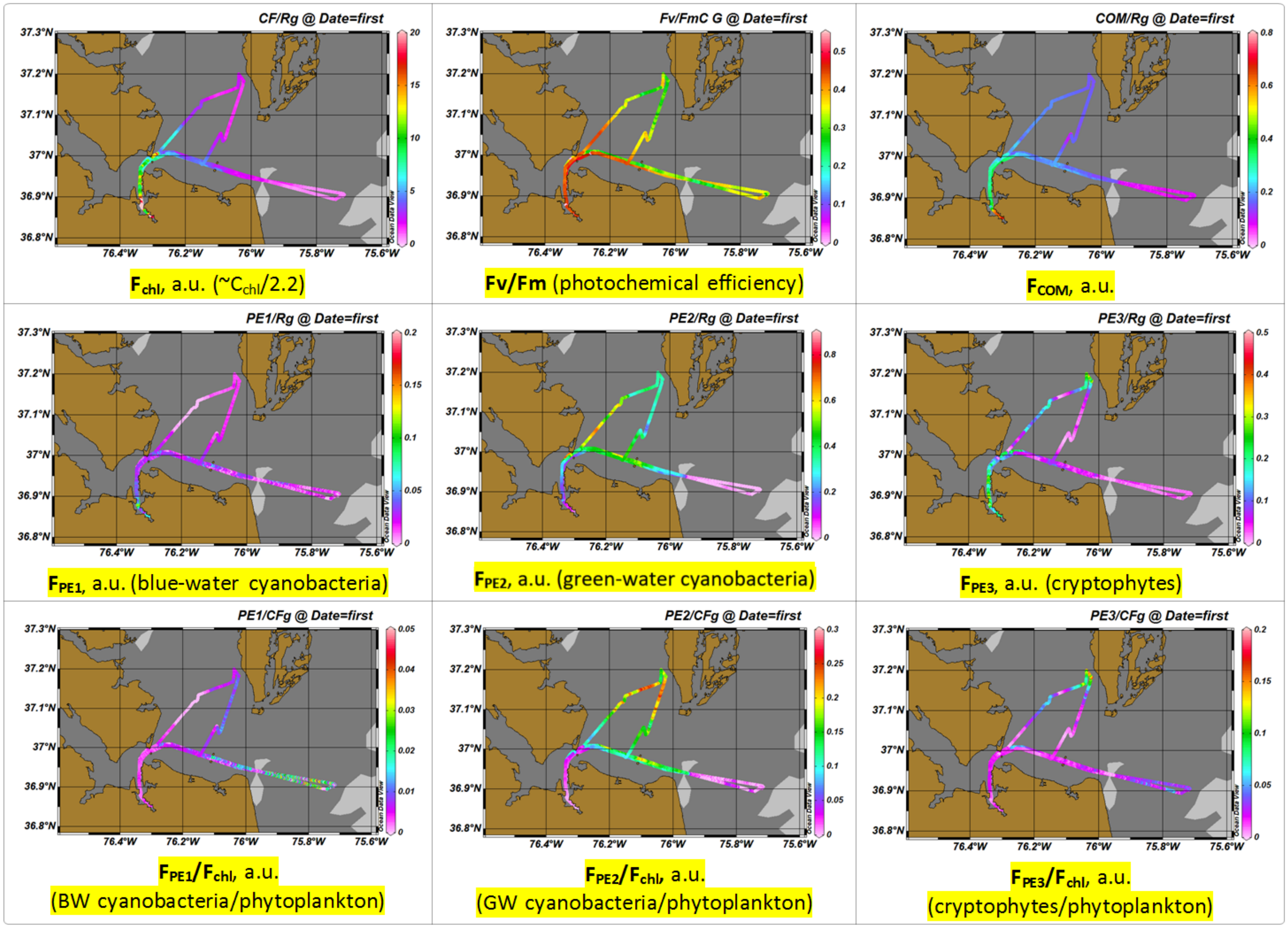


Absorption cross-section



Laser elastic scattering

ALFA: Underway measurements in Chesapeake Bay



F_{chl}, a.u. (~C_{chl}/2.2)

Fv/Fm (photochemical efficiency)

F_{COM}, a.u.

F_{PE1}, a.u. (blue-water cyanobacteria)

F_{PE2}, a.u. (green-water cyanobacteria)

F_{PE3}, a.u. (cryptophytes)

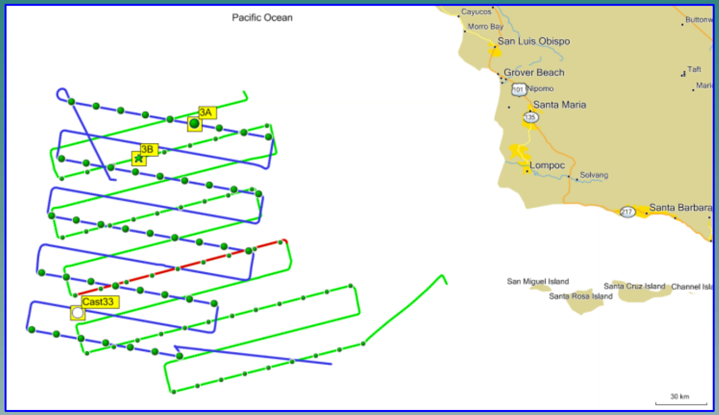
F_{PE1}/F_{chl}, a.u. (BW cyanobacteria/phytoplankton)

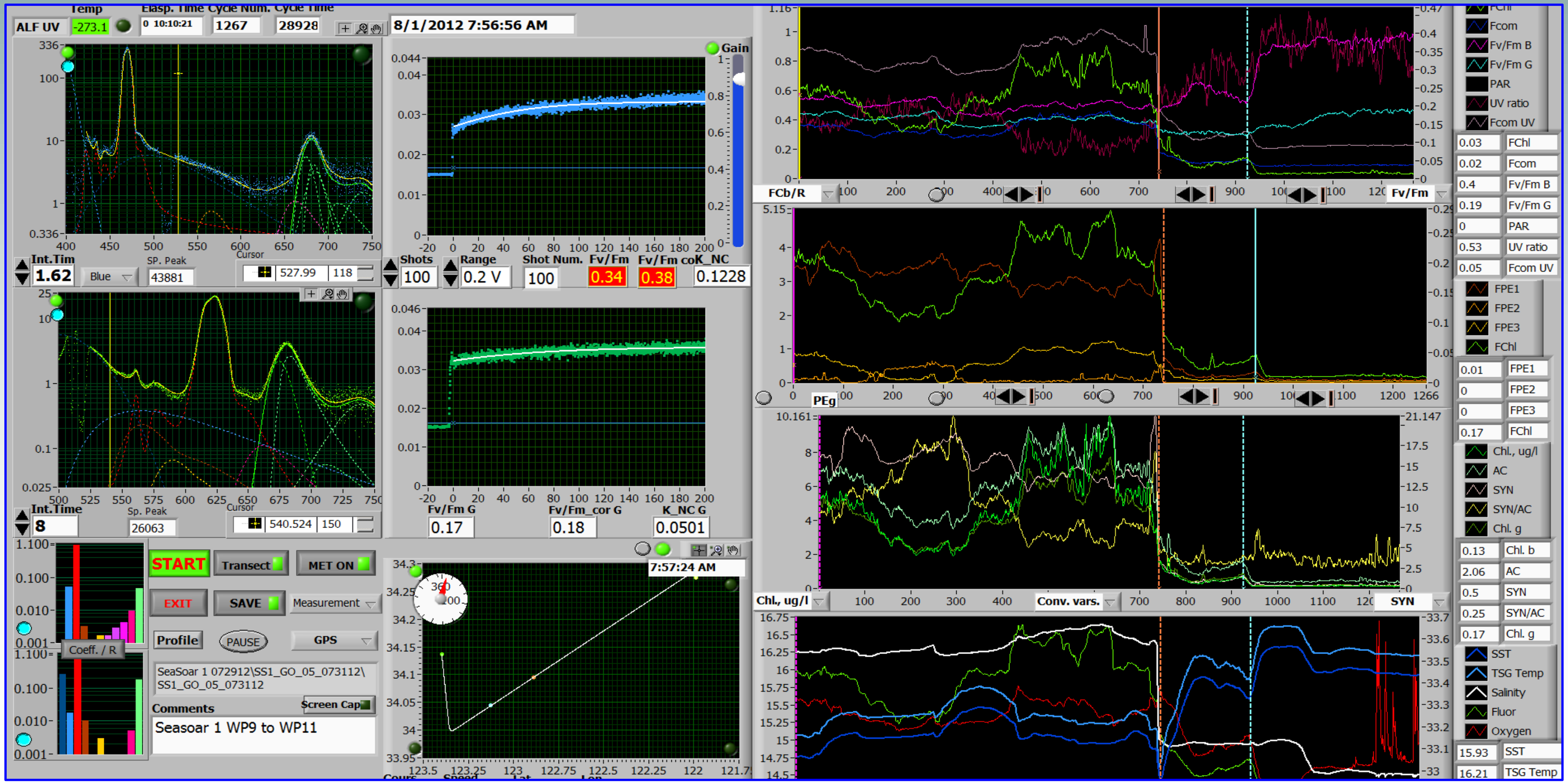
F_{PE2}/F_{chl}, a.u. (GW cyanobacteria/phytoplankton)

F_{PE3}/F_{chl}, a.u. (cryptophytes/phytoplankton)

(Aug. 2013; measured by Gilerson et al.)

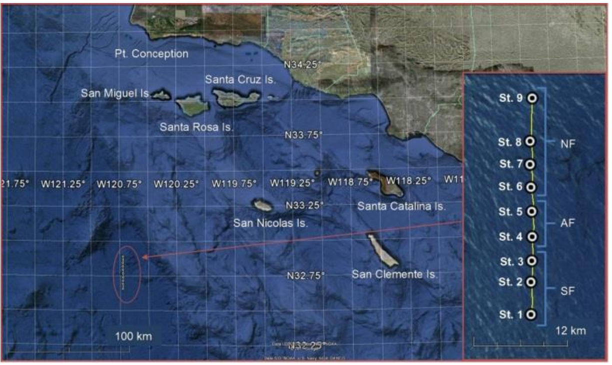
ALF: Mapping biological responses across oceanic fronts

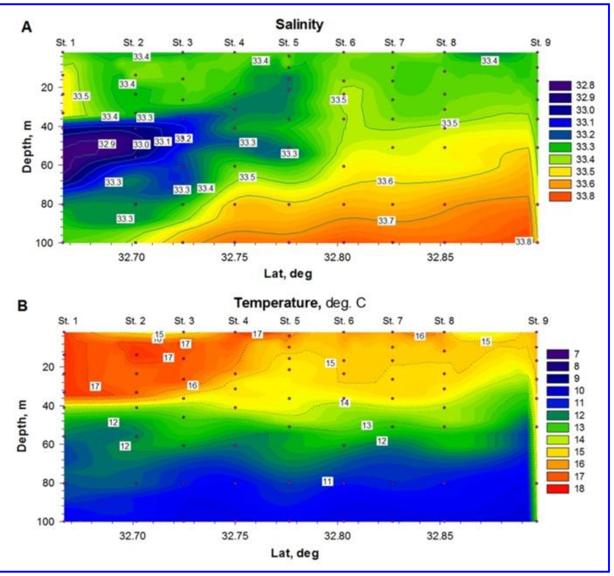




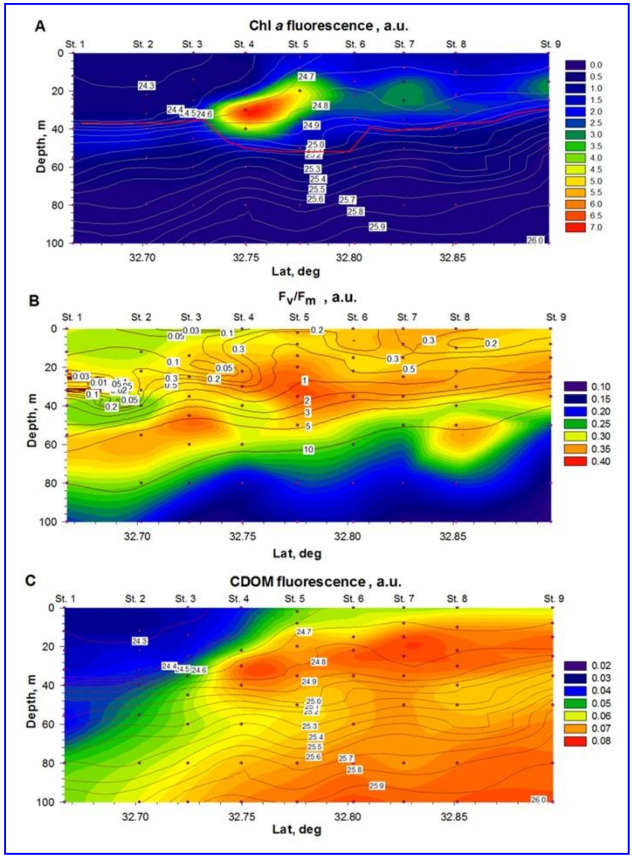
ALF: Variability in phytoplankton biomass, physiology, structure and COM across the oceanic fronts

Chekalyuk et al., Laser fluorescence analysis of phytoplankton across a frontal zone in the California Current ecosystem, **J. Plankton Res.**, **34**(9), 761-777 (**2012**)

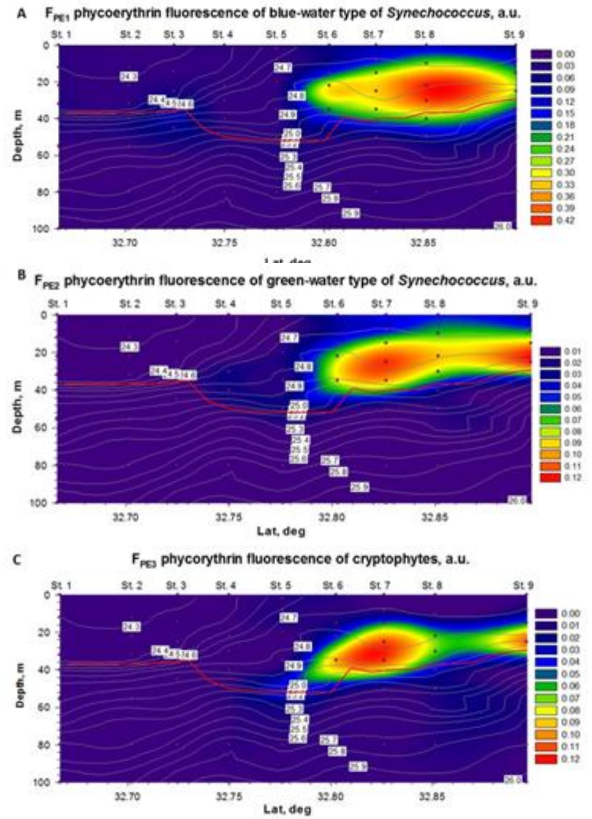




Distributions of seawater salinity (**A**) and temperature (**B**) in the euphotic layer across the A-front.

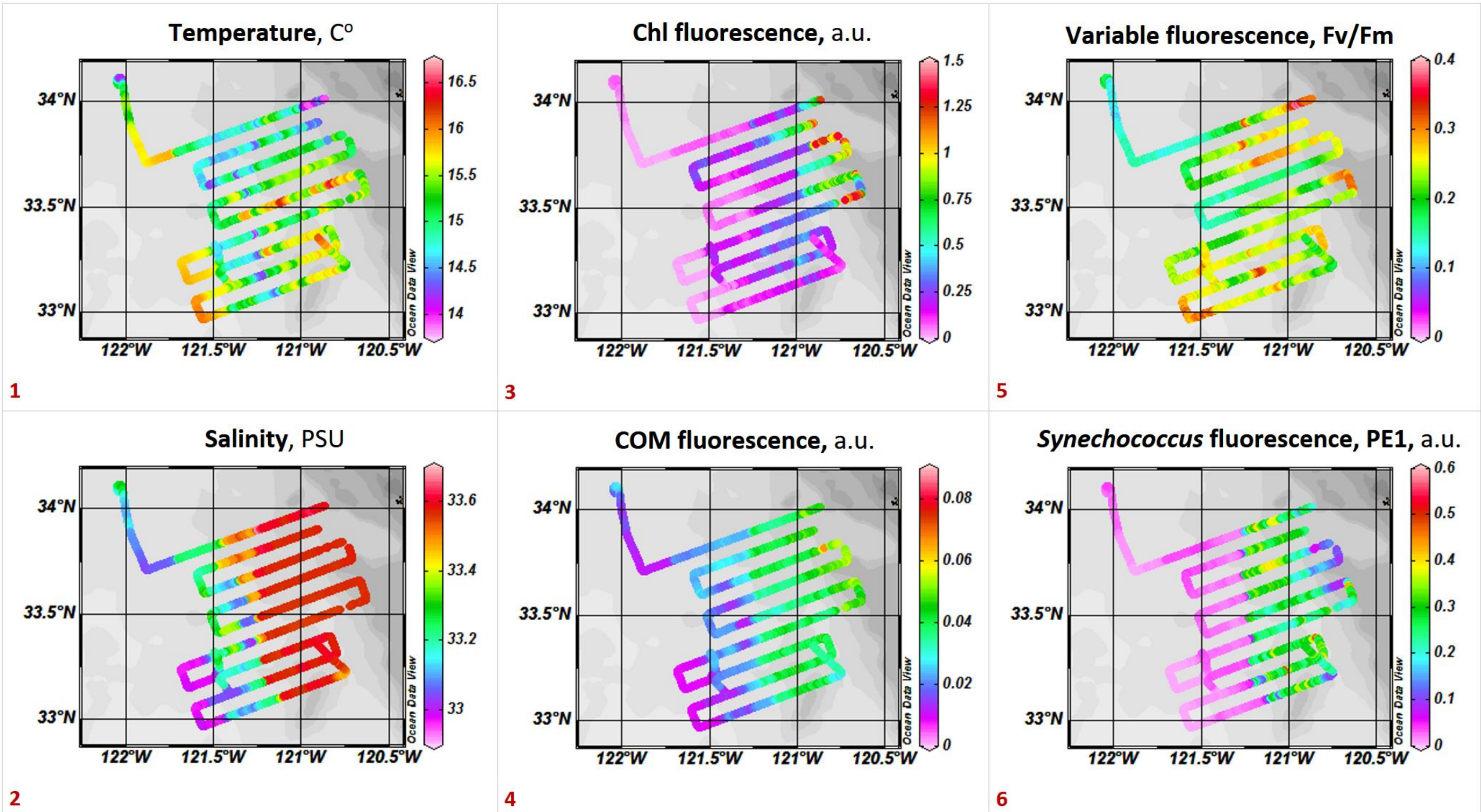


Spatial distributions of Chl *a* (**A**), phytoplankton photochemical efficiency F_v/F_m (**B**), and CDOM (**C**) across the frontal zone.



Spatial distributions of blue-water (**A**) and green-water (**B**) types of cyanobacteria and cryptophytes (**C**) across the frontal zone.

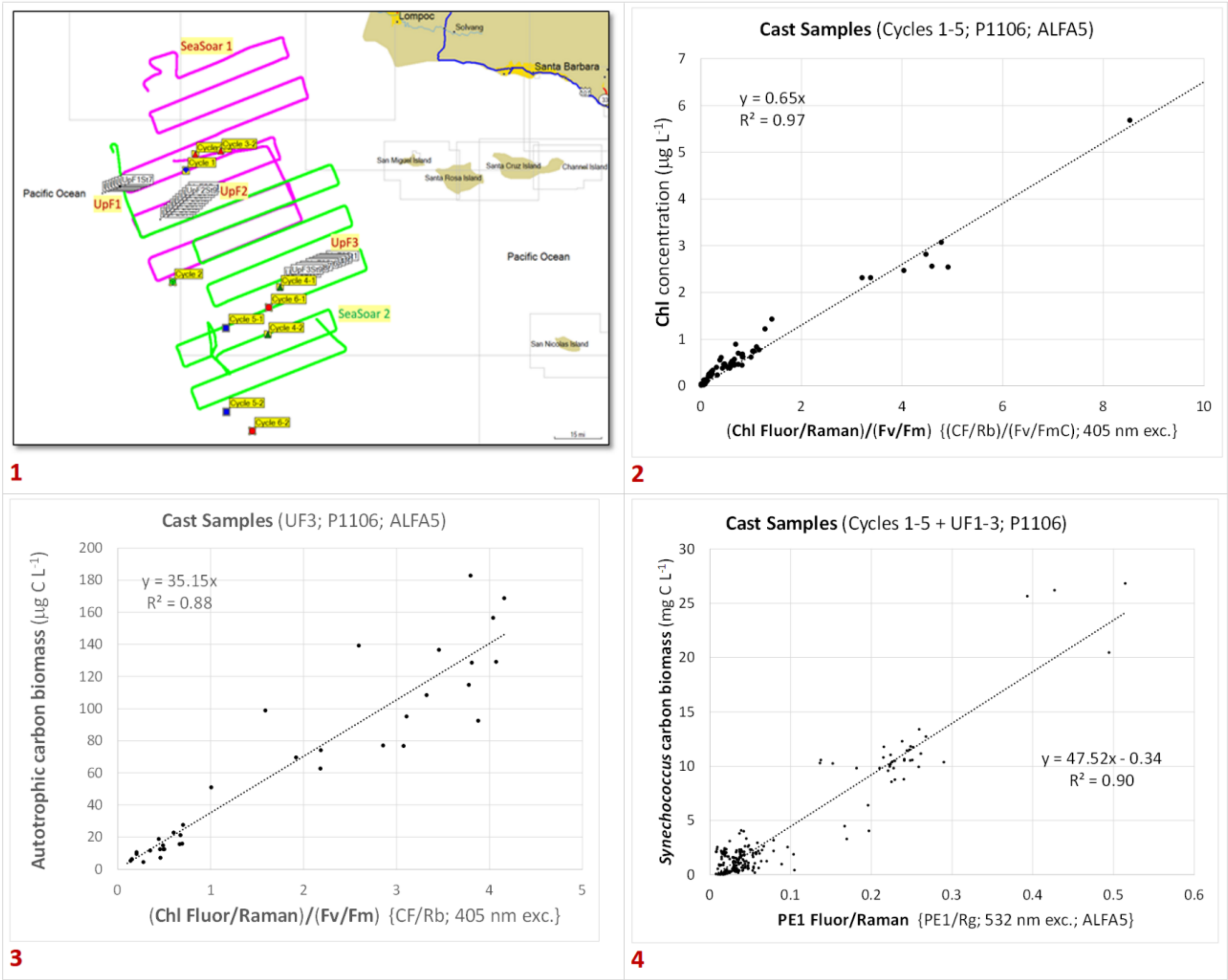
ALF: California Current Synoptic Survey (SIO, NSF), CCE LTER, 2011



Underway measurements of synoptic-scale surface distributions of sea-surface **temperature** (1), **salinity** (2), **Chl** fluorescence (3; ALF), colored organic matter (**COM**) fluorescence (4; ALF), variable fluorescence (= phytoplankton photochemical efficiency), **Fv/Fm** (5; ALF), and phycoerythrin fluorescence of oceanic cyanobacteria ***Synechococcus*, PE1** (6; ALF). California Current Ecosystem (CCE, SIO) Long-Term Ecological Research (LTER, NSF) Process cruise P1106; 3-6 July 2011.

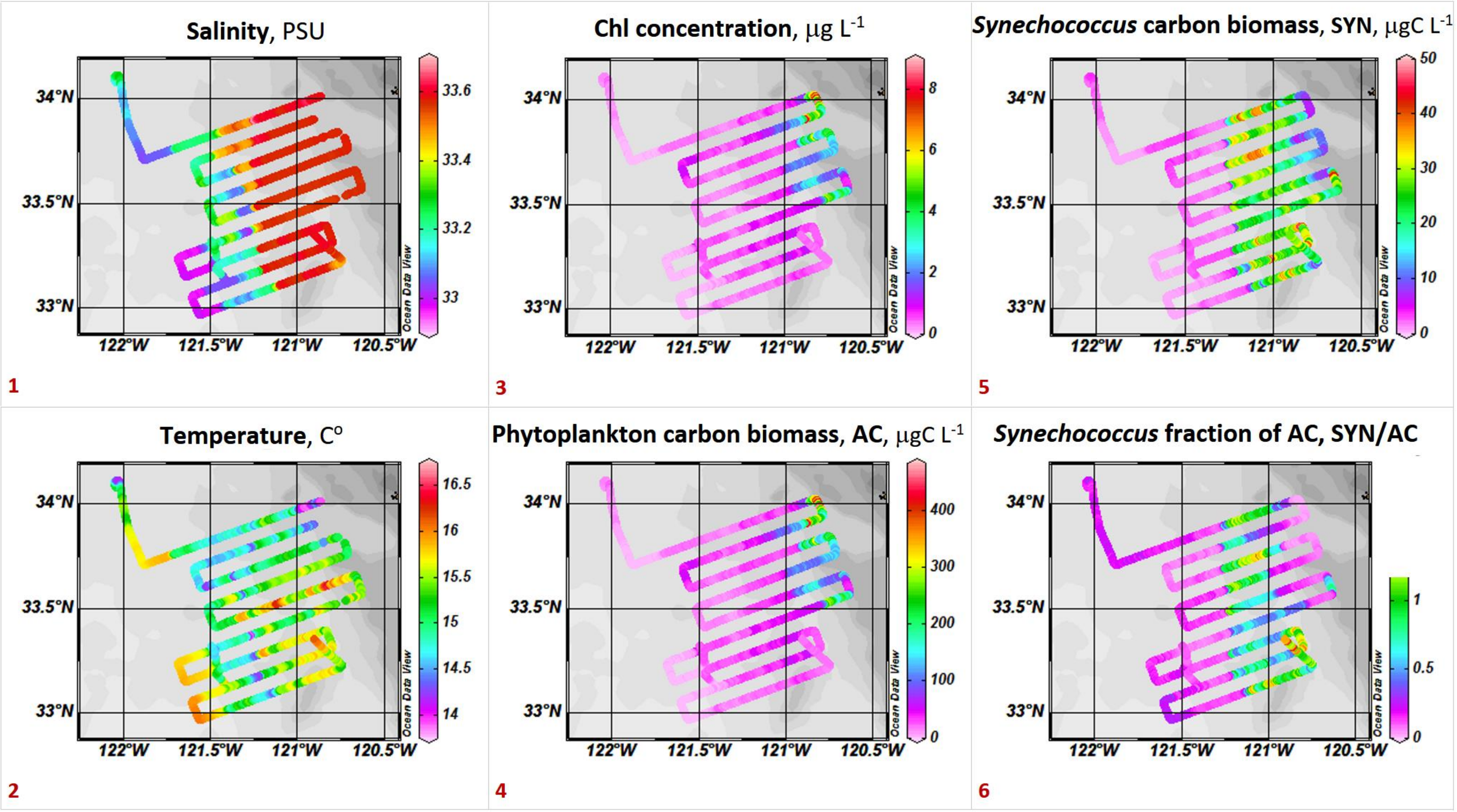
*Note: Both **Chl fluorescence** and variable fluorescence, **Fv/Fm**, were affected by solar-induced non-photochemical quenching (NPQ).*

ALF: California Current Synoptic Survey (SIO, NSF), CCE LTER, 2011



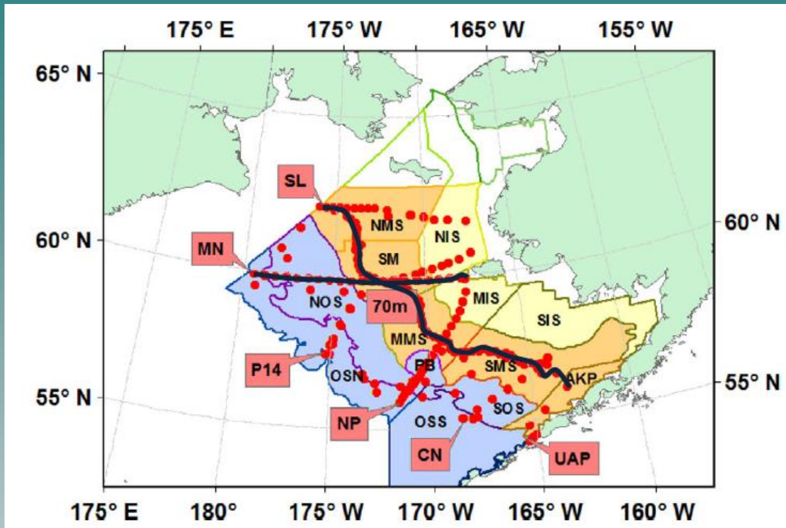
1: A map of SS1 and SS2 **ALF transect measurements** and sample collection (CCE LTER Cruise P1106; June-July 2011). **2:** Relationship between **Chl concentration** (µg L^{-1}) and ALF measurements of **Chl fluorescence** normalized to Raman (CF/Rb) and variable fluorescence (Fv/Fm; 405 nm excitation). **3:** Relationship between **carbon biomass of autotrophic phytoplankton** (**AC**, µg C L^{-1}) and ALF measurements of **Chl fluorescence** normalized to Raman and variable fluorescence (Fv/Fm); 405 nm excitation). **4:** Relationship between ***Synechococcus* carbon biomass** (**SYN**; µg C L^{-1}) and ALF measurements of Raman-normalized **PE1 fluorescence** of oceanic cyanobacteria (**PE1/Rg**; 532 nm excitation).

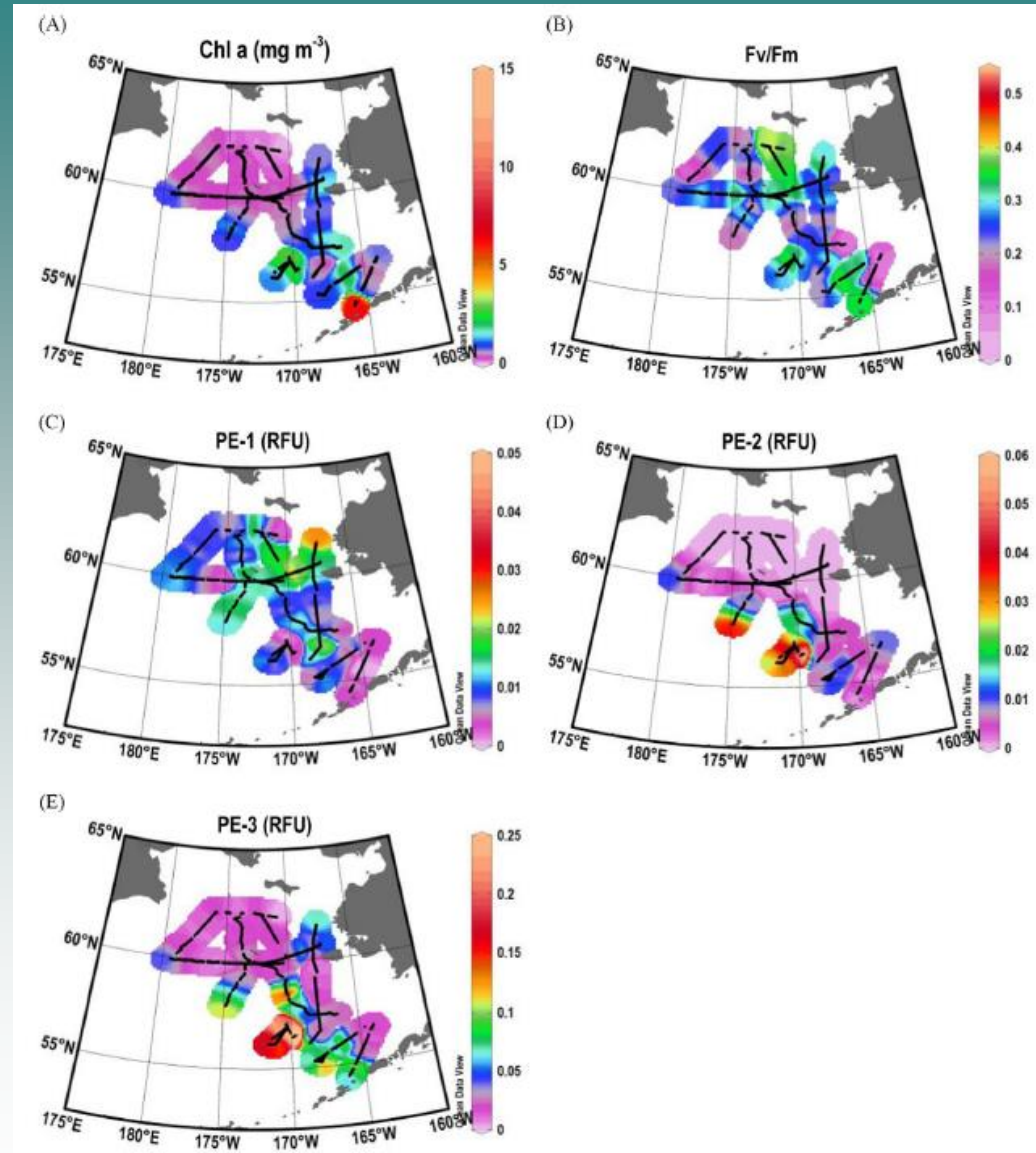
ALF: California Current Synoptic Survey (SIO, NSF), CCE LTER, 2011



Transect distributions of Chl concentration (**Chl**, 3), total phytoplankton carbon biomass (**AC**, 4), *Synechococcus* carbon biomass (**SYN**, 5), and fraction of *Synechococcus* in total phytoplankton carbon biomass (**SYN/AC**, 6) were calculated from the ALF underway fluorescence measurements corrected for solar-induced non-photochemical quenching (NPQ). California Current Ecosystem (CCE, SIO) Long-Term Ecological Research (LTER, NSF) Process cruise P1106; 3-6 July 2011.

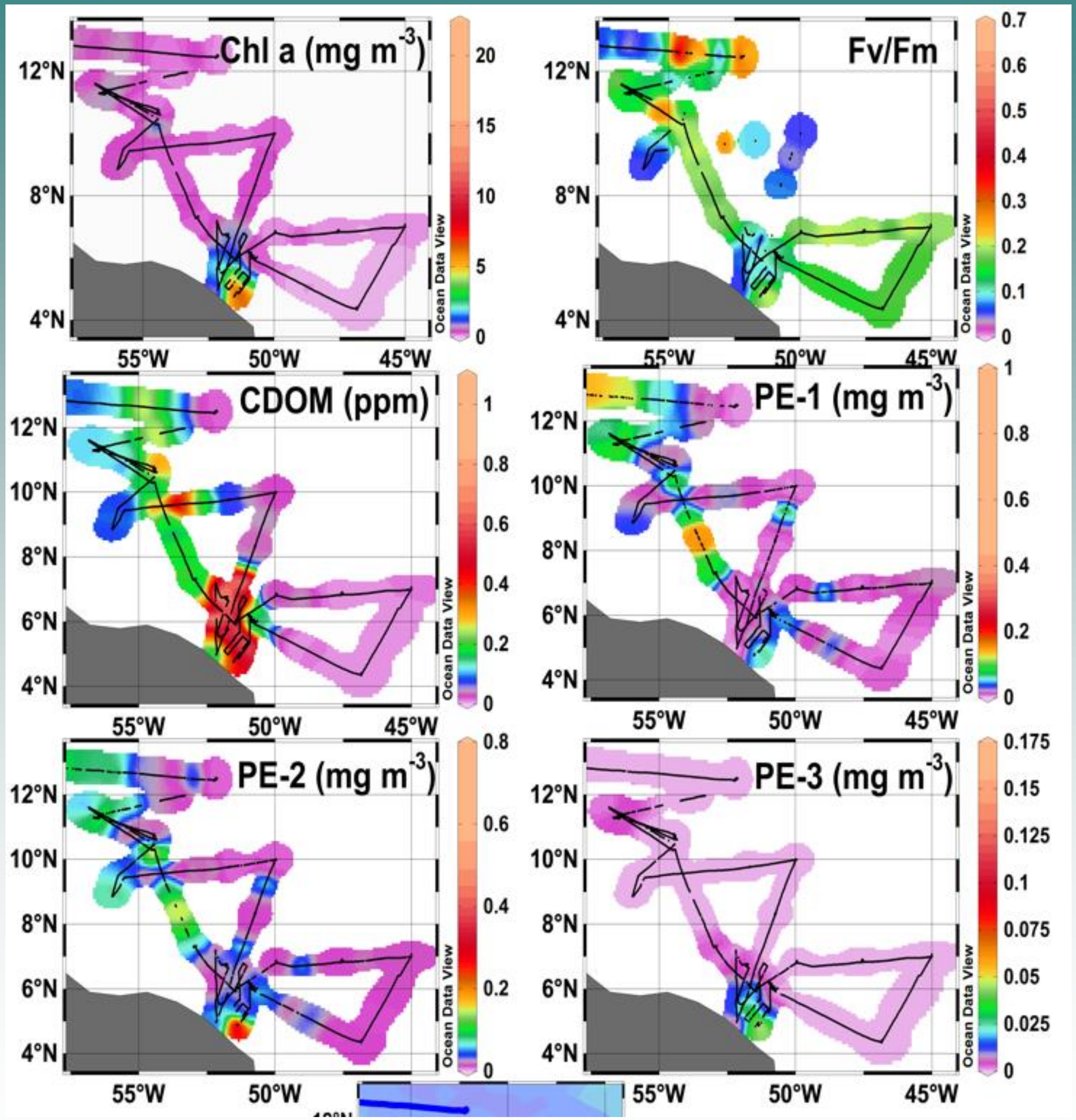
ALF: Phytoplankton characterization in Bering Sea





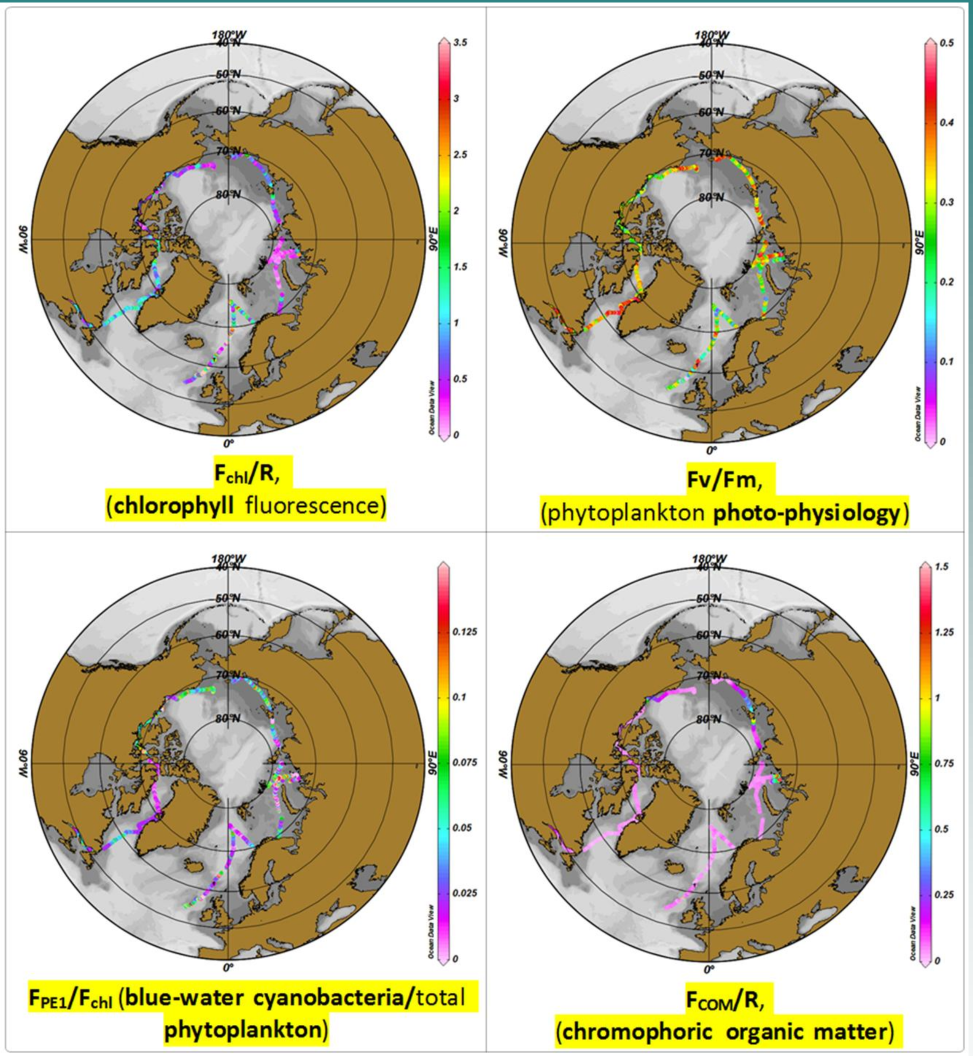
Goes, J.I., et al., Fluorescence, pigment and microscopic characterization of Bering Sea phytoplankton community structure and photosynthetic competency. Deep-Sea Res. II (2014), http://dx.doi.org/10.1016/j.dsr2.2013.12.004i

ALF: Influence of Amazon River discharge on phytoplankton bio-geography



Goes, J.I., et al., Influence of the Amazon River discharge on the biogeography of phytoplankton communities in the western tropical north Atlantic. Progress in Oceanography 120, 29-40 (2014).

ALFA: Arctic Seas survey (8 month deployment)



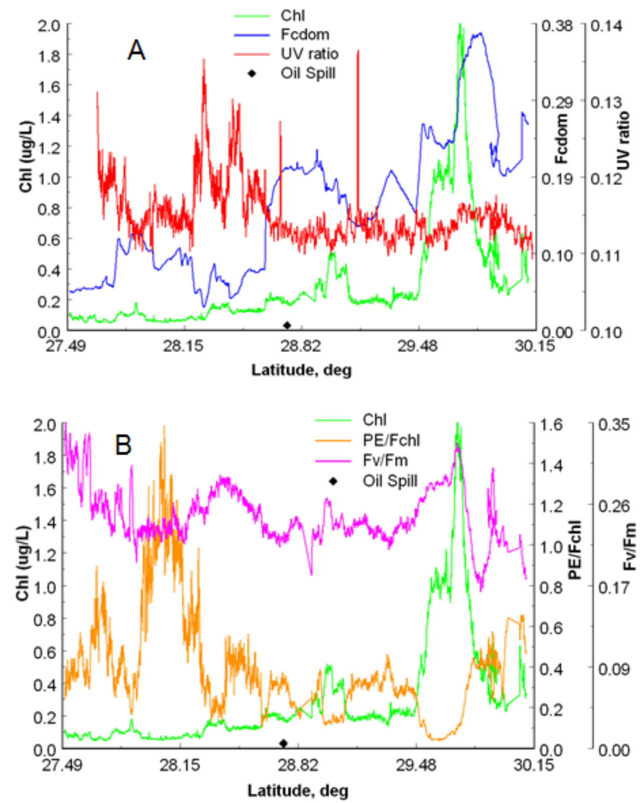
Global-scale underway ALFA measurements to survey the impact of climate change on bio-environmental situation in the Arctic Seas (May – Dec 2013, R/V Tara; Dr. Boss (U. of Maine)).

Matsuoka, A., et al. Pan-Arctic optical characteristics of colored dissolved organic matter: Tracing dissolved organic carbon in changing Arctic waters using satellite ocean color data. Remote Sensing of Environment, V. 200, pp. 89-101; https://doi.org/10.1016/j.rse.2017.08.009 (2017)

ALF: Evaluation of bio-environmental impacts of Deepwater Horizon Oil Spill (RAPID/NSF 2010)

PIs: A. Chekalyuk, A. Subramaniam and A. Thurnherr (LDEO of Columbia University)

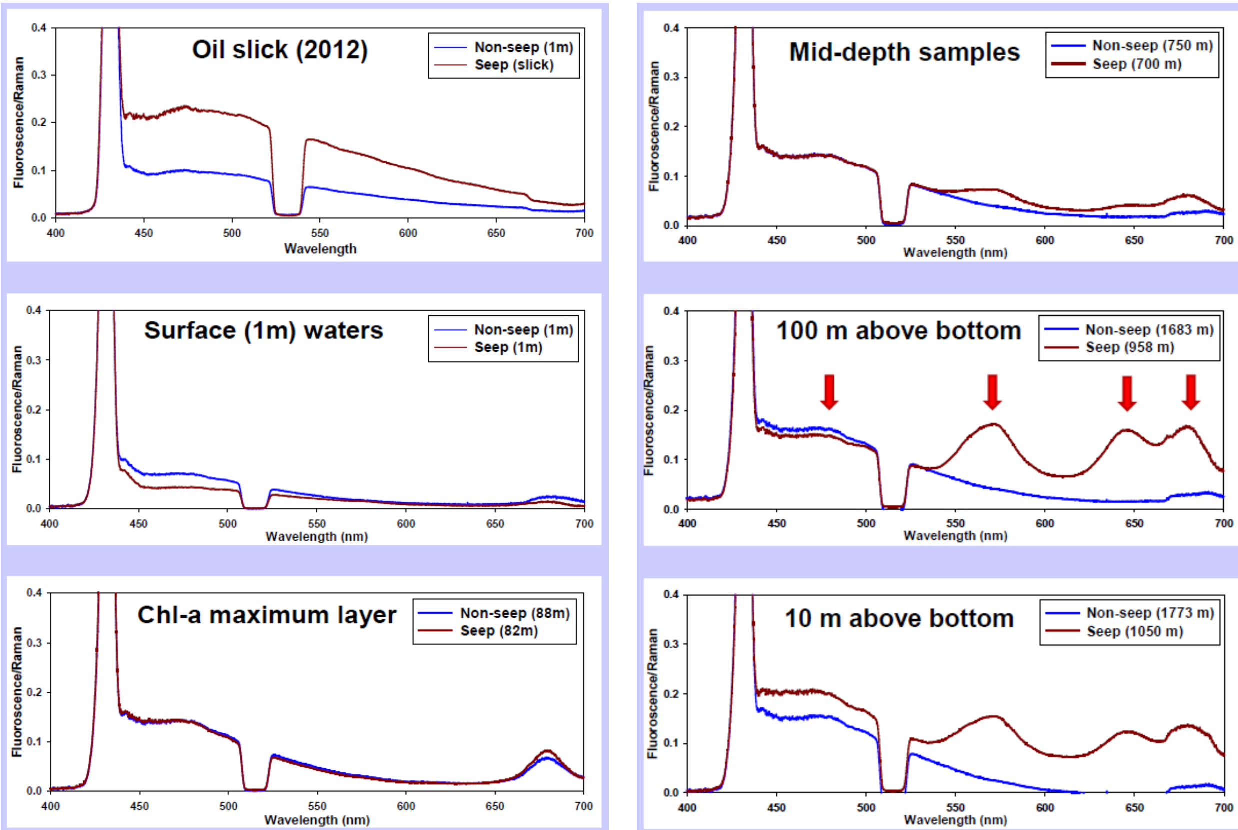
Fig. 1 A map of the major underway transect measurements and sampling stations in the area of study. Location of the Deepwater Horizon accident is marked with the flag.

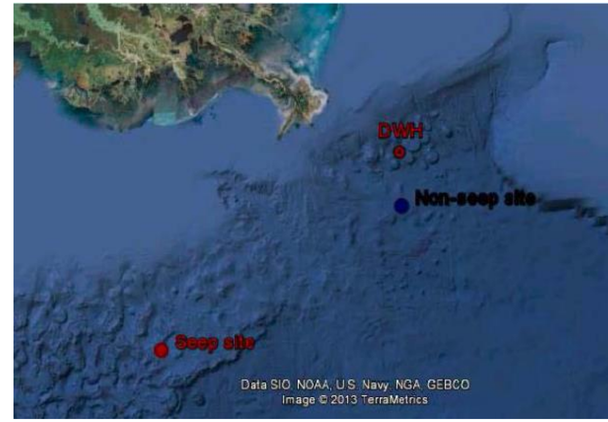


Horizontal distributions of the key fluorescence variables retrieved from the ALF underway transect measurements in the Gulf of Mexico (a synoptic-scale transect is displayed with a red line in Fig. 1). The black diamond indicates a location of the Deepwater Horizon accident.

D' Souza, N. A., et al. Elevated surface chlorophyll associated with natural oil seeps in the Gulf of Mexico. **Nature** Geoscience, doi:10.1038/ngeo2631 (2016) .

ALF: Unique Spectral Signatures Near Oil Seeps





The ALFA can be used to rapidly characterize fluorescent materials suspended in natural waters including phytoplankton pigments and fresh oil.

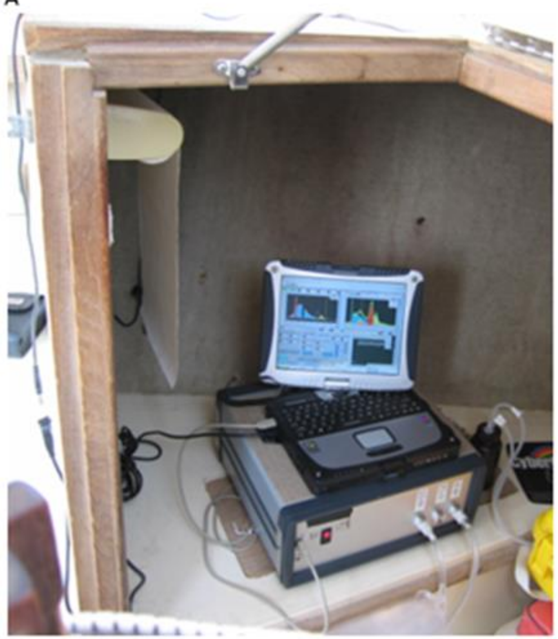
Note: The **unique fluorescence signatures** near oil seeps *could not be detected by conventional Chl or oil/hydrocarbon fluorometers*.

Fluorescence spectra of water samples near the oil seep (brown graphs) vs. water spectra at non-seep location.

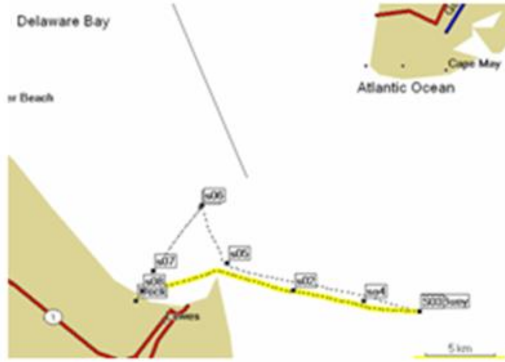
Note: The deep **sample spectra** at the seep site *did not resemble* **fresh oil or PAHs**.

ALF: Validation of Satellite Chl data in Delaware Bay

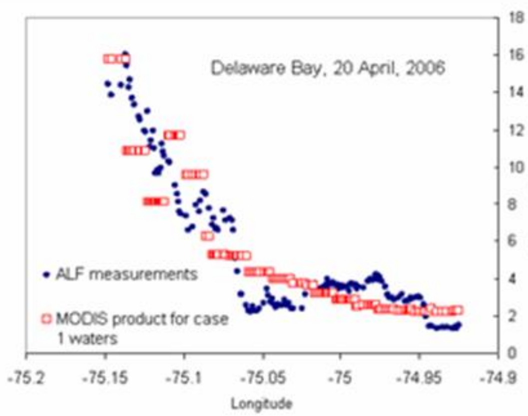
A



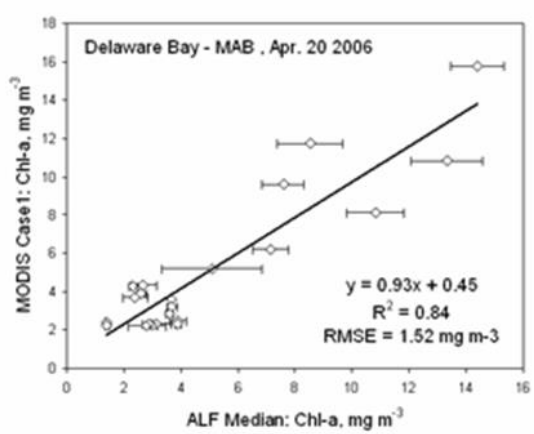
B



C



D



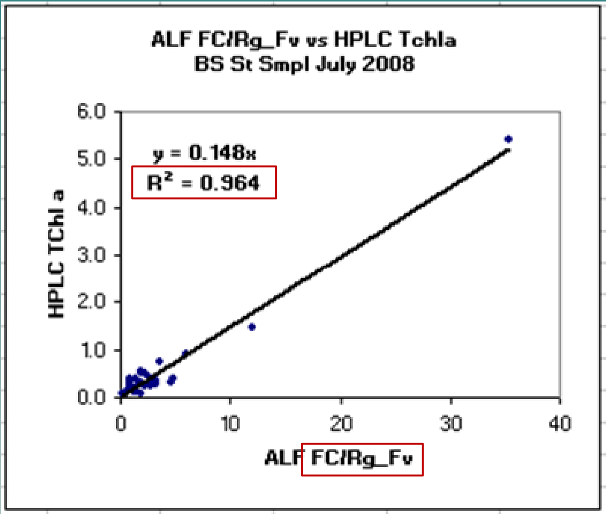
E

A,B: High-resolution ALF underway measurements on a speed boat (NASA – U. of Delaware; 2006).

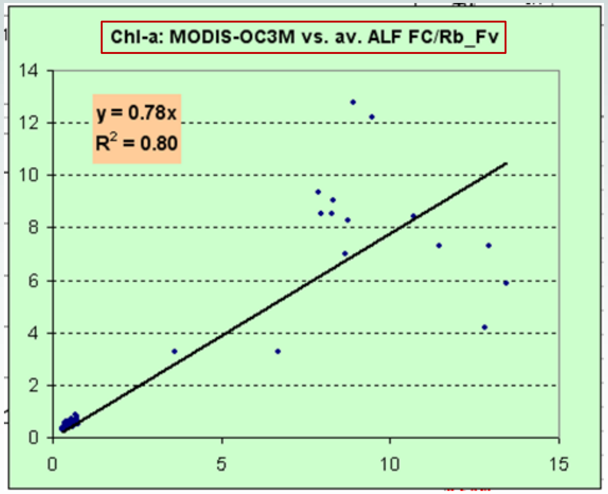
C: A map of the ALF transect survey in the Delaware Bay mouth.

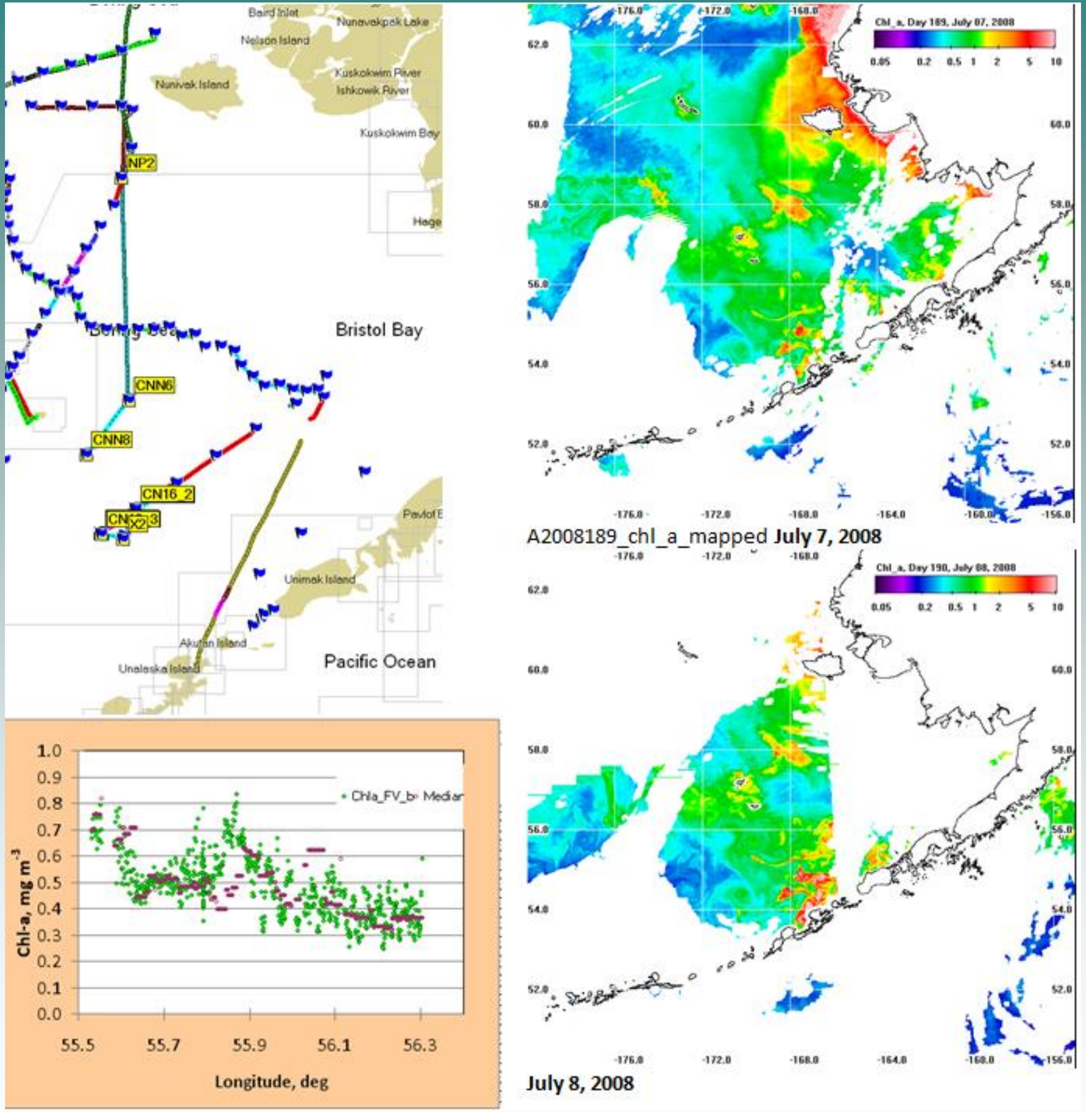
D, E: ALF Chl measurements vs. satellite ocean color data.

ALF: Validation of Satellite Chl data (Bering Sea, 2008)



Calibration of the ALF Chl fluorescence corrected for the solar-induced NPQ quenching, using HPLC Chl measurements

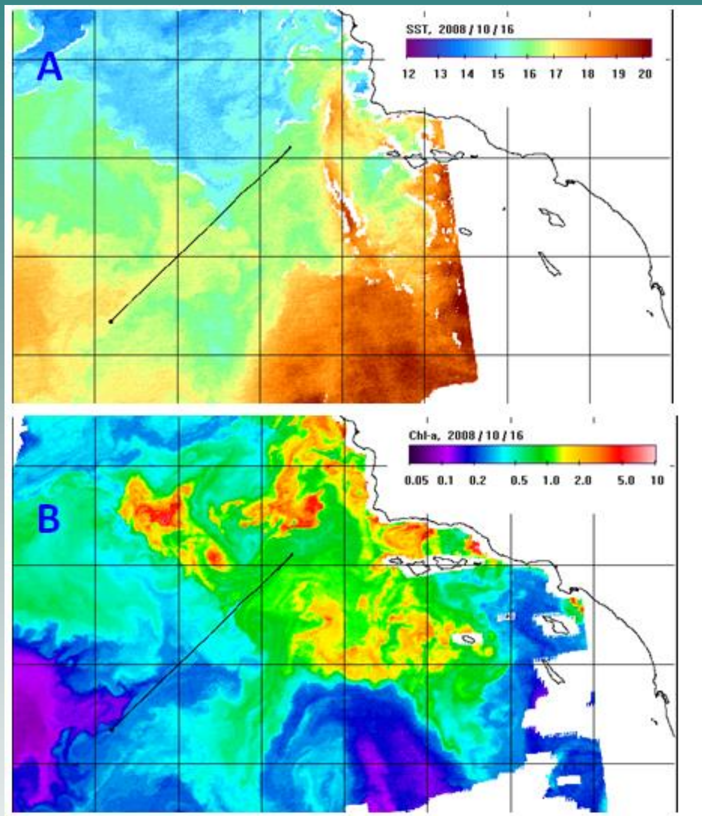


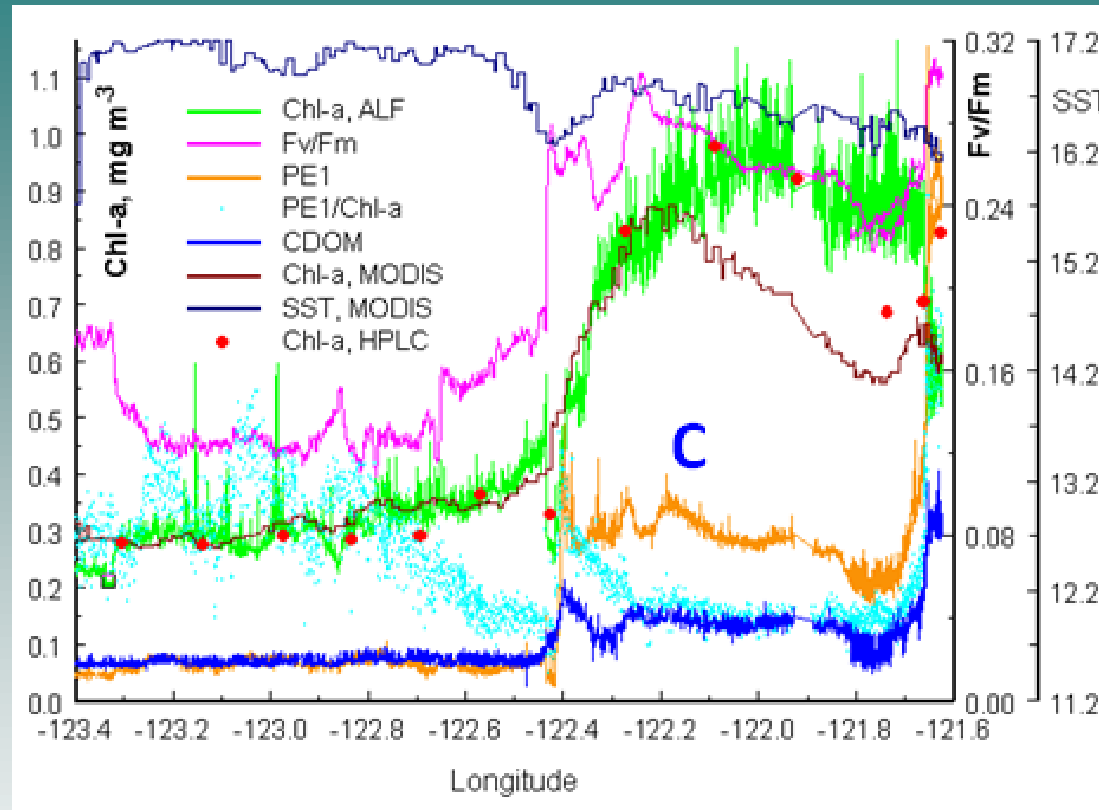


Matching MODIS Aqua Chl and ALF underway Chl data

(ALF measurements by Dr. Goes (LDEO))

ALF: Validation of Satellite Chl Data in California Current





Matching MODIS Aqua SST (A, C) and Chl-a (B, C) data with ALF shipboard underway measurements and HPLC Chl-a sampling (C).

ALF measurements can be used:

- for **validation** of satellite algorithms and assessment of uncertainties;
- to support development of the **new ocean color products** (e.g. phycobiliprotein biomass, phytoplankton functional types, etc.).

ALF: References

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7. Goes, J.I., et al. Biogeography and ecophysiology of phytoplankton communities of the Amazon River Plume. Progress in Oceanography 120, 29-40 (2014)

8. Goes, J. I., et al. Fluorescence, pigment and microscopic characterization of Bering Sea phytoplankton community structure and photosynthetic competency in the presence of a Cold Pool during summer. Deep-Sea Research –II (2013) doi:10.1016/j.dsr2.2013.12.004

9. Chekalyuk, A.M., et al. The Aquatic Laser Fluorescence Analyzer: field evaluation in the northern Gulf of Mexico. Optics Express. 22, 21641-21656 (2014)

10. D' Souza, N. A., et al. Elevated surface chlorophyll associated with natural oil seeps in the Gulf of Mexico. Nature Geoscience, doi:10.1038/ngeo2631 (2016)

11. Stukel, M.R., et al. Mesoscale ocean fronts enhance carbon export due to gravitational sinking and subduction. Proceedings of the National Academy of Sciences of the United States of America, doi:10.1073/pnas.1609435114 (2017)

12. Matsuoka, A., et al. Pan-Arctic optical characteristics of colored dissolved organic matter: Tracing dissolved organic carbon in changing Arctic waters using satellite ocean color data. Remote Sensing of Environment, V. 200, pp. 89-101; https://doi.org/10.1016/j.rse.2017.08.009 (2017)

Patents:

PT1. Chekalyuk, A.M. "Spectral and Temporal Laser Fluorescence Analysis such as for Natural Aquatic Environments", US Patent 8970841 (Mar. 3, 2015).

PT2. Chekalyuk, A.M. "Optical Analysis of Emissions from Stimulated Liquids", US Patent 9618449 (Apr 11, 2017).

Conclusions:

- **Aquatic Laser Fluorescence (ALF)** analysis can be used in a broad range of applications, including analysis of **phytoplankton pigments, photo-physiology, community structure, CDOM, oil and PAHs**
- Combining **spectral** and **temporal** measurements of **laser-**stimulated emission provides rich information for scientific and environmental studies
- The **ALF technique can serve as a useful tool** for oceanographic research, environmental monitoring, biological, industrial applications, health care, etc.