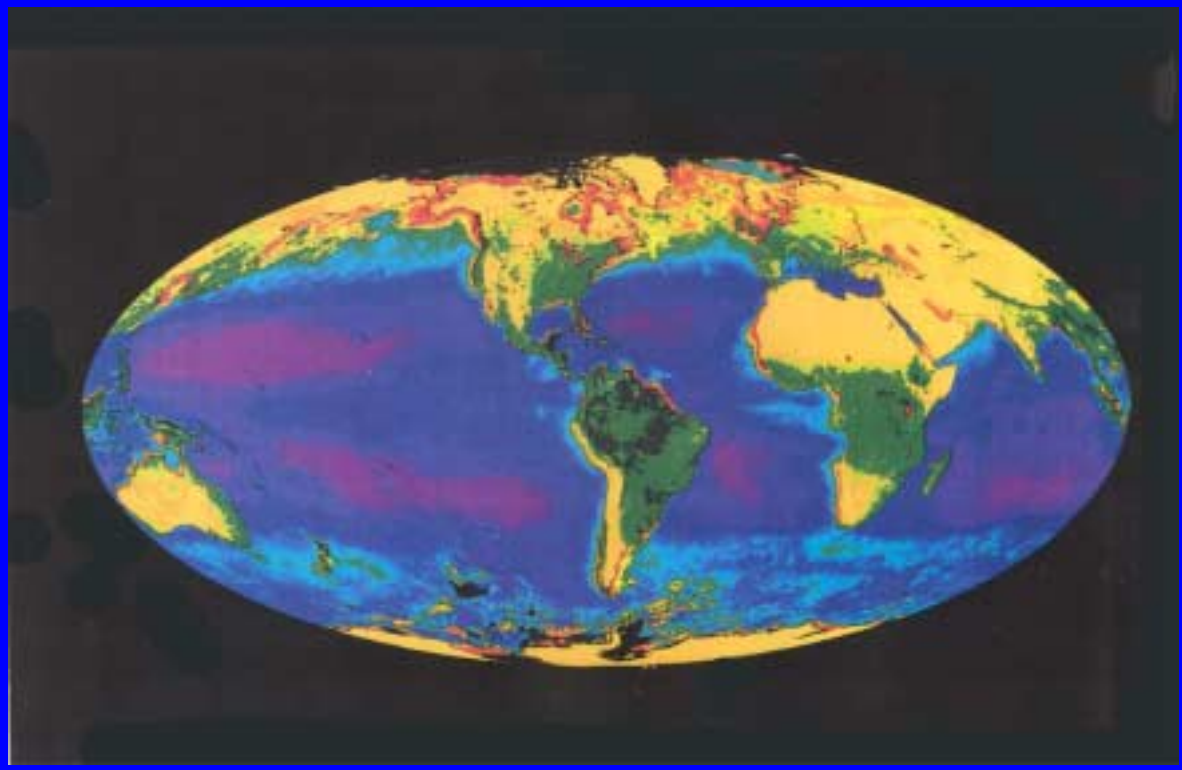
Why and how we created JGOFS and the Lessons Learned

or

The Once and Future JGOFS Ocean

Peter G. Brewer

Monterey Bay Aquarium Research Institute

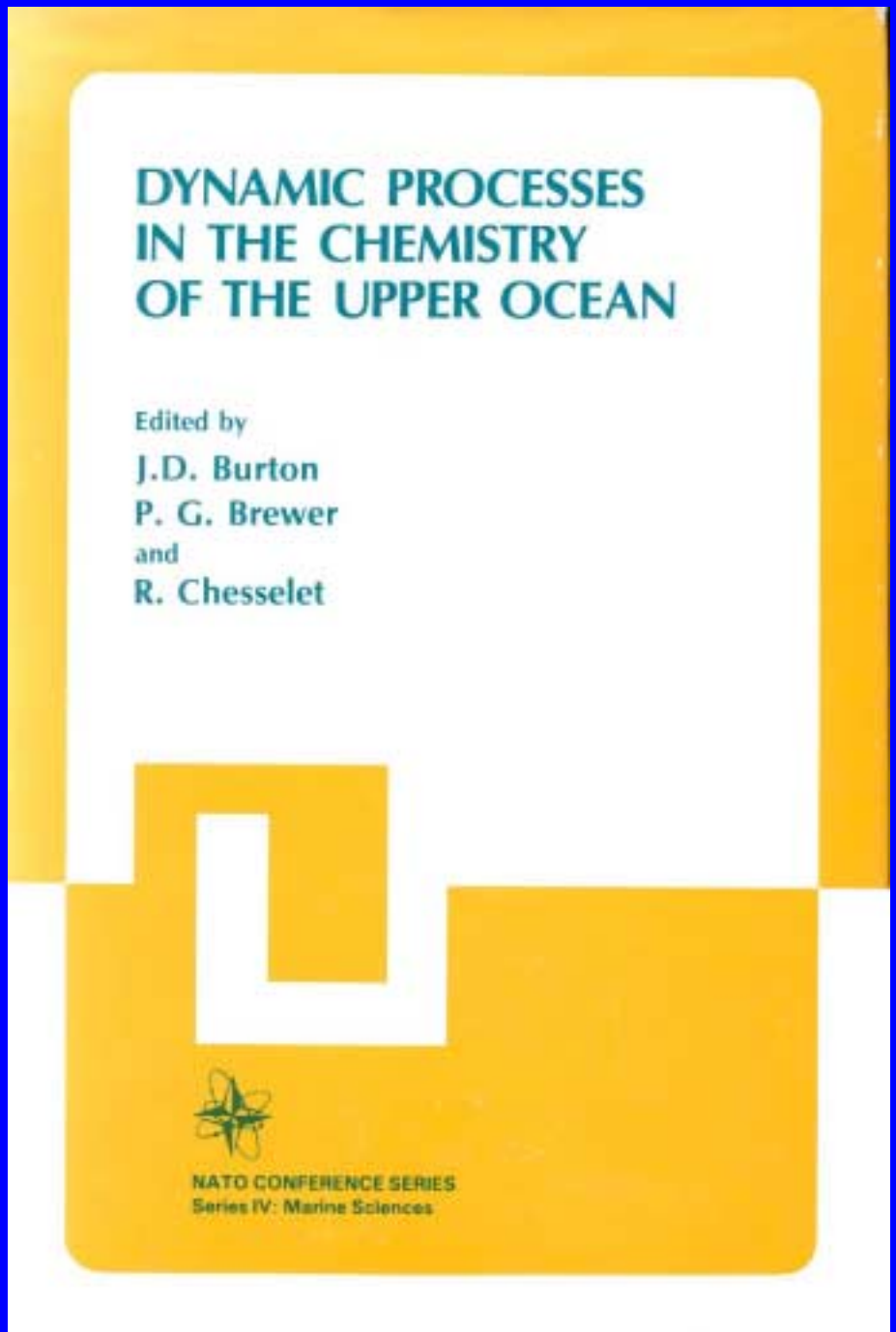


Goals of JGOFS

- *To determine and understand on a global scale the processes controlling the time-varying fluxes of carbon and associated biogenic elements in the ocean, and to evaluate the related exchanges with the atmosphere, sea floor and continental boundaries.*

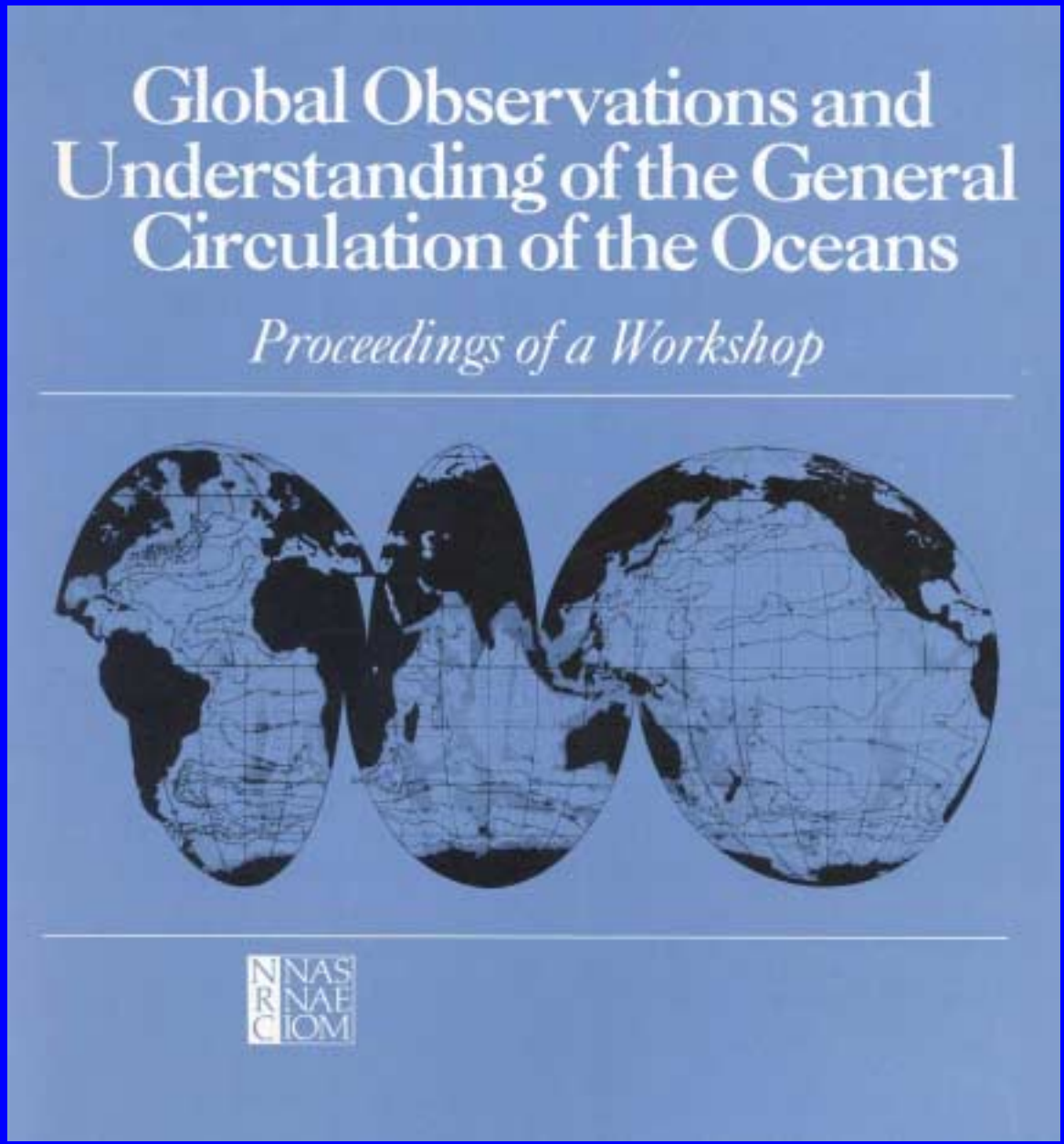
- *To develop a capacity to predict on a global scale the response of oceanic biogeochemical processes to anthropogenic perturbations, in particular those related to climate change.*

These goals were essentially roughed out 16 years ago, immediately after the 1987 meeting at ICSU house and they have served us well.



The NATO ARI held at Jouy-en-Josas 6-12 July, 1983 had an important influence:

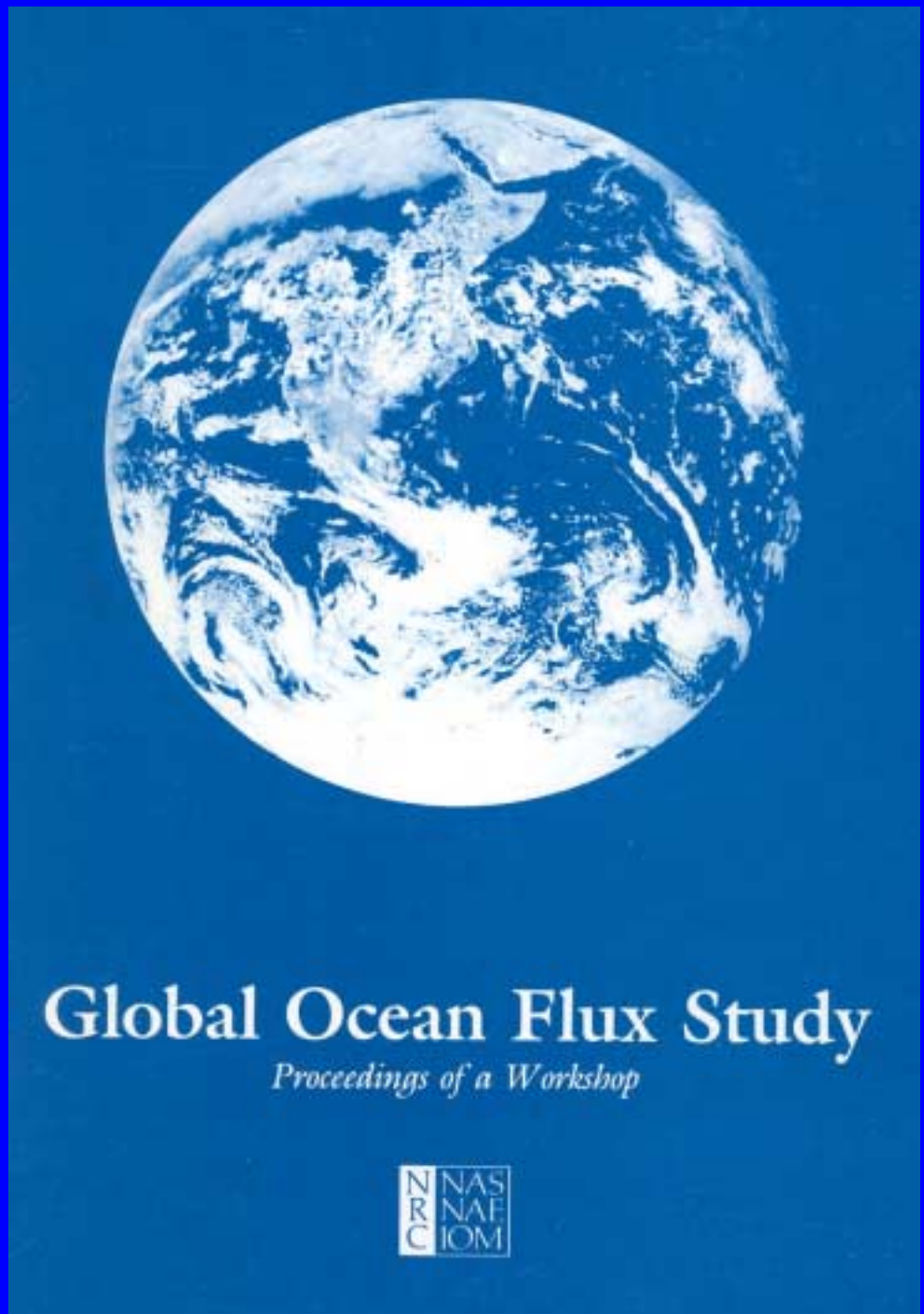
- *Ken Bruland presented the first Th^{234} data linking radionuclides and productivity.*
- *Peter Brewer examined the extraordinary gap between physical and biological views of the ocean CO_2 system.*
- *Bernt Zeitschel happily speculated on floating sediment trap programs.*
- *John Steele was impressed*
- *We were eaten by mosquitoes, and received pieces of the Eiffel Tower as souvenirs.*



One month later ….

The August 1983 U.S. WOCE Meeting, held at the NAS Woods Hole Center preceded the GOFS meeting by a year, and had important influence.

Reconciling the CO_2 system interests of these two programs would be a major challenge.



The GOFS Workshop, held at NAS, Woods Hole, Sept. 10-14, 1984 marked the formal emergence of a planning effort that had been in progress for some time.

John Steele, Jim Baker, Wally Broecker, Jim McCarthy, and Carl Wunsch for the NAS Board were the "Ad Hoc Group"*

Ken Bruland, Alice Alldredge, Jim Baker, Wally Broecker, Dick Eppley, Glenn Flierl, Ross Heath, Sus Honjo, Bill Jenkins, Jim McCarthy, and John Steele were the Planning Committee.*

Nancy Maynard was Staff Director of the NAS Board on Ocean Science & Policy.

The 1984 GOFS Workshop
Background Papers – What did they say?

Working Group I: Satellite/Surface Productivity

Blooming off the U.S. East Coast: Otis Brown et al.
" bloom .. For a 28 day period off the east coast using NOAA-7 AVHRR and CZCS .. In April/May of 1982"

Relations between Primary Production and Ocean Chlorophyll Determined by Satellite: R.W. Eppley
"non-uniform measurements and interpretation …error coefficient of 59% … a new range of possibilities. There is much to be done"

Ocean Color for the Estimation of Global Marine Primary Productivity: R.C. Smith
"The remote sensing of ocean color is well understood. The key point … is to demonstrate that a quantitative image can be treated as an array of data."

1984 Background Papers

Working Group II:
Photic Zone: Production rates and Particle Fluxes Exiting the Surface

Utilization of Phytoplankton production in the Surface Layer: B. Frost
"very much in a state of flux (!) … the microbial loop seems to be immensely important for nutrient regeneration …"

The flux of particulate organic matter out of the euphotic zone: G. Knauer et al.
"Agassiz 1888 "rain" of organic particles…two layer system …large particle production … given high priority."

Measuring Ocean Primary Production: J. J. McCarthy
"timely and perplexing problem … episodic upward flux … new generalizations are emerging that will permit .. rates and fates."

1984 Background Papers

Working Group III: *Transformations in the Ocean's Interior*

Macroscopic Organic Aggregates: A Alldredge
"Marine snow .. Aggregates, flocs etc. … healthy plankton make up 75% of the living biomass on deep sea snow."

Radionuclide Fluxes in the Ocean Interior: M. P. Bacon
"Members of the natural radionuclide decay series can serve as powerful tools .. a continual reworking of the particulate matter before reaching the sea floor."

Seasonality of Particle Fluxes in the Ocean's Interior: W.G Deuser
"Six years of sediment trapping in the Sargasso Sea at 3200m, with rapid particulate transport of 50-100m per day."

Towards a Global Ocean Flux Experiment: A tracer geochemists approach: W. Jenkins. Pulsed and variable fluxes may explain high O_2 based productivity.

Production, Transformation and transfer of organic compounds in the sea: C. Lee et al. Biogeochemistry of individual organic compounds.

1984 Background Papers

Working Group IV: Benthic Transformations and the Sediment Record

Sediment traps, Particle Fluxes, and Benthic Boundary Layer Processes: J. Dymond
"Comparisons of sediment burial rates and particulate fluxes .. Surprisingly high resuspension of primary flux."

Benthic Organic Carbon Cycles: Toward a Balance of Fluxes from Particle Settling and Pore Water Gradients: S. Emerson and J. Dymond.
"Benthic chamber experiments should be combined with pore water measurements."

Study of Ocean Fluxes in Time and Space by Bottom-Tethered Sediment Traps: S. Honjo
"State-of- the- art automated sediment traps with large apertures for three-dimensional spatial expanse throughout an entire ocean basin with prod. time series"

Measured Fluxes across the Sediment-Water Interface: K. Smith
"Benthic chambers and core-incubation… to study organic matter recycling"

1984 Background Papers

Working Group V: Modeling

A Preliminary Model of the Role of Upper Ocean Chemical Dynamics in Determining Oceanic O_2 and Atmospheric CO_2 Levels:
J. Sarmiento and J. R. Toggweiler
"Analytical solution for a one-and-a half dimensional "pipe" model. ..atmospheric CO_2 can be varied by changing level of pre-formed nutrients…last ice age."

Two papers were inserted into the GOFS report during editing so as to provide substance for topics raised during the meeting:

- ***"Aluminum Concentrations and Fluxes in the Ocean" Derek Spencer***
- ***"A New Model for the Role of the Oceans in Determining Atmospheric pCO_2" J. L. Sarmiento and J. R. Toggweiler***

1985-1987 - Building a Program

After the GOFS Woods Hole Meeting the hard work of building a program began. Ken Bruland, Jim McCarthy, Peter Jumars and I were asked to form a Steering Committee. This did not sit well with everyone.
Some key events:

- *Spring 1985 – pitch to Burt Edelson, NASA*
  First planning meeting "Ad-hoc group on particle fluxes in the ocean" 21 May, 1985 (WHOI)

- *Summer 1985 – the "Telemail" months begin with Omnet as the provider*

- *Fall 1985 – Proposal for a 3 pronged attack: Time Series, Global Survey, Process Studies. [Data Management, and Synthesis & Modeling, were to follow.]*

- *Winter 1985- Establishment of a GOFS Planning Office at WHOI, later to be joined by Hugh Livingston. This made an enormous difference.*

Building a Program continues -

- ***Spring 1986** – North Atlantic Planning (U.S. GOFS Report 2) – in practice the meetings began in late 1985*

***Fall 1986** – WOCE Core 1 Meeting, NAS, D.C. – Joint CO_2 strategy agreed to on a handshake. Plan taken immediately to SCOR meeting in Hobart. Enthusiasm by SCOR, superb help from Liz (Gross) begins.*

- ***November 1986** The "Pac-Man" image on the cover of EOS.*

- ***1987** February 17-20, Meeting at ICSU House, Paris. Jim Baker (Chair), Gerold Siedler (SCOR). First global ocean color satellite image. First N. Atlantic geochemical mass balance effort. DOC challenge. Agree to N. Atlantic start. JGOFS proposed as SCOR initiative. Bernt Zeitschel proposed as Chair.*

- ***September 7-11, 1987.** Roger Chesselet organizes N. Atlantic Planning Meeting, Paris. Ozone correction to ocean color from Andre Morel.*

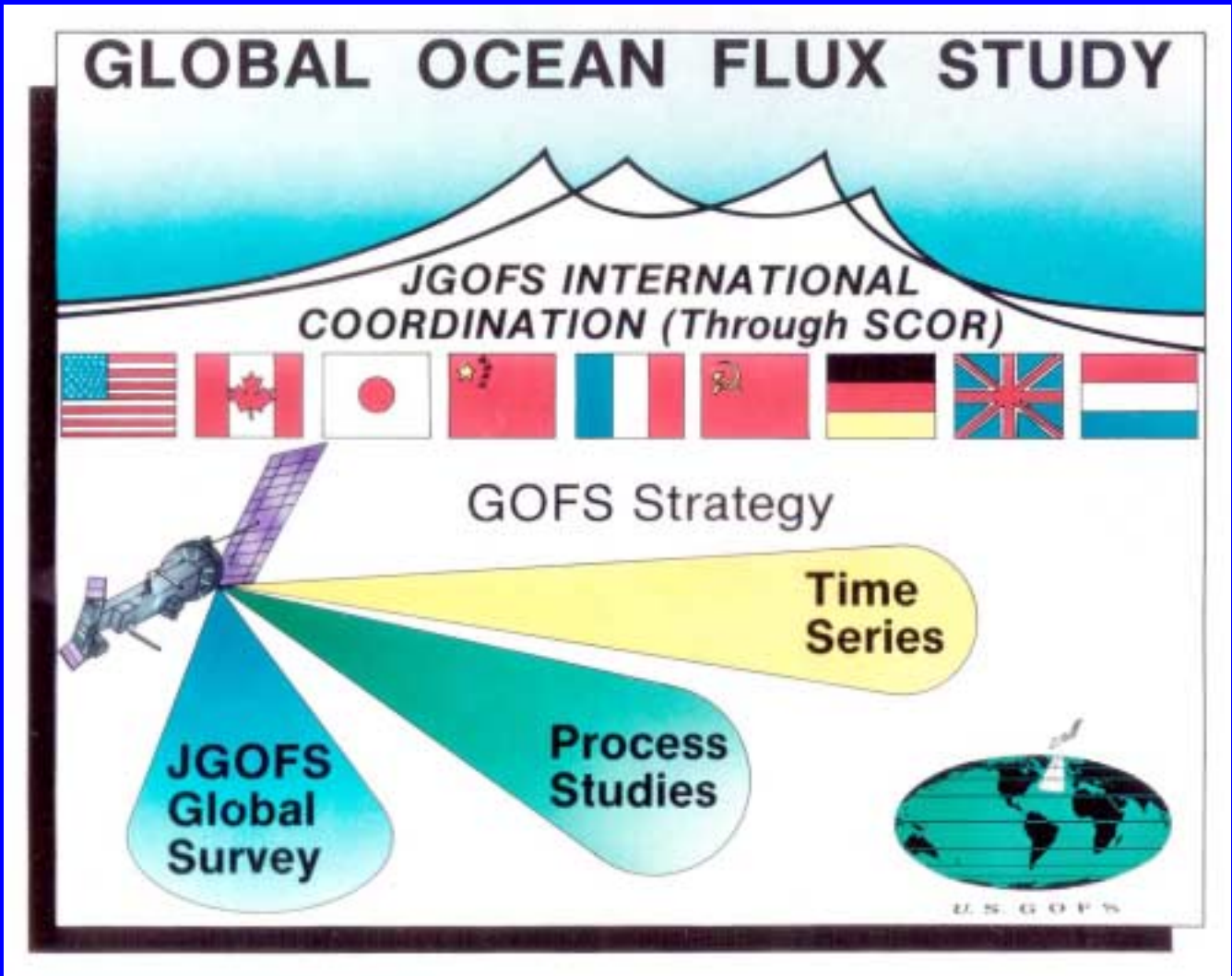
- ***October 1987** SCOR Zurich meeting formally adopts JGOFS*

- ***January 25-28 1988, Miami.** First JGOFS Scientific Planning Committee*

- ***September 13-15 1988, The Hague.** 2cnd JGOFS Scientific Planning Committee*

- ***March 1989.** JGOFS North Atlantic Bloom Experiment begins.*

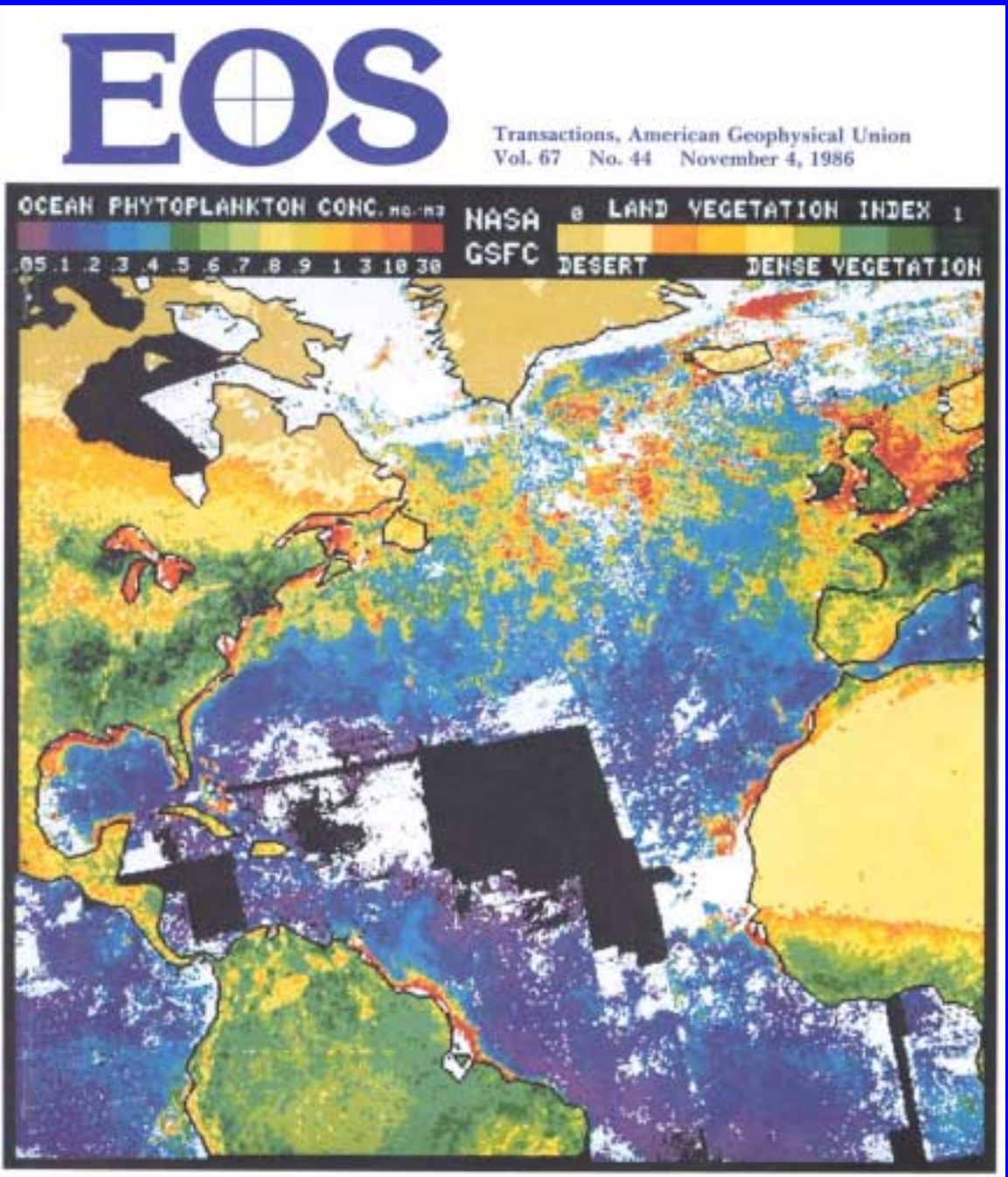
Our concept of "International" ocean science is still odd. We have truly international planning meetings, and data workshops – and any modern shore laboratory has an amazing mix of international personnel. But our cruises are almost 100% national.



This image, now battered and faded, is the original used by Otis Brown at the 1984 GOFS meeting.

It shows the then state-of-the-art of satellite ocean color data processing in laboriously recovering a picture of the spring bloom off the U.S. East coast.

This was a principal part of the ammunition used to persuade NASA to proceed with support for an ocean biogeochemical cycles program.



The "Pac-Man" image on the cover of the 1986 Fall Meeting issue of EOS was a coup.

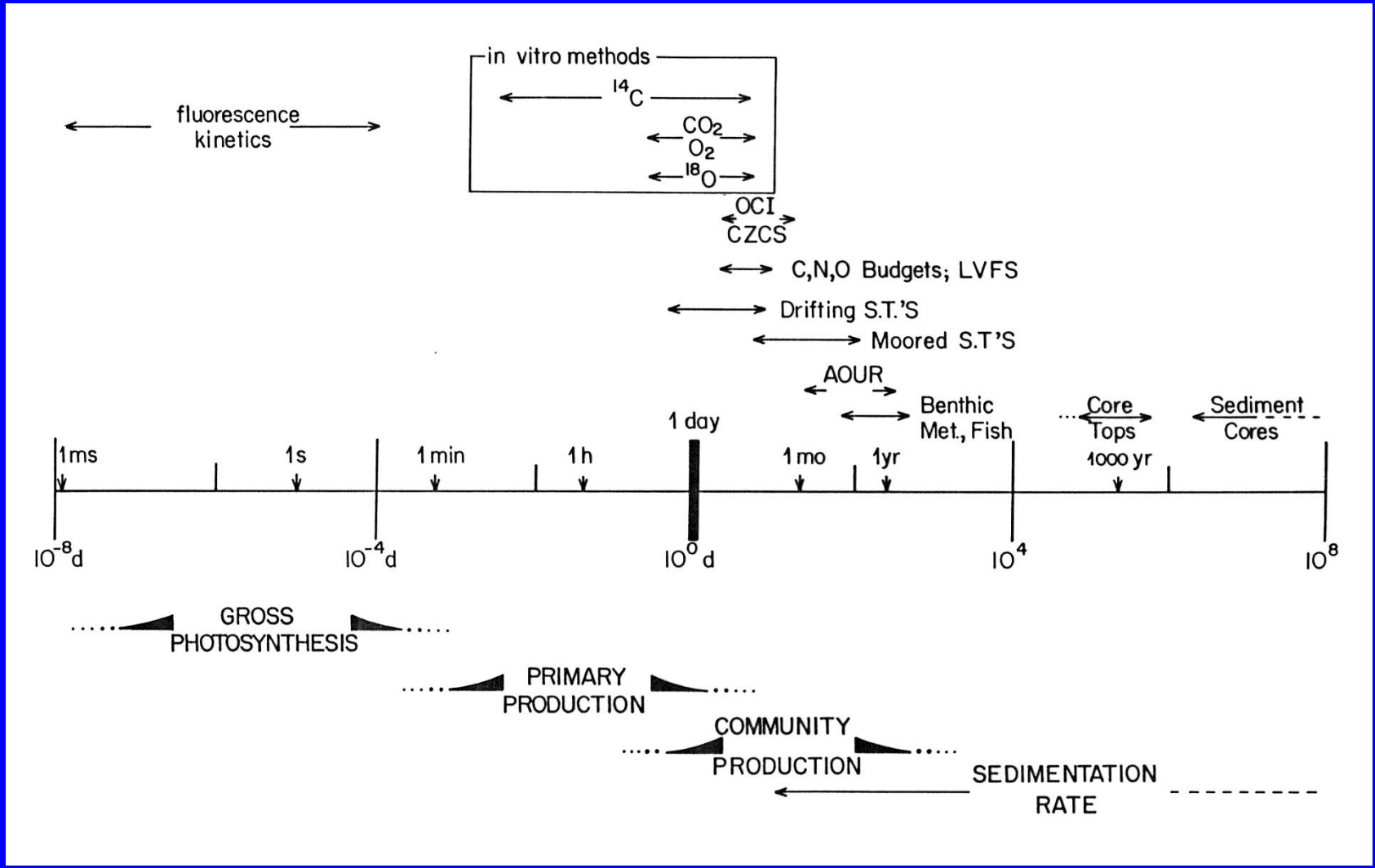
The two papers accompanying this were :

"The Global Ocean Flux Study (GOFS) by Brewer, Bruland, Eppley, and McCarthy.

And "Monthly Satellite-Derived Phytoplankton Pigment Distribution for the North Atlantic Ocean Basin" by Esaias, Feldman, McClain, and Elrod.

This linked the NSF/NASA GOFS effort in very public ways, and cemented a long partnership.

This figure from the EOS paper illustrates the enormous range of time/space scales that were under consideration. A daunting requirement for a coherent program. The scale covers 10^{16} time units!



United States Global Ocean Flux Study

GOFS NEWS

Volume 1, Number 1 May 1989

U.S. GOFS

JGOFS Bloom Study Gets Underway In North Atlantic

Research vessels from five nations are tracking the course of the spring phytoplankton bloom in the North Atlantic as the Joint Global Ocean Flux Study's pilot program gets underway. Sponsored by National Science Foundation's Ocean Sciences Division, U.S. investigators are conducting their studies aboard R/V *Atlantis II*, recently refitted to meet the particular needs of the North Atlantic Bloom Experiment.

Atlantis II left Woods Hole on March 14 for Madeira. During the first leg of her cruise, north to Reykjavik, chief scientist Susumu Honjo of Woods Hole Oceanographic Institution deployed deep sediment trap moorings at 34°N and 47°N.

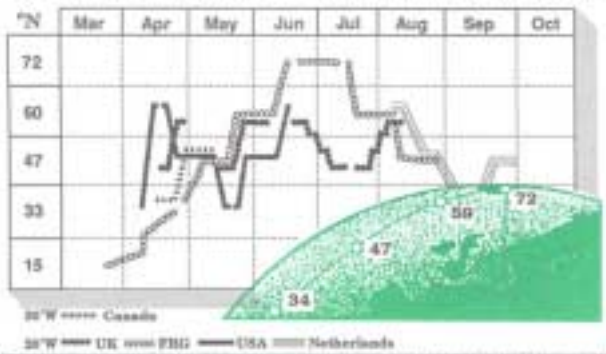
After a brief trip to deploy the Marine Light/Mixed Layer (MLML) mooring for the Office of Naval Research at 50°N, Chief Scientist John Marra of the Lamont-Doherty Geological Observatory sailed from Reykjavik on April 18 to spend approximately three weeks near 47°N with the primary purpose of carrying out Lagrangian studies

Atlantis II left Woods Hole on March 14 to start the U.S. part of the JGOFS Bloom Study.

while following drifters. Hugh Ducklow of the University of Maryland's Horn Point Laboratory, Chief Scientist for Leg 3, will repeat this procedure, sailing from the Azores on May 15. During these two process-oriented legs, the *Atlantis II* will coordinate with the Federal Republic of Germany's *Meteor*, the United Kingdom's *Discovery II* and the National Aeronautic and Space Administration's P-3 flight program. The P-3 will fly from Newfoundland to Madeira at low altitude, acquiring data on chlorophyll fluorescence and temperature across the Atlantic to provide basin-scale views of the bloom field prior to and after the Bloom Study.

Jim Yoder of Skidaway Institute of Oceanography will provide the scientific liaison between the NASA remote sensing program and the JGOFS vessels. Steve Piotrowicz of NOAA's Oceans and Atmosphere Research Division will serve as liaison between the ships and the National Oceanic and Atmospheric Administration's Advanced Very High Resolution Radiometer (AVHRR) remote sensing effort from Plymouth, England. During a series of joint-ship exercises at 47°N and 60°N, *Atlantis II* will collaborate with *Meteor* and *Discovery II* to intercalibrate measurements and attempt to synthesize the U.S. and F.R.G. Lagrangian (time series) observations with the Eulerian (spatial) survey program to be undertaken by the U.K.'s Biogeochemical Ocean Flux Study (BOFS).

(continued on page two)



National cruise transects for Bloom Study. (Courtesy of BOFS Planning Office, Plymouth, U.K.)

The GOFS Newsletter began in 1989 and was widely admired as an excellent resource thanks to the efforts of Mardi Bowles, Hugh Livingston, Anne Edwards, Mary Zawoysky, many loyal contributors, and the support of NSF.

It was always a source of concern that it was not "JGOFS News" but the name and the source stuck. In practice it had wide and enthusiastic international reporting and readership. The many articles excellent reading today. The origin of the triangular satellite footprint in the masthead was a source of puzzlement. It was never changed.

The North Atlantic Experiment was conceived from the outset as a multi-ship, plus satellite and aircraft experiment. It was only in this way that extended time coverage could be gained.

The Spring Bloom from 500 Feet (or How I Joined the JGOFS Air Corps and Lived to Tell the Story)

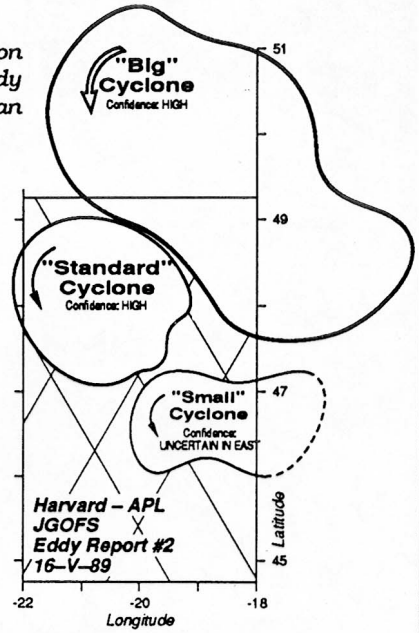
The JGOFS Air Corps provided invaluable service in the pre-satellite years

I learned, for example, that an Irish pub is a far better place to sit out an Atlantic storm than the cabin (and head) on an oceanographic research ship. I also adjusted to military base life, learned how to play darts and even got to like the theme song from "Top Gun," which seems to play endlessly at all officers' clubs.

As an unexpected bonus, we picked up new and unique bar trashing methods from some F-15 pilots based in Kef.

A. R. Robinson
D. J. McGillicuddy
J. Calman

Harvard/APL Modelers Forecast Eddies in North Atlantic for JGOFS Pilot Program



Collaboration between shipboard researchers, the NASA P-3 team and modelers ashore provided participants in the North Atlantic Bloom Experiment with a useful look at the physical structure and dynamics of the ocean in the vicinity of 47°N, 20°W, the focus of the Joint Global Ocean Flux Study (JGOFS) pilot program.

Allan Robinson of Harvard University led a modeling effort during May that synthesized data collected by investigators aboard research vessels *Discovery*, *Meteor* and *Atlantis II*, the P-3 airplane and the GEOSAT altimeter to provide a description of the eddy field in the JGOFS study area and predictions of its evolution.

Reports produced jointly by Robinson and graduate student Dennis McGillicuddy at Harvard and Jack Calman at the Johns Hopkins Applied Physics Laboratory and transmitted to the ships in the North Atlantic identified three eddies of various sizes. The accompanying figure shows the predicted location and shape of these eddies for May 16.

Eddies are the oceanic counterpart of weather systems in the atmosphere, Robinson explained, smaller and slower than atmospheric cyclones but very energetic in comparison with their backgrounds. Knowledge of the physical variables in the ocean enhances the interpretation of biological data, he added, noting that the ability to predict and model eddies has been evolving very rapidly.

Combining satellite information on the hills and valleys in ocean surface height with subsurface data on temperature, pressure and salinity from instruments in the water column makes it possible to model the existence and evolution of eddies, Robinson said. He observed that the nature of the eddy field in the JGOFS study area was almost unknown.

The in situ data is critical to interpreting the information from the

The use of GEOSAT and P-3 XBT Data during the NABE cruise lead Dennis McGillicuddy and colleagues to provide near real-time estimates of the local eddy field. Hugh Ducklow relocated the Atlantis II to sample the center of the largest eddy, and found the drifters headed off in all directions! A revised analysis soon followed.

This early effort to use satellite data in near-real time preceded the TOPEX era, was suggested in the GOFS paper by Bill Jenkins, and has lead to work on episodic mixing continuing today.

French President Francois Mitterand Holds Conference on Planet Earth

by Peter G. Brewer

At the invitation of French President Francois Mitterand, 275 scientists and policymakers from more than 40 countries attended a two-day conference on "Planet Earth" in Paris during June. Proposed by Claude Allegre of the Institut du Physics de Globe to Hubert Curien, French Minister for Research and Technology, the meeting attracted attention at the highest governmental levels. President Mitterand spoke and served as chairman of the closing session.

Your JGOFS reporter attended and notes that issues relating to the oceanic role in global change were high on the agenda.

International News

PLANETE TERRE

PROGRAMME

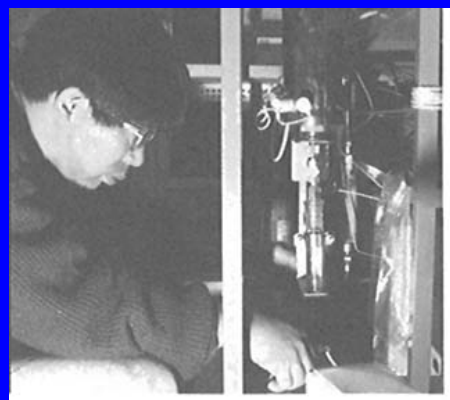
PARIS 12/13 JUIN 1989

The 1989 meeting at the Elysee raised the stakes in the global change game. President Mitterand's call for action drew an immediate response from President Gorbachev, who was concerned that French commitments to buy large amounts of natural gas would be affected.

The pressure on the U.S. to act was elevated and the economics of climate became a major issue.

The Strange Case of DOC

The manuscript by Sugimura and Suzuki provoked an extraordinary response.This purported to show a strong correlation between DOC and AOU, thereby fundamentally challenging long established concepts of ocean biogeochemistry.The technique was examined in great detail, and shown be excellent, although the DOC-AOU correlation did not exist. DOC data are now solid, and provide essential mass balance.



Japanese Scientist Joins U.S. Bloom Cruise

Yoshimi Suzuki returned from his first cruise on a United States research vessel with a harvest of new and provocative data on levels of dissolved organic carbon (DOC) present in the waters of the North Atlantic. A marine chemist from the Meteorological Research Institute in Ibaraki, Japan, Suzuki spent 30 days at sea with U.S. investigators aboard RV *Atlantis II* during the JGOFS North Atlantic Bloom Experiment this spring.

Working side by side, the Japanese scientist and Woods Hole Oceanographic Institution chemist Edward Peltzer collected daily samples from various depths in the water column, developing a profile of data on DOC over time and space as the ship moved northward and the spring phytoplankton bloom developed. Using different equipment with similar techniques and sharing samples with British researchers aboard RV *Discovery*, the two investigators found that their numbers agreed remarkably well after initial signal integration problems were resolved.

Suzuki's high-temperature method of analysing DOC first attracted attention two years ago when he reported figures from North Pacific waters that were two to four times higher than those obtained by traditional methods of analysis. U.S. researchers have recently been able to duplicate his results, suggesting that a missing piece of the oceanic carbon cycle has been found.

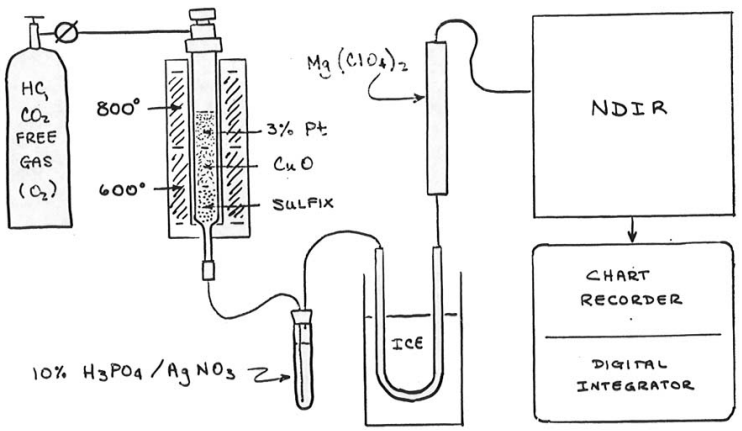
Earlier techniques only measured a fraction of the total, missing the labile or biological portion of DOC in surface and deep waters, Suzuki explained. This missing fraction appears to play an important role in the consumption of oxygen and remineralization of organic nutrients in the deep waters, calling into question the traditional assumption that these processes can be explained by particle flux alone.

The numbers he and Peltzer obtained indicate that the surface waters of the North Atlantic contain less DOC than those of the North Pacific, while the deeper waters contain more. Noting that the Pacific mixes more slowly than the Atlantic, he added that DOC distribution appears to be controlled primarily by lateral flux in the deep Pacific and by convection in the Atlantic.

The ocean contains a major understudied reservoir of carbon, said WHOI chemist Peter Brewer. The new data on DOC reveal information on the cycling of carbon in the ocean in a way that no other study has been able to do and help shed light on the ways in which the ocean affects carbon dioxide levels in the atmosphere, he added.

Suzuki's participation in the Bloom study was supported with funds from the Andrew W. Mellon Foundation, arranged through the U.S. GOFS Planning Office. He and Peltzer plan to submit a joint publication to Nature on the results of their work in the North Atlantic.

Characterized by his shipmates as a tireless worker, Suzuki expressed his appreciation of the good planning and technical help aboard *Atlantis II*. On a Japanese ship, where technical support is often unavailable, he said he would have had to work 20-hour days.



INSTRUMENT	Shimadzu	Ionics	WHOI
Furnace T °C	680	800	800
Catalyst	Pt/quartz	Pt	3% Pt
Carrier	Air	O_2	O_2
CuO Catalyst	No	No	Yes
Sulfix	No	No	Yes
Acid trap	Yes	Sn	Yes
Condenser	Yes	No	Yes
Desiccant	No	No	Yes

4504 Air-sea interactions
KEEPING GLOBAL CHANGE HONEST
W.S. Broecker (Lamont-Doherty Geological Observatory of Columbia University, Palisades, NY 10964)

The lure of global change funding creates the temptation to exaggerate the relevance of research projects to the greenhouse warming problem. Such exaggeration makes the task of policy makers far more difficult. They must not only try to sort out the conflicting scientific opinion but also figure out where science ends and entrepreneurship begins. The claim by the JGOFS program that biological cycling of carbon in th[illegible] of fossil fuel CO_2 by the sea is a[illegible] feeling is that marine biology ve[illegible] ocean uptake. If it does the rout[illegible] overfishing on marine ecology, [illegible] our capacity to document.

Not everyone agreed with the research thrust

The comment by Wally Broecker that "I would give JGOFS a better ranking than WOCE" was divisive and drew sharp responses … but ..

Greenhouse Bandwagon Rolls On

How much must you know about Earth to predict how mankind's depredations will change it in the next millennium? Should you understand in a general way how the ocean sucks carbon dioxide, a greenhouse gas, out of the atmosphere? Sure. Do you need a research project to learn all the details of how the ocean carries that carbon into the deep sea? Wallace Broecker thinks that's irrelevant to global change, and he is taking the unusual step of telling his colleagues so in the next issue of *Global Biogeochemical Cycles*.

It's not that the science in that project—the Joint Global Ocean Flux Study (JGOFS)—and others like it isn't worthwhile, Broecker says; it's the trendy, grant-enticing packaging that gets his goat. Too many scientists with too little to contribute to predicting the fate of the planet have discovered the funding benefits of jumping on the global change bandwagon, says the prominent and sometimes cantankerous marine geochemist at Lamont-Doherty Geological Observatory. He sees "a growing tendency for environmental science programs to hitch their wagons to the greenhouse star." He adds: "Let's keep global change honest!"

Broecker's concern is that mislabeling will leave policy-makers, rather than scientists, to sort out "where science ends and entrepreneurship begins." And some earth scientists agree. Paleoclimatologist Thomas [illegible] enough to base JGOFS on a single scenario such as Wally's."

Broecker is ready to respond to such arguments with what he considers an even more egregious case, the World Ocean Circulation Experiment (WOCE). A 40-nation effort to understand ocean circulation, WOCE was conceived before global change became popular, says climate modeler Robert E. Dickinson of the University of Arizona. But, he notes, it is "now selling itself in terms of global change, though sometimes it's a little hard to see the connection." Broecker is harsher: "I would give [even] JGOFS a better ranking than WOCE."

Wallace Broecker

Joe Pinkston/Columbia U.

But then again, Dickinson isn't convinced that the selling of WOCE is such a bad thing. Who's to say, he asks, that a detailed understanding of ocean currents won't prove vital in an effort to understand the climatic effects of carbon dioxide? "If global change were too focused, we would probably miss things," he says. Modeler Gerald North of Texas A&M also tends to be tolerant of less-than-precise labeling of projects. Giving a fundamental science project a fashionable rubric is sometimes the best way to keep essential money flowing, he says.

In any case, Dickinson says, the trend Broecker deplores is already on the wane. A few years ago, he notes, some researchers hoped public interest in global change would provide an opportunity to stage studies on the grand scale of the International Geophysical Year of 1957-58. Global change, they thought, justified studying everything from Earth's core to its magnetosphere to the surface of the sun. Much of that undiscriminating holistic approach is already gone, Dickinson says, and the weeding continues.

In the most recent budget cycle, for example, the National Science Foundation withdrew its mid-ocean ridge study from the federal global change package and reclassified it as basic science. RIDGE (Ridge Interdisciplinary Global Experiment) will indeed study a source of climate change: variations in the output of carbon dioxide-laden fluids from hot springs on the ocean floor. The only catch is that the resulting climate changes take millions of years. Not quite what's needed to predict the globe's temperature in 2025. ■ RICHARD A. KERR

Boston Loses 1992 AIDS Meeting

Global Change Program

Wallace Broecker is quoted by Richard A. Kerr (News & Comment, 23 Aug., p. 845) as proclaiming that the World Ocean Circulation Experiment is an "egregious" example of "trendy, grant-enticing packaging" linked to the "global change bandwagon." Those people who have worked hard to design an effective global change program were not even given the courtesy of being asked for a response.

The substance of the issue is that the World Ocean Circulation Experiment (WOCE) is directed at achieving a zero-order understanding of how the ocean transports momentum, heat, fresh water, and biochemically active substances; how, where, and why these quantities are exchanged with the atmosphere; and how they change through time. For example, the ocean carries about half the global meridional flux of heat from equator to pole and is a major factor in determining today's climate state. We do not know whether this flux is stable from month to month or from year to year, nor do we know what mechanisms control its value. WOCE attempts to bring about an understanding of these processes, among a myriad of other related goals. Assertions that such problems are not connected with understanding global change are foolish. Those who insist that their own specific interests define the boundaries of useful and interesting work appear to be practicing a form of religious fundamentalism that should not be confused with science.

CARL WUNSCH*
Center for Meteorology and Physical Oceanography, Department of Earth, Atmospheric, and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA 02139

*Co-Chairman, U.S. Steering Committee for the World Ocean Circulation Experiment.

These comments drew strong responses. The goals of JGOFS required dealing with a "real", and not a simpler "tracer" ocean.

But the ability to separate the fossil fuel signal from the biological cycle was too hard for some to grasp.

The "missing carbon" phrase was unfortunate at best, and it misled many. The NABE experience finally laid many misconceptions to rest.

AT 1,411 METERS we spot the muddy bottom and head north to seek the canyon wall. An unexpected current buffets us for a few moments. Abruptly it vanishes, and at 1,512 meters we are staring at a wall landscaped with crinoids, sea anemones, sponges, and sea stars.

We are surely the first humans to lay eyes on this wall. But at this moment Robie's mind is back on larvaceans. The seafloor is littered with clumps of larvacean houses. He is excited that so much mucus is making it down without being eaten. An arcane, perhaps bizarre reason to be excited? Hardly.

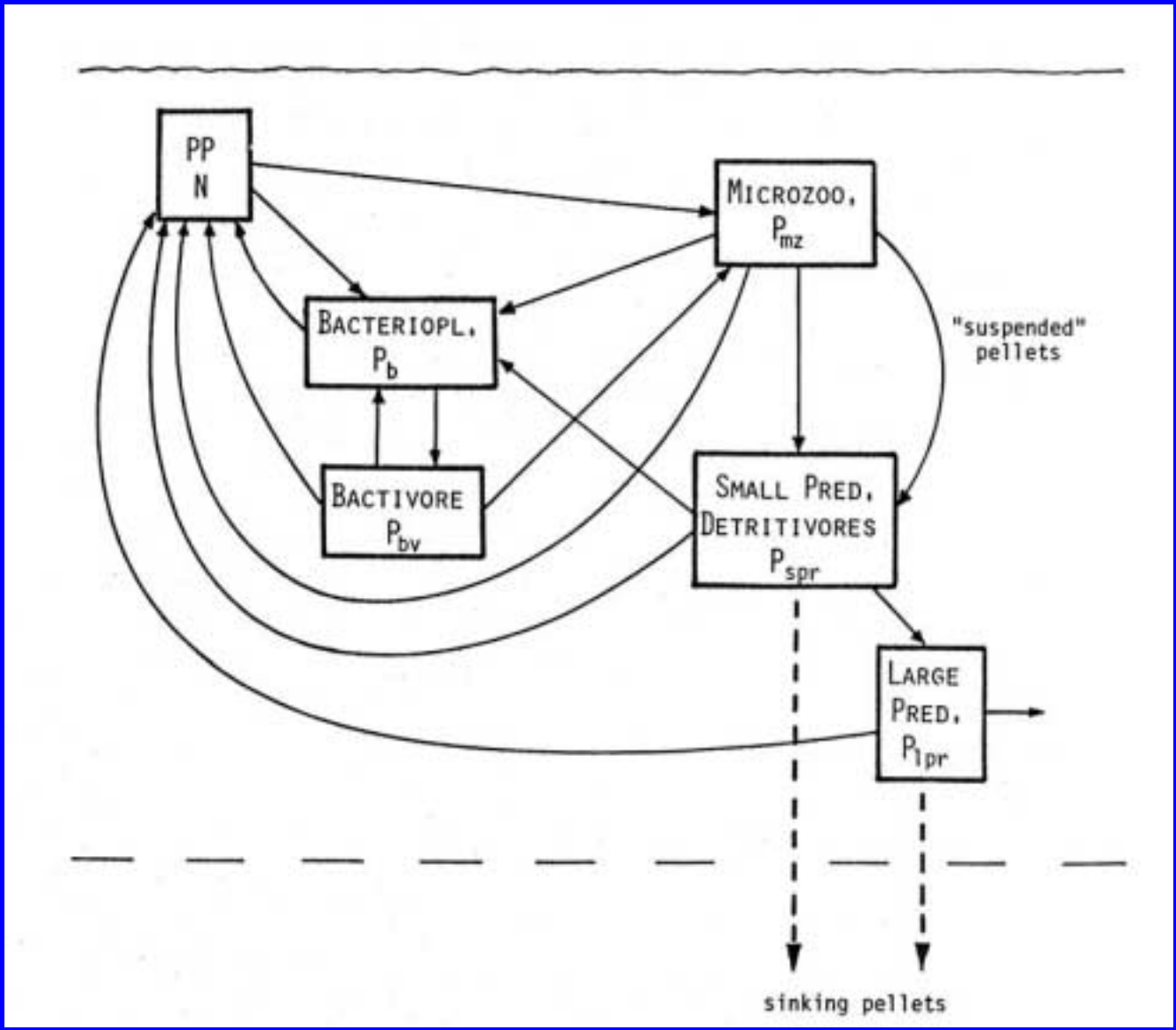
Scientists who study the flow of carbon through the biosphere have been puzzled. They cannot find all the excess carbon dioxide that their calculations say humans, by burning fossil fuels, are pumping into the atmosphere. Even though carbon dioxide levels are rising ominously, some process, likely biological, seems to be moderating the buildup.

One way nature removes CO_2 is through photosynthesis in the oceans. Plankton turn dissolved CO_2 into organic matter, which may later be eaten by animals. The animals then return to the atmosphere, through their own respiration, much of the carbon the plankton removed. Organic matter also falls [illegible]

The Role of JGOFS and NSF in Guiding the Development of an Fe Enrichment Experiment

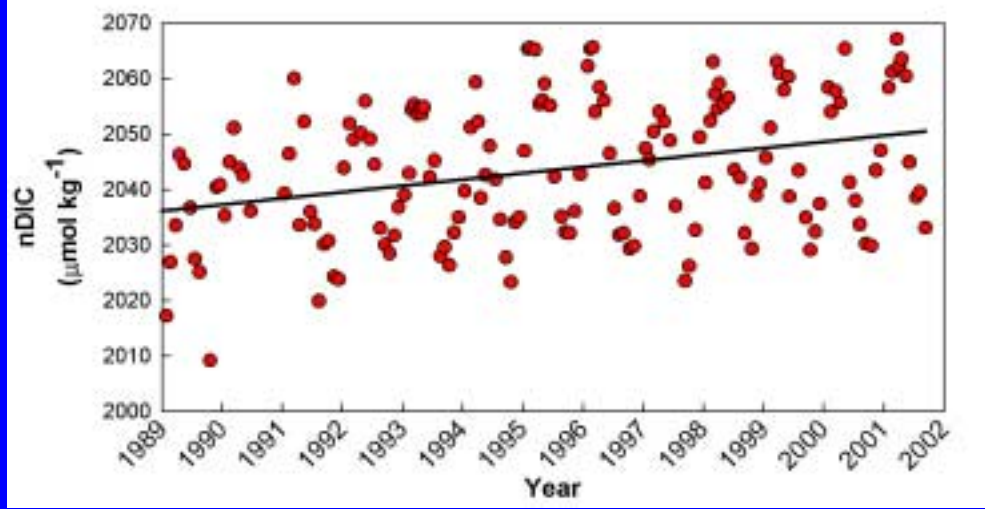
- *John Martin brought his hypothesis to the US JGOFS Steering Committee for endorsement and support within the JGOFS framework.*
- *The SC voted against this since it was not part of the planning process that had been carefully carried out.*
- *Neil Andersen and I consulted, and agreed that John was correct, and the work would be of great value.*
- *A creative exchange with ONR was arranged, so that through an exchange of P.I. Support the Fe experiment could proceed while still preserving the norms of SC guidance.*
- *Later a painful but memorable conversation with John in his kitchen lead to the his acceptance of a co-P.I. to provide continuity in case of his incapacity.*

Bruce Frost's 1984 Ecosystem Model from the GOFS Report

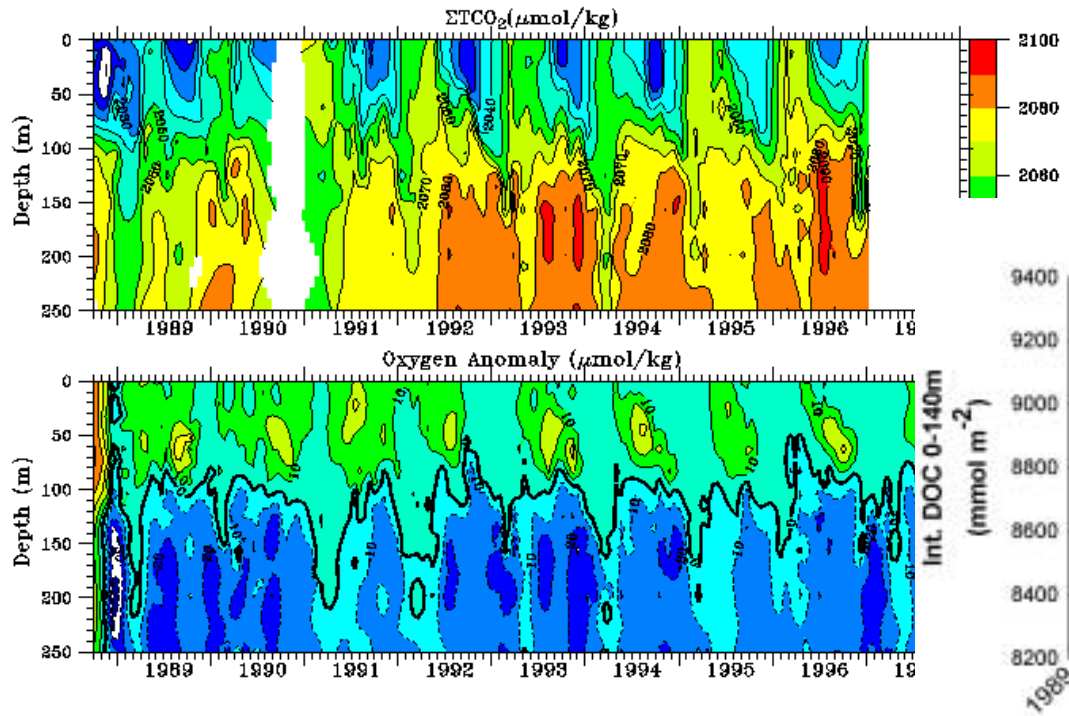


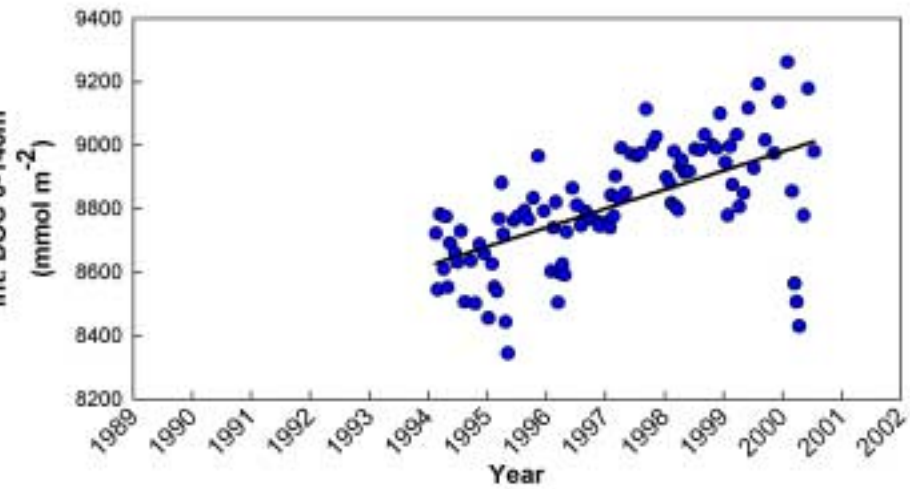
The population of models of this kind with real data has provided many breakthroughs in JGOFS.

The huge importance of the microbial loop was under-estimated by geochemists. It accounts for the extraordinarily rapid re-cycling of organic matter, and thus the inefficiency of Fe-CO_2 sequestration.

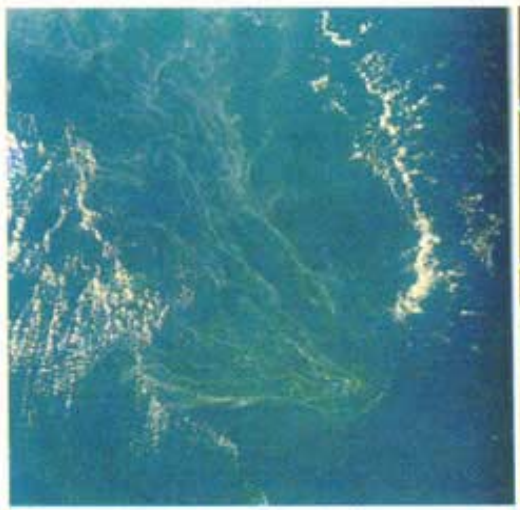


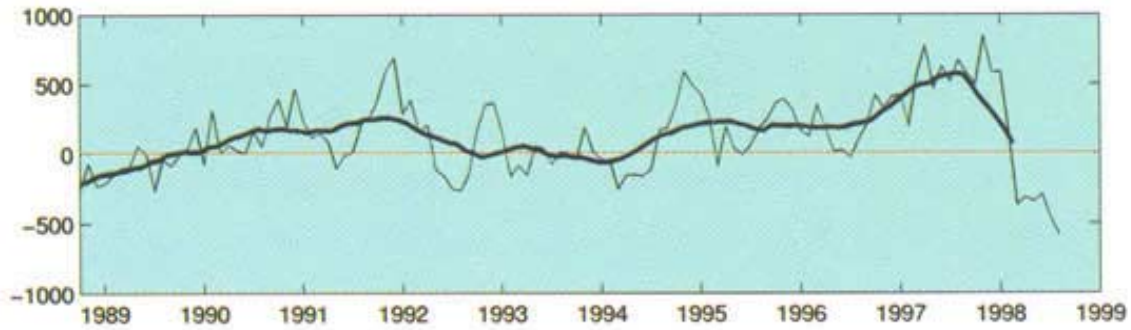
The BATS station beautifully reveals the rise in ocean TCO_2. However the summer draw-down, and oxygen anomaly, indicate microbial(?) processes not yet fully understood. Modeling of these data provides fertile ground for theory and prediction.

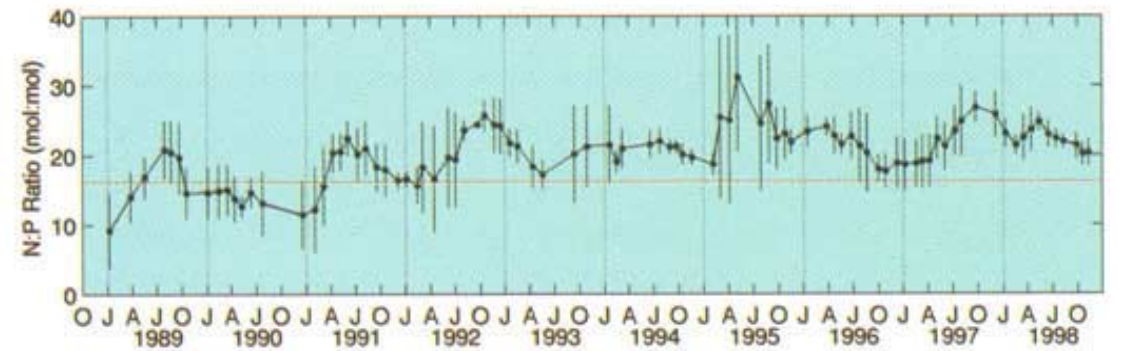




Ocean Time Series Stations







HOTS data – D. Karl

The observed trend towards N fixation in the Pacific gyre is unanticipated, and possibly heralds a major climate driven shift in marine ecosystems of very large scale. The long term significance is unknown. "Good" or "Bad"?

More observations are needed through international networks. They may place increasing pressure on governments to act.

The 14 year record at Bermuda and Hawaii shows ΣCO_2 increasing at 0.06% per yr. DOC is increasing 10x faster.

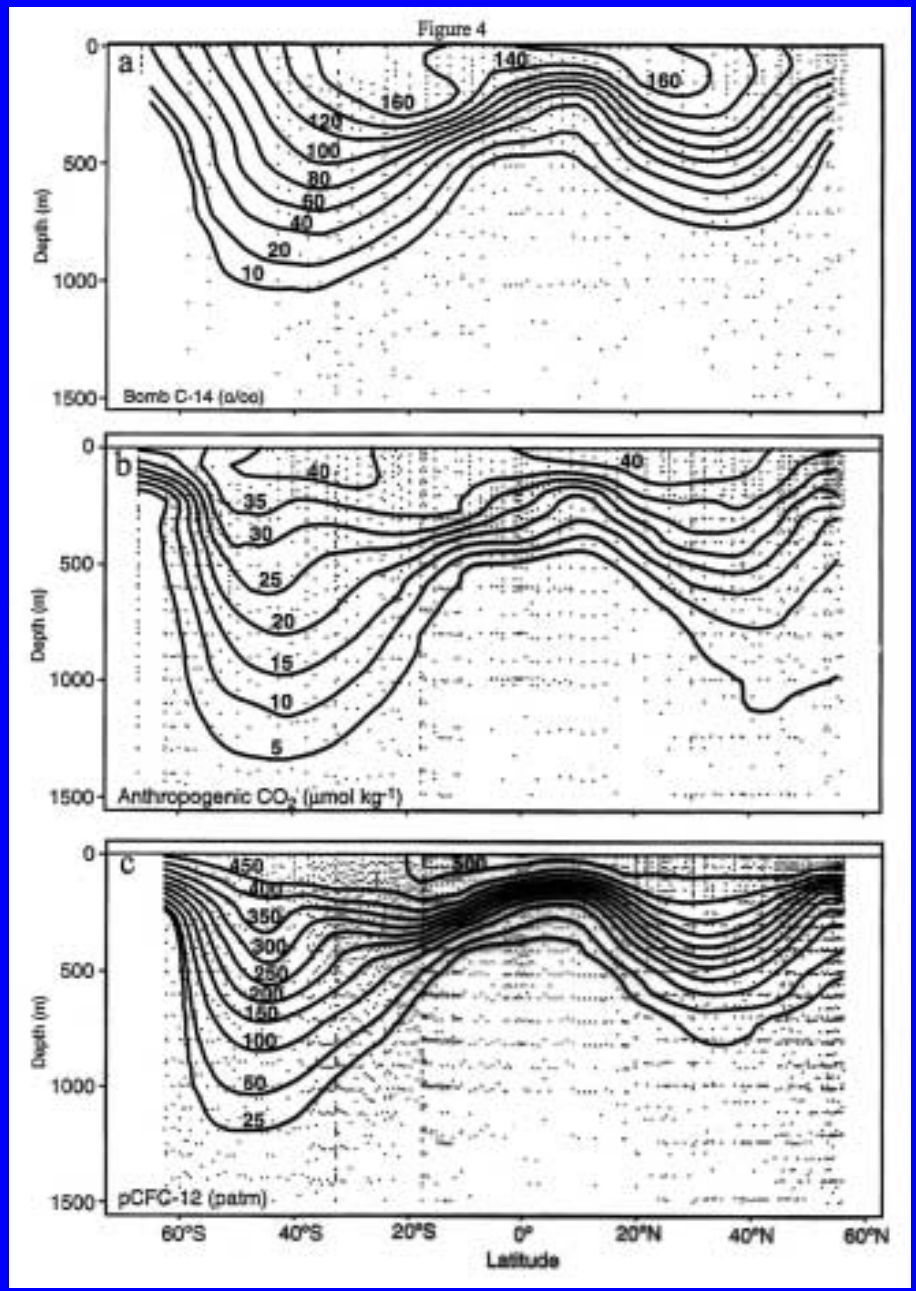
What Will the Ocean of the Future Look Like? - And How Will We Observe and Understand It?

- *In the early days of JGOFS we learned how the ocean influenced the carbon cycle, and there was a sense, possibly naïve, that ocean biogeochemical cycles would influence the unfolding "climate" or "global change" story. The fossil fuel signal was small compared to the background ocean cycles.*

- *In the near future the anthropogenic CO_2 signal will overwhelm nature, and the CO_2 will tend to drive the ocean biogeochemical cycles.The accumulated CO_2 burden is now >300 billion tons of CO_2 and is rising.*

- *There is little political will to change this, and even extreme "stabilization" scenarios assume that CO_2 will only be put into the air at the rate at which it is removed by "natural" processes. The land biosphere will tend to saturation, and thus ocean uptake will be dominant. The use of expanded nuclear or other sources simply means that fossil fuels will be burned more slowly. There is no scenario in which fossil fuels are eliminated, and thus we must face the science of a high CO_2 ocean. This will pose substantial new challenges!*

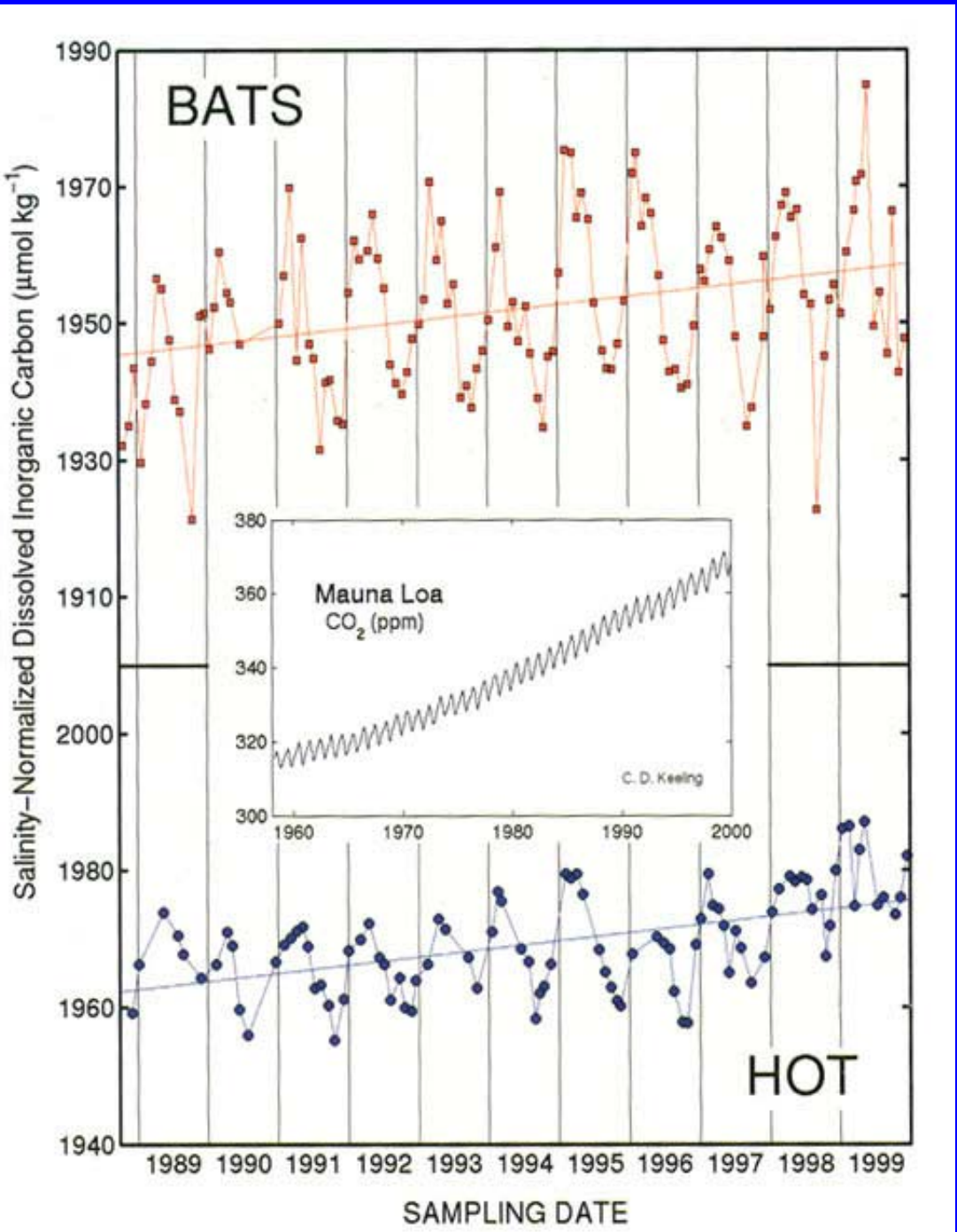
Ocean CO_2 "Disposal" Today *From Sabine et al. (2002)*



Results of the JGOFS/WOCE survey. Pacific meridional section of ^{14}C (top), fossil fuel CO_2 (middle), and pCFC-12 (lower).

The fossil fuel signal has penetrated to >1000m. Surface values reach 50µmol/kg (2.2 mg/kg). The inventory is 44.5±5 Pg C in 1994.

We had already disposed of 163 billion tons of CO_2 in Pacific Ocean waters by the early 1990's, and global surface ocean CO_2 "disposal" is now about 20-25 million tons per day. This will continue apace.

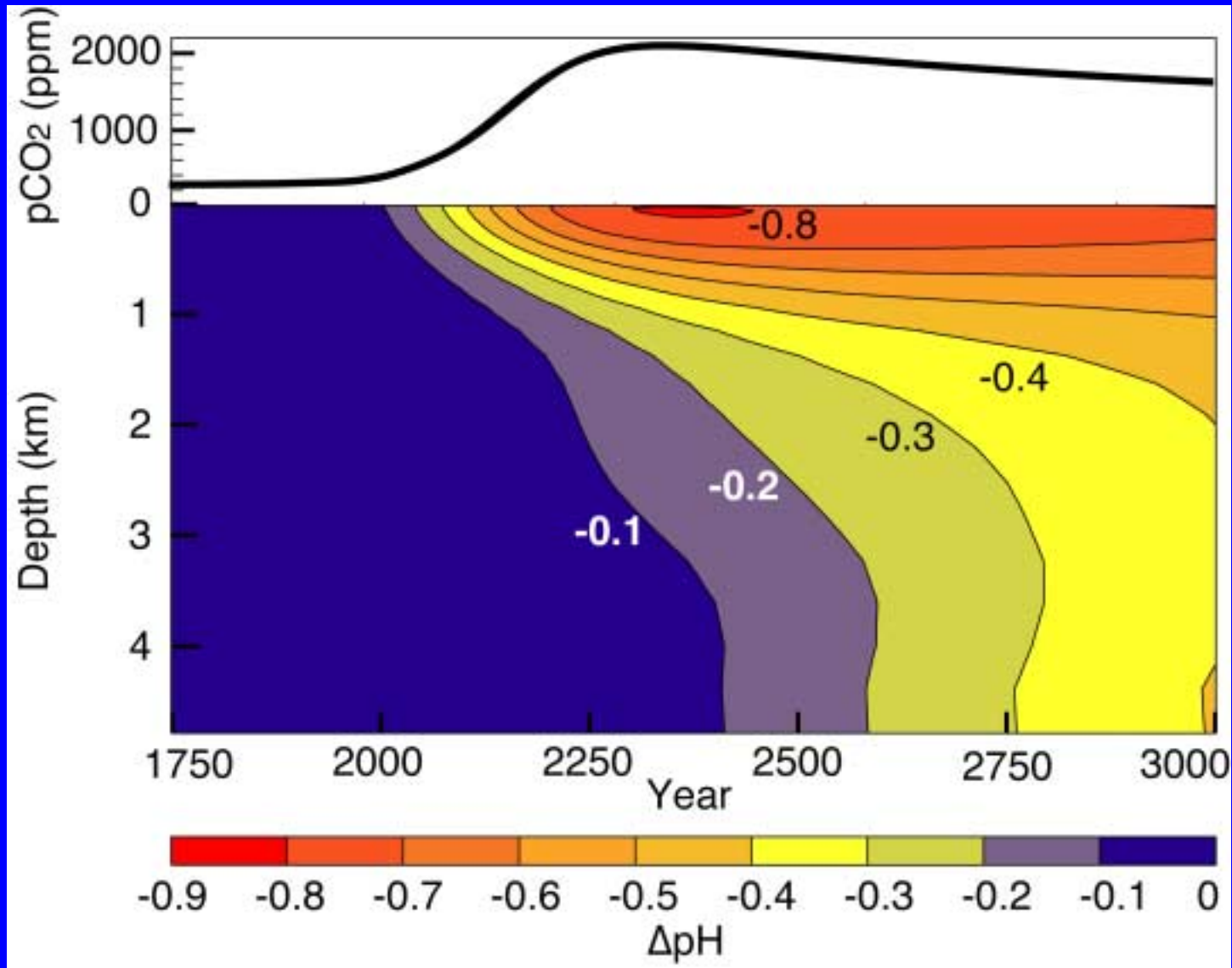


We only have two true time series stations with the full suite of measurements – the MBARI station comes close. Both the BATS and HOT sites show the expected upward trend in CO_2.

But how high will they go? – and are there limits to what the modern ocean will "tolerate"?

Dangerous interference with physical climate is much debated. But the concept of limits to acceptable ocean chemistry/biology has not been addressed.

Atmospheric CO2 and average ocean ΔpH resulting from historic CO2 (1750–2000), IS92a emissions (2000-2100), and logistic CO2 emissions (2100-3000) (~5700 GtC total) Calculated using LLNL ocean GCM assuming neutral land biosphere.



From Caldeira 2003

The evolving chemistry of surface sea water under "Business as Usual"

Time	pCO_2	Total CO_2	pH	HCO_3^-	CO_3^{2-}	H_2CO_3
yr.	µatm	µmol kg^{-1}		µmol kg^{-1}	µmol kg^{-1}	µmol kg^{-1}
1800	280	2017	8.191	1789	217	10.5
1996	360	2067	8.101	1869	184	13.5
2020	440	2105	8.028	1928	161	16.5
2040	510	2131	7.972	1968	144	19.1
2060	600	2158	7.911	2008	128	22.5
2080	700	2182	7.851	2043	113	26.2
2100	850	2212	7.775	2083	97	31.8

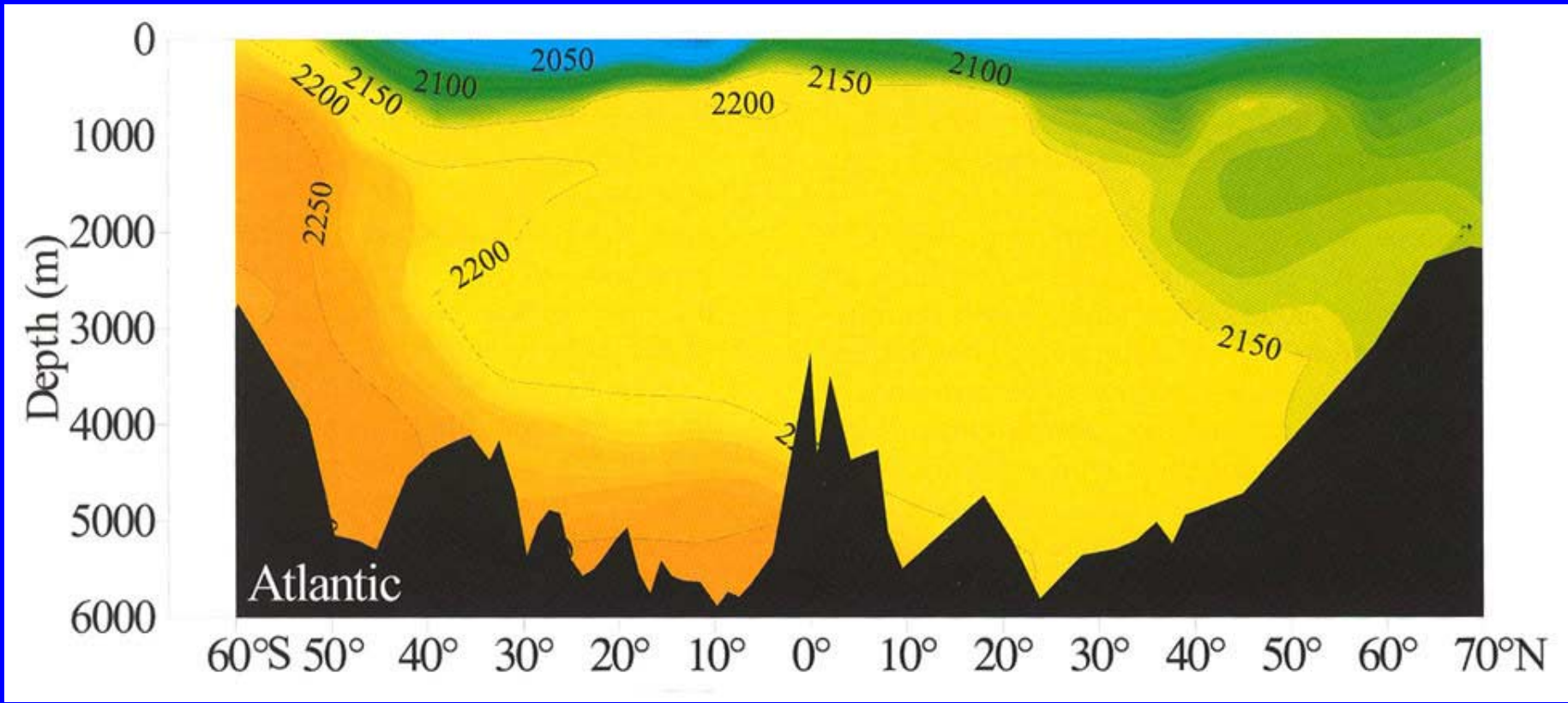
From Brewer, 1997

Under IPCC "Business as Usual" the pH of surface sea water drops by 0.4 pH units by 2100. $CO_3^=$ in surface water drops by 55% from pre-industrial values. It will be hard to meet even these goals.

Fossil fuel CO_2 is now a major ion of sea water.

The Pre-Industrial CO_2 signal for the Atlantic Ocean: from Feely et al (2001)

By the year 2060 the increase in surface water TCO_2 will be ≅140 μ mol/kg. This is very close to the total pre-industrial water column variation seen at e.g. Bermuda. Surface pH will be ~ 0.3 pH units lower, and these trends will be VERY hard to reverse. It thus seems probable that we will dominate the natural cycle with unknown consequences. The "mesocosms" and models of today are not enough.



How are elevated environmental CO_2 levels investigated on land?

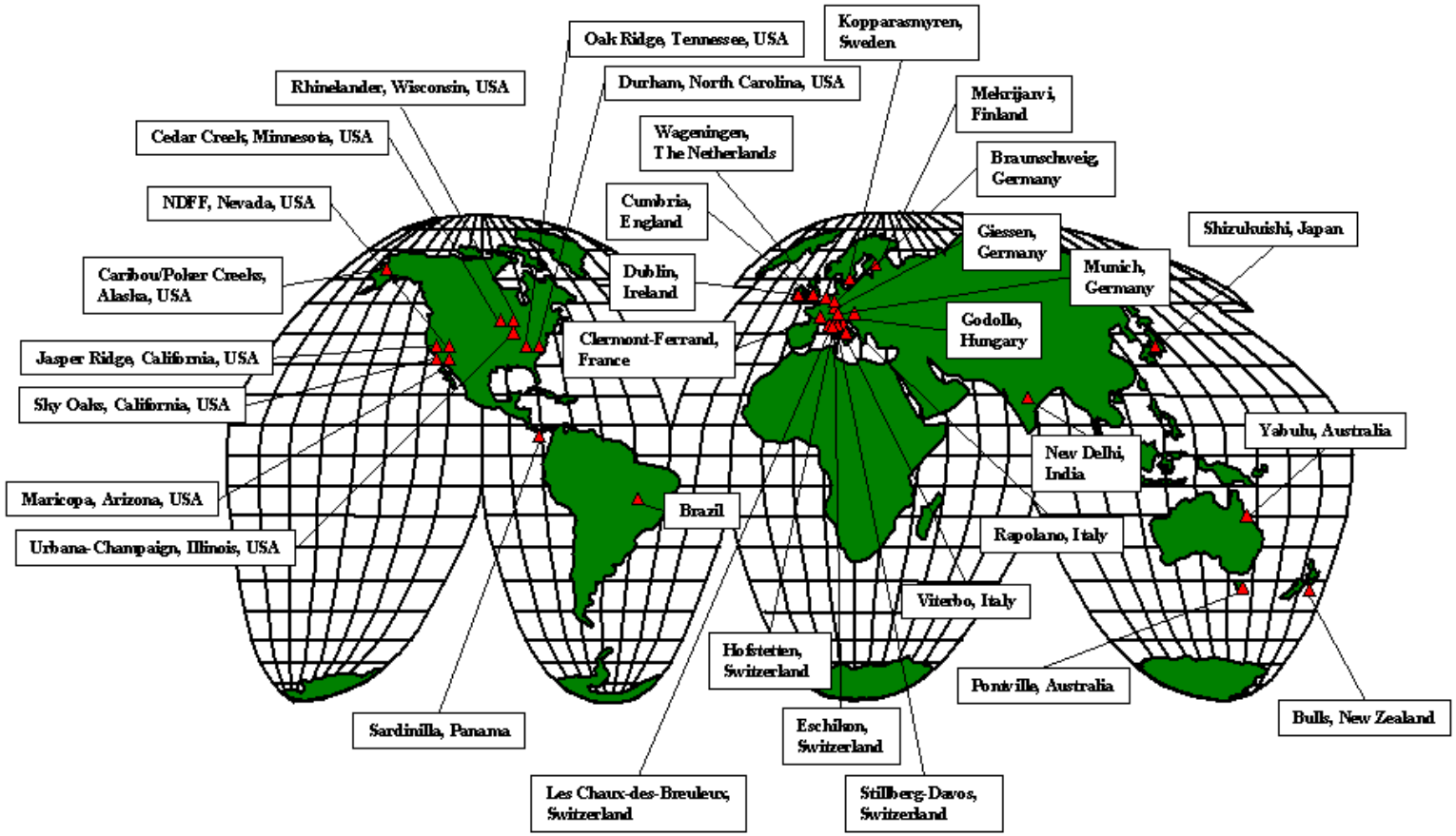
Large Scale CO_2 Enrichment Experiments on Land

FACE (Free Air CO_2 Enrichment)

FACE experimental site in a 13 year old 14m high Loblolly Pine plantation in North Carolina. The rings are 30m diameter. There are 3 experimental rings and 3 blanks. The CO_2 concentration was enriched by 200ppm over modern air (~560 ppm). The experiment ran for 2 years +. The result was a 26% increase in productivity, but cautions were given that this may not be sustainable or typical.

From DeLucia et al. (1999)

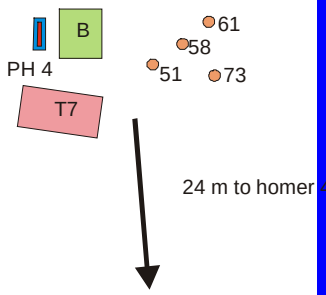
FACE Experimental Sites – *there are two ocean time series stations!*

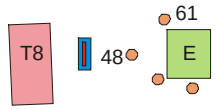


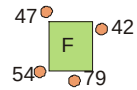
View of FACE Site Showing Piping, Valves, and Sensors

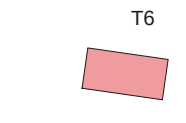
The complexity of such a site would pose challenges in the ocean where system servicing would be carried out by ROVs, and piping would extend to depth. Is this possible?

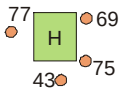
CO2 release exp. II – Oct. – Dec. 2001

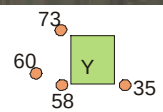


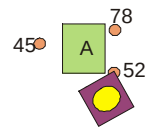


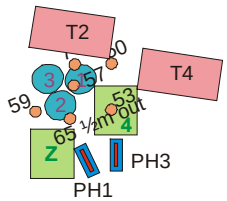




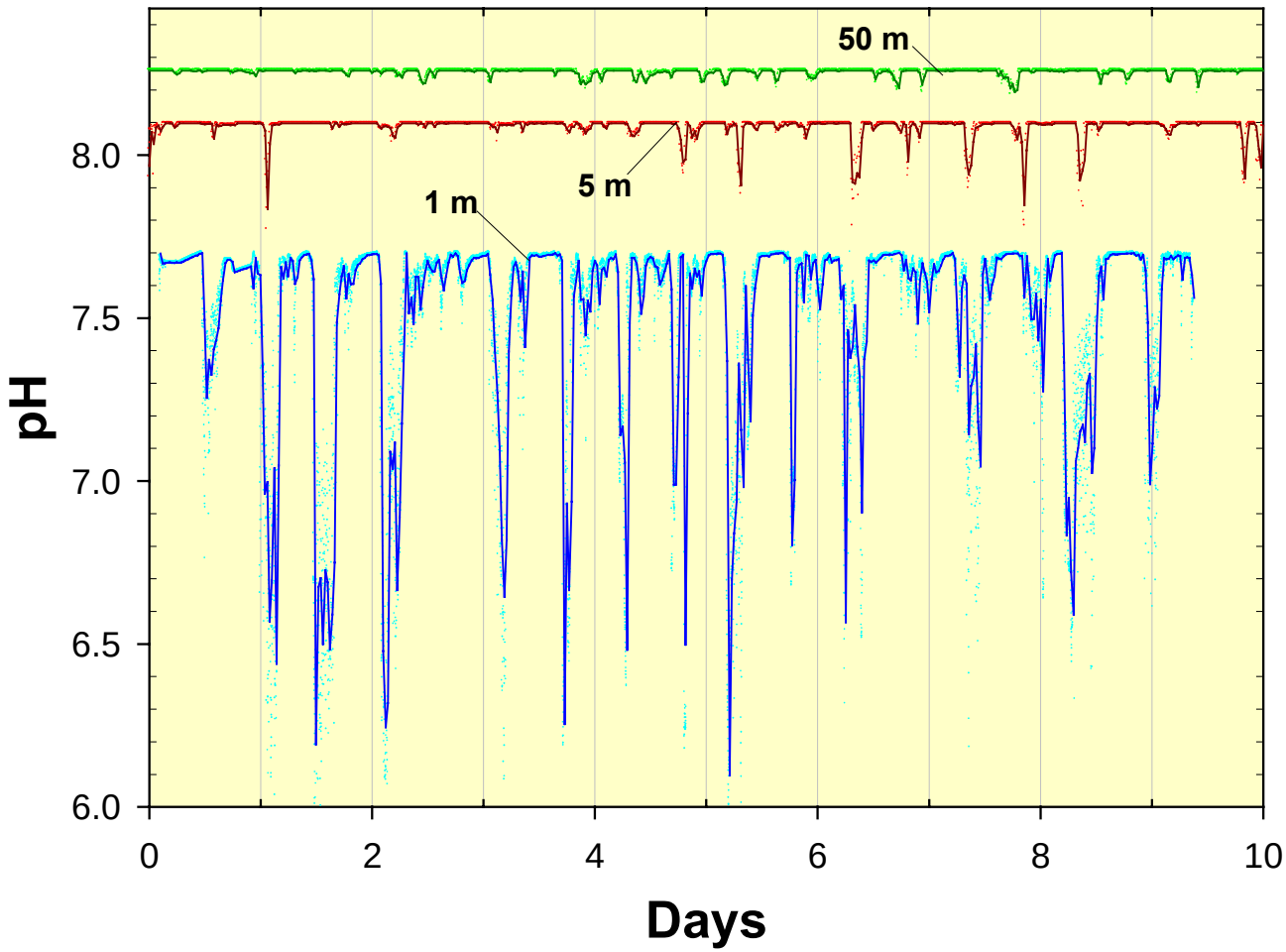








Data fragment over 10 days from recording pH sensors at 1, 5, and 50m distance from the central CO_2 corral site. The instrument drift has been removed, and the baseline data normalized to true ocean background values.



Acknowledgements

•To all those who did the work, at sea and on land

• To the National Science Foundation for 20 years of support

•To NASA for finally flying a superb sensor under difficult constraints

• To my colleagues in the Planning Office for constant support

• To those who are no longer with us:
John Martin, Roger Chesselet …..

• To the David & Lucile Packard Foundation for leadership in new ocean Science and Technology

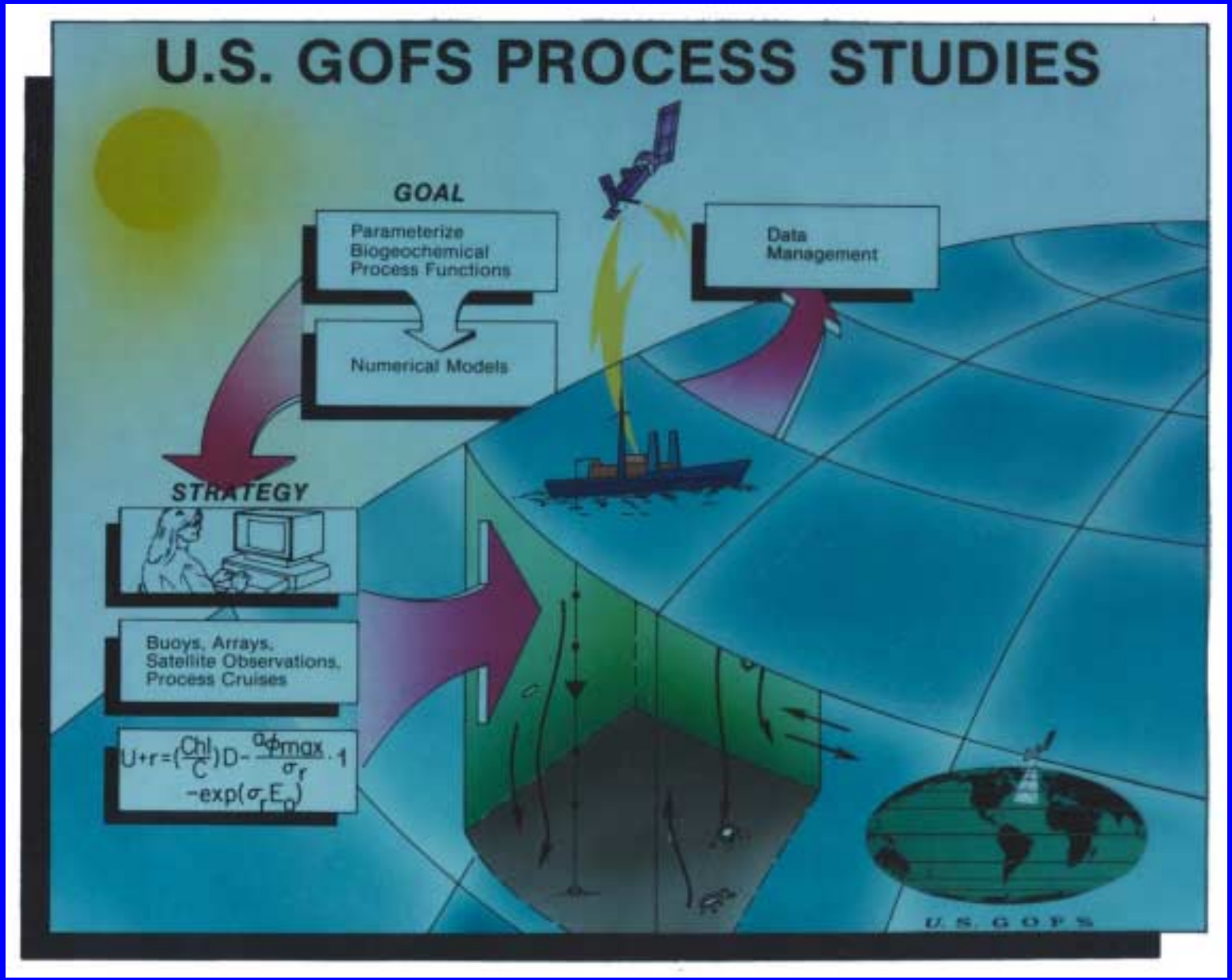
and ….

Epiloque

Jack Gibbons, former Presidential science advisor, was fond of quoting Edna St. Vincent Millay:

> ***"Upon this gifted age, in its dark hour,***
> ***Rains from the sky a meteoric shower***
> ***Of facts … They lie unquestioned, uncombined.***
> ***Wisdom enough to leech us of our ill***
> ***Is daily spun; but there exists no loom***
> ***To weave it into fabric."***

The JGOFS community began with an incoherent mixture of techniques and observations – and played a major role in weaving the fabric of global biogeochemical cycles that we see today. It is a remarkable achievement.


U.S. GOFS PROCESS STUDIES
GOAL
Parameterize Biogeochemical Process Functions
Numerical Models
Data Management
STRATEGY
Buoys, Arrays, Satellite Observations, Process Cruises
$U+r=(\frac{Chl}{C})D-\frac{a\phi_{max}}{\sigma_r}\cdot 1-\exp(\sigma_r E_0)$
U.S. GOFS