How do autonomous assets expand the temporal and spatial footprint of a shipboard process study?

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Challenges & the Limits of Conventional Approaches

- **Ships** – broad measurement suite, but timing difficult and persistence impractical.
- **Moorings** – persistence good, but submesoscale sampling difficult.
- **Remote Sensing** – broad (x,y,t) coverage (selected variables), but clouds limit utility, no subsurface structure.
- **Models** – need improved understanding of processes.
NAB 2008: April – June
Autonomous Study of the Subpolar North Atlantic Bloom
Why the subpolar North Atlantic?
- responsible for 20% of global ocean’s net uptake of CO$_2$
- undergoing significant changes

Why an autonomous approach?
- Wide range of space and time scales
  - ocean is *patchy* from meters to kilometers
  - blooms are *ephemeral*, difficult to ‘catch’ a bloom
  - understand as much of annual cycle in open ocean

What did we try to resolve?
- complexity of space and time scales
- mechanisms for bloom initiation (climate change & phenology)
- changes in phytoplankton community composition in S & T
- variety of carbon productivities
R/V Knorr with 28 scientists (half were students) – 7 countries
• **Combination** of autonomous assets, ships, satellites, models
• **Persistence** – deploy before bloom, resolve entire evolution
• **Cooperative** sampling by different vehicles and lots of data

**Mixed layer float** –
defined Lagrangian frame. Daily profiles to 230 m.

**Gliders** – spatial context.
Survey around floats.
Profile to 1000 m ~ 5 hr.

**R/V Knorr & Sæmundsson** –
calibration, proxy data.
Extensive biological and chemical measurements.
## More Variables

### CTD/Rosette
- Discrete samples
  - Pigment analysis
  - Phytoplankton
  - POC
  - absorption(λ)

### Lagrangian Float
- CTD
- PAR (Ed)
- \( b_{bp} \)
- Chl fluor
- Oxygen
- C-Star

### Seagliders
- CTD
- PAR (Ed)
- \( b_{bp} \)
- Chl fluor
- Oxygen
- C-Star
Careful calibration of all sensors

1. Mass factory calibration – before and after experiment

2. In situ calibration – simultaneous profiles of ship CTD and float or glider, multiple times, proximity matters

3. Made six to ten different sensors agree \((\text{bb, c, Chl, O2, NO3})\)

![Before cross-calibration](image1)

![After cross-calibration](image2)
Highly detailed documentation of data – in BCO-DMO

North Atlantic Spring Bloom Experiment (NAB2008) Data Policy

INTRODUCTION
The 2008 North Atlantic Spring Bloom program includes autonomous, ship-based and remotely sensed measurements as well as numerical efforts. The highly collaborative, interdisciplinary nature of this project, success rests on open sharing of observational data and numerical results. This data policy attempts to address the following goals:

- Encourage open, collaborative sharing of NAB2008 data, both between experiment participants and with the general oceanographic community.
- Provide guidelines to coordinate analysis efforts and govern distribution and use of NAB2008 data.
- Ensure that NAB investigators receive appropriate credit for the data produced by their efforts.

DATA POLICY
The data are the intellectual property of the collecting investigator(s). It is not ethical to publish data without offering co-authorship or, if the invitation of co-authorship is declined, to provide minimal acknowledgment.

While observational data and NAB2008 participants, the intellectual collection of a data set enables data sharing. Presentation of descriptive reports directly from the data is the primary method to collect the data. NAB2008 investigators are encouraged to use the following guidelines:

- Encourage open, collaborative sharing of NAB2008 data, both between experiment participants and with the general oceanographic community.
- Provide guidelines to coordinate analysis efforts and govern distribution and use of NAB2008 data.
- Ensure that NAB investigators receive appropriate credit for the data produced by their efforts.

The 2008 North Atlantic Bloom Experiment

Calibration Report #7
Intercalibration of the Backscatter sensors from Float 47 & Knorr cruise

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5-15-2009

The 2008 North Atlantic Bloom Experiment
Calibration Report #2
Intercalibration of the C-Star Beam Transmissometers from Floats 47 & 48, Knorr cruise and the Bjarne Samundsson cruises

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Preliminary Version 1.3, January 15, 2009

The 2008 North Atlantic Bloom Experiment
Calibration Report #3
Calibration of the Dissolved Oxygen Sensors from Float 48 and Winlinder bottle samples from Knorr Cruise

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Version 1.3 March 11, 2009

Summary
The Seabird SBE-43 oxygen sensor and the Aanderaa optode on float 48 both require calibration and removal of various sensor biases. The optode is poorly calibrated in terms of dissolved oxygen, temperature and pressure. The SBE-43 exhibits biases due to attempts to reduce pumping energy. By intercomparing these sensors along the entire
Build proxies to project $$\$\$\$$ ship measurements to simple optical measurements

All models proxies are wrong but some are useful; bulk measurements are not obsolete.

Cetinic et al., 2012
The spring bloom:

- began before ship arrived
- diatom bloom
- patchy

Mahadevan el al. 2012
ML shallows rapidly and bloom begins YD 110.

Backscatter and beam attenuation rise.

Dissolved oxygen concentration rises, ML nitrate decreases.

ML restratification typically attributed to solar warming, but...

ML cools during bloom initiation.

What initiates bloom?

Alkire el al. 2012
Bloom initiation:
- onset coupled stratification.
- without ML eddies, stratification & bloom delayed 20-30 days.
- similar timing across all platforms.
- termination when silicate is exhausted.

Eddy-drive Restratification:
- submesoscale (1-10 km) ML eddies 'slump' lateral density gradients.
- converts horizontal density contrasts to vertical stratification.

Mahadevan el al. 2012

Eddy-Driven Stratification Initiates North Atlantic Spring Phytoplankton Blooms

Amala Mahadevan, Eric D’Asaro, Craig Lee, Mary Jane Perry

Springtime phytoplankton blooms photosynthetically fix carbon and export it from the surface ocean at globally important rates. These blooms are triggered by increased light exposure of the phytoplankton due to both seasonal light increase and the development of a near-surface vertical density gradient (stratification) that inhibits vertical mixing of the phytoplankton. Classically and in current climate models, that stratification is ascribed to a springtime warming of the sea surface. Here, using observations from the subpolar North Atlantic and a three-dimensional biophysical model, we show that the initial stratification and resulting bloom are instead caused by eddy-driven slumping of the basin-scale north-south density gradient, resulting in a patchy bloom beginning 20 to 30 days earlier than would occur by warming.
Patchy bloom due to patchy stratification

Phytoplankton growth highest where stratification is strongest (increased light exposure).

Stratification controls bloom patchiness.... Scales and shapes contain information about dominant processes.

ML eddies produce patchy (1-10 km) stratification, straining into elongated filaments. Consistent with NAB08 observations & simulations.

Other factors (e.g. differential nutrient supply, grazing) may also drive patchiness.

Mahadevan el al. 2012
Lagrangian float followed a patch in April and May, measuring NO3, O2, POC (float sensors well calibrated by ship)

Alkire et al., 2012
Net Community Production from Lagrangian O2 and NO3

\[ NCP = \text{Primary Production} - \text{Respiration} \]
\[ = \text{Decrease in NO}_3 \times \text{C:N Redfield} \]
\[ = \text{Increase in O}_2 + \text{O}_2 \text{ loss to atmosphere} \times \text{O:C (PQ)} \]
\[ = \text{Increase in POC} - \text{Carbon Export} + [\text{increase in DOC}] \]

Much of net fixed carbon is exported.

Export ratio
\[ = \text{Export} / \text{NCP} \]
\[ \sim 30 - 70\% \]

Alkire et al., 2012
Net Community Production from Eularian measurements of O2 & POC from 3 gliders in June

- Eulerian reference frame – great care to account for local rate of change, vertical mixing, air-sea exchange, and horizontal advection.
- NCP for O2 ~ 1.0 mol C m-2
- POC export ~ 0.6 mol C m-2
- Carbon production and export was comparable to that during diatom spring bloom.

Alkire et al., 2014

(glider sensors well calibrated by ship)
Optical proxy for community composition: Chl F/bbp

Cetinic et al., 2015
Sub-mesoscale fronts structure spatiotemporal patterns in marine phytoplankton diversity

Similarities in community composition within and outside the patch were driven by small generalist taxa whereas differences were driven by typical bloom species (especially of the genus *Chaetoceros*), resulting in two functionally different communities despite very similar environmental conditions.

Mousing et al. (submitted)
Gliders observe large scale carbon flux event below 200 m

- Sinking of diatom aggregates (optical spikes).
- How much carbon passes through the twilight zone?
- Diatom spores are resistant.

Briggs et al., 2011
Martin et al., 2011
Rynearson et al., 2013
Eddy-driven subduction exports particulate organic carbon from the spring bloom

Omand et al., 2015
Omand et al., 2015
Net phytoplankton productivity

Ship-based P vs. E normalized to Chl

Hourly from float – Chl, PAR, PP/Chl, PP

(K. Gudmundsson et al., in prep.)

Daily estimates of water column PP
Characterize the state of the carbon cycle – autonomously

D’Asaro et al.
How do autonomous assets expand the temporal and spatial footprint of a shipboard process study?

This is still a research question.

In NAB 2008, learned how to do the patch, but not the basin. There’s more to learn.