Ocean Solutions to Global Climate Challenges: ARPA-E's Perspective on Ocean-Based Carbon Dioxide Removal

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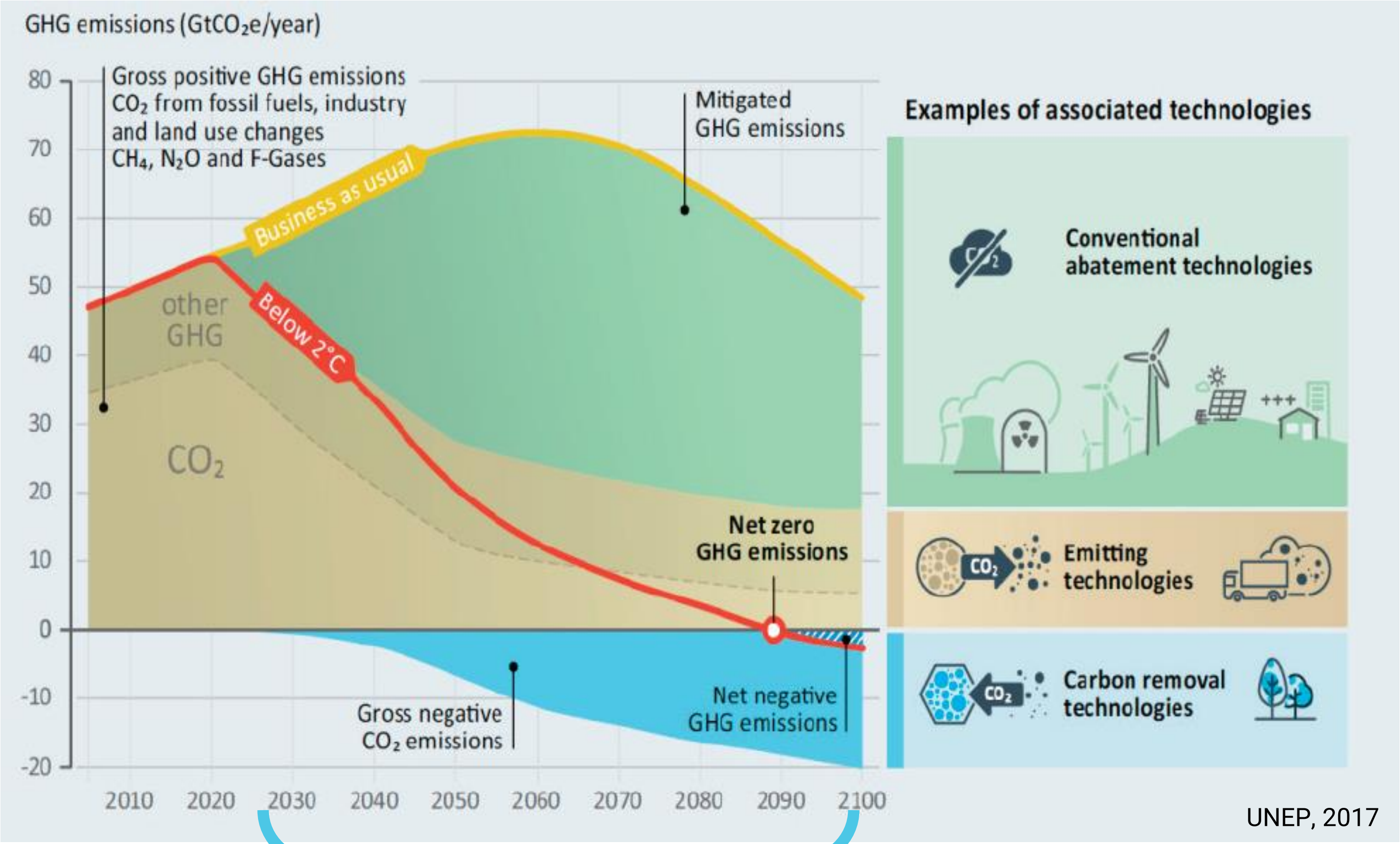
Who We Are

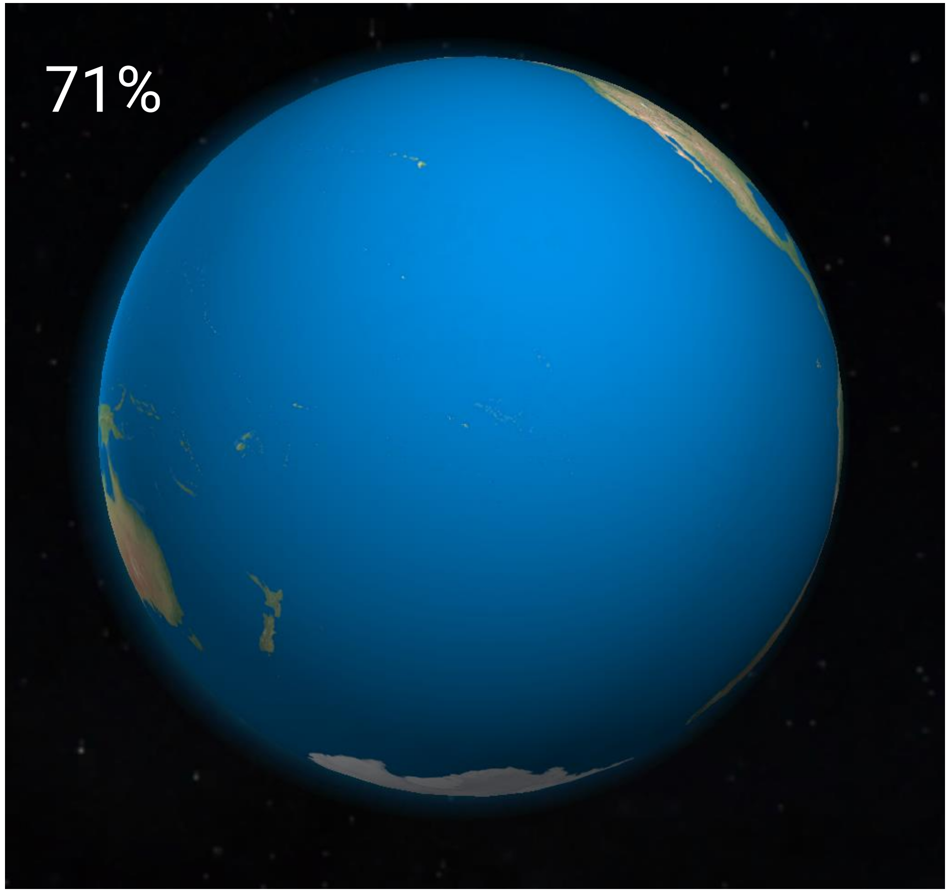
CHANGING WHAT'S POSSIBLE

- We fund high-risk, potentially high reward technology development in the energy and emissions space
- Part of the Department of Energy
- ~**$450M** of awarded projects per year
- Modeled after the *DARPA* approach to rapid research and development
- Emphasize **impact and scale**: research and development funding is focused towards **commercialization**

"If it works, will it matter?"

How does ARPA-E think about the ocean?





How will we capture this carbon, and where will we store it?

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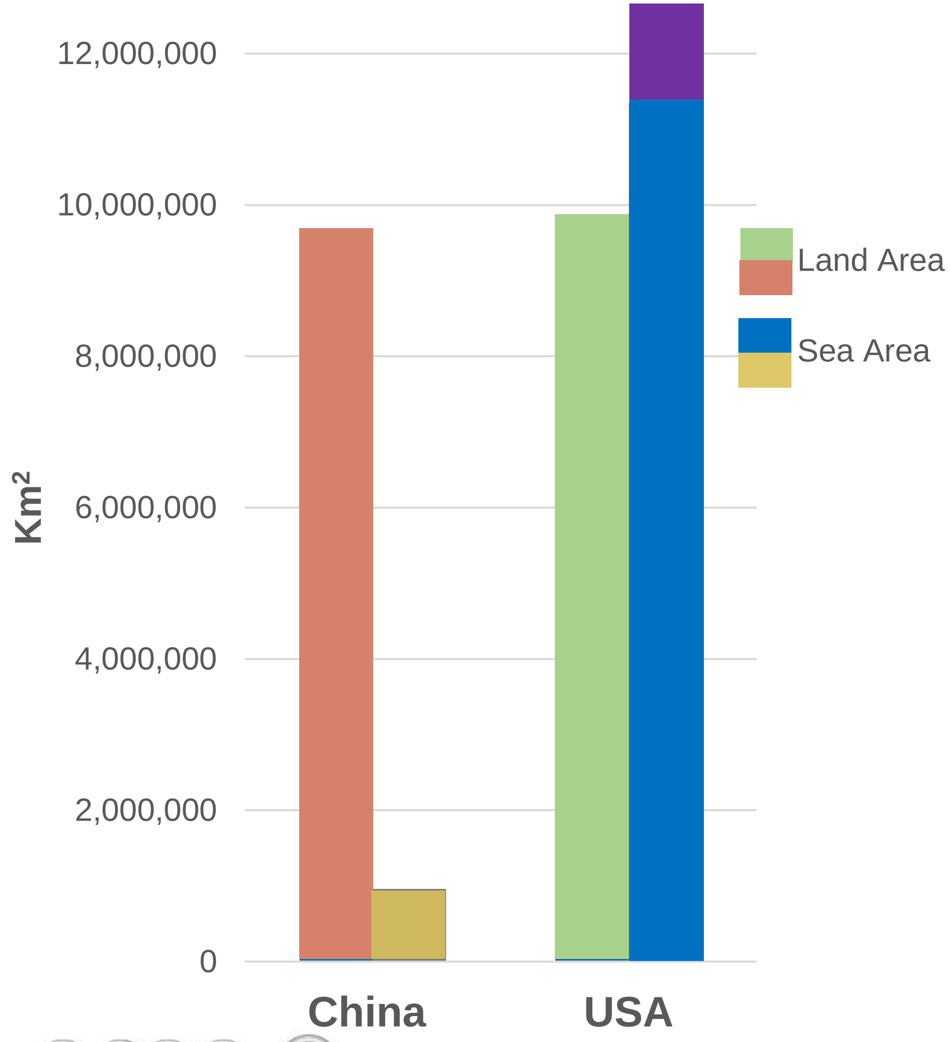
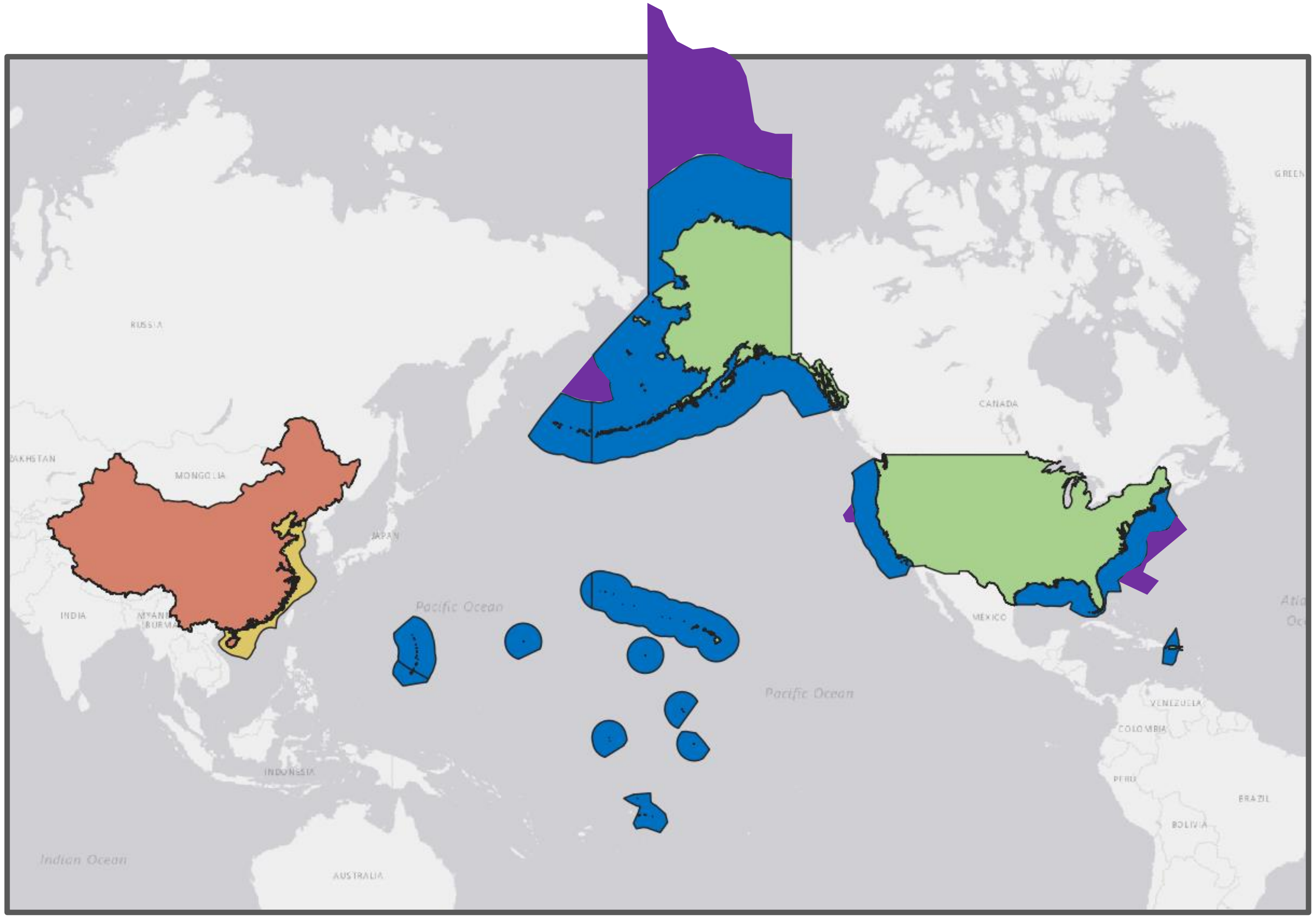
How does ARPA-E think about the ocean?

The U.S. has the world's ~~second~~ largest maritime Exclusive Economic Zone (EEZ)





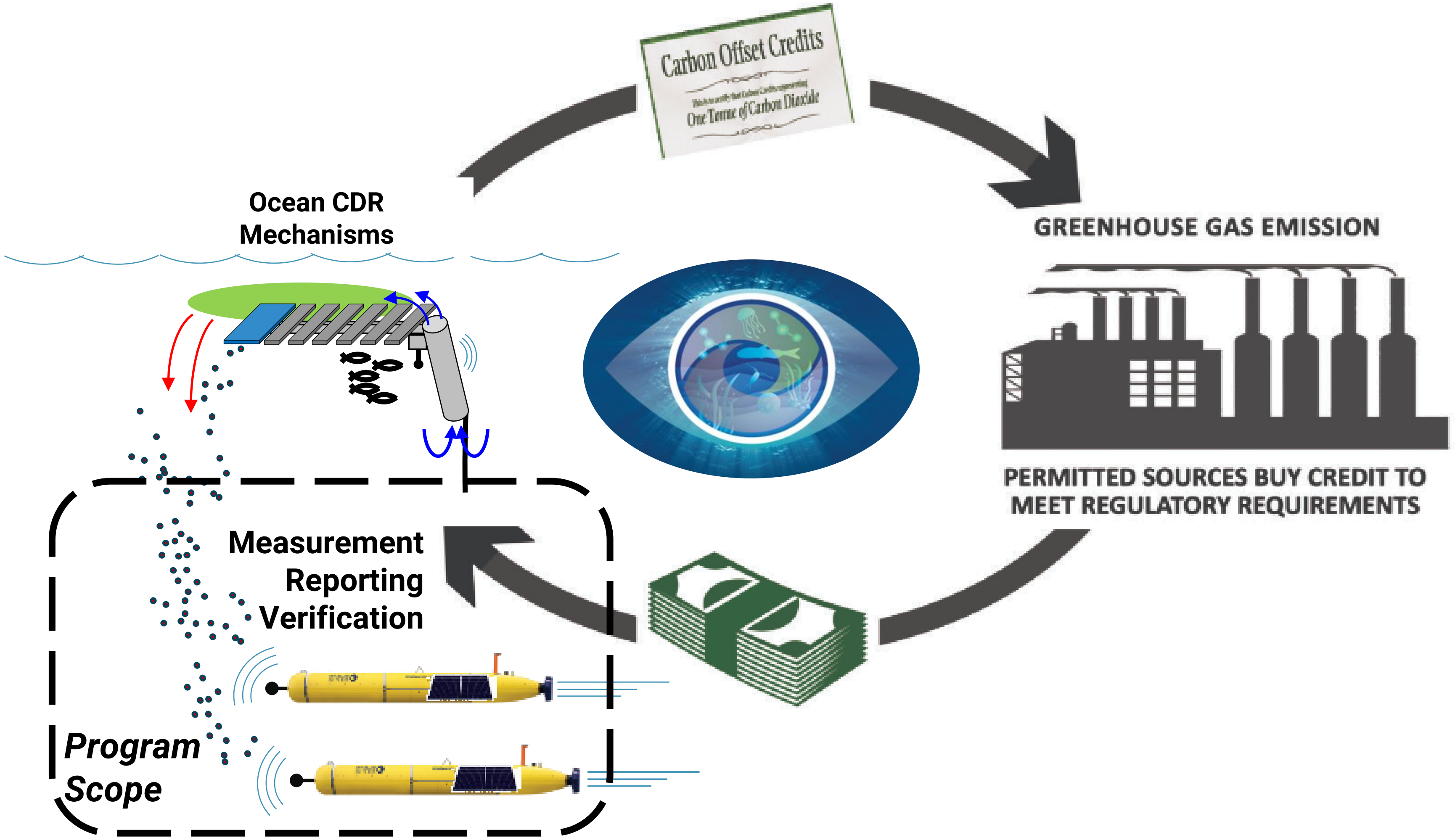
ARPA-E's First Program on Ocean Carbon Removal

SEA-CO2: Sensing Exports of Anthropogenic Carbon through Ocean Observation

What are we trying to do?
Create viable Measurement, Reporting and Validation (MRV) technology for marine Carbon Dioxide Removal (mCDR) processes

Technical Areas:

1. *Develop volumetric, scalable **carbon sensing** technology (7 teams)*
2. *Create effective **models** to estimate CDR performance (4 teams)*



$37.3M, 3 years, kicked off in January 2024

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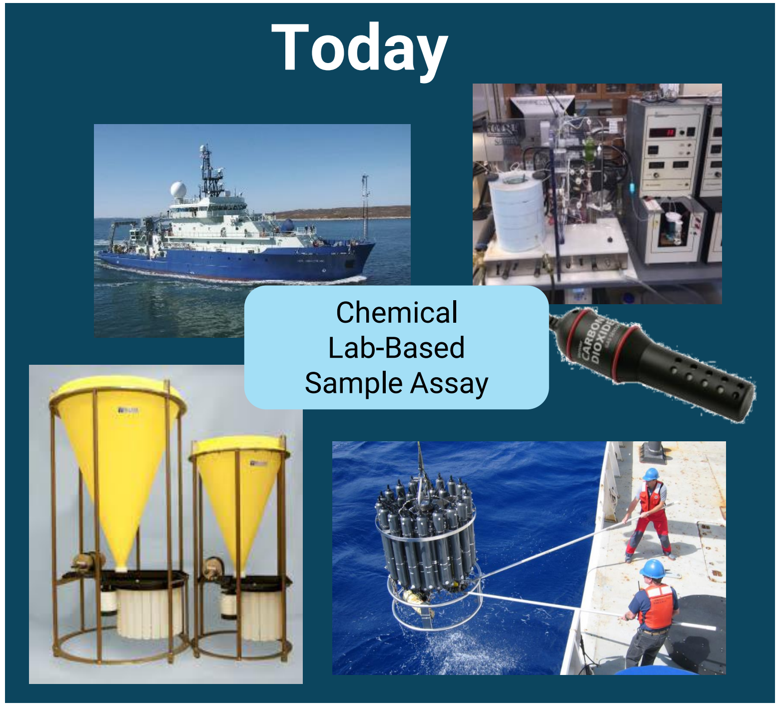
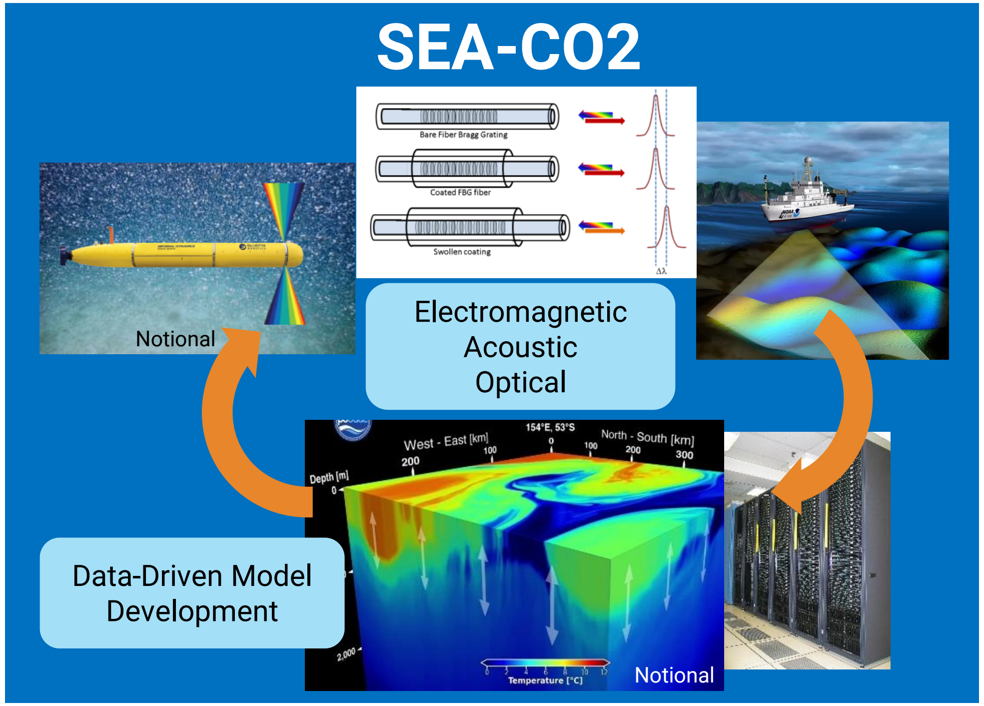
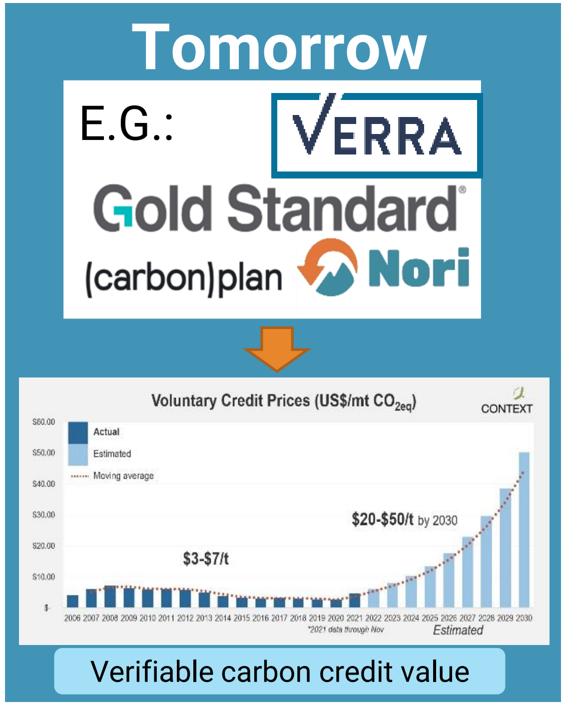
Enable a gigaton-scale carbon capture industry, fastest.

- Quantification gives marine CDR financial value in a carbon market
- Ocean CDR potentially the least industrial disruption and adverse impact
- Enables rapid scalability to reverse our *existential climate crisis*







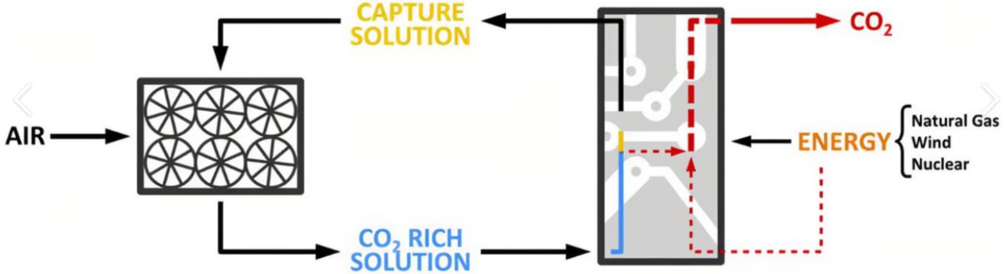
The Energy Cost of Gigaton Scale CO2 Removal

REDUCE emissions

But also:

IMPROVE efficiency

External energy cost to remove 1 GT CO_2e



Direct Air Capture ~ 2,000 TWh, 50% of all US electricity consumption in 2022

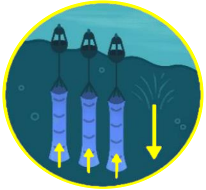
Macroalgal Cultivation ~225 TWh

Alkalinity Enhancement 100-3500 TWh

Iron Fertilization 8-250 TWh

Electrochemical < 2,000 TWh

Ecosystem Restoration ~0 TWh!



Artificial Upwelling ~208 TWh

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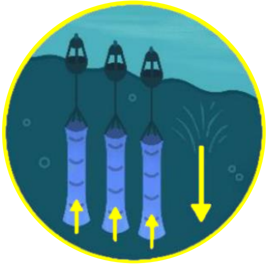
Marine CDR Approaches

Ocean Iron Fertilization

Alkalinity Enhancement

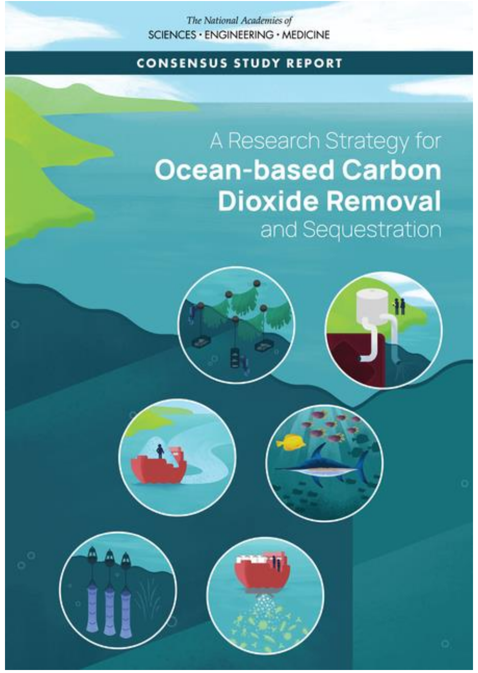
Artificial Upwelling



Biomass Sinking

Ecosystem Restoration

Electrochemical

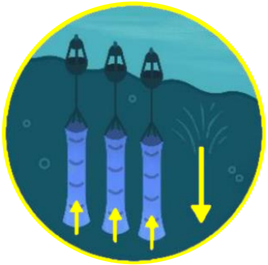


https://nap.nationalacademies.org/read/26278

Validation of marine CDR is holding us back in all cases

*"So in estimating the effectiveness of [**IRON FERTILIZATION**] for ocean CDR,* ***there remains a large uncertainty****…"*

*"[**ALKALINITY ENHANCEMENT**] has potential benefits…although* ***empirical data are necessary to determine the effectiveness****…"*



"…hence ***there is significant uncertainty*** *as to where and when [**ARTIFICAL UPWELLING**] could generate net carbon sequestration."*

*"In principle, [**SEAWEED CULTIVATION**] should work, but* ***there is a large degree of uncertainty****…"*

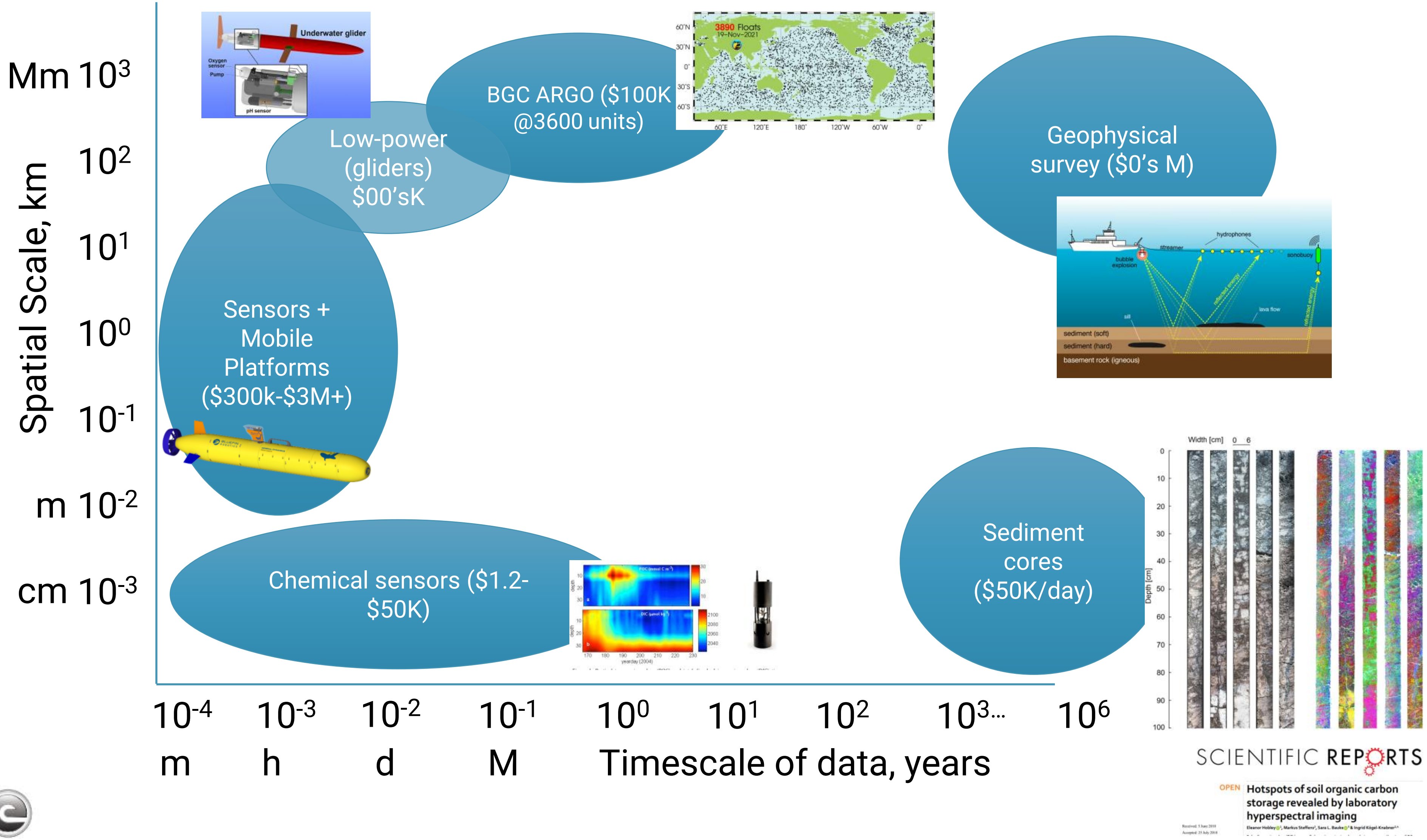
"Although [recovery of] ***MARINE ECOSYSTEMS*** *have been proposed as a climate solution,* ***there is a fair amount of uncertainty****…"*

*"…**ELECTROCHEMICAL PROCESSES** that couple with the world's oceans* ***may exert unintended consequences****."*

https://nap.nationalacademies.org/read/26278

Sensing Challenges Today: Time, Distance, Resolution, Cost

Scale limits of present-day carbon sensing approaches



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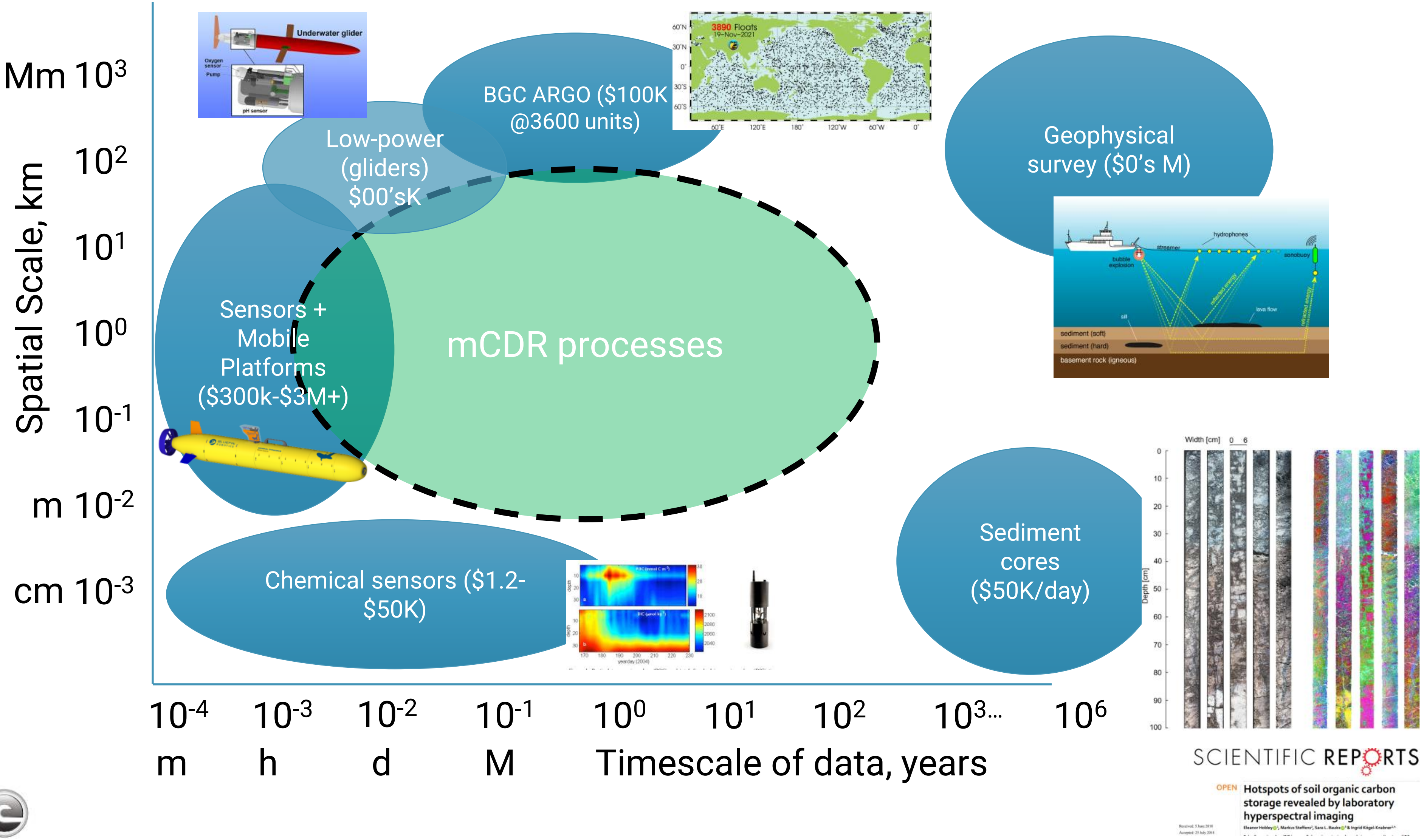

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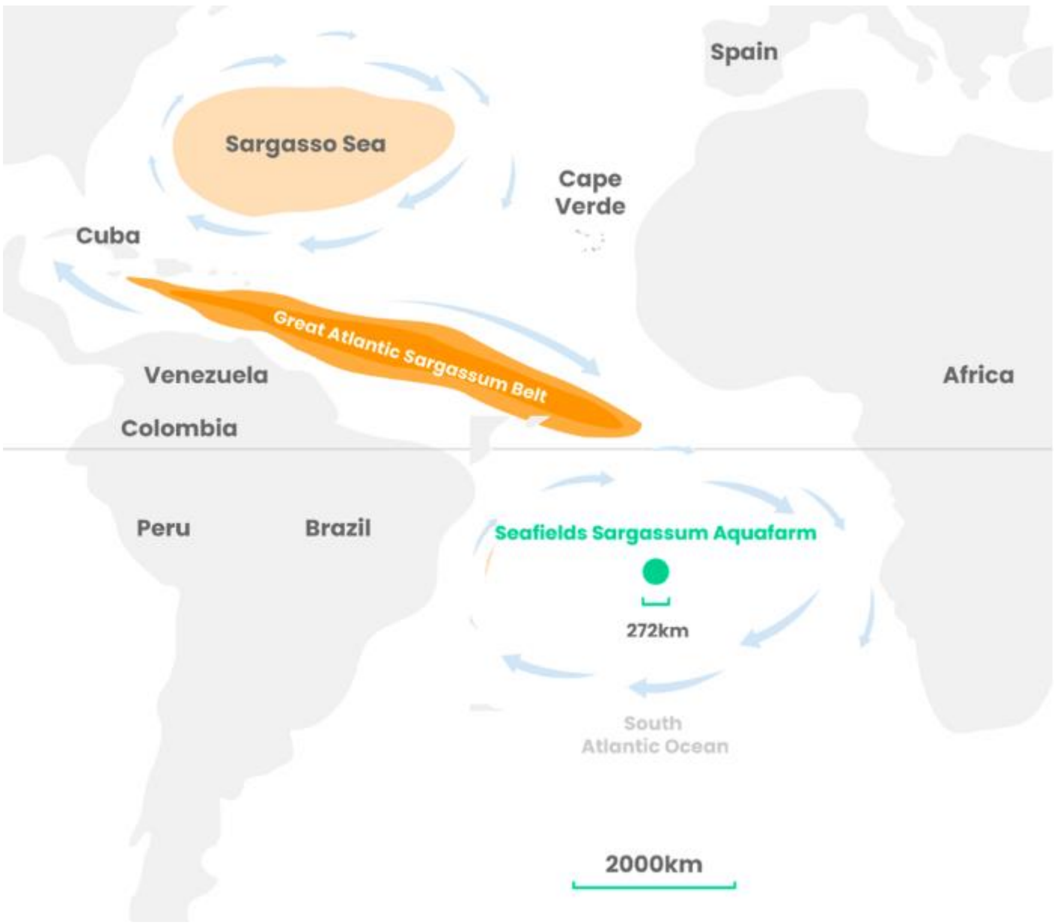
Volumetric Survey Requirements and Economic Scale

- 55,000 km^2 area surveyed every two weeks = 150 km^2/h.
- Survey to 1 km depth (Siegel *et al.*, 2021) using a vehicle traveling nominally at 3 kt (6 km/h), would mean a continuous cross-sectional survey area of 25 x 1 km is required.
- The optical depth of blue-green laser sensors is max. ~100 m, thus we would need min. ~625 vehicles.
- If CO2 drawdown is priced at $100/ton, and assuming a 5% MRV cost ($5 billion per gigaton), that's $8m per system, per year.

Seafields



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SEA-CO2 Program Metrics

Description	Quantitative Value	Details
Volumetric Capability	150 km^3/h (volume or 3D sensing) 150 km^2/h (sediment or 2D sensing)	Volumetric or area-sensing requirement when the MRV approach is scaled to 1 gt CO_2/yr size . Note that this metric implies the requirement of a competitive techno-economic analysis for a future scaled market, where MRV costs should not exceed 5% of the value of CO_2 drawn down.
Accuracy	See SOA Table in FOA	Accuracy of new sensor designs must be within 10% of the state-of-the-art for individual carbon parameters.
Size, Weight and Power	COTS platform	Requirement to match what is offered by an appropriate COTS platform available today or within 18 months of project start.
Sensor Endurance	1 year	Sensors must function continuously or at appropriate cycle rates without physical human intervention for one year or more.
Model Accuracy (historical data)	RMSE ≤ 0.25 ACC ≥ 0.7	Performance of MRV models based on hold-out historical data must meet state-of-the-art values.

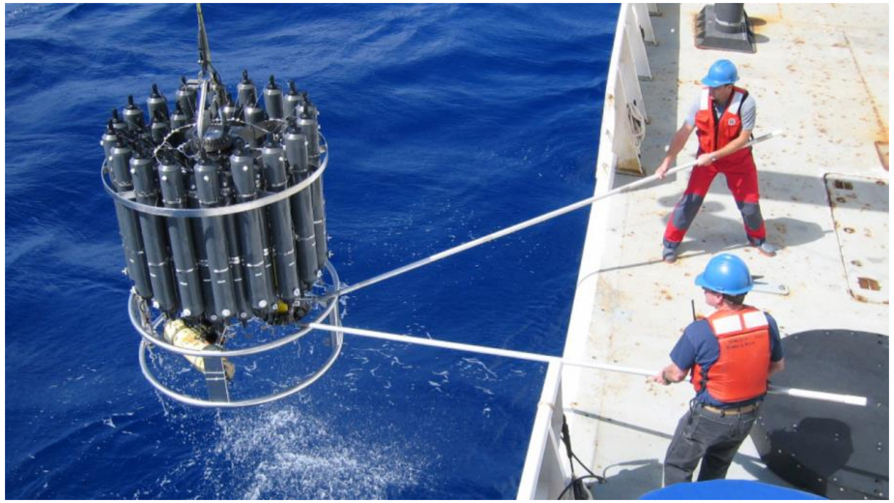
Other requirements:

- Submission of manuscripts describing fundamental principles of new sensor technology and bench-scale demonstrations. Approaches and reports of experimental outcomes must pass peer review.
- Sensors must be developed while considering economies of scale.

Today's Sensors

- Point measurements, direct sampling and laboratory titrations
- ISFET or Optical (IR absorption) techniques
- Emphasis on accuracy and calibration

Niskin bottle wet-chemistry assay: 4h for 6,000 m



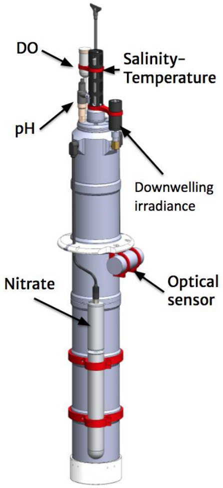
pCO$_2$ sensing via IR sample: 2.5 min per sample

NOAA/NCEI Handbook:
Focus on accuracy and precision

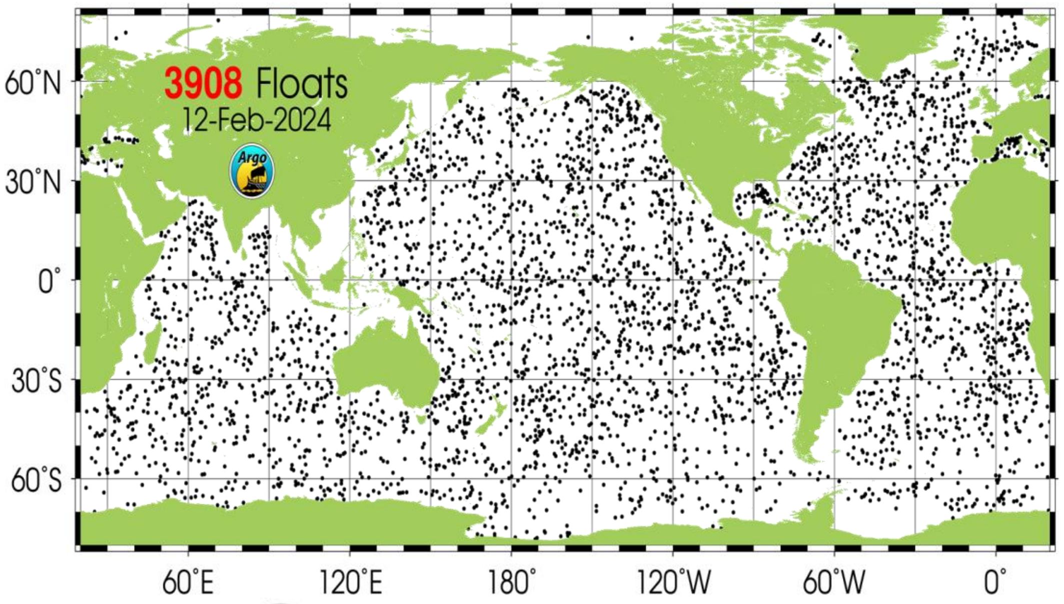
What are the grand challenges?

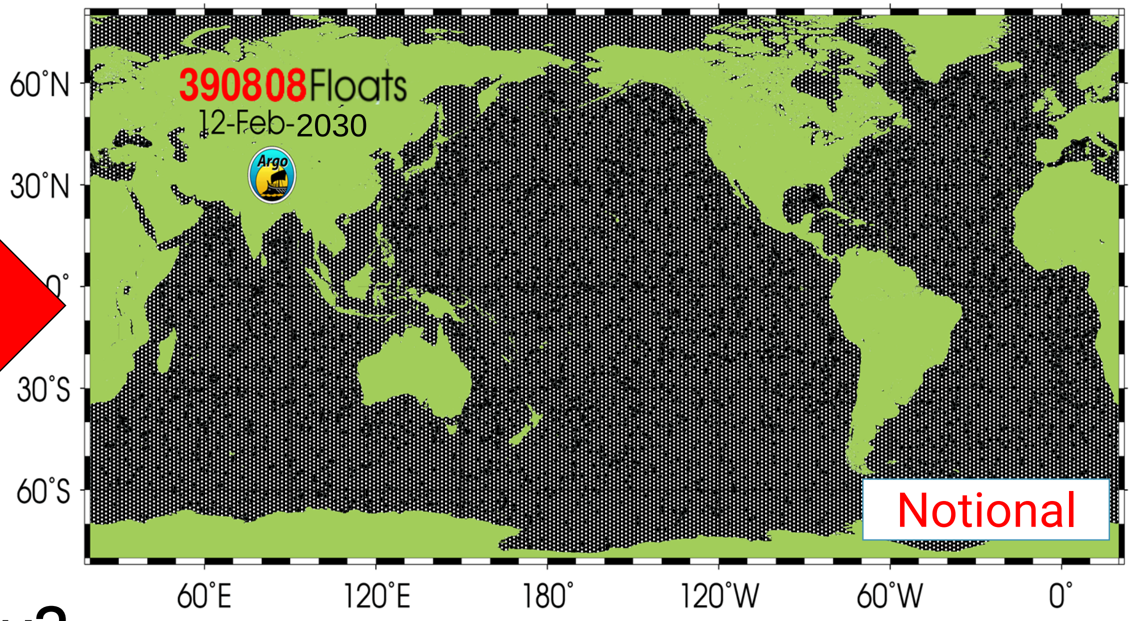
1. Paradigm shift in ocean chemical sensing: inward to outward looking
2. Inexpensive, regular, reliable, volumetric access

Scaling ARGO



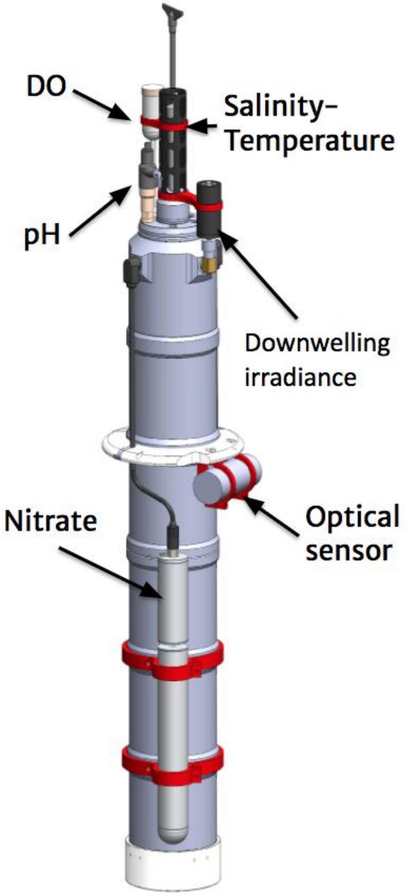
BioGeoChemical ARGO:
~$100,000 per system
3-5 year life

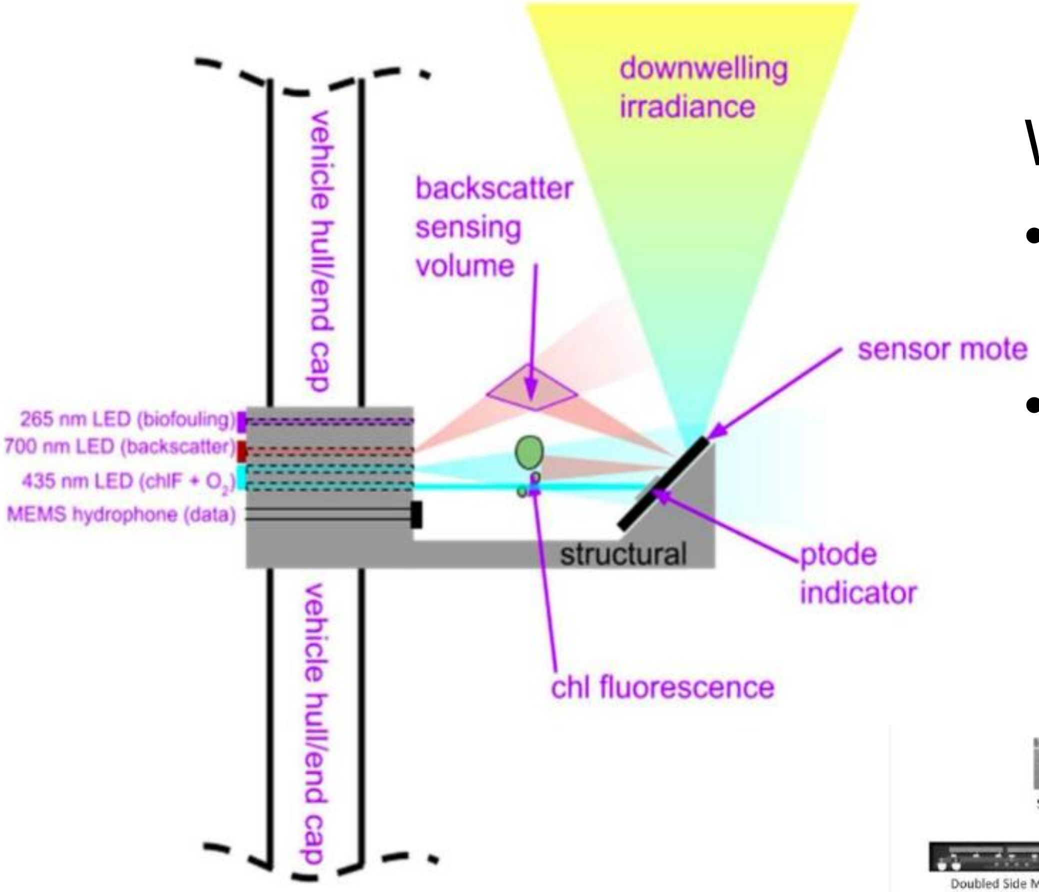




How?

Scalable, Multiparameter Chip-Size Carbon Sensors

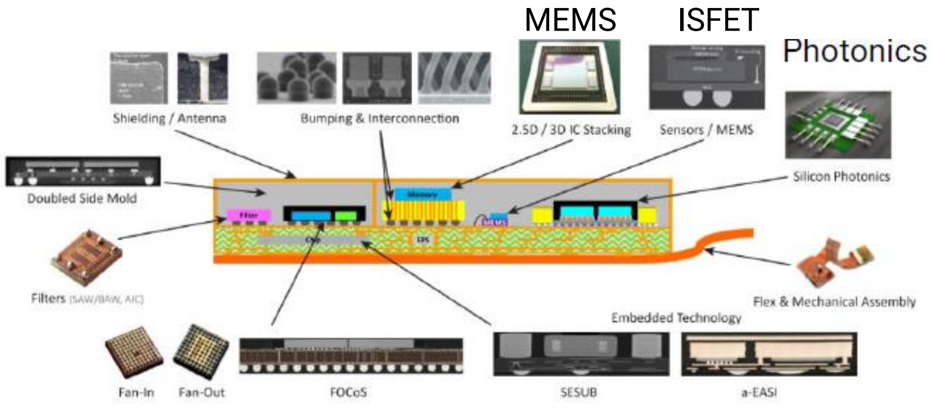




While maintaining capability:

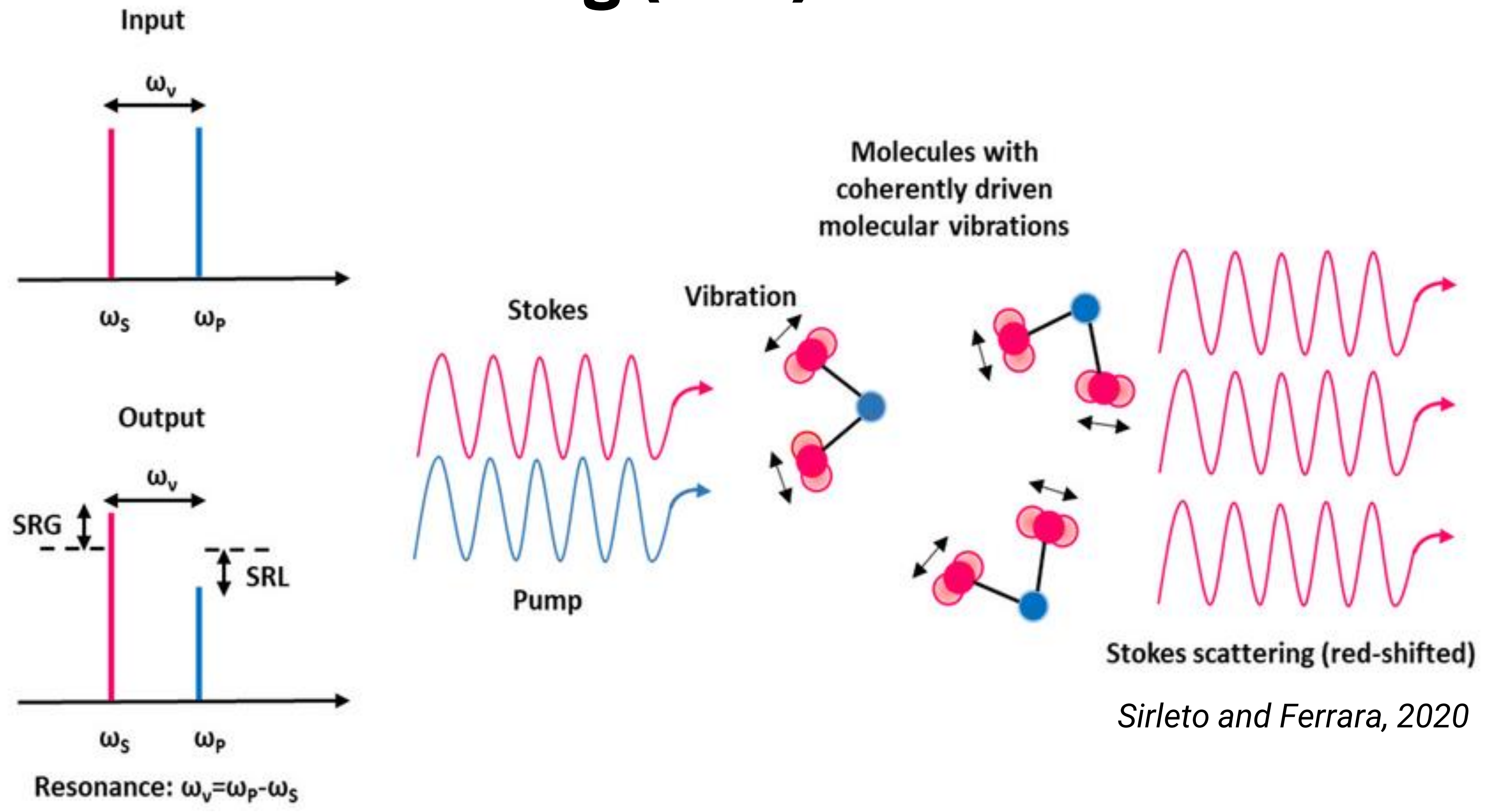
- Can we reduce costs from $100k today to $10's of k?
- Can we build and calibrate 100's of units at a time?

Building blocks for heterogeneous integration



from: aseglobal.com

Stimulated Raman Scattering (SRS)

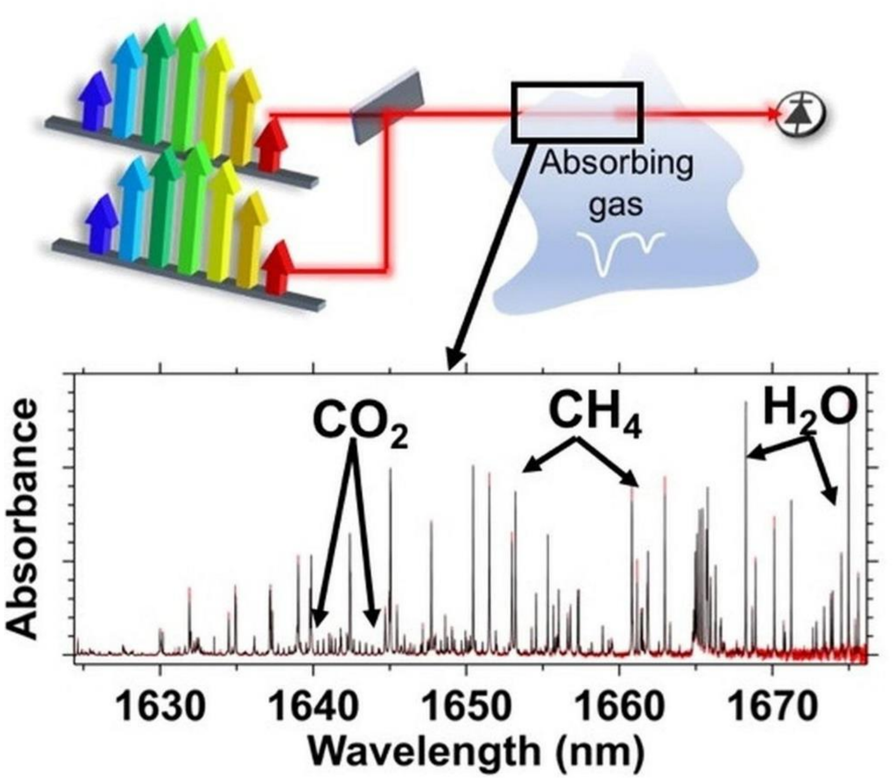


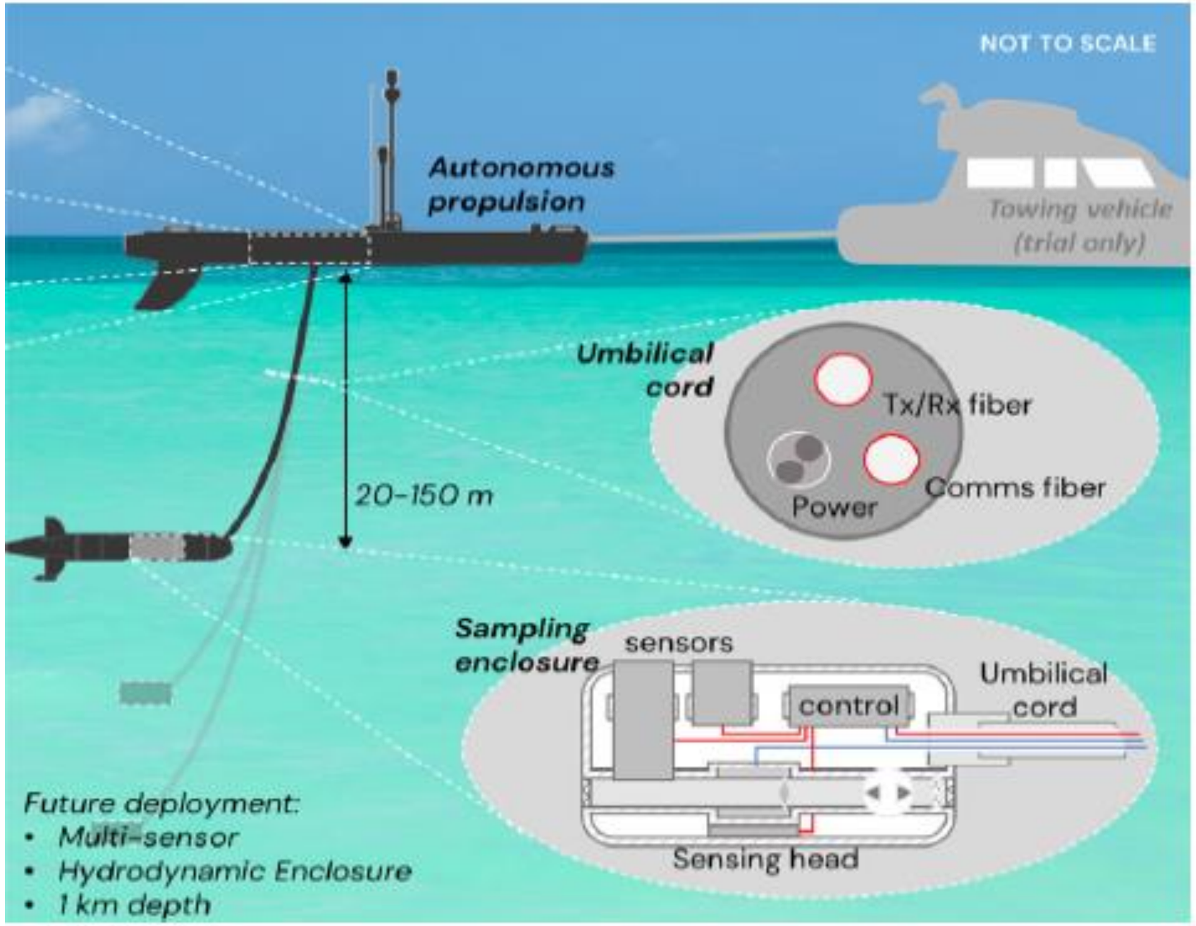
Sirleto and Ferrara, 2020

"A pump and Stokes laser beams, whose frequency difference matches a particular vibrational mode, drive the molecule at $\omega_v = \omega_S - \omega_P$, producing coherent Raman signals at $\omega_S = \omega_P + \omega_v$. SRS modalities are: SRG, stimulated Raman gain; SRL, stimulated Raman loss. Stimulation enhances the Raman signal by O. 10^5"

SLEUTH: Spectroscopy of Liquid Environments Using Towed optical sensor Heads

Dual comb, mode-locked laser spectroscopy of complex in-water molecules, in-situ, using Stimulated Raman Scattering





Boulder

ofs

LIQUID ROBOTICS
A Boeing Company

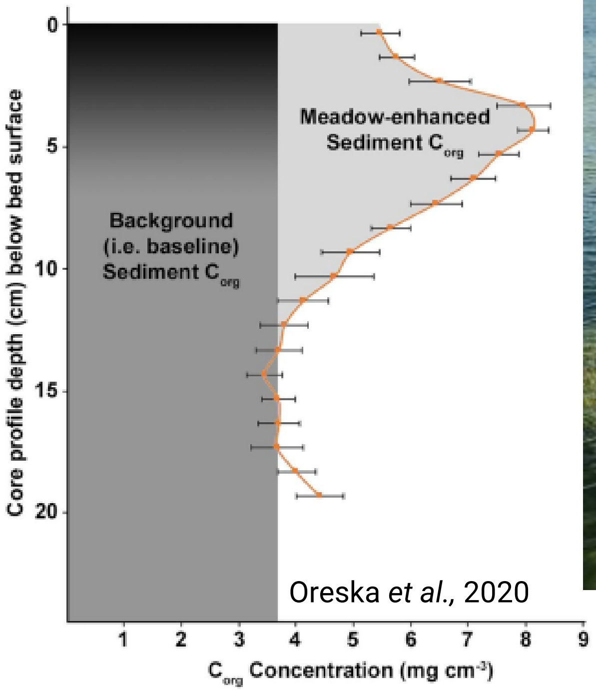
cambridge consultants
Part of Capgemini Invent

FIU
FLORIDA INTERNATIONAL UNIVERSITY

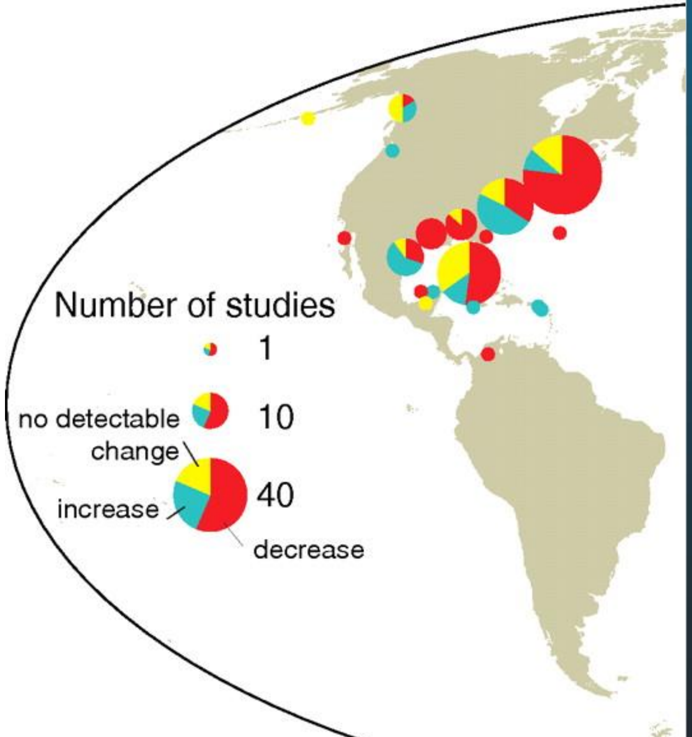
THE UNIVERSITY OF CALIFORNIA · IRVINE · LET THERE BE LIGHT

MRV Enables More Accurate Valuation of Ecosystem Restoration

"Restoring 15% of converted lands in priority areas could ... sequester 299 gigatons of CO2 – 30% of the total CO2 increase in the atmosphere since the industrial revolution." – Strassburg et al., 2020



Oreska *et al.*, 2020



Changes in seagrass bed area, Waycott *et al.*, 2009

"Seagrass accounts for 10 per cent of the ocean's capacity to store carbon… despite occupying only 0.2 per cent of the sea floor, and it can capture carbon from the atmosphere up to 35 times faster than tropical rainforests." – UNEP, 2019

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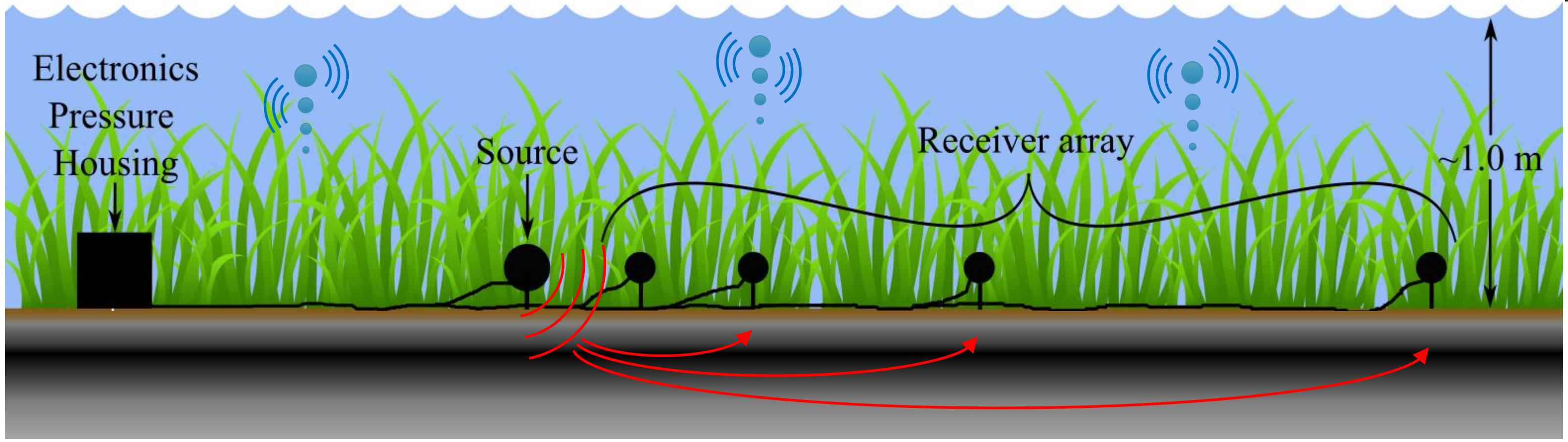
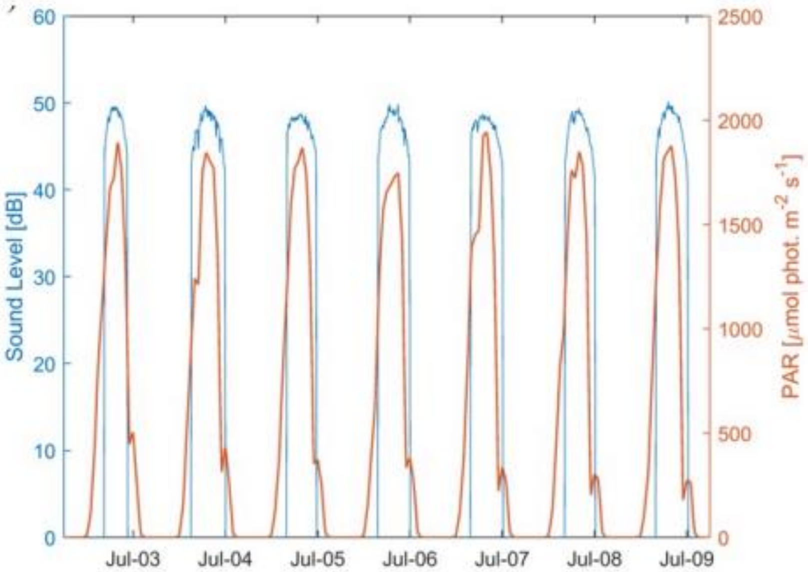
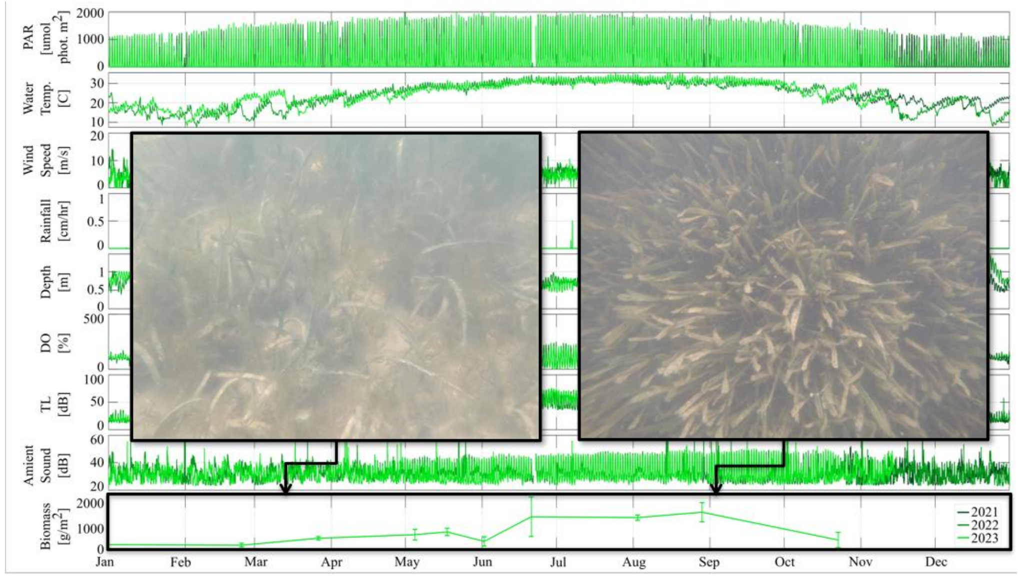
The Key: Measurement and Verification

Can we hear carbon capture by seagrass and listen for storage in anoxic coastal sediments over entire seagrass beds?







Distributed Fiber, Time-of-Flight Sensing


SILIXA

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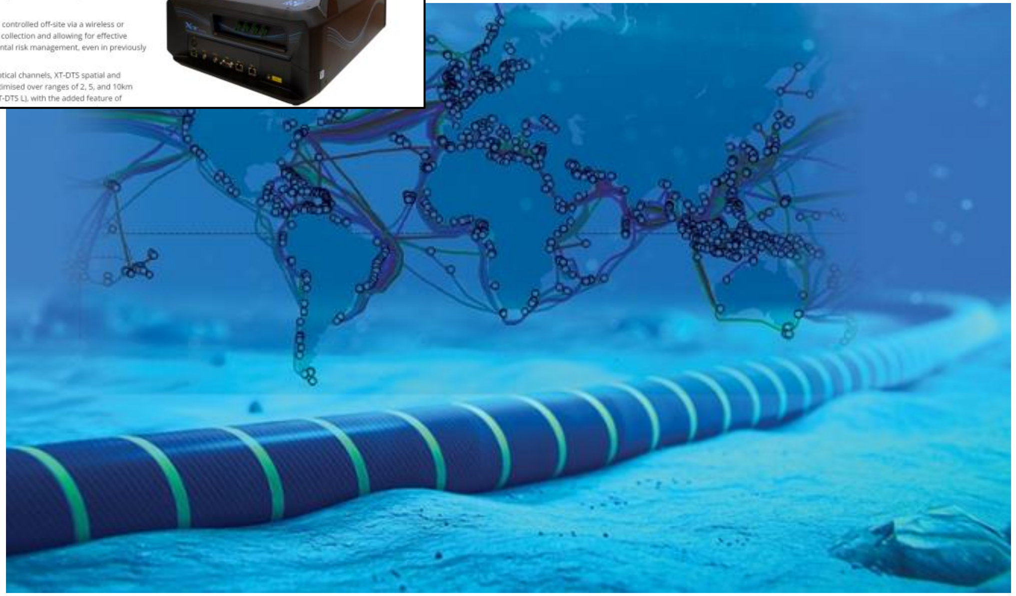
XT-DTS™

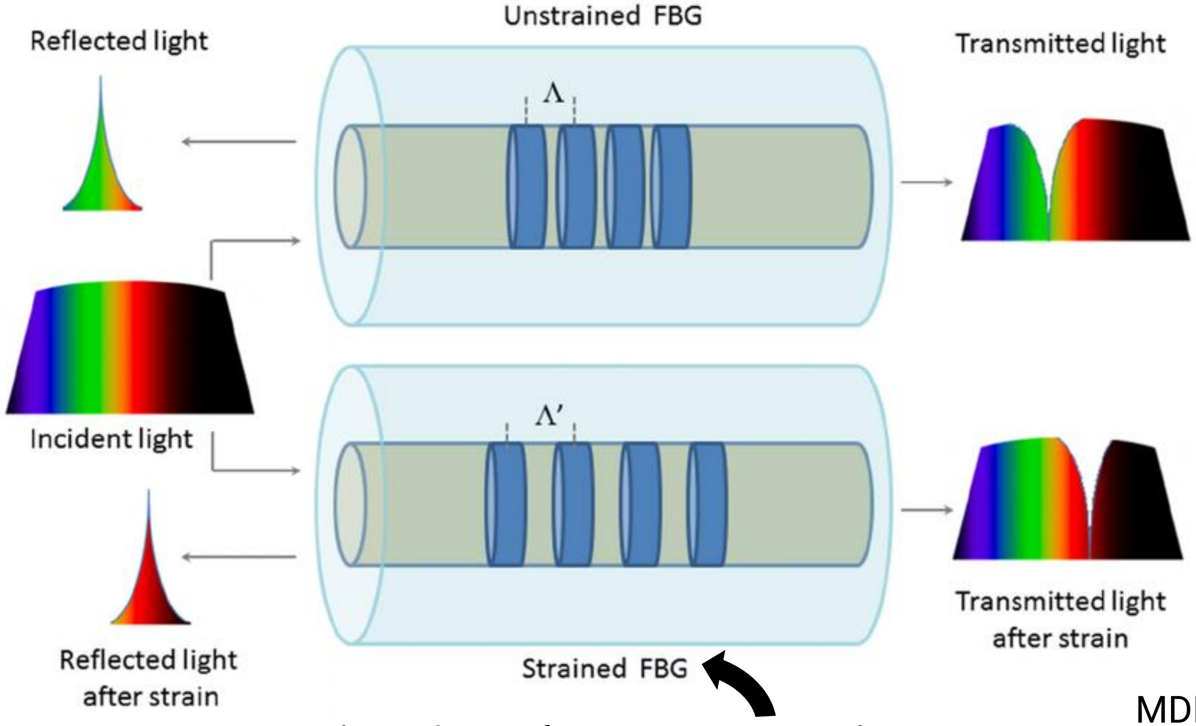
Silixa's ruggedised distributed temperature sensor, XT-DTS™, is the highest performing DTS for remote and hostile environments.

Designed for remote operation in hostile environments, XT-DTS maintains the highest measurement performance while achieving a class-leading operating temperature range. Its low power consumption enables operation with solar or wind power.

The XT-DTS can be configured and controlled off-site via a wireless or satellite link enabling remote data collection and allowing for effective asset optimisation and environmental risk management, even in previously unreachable locations.

Now available with either 4 or 8 optical channels, XT-DTS spatial and temperature resolution can be optimised over ranges of 2, 5, and 10km (XT-DTS M) or 10, 20, and 35km (XT-DTS L), with the added feature of





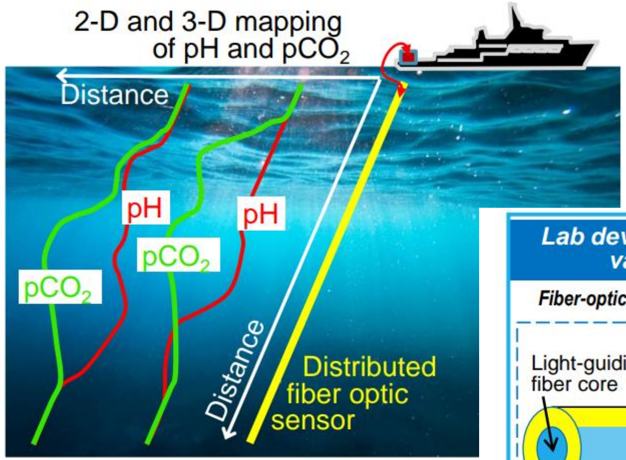
Mechanical strain from temperature or vibration

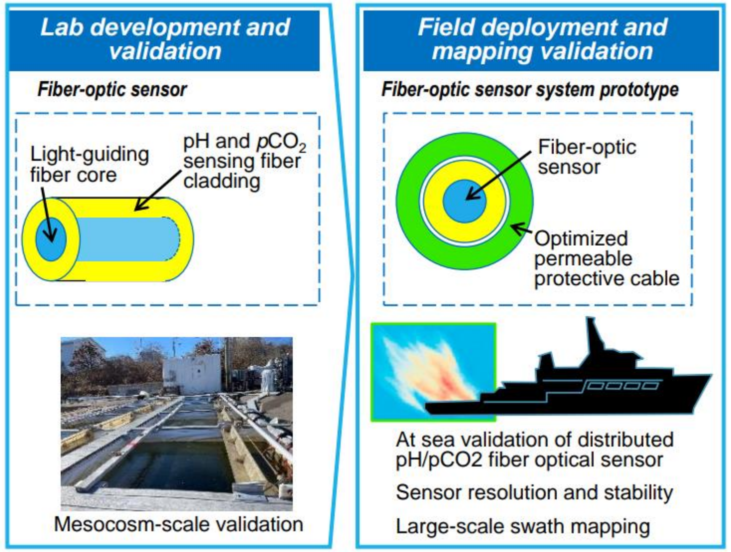
MDPI

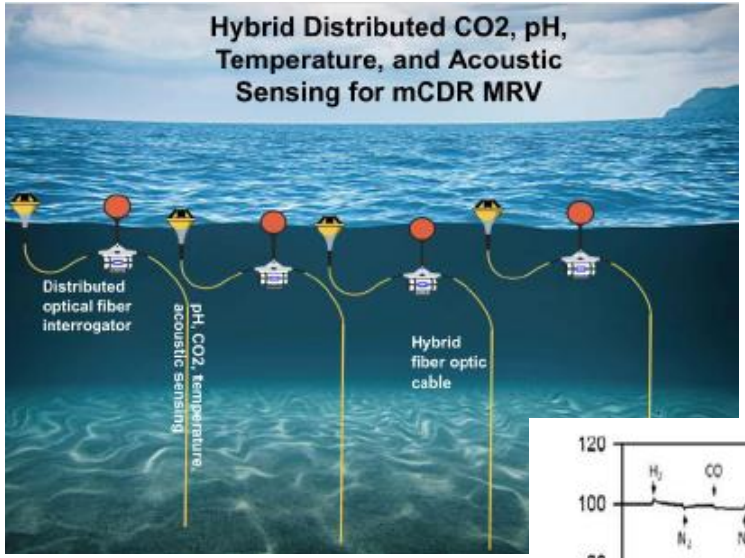
"An optical pulse is launched into the fiber, the environment interacts with the light pulse along the length of the fiber, and backscattered or reflected light intensity is recorded during precisely time-gated periods that correspond to a specific distance along the fiber"

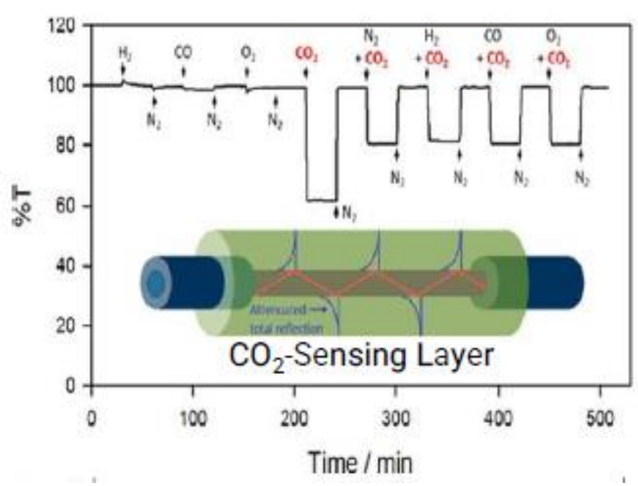
Distributed Fiber Chemical Sensing

Can we sense pH and pCO_2 instantaneously at km^3 scales, at <1m resolution?









SEA-CO2 Modeling Projects

- Mature MRV will be conducted though modeling of real CDR approaches, and a few validation measurements
- With enough data, modern algorithms can be used to reduce bias and error in mCDR models
- Precedent: Weather derivatives market model (ca. 1996~).

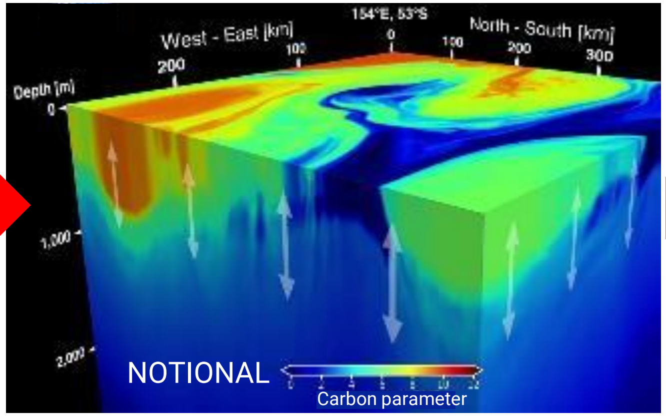
Lead Institutions: Model Development

Bigelow Laboratory for Ocean Sciences

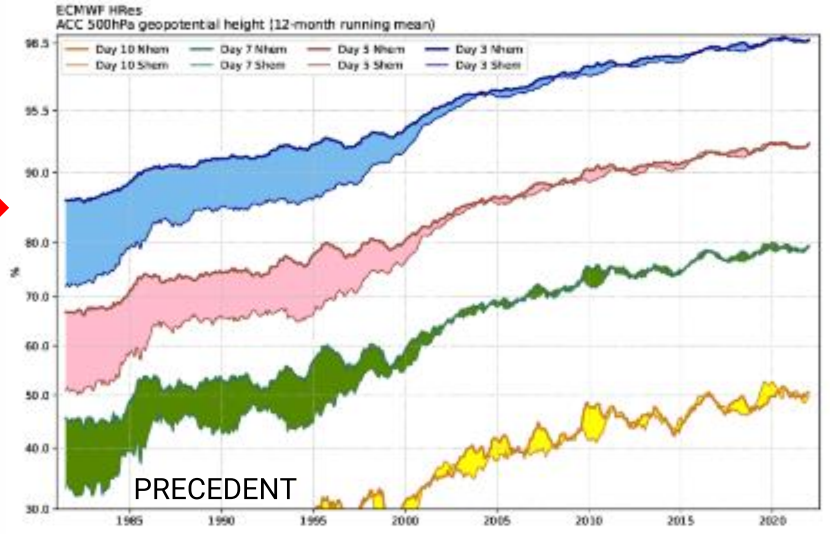
atdepth MRV

Pacific Northwest NATIONAL LABORATORY

[C]Worthy



Skill Improvements (ECMWF)



Major improvements, mainly due to satellite data and improved models

For Example: VERRA (carbon)plan Gold Standard Nori

A scalable, integrated, real-time GPU-based modeling system to enable MRV for mCDR

atdepth MRV

Approach

Oceananigans.jl

Fast and friendly fluid dynamics on CPUs and GPUs.

+

OceanBioME CLIMATE REPAIR GORDON AND BETTY MOORE FOUNDATION

+

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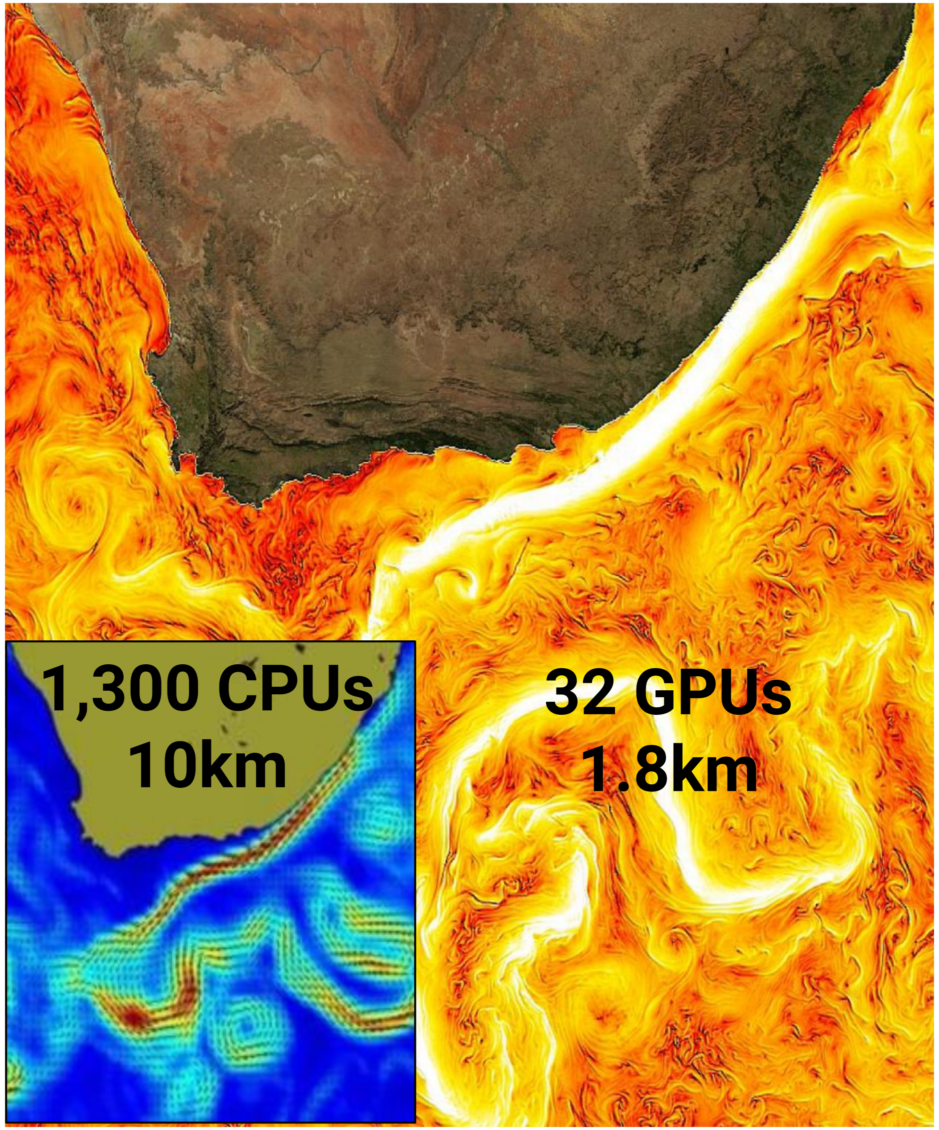
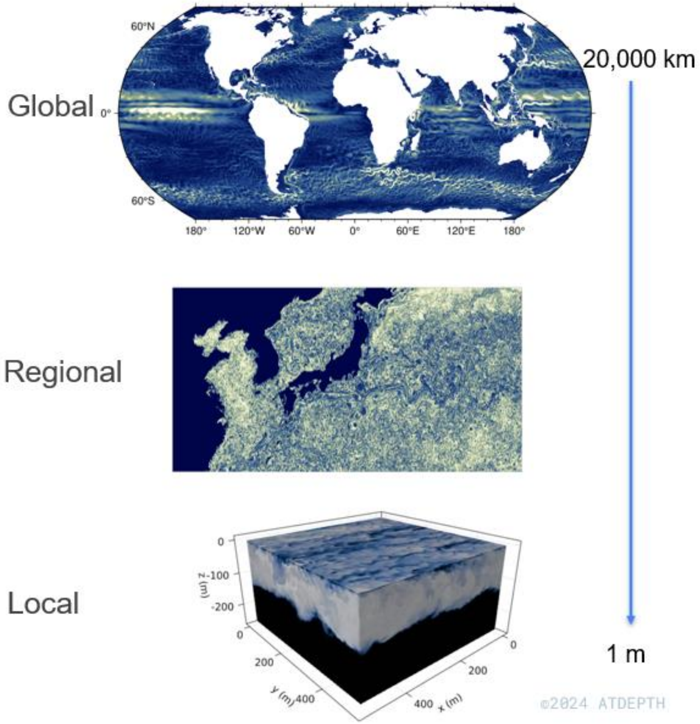
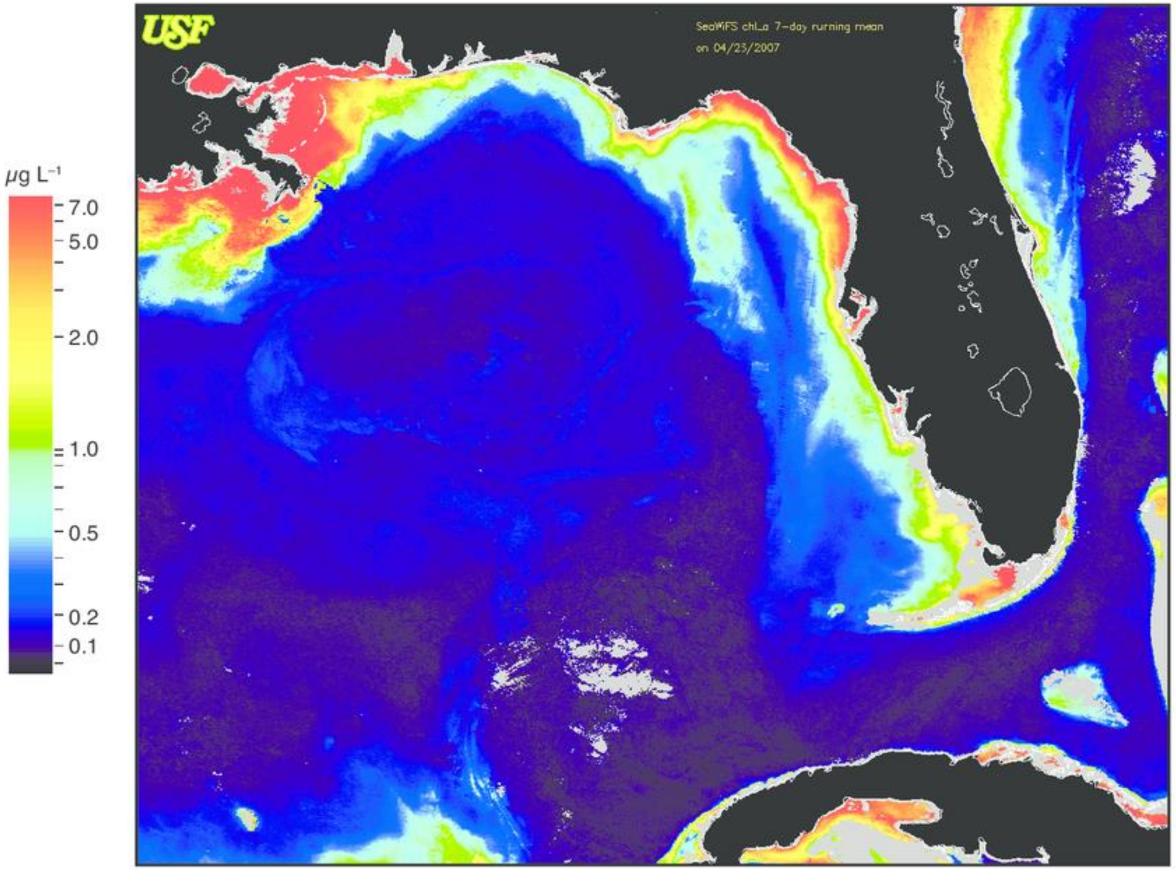


Silvestri, S. et al., (2023). *arXiv preprint arXiv:2309.06662*.

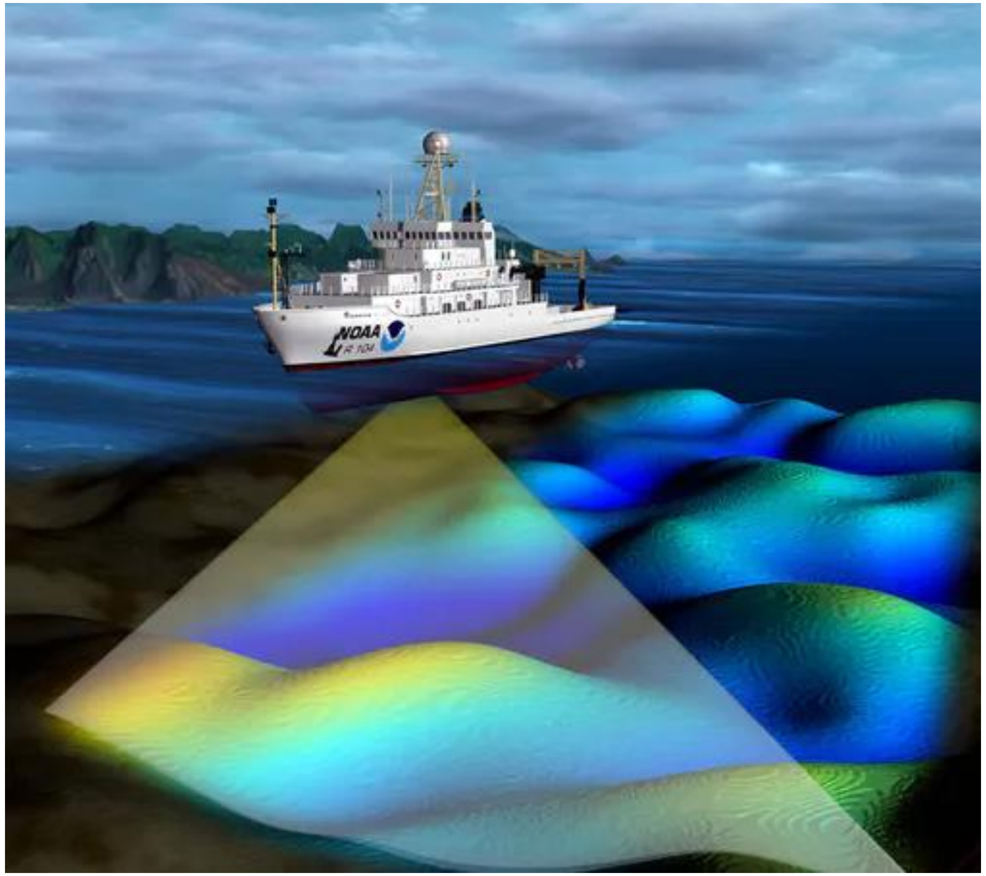
Goal



Technical Goals: Sense at Large Scales, Reduce Cost Per Measurement



…but with undersea sensors



…but for carbon, rather than sound

SEA-CO2: ARPA-E's First Program on Ocean Carbon Removal


Blade runner

Our Choice


Medium

More than a science program, the purpose of SEA-CO2 is to **enable the scaled reversal of climate change** in the fastest, most efficient manner possible.

More than a funding agency, ARPA-E supports teams beyond financial awards

• Funding • Technical guidance • Networking • Showcasing • Follow-on opportunities

“We can do this because we’ve done it before”