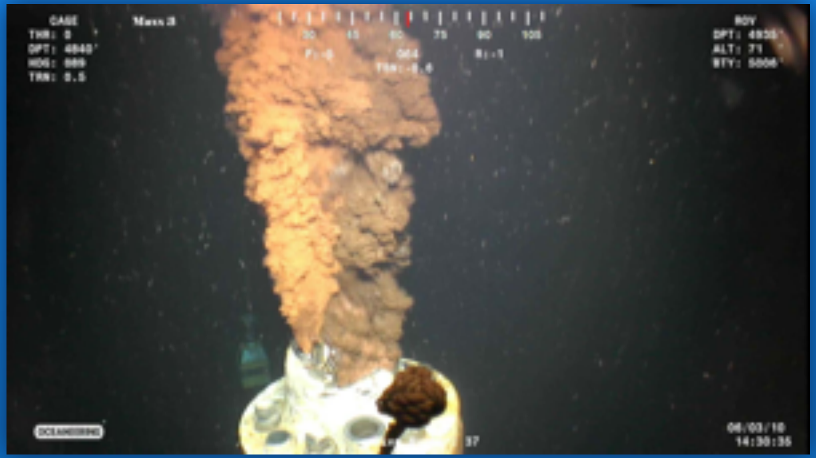
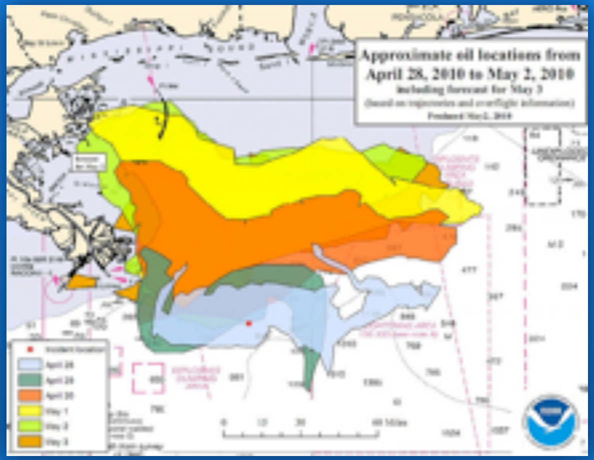
ATOEM:
Autonomous Transient Ocean Event Monitoring

Kevin M. Ulmer - Ph.D.
Seaquester.org
Woods Hole Oceanographic Institution

Deepwater Horizon





All at sea

US agencies have moved too slowly in gathering key data on the oil spill in the Gulf of Mexico.

When disaster strikes, the priority for governments and individuals alike is to limit the damage and help the people affected. But also critical is the rapid, coordinated collection of data to document the disaster. Getting a full picture of exactly what happened can be a huge help in planning recovery efforts, minimizing losses in future disasters and, if need be, in holding guilty parties accountable.

NATURE Vol 465 27 May 2010

Fukushima

Woods Hole Oceanographic Institution PRESENTS

フクシマと海

Fukushima
AND THE OCEAN

Thursday, May 9, 2013 • 6:30 – 9:30 p.m.

Woods Hole Oceanographic Institution
Redfield Auditorium, 45 Water St., Woods Hole, MA

PRESENTATIONS 6:30 - 8:00

The Fukushima Disaster: An Overview
Mitsuo Uematsu, University of Tokyo

Radioisotopes in the Ocean
Ken Buesseler, Woods Hole Oceanographic Institution

Radioisotopes in Marine Life
Jota Kanda, Tokyo University of Marine Science and Technology

Seafood Safety and Public Policy
Hiroyuki Matsuda, Yokohama National University

Impacts of Radioactivity on Human Health
James Seward, Lawrence Livermore National Laboratory

The Role of the Media in Disasters
Dennis Normile, Science magazine

Tsunamis and Nuclear Power in the U.S.
Jian Lin, Woods Hole Oceanographic Institution

PANEL DISCUSSION 8:00 - 9:30
Moderated by Heather Goldstone, host of *Living Lab*, WCAI, Cape & Islands NPR

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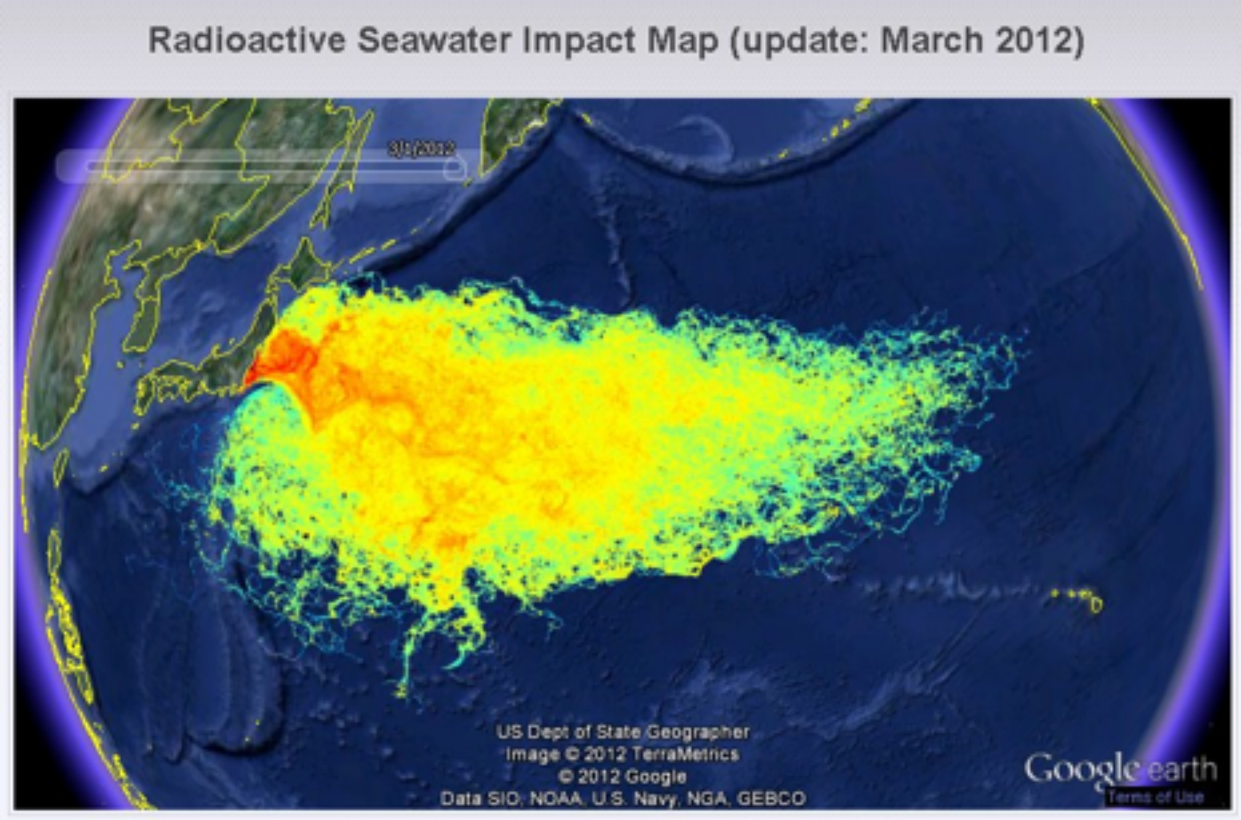
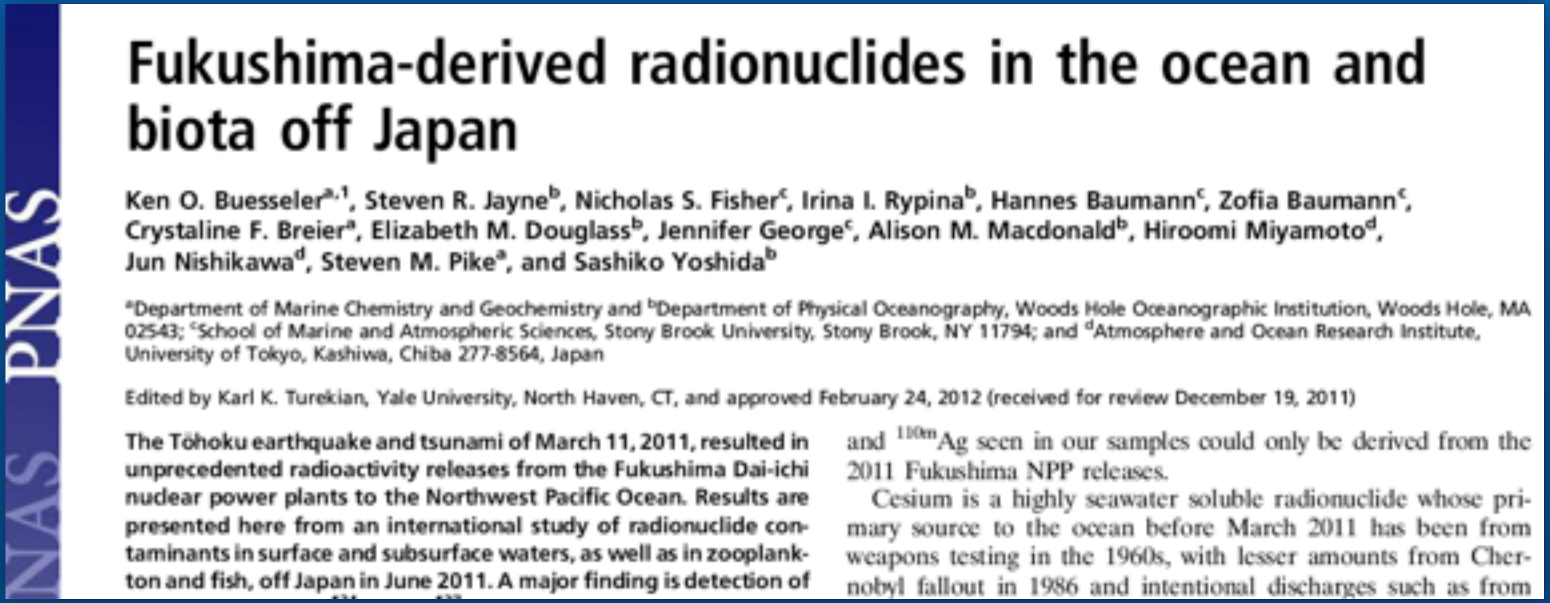
Center for Marine & Environmental Radioactivity

OPEN TO THE PUBLIC
For directions, parking, and more information, call 508.289.2252 or visit:
www.whoi.edu/fukushima



Radioactive Seawater Impact Map (update: March 2012)



Fukushima-derived radionuclides in the ocean and biota off Japan

Ken O. Buesseler[a,1], Steven R. Jayne[b], Nicholas S. Fisher[c], Irina I. Rypina[b], Hannes Baumann[c], Zofia Baumann[c], Crystaline F. Breier[a], Elizabeth M. Douglass[b], Jennifer George[c], Alison M. Macdonald[b], Hiroomi Miyamoto[d], Jun Nishikawa[d], Steven M. Pike[a], and Sashiko Yoshida[b]

[a]Department of Marine Chemistry and Geochemistry and [b]Department of Physical Oceanography, Woods Hole Oceanographic Institution, Woods Hole, MA 02543; [c]School of Marine and Atmospheric Sciences, Stony Brook University, Stony Brook, NY 11794; and [d]Atmosphere and Ocean Research Institute, University of Tokyo, Kashiwa, Chiba 277-8564, Japan

Edited by Karl K. Turekian, Yale University, North Haven, CT, and approved February 24, 2012 (received for review December 19, 2011)

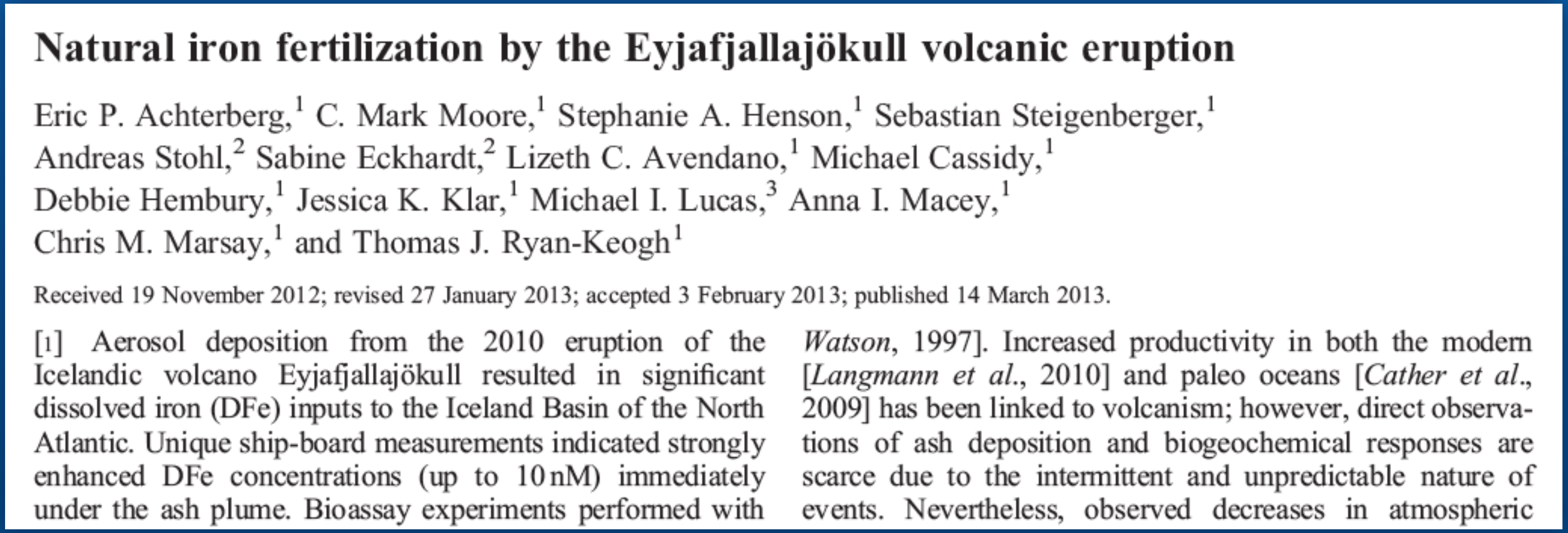
The Tōhoku earthquake and tsunami of March 11, 2011, resulted in unprecedented radioactivity releases from the Fukushima Dai-ichi nuclear power plants to the Northwest Pacific Ocean. Results are presented here from an international study of radionuclide contaminants in surface and subsurface waters, as well as in zooplankton and fish, off Japan in June 2011. A major finding is detection of

and ^{110m}Ag seen in our samples could only be derived from the 2011 Fukushima NPP releases.

Cesium is a highly seawater soluble radionuclide whose primary source to the ocean before March 2011 has been from weapons testing in the 1960s, with lesser amounts from Chernobyl fallout in 1986 and intentional discharges such as from

5984–5988 PNAS April 17, 2012 vol. 109 no. 16

Eyjafjallajökull



Natural iron fertilization by the Eyjafjallajökull volcanic eruption

Eric P. Achterberg,[1] C. Mark Moore,[1] Stephanie A. Henson,[1] Sebastian Steigenberger,[1]
Andreas Stohl,[2] Sabine Eckhardt,[2] Lizeth C. Avendano,[1] Michael Cassidy,[1]
Debbie Hembury,[1] Jessica K. Klar,[1] Michael I. Lucas,[3] Anna I. Macey,[1]
Chris M. Marsay,[1] and Thomas J. Ryan-Keogh[1]

Received 19 November 2012; revised 27 January 2013; accepted 3 February 2013; published 14 March 2013.

[1] Aerosol deposition from the 2010 eruption of the Icelandic volcano Eyjafjallajökull resulted in significant dissolved iron (DFe) inputs to the Iceland Basin of the North Atlantic. Unique ship-board measurements indicated strongly enhanced DFe concentrations (up to 10 nM) immediately under the ash plume. Bioassay experiments performed with

Watson, 1997]. Increased productivity in both the modern [*Langmann et al.*, 2010] and paleo oceans [*Cather et al.*, 2009] has been linked to volcanism; however, direct observations of ash deposition and biogeochemical responses are scarce due to the intermittent and unpredictable nature of events. Nevertheless, observed decreases in atmospheric

GEOPHYSICAL RESEARCH LETTERS, VOL. 40, 921–926, 2013

Transient Ocean Event Monitoring

- Rapid deployment
- Large and changing areal extent
- Surface to sea floor
- Long-term observation
- Full complement of sensors and samplers
- Real time data reporting
- Low cost

Distributed Sensors

Argo

Welcome to the Argo home page

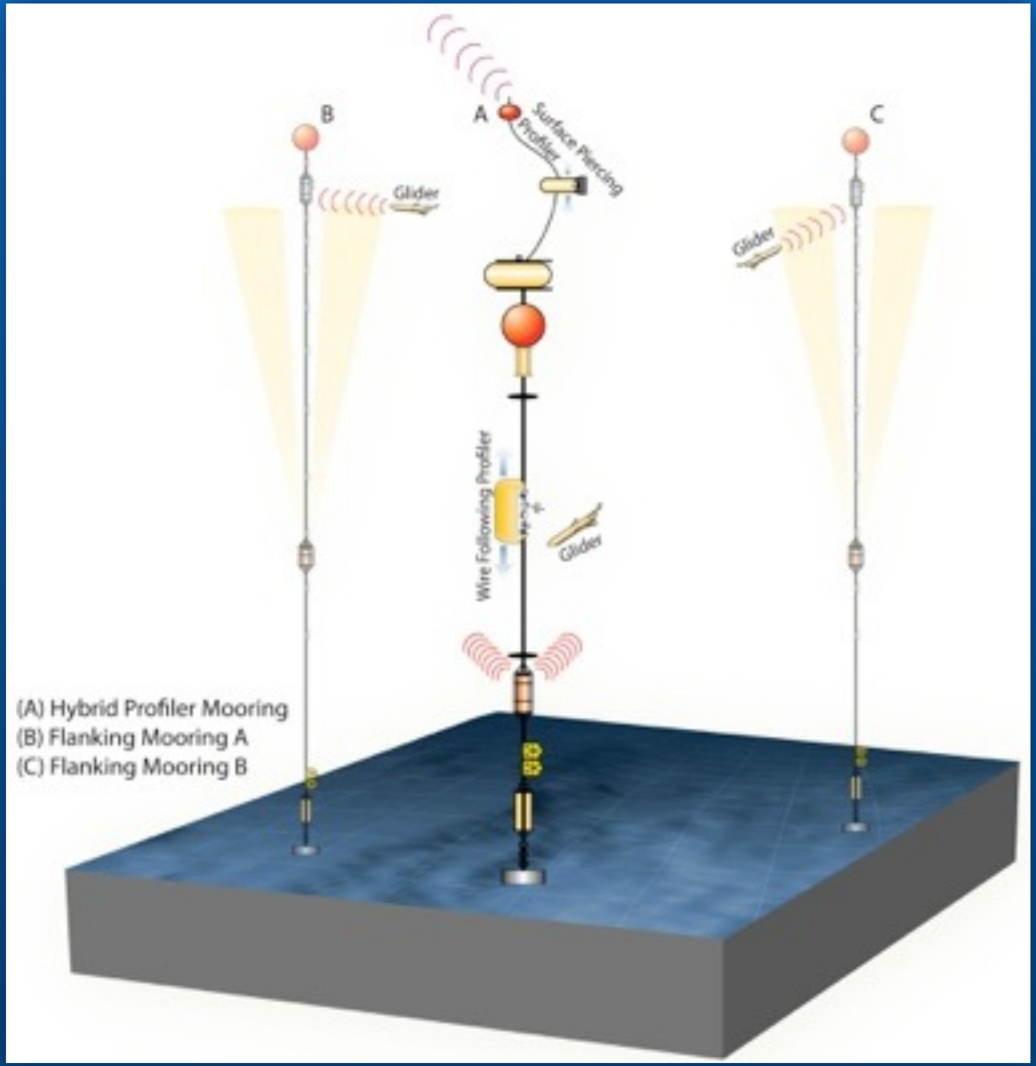
part of the integrated global observation strategy

- $30,000 each!
- STD (Salinity, Temperature & Depth) only

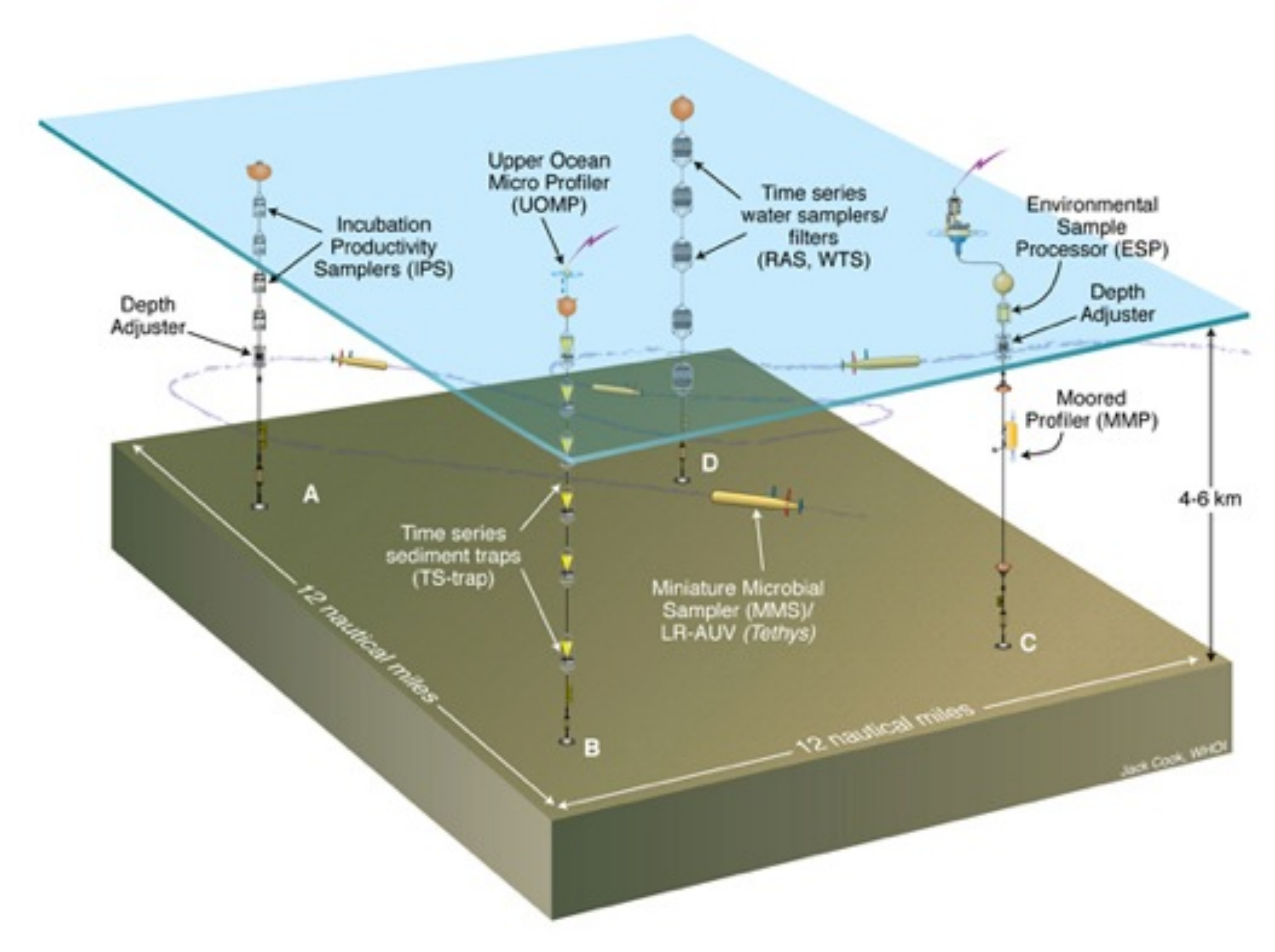
Ocean Observatories

OOI
OCEAN OBSERVATORIES INITIATIVE

Global Biogeochemical Flux Observatory Initiative



Station PAPA - Global Node

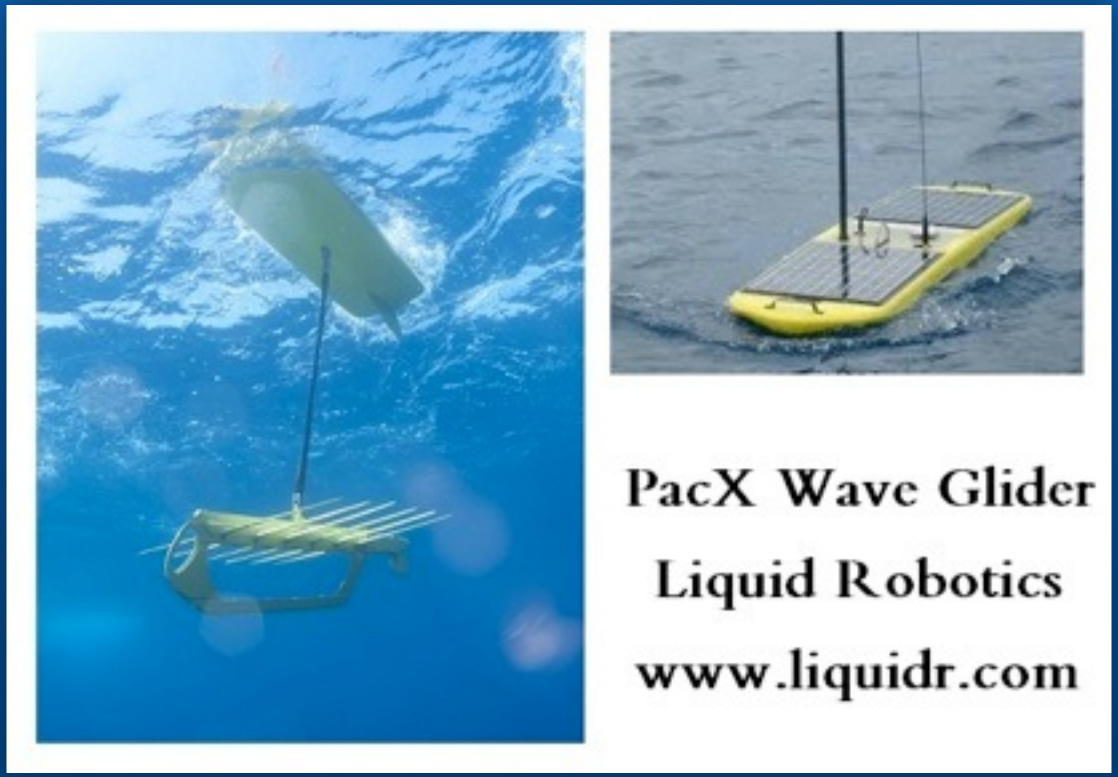


AUV Range & Endurance

Rutgers “Scarlet Knight” crosses Atlantic 2009

MBARI *Tethys*

Pacific crossing 2012



A Changing Research Fleet

NEWSFOCUS

A Sea Change for U.S. Oceanography

Marine scientists are confronting declining budgets and a shrinking research fleet as torrents of data from new technologies remake their field

SINCE 1996, OCEANOGRAPHER KIPP Shearman has relied on a duo known around the lab as Bob and Jane to measure chlorophyll and other environmental parameters in the ocean off the Oregon coast. Roaming the sea for 3 to 5 weeks at a time, the pair never complains and comes up for air just every 6 hours. They're 2-meter-long automated submersibles called gliders, and the reams of data they've collected have allowed Shearman's team at Oregon State University, Corvallis, to make novel insights into changing marine ecosystems.

The gliders are cheaper than sending scientists out in ships to make measurements, Shearman says, and they can remain at sea nearly indefinitely. He named the machines after some senior colleagues, and, "We kid them that we're replacing them with robots."

There's a glimmer of truth to that notion. Two cultural shifts are simultaneously shaking the foundations of oceanography in the United States—and fueling a debate about the future direction of a fast-changing field. Fewer scientists are going to sea as a result of a shrinking science fleet, flat budgets, and skyrocketing costs. At the same time, oceanographers are using a growing array of high-tech devices—such as satellites, gliders, and vast networks of sensors tethered to the sea floor—to remotely collect more data than ever before without getting wet.

The trends are helping to transform oceanography "from small science to big science," says technologist James Bellingham of Monterey Bay Aquarium Research Institute (MBARI) in Moss Landing, California. That shift, in turn, is affecting how researchers study an increasingly urgent set of problems, including overfishing, ocean warming, and acidifying seas. It is also altering the culture of oceanography, including how scientists share data and how young oceanographers are trained.

The churning is prompting contradictory emotions, however. The decline of the U.S. science fleet is "a catastrophe that's happening in slow motion," warns Bruce Appelgate, who heads ship and marine operations at the Scripps Institution of Oceanography in San Diego, California. But "we've entered a new era in oceanography, and it's for the best," declares oceanographer Sydney Levitus of the U.S. National Oceanic and Atmospheric Administration (NOAA) in Silver Spring, Maryland.

Online
sciencemag.org
Podcast interview with author Eli Kintisch (http://scim.ag/pod_6124).

A waning fleet

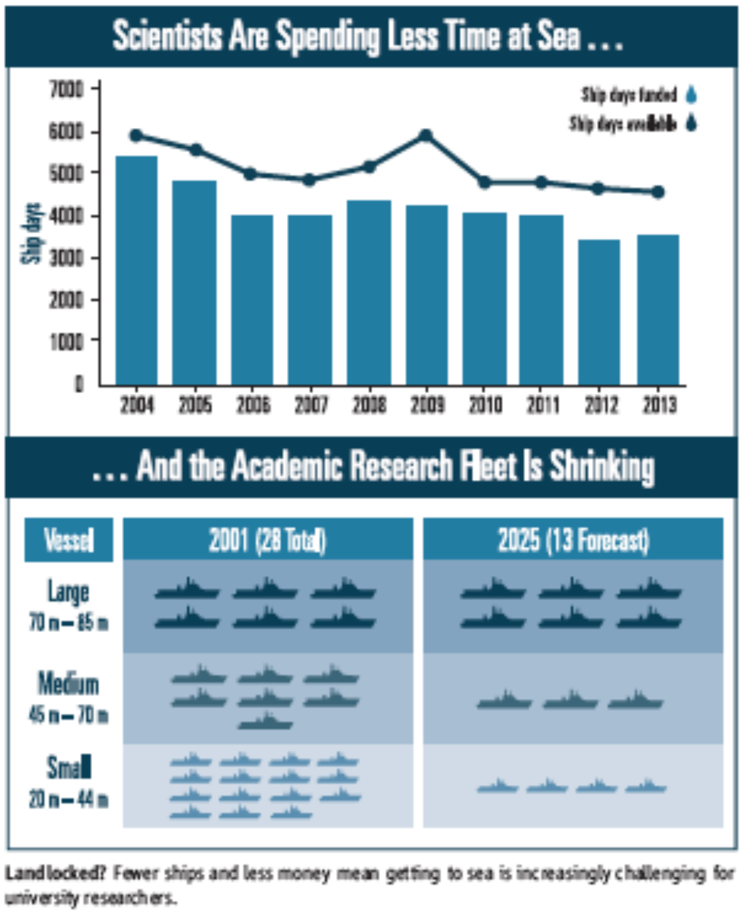
A symbol of the changes remaking marine science floats alongside the dock at the Woods Hole Oceanographic Institution (WHOI) in Massachusetts. In its glory days, the research vessel *Atlantis* boasted adventures that kept it at sea for 10 months a year. Last year, it was out of port for only 8 months. Idle, the 84-meter-long vessel has the vacant feel of an abandoned steel office building, albeit a floating one. Labs and workshops sit empty; just a few crew members and students were busy during a recent visit. "We've had our thumb out looking for work," says Captain A. D. Colburn. He was "grateful" that Canadian scientists hired the ship for a monthlong mapping mission this past summer. But fewer U.S. researchers are using *Atlantis* as a result of funding issues and because its equipment is undergoing recertification tests to deploy its celebrated partner craft, the piloted submersible *Alvin*. So Colburn is confronting "a lot of face time with my computer," he says glumly, echoing a common refrain these days among oceanographers.

The dormancy is a product of decades-long policy shifts. During the Cold War, the U.S. Navy was the main benefactor of the nation's marine scientists, whose studies on ocean mixing and sound scattering served

$50,000 per diem

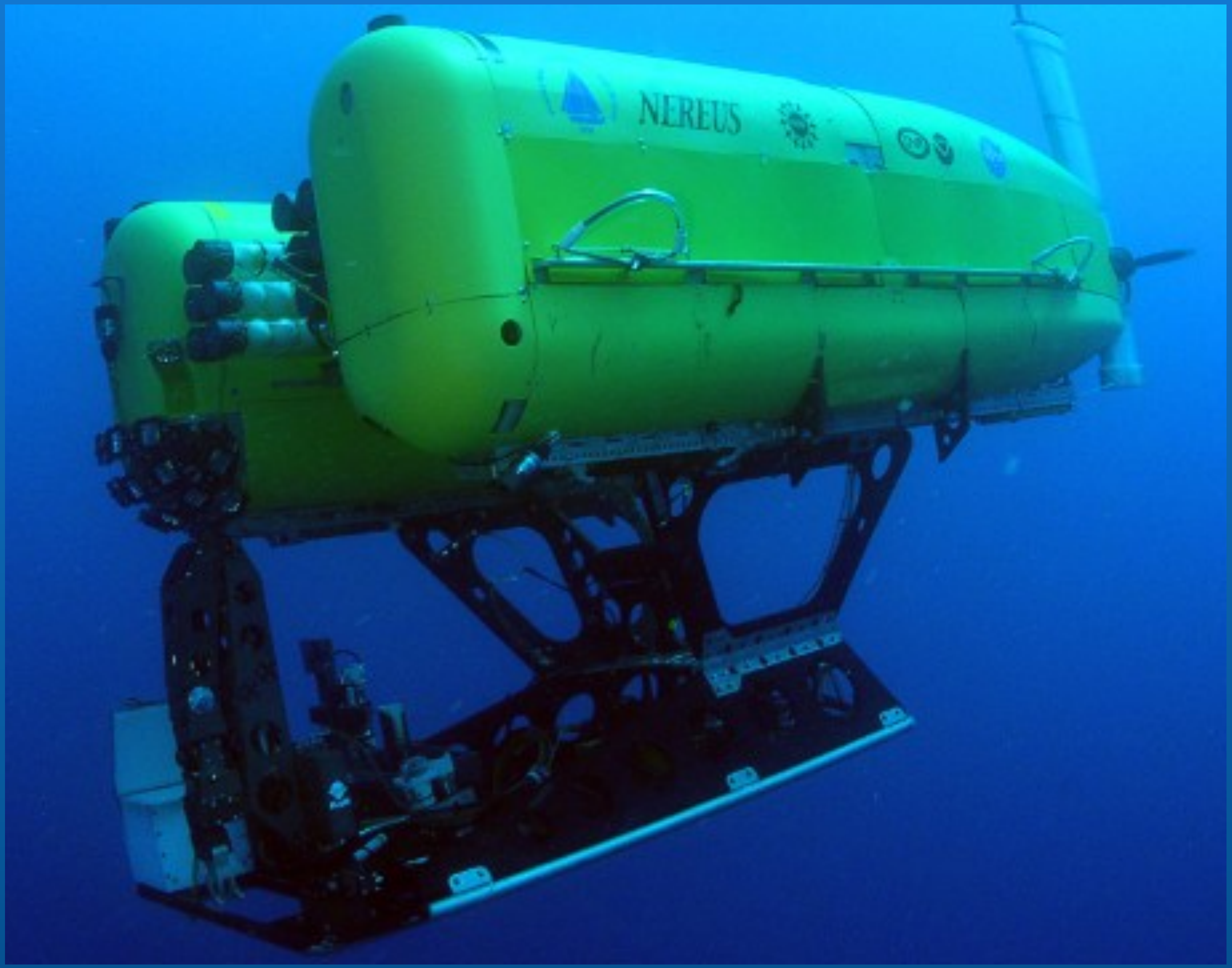
AGOR 27 R/V Neil Armstrong and AGOR 28 R/V Sally Ride (left) under construction at Dakota Creek Industries (DCI) in Anacortes, Wash.

$75 million each



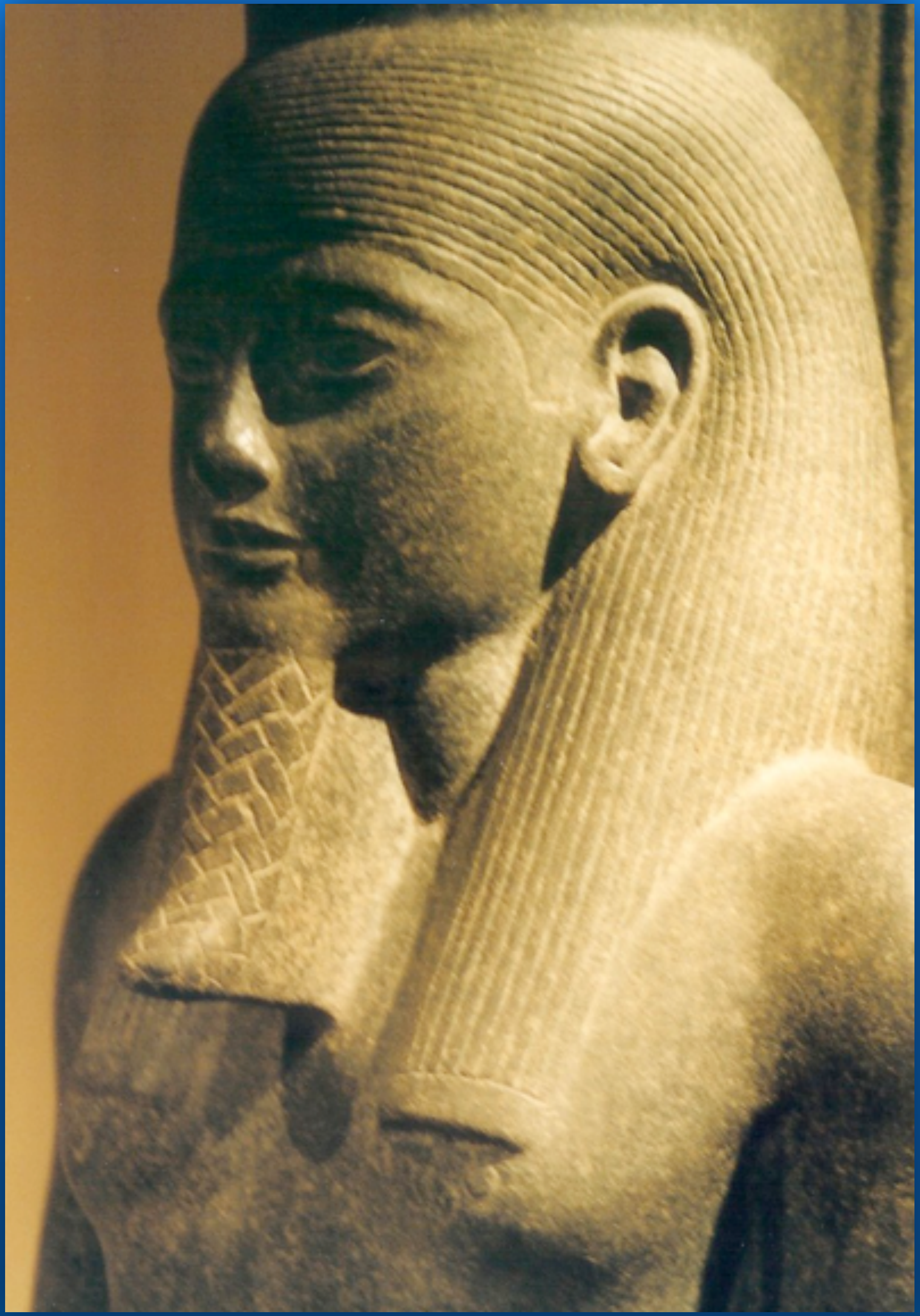
Landlocked? Fewer ships and less money mean getting to sea is increasingly challenging for university researchers.

Man *vs* Machine



Atoem

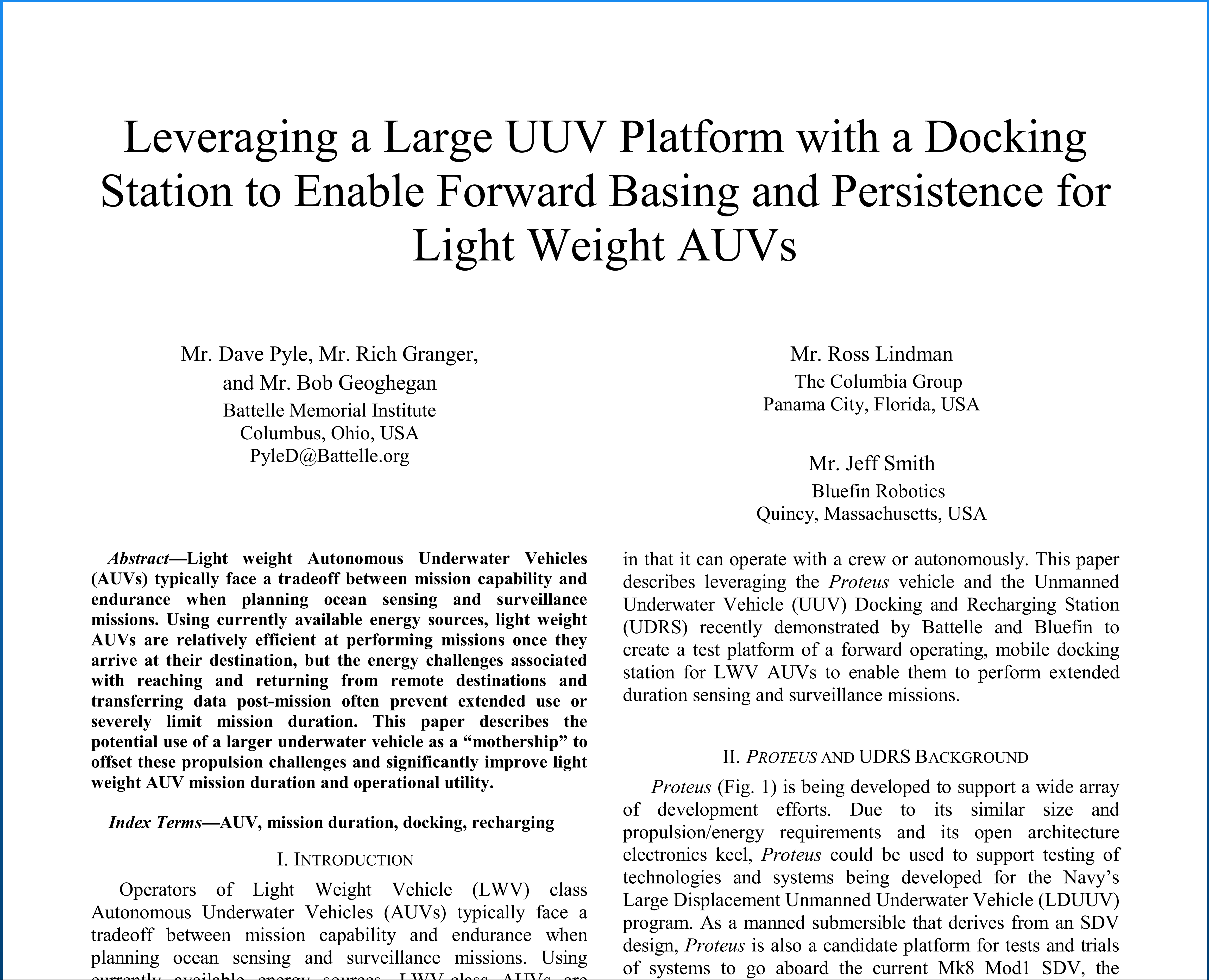
Atoem (Atum, Atem, Tem) was a self-created deity, the first being to emerge from the darkness and endless watery abyss that girdled the world before creation.



ATOEM

- “Conventional” diesel-electric submarine “mothership”
- Fully autonomous operation
- Stripped of all requirements for human occupation
- “Torpedo tubes” for docking of AUVs
- Modular, reconfigurable design
- Standardized, low cost to manufacture
- Configurations for airborne deployment

Oceans 2012, Virginia Beach, VA



Leveraging a Large UUV Platform with a Docking Station to Enable Forward Basing and Persistence for Light Weight AUVs

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and Mr. Bob Geoghegan
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***Abstract*—Light weight Autonomous Underwater Vehicles (AUVs) typically face a tradeoff between mission capability and endurance when planning ocean sensing and surveillance missions. Using currently available energy sources, light weight AUVs are relatively efficient at performing missions once they arrive at their destination, but the energy challenges associated with reaching and returning from remote destinations and transferring data post-mission often prevent extended use or severely limit mission duration. This paper describes the potential use of a larger underwater vehicle as a "mothership" to offset these propulsion challenges and significantly improve light weight AUV mission duration and operational utility.**

***Index Terms*—AUV, mission duration, docking, recharging**

I. INTRODUCTION

Operators of Light Weight Vehicle (LWV) class Autonomous Underwater Vehicles (AUVs) typically face a tradeoff between mission capability and endurance when planning ocean sensing and surveillance missions. Using currently available energy sources, LWV class AUVs are

in that it can operate with a crew or autonomously. This paper describes leveraging the *Proteus* vehicle and the Unmanned Underwater Vehicle (UUV) Docking and Recharging Station (UDRS) recently demonstrated by Battelle and Bluefin to create a test platform of a forward operating, mobile docking station for LWV AUVs to enable them to perform extended duration sensing and surveillance missions.

II. *PROTEUS* AND UDRS BACKGROUND

Proteus (Fig. 1) is being developed to support a wide array of development efforts. Due to its similar size and propulsion/energy requirements and its open architecture electronics keel, *Proteus* could be used to support testing of technologies and systems being developed for the Navy's Large Displacement Unmanned Underwater Vehicle (LDUUV) program. As a manned submersible that derives from an SDV design, *Proteus* is also a candidate platform for tests and trials of systems to go aboard the current Mk8 Mod1 SDV, the

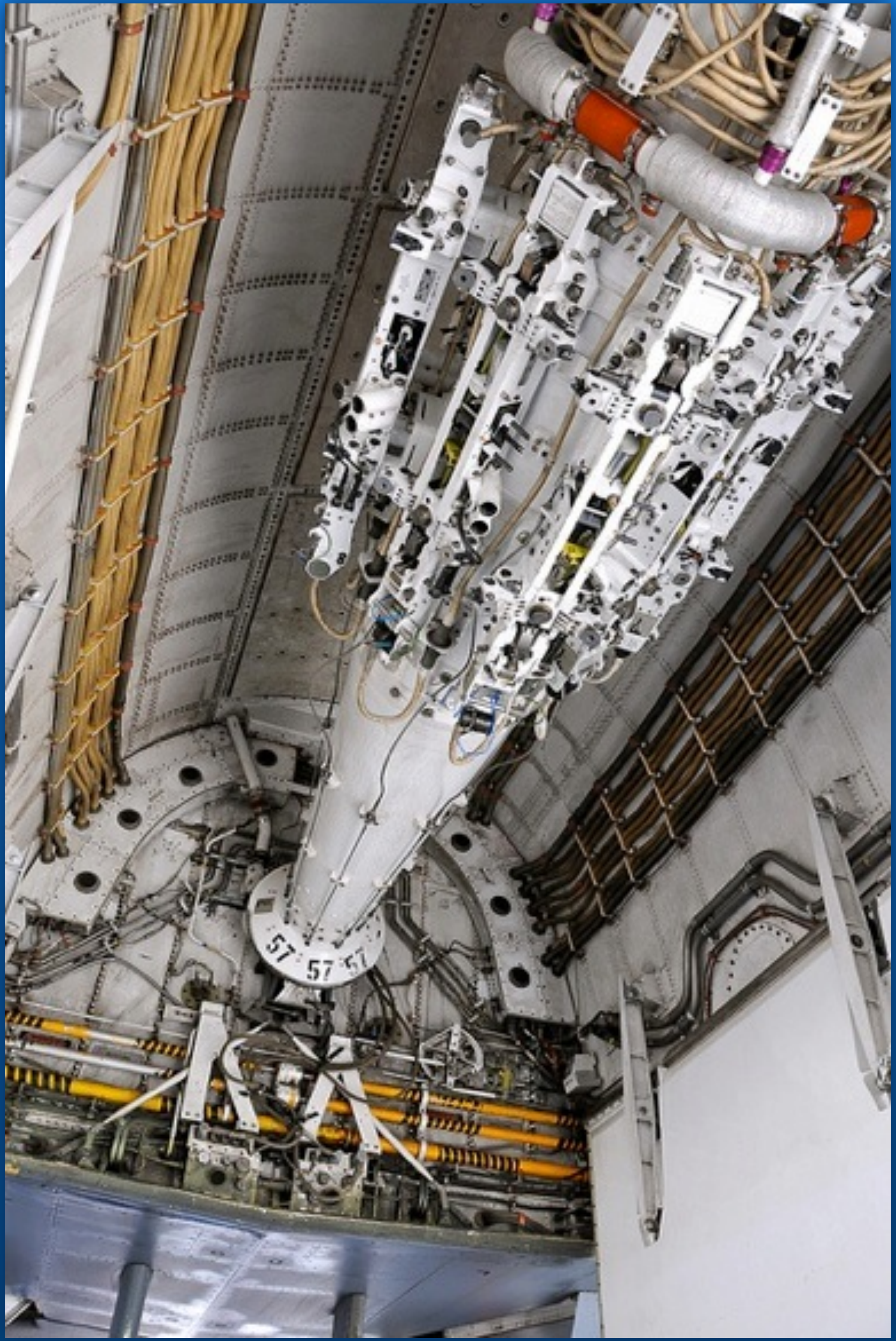
Large Displacement Unmanned Underwater Vehicles (LDUUV)

Proteus

LSV-2 *Cutthroat*

Weight: 205 tons (185,000 kg) Length: 111 feet (33.83 meters) Beam: 10 feet (3.05 meters)

B-1 Rotary Bomb Bay



Differing Requirements

	ATOEM	Military
Theater of Operation	Deep, open ocean	Littoral
Critical Features	Range & duration	Stealth
Cost	Primary	Secondary
Measurements	Ocean observation	Intel

Amateur Subs

Euronaut - Germany

UC3 *Nautilus* - Denmark

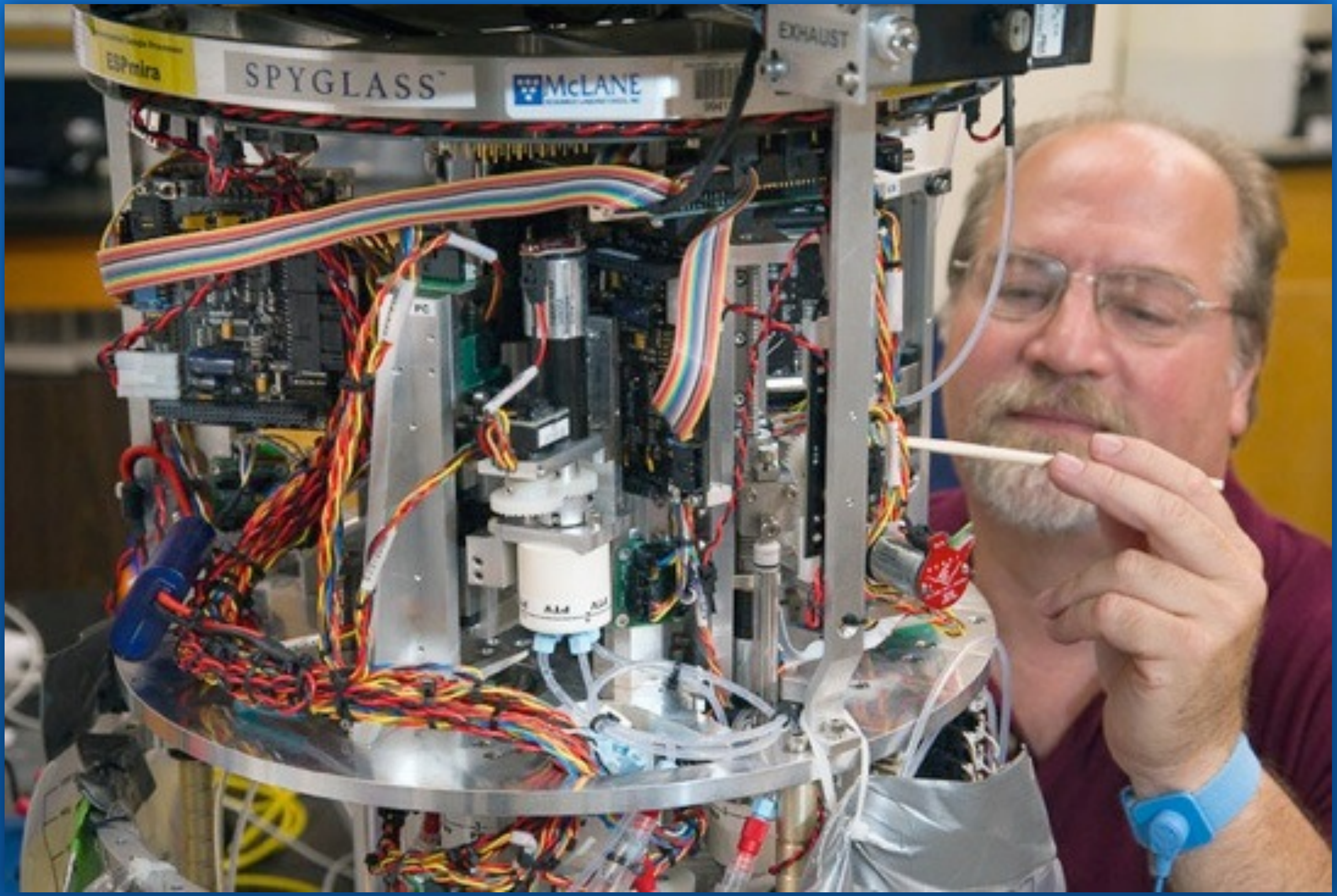
Design for Large-Scale Production

Photo # 80-G-351875 Japanese midget submarines in drydock at Kure, 19 October 1945

Mass Production

- Composite materials instead of steels & titanium
- Molding and casting instead of welding
- Modular and reconfigurable
  - Propulsion & power generation
  - Buoyancy & trim control
  - Fuel storage
  - Batteries
  - Control, navigation & communication
- Vendor-specific AUV modules

Onboard Robotic Laboratory



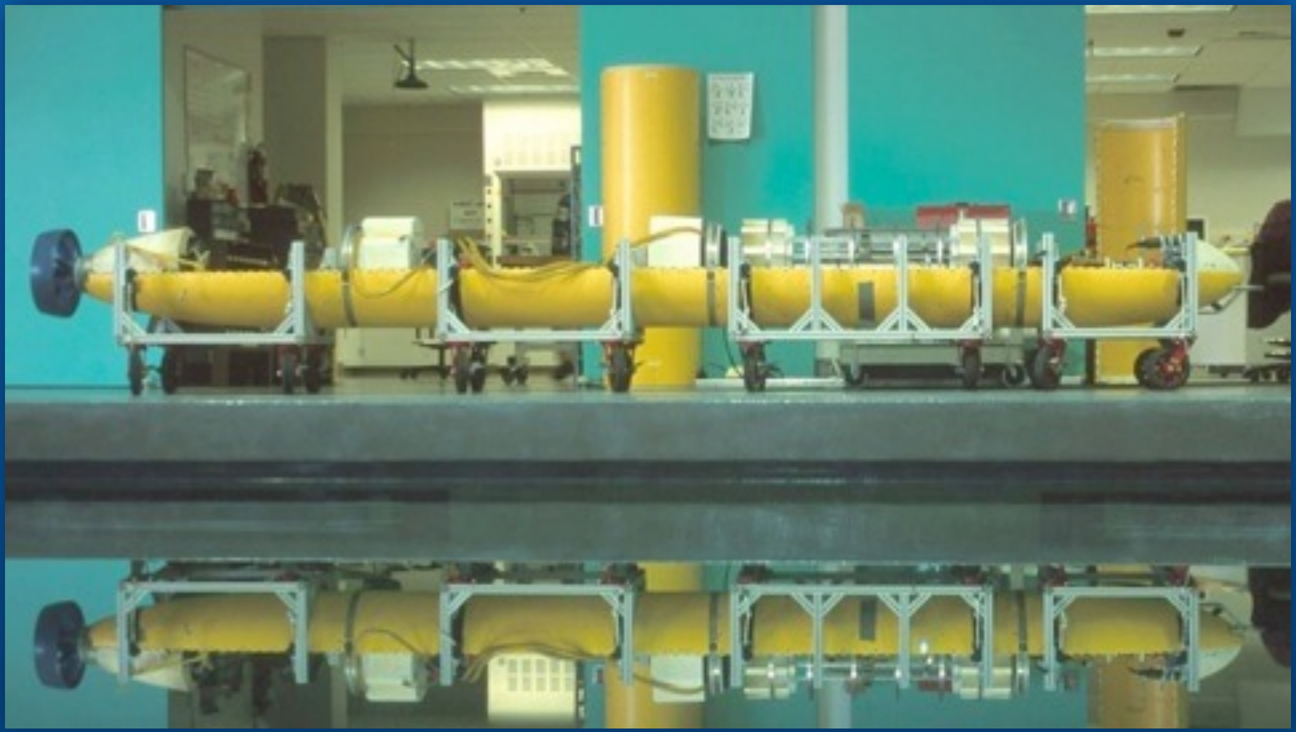
Environmental Sample Processor (ESP)

McLANE®
RESEARCH LABORATORIES, INC.

- Transfer samples from AUV
- Raw sample-to-result
- Sample archiving
- Multiple analytical techniques
- Replenish reagents & consumables in AUVs

MBARI “Gulper”

Modular "Russian Doll" Design & Scaling - "Fractal Sampling"



MBARI *Dorado* class AUV

Airborne Deployment

Airborne Systems

- GigaFly™ GPS-guided precision ram-air parachute delivery
- 40,000 lb payload capacity
- 14 ft/sec rate of descent
- 25,000 ft x 22 km release point
- Delivery accuracy ≤ 100 m
- 10,400 square ft canopy
- Chute recovery?

C-130J-30 Super Hercules

- 44,000 lb payload (20,000 kg)
- 55 feet (16.9 meters) long x 119 inches (3.12 meters) wide x 9 feet (2.74 meters) high

C-17 Globemaster III

- 160,000 lb payload (72,500 kg)
- 68.2 feet (20.78 m) long x 18 feet (5.49 m) wide x 12.3 feet (3.76m)/14.8 feet (4.50m) high

DSRV - *Mystic*

- 76,000 lbs (34,473 kg)
- 49 ft (15 m) long x 8 ft (2.4 m) beam

DSRV *Avalon*

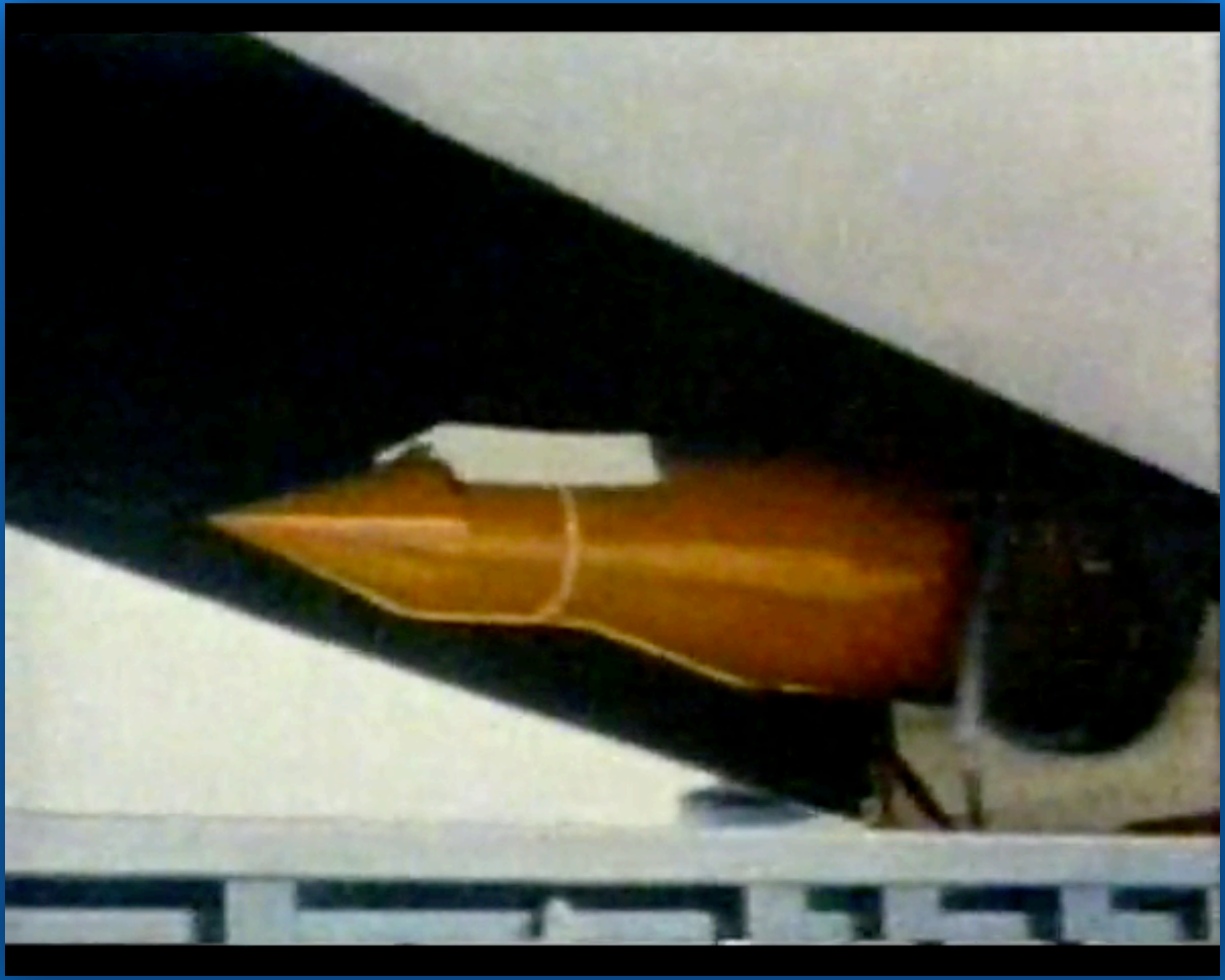

AIR FORCE RESERVE
AVALON
DS
DSRV
2
U.S. NAVY D.S.R.V. L.T.V. 4
WIDE
LOAD

C-5M Galaxy

- 285,000 lb (129,274 kg) payload
- 121 ft (37 m) long x 13.5 ft (4.1 m) high x 19 ft (5.8 m) wide

LSV-2 *Cutthroat*

Weight: 205 tons (185,000 kg) Length: 111 feet (33.83 meters) Beam: 10 feet (3.05 meters)



Minuteman I ICBM - C-5 Galaxy

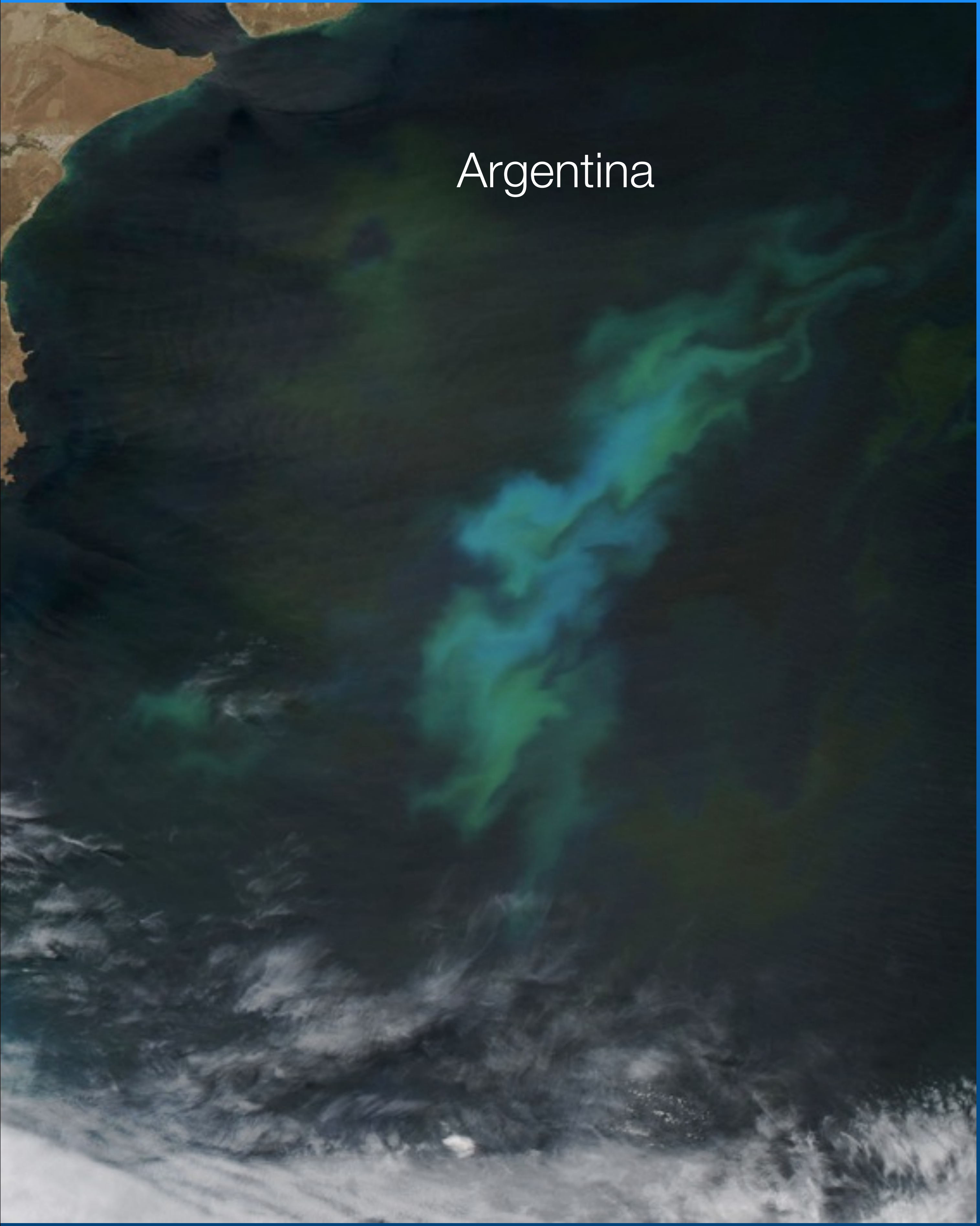
86,000 lbs (39,000 kg)

Safety, Security & Legal

- Largely submerged operation in open ocean minimizes surface collision potential
- Subject to piracy or vandalism on surface
- Threat recognition & avoidance
    - Authorized approach identification
    - Submerge & hide or flee
- Legal status in international waters?

Carbon “*Sea*questration”

Natural Phytoplankton Bloom



“Give me half a tanker of iron,
and I’ll give you an ice age”

John H. Martin

A New Iron Age, Or A Ferric Fantasy

by John H. Martin

I first became interested in iron in the ocean at a U.S. JGOFS steering committee meeting in San Francisco during December 1986 at which Bruce Frost of the University of Washington gave an excellent briefing on the abundance of unused major nutrients in the offshore waters surrounding Antarctica.

Bruce outlined various hypotheses concerned with cold temperatures, low light levels, high grazing rates and the like. After his presentation I told him that I enjoyed his talk, but that the real reason for the nonutilization of major nutrients was Fe deficiency, after all.

Bruce smiled, covered his ears and said that it was too simple and he didn't want to hear about it. Jim McCarthy of Harvard University's Museum of Comparative Zoology joined us and soon said that he didn't want to hear about iron either. Naturally, this good-natured challenge made me all the more anxious to tell them about it. In order to do so, I had to quit bluffing and see if there really was any serious evidence for oceanic Fe deficiency.

After I returned to my office at Moss Landing Marine Laboratories, I started to go through the clutter on my desk. After some frantic digging, I found a top-quality Fe data set produced by my MLML associate Mike Gordon plus a reprint from Bob Duce, the famed atmospheric chemist from the University of Rhode Island.

Bob estimated that fallout of iron-rich atmospheric dust provided about 50% of the Fe needed by open-ocean phytoplankton. I plugged Mike Gordon's latest Fe numbers into Bob's formula, and the new estimate suggested that 95%, not 50%, of the phytoplankton's Fe requirement had to come from fallout from the atmosphere. It also suggested that the deep ocean water in the Pacific, once raised to the surface, was basically infertile because it didn't contain enough iron to allow the phytoplankton to make use of the available NO_3.

From my old days with Bob Duce in the IDOE (International Decade of Ocean Exploration) Pollutant Transfer Program, I recalled that the dust input into the Antarctic was very low. Looking for a more recent Antarctic estimate, I came across the French/Soviet Vostok ice core work of De Angelis and his colleagues, which showed that the present-day dust level was indeed very low. During the ice ages, however, it had been much higher.

Illustration by E. Paul Oberlander

My investigation led me onward to the scenario created by talented Princeton modelers Jorge Sarmiento and Robbie Toggweiler concerning atmospheric carbon dioxide, the biological pump and the use or nonuse of major nutrients in the Southern Ocean.

Then another French/Soviet team of glaciologists (Barnola et al.) published their CO_2 data from the Vostok ice core. When the Vostok Fe data were superimposed on the CO_2 data, the result was a striking inverse relationship. Mutterings increased from the growing numbers of Fe skeptics.

A desire to learn more about the Antarctic led me to a review of the expedition of the British research vessel *Discovery*. Those were the days (1925-27) when persons were persons and the scientists were gone for three years!

Sir Alister Hardy F.R.S. describes this monumental effort in writing, water color and fascinating detail in his book *Great Waters*. The British scientists went to the Antarctic to study the relationship between phytoplankton, krill and the whale fishery.

While reading the book through my iron-glazed eyes, I looked for evidence in support of the Fe hypothesis and noted the mention of great abundance of phytoplankton and krill, not to mention whales, on the shallow, iron-rich South Georgia whaling grounds. To my surprise and

(Cont. on page 11)

JGOFS-IGAC Cooperation Planned On Ocean/Atmosphere Interactions

Recognizing their common interest in understanding the biogeochemical exchanges between the atmosphere and the ocean, a working group of representatives of the Joint Global Ocean Flux Study (JGOFS), the International Global Atmospheric Chemistry (IGAC) program and the International Geosphere-Biosphere Programme (IGBP) got together in San Francisco last December to define overlapping areas of interest and look for ways to work together.

Peter Liss from IGBP served as chairman. Also attending were IGBP representatives Patrick Holligan and James McCarthy. JGOFS participants were Richard Gammon, Margaret Leinen and John Martin. Robert Charlson, Robert Duce and Joseph Prospero represented IGAC, and David Hurd attended from the National Science Foundation.

The meeting was held under the aegis of IGBP's Coordinating Panel 2. Both JGOFS and IGAC have been designated as IGBP core programs.

Participants agreed that certain important biogeochemical interactions require interdisciplinary investigation. JGOFS and IGAC are linked, the meeting report noted, by "the recognition that the living ocean strongly modifies the trace gas composition of the atmosphere and that, for climate prediction, experimental and modeling studies of this interaction are required, and further that atmospheric deposition can affect ocean productivity."

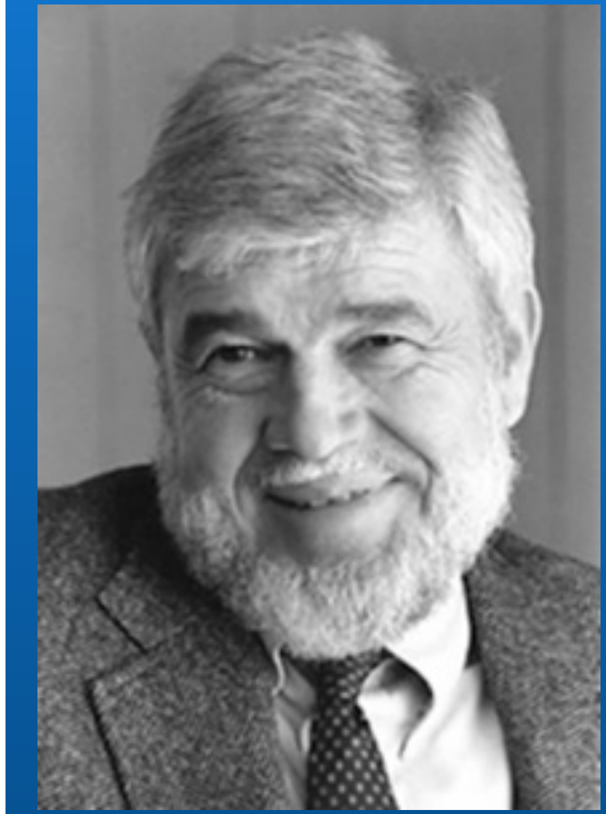
Among the scientific topics discussed was the issue of atmospheric inputs to the oceans. Discussion focused on three aspects of the problem: the effect of clouds and ozone on the quantity and quality of light at the ocean surface; the deposition of continental dust as a source of iron for open ocean phytoplankton, and the supply of nutrients such as nitrogen and ammonium to the surface waters in the form of aerosols.

Ocean inputs to the atmosphere formed the next topic. Workshop participants discussed the role of emissions of dimethylsulfide, a byproduct of algal metabolism, in the atmospheric sulfur budget, the formation of cloud condensation nuclei and the acid-base chemistry of rainwater. Also discussed were a

(Cont. on page 6)

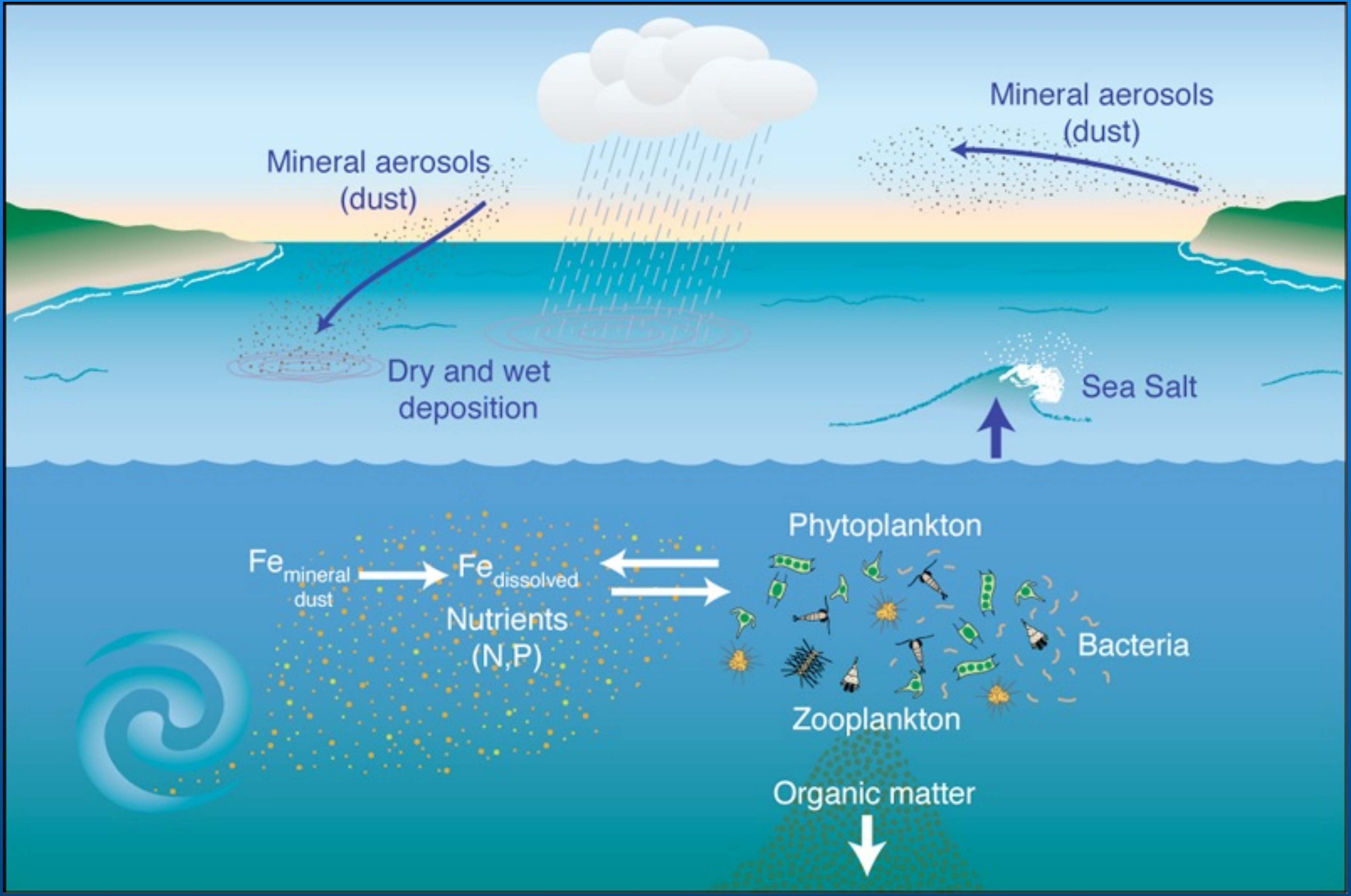
"Give me half a tanker of iron, and I'll give you an ice age"

July 1988

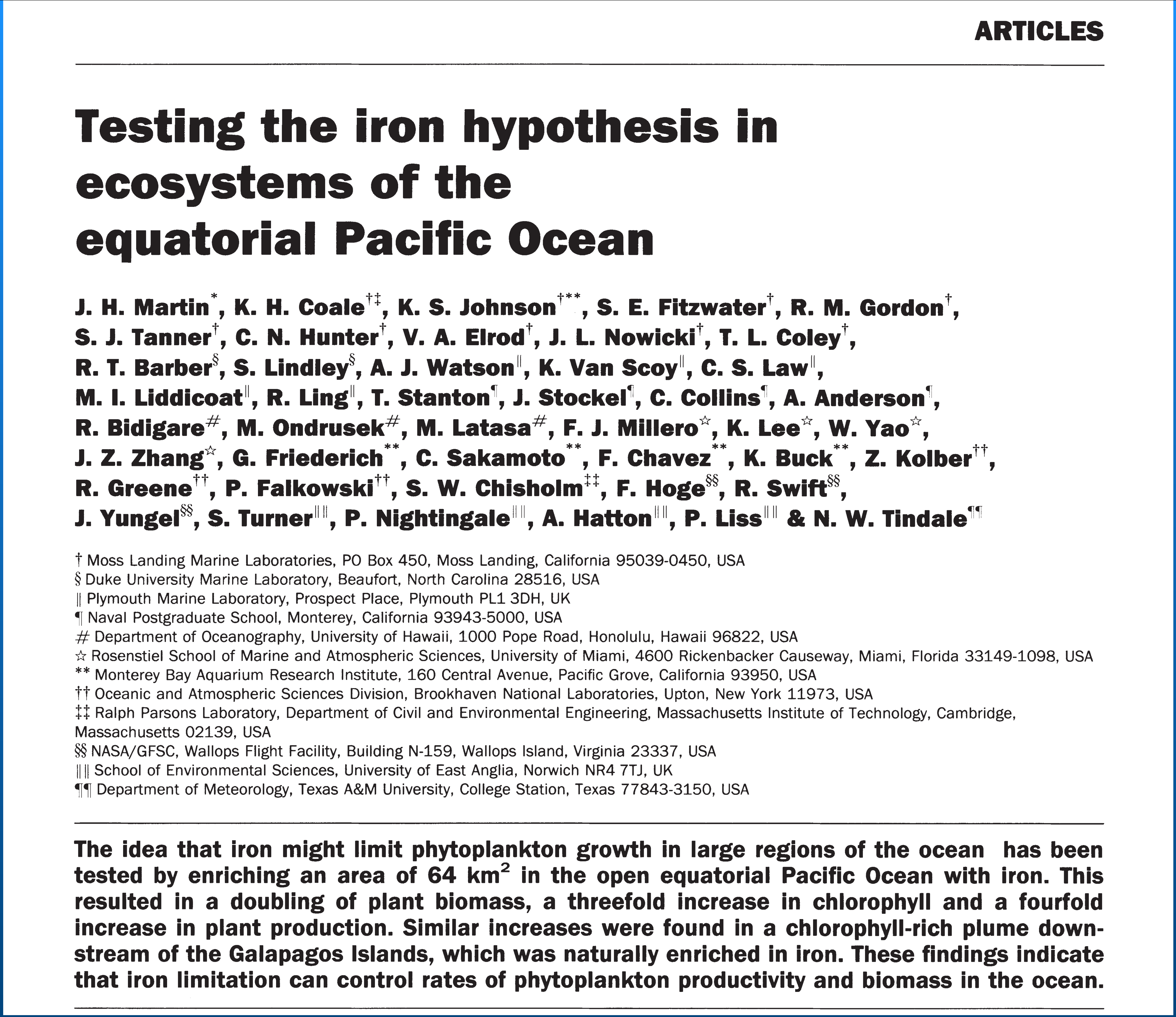


John H. Martin

The Iron Hypothesis



http://www.whoi.edu/science/MCG/dept/facilities/sea_aer/maintextpg.html



Testing the iron hypothesis in ecosystems of the equatorial Pacific Ocean

J. H. Martin[*], K. H. Coale[†‡], K. S. Johnson[†], S. E. Fitzwater[†], R. M. Gordon[†], S. J. Tanner[†], C. N. Hunter[†], V. A. Elrod[†], J. L. Nowicki[†], T. L. Coley[†], R. T. Barber[§], S. Lindley[§], A. J. Watson[‖], K. Van Scoy[‖], C. S. Law[‖], M. I. Liddicoat[‖], R. Ling[‖], T. Stanton[¶], J. Stockel[¶], C. Collins[¶], A. Anderson[¶], R. Bidigare[#], M. Ondrusek[#], M. Latasa[#], F. J. Millero[☆], K. Lee[☆], W. Yao[☆], J. Z. Zhang[☆], G. Friederich[**], C. Sakamoto[**], F. Chavez[**], K. Buck[**], Z. Kolber[††], R. Greene[††], P. Falkowski[††], S. W. Chisholm[‡‡], F. Hoge[§§], R. Swift[§§], J. Yungel[§§], S. Turner[‖‖], P. Nightingale[‖‖], A. Hatton[‖‖], P. Liss[‖‖] & N. W. Tindale[¶¶]**

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The idea that iron might limit phytoplankton growth in large regions of the ocean has been tested by enriching an area of 64 km^2 in the open equatorial Pacific Ocean with iron. This resulted in a doubling of plant biomass, a threefold increase in chlorophyll and a fourfold increase in plant production. Similar increases were found in a chlorophyll-rich plume downstream of the Galapagos Islands, which was naturally enriched in iron. These findings indicate that iron limitation can control rates of phytoplankton productivity and biomass in the ocean.

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ENVIRONMENT

Ocean Iron Fertilization—Moving Forward in a Sea of Uncertainty

It is premature to sell carbon offsets from ocean iron fertilization unless research provides the scientific foundation to evaluate risks and benefits.

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The consequences of global climate change are profound, and the scientific community has an obligation to assess the ramifications of policy options for reducing greenhouse gas emissions and enhancing CO_2 sinks in reservoirs other than the atmosphere (*1*, *2*).

Ocean iron fertilization (OIF), one of several ocean methods proposed for mitigating rising atmospheric CO_2, involves stimulating net phytoplankton growth by releasing iron to certain parts of the surface ocean. The international oceanographic community has studied OIF, including 12 major field programs with small-scale, purposeful releases of iron since 1993 (*3*, *4*). Although these experiments greatly improved our understanding of the role of iron in regulating ocean ecosystems and carbon dynamics, they were not designed to characterize OIF as a carbon mitigation strategy. The efficacy by which OIF sequesters atmospheric CO_2 to the deep sea remains poorly constrained, and we do not understand the intended and unintended biogeochemical and ecological impacts. Environmental perturbations from OIF are nonlocal and are spread over a large area by ocean circulation, which makes long-term verification and assessment very difficult. Modeling studies have addressed sequestration more directly and have suggested that OIF in areas of persistent high nutrients (so-called high-nutrient, low-chlorophyll areas) would be unlikely to sequester more than several hundred million tons of carbon per year. Thus, OIF could make only a partial contribution to mitigation of global CO_2 increases.

Despite these uncertainties in the science, private organizations are making plans to conduct larger-scale iron releases to generate carbon offsets. We are convinced that, as yet, there is no scientific basis for issuing such carbon credits for OIF. Adequate scientific information to enable a decision regarding whether credits should be issued could emerge from reducing uncertainties; this will only come through targeted research programs with the following specific attributes:

- Field studies on larger spatial and longer time scales, because ecological impacts and CO_2 mitigation are scale-dependent.
- Consideration of OIF in high- and low-nutrient regions to understand a wider range of processes that are affected by iron, such as nitrogen fixation and elemental stoichiometry.
- Detailed measurements in the subsurface ocean to verify the fate of fixed carbon, including remineralization length scales of carbon, iron, and associated elements.
- Broad assessment of ecological impacts from bacteria and biogeochemistry to fish, seabirds, and marine mammals.
- Characterization of changes to oxygen distributions, biophysical climate feedbacks, and cycling of non-CO_2 greenhouse gases, such as methane, nitrous oxide, and dimethylsulfide.
- Long-term monitoring and use of models to assess downstream effects beyond the study area and observation period.
- Improved modeling studies of the results and consequences of OIF, including higher spatial resolution, better ecosystem parameterization, inclusion of other greenhouse gases, and improved iron biogeochemistry.
- Analysis of the costs, benefits, and impacts of OIF relative to other climate and carbon mitigation schemes and to the impacts of global change if we take no action.

The organization of such experiments is as critical as the scientific design. The scope of the problem will require individual sponsors and partnerships of national science agencies, philanthropies, and commercial entities. Academic scientists need to be involved but must maintain independence. This can be accomplished by regulating experiments in a uniform manner under such international agreements as the London Convention, widely distributing science plans and results via open meetings and peer-reviewed journals, and requiring clear and explicit statements of conflicts of interest.

This group feels it is premature to sell carbon offsets from the first generation of commercial-scale OIF experiments unless there is better demonstration that OIF effectively removes CO_2, retains that carbon in the ocean for a quantifiable amount of time, and has acceptable and predictable environmental impacts. As with any human manipulation of the environment, OIF carries potential risks, as well as potential benefits; moving forward on OIF should only be done if society is willing to acknowledge explicitly that it will result in alteration of ocean ecosystems and that some of the consequences may be unforeseen. We are currently facing decisions on climate regulations, such as the post-Kyoto framework discussed in Bali, carbon cap-and-trade bills in the U.S. Congress, and consideration of OIF by the parties to the London Convention, and we feel that ocean biogeochemical research will help inform these important policy decisions.

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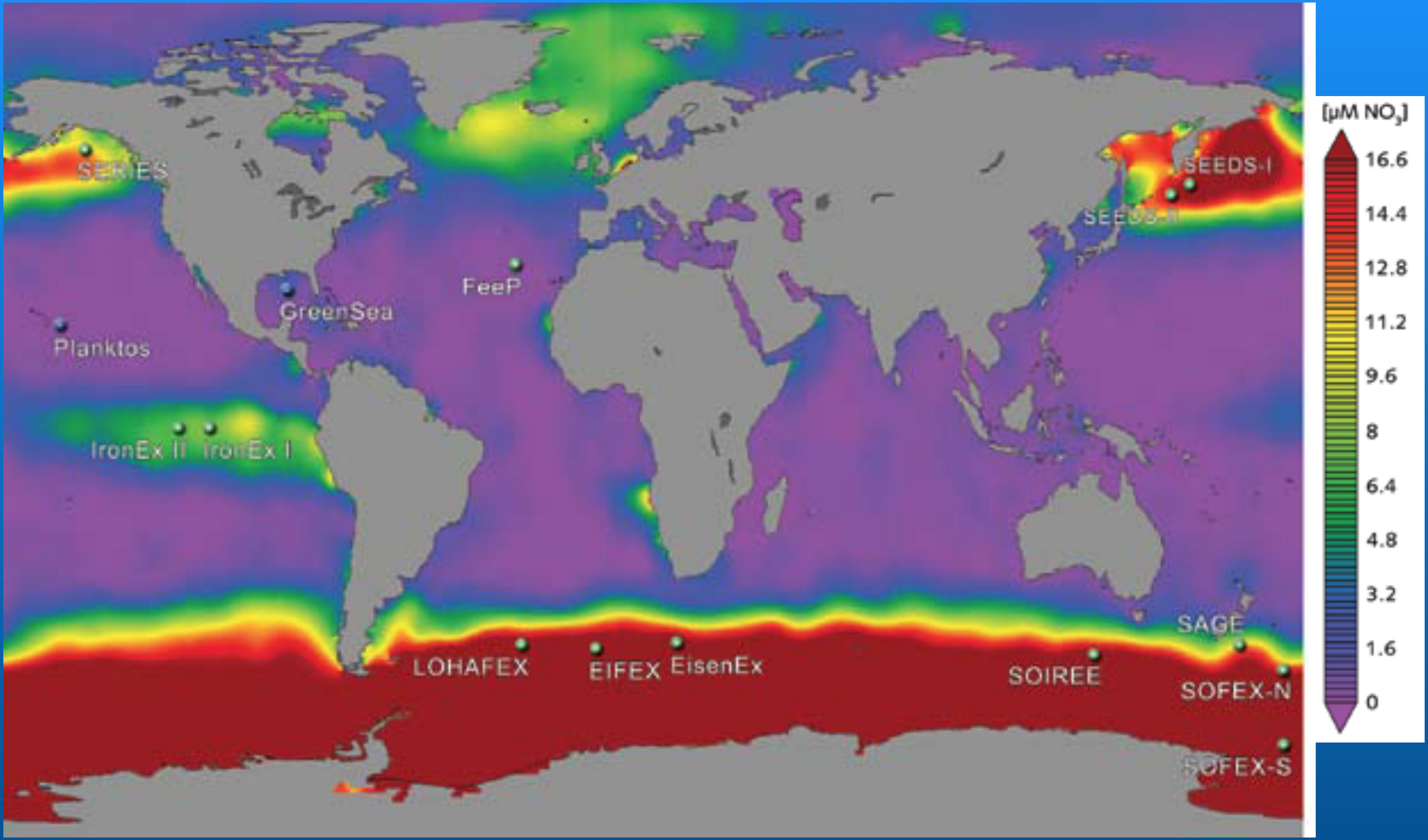

Figure 4. Locations of major artificial iron enrichment experiments, including the pilot demonstrations of GreenSea Venture and Planktos. Color heat map represents surface nitrate concentrations with warmer colors indicating higher concentrations, showing three major HNLC regions in the Southern Ocean, the eastern equatorial Pacific, and the subarctic Pacific. Data from National Virtual Ocean Data System, http://ferret.pmel.noaa.gov/NVODS/; analyzed nitrate data from the World Ocean Atlas 2005

ARTICLE

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Deep carbon export from a Southern Ocean iron-fertilized diatom bloom

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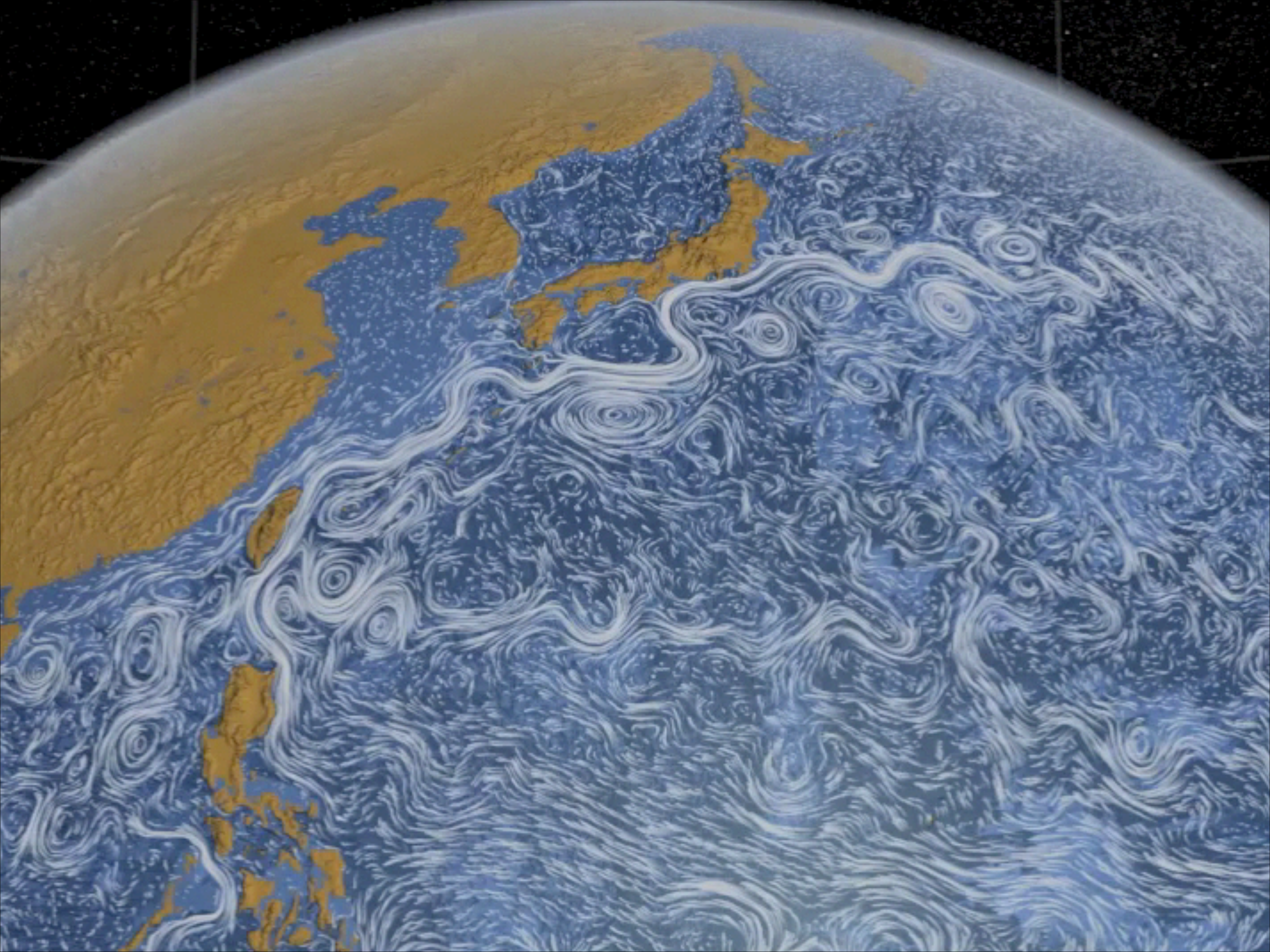
Fertilization of the ocean by adding iron compounds has induced diatom-dominated phytoplankton blooms accompanied by considerable carbon dioxide drawdown in the ocean surface layer. However, because the fate of bloom biomass could not be adequately resolved in these experiments, the timescales of carbon sequestration from the atmosphere are uncertain. Here we report the results of a five-week experiment carried out in the closed core of a vertically coherent, mesoscale eddy of the Antarctic Circumpolar Current, during which we tracked sinking particles from the surface to the deep-sea floor. A large diatom bloom peaked in the fourth week after fertilization. This was followed by mass mortality of several diatom species that formed rapidly sinking, mucilaginous aggregates of entangled cells and chains. Taken together, multiple lines of evidence—although each with important uncertainties—lead us to conclude that at least half the bloom biomass sank far below a depth of 1,000 metres and that a substantial portion is likely to have reached the sea floor. Thus, iron-fertilized diatom blooms may sequester carbon for timescales of centuries in ocean bottom water and for longer in the sediments.



Next Steps

- Detailed design requirements
- Materials & manufacturing methods evaluation
- ≤ $1 million exclusive of AUVs
- Fleet of > 1,000 ATOEM platforms
- Discussions with AUV manufacturers
- Open Source?
- Crowd Funding?

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RADM USN (Retired)