Ocean acidification SIS (OASIS): 2013-2016
Results and findings

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Marine Biogeochemistry and Oceanography (214); Marine Biology (211), Ecotoxicology (213)
Rise in CO$_2$ & decline in pH

Adapted from Doney et al. (2009)

Central N. Pacific

atm CO$_2$ (ppm)

sw pCO$_2$ (ppm)

sw pH

Largest rate of change in CO\textsubscript{2} in the last 300 million years

- Most recent analog to present day rise in CO\textsubscript{2} was in the Paleocene/Eocene Thermal Maximum (PETM)
- The current rate of atmospheric CO\textsubscript{2} increase is at least 10x faster than the PETM

![Graph showing carbon/climate perturbation events and oceanic pH over time](image)

Turley et al. (2006); Honisch et al. (2012); Ridgwell and Schmidt (2010)
NIVA’s SIS on Ocean Acidification (2013-2016)

**Themes 1, 2 & 3**
- **Acid Mar (Sørensen)**
- ALF-OAI – OA lab instrumentation (Bellerby)
- ALF-OAM – OA lab instrument metrology (Reggiani)
- CoMICS – Carbonate ion sensor (Reggiani)
- COAST-ALOA – OA data from FerryBox (Sørensen)
- CARBOSYS – CO₂ variability Norway/Arctic waters (Bellerby)

**Theme 4 Modeling**
- ArcticOA – Ecosystem model development (Bellerby)
- ARSEC1 + 2 – Arctic Regional Seas Ecosystem Change (Wallhead)

**Theme 5 Effects**
- OA-TROPHIC – Temperate plankton OA mesocosm experiment (King)
- OA-RESPONSE – Microscale OA experimental system (Macken/Tollefsen)
- ECOACID – Kelp/urchin OA mesocosm experiment (Hancke)
- OCEANCERTAIN – Arctic and Mediterranean OA/DOC mesocosm experiments (King)

**Theme 5 Socioeconomics**
- OA-SERVICES – Scenarios of ecosystem services (Chen)

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**Themes**

1. Development of autonomous OA sensors
2. Advanced analytical competence and capacity
3. Remote platforms for OA observations
4. Model scenarios of OA
5. Effects on organisms and ecosystems
6. Socioeconomic aspects of OA
OA observations from FerryBox ship of opportunities

All projects in Themes 1-3

M/S Norbjørn  
M/S Trollfjord

M/S Norrøna  
M/S Color Fantasy

A. King  
02.10.2017
Carbonate system measurements

ALF-OAI, ALF-OAM, Acid Mar, CoMICS: Sørensen, Bellerby, Reggiani, King, Norli

• **Analytical lab:** VINDTA total alkalinity (AT) and total dissolved inorganic C (CT), CO₂ calibration lab (NOAA), LICOR-7000 (Reggiani, King, Norli, Sørensen, Bellerby)

• **Franatech/NIVA:** Membrane/IR pCO₂ detector; Combination of pCO₂, pH, and AT sensors in development (FP7 NEXOS) (Reggiani, Sørensen, King, Bellerby)

• **NIVA-WAG:** Spectrophotometric pH sensor for FerryBox surface measurements; Spectrophotometric [CO₃²⁻] sensor under development (H2020 JERICO-NEXT, H2020 INTAROS) (Reggiani, Marty)

• **SubCtech:** Deep Sea pCO₂ sensor for measurements on benthic landers and buoys (Reggiani, Jaccard)
Underway pH and pCO₂ measurements

COAST-ALOA: Sørensen, Reggiani, King, Bellerby, Norli, Jaccard

Ex. 1: M/S Trollfjord (Hurtigruten) seasonal/spatial variability in pH (Reggiani et al., 2016 JoMS)

Ex. 2: M/S Norbjørn coverage of coast, N. Atlantic, and Arctic (Sorensen, King, Norli et al., in prep)
## Ocean acidification from space

**CARBOSYS: Bellerby**

### Table: Data Sets and References

<table>
<thead>
<tr>
<th>Data Set Name and Reference</th>
<th>Temporal Period</th>
<th>Geographic Location</th>
<th>Variables</th>
</tr>
</thead>
<tbody>
<tr>
<td>SOCAT v2.0&lt;sup&gt;27&lt;/sup&gt;</td>
<td>1968–2011</td>
<td>Global&lt;sup&gt;*&lt;/sup&gt;</td>
<td>$f_{CO_2}$, SSS, SST</td>
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<tr>
<td>LDEO v2012&lt;sup&gt;28&lt;/sup&gt;</td>
<td>1980–present</td>
<td>Global&lt;sup&gt;*&lt;/sup&gt;</td>
<td>$f_{CO_2}$, SSS, SST</td>
</tr>
<tr>
<td>GLODAP&lt;sup&gt;29&lt;/sup&gt;</td>
<td>1970–2000</td>
<td>Global</td>
<td>TA, DIC, SSS, SST, Nitrate</td>
</tr>
<tr>
<td>CARINA AMS v1.2&lt;sup&gt;30&lt;/sup&gt;</td>
<td>1980–2006</td>
<td>Arctic</td>
<td>TA, DIC, SSS, SST</td>
</tr>
<tr>
<td>CARINA ATL v1.0&lt;sup&gt;31&lt;/sup&gt;</td>
<td></td>
<td>Atlantic</td>
<td></td>
</tr>
<tr>
<td>CARINA SO v1.1&lt;sup&gt;32&lt;/sup&gt;</td>
<td></td>
<td>Southern Ocean</td>
<td></td>
</tr>
<tr>
<td>AMT&lt;sup&gt;33&lt;/sup&gt;</td>
<td>1995–present</td>
<td>Arctic</td>
<td></td>
</tr>
<tr>
<td>NIVA Ferrybox&lt;sup&gt;34&lt;/sup&gt;</td>
<td>2008–present</td>
<td>Arctic</td>
<td>$f_{CO_2}$, SSS, SST, Chl, pH</td>
</tr>
<tr>
<td>OWS Mike&lt;sup&gt;35&lt;/sup&gt;</td>
<td>1948–2009</td>
<td>Arctic</td>
<td>TA, DIC, SSS, SST, Chl</td>
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<tr>
<td>RAMA Moored buoy array&lt;sup&gt;36&lt;/sup&gt;</td>
<td>2007–present</td>
<td>Bay of Bengal</td>
<td>SSS, SST</td>
</tr>
<tr>
<td>ARGO buoys&lt;sup&gt;37&lt;/sup&gt;</td>
<td>2003–present</td>
<td>Global</td>
<td>SSS, SST</td>
</tr>
<tr>
<td>OOI&lt;sup&gt;38&lt;/sup&gt;</td>
<td>2014 onward</td>
<td>Global (six sites)</td>
<td>$f_{CO_2}$, SSS, SST, Nitrate</td>
</tr>
<tr>
<td>SOCCOM&lt;sup&gt;39&lt;/sup&gt;</td>
<td>2014 onward</td>
<td>Southern Ocean</td>
<td>SSS, SST, pH, Nitrate</td>
</tr>
</tbody>
</table>

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NIVA Ferrybox<sup>34</sup> | 2008–present | Arctic | $f_{CO_2}$, TA, DIC, SSS, SST |

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*Note: Additional details and references provided in the original text.*
**Coupling via the Framework for Biogeochemical Modelling (FABM, Bruggeman and Bolding, 2014) (Wallhead)**

**ERSEM, adapted to high N. latitudes (Wallhead)**

**BROM, potential near-field 1D model (Yakushev et al., 2017) (Yakushev, Protsenko)**

**20km ROMS model, collaboration with Met. No. (far field model)**

- Atmospheric/tidal forcing from ECMWF (Kristiansen)
- Physical BCs/ICs from SODA reanalysis (Kristiansen)
- Riverine forcing from discharge databases + INCA model (Staalstrøm, Lin)
- BGC BCs/ICs from NORESM bias-corrected to WOD/ICES/GLODAPv2 databases (Wallhead)

**ARSEC & ARSEC2: Wallhead, Kristiansen, Staalstrøm, Lin, Yakushev, Protsenko, Bellerby**

**Physical-biogeochemical models of present/future OA scenarios (Theme 4)**
Regional simulations can help to identify potential hotspots of change

Validation and bias correction underway

Seasonal variability in carbonate system variables
Coupled 1D transport Ice-Pelagic-Benthic Model (with ERSEM plankton and BROM biogeochemistry)

- First of its kind: coupling of ice, seawater, and sediment biogeochemical models
- Captures general seasonal patterns; ongoing work on validation and publication

Yakubov, Yakushev, Wallhead et al. (in prep.)
Effects of OA on organisms and ecosystems (Theme 5)

“Micro” -scale/multiple stressor single species bacteria/phyto/zoo-plankton (<1 ml, days)

“Meso”-scale mesocosms – natural plankton communities, macroalgae, urchins… (1 to 40 m³, weeks/months)

“Macro” -scale single species and natural plankton communities (50 ml to 20 L, weeks)
Air:CO₂ mixtures

Air Bubbling System

Miniaturized climate chamber

Radiation stress

Chemical/nutrient stress

Temperature stress

OA-RESPONSE: Tollefsen, Xie, Skogan, Macken, Norli, King

Ex. 1: Microscale multistressor experimental systems
Ex. 1: Microscale multistressor experimental systems

**OA-RESPONSE: Tollefsen, Xie, Skogan, Macken, Norli, King**

- OA did not have a large effect on growth rate of *S. costatum*; small increase in growth at moderate CO₂ treatment
- Adding UV and Cu stressors negatively affected growth rate, but it did not enhance CO₂ effect

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**Skeletonema costatum** (temperate diatom)

**OA only**

- **CO₂ (ppm)**: 350, 500, 1000
- **Growth rate (d⁻¹)**: 0.0, 0.5, 1.0, 1.5, 2.0

**OA+UV**

- **Growth rate (d⁻¹)**: 0.0, 0.5, 1.0, 1.5, 2.0

**OA+Cu**

- **Cu (μg/L)**: 12.5, 25, 50, 100, 200, 400, 800
- **Growth inhibition (%)**:
  - **350 ppm**: UV-, UV+
  - **750 ppm**: UV-, UV+
  - **1000 ppm**: UV-, UV+

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Tollefsen, Macken, et al. (in prep.)
Ex. 1: Microscale multistressor experimental systems

**OA-RESPONSE: Tollefsen, Xie, Skogan, Macken, Norli, King**

- *S. costatum* resilient to $\uparrow$ pCO$_2$
- Include more OA sensitive species
- Promising new experimental technology
- Important multistressor combination for Norwegian coast could be: pH x DOC x T x nutrients

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**Additive**

**Antagonistic**

**Synergistic**
Arctic mesocosm experiments: DOC supports heterotrophy and acidification

- DOC addition to Arctic mesocosms resulted in:
  - ↑ growth of heterotrophic bacteria
  - ↑ respiration relative to photosynthesis
  - ↑ "acidification" (-0.05 to -0.15 pH)
- ↑ input of DOC from rivers due to climate change could alter foodweb to microbial loop and also ↓ pH

Phytoplankton are the primary producers of the ocean:
- Base of the marine food web
- ~50% of global carbon fixation
- Bloom dynamics can

King, Bellerby, Reggiani et al. (in prep.)
Ex. 2: Future OA scenarios on Arctic plankton communities

OCEANCERTAIN, OA-RESPONSE: King, Bellerby, Reggiani, Norli

Arctic macrocosm experiments: Differing physiological response of Arctic copepods to OA

Calanus glacialis

- Key Arctic copepod
- 2-4mm length
- 70–80% of the zooplankton biomass in Arctic shelf seas:
- Key herbivore
- Important prey for seabirds, fish, whales

Kongsfjord, Svalbard

Disko Bay, Greenland

• Decreased ingestion and increasing in Calanus glacialis (CIV) metabolism from Svalbard, but not Greenland
• ~19-55% decrease in “scope for growth” by year 2100 projected pCO₂ levels
Ex. 3: Negative effects of OA on different functional types of plankton

ECO-OA: Bellerby (and King, Ramirez, Falkenberg)

- Calcifying phytoplankton – coccolithophore *Emiliania huxleyi*
- Growth rate lowered at high CO$_2$ and cell density decreased >50% from present day CO$_2$ to year 2100 projected CO$_2$
- Particle and organic matter sinking rates decreased by ~25%

Ex. 4: Positive effects of OA sugar kelp

ECO-ACID: Hancke, Fagerli, Borgersen, Gundersen, Norderhaug, King, Johansen, Bellerby

• Mesocosms manipulation at NIVAs experimental facility Solbergstrand
• Incubation tanks (1m³) with adult kelp individuals under 16:8h illumination
• CO₂ manipulations: according to IPPC predictions:
  \[ \text{pH} = 7.6 \ (2100), \ 7.8 \ (2050); \ \text{and present day} \ 8.0 \ (\text{control}) \]
• Time series of 15 variables including growth rates, photosynthetic performance, C/N content
Ex. 4: Positive effects of OA sugar kelp

ECO-ACID: Hancke, Fagerli, Borgersen, Gundersen, Norderhaug, King, Johansen, Bellerby

• Kelp growth and photosynthesis was stimulated by elevated CO₂ levels (lower pH) after 88 days

• Mesocosms can be used for manipulation experiments with other benthic and pelagic species

• Mesocosms can be expanded to investigate multi-stressor long-term responses of OA and land-ocean interactions on single/multiple species

• Kelp responses to elevated CO₂ can be applied to ecosystem models with implications for kelp forest carbon budgets and estimates of future ecosystem services
• A hotspot in the north of Norway between 65N and 70N where there is a potential for *Saccharina latissima* regrowth

• Prediction under A1B scenarios and will be updated with RCP85 scenario

• Mean kelp carbon storage per 25m quadrat = 625 kg C

  → Regrowth carbon storage in 50 y = **4.2 Mt C**

  → Reduction of social cost of C in 50 y = **0.9-3.4 billion NOK**
Summary

1) Expansive OA observing capacity in the North Sea, Norwegian Coast, North Atlantic Ocean, Barents Sea Opening

2) Cutting edge instruments and sensors for high precision and accuracy carbonate system measurements

3) Highly integrated and developed physical/biogeochemical models for Norwegian/Arctic waters

4) Diverse experimental approaches for assessing the potential biological/biogeochemical impacts of OA

5) Cross-disciplinary pilot study of scenario-based assessments of socioeconomic impacts of OA
By the numbers

**Publications:**
28 papers published or under review in peer reviewed journals, 2 synthesis white papers, 1 book chapter, and more to come!

**External projects leveraged by OASIS:**
- **FRAM Centre** Ocean Acidification Flagship (2015-2017)
- **Miljødirektoratet** OA Monitoring (2013-2020)
- **AMAP** Socioeconomic effects of OA (2016-2017)
- **NERC UK** Changing Arctic (2016-2019)
- **UK-NORWAY** State of the Polar Oceans (2017)
Future directions

- Finalize and submit manuscripts for publication
- Seek further external funding to continue observations and research
- Combine efforts towards multistressor approach for ecosystem effects

Please join us for:
OASIS Day at Forskningsparken, Oslo
Friday 8 December 2017