Measurement, Reporting and Verification (MRV) Technologies for Marine Carbon Dioxide Removal (mCDR)

A Workshop Convened by:

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Summary

The United Nations states that "the ocean generates 50 percent of the oxygen we need, absorbs 25 percent of all carbon dioxide emissions and captures 90 percent of the excess heat generated by these emissions. It is not just 'the lungs of the planet' but also its largest 'carbon sink' – a vital buffer against the impacts of climate change"[1]. The ocean plays an influential role in the biological carbon cycle of the earth. The elevated levels of carbon dioxide emissions in the atmosphere have led to rising ocean temperatures and acidification, thus lowering the ocean's capacity to absorb further carbon dioxide emissions and causing damage to the ocean's ecosystems. There is a need to limit, or better yet, to reverse the damage to the ocean's ecosystems, and there is an opportunity for the ocean to have a major role in 'carbon capture and storage' that is the removal of additional carbon dioxide, referred to as marine Carbon Dioxide Removal (mCDR).

This workshop focused on the measurement, reporting and verification (MRV) technologies and policy considerations needed to enable mCDR. The 1-day event was held in conjunction with the Ocean-Climate Solutions Summit in Boston (organized by the Ocean Frontier Institute). The workshop convened thirty-six experts from technology start-ups, academia, and government agencies. The discussions centered on the opportunity, status, and needs of marine CO_2 removal technologies across multiple chemical and biological pathways, emphasizing the need to collect significantly more data than is available today.

The group identified many areas of common concern, including shared definitions of scale for pilot studies, the need for an accepted framework of criteria (or "gates") for projects to move from pilot to various operational stages, and the need for continued community collaboration to develop best practices and standards to inform policy and regulation. Proposed follow-on activities include:

- Webinars to inform the wider engineering community of this emerging field.
- Continuation of the discussions as part of an IEEE SA Industry Connections program.
- Further discussion of potential roadmaps and standards within this group, or an IC group.
- Greater engagement with other organizations and NGOs pursing similar activities.

[1] United Nations (2023). The ocean – the world's greatest ally against climate change. [online] United Nations. Available at: https://www.un.org/en/climatechange/science/climate-issues/ocean#:~:text=The%20ocean%20generates%2050%20percent.

Introduction

The IEEE Future Directions SusTech Initiative is related to the IEEE Planet Positive 2030 Initiative, supported by IEEE SA. The IEEE Planet Positive 2030 Draft Compendium *Strong Sustainability by Design—Prioritizing Ecosystem and Human Flourishing with Technology-Based Solutions* has identified topics for face-to-face and online workshops[2].

The Ocean has a critical role to play in mitigating anthropogenic climate change. It is the site of active biological carbon cycles. It offers a vast surface area as an alternative to land for capturing and removing dispersed carbon from the atmosphere and, ultimately, for restoring sustainability to Earth's ecosystems. However, working in oceanic environments is extremely challenging, and the mCDR industry is immature. Robust, cost-effective technologies for scaling and monitoring ocean-based facilities, quantifying intended and unintended environmental impacts, measuring the efficacy and permanence of carbon removal, and modelling and predicting climate-relevant effects are needed.

For this workshop, we brought together engineers, oceanographers, environmentalists, technologists, and data scientists from a variety of organizations including a strong presence of industry, to share knowledge and:

1. Receive a comprehensive overview of the role of ocean-based solutions for the climate crisis.
2. Explore the status of various mCDR technology pathways with respect to measurement, reporting and verification (MRV) feasibility.
3. Describe existing gaps between current MRV technologies, progress needed, and innovative ideas to implement mCDR reliably and at scale.

Three technology pathways for carbon sequestration in the ocean were presented: alkalinity enhancement, electrochemical carbon dioxide removal and biological: (1) Alkalinity enhancement consists of chemical inputs to increase the ocean's alkalinity; (2) Electrochemical methods extract acidic fluids from seawater, thereby reducing dissolved carbon dioxide; and (3) Biological pathways cultivate large amounts of micro- or macro-algae (e.g. seaweed) and then sink it deep into the ocean, thus removing it from the biological carbon cycle.

[2] Please refer to: https://sagroups.ieee.org/planetpositive2030/our-work/.

The ocean plays a significant role in addressing carbon pollution. The ocean has already absorbed 25% of human carbon emissions and may support up to 25% of future carbon removal activities. Understanding the carbon cycle in the ocean and the potential to remove and permanently store excess CO_2 is a key area for urgent research and development. On the pathway to net-zero greenhouse gas emissions by 2050, understanding the potential for mCDR and the measurement, reporting and verification (MRV) required to deploy mCDR at scale is crucial.

As Christopher Whitt, President IEEE Ocean Engineering Society, has indicated many times: we know less about the ocean than about the surfaces of the Moon and Mars. Data collection and communication of said data (in water communication) is extremely difficult. Hence, MRV technologies are mostly in preliminary stages of development and deployment.

Invited Speakers

- **Christopher Whitt** of Irving Shipbuilding: Welcome and Objectives of the Workshop
- **Craig Mclean** of Woods Hole Oceanographic Institution: on Policy and Social Implications of Carbon Removal
- **Nikhil Neelakantan** of Ocean Visions: on Existing Technology Roadmaps
- **Mike Kelland** of Planetary Technologies: on Ocean Alkalinity Enhancement Pathways
- **Matthew Eisaman** of Yale University and Ebb Carbon: on Electrochemical Pathways
- **Sophie Chu** of Captura on Direct Ocean Capture Technologies
- **Brad Rochlin** of Running Tide on Nature-Based Capture Pathways
- **Simon Freeman** of ARPA-E on an Overview of MRV Technologies

Workshop Agenda

The workshop agenda was designed to provide a sufficient landscape overview and knowledge sharing to foster effective breakout discussions while maximizing time for discussions and interaction.

7:30	Breakfast & Registration	
8:00	Christopher Whitt	Welcome - Overview
8:15	Craig Mclean	Policy for mCDR
8:30	Simon Freeman, ARPA-E	MRV Overview
8:45	Nikhil Neelakantan, Ocean Visions	Existing Roadmaps
9:00	Mike Kelland, CEO Planetary	OAE Pathway
9:15	Matt Eisaman, Ebb Carbon	Electrochemical
9:30	Sophie Chu, Captura	Direct Ocean Capture
9:45	Brad Rochlin, Running Tide	Biological
10:00	Attendee Introductions: Name, Country, Expertise	
10:15	Coffee Break	
10:30	Breakout Sessions 1: *Pilot projects, initial studies*	
Breakout 1	Dissolution	Facilitators TBD
Breakout 2	Depletion	
Breakout 3	Sea-Air Exchange	
Breakout 4	Other Biological Pathways	
12:00	Lunch Buffet	
13:00	Breakout Sessions 2: *Larger scale, scaling up*	
Breakout 1	Dissolution	
Breakout 2	Depletion	
Breakout 3	Sea-Air Exchange	
Breakout 4	Other Biological Pathways	
15:00	Coffee Break	
15:20	Group Presentations & Discussions	
17:00	Closing Remarks	Christopher Whitt

Summaries of Presentations

Policy and Social Implications of Carbon Removal (mCDR)

This presentation captured the core policy considerations and strategic recommendations for advancing marine carbon dioxide removal while addressing regulatory, social, and environmental challenges.

This presentation by Craig McLean from the Woods Hole Oceanographic Institution addressed the essential policy considerations for Marine Carbon Dioxide Removal (mCDR) and Monitoring, Reporting, and Verification (MRV) frameworks. The presentation highlighted the urgent need for planning and establishing robust policies to manage the deployment of mCDR technologies effectively and responsibly.

Key Themes and Policy Challenges

1. **Regulation and Governance**:
   - **Regulatory Bodies:** the absence of cohesive regulatory oversight among key agencies such as the Army Corps of Engineers (ACOE), Environmental Protection Agency (EPA), National Oceanic and Atmospheric Administration (NOAA), and the U.S. Coast Guard (USCG), including international bodies like the International Maritime Organization (IMO).
   - **Governance Issues:** There are challenges related to governance, permits, and jurisdictional determinations across domestic, federal, and international law, including adherence to protocols such as the London Dumping Convention.
2. **Risk vs. Reward**:
   There is a need for balancing the precautionary principle and the urgency of environmental action. There is a need for transparent data sharing, proprietary result dissemination, and the importance of surety bonds and mitigation costs.
3. **Inclusion, Equity, and Funding**:
   Issues of inclusion and equity were highlighted, particularly regarding how to fund mCDR initiatives. There is a need for a dependable and verified authority to referee scientific assertions and ensure equitable access and participation.
4. **Monitoring and Verification (MRV)**:
   Reykjavik Protocol Considerations: We should adhere to the best available science, peer-reviewed methodologies, environmental and social assessments, community

engagement, and comprehensive monitoring and mitigation plans. Auditable data and public transparency are important.

5. **Model Legislation**:
The development of model federal legislation is crucial for advancing safe and responsible mCDR research. Key aspects include defining agency authority, forming interagency working groups, establishing research zones, permitting processes, environmental review requirements, financial assurances (such as bonds), permit suspension and cancellation protocols, and fostering international cooperation.

Recommendations and Next Steps

1. **Building Reliable Frameworks**:
Establish a robust framework for mCDR that includes clear guidelines on regulation, permitting, and financial assurance. This should be underpinned by a strong governance structure that integrates various regulatory bodies and international protocols.
2. **Enhancing Public Understanding and Engagement**:
Increase public understanding and engagement in mCDR initiatives. This involves transparent communication about risks, benefits, and the overall impact of mCDR projects on marine ecosystems and climate change mitigation.
3. **Ensuring Equity and Inclusion**:
Develop mechanisms to ensure that mCDR technologies and policies are inclusive and equitable, providing fair opportunities for all stakeholders and communities to take part and benefit.
4. **Advancing Research and Innovation**:
Support ongoing research and innovation in mCDR to refine methodologies, assess environmental impacts, and improve the efficacy of carbon removal technologies. Encourage collaboration among scientists, policymakers, and industry leaders to address emerging challenges and opportunities.
5. **Implementing Rigorous MRV Protocols**:
Adopt rigorous MRV protocols to ensure that mCDR projects are effectively monitored, reported, and verified. This will enhance the credibility and accountability of carbon removal efforts and support long-term environmental sustainability.

Conclusion

The presentation concluded with a call to action for stakeholders to "run a tight ship" in the deployment of mCDR technologies. It emphasized the need for careful planning, comprehensive policy frameworks, and a balanced approach to managing risks and achieving societal benefits through marine carbon dioxide removal initiatives.

MRV Overview

Overview

The presentation by Simon Freeman, ARPA-E Program Director, focused on the state-of-the-art practices and goals for MRV in Marine Carbon Dioxide Removal (mCDR). It discussed the significance of mCDR, the potential methods, the challenges in validation, and the technological advancements needed for effective MRV.

Significance and Challenges of mCDR

1. **Importance of mCDR**:
   Marine CDR is crucial for addressing climate change, with the potential to capture and store significant amounts of CO_2 from the atmosphere. The ocean's ability to draw down carbon is extensive and offers scalable solutions at a relatively low cost compared to terrestrial methods.
2. **Potential Methods**:
   - **Artificial Upwelling**: Enhancing nutrient availability in low-productivity regions to boost CO_2 absorption.
   - **Iron Fertilization**: Adding iron to high-nutrient, low-chlorophyll areas to stimulate phytoplankton growth and subsequent carbon sequestration.
   - **Seaweed Cultivation**: Using seaweed to capture CO_2 and store it in deep ocean layers.
   - **Alkalinity Enhancement**: Increasing Ocean alkalinity to enhance CO_2 absorption.
   - **Electrochemical Processes**: Applying electrochemical techniques to facilitate CO_2 removal from ocean water.
3. **Validation Challenges**:
   There is significant uncertainty in the effectiveness of various mCDR methods due to limited empirical data. Each technique requires rigorous validation to quantify its impact accurately and ensure environmental safety.

MRV Technological Developments

1. **MRV Technology Goals**:
   - **Volumetric Carbon Sensing**: Developing scalable technologies to measure the volume of CO_2 captured.

- **Effective Modeling**: Creating accurate models to estimate the performance of mCDR technologies and validate carbon removal processes.

2. **External Energy Costs**:
   Methods like artificial upwelling and iron fertilization require significantly less energy than Direct Air Capture (DAC).
3. **Marine Carbon Cycle Measurement**:
   Current state-of-the-art sensors and techniques for measuring marine carbon parameters include pH sensors, total dissolved inorganic carbon (DIC) analysis, and fugacity of CO_2 measurements. These are essential for accurate MRV.

Innovations in Sensors and Models

1. **State-of-the-Art Sensors**:
   Presently, sensors for marine carbon measurement rely on direct sampling, optical techniques, and laboratory titrations. Future advancements aim to enhance these technologies for better accuracy, reduced costs, and the ability to measure at full ocean depth.
2. **Modeling Advances**:
   The development of new models for mCDR will shift from current ecosystem and carbon flux models to more sophisticated systems capable of simulating large-scale carbon processes. These models will play a critical role in validating the effectiveness of mCDR and integrating MRV into carbon market mechanisms.
3. **Technical Trade-offs**:
   The presentation highlighted the balance between cost and survey capability in sensor deployment, emphasizing the need for cost-effective, reliable sensing solutions to cover large oceanic areas.

Future Directions

1. **Goals for mCDR Models**:
   Future models aim to provide accurate, large-scale assessments of mCDR interventions, supporting the development of MRV frameworks that can quantify carbon removal and supply data for policy and market validation.
2. **ARPA-E Program**:
   ARPA-E's SEA-CO_2 program is set to advance mCDR technologies, focusing on scalable sensing solutions and effective MRV to enable the marine CO_2 removal industry.

Conclusion

The presentation concluded with a call to stay informed about upcoming developments in the ARPA-E SEA-CO_2 program and emphasized the importance of innovative MRV technologies for enabling and validating large-scale marine carbon dioxide removal efforts.

Existing Roadmaps

The presentation highlighted Ocean Visions' efforts in creating actionable, coordinated strategies for addressing the ocean-climate crisis through structured, adaptable road maps that support innovation and practical solutions in marine CDR.

The presentation by Nikhil Neelakantan outlined the existing roadmap developments by Ocean Visions, a nonprofit organization dedicated to advancing solutions for the ocean-climate crisis. These roadmaps are strategic guides designed to coordinate and catalyze global efforts in marine carbon dioxide removal (CDR). The presentation emphasizes the importance of building capacity, reducing carbon emissions, removing carbon pollution, and repairing marine ecosystems, forming the framework for their strategic agenda.

Ocean Visions' Role and Strategic Agenda

Ocean Visions works at the intersection of science, engineering, innovation, business, and policy, mobilizing diverse disciplines and sectors. Its strategic agenda focuses on:

1. **REACH**: Building global capacity for ocean-climate solutions.
2. **REDUCE**: Developing ocean-based pathways to a low-carbon society.
3. **REMOVE**: Creating ocean-based methods for carbon pollution cleanup.
4. **REPAIR**: Stabilizing critical marine ecosystems to prevent tipping points.

Their approach includes working on well-defined problems, convening multi-disciplinary collaborations, identifying promising solutions, and fostering enabling environments for near-term action.

Developing Road Maps

Ocean Visions employs a comprehensive process for developing road maps:

1. **Preparation**:
   - Conducting literature reviews.
   - Interviewing experts.
   - Drafting initial outlines.
2. **Collective Discussion**:
   - Hosting multiple online workshops.
   - Facilitating discussions to gather feedback and new information.
3. **Compilation**:
   - Assimilating new information from workshops.
   - Conducting expert reviews before publishing.

The road maps serve as living documents that are continuously updated to reflect changing priorities and technological advancements. They aim to provide a snapshot of the current state, outline first-order priorities, and offer a blueprint for coordinated action among researchers, entrepreneurs, and funders.

Macroalgae Research Framework and Federal Legislation

Ocean Visions has convened working groups to enhance understanding and evaluate the effectiveness of macroalgae (seaweed) for long-term carbon sequestration by sinking it into the deep ocean. Additionally, the organization collaborates with the Sabin Center for Climate Change Law to develop model federal legislation to advance safe and responsible ocean-based CDR research in U.S. waters.

Engagement and Impact

Ocean Visions actively participates in international forums, such as the UN Ocean Conference and COP, to ensure that ocean-based climate solutions are adequately considered. Their road maps and strategic guidance are designed to be accessible to non-experts, helping to surface priorities and integrate diverse actions. The organization emphasizes the need for clear audience targeting, ease of use, impact measurement, and ongoing updates to ensure the road maps remain relevant and effective.

Lessons Learned

Key lessons from the road map development process include the importance of presentation and ease of use, the need for impact measurement, and the necessity of establishing a process for regular updates. These insights help ensure the road maps effectively guide and mobilize efforts towards ocean-climate restoration.

OAE Pathways

Overview

The presentation by Mike Kelland of Planetary Technologies outlined the processes and methodologies for Monitoring, Reporting, and Verification (MRV) in the context of ocean-based carbon dioxide removal (CDR). It focused on the generation and use of by-product alkalinity to sequester carbon and balance atmospheric CO_2 levels. The presentation detailed how these processes are measured and modeled to ensure accurate tracking and efficacy of carbon removal efforts.

Core Concepts and Processes

1. **By-Product Alkalinity Characterization**:
   By-product alkalinity is the term for the matter used to start the alkalinity enhancement process. Understanding the chemical properties and dissolution behaviors of the alkalinity used for ocean enhancement is essential for safely dosing it in the ocean.
2. **Safe Dosing in the Ocean**:
   Alkalinity is carefully dosed into the ocean to enhance its ability to absorb atmospheric CO_2. This process requires precise management to avoid adverse effects on marine ecosystems while maximizing the ocean's capacity to sequester carbon.
3. **Carbon Measurement**:
   The effectiveness of the dosing process is measured by monitoring changes in oceanic pH and partial pressure of CO_2 (pCO_2). These changes help assess how well the added alkalinity is dissolving and integrating into the ocean's carbonate system, thereby enabling enhanced CO_2 uptake.

4. **Equilibration and Chemistry Adjustment**:
   The added alkalinity helps adjust the chemistry of the ocean, promoting the dissolution of CO_2 and maintaining a balance between atmospheric and oceanic CO_2 levels. This equilibration process is critical for the long-term sustainability and effectiveness of ocean-based CDR.

Monitoring and Modeling

1. **Large-Scale Observations and Models**:
   Large-scale observational data and models are needed to monitor the impact of alkalinity addition. These tools are crucial for understanding the spatial and temporal dynamics of ocean alkalinity enhancement (OAE) and its effect on CO_2 sequestration.
2. **Methodology References**:
   Organizations like Isometric are developing specific methodologies and protocols for conducting MRV in OAE. These methodologies guide the collection and analysis of data related to pH changes, pCO_2 variations, and other critical parameters that indicate the success of carbon removal activities.

Implementation Challenges

1. **Low vs. High Solubility OAE**:
   The presentation differentiated between low solubility and high solubility OAE techniques, highlighting the unique challenges and considerations for each approach. For example, high solubility OAE may require more sophisticated monitoring due to faster chemical reactions and greater impact on local ocean chemistry.
2. **Ocean CO_2 Removal**:
   Effective ocean CO_2 removal involves integrating various strategies and understanding the complex interactions between added alkalinity and oceanic processes. The presentation underscores the importance of thorough MRV to capture these interactions and validate the carbon removal achieved.

Conclusion

The presentation highlighted the necessity of using standardized protocols to ensure accurate and reliable verification of carbon removal, addressing both the opportunities and challenges associated with ocean alkalinity enhancement.

Electrochemical Pathways

Overview

The presentation by Matthew Eisaman, a professor at Yale University and co-founder of Ebb Carbon, addressed the challenges and strategies for Monitoring, Reporting, and Verification (MRV) in the context of Marine Carbon Dioxide Removal (mCDR) through electrochemical methods. It provided insights into how electrochemistry can be integrated into mCDR processes and discusses the implications for MRV practices to ensure accurate and effective carbon removal monitoring.

Electrochemical Approaches to mCDR

1. **Electrochemical Generation of Alkalinity**:
   The general approach uses electrochemistry to generate alkalinity from brine, which is crucial for ocean alkalinity enhancement (OAE). This process involves bipolar membrane electrodialysis (BPED) to create alkaline seawater, which can then be used to increase the ocean's capacity to absorb CO_2 by shifting the carbonate system.
2. **Ocean Alkalinity Enhancement (OAE)**:
   OAE involves increasing the alkalinity of seawater, which allows the ocean to function as a "sponge" for atmospheric CO_2. This is achieved by extracting acid from seawater and using it beneficially on land, thus reducing the overall acidity of the ocean and promoting CO_2 absorption.
3. **Indirect Ocean Capture (IOC)**:
   IOC, also referred to as direct ocean capture (DOC) or CO_2 stripping, involves the cyclic process of adding acid to seawater to decrease pH and total alkalinity (TA), extracting CO_2, and then using base to restore pH and TA. This process enables the ocean to function as a "pump" to sequester atmospheric CO_2.

MRV Considerations for Electrochemical mCDR

1. **Impact on MRV**:
   Electrochemistry's primary influence on MRV is through the type of alkalinity generated and its dispersal method rather than the electrochemical process itself. Accurate MRV depends on tracking how alkalinity is processed and dispersed, ensuring that the amount of CO_2 removed is consistently reflected in observed data.

2. **Methodologies for MRV**:
   - **Sensor Networks**: Deploy sensor networks to measure key parameters such as pH, TA, and dissolved inorganic carbon (DIC) before and after OAE interventions.
   - **Oceanographic Observations**: Use oceanographic data to inform and constrain models that predict CO_2 removal outcomes.
   - **Comparison Models**: Develop models to compare intervention scenarios against counterfactuals (scenarios without intervention) to determine CO_2 removal efficacy.
   - **Uncertainty Estimation**: Produce probability distributions for carbon removal to quantify uncertainties and validate MRV results.
3. **OAE Pathways and Alkalinity Processing**:
   Different pathways for OAE include processing alkalinity on the seafloor, coastal, and offshore surface oceans using minerals, brine, or solid forms of alkalinity. Each method requires specific MRV strategies to account for the unique environmental and logistical challenges.

Roadmap for Ebb Carbon

1. **Efficacy and Safety**:
   Establish and verify the efficacy and safety of OAE via acid removal through university research and pilot projects. This involves testing the system performance and MRV protocols under real-world conditions to ensure reliable CO_2 removal and ocean de-acidification.
2. **Commercial System Development**:
   Develop and refine Ebb Carbon's commercial system to deliver verified CO_2 removal results, leveraging partnerships with national labs and academic institutions.
3. **Long-Term Goals**:
   Aim to provide a scalable and effective solution for carbon removal and ocean health, integrating advanced electrochemical methods with robust MRV systems to track and confirm the environmental impact.

Conclusion

The presentation highlighted the potential of electrochemistry in enhancing marine carbon dioxide removal and the critical role of MRV in ensuring accurate, reliable, and transparent tracking of CO_2 removal. It underscores the importance of integrating scientific research, technological innovation, and comprehensive monitoring strategies to advance mCDR and support global climate mitigation efforts.

Direct Ocean Capture

The presentation underscored the promise of Direct Ocean Capture (DOC) in addressing global carbon emissions through innovative technological approaches, backed by significant funding and rigorous scientific evaluation. The successful implementation of these projects could play a crucial role in achieving long-term climate goals.

Overview

The presentation by Sophie Chu of Captura explored the innovative approaches to Direct Ocean Capture (DOC) in the context of marine carbon dioxide removal (CDR). It outlines various methodologies for capturing CO_2 from the atmosphere or the upper hydrosphere, aiming for its secure storage in geological formations, biobased systems, ocean reservoirs, or conversion into long-lived products. These strategies are critical for mitigating climate change by reducing atmospheric CO_2 levels.

Funding and Project Initiatives

In October 2020, ARPA-E allocated $3 million to support three pioneering DOC projects under its Innovating Through Unconventional Ideas Program. These projects are:

1. **California Institute of Technology, Pasadena, CA**: Received $850,000 for developing an offshore, stand-alone system for efficient CO_2 removal from ocean water.
2. **University of North Dakota Energy & Environmental Research Center, Grand Forks, ND**: Granted $500,000 for the hydrolytic softening of ocean water to enhance CO_2 removal.
3. **Massachusetts Institute of Technology, Cambridge, MA**: Awarded $650,000 for electrochemically modulated CO_2 removal from ocean waters.

Frontier Carbon Removal Pre-Purchases

The presentation mentioned the DOC-specific pre-purchase initiatives, highlighting three out of 30 projects under a broader carbon removal strategy. These initiatives represent the forefront of research and development in DOC technologies, aiming to create scalable and economically viable solutions for CO_2 sequestration from ocean water.

Simulation and Environmental Impact

A 100,000-ton 3-month simulation off the Southern California coast, using a regional ocean model integrated with biogeochemistry, provided insights into DOC's efficacy and environmental impact. Key findings include:

- DOC can induce CO_2 flux into the ocean or mitigate CO_2 flux out during outgassing periods.
- CO_2 uptake increases as the plume dilutes and spreads, indicating a potential for long-term CO_2 sequestration.
- The plume remains in the surface mixed layer, with elevated pH levels being very localized.

These findings confirm preliminary models and suggest that DOC could effectively enhance oceanic CO_2 uptake over time, with minimal broad-scale environmental impact.

Collaboration and Future Prospects

The project involved collaboration with the Southern California Coastal Water Research Project, ensuring rigorous validation through open-access data platforms and third-party verification. The results provide a foundation for future DOC applications, emphasizing the importance of continued research and interdisciplinary cooperation to optimize these technologies for large-scale deployment.

Biological Pathways

Overview

The presentation by Brad Rochlin of Running Tide, a global ocean health company, discussed their innovative approaches to biological marine carbon dioxide removal (mCDR). It highlighted their commitment to responsibly implementing carbon removal technologies in natural systems, developing supportive carbon policies, and establishing robust verification infrastructure for the carbon market.

Key Concepts and Initiatives

1. **Carbon Cycle and Human Impact**:
   Traditionally, the global carbon cycle maintained a balance, naturally moving carbon between fast cycles (surface ocean, biosphere, atmosphere) and slow cycles (geologic reservoirs, deep ocean). However, human activities have disrupted this balance by transferring copious amounts of carbon from slow to fast cycles, primarily through fossil fuel use.
2. **Carbon Removal as Mass Transfer**:
   To restore balance, there is a need to move significant carbon masses from the fast cycle back to the slow cycle. Running Tide focuses on amplifying natural processes to facilitate this transfer, particularly through their carbon removal field trials.

Carbon Removal Solutions

1. **Field Trials and Deployment**:
   Running Tide is conducting the world's largest durable carbon removal field trials. They process carbon from Canadian wood residue, coat it in alkaline minerals, and deploy it in the ocean south of Iceland, in partnership with a Norwegian shipping company. The deployment is monitored using verification hardware sensors to track carbon removal efficacy.
2. **Technologies and Approaches**:
   - **Macroalgae Carbon Sinking**: Involves using macroalgae to sequester carbon by sinking it to deep ocean layers.
   - **Enhanced Weathering**: Uses minerals to increase ocean alkalinity, promoting CO_2 absorption.
   - **Ocean Alkalinity Enhancement (OAE)**: Adds alkalinity to the ocean to increase its capacity to absorb atmospheric CO_2.
   - **Coastal Restoration and Biomass Carbon Sinking**: Utilizes natural processes like rewilding and coastal water treatment to enhance carbon sequestration.

Monitoring and Measurement

1. **Laboratory Testing**:
   Running Tide conducts extensive laboratory tests to understand the interactions between biological materials and environmental conditions. This data informs their models and helps predict the behavior of carbon removal materials.

2. **In-Situ Measurements**:
   A fleet of ocean sensors collects real-time data on ocean conditions, including the float times, trajectories, and biological growth of deployed materials. This provides a live view of the ocean and helps validate the models.
3. **Environmental and Biogeochemical Models**:
   The company uses advanced models built on the best available science to quantify the impact of their carbon removal techniques. These models help understand the broader environmental effects and provide a foundation for the quantification system.

Environmental Impact and Research

1. **Environmental Exposures Catalogue**:
   Running Tide has published a catalogue that details the potential environmental impacts of their system. This document, independently reviewed by Deloitte, categorizes impacts based on their severity and likelihood, and helps guide research and mitigation efforts.
2. **Research Programs**:
   Deep Sea Research: Includes experiments at various ocean depths (e.g., Fram Strait, Cascadia Basin) to study the long-term impacts of carbon removal materials on the deep ocean. These programs aim to understand the degradation rates of carbon removal materials, the organisms involved, and the resulting environmental impacts.
3. **Cataloging Environmental Impacts**:
   The company prioritizes researching impacts on the benthos, focusing on how quickly carbon removal materials degrade and under what conditions, as well as the effects on marine organisms and carbon incorporation into sediments.

Conclusion

Running Tide's presentation highlighted their strategic approach to biological mCDR through responsible implementation, extensive monitoring, and environmental research. They leverage natural processes to move carbon from fast to slow cycles, supported by robust modeling and verification systems to ensure effective and environmentally sound carbon removal. Their field trials and research efforts are designed to contribute significantly to global carbon sequestration and ocean health restoration.

Reports from the Discussion Groups

The structure for the breakout group discussions is summarized below. For both morning and afternoon breakouts, attendees were divided into four groups:

Group 1: Dissolution Pathways

Group 2: Depletion Pathways

Group 3: Sea-Air Exchange

Group 4: Other Biological Pathways

Each group discussed the same topic areas:

- **Measurement Strategies**
- **Measurement Hardware**
- **Process Studies**
- **Data Assimilation**
- **Modeling and Simulation**
- **Policy**

Within each topic area, three identical questions were posed:

1. **Development state of technologies.**
2. **Development gaps and needs.**
3. **Top technical priorities.**

In the **morning** breakout, the discussion focused on near-term pilot projects and test studies.

In the **afternoon**, the focus was on challenges for scaling up.

Not all questions could be answered by all groups depending on expertise within each group, but group composition changed from morning to afternoon.

All groups combined their notes from both sessions into one output document. Output documents are pasted in the following pages.

Group 1: Dissolution Pathways

Measurement Strategies

- Development State of Technologies:
  - Biological
    - cytometry, drop camera reviews for sedimentation, sedimentary analysis, eDNA
    - Pretesting alkaline materials for toxicity assessment
    - Nutrient Analysis
      - Assays are done pre-addition/post-addition/outfall
  - Efficacy of dissolution
    - Effluent studies (background total suspended solids (TSS)/pH/pCO2)
  - Periodic
    - Sediment analysis, impact to benthic species
- Development Gaps and Needs :
  - Once you have modified the inorganic carbon eqbm, what is the impact to the secondary biological carbon pumps (BCP)- lots we don't know about the BCP
  - Measuring more global impacts over space and time
- Top Technical Priorities
  - For scaling up
    - Better sensors (more energy efficient), To scale and cut costs, are there other applications that might pay for them?, do we do a lot of small distributed sensors?
    - Distributed sensor network that synch with each other
    - Collecting Baseline data
    - Sacrifice accuracy for each individual parameter by measuring multiple parameters

Measurement Hardware

- Development State of Technologies
- Development Gaps and Needs
  - Length scale of these environmental phenomenon (how far are the particles going)
  - Step change in manufacturability (currently very manual since volumes are low)
  - Gaps in measurement
    - DIC- miniaturizing them
    - Alkalinity -miniaturizing them to be small to be on Argo float
    - In situ/real time eDNA
  - Minimizing intervention (built in self test/built in self repair), keeping system robust
  - Universalization vs per project/per area (How much customization do we need?)
  - Standardization
- Top Technical Priorities
  - Distributed sensor network for carbonate chemistry (Robust global baseline monitoring system)
  - Synchronization
  - Continuously check baseline effects as you are adding alkalinity
  - Standardization

Process Studies

- Development State of Technologies

- Development Gaps and Needs

- Top Technical Priorities

Data Assimilation

- Development State of Technologies
    - Data out there is not often appropriate (for different purposes, in different systems and formats)
    - Issues in accuracy and labeling
- Development Gaps and Needs
    - Finding most efficient way to sample data to include in models
    - More efficient way to get data from field and then to include in models
    - Scaling (Data Standardization)
    - Need to figure out what data can be shared vs what is proprietary (an asset)

- Top Technical Priorities
    - Standardization of data verification and making it fit for use
    - Improved Access to data (in several countries, data sets are closed because of it being sensitive)
    - SHared access

Modeling and Simulation

- Development State of Technologies
  - Building a particle distribution model
- Development Gaps and Needs
  - Making distributed measurements and including it in models is challenging
  - Physical models need to be of sufficient scale to match dissolution rates
  - Chemical flux models need work (CO_2 impact)-more sophisticated non-equilibrium effects
  - Biological models also need work (back to impact of dissolution to the biological carbon pump)
  - Should we model non-linear effects?
  - Modeling seasonality (annual and decadal)
  - Scaling
    - Resolution
    - speed up
    - Reduce the computational cost
  - How do you objectively quantify the quality of the model?
  - Competing models vs one universal model
  - Structure

- Top Technical Priorities
  - Modeling simulation development need: how small does it need to be to match dissolution rates

Policy (Permitting, Legislation) e.g. Environmental Impact Assessments

- **Development State of Technologies**
  - Policies not fit for ocean CDR research
  - LC/LP used as guidance but not ratified
- **Development Gaps and Needs**
  - Permits need to evolve (allow research) and change as risks and benefits are known
  - Contextualize with the risks of not doing anything
  - Building out the market
  - Scaling
  - International frameworks should include CDR
  - Standardization of MRV across markets
- **Top Technical Priorities**
  - Make permits clear (like coastal wastewater)
  - Regulation to enumerate the benefits also, not risk mitigation
  - Build out Carrot side of the policy (subsidies, tax credits)

Group 2: Depletion Pathways

Measurement Strategies

- Development State of Technologies

    pCO2 change - must take sample into lab

    change in total alkalinity (TA)

    Change in pH

    Dissolved inorganic carbon (ion chromatography)

    Satellite for surface current
- Development Gaps and Needs

    In situ capability

    Dissolved inorganic carbon

    Current and turbulence data at depth - inertial?
- Top Technical Priorities
    - Having correlatable data

Measurement Hardware

- Development State of Technologies

    pH - colorimetric technique

    Sequential time stamp - on an AUV, float
- Development Gaps and Needs

    Comms, rechargeable

    Ecological sensor, acoustic, visual
- Top Technical Priorities
    - Cheap
    - Longer lifetime
    - Pressure resilient sensors
    - Accuracy
    - Communications -

Process Studies

- Development State of Technologies

- Development Gaps and Needs
  - How much actually do we need to measure depletion at depth? Only surface matters - air-sea exchange happens, measuring depleted water at depth means you lost it.

- Top Technical Priorities
  - Understanding what a process study is
  - How to scale up
  - Ecosystem effects

Data Assimilation

- Development State of Technologies

  Available on drop box but not meant to be shared

  IEEE Data Port
- Development Gaps and Needs

  Consistent meta data

  Not designed for general public

  Minimum amount of data needed to be transmitted? - compression
- Top Technical Priorities

Modeling and Simulation

- Development State of Technologies

    Inputs: Bathymetry, wind, weather, satellite data

- Development Gaps and Needs

    Inputs for current at depth - acoustics?

- Top Technical Priorities
    - High resolution (sub m) real time simulation
    - Digital twin of CDR event

Policy (Permitting, Legislation) e.g. Environmental Impact Assessments

- Development State of Technologies

    Navy

- Development Gaps and Needs

- Top Technical Priorities
    - Identify model key outputs for decision makers
    - Near shore projects are easier to do but harder to permit
    - International standard?

Group 3: Sea-Air Exchange

Measurement Strategies

- Development State of Technologies
  - Measuring flux at interface or upper 10s of meters vs stock over water column
  - Directly through pCO_2 flux measurements or indirectly through calculation using other carbonate parameters
  - Wind speed estimations
  - Highest accuracy
- Development Gaps and Needs
  - Measuring carbonate parameters in situ subsurface
  - Need broad swath measurements, maybe not as high accuracy
- Top Technical Priorities

Measurement Hardware

- Development State of Technologies
  - MAPCO2/ASVCO2 air-sea pCO_2 measurements, year long deployments, +/- 2 ppm
  - ISFET pH and TA
- Development Gaps and Needs
  - pCO_2 acoustics
  - Satellite
  - Stable reference
  - Biofouling
  - Takes long time to develop ~10 years from prototype to commercialization, sense of urgency
- Top Technical Priorities
  - Scalable, affordable, in situ, reagent-free, calibration-free, low maintenance sensors
  - Calibration/maintenance, batch calibration, calibration through design
  - Take equipment/learnings from other industries (semiconductor)

Process Studies

- Development State of Technologies
  - Overconstrained laboratory and field studies

- Development Gaps and Needs
  - Not complete understanding of community ecosystem effects and feedback
  - Unknown feedback loops
  - How representative is small scale study to large scale
  - For models and QC, scaling from small to large
  - How does efficiency scale? How to account for that?
  - Select few experts running small scale experiments, how will that work with large scale, knowledge transfer
- Top Technical Priorities

Data Assimilation

- Development State of Technologies
  - ARGO has data repository with standards that can help with data assimilation
  -
- Development Gaps and Needs
  - Data standards
  - Metadata format
  - Community consensus on vocabulary (acronyms, etc.)
  - Managing massive datasets
  - **Quality control**
  - Deal with different observational platforms across time and space
- Top Technical Priorities
  - Centralize data standards, metadata, and data management, user-friendly
  - Quality control, automated at least first level
  - Bridging communities that have already experienced in tackling these challenges (apply to all sections)

Modeling and Simulation

- Development State of Technologies
  - ROMS (based in Fortran)
- Development Gaps and Needs
  - Models are computationally intensive, need to move towards cloud based computing
  - Making models and data more accessible and user friendly (easier to set up for different regions)
  - Process design kit
  - Quantifying uncertainty of the model in the removed CO_2
- Top Technical Priorities

Policy/Standards (Permitting, Legislation) e.g. Environmental Impact Assessments

- Development State of Technologies
  - Currently operating under existing water processing (wastewater/desalination) permitting limitations
  - Essential ocean variables (highest quality, climate quality)
  - National Institute of Standards and Technology calibration measurements
  - IEEE standardizes the way methods are used in industry
- Development Gaps and Needs
  - Track marine animals to track response to chemical exposure
  - Standards designed specifically for CDR
  - What measurements count as removal, international maritime organization helpful guidance from emissions perspective
  - Standards around measurements, voluntary market => compliance market, SEC
  - Develop policy with NOAA, ocean experts
  - How to cover all different types of CDR/MRV
  - Standardizing scale (what is small vs large, depends on process)
  - International concerns, fisheries, can't control where water goes
  - Community engagement - getting people to believe in climate change took a long time, some still don't, go ahead without them, engage more social scientists to do the community engagement not on the CDR company
  - Who is our customer? Who do we want our customers to be? We don't want companies to buy carbon credits to justify
  - Checklist for verifying carbon
  - Environmental impacts are different at different scales (wind turbines)
  - Leverage oil/gas industries to move CDR
- Top Technical Priorities
  - Establish standards (decide who sets the standards)
  -

Group 4: Other Biological Pathways

Measurement Strategies

- Development State of Technologies
  - Sediment traps and radio isotopes – spatial limitations
    - WHOI in the process of developing a new sediment trap – similar to ARGO floats, can be deployed up to 6 months
      - Pre-programmed when deployed
      - Potential application for iron fertilization
- Development Gaps and Needs
  - Macroalgae – growth rate modeling that is fit for purpose
  - Full ecosystem measurements – comprehensive (and tolerable) ecosystem impacts, phytoplankton, microbial communities, lignin degradation
    - Tool selection for the deposition is less important than scaled environmental measurements
  - Better determination of the end state of organic biomass
  - Do we need real time data monitoring or monitoring over time
  - Development of baselines – not enough to rely on research institutes, need to establish these on a site-by-site basis
- Top Technical Priorities
  - Counteracting seaweed production with phytoplankton approaches – sargassum approaches

Measurement Hardware

- Development State of Technologies
  - Can we look at the deep seabed mining ecosystem and technology as an opportunity for knowledge sharing
  - Instrumentation depends on the deployment system
  - Do we understand the mechanics enough in the upper layers that we don't need to focus on the bottom?
    - A push to develop new instruments that can measure fluxes
- Development Gaps and Needs
  - **Start with the observations, then get to modeling – most deep ocean models are not good enough yet**
  - Camera systems in the deep ocean
  - Density of material sinking
  - **Massive cost-per-instrument – what is "good enough" for initial layers of instrumentation**
    - Typically today – does the harm exceed the benefit gained?
    - **eDNA sampling as an example – the ability to do this fairly easily and at scale today**
  - Deep ocean oxygen systems
- Top Technical Priorities
  - New sensors to measure pCO_2 and the longevity of CO_2 sensora

Process Studies

- Development State of Technologies

- Development Gaps and Needs
  - Site selection as a potential issue – low oxygen areas vs high oxygen areas, degradation rates

- Top Technical Priorities

Data Assimilation

- Development State of Technologies
- Development Gaps and Needs
  - We collect the data – then what do we do with it. Data is being collected everywhere how it gets used and what does it connect to is the challenge.
    - US government global ocean database
    - Decade of ocean action - going away from "open data" to "deposited data" that is usable and actionable
    - CarbonPlan CDRxiv example
  - **Using sites that have an established baseline given the climate volatility we are seeing (compared to historical averages)**
- Top Technical Priorities
  - How this data will be collected and distributed
  - **Clear and comment set of parameters to ensure consistency of data**
    - Geotrace example – inter-calibration of measurements across data sets ("standard" seawater)

Modeling and Simulation

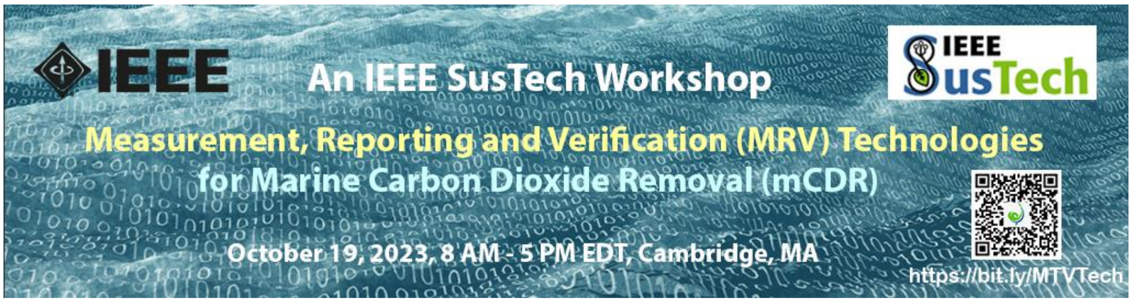
- Development State of Technologies
- Development Gaps and Needs
    - Many technologies/pilots start locally – need to establish time series at local sites
        - Classic way to do this is sensored and instrumented moorings (ex: Bedford Basin)
            - pCO2, alkalinity, all the major carbon parameters, salinity, temp, eDNA, biological metrics
            - Can this be a model for baselining that can be brought to other areas?
            - To add – turbulence and CO2 flux, inside and outside of the project release. Also non-CO2 gases
        - Massive data set, but localized and can be effectively characterized
        - Likely needs to be seasonal (with seasonal productivity) to inform when and where to deploy projects
    - Circulation models
- Top Technical Priorities

Policy (Permitting, Legislation) e.g. Environmental Impact Assessments

- Development State of Technologies
    - There are very few established pathways for biological mCDR research, includling London Convention/London Protocol
- Development Gaps and Needs
    - Offshore wind example – better characterizations of benefits and cost
    - Requirement for baselining
    - Enhanced global ocean observation system – EIAs are typically highly localized, but baselines for open ocean will be distributed
        - Seasonal baselines, not continuous measurement – "good enough" to start
    - NSF, other funders can dictate require measurement parameters
    - "Attribution science" that can determine climate variability
    - US government – 30 agencies claim to have authority over the oceans, ~6 tend to show up (EPA does not)

Appendix A: Invitation

Measurement, Reporting and Verification (MRV) Technologies for Marine Carbon Dioxide Removal (mCDR)



In-person workshop in collaboration with the Ocean Climate Solutions Summit and the IEEE Oceanic Engineering Society. Thursday, October 19, Hyatt Regency Boston-Cambridge, Cambridge MA.

Moderators

Maike Luiken, PhD, SMIEEE, IEEE-HKN, FEIC, chairs Planet Positive 2030 – an initiative of the IEEE Standards Association – as well as the P7800 Standards Working Group: Recommended Practice for Addressing Sustainability, Environmental Stewardship and Climate Change Challenges in Professional Practice. She served as the IEEE VP, Member & Geographic Activities, 2021, as President of IEEE Canada during 2018-19 and, 2018, as Chair, Policy Track, IEEE Internet Initiative. Maike is and has been for more than 15 years a staunch supporter of sustainable development. She is a managing director, R&D, at a start-up company and Adjunct Research Professor, Western University, Canada. Previously, in Sarnia, Canada, she led the Bluewater Sustainability Initiative, 2006 – 2013.

Professor Wei-Jen Lee received the B.S. and M.S. degrees from National Taiwan University, Taipei, Taiwan., and the Ph.D. degree from the University of Texas, Arlington, in 1978, 1980, and 1985, respectively, all in Electrical Engineering.

In 1986, he joined the University of Texas at Arlington, where he is currently a professor of the Electrical Engineering Department and the director of the Energy Systems Research Center. He has been involved in the revision of IEEE

Std. 141, 339, 551, 739, and 1584, and the development of 1584.1, 1584.2, 3002.8, and 3002.9. He is the past President of the IEEE Industry Application Society (IAS), the chair of IEEE TAB (Technical Activity Board) Climate Change Program, co-chair of IEEE Sustainable Development Ad Hoc Committee, member of IEEE Ad Hoc Committee to Coordinate IEEE's Response to Climate Change (CCIRCC), member of IEEE TAB Hall of Honor Committee, member of Pillar 4 of the Global Power Systems Transformation (G-PST), chair of IEEE Smart Grid program, chair of IEEE Smart Cities Education Committee, member of IEEE Smart Grid Operation and Education Committees, and member of United Nations (UN) Council of Engineers for the Energy Transition (CEET).

Christopher Whitt (M.Eng., PE, SMIEEE) – Irving Shipbuilding, Halifax, Nova Scotia, Canada, and President, IEEE Oceanic Engineering Society

Keynote Speakers

These distinguished participants will present overviews on the following topics:

- **Christopher Whitt** of Irving Shipbuilding: Welcome and Objectives of the Workshop
- **Craig Mclean** of Woods Hole Oceanographic Institution: on Policy and Social Implications of Carbon Removal
- **Nikhil Neelakantan** of Ocean Visions: on Existing Technology Roadmaps
- **Mike Kelland** of Planetary Technologies: on Ocean Alkalinity Enhancement Pathways
- **Matthew Eisaman** of Yale University and Ebb Carbon: on Electrochemical Pathways
- **Sophie Chu** of Captura on Direct Ocean Capture Technologies
- **Brad Rochlin** of Running Tide on Nature-Based Capture Pathways
- **Simon Freeman** of ARPA-E on an Overview of MRV Technologies

Abstract

Oceans have a critical role to play in mitigating anthropogenic climate change. Not only are they the site of active biological carbon cycles, but they offer a vast surface area as an alternative to land for capturing and removing dispersed carbon from the atmosphere, and ultimately, for restoring sustainability in Earth's ecosystems. However, working in oceanic environments is extremely challenging, and this industry is immature. Robust, cost-effective technologies for scaling and monitoring ocean-based facilities, for quantifying intended and unintended environmental impacts,

for measuring the efficacy and permanence of the sequestration of carbon, and for modelling and predicting climate-relevant effects, are needed.

In this workshop, we aim to bring together oceanographers, environmentalists, technologists, and data scientists to share knowledge, and:

1. Receive a comprehensive overview of the role of ocean-based solutions for the climate crisis.
2. Explore the status of various mCDR technology pathways with respect to measurement, reporting and verification (MRV) feasibility.
3. Describe existing gaps between current MRV technologies, progress needed, and innovative ideas to implement mCDR reliably and at scale.

The outcome of this workshop will be summarized in a report on new IEEE Sustainability Technologies Roadmaps. A virtual workshop will be scheduled shortly thereafter to invite broader participation and build on the momentum of ideas generated. Working groups will be formed to carry-on the technology roadmapping mission of the IEEE SusTech Initiative.

To prepare for this workshop, we recommend becoming familiar with the Ocean Vision's mCDR Roadmap

Workshop Information

The meeting will be held at the Hyatt Regency Boston-Cambridge , 575 Memorial Drive, Cambridge, Massachusetts, USA. Room reservations: +1 617-492-1234.

Your free workshop registration includes breakfast, AM and PM coffee breaks, and lunch catered in the meeting room. Discounted $15 self-parking is also available upon request.

Meeting time is 8 AM to 5 PM EDT in Charles View Meeting Room (16th Floor), with the breakfast buffet starting at 7:30 AM.

Appendix B: Attendee Information

Dear Colleague,

Thank you for registering for the upcoming IEEE Future Directions SusTech Initiative's in-person workshop on **Measurement, Reporting and Verification (MRV) Technologies for Marine Carbon Dioxide Removal (mCDR).**

We are looking forward to a ground-breaking event and are proud to announce that it has been endorsed by the United Nations' Decade of Ocean Science for Sustainable Development as a Decade Activity!

Please review the information below:

Workshop Location

Hyatt Regency Boston-Cambridge, 575 Memorial Drive, Cambridge, Massachusetts
Charles View Meeting Room (16th Floor)
Breakfast served at 7:30 AM
Self-parking discount voucher ($15) available upon request in the meeting room

Workshop Preparation

1. Please review and become familiar with Ocean Vision's **mCDR Roadmap**
2. Log into and bookmark our shared workshop Google folder. The folder will be filled with technical documents such as presentations, the agenda, and brainstorming

templates. You should have received an email notification from Google when you were added to the folder. Access issues? Email organizer.

Workshop Agenda

7:30 AM – Breakfast buffet
8:00 AM – Welcome and workshop overview – C. Whitt
8:15 AM – Keynote presentations – C. Mclean, S. Freeman, N. Neelakantan, M. Kelland, M. Eisaman, S. Chu, B. Rochlin
10:00 AM – Attendee introductions
10:15 AM – Coffee break
10:30 AM – Breakout sessions
Noon – Lunch buffet
1:00 PM – Breakout sessions
3:00 PM – Coffee break
3:20 PM – Group presentations
5:00 PM - Adjourn.

Please consult our Event Page for further details.

We look forward to seeing you in Cambridge!

In case your plans have changed, and you are no longer able to attend, kindly drop us a note.
Event held in collaboration with the ***Ocean Climate Solutions Summit*** *and* ***the IEEE Oceanic Engineering Society***

Endorsed by:

2021 2030 United Nations Decade of Ocean Science for Sustainable Development

Appendix C: Article on mCDR in IEEE Climate Change website

https://climate-change.ieee.org/news/ocean-engineering/

Ocean engineering extends to understanding the capture and storage of carbon dioxide from the atmosphere and sequestering it underground. Ocean acidification, stemming from increased carbon dioxide absorption by the oceans, is a pressing issue. Ocean engineers are contributing to strategies for monitoring and mitigating its effects [6].

"Three major technology pathways hold promise in the field of carbon sequestration: biological, alkalinity enhancement, and electrochemical carbon dioxide removal (CDR)," says Whitt. "Alkalinity enhancement focuses on using low- or no-carbon energy and chemical inputs to increase the ocean's alkalinity, thus reducing carbon dioxide levels. Electrochemical methods use chemistry laboratory equipment to extract acidic fluids from seawater, thereby reducing dissolved carbon dioxide."

Of these, electrochemical technology appears to be the most technically mature. The chemical pathway involves processing byproducts or residues, such as waste from mining operations, near a body of water, effectively neutralizing emissions. The dynamic nature of water bodies makes measurement complex, given that chemical processes can span weeks or even months. Demonstrations of both technologies are currently underway.

The biological pathway entails the cultivation of more seaweed or similar and then sinking it into the deep ocean to prevent it from re-entering the biological carbon cycle; essentially, enhancing the natural seaweed growth process. For example, a fully automated facility can be situated in the ocean, hundreds of kilometers offshore, cultivating a vast quantity of organic material with the goal of harvesting it and sinking it to depths ranging from 1,000 to 4,000 meters below the surface, while ensuring these materials remain intact and resistant to decomposition or drifting away [7].

"The IEEE Ocean Engineering Society is unique among IEEE Societies in that its fields of interest cover a physical domain rather than a technology one," says Whitt. As a result, the Society includes interests in robotics, signal processing, and communications and power and energy. "Our work encompasses a wide spectrum of IEEE technologies, integrating sensors in marine environments, satellite and remote sensing capabilities, robotics and automation, as well as the deployment of gliders and vessels to capture measurements. We then employ large-scale modeling techniques empowered by machine learning and artificial intelligence (AI) to estimate parameters across extensive geographical areas. Carbon dioxide removal (CDR) technologies present an exceptional opportunity for IEEE members to use their expertise and contribute meaningfully to our shared mission," he says.

Share this article:

[6] G. K V, N. K. M and M. V. Ramesh, "IoT based Ocean Acidification monitoring system with ML based Edge Analytics," 2022 4th International Conference on Inventive Research in Computing Applications (ICIRCA), Coimbatore, India, 2022, pp. 345-353, doi: 10.1109/ICIRCA54612.2022.9985728.

[7] K. Ouchi, M. Kurahashi, M. Shibuya, S. Tabeteta and K. Iseki, "The real sea experiment of seaweed growing with DOW," 2016 Techno-Ocean (Techno-Ocean), Kobe, Japan, 2016, pp. 235-238, doi: 10.1109 look/Techno-Ocean.2016.7890652.

[8] J. King, D. Pascual, M. P. Clarizia and P. de Maagt, "Can GNSS-Reflectometry Support Global Monitoring of Floating Matter in the Ocean?" 2021 IEEE International Geoscience and Remote Sensing Symposium IGARSS, Brussels, Belgium, 2021, pp. 7520-7521, doi: 10.1109/IGARSS47720.2021.9553736.

END OF REPORT