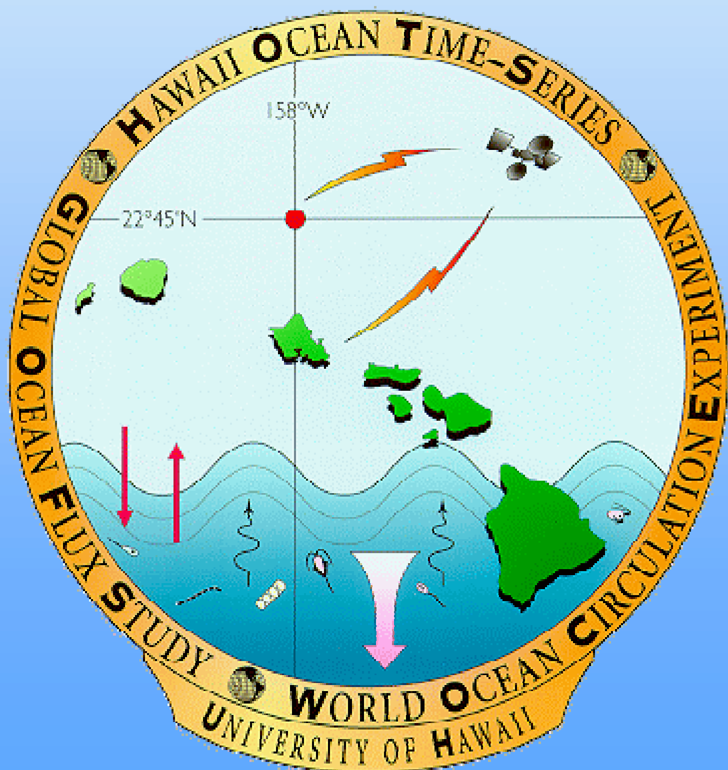
JGOFS Accomplishments and New Challenges



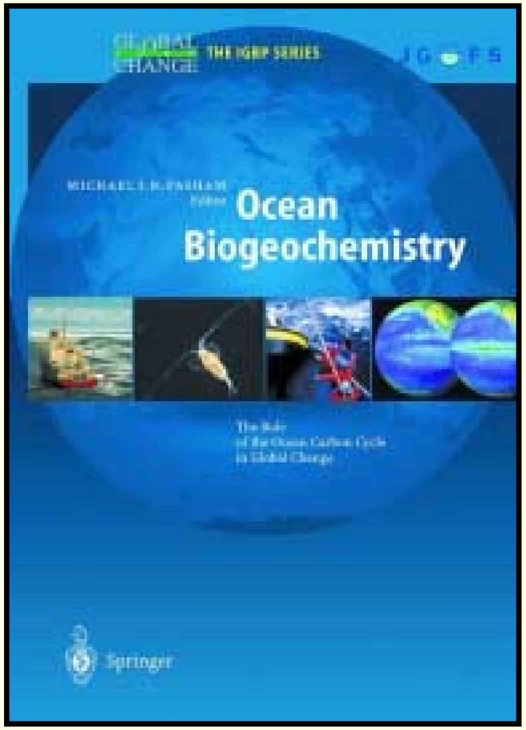
David M. Karl
USA

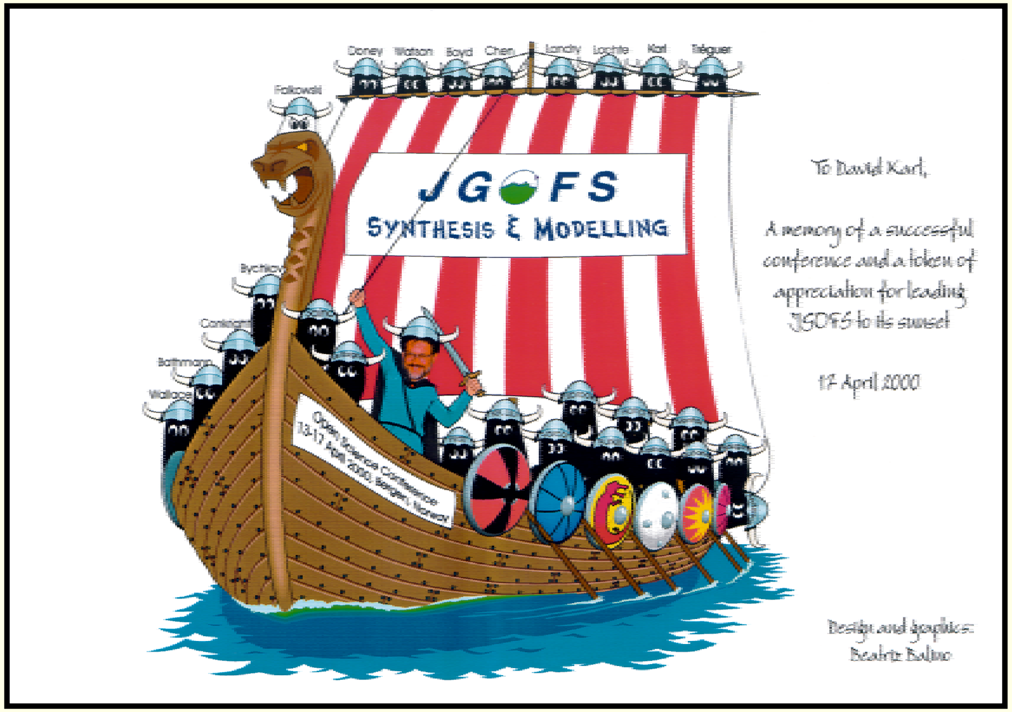
JGOFS

ACKNOWLEDGMENTS

- Local organizing committee: Mark, Mardi, Ken, Duck, Liz, Roger and Mary
- JGOFS planners, field participants and data synthesizers/modelers: 1982-present
- National and international funding agencies who provided the support to make JGOFS happen!

ACKNOWLEDGMENTS

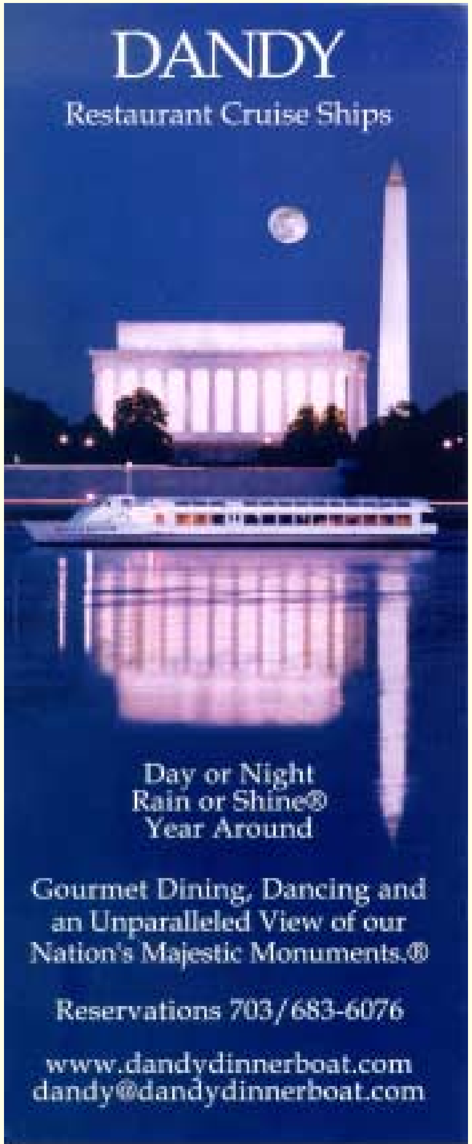




- Mike Fasham for his heroic efforts following the Bergen JGOFS-OSC in 2000

ACKNOWLEDGMENTS

- Debbie Steinberg, Chair, and her Scientific Program Steering Committee



All aboard!

Nina's Dandy

"The ship for all reasons, and the ship for all seasons"

Potomac River
luncheon cruise
departs today
at 1300 hrs!!

PREFACE

- Undersampling is a fact of life in oceanography: Our understanding is limited by lack of field observations (ignorance >> knowledge)
- Ocean biogeochemistry and metabolism are time-variable, climate-sensitive, non steady-state processes that must be studied as such
- Microbial community structure matters – variations thereof control C-N-P biodynamics and carbon sequestration in the sea

OUTLINE

- What was achieved by JGOFS?
- Case study: Hawaii Ocean Time-series (HOT)
- Where do we go from here?

WHAT IS JGOFS?
(http://www.uib.no/jgofs)

- International, multi-disciplinary programme with participants in more than 20 countries
- Launched in Paris in Feb 1987 under auspices of SCOR-ICSU
- In 1989 became a core project of IGBP
- Field work began in Oct 1988 with establishment of two open ocean time-series programmes (HOT/BATS)

JGOFS

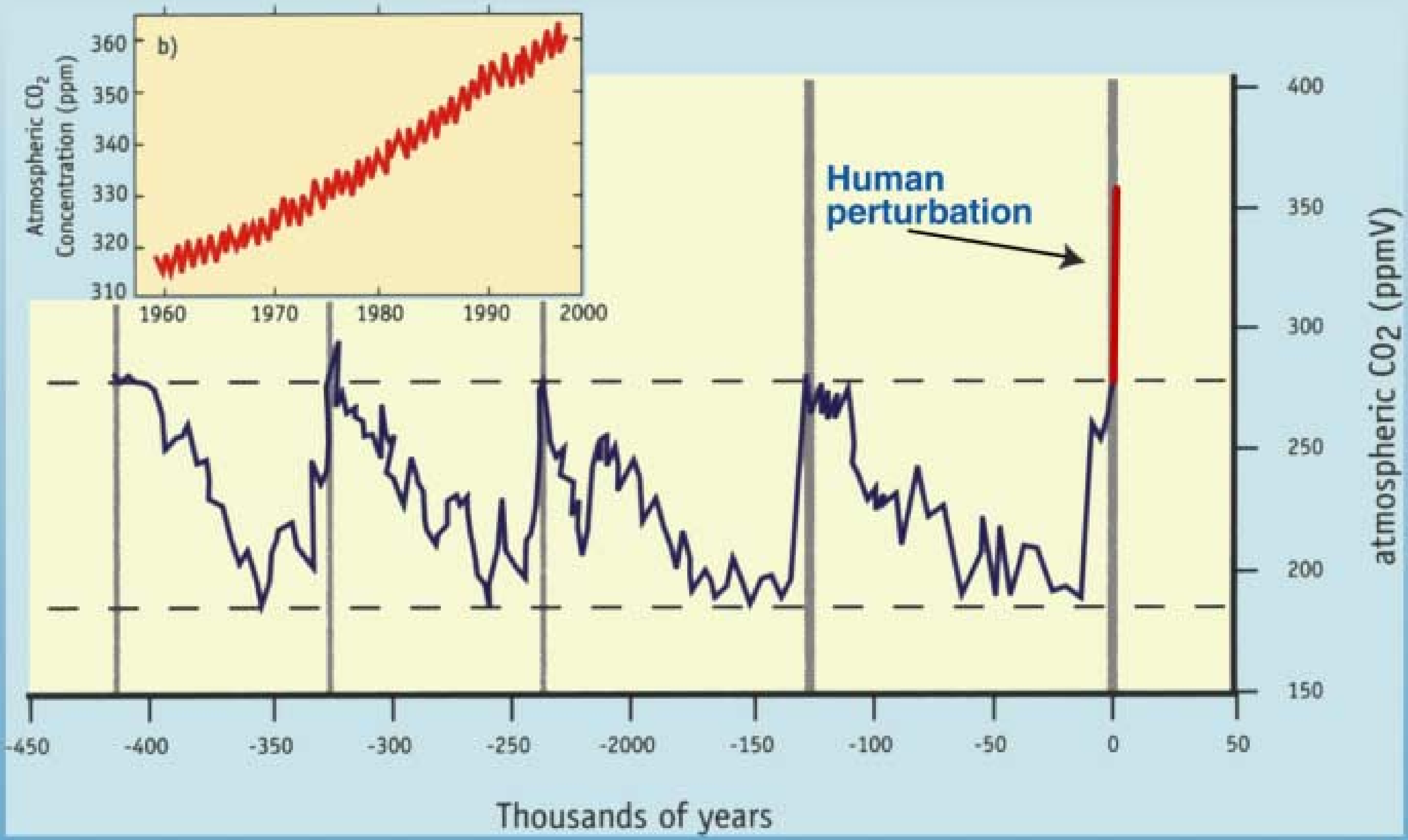
J*oint*	**J***oy of*
G*lobal*	**G***oing*
O*cean*	**O***ut*
F*lux*	**F***rom*
S*tudy*	**S***hore*

"When men (and women) come to like a sea-life,
They are not fit to live on land"
Samuel Johnson (1709-1784)

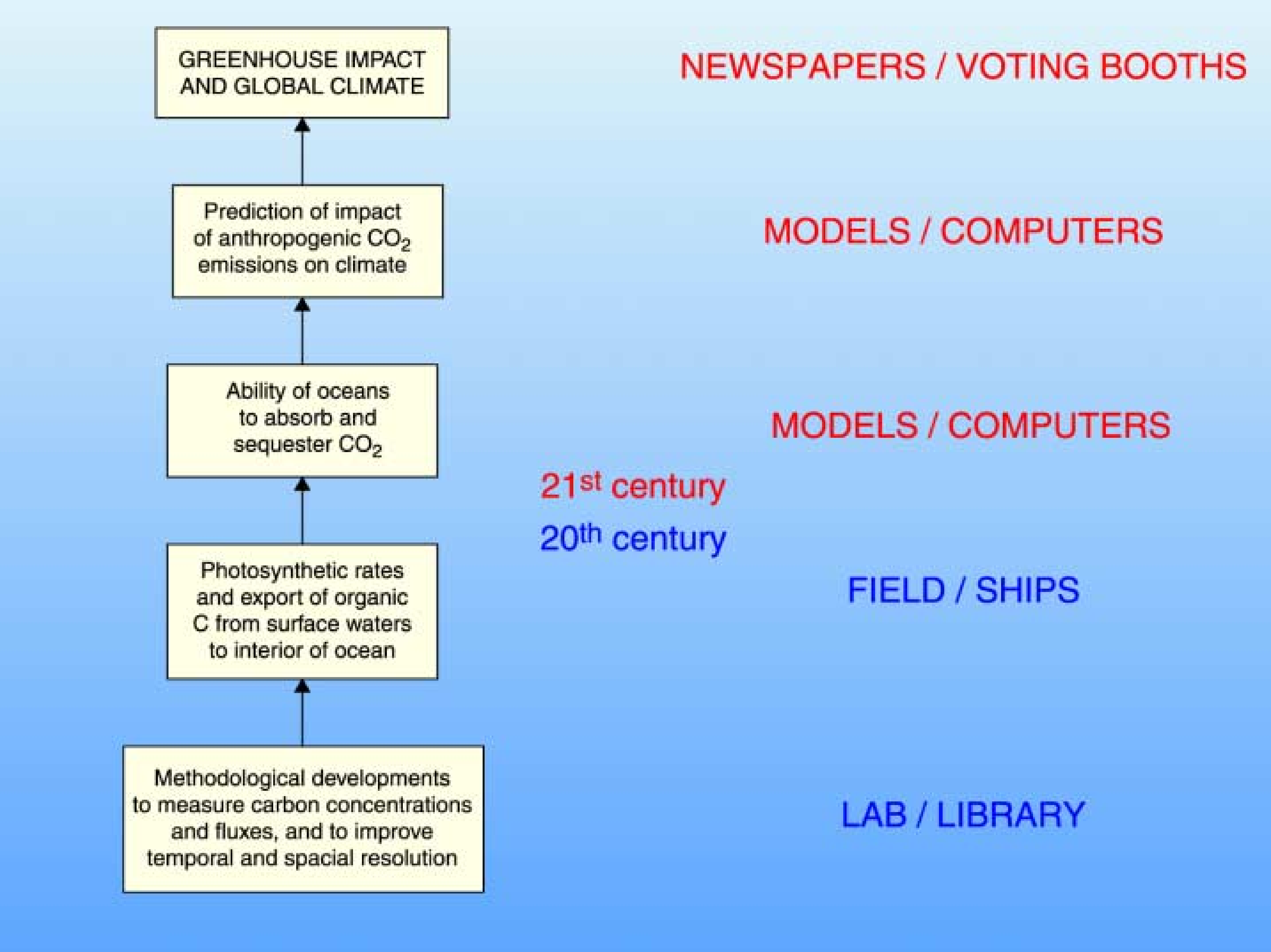
JGOFS "MARCHING ORDERS" REDUCING UNCERTAINTIES

- To determine and understand on a global scale the processes controlling time-varying fluxes of carbon and associated biogenic elements
- To develop a capability to predict the response of oceanic biogeochemical processes to natural and anthropogenic perturbations

i.e., to better understand marine microbial ecology!



b)
Atmospheric CO_2 Concentration (ppm)
360
350
340
330
320
310
1960
1970
1980
1990
2000
Human perturbation
atmospheric CO2 (ppmV)
400
350
300
250
200
150
-450
-400
-350
-300
-250
-2000
-150
-100
-50
0
50
Thousands of years



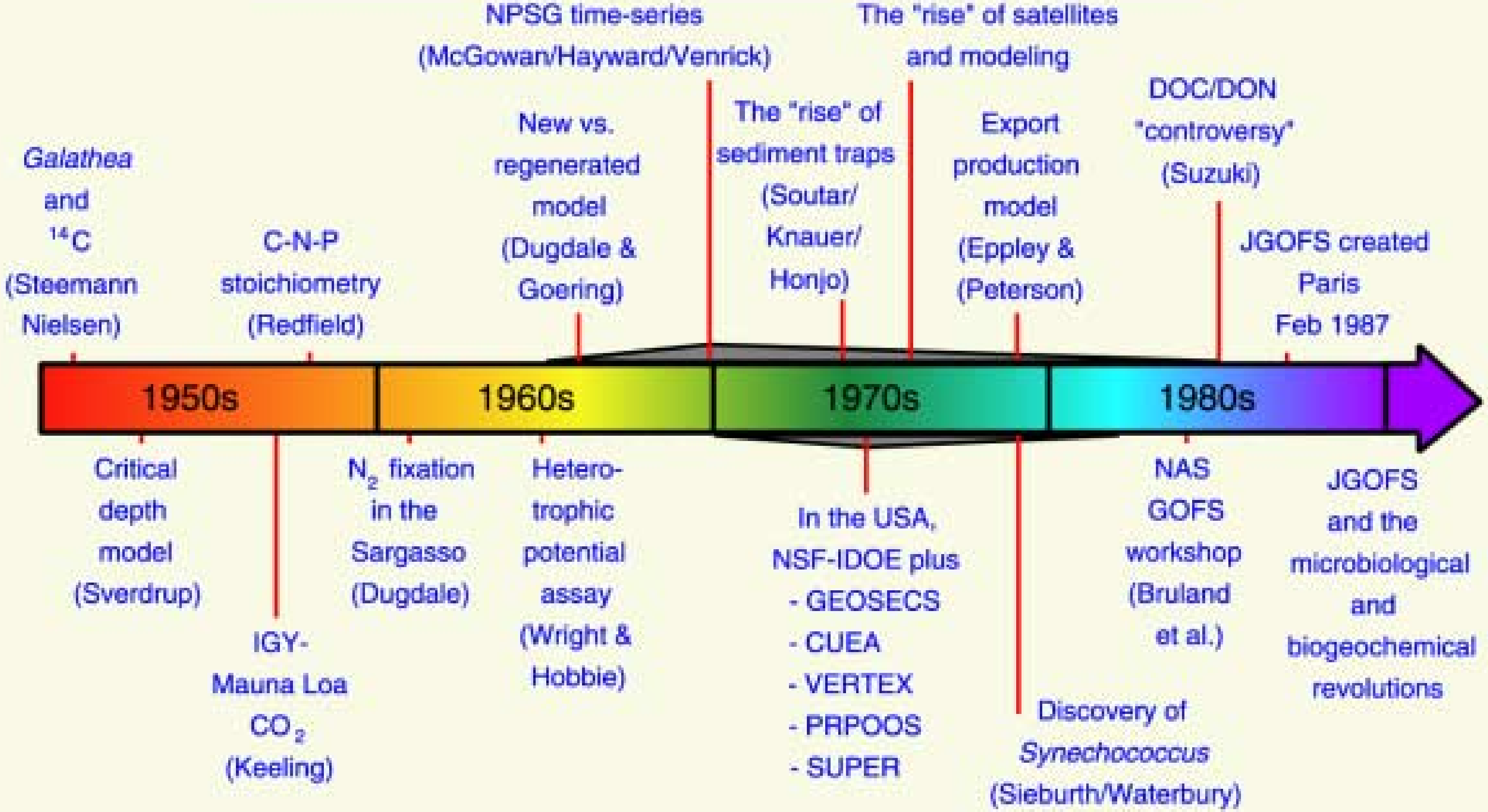
GREENHOUSE IMPACT AND GLOBAL CLIMATE
NEWSPAPERS / VOTING BOOTHS
Prediction of impact of anthropogenic CO_2 emissions on climate
MODELS / COMPUTERS
Ability of oceans to absorb and sequester CO_2
MODELS / COMPUTERS
21st century
20th century
Photosynthetic rates and export of organic C from surface waters to interior of ocean
FIELD / SHIPS
Methodological developments to measure carbon concentrations and fluxes, and to improve temporal and spacial resolution
LAB / LIBRARY

JGOFS CHRONOLOGY

- The JGOFS foundation – key biogeochemical contributions

  (pre-1987)
- Knowledge gained during the JGOFS-era (circa 1987-2003)
- Future “JGOFS-like” research prospectus (post-2003)

FOUR DECADES OF "JGOFS" RESEARCH IN THE PRE-JGOFS ERA



Exploration --- Discovery --- Synthesis & Hypothesis Testing --- More Exploration

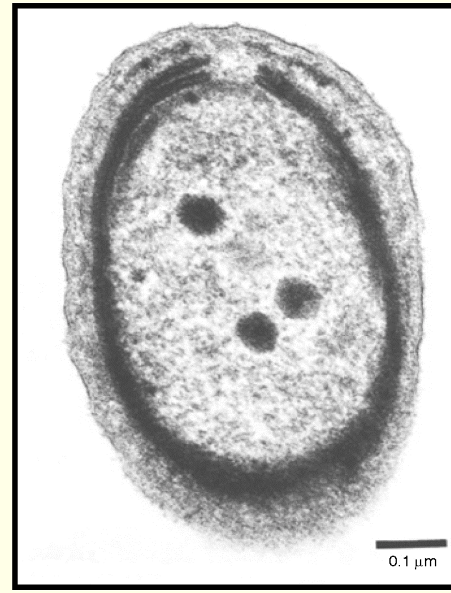
PARADIGMS CIRCA 1987

- Climax community: time/space invariant
- Fixed C-N-P stoichiometry of life
- New (NO_3^-) vs. regenerated (NH_4^+) production and NO_3-based export models (N-limitation)
- Fixed subeuphotic zone remineralization
- Net autotrophic metabolic balance
- Well characterized and easily modeled

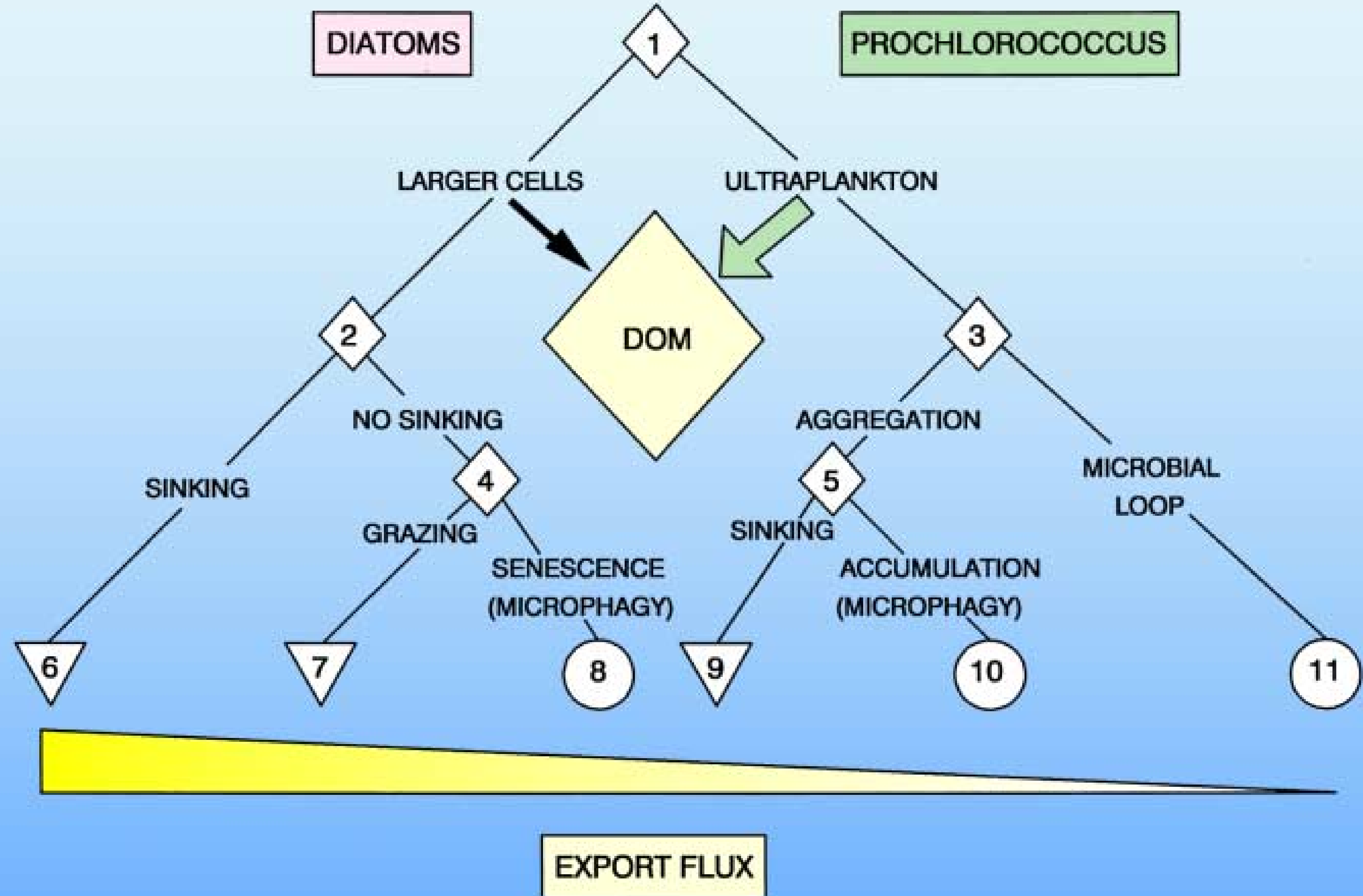
NOVEL MICROBES, NOVEL ECOLOGIES

- 1988: *Prochlorococcus* (Chisholm)
- 1992: pelagic *Archaea* (DeLong/Fuhrman)
- 2000: rhodopsin-containing photoheterotrophs (Béjà and DeLong)
- 2000: rediscovery of AAPs (Kolber et al.)
- 2001: novel N_2-fixers (Zehr et al.)
- 2001: novel picoeukaryotes (Vaulot et al.)
- 2002: SAR 11 (Rappé and Giovannoni)
- 2003 and beyond: ??

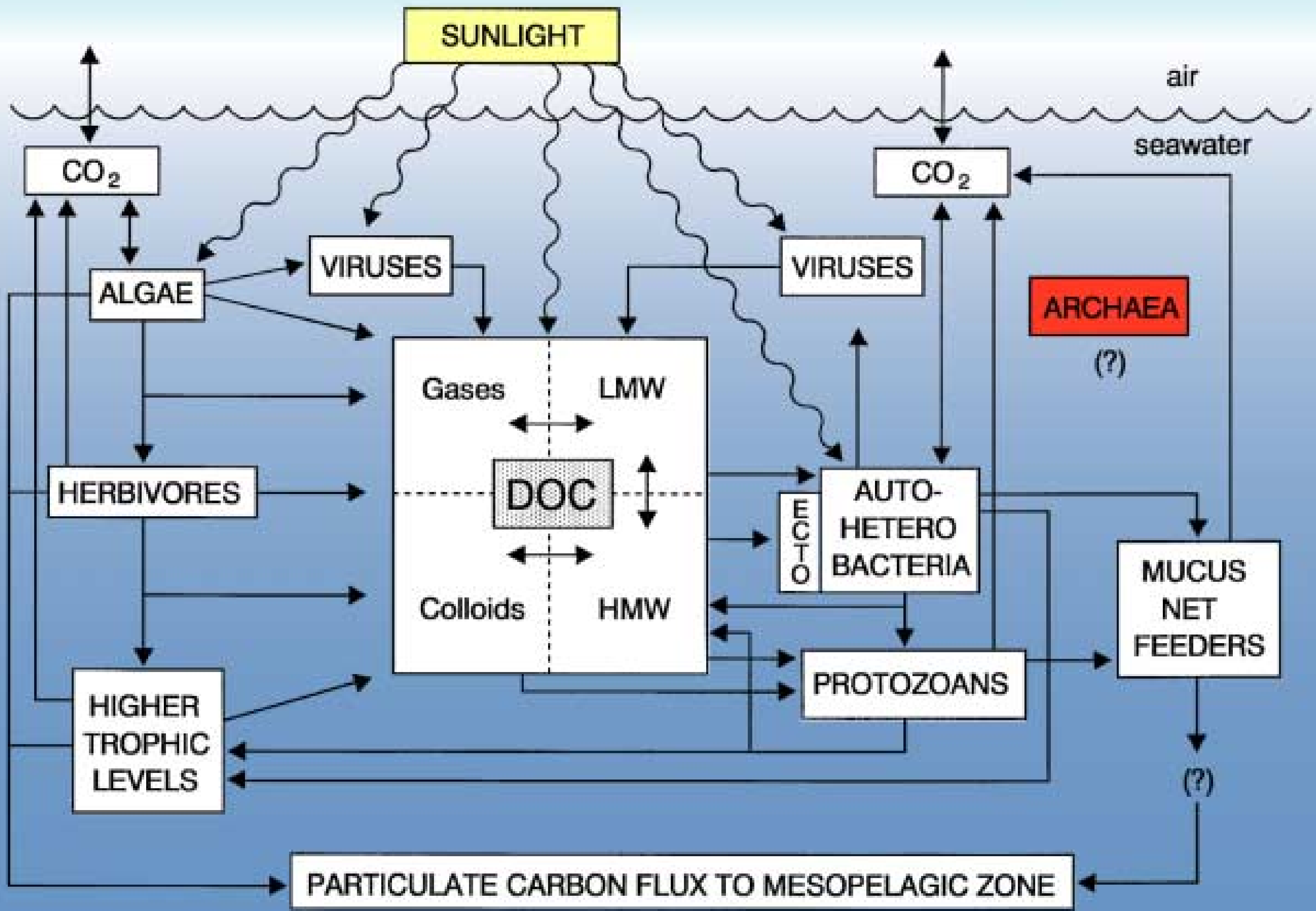
Pennycoccus chisholmi



Prochlorococcus marinus – MIT 9313 (Ting et al. 1999)



DIATOMS
1
PROCHLOROCOCCUS
LARGER CELLS
ULTRAPLANKTON
DOM
2
3
NO SINKING
AGGREGATION
SINKING
4
5
MICROBIAL
LOOP
GRAZING
SENESCENCE
(MICROPHAGY)
SINKING
ACCUMULATION
(MICROPHAGY)
6
7
8
9
10
11
EXPORT FLUX


SUNLIGHT
air
seawater
CO_2
CO_2
ALGAE
VIRUSES
VIRUSES
ARCHAEA
(?)
Gases
LMW
DOC
Colloids
HMW
ECTO
AUTO-
HETERO
BACTERIA
HERBIVORES
MUCUS
NET
FEEDERS
HIGHER
TROPHIC
LEVELS
PROTOZOANS
(?)
PARTICULATE CARBON FLUX TO MESOPELAGIC ZONE

MICROBIAL GENOME SEQUENCING: A "PROGRESS REPORT"

- 1st complete genome 1995; by the end of 2003, >300 selected genomes will be available
- 30-50% of putative genes have no known function (metabolic regulation/ecology?)
- Horizontal (lateral) gene flow is commonplace so "species" concept is questionable

NOT EVEN THE TIP OF THE ICEBERG!

Knowns	*Unknowns*
• Less than 1% of species	• Novel microbes and habitats
• Only 1 “model” system	• Novel physiology/ biochemistry

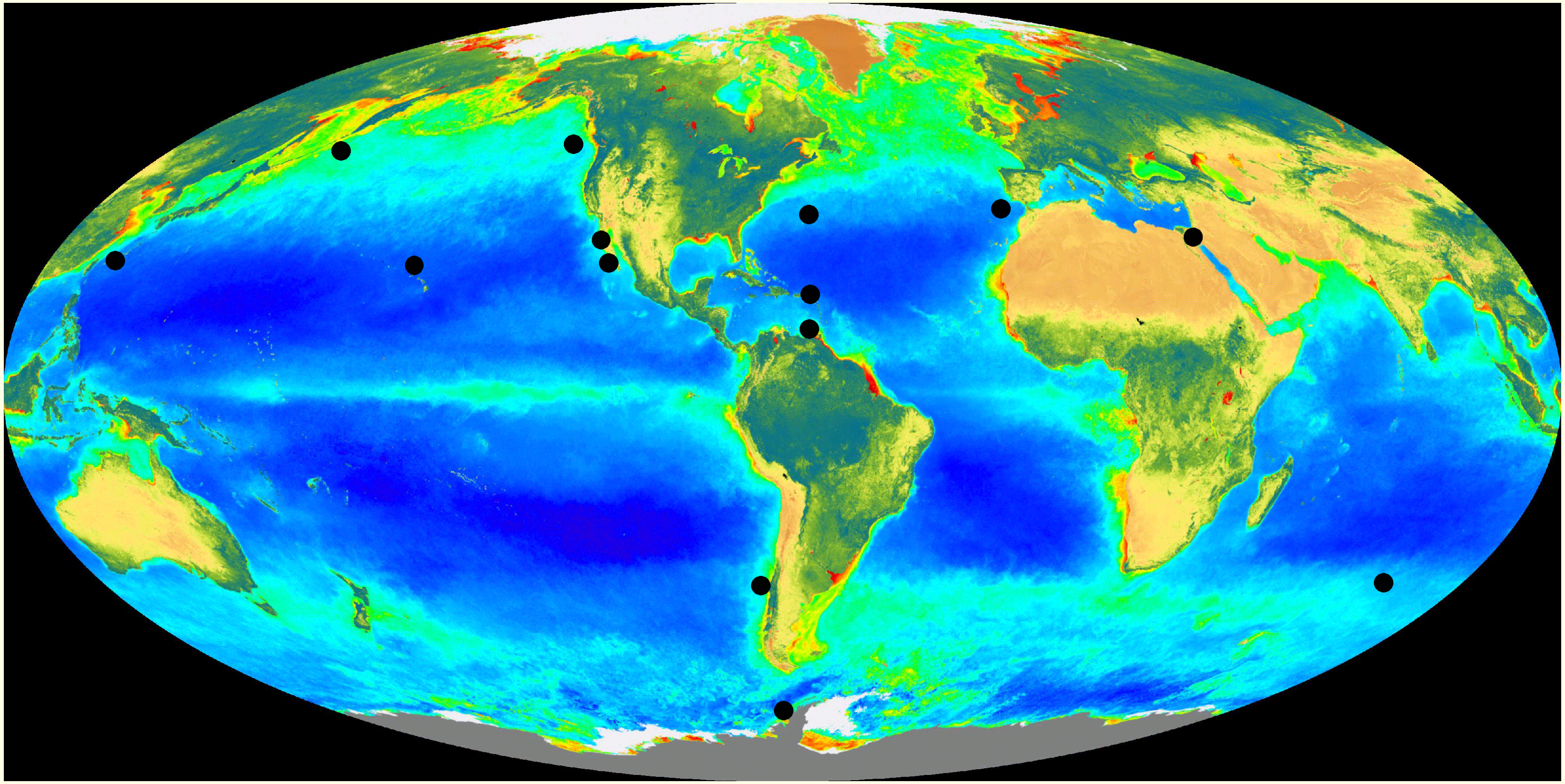
SHIFTING PARADIGMS

- A diverse, uncharacterized “microbial soup”
- Novel carbon and energy flow pathways: transient net metabolic state
- Dynamic selection pressures and temporal shifts in community structure
- Flexible C-N-P stoichiometry
- N_2-based new production and P/Fe control of ecosystem dynamics

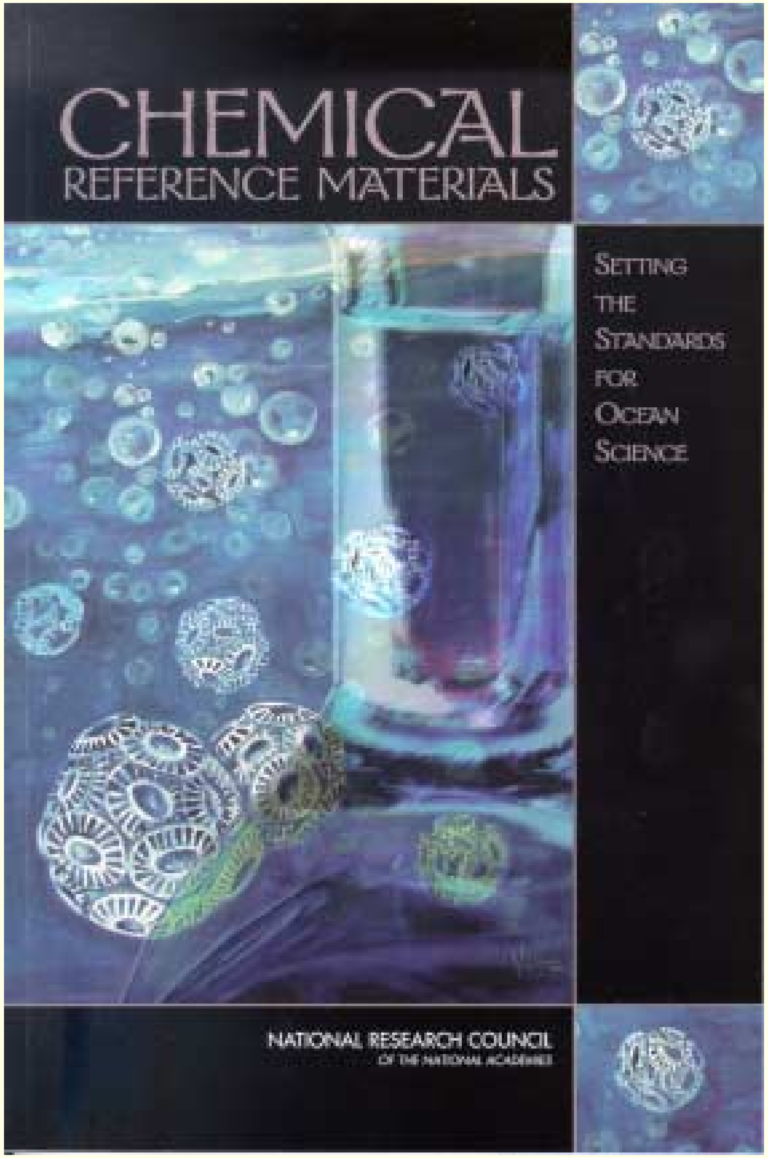
JGOFS

- International and transdisciplinary partnerships built on trust and respect
- Joint field campaigns to address “big” questions in marine biogeochemistry
- Free and open data and idea sharing policies

Biogeochimistes sans frontières



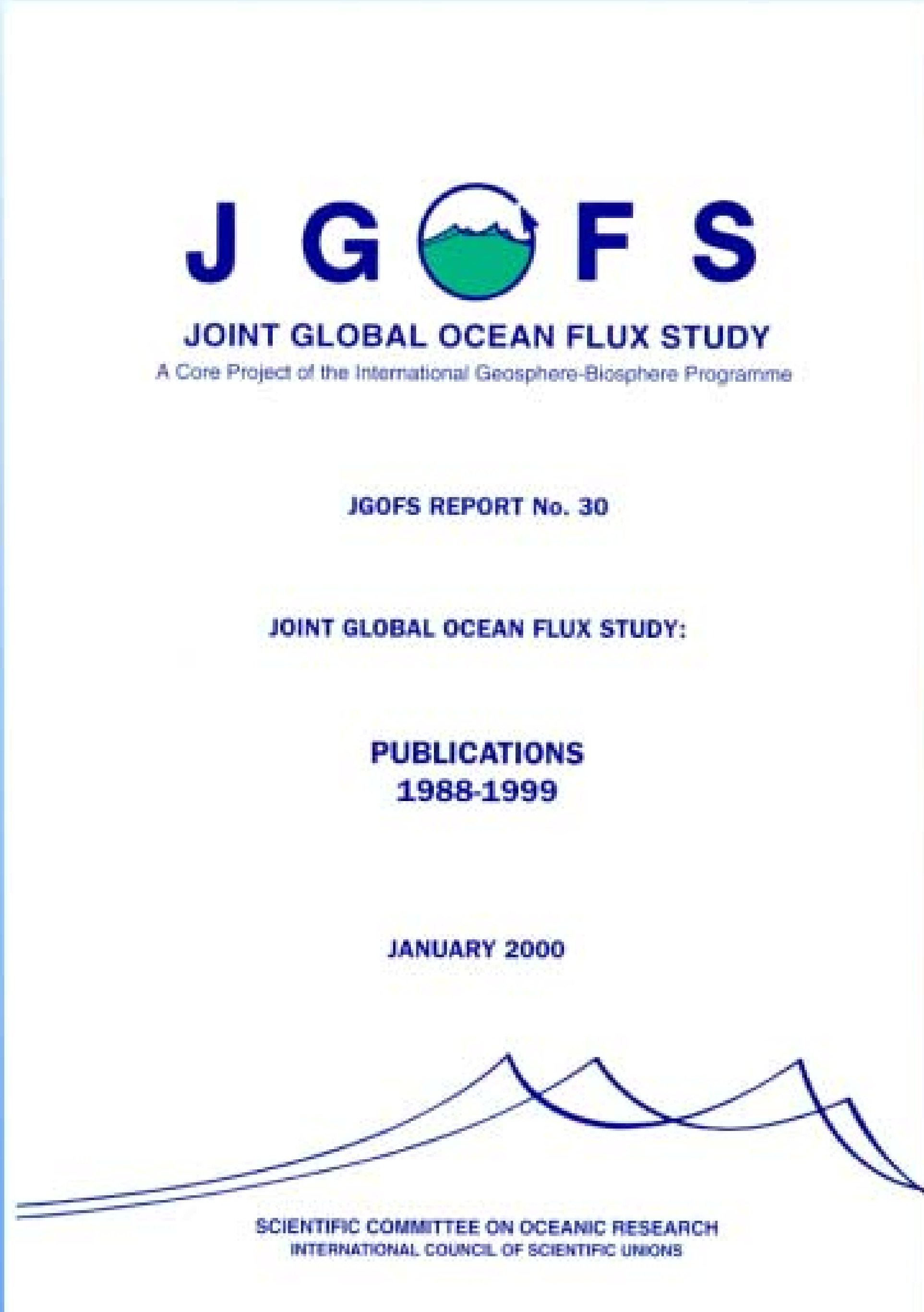
Biogeochemists without borders



Important progress on biogeochemical reference materials has been made during JGOFS era, especially:

- DIC-alk (A. Dickson)
- DOC (D. Hansell)
- DON (J. Sharp)
- Pigments
  (R. Bidigare et al.)

JGOFS: To create and disseminate knowledge


JGOFS

JOINT GLOBAL OCEAN FLUX STUDY

A Core Project of the International Geosphere-Biosphere Programme

JGOFS REPORT No. 30

JOINT GLOBAL OCEAN FLUX STUDY:

PUBLICATIONS
1988-1999

JANUARY 2000

SCIENTIFIC COMMITTEE ON OCEANIC RESEARCH
INTERNATIONAL COUNCIL OF SCIENTIFIC UNIONS

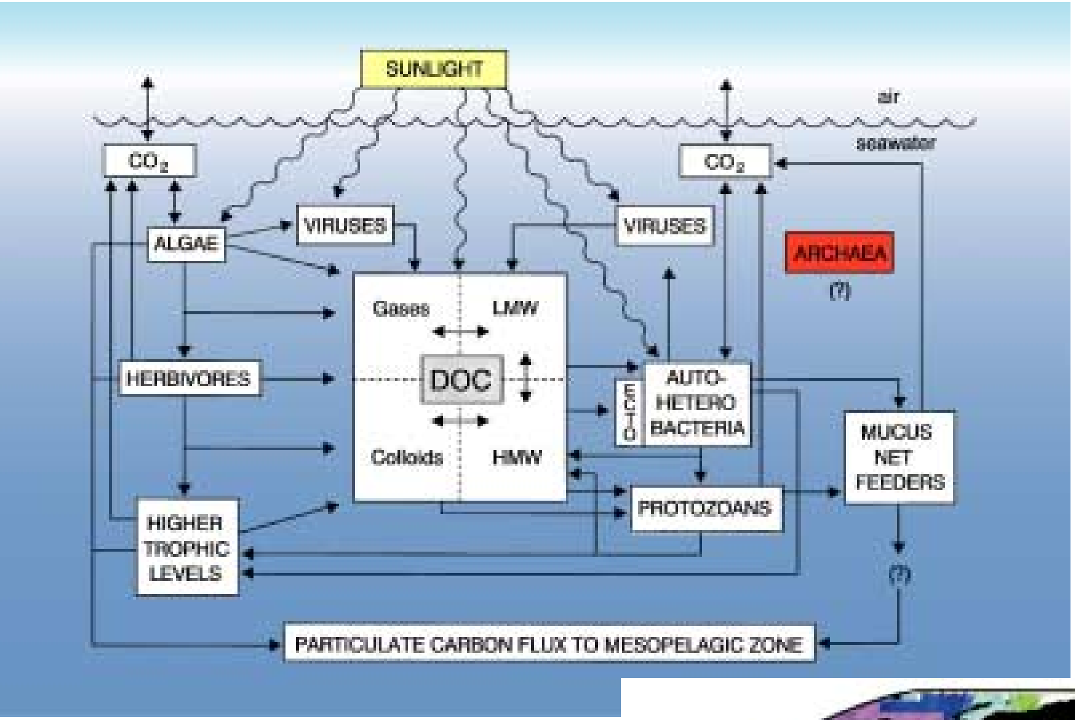
- From A - to - Z Abraham (1998) to Zuddas and Mucci (1998)
- 2660 publications 1988 - 1999
- Several key syntheses, with more to come!

TO CREATE AND DISSEMINATE KNOWLEDGE

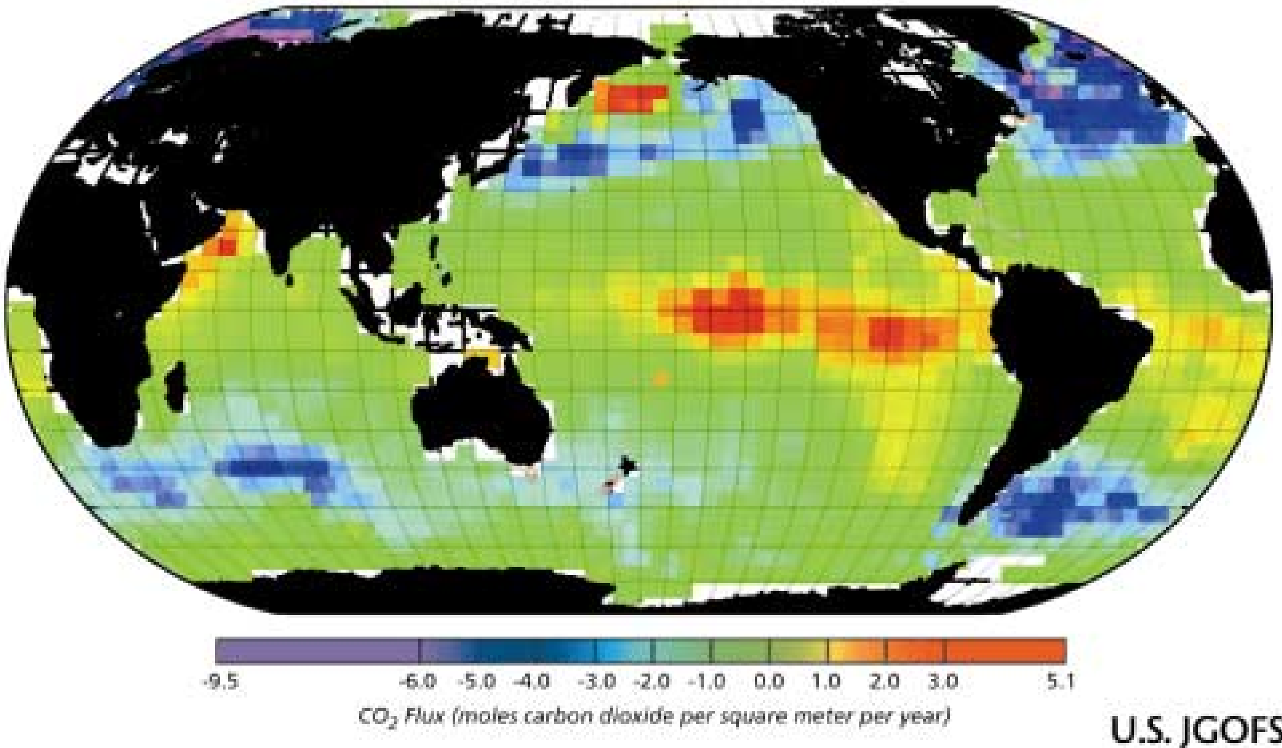
GLOBAL
I G B P
CHANGE

International Council for Science

Scientific Committee on Oceanic Research



How do we get from the marine food web to a global assessment of CO_2 flux???



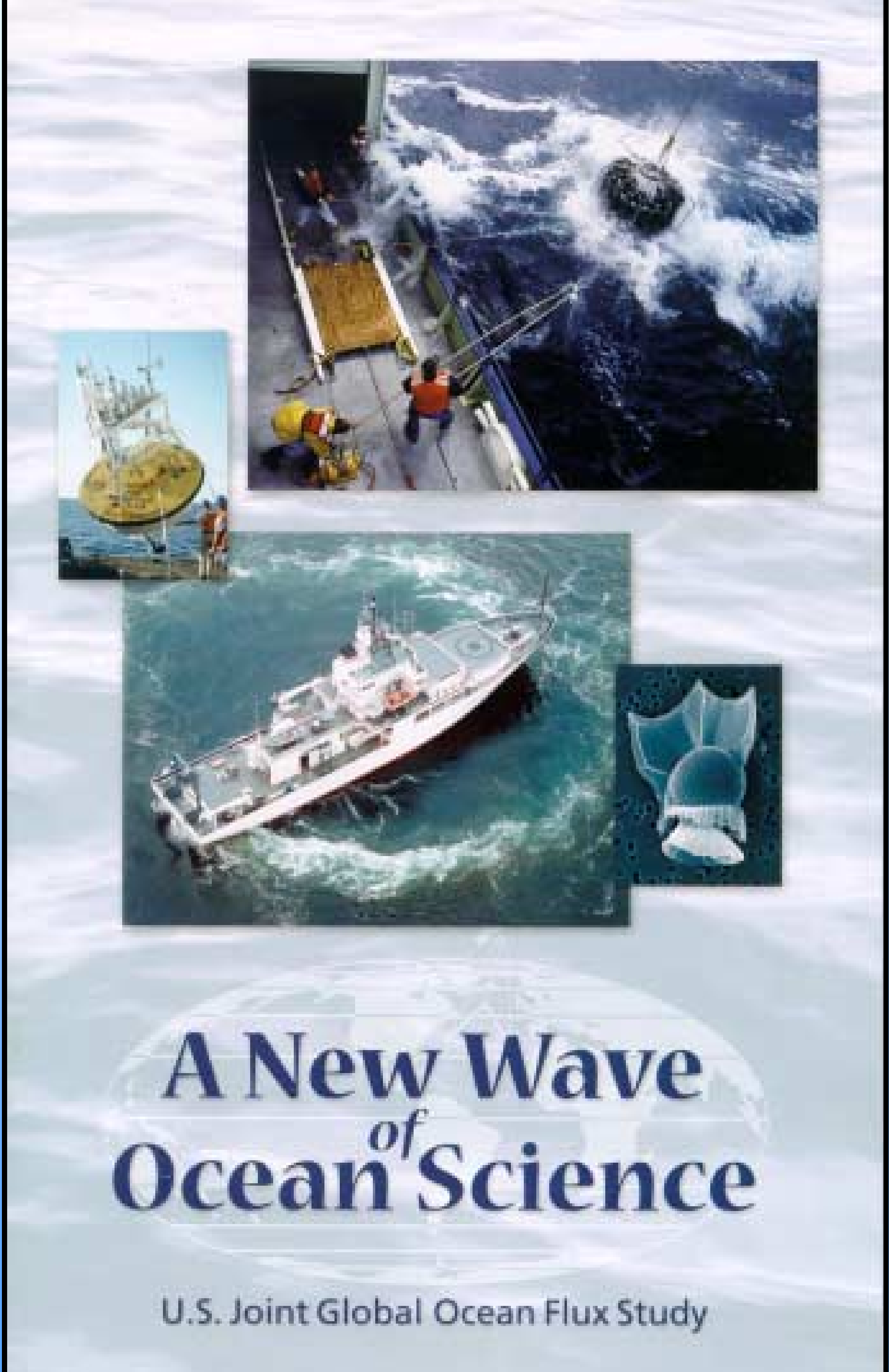
With great difficulty!

CONTROLS ON ECOSYSTEM DYNAMICS

- ***Physical***: turbulence, light, temperature
- ***Chemical***: nutrient loading, trace element availability
- ***Biological***: community composition, food web structure, N_2-fixation
- ***Climate and Human Influences***: ENSO, PDO-NAO, land use, population, deserts-dust

BARRIERS TO LINKING CLIMATE CHANGE TO OCEAN BIOLOGY

- Natural habitat variability
- Lack of consistent, long-term ocean observations
- Changing bio-ocean paradigms
- Other ($$, motivation, human resources, technology)

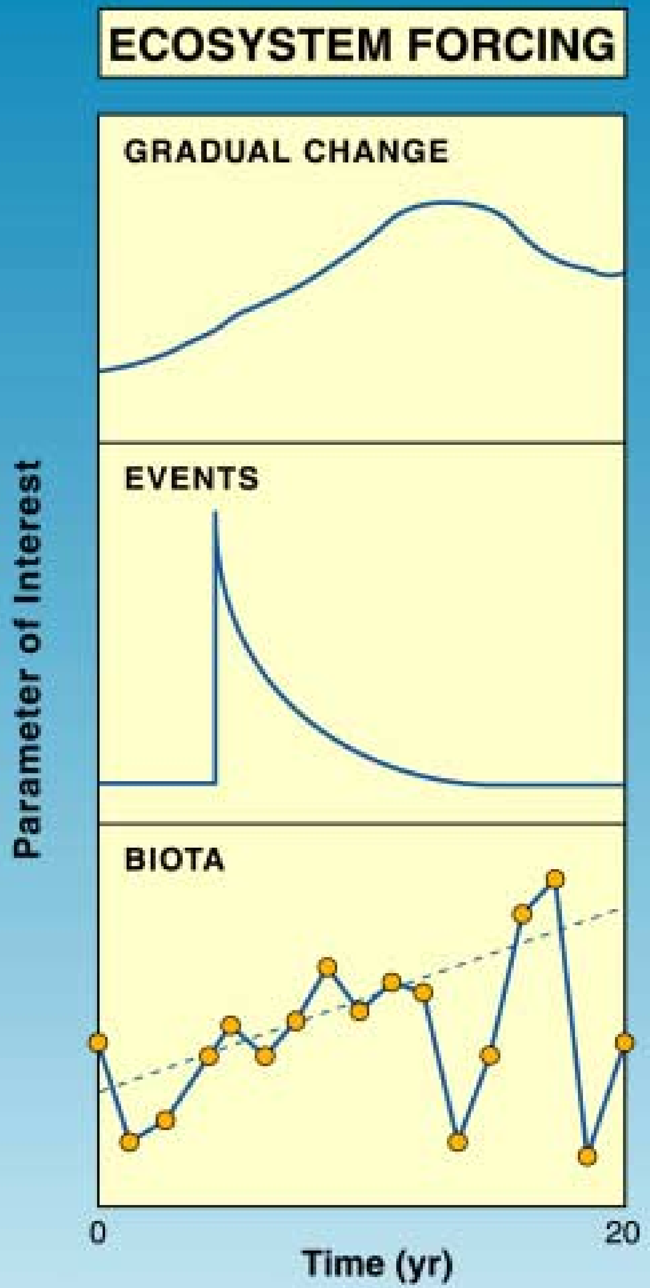


JGOFS

- Transdisciplinary
- C-N-P cycles
- Process studies, time-series, data assimilation and modeling
- Hypothesis generation and testing
- Education and training

OCEAN TIME-SERIES PROGRAMS

- Description of large ecosystems and how they function using a multidisciplinary approach
- Detection of low frequency temporal variability in physical and biogeochemical processes
- Determination of natural dynamics resulting from complex biological, chemical and physical effects
- Climate-Ecosystem linkages

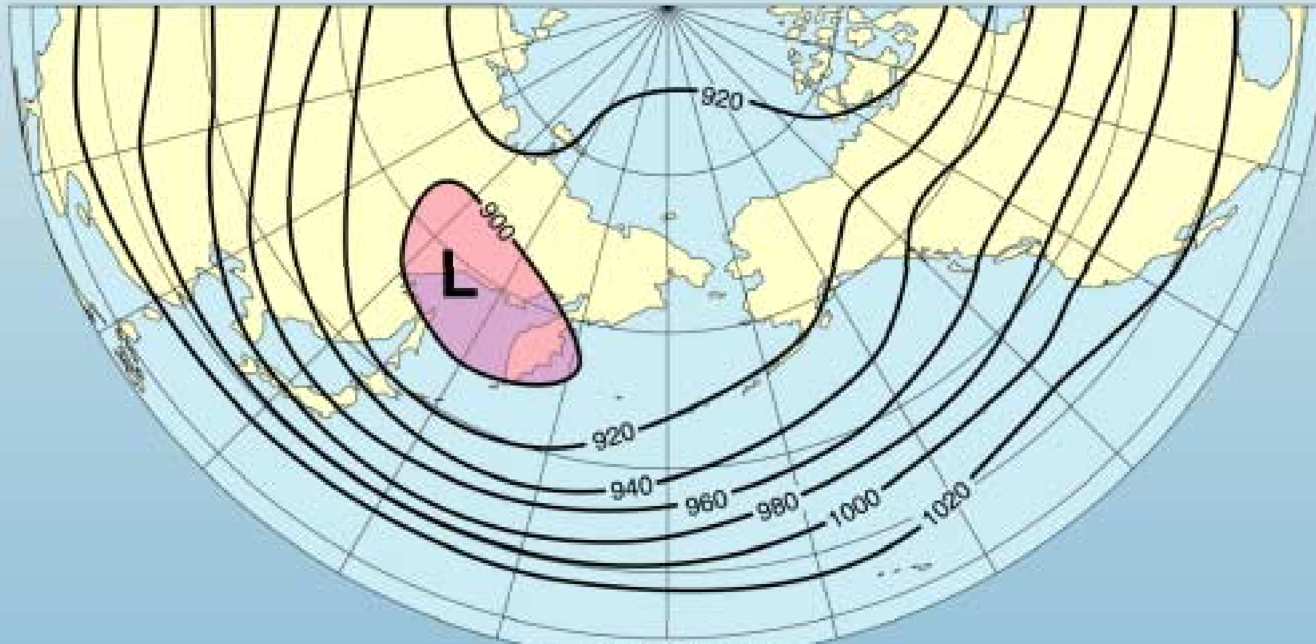


Strayer et al. 1986

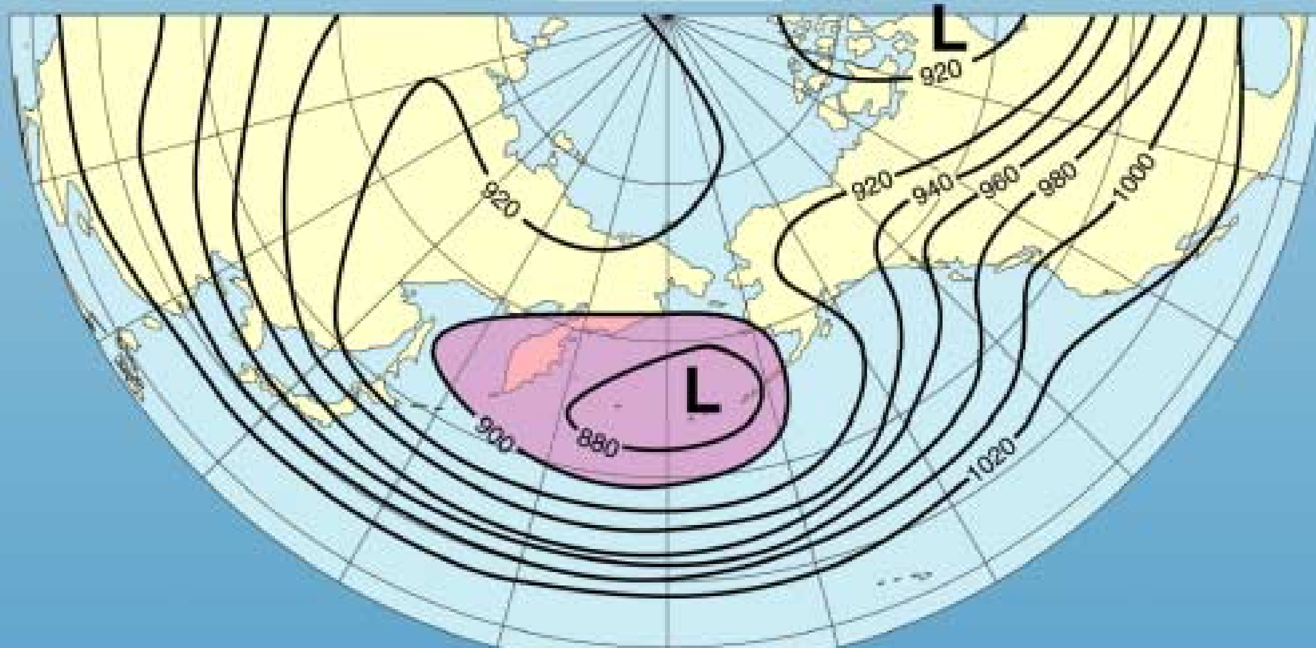
- Variable physical forces at work
- Biological effects have thresholds, complex feedbacks and other interactions
- Look for changes in emergent ecosystem properties

CLIMAX COMMUNITY THEORY (Clements 1916, Whittaker 1953)

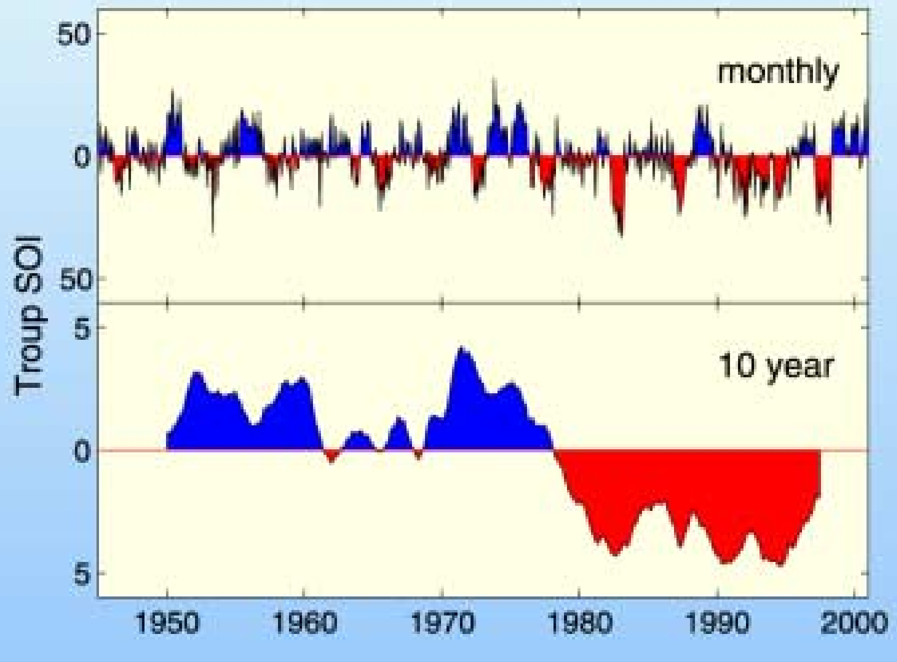
- Succession - orderly process of community development involving changes in community structure, function and dynamics - reasonably directional and predictable
- Driven by changes in physical environment - i.e., climate
- Culminates in a stable, terminal ecosystem - the Climax community - maximum utilization of resources
- Under ruling climate, the community does not change and conversely, climate change will drive ecosystem change



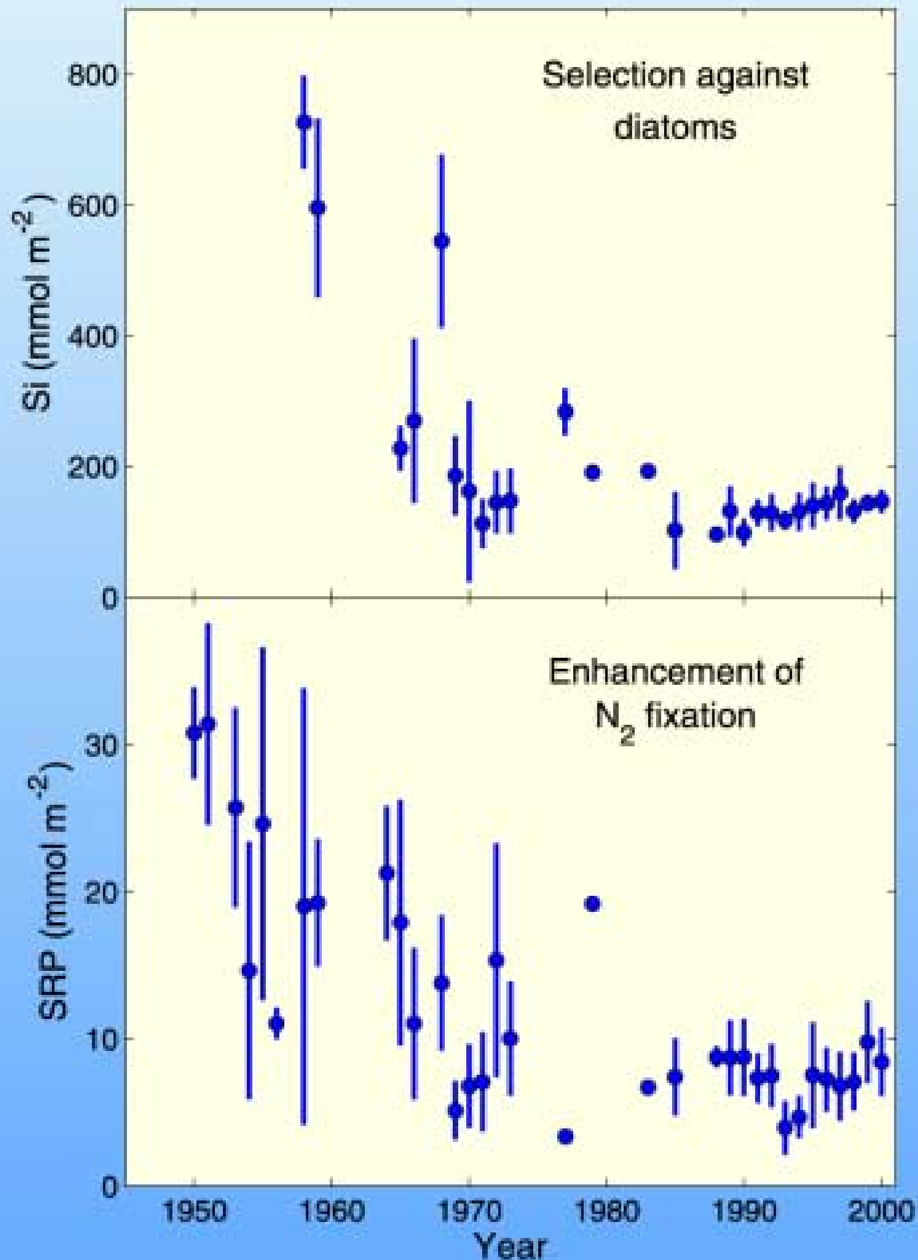
1947–1972

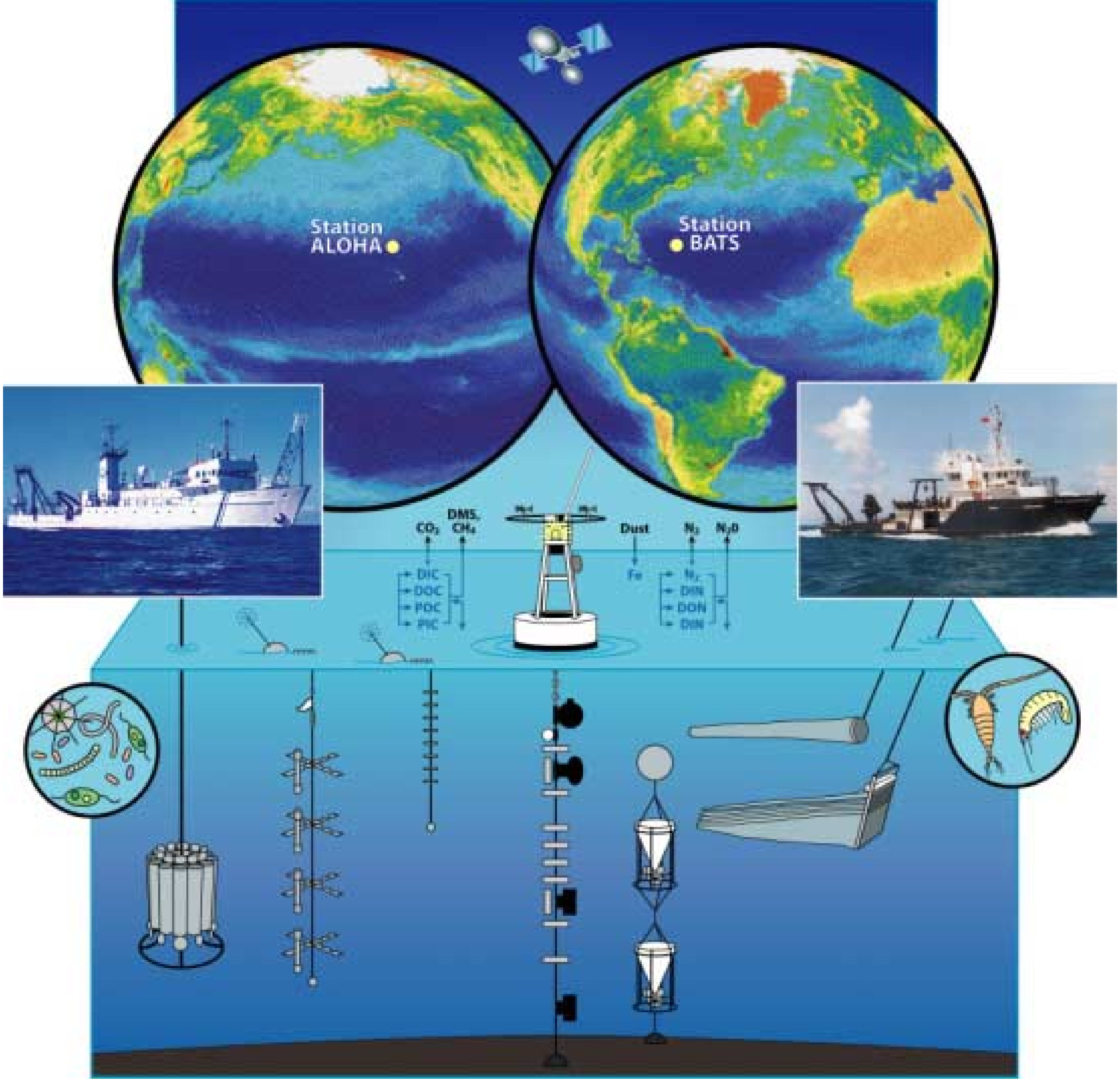


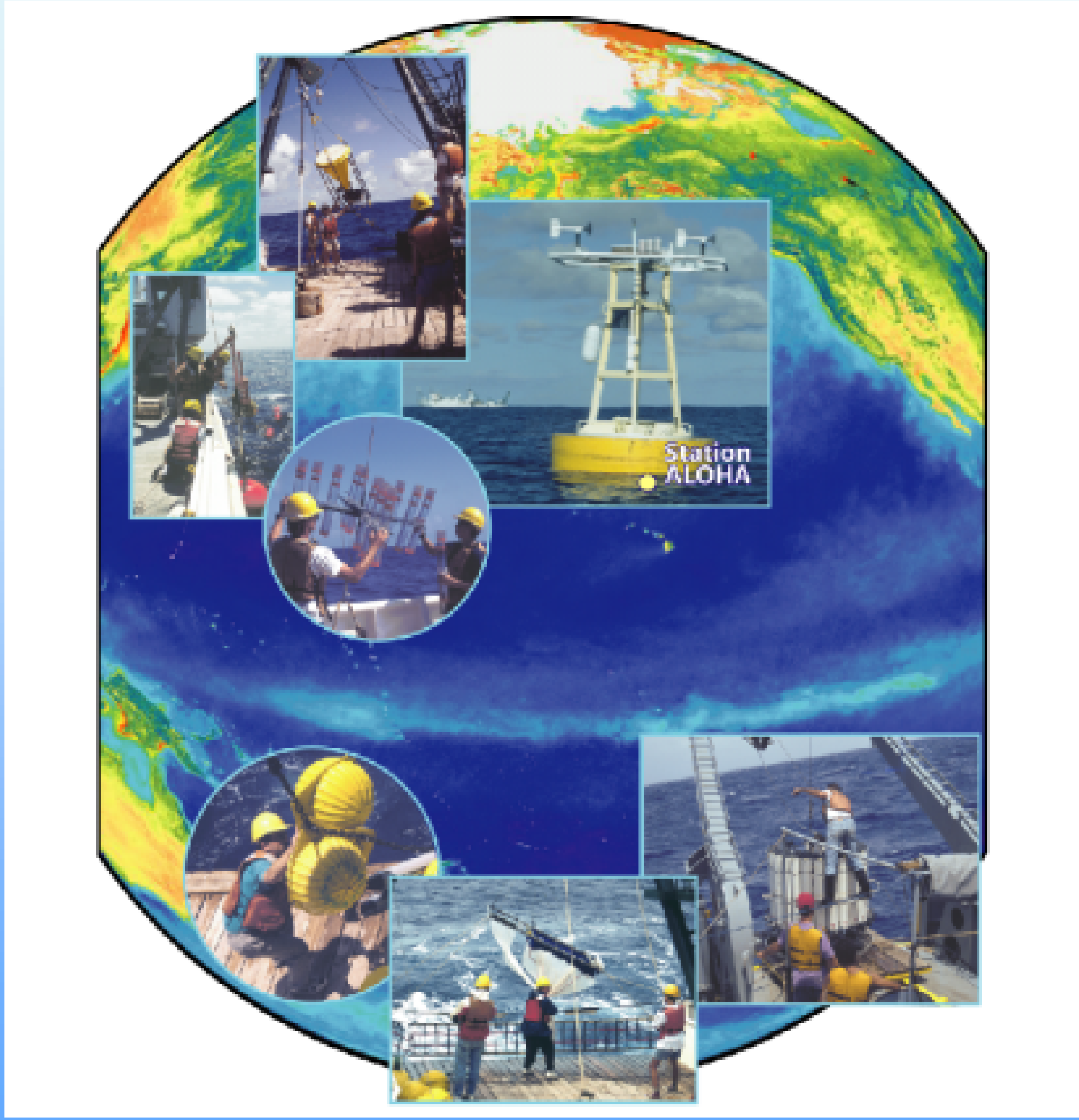
1976–1977



NUTRIENT DYNAMICS IN THE NORTH PACIFIC SUBTROPICAL GYRE

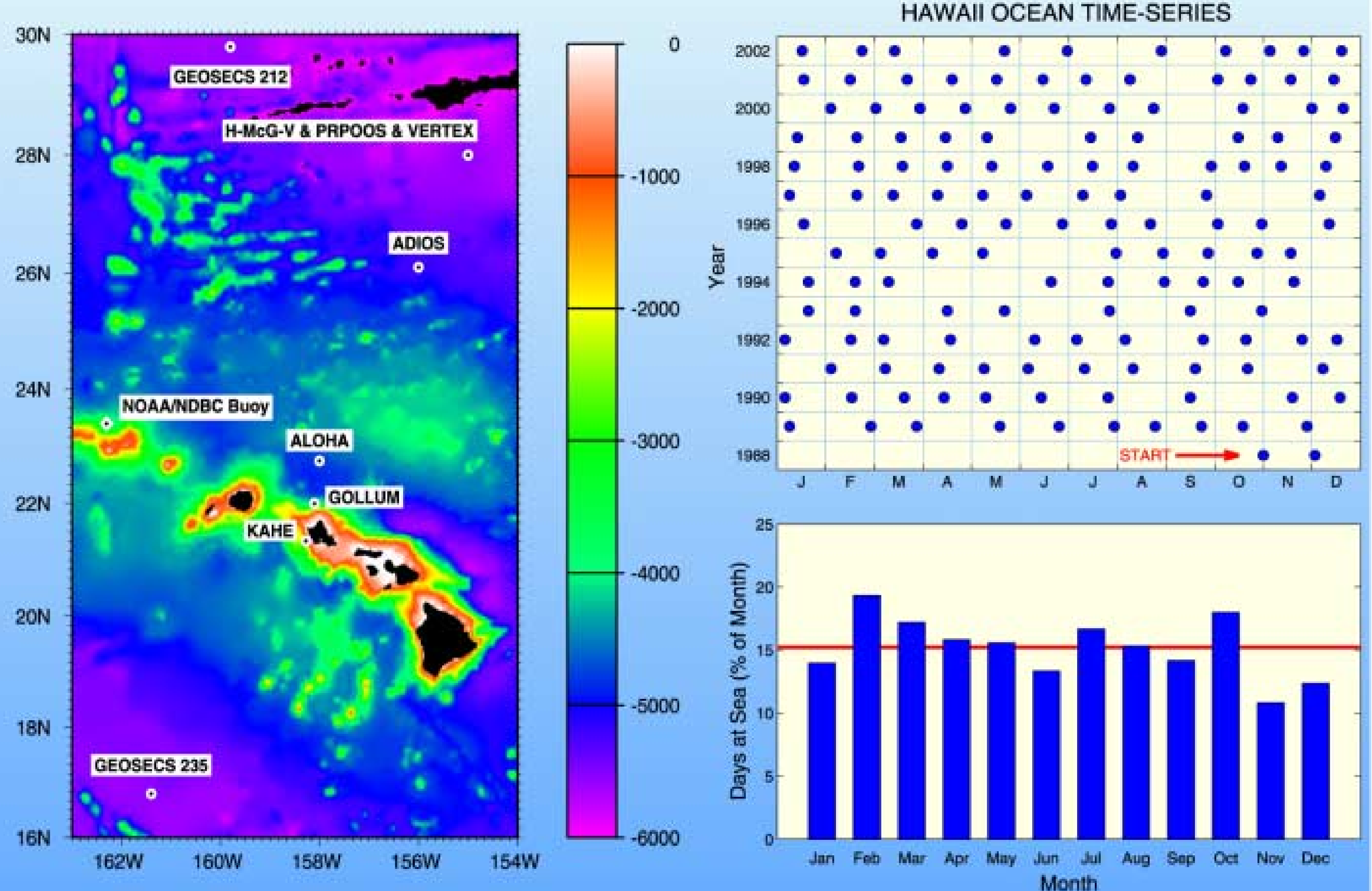



Station
ALOHA
Station
BATS
CO_2
DMS,
CH_4
Dust
N_2
N_2O
DIC
DOC
POC
PIC
Fe
N_2
DIN
DON
DIN

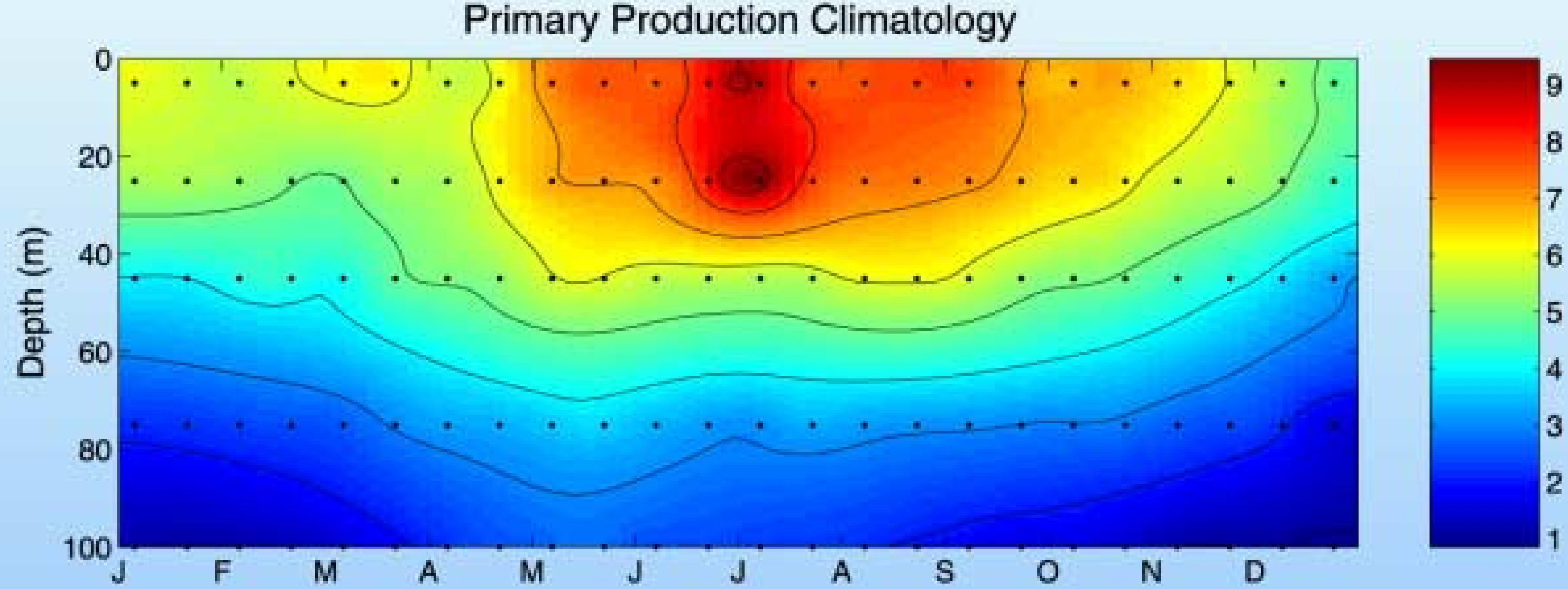


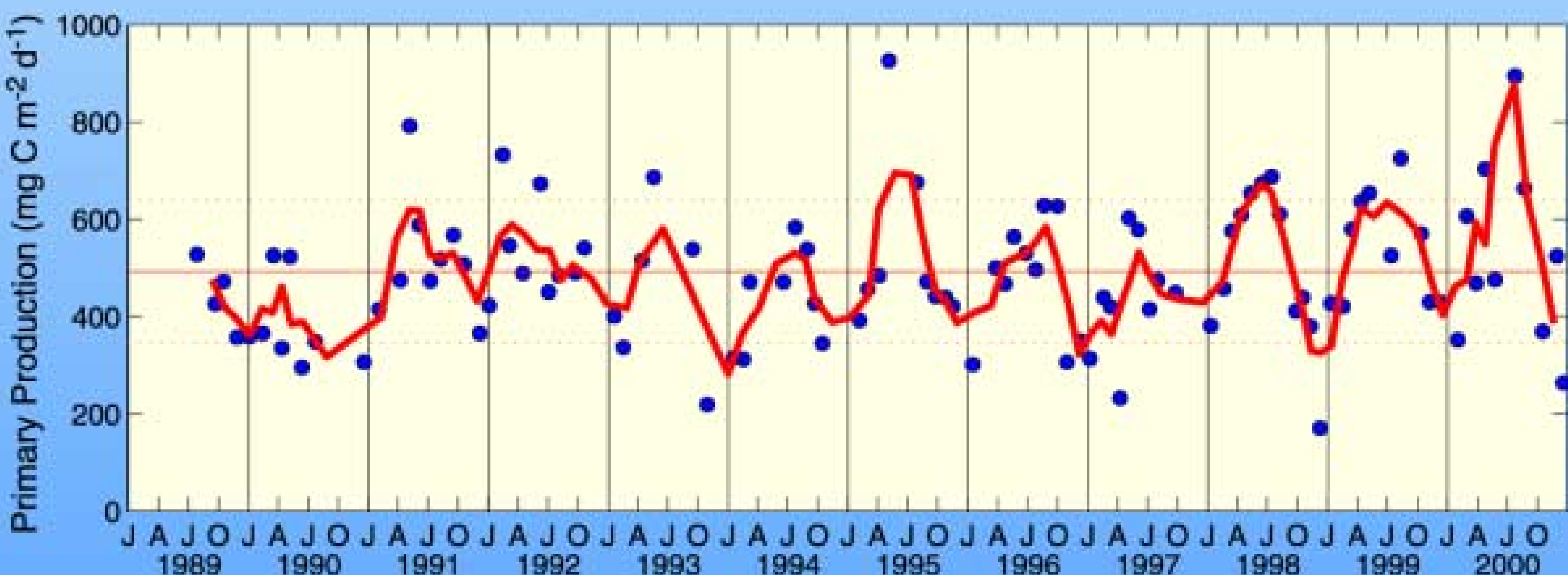
- Approximately monthly cruises to Sta. ALOHA (22°45’N, 158°W) since Oct 1988
- Core physical, chemical and biological measurements (e.g., CTD, DIC-alk, nutrients, DOC-N-P, POC-N-P) and bio-optics
- Rate measurements (e.g., primary production and particulate matter export)
- Zooplankton
- Satellites and moorings

THE TWO FACES OF THE NORTH PACIFIC GYRE

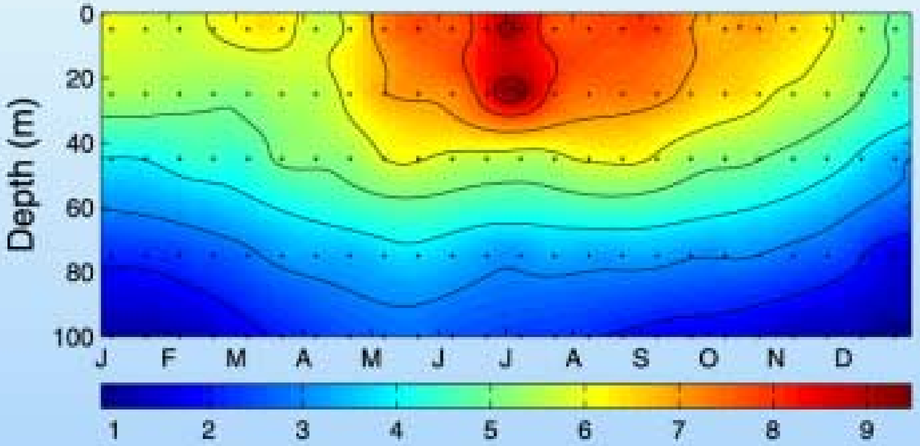


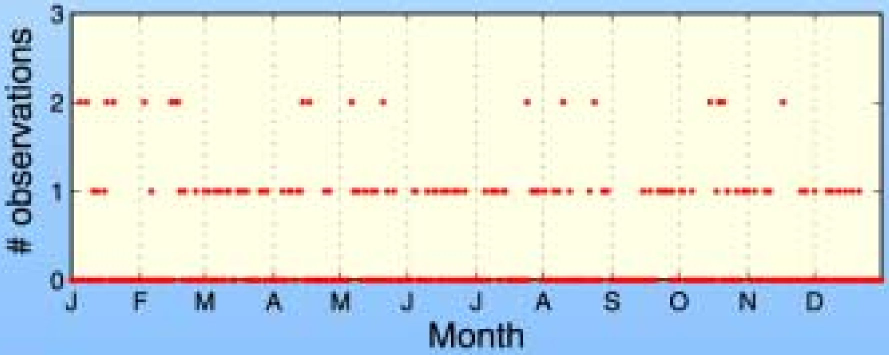
GEOSECS 212
H-McG-V & PRPOOS & VERTEX
ADIOS
NOAA/NDBC Buoy
ALOHA
GOLLUM
KAHE
GEOSECS 235
30N
28N
26N
24N
22N
20N
18N
16N
162W
160W
158W
156W
154W
0
-1000
-2000
-3000
-4000
-5000
-6000
HAWAII OCEAN TIME-SERIES
Year
2002
2000
1998
1996
1994
1992
1990
1988
START
J F M A M J J A S O N D
Days at Sea (% of Month)
25
20
15
10
5
0
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
Month

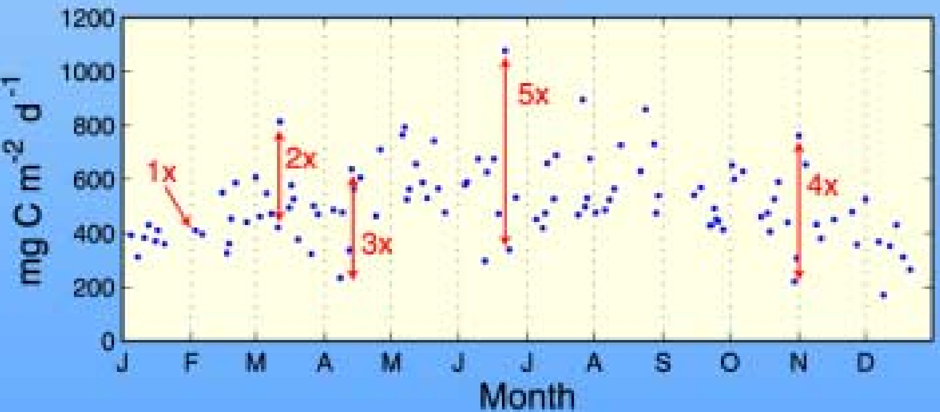

Primary Production Climatology
Depth (m)
0
20
40
60
80
100
J F M A M J J A S O N D
1 2 3 4 5 6 7 8 9


Primary Production (mg C m-2 d-1)
0
200
400
600
800
1000
J A J O J A J O J A J O J A J O J A J O J A J O J A J O J A J O J A J O J A J O J A J O J A J O
1989 1990 1991 1992 1993 1994 1995 1996 1997 1998 1999 2000

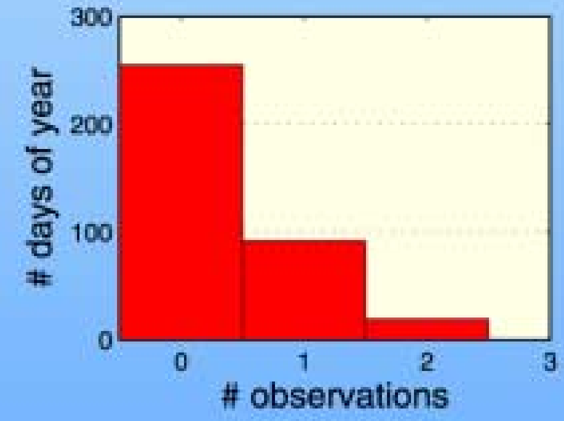
Primary Production Climatology







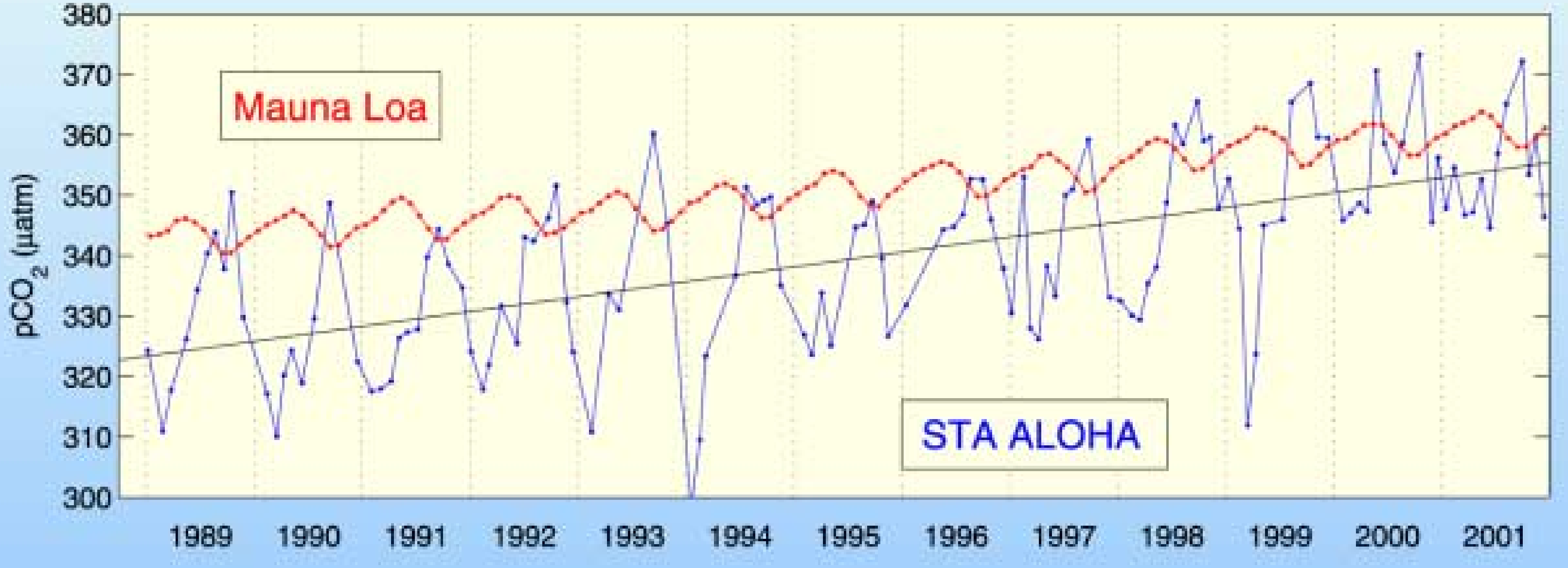
- 111 depth profiles (1989-2002)
- < 200 to > 1000 $mg\ C\ m^{-2}\ d^{-1}$ (mean = 510)



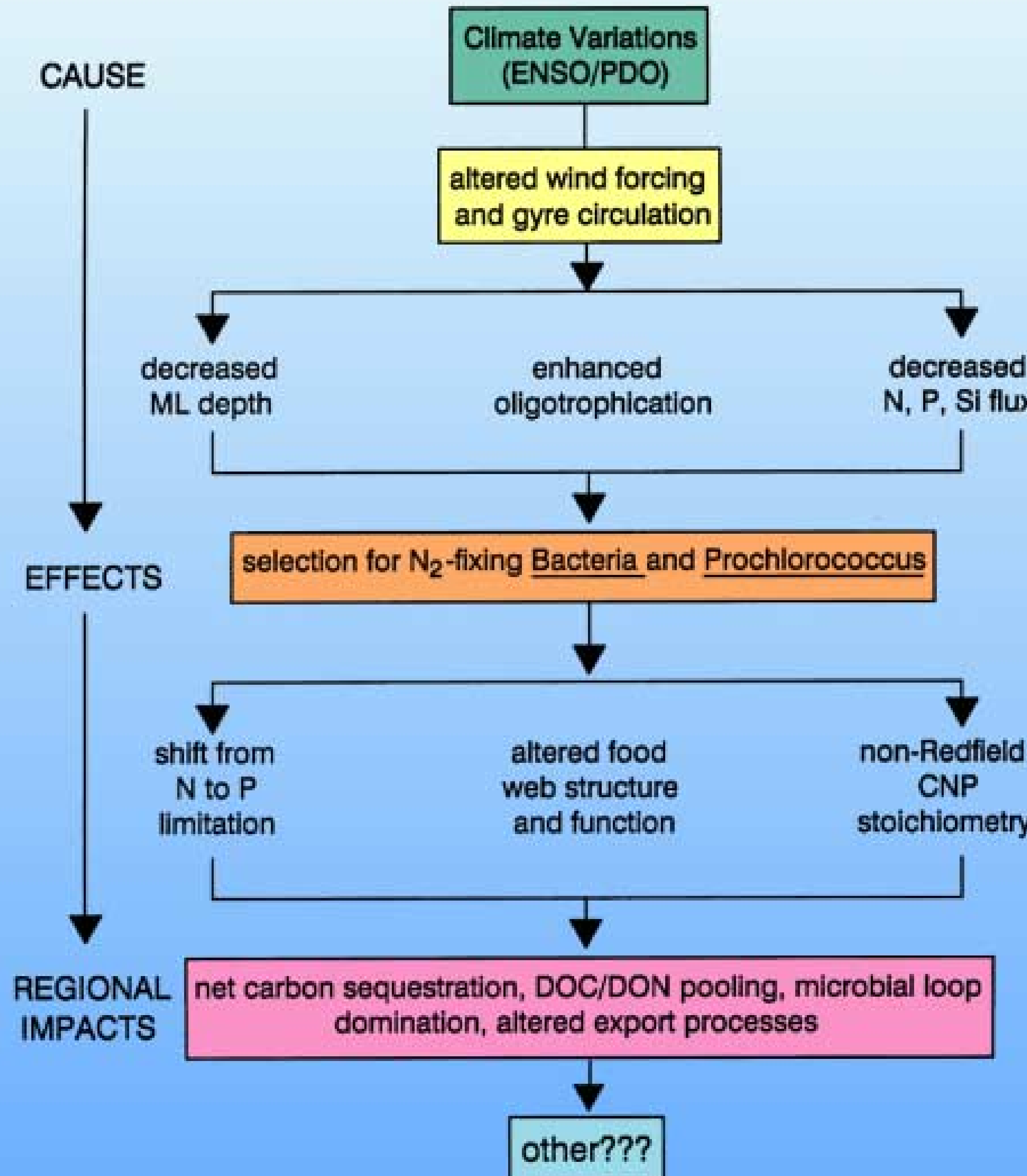
- well resolved seasonal cycle, but low predictive value

HOT BIOGEOCHEMICAL ENIGMAS: SELECTED EXAMPLES

- Variable strength of carbon dioxide sink
- Variable primary production and export
- Changes in community structure, especially Prokaryote:Eukaryote ratio
- Role of N_2 fixation and possible Fe (dust) control of carbon sequestration



- The Subtropical North Pacific habitat is a net sink for atmospheric carbon dioxide
- The strength of the net sink (ΔpCO_2) is seasonally variable and, perhaps, getting weaker with time over the past decade
- These variations may be the direct result of climate (e.g., E vs. P) or climate effects on the biological pump

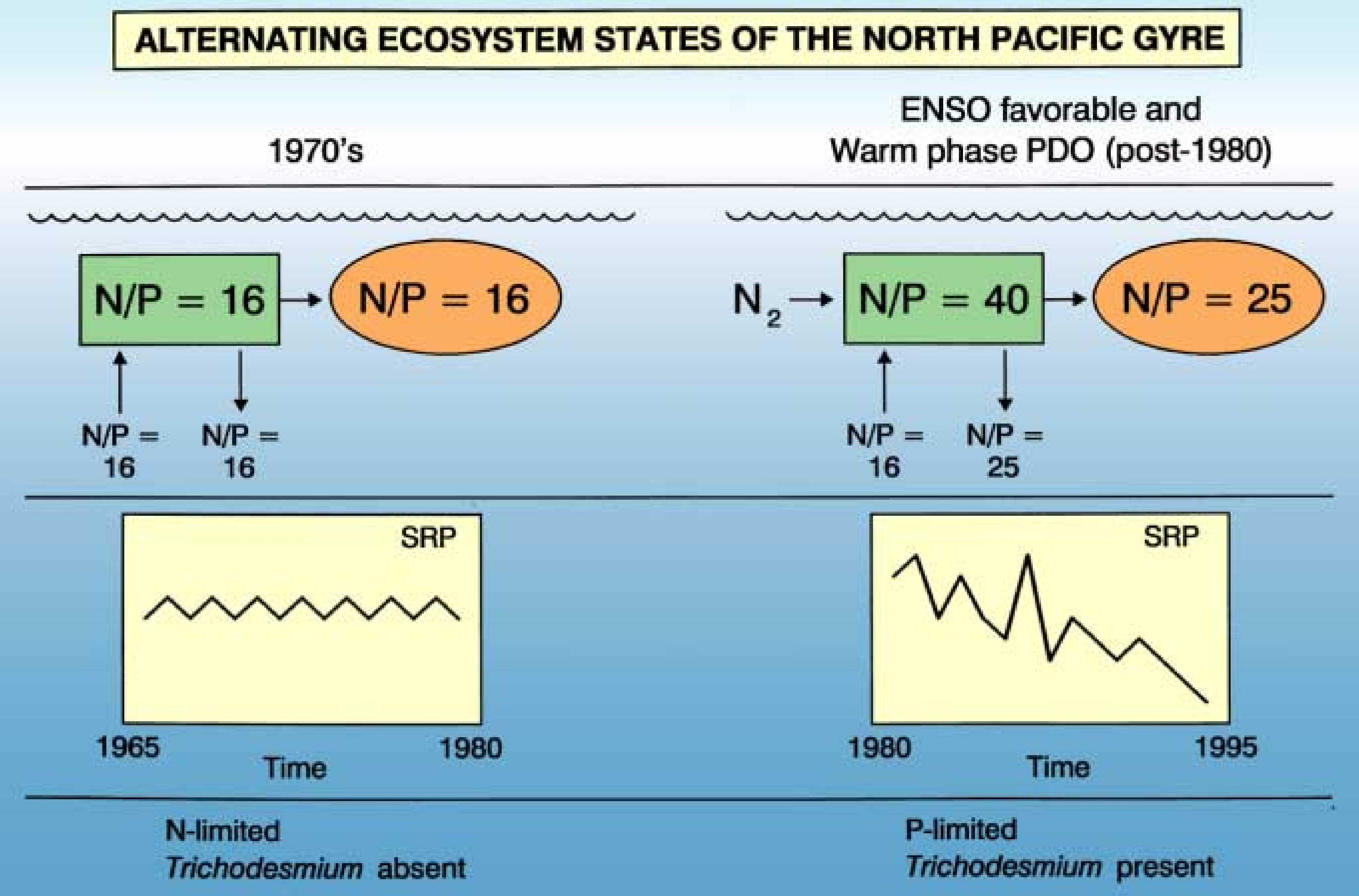

CAUSE
EFFECTS
REGIONAL IMPACTS
Climate Variations (ENSO/PDO)
altered wind forcing and gyre circulation
decreased ML depth
enhanced oligotrophication
decreased N, P, Si flux
selection for N_2-fixing Bacteria and Prochlorococcus
shift from N to P limitation
altered food web structure and function
non-Redfield CNP stoichiometry
net carbon sequestration, DOC/DON pooling, microbial loop domination, altered export processes
other???

MICROBIOLOGICAL N_2 FIXATION

- Discovered in late 19th century in soil bacteria
- H. B. Bigelow (1931): "The possibility that so-called N_2 fixers may also fertilize seawater must be taken into account"
- R. Dugdale discovered N_2 fixation in Sargasso Sea in 1961
- Process was considered to be negligible in pre-JGOFS era, but significant during JGOFS

NUTRIENT DYNAMICS IN THE SUBTROPICAL NORTH PACIFIC OCEAN

- *Past Dogma:* N limits biomass accumulation and production rates
- *Contrariant Viewpoint:* P or some trace nutrient limits biomass accumulation and production rates
- *New Hypothesis:* There is a systematic, temporal alternation between N and P/Fe control of plankton processes, resulting from complex interactions between the ocean and the atmosphere, that may have important consequences for biogeochemical cycling rates and processes in the sea


ALTERNATING ECOSYSTEM STATES OF THE NORTH PACIFIC GYRE
1970's
ENSO favorable and
Warm phase PDO (post-1980)
N/P = 16
N/P = 16
N/P = 16
N/P = 16
N_2
N/P = 40
N/P = 25
N/P = 16
N/P = 25
SRP
1965
1980
Time
SRP
1980
1995
Time
N-limited
Trichodesmium absent
P-limited
Trichodesmium present

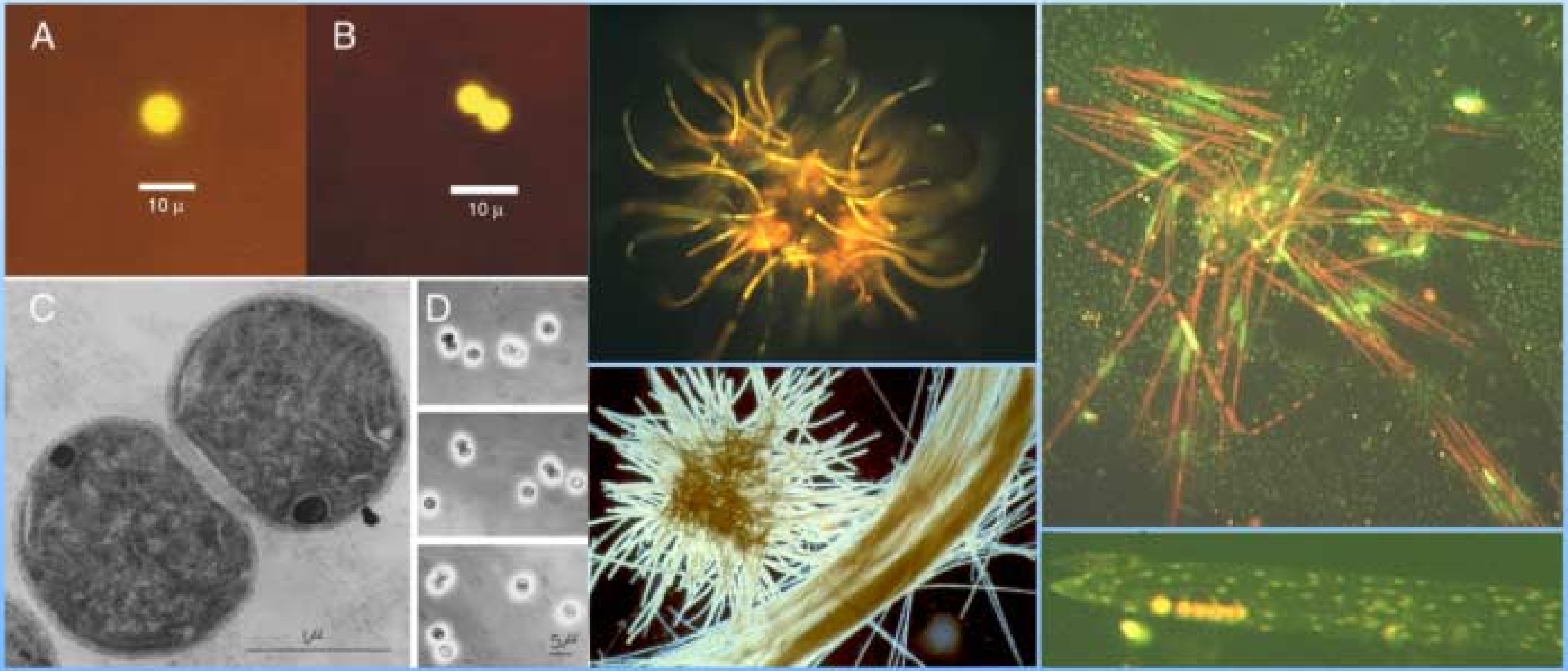
EVIDENCE FOR N_2 FIXATION

- Inability to balance N-cycle
- Presence of putative N_2 fixing microbes
- Altered DOM/POM/export stoichiometry
- Direct field measurements of N_2 fixation
- Natural ^{15}N isotope balance
- P pool drawdown over last decade
- DIC pool drawdown each summer

DIVERSITY OF N_2 FIXERS AT STA. ALOHA

Picoplankton	*Trichodesmium*	Diatoms/*Richelia*
- small (<2 µm)	- large (>20 µm)	- large (>20 µm)
- “background” population	- bloom forming	- bloom forming
- dispersed	- floaters/migrators	- sinkers/migrators
- consumed by protozoans	- not readily consumed	- consumed by zooplankton
- high turnover / low export	- low turnover / low export	- variable turnover / high export

The Rogues Gallery



Pico

Tricho

Diatomic diatom

EVIDENCE FOR N_2 FIXATION

- Inability to balance N-cycle
- Presence of putative N_2 fixing microbes
- Altered DOM/POM/export stoichiometry
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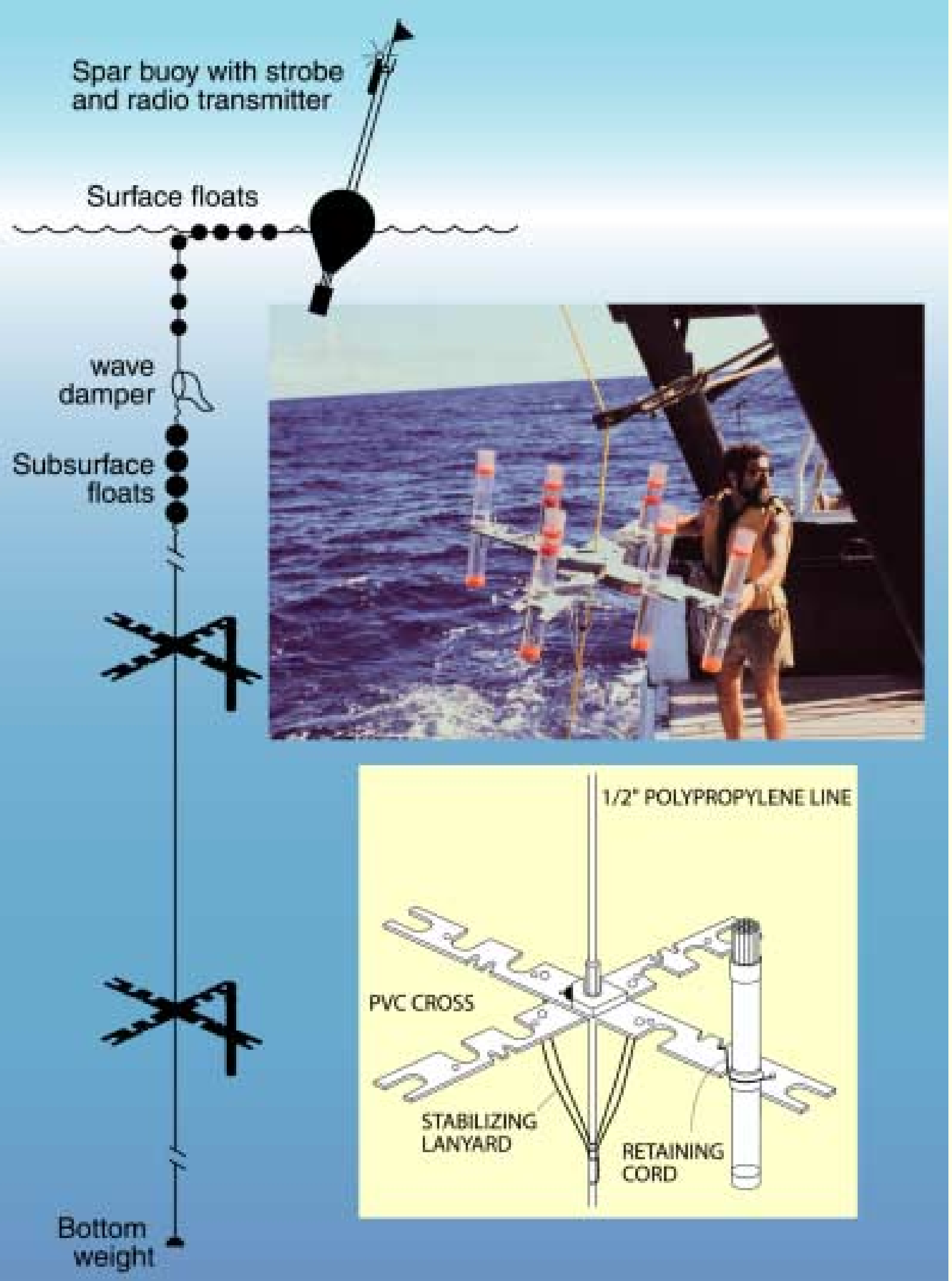
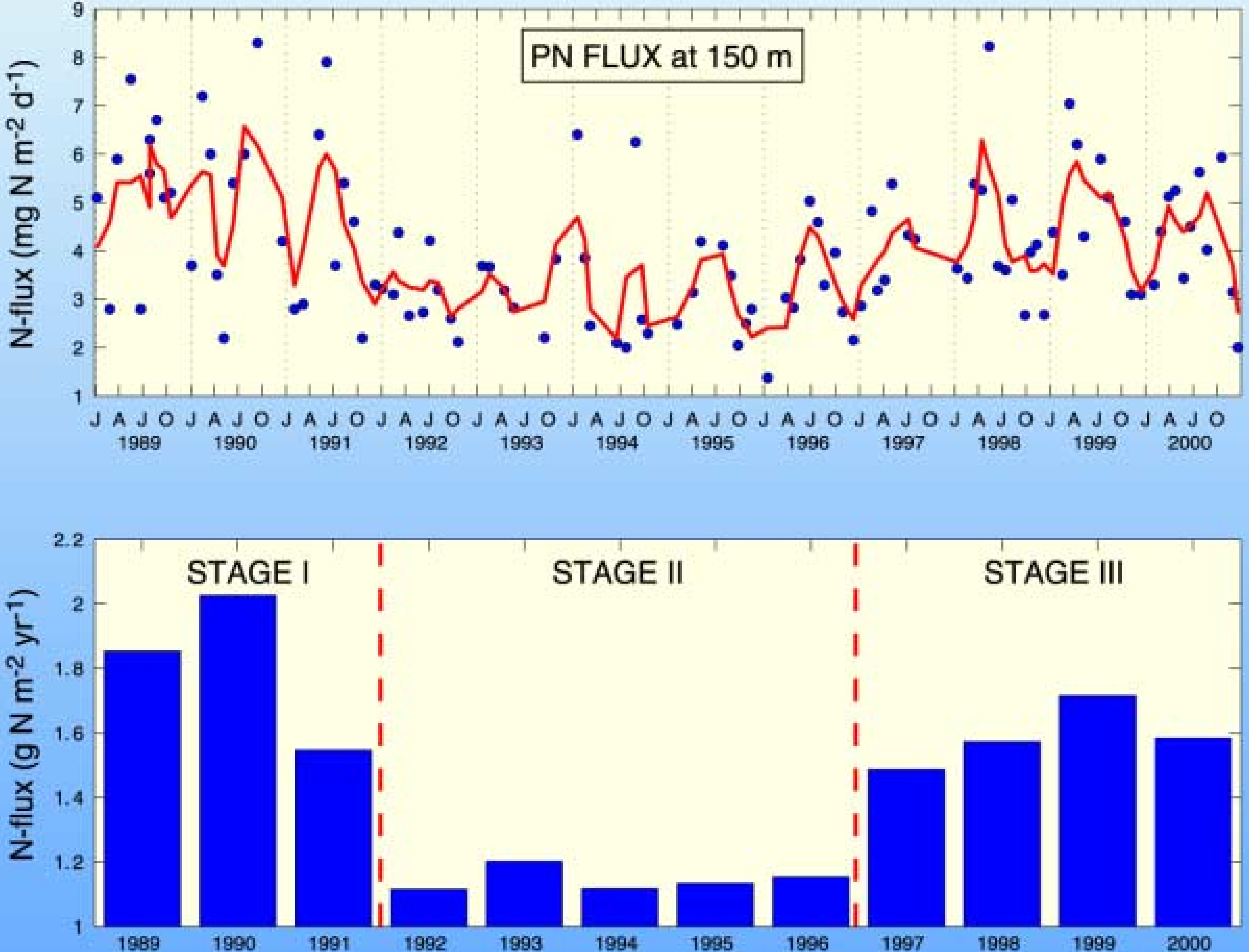


- Approximately monthly collections (48-60 hr per month)
- 150 m reference depth (1988-present)
- 300, 500 m reference depths (1988-1995)


PN FLUX at 150 m
N-flux (mg N m-2 d-1)
J A J O J A J O J A J O J A J O J A J O J A J O J A J O J A J O J A J O J A J O J A J O J A J O
1989 1990 1991 1992 1993 1994 1995 1996 1997 1998 1999 2000
STAGE I
STAGE II
STAGE III
N-flux (g N m-2 yr-1)
1989 1990 1991 1992 1993 1994 1995 1996 1997 1998 1999 2000

δ^{15}N OF NEW N SOURCES AT STATION ALOHA

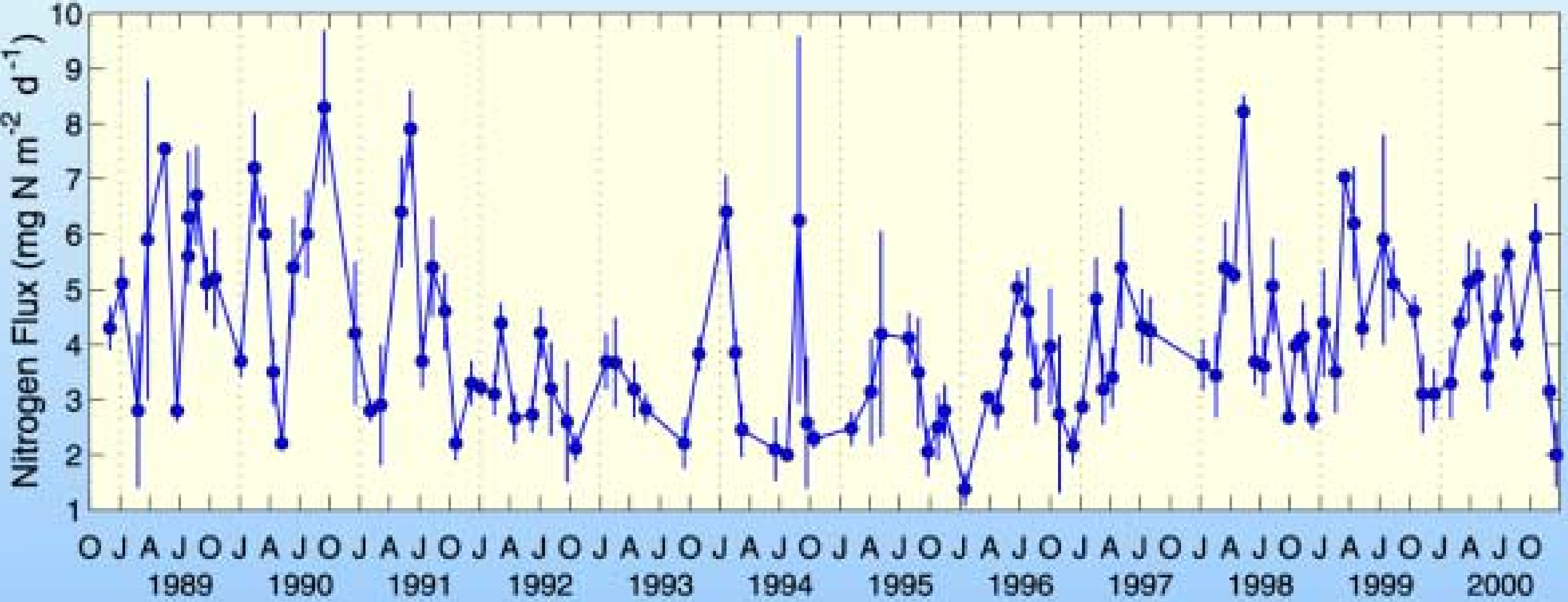
δ^{15}N (N_2 Fixation) ≈ 0 ‰

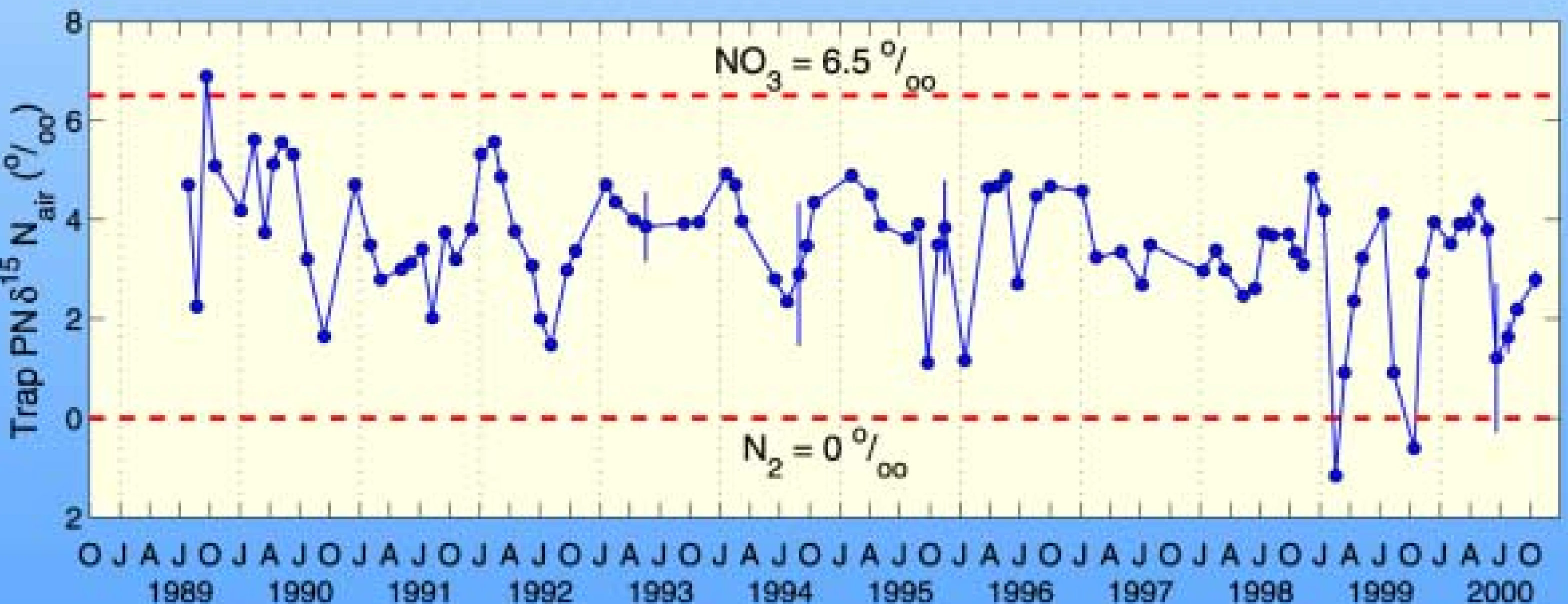
Slight equilibrium fractionation during dissolution is roughly counteracted by slight kinetic fractionation during fixation

δ^{15}N (NO_3^- uptake) ≈ 6.5 ‰

Approximate deepwater value – no fractionation occurs during uptake because reaction is taken to completion; i.e., NO_3^- is taken up as fast as it is delivered

Dore et al. (2002), L&O, 47: 1595-1607

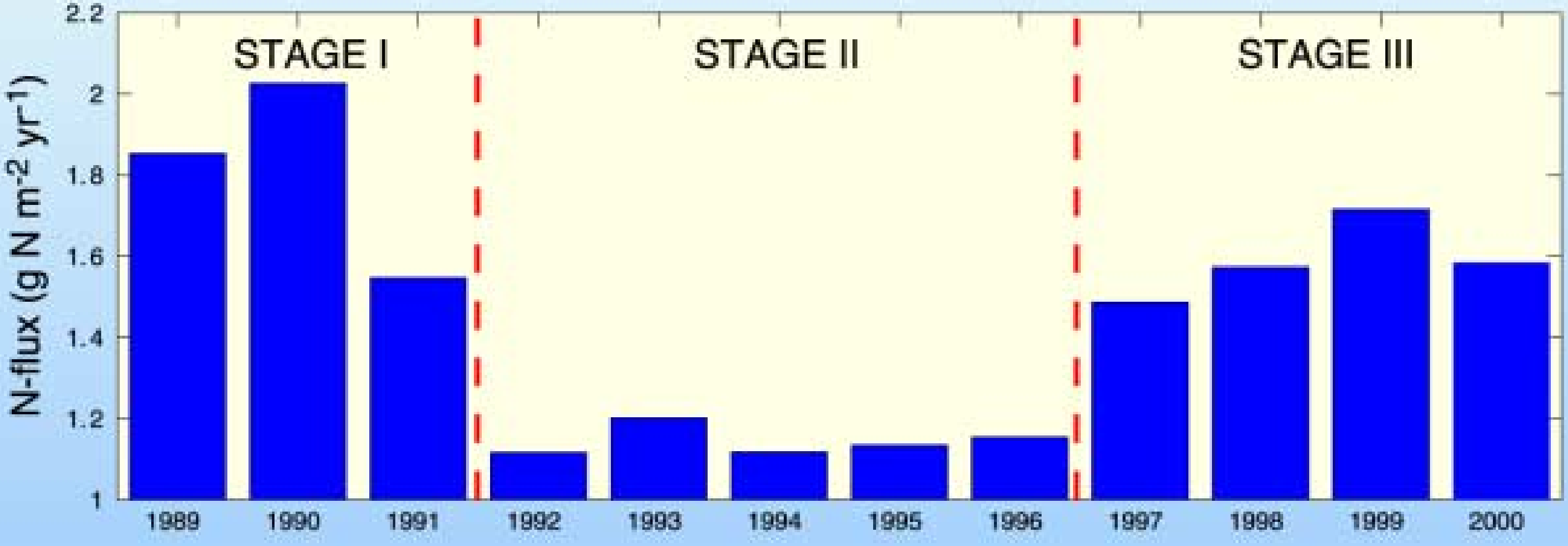




N_2 FIXATION AT STATION ALOHA (1990-2000)

- N_2 accounts for 47±9% of "new" N
- Large interannual variations:

  36% in 1993 vs. 69% in 1999
- Relative importance of N_2 vs. NO_3^- as a source of new N has increased since 1995



STAGE I

- Nitrate-supported N flux
- High export
- Low DOM storage

STAGE II

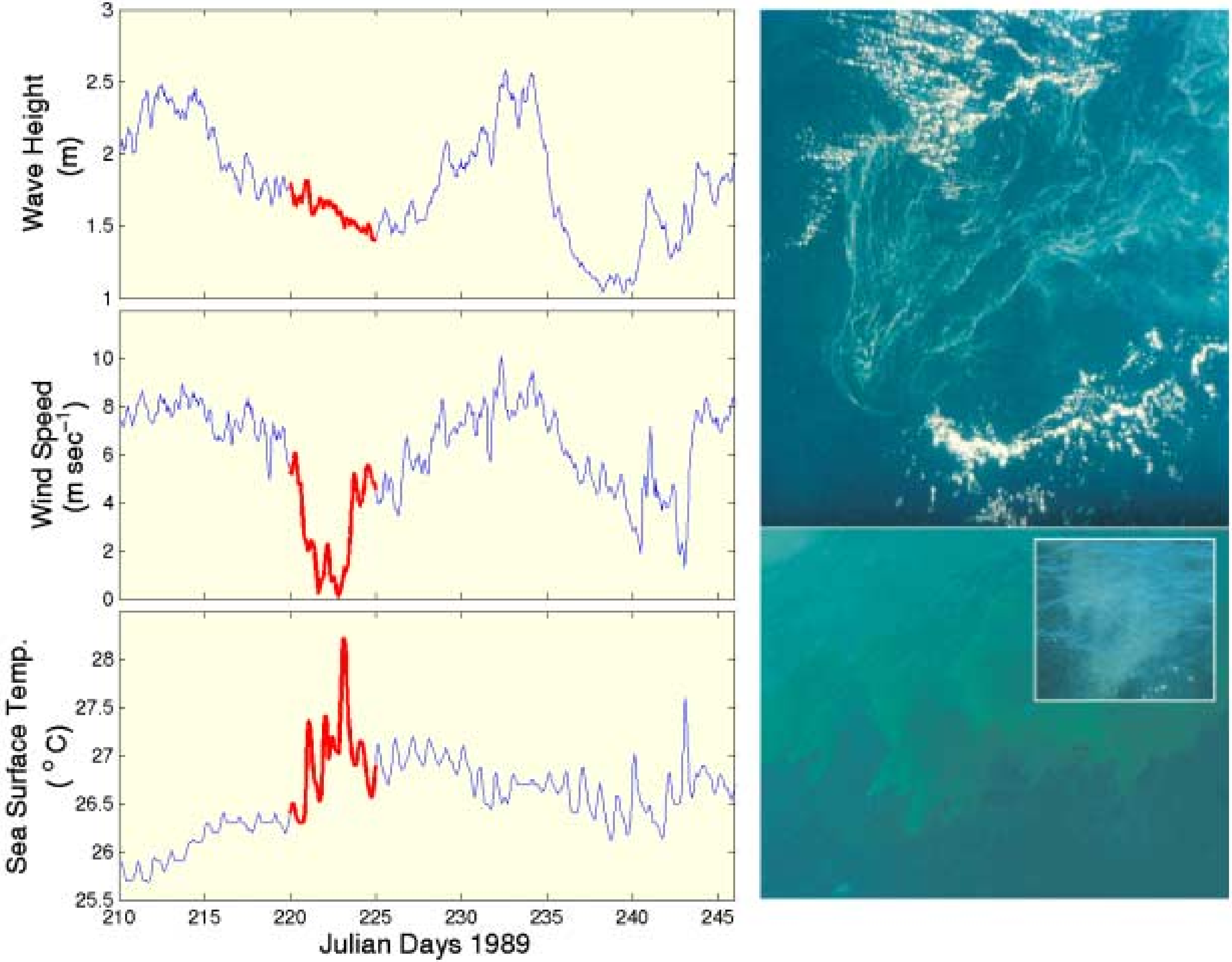
- Transition
- Low export
- High DOM storage

STAGE III

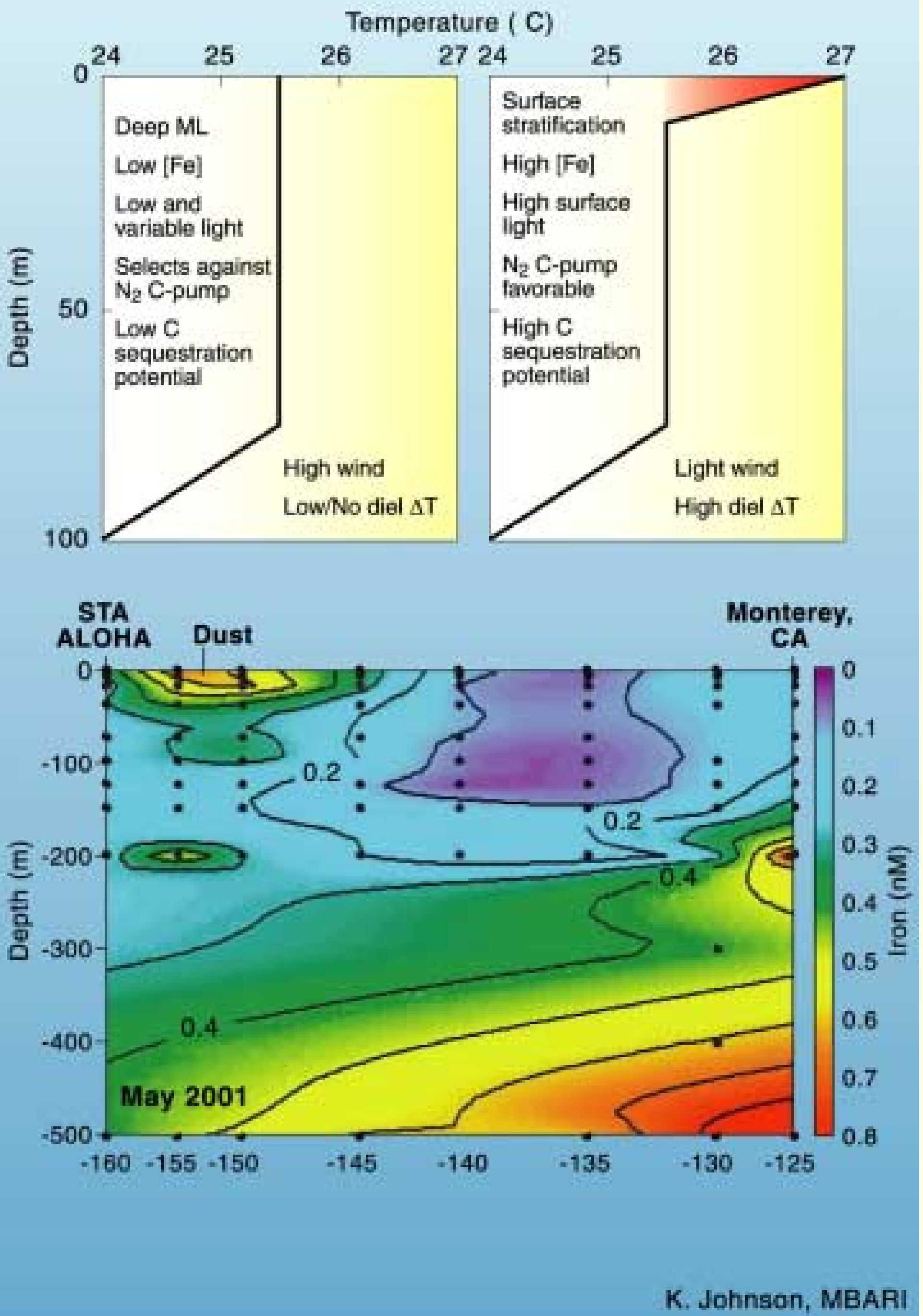
- N_2-supported N flux
- High export
- High DOM storage

MICROBE-DUST CONNECTIONS

- Microbes require Fe for metabolism, especially N_2 fixation
- Fe delivery to the open ocean is via atmospheric dust deposition
- Dust deposition is a climate-sensitive parameter

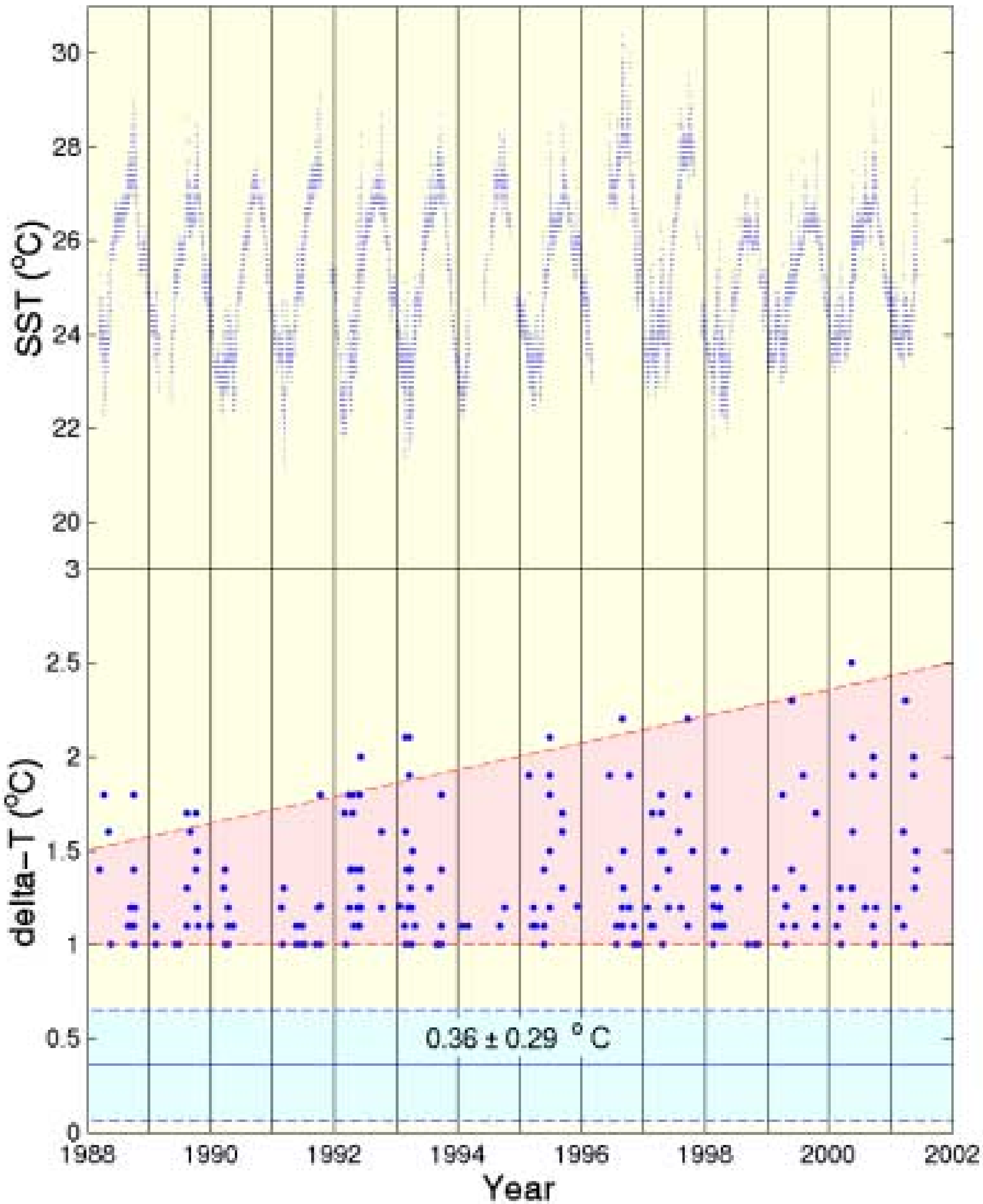


Wave Height (m)
3
2.5
2
1.5
1
Wind Speed (m sec^{-1})
10
8
6
4
2
0
Sea Surface Temp. (°C)
28
27.5
27
26.5
26
25.5
210
215
220
225
230
235
240
245
Julian Days 1989

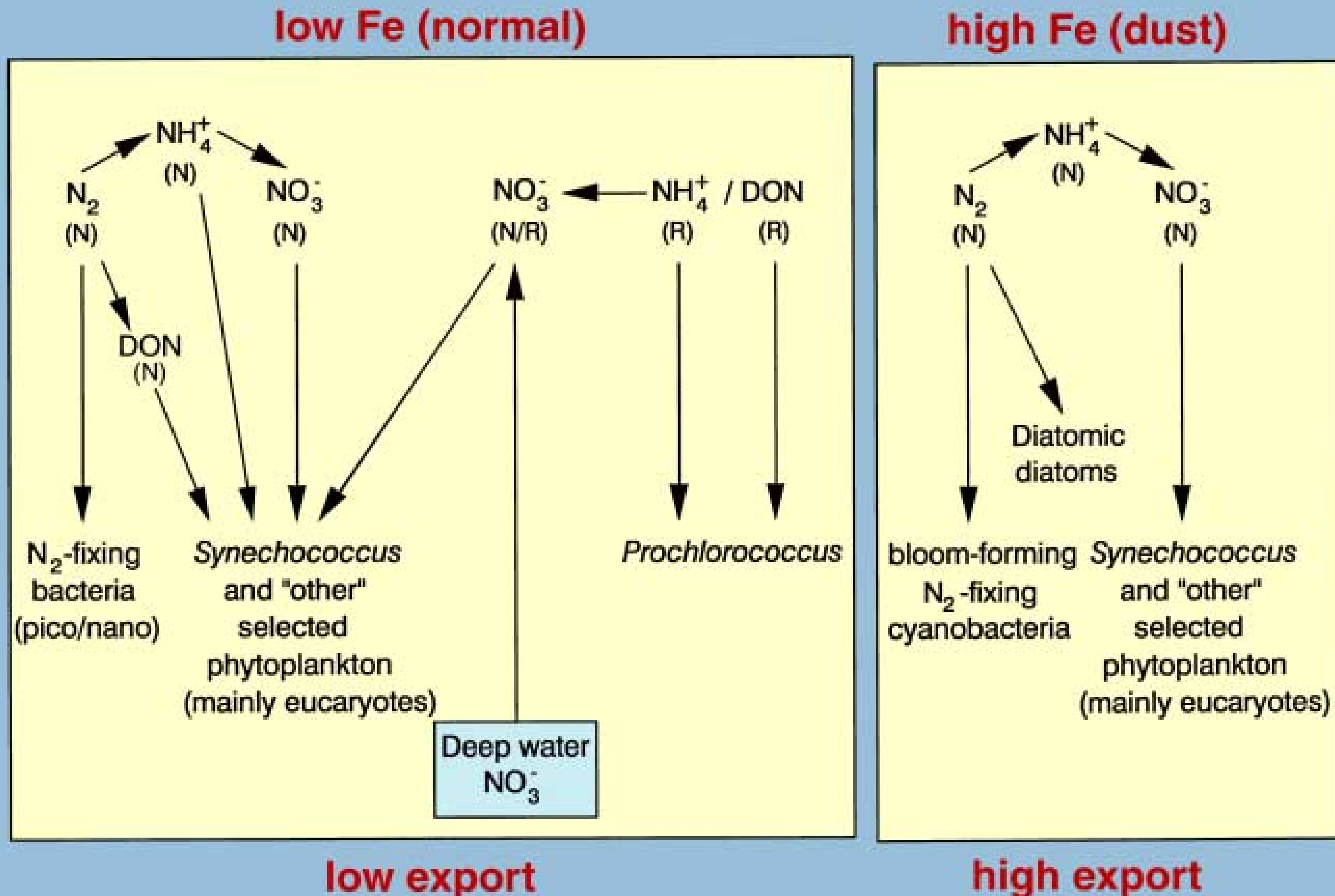


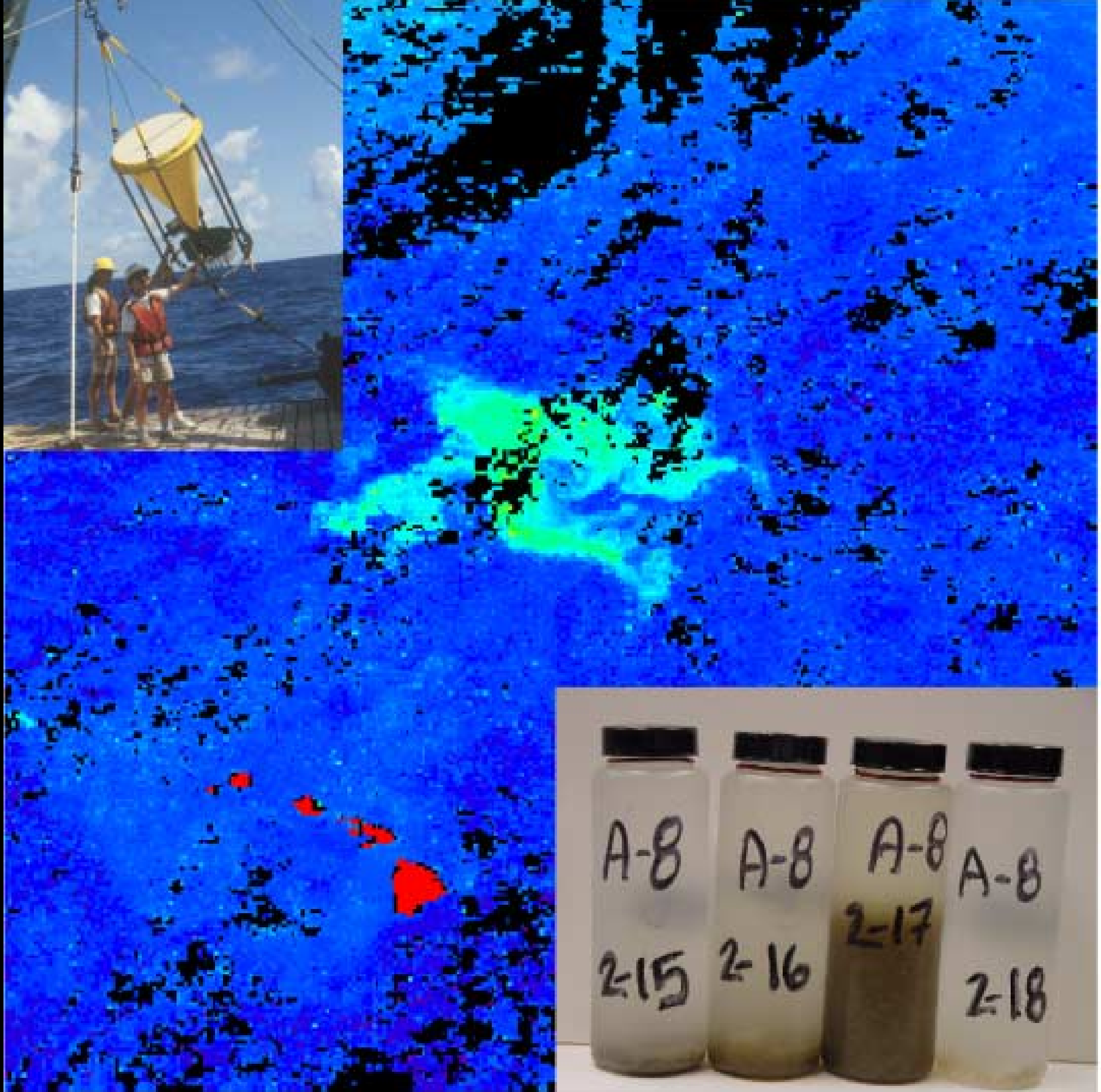
- Fe deposition is a necessary but insufficient condition for a bloom
- A shallow mixed-layer and calm conditions enhance the overall impact

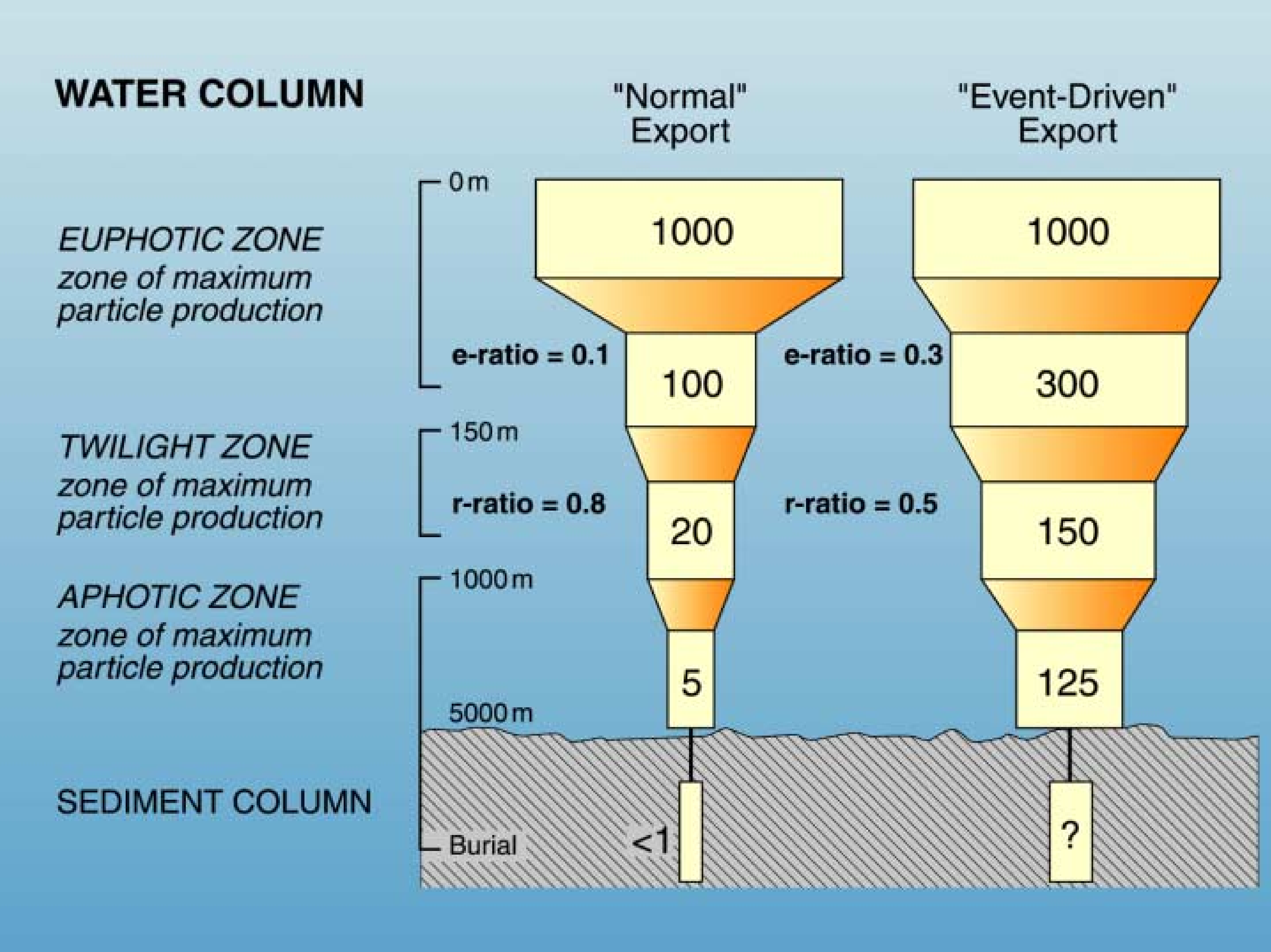
NDBC Buoy 51001

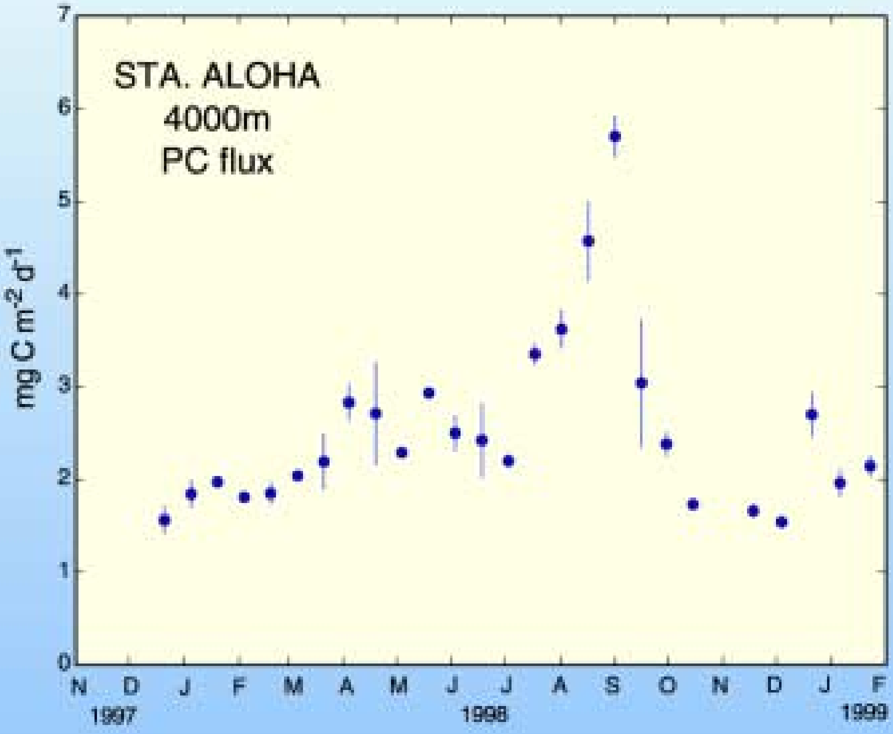


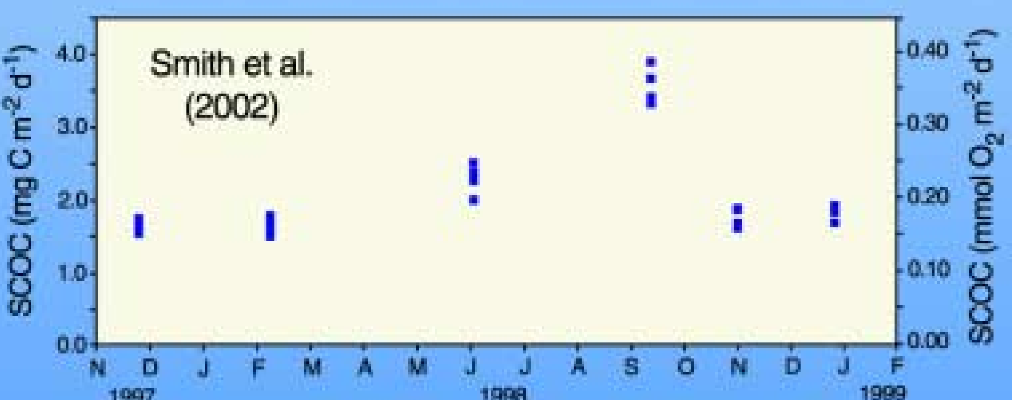
STATION ALOHA: New vs. Regenerated N Revisited




A-8
2-15
A-8
2-16
A-8
2-17
A-8
2-18


WATER COLUMN
"Normal" Export
"Event-Driven" Export
0 m
EUPHOTIC ZONE
zone of maximum particle production
1000
1000
e-ratio = 0.1
100
e-ratio = 0.3
300
150 m
TWILIGHT ZONE
zone of maximum particle production
r-ratio = 0.8
20
r-ratio = 0.5
150
1000 m
APHOTIC ZONE
zone of maximum particle production
5
125
5000 m
SEDIMENT COLUMN
Burial
<1
?

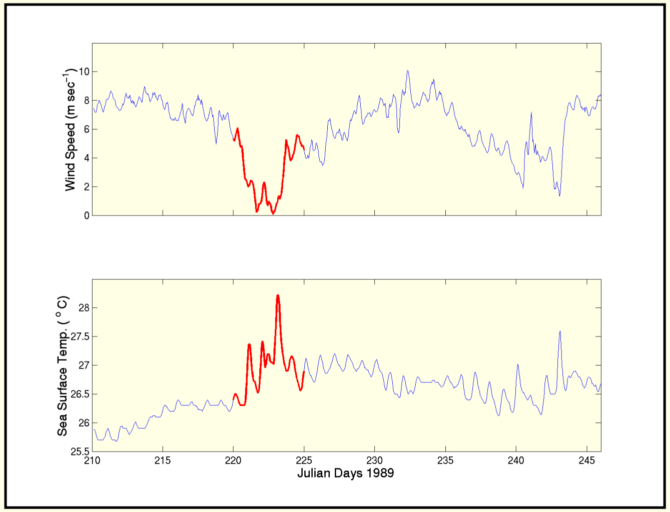


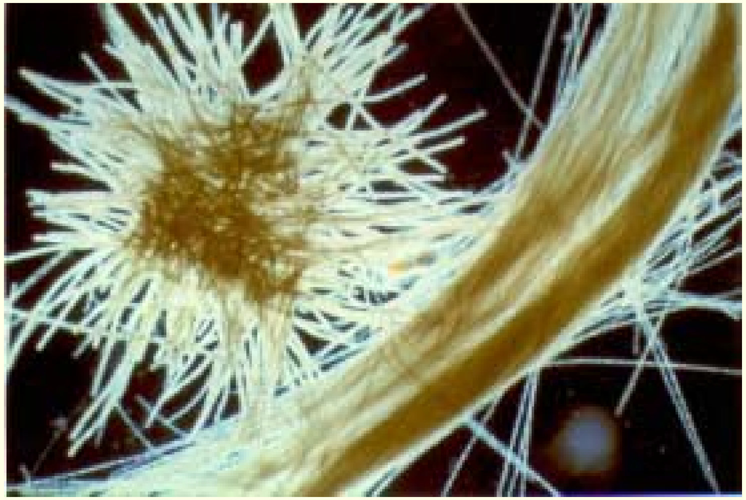


Free-Vehicle
Grab Respirometer
(K. Smith, SIO)

STA. ALOHA CARBON SEQUESTRATION FORECAST

Light trade winds with a diel SST change of 2-3°C and a 50% probability of significant N_2 fixation, increasing to 90% during periods of aperiodic dust (Fe) deposition, followed by pulsed export of organic matter to the abyss.





SHIFTING BIOGEOCHEMICAL-ECOLOGICAL PARADIGMS

- *Then:* Climax, time stable community

  Now: Complex, time variable community
- *Then:* eukaryote photoautotrophy

  Now: eukaryotes plus anoxygenic/oxygenic prokaryotic photoautotrophs + photoheterotrophs
- *Then:* N-limitation / nitrate-based new production hypothesis

  Now: P-Fe co-limitation and Fe + N_2 fixation + P syntrophy – “new” production via “new” microbes

Conclusion: Community structure matters!

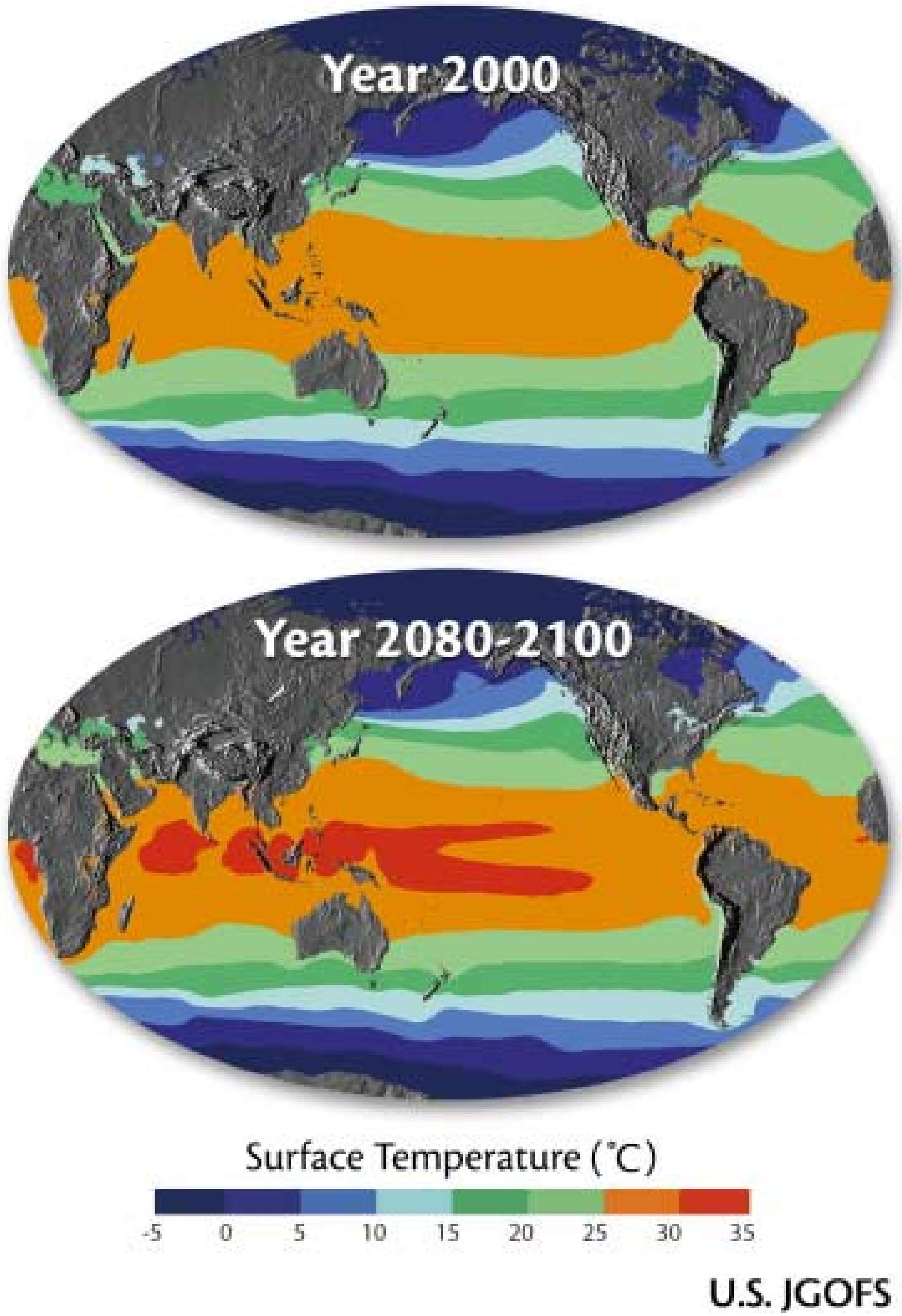
JGOFS MISSION
circa 1987

"reducing uncertainty…"

JGOFS CONTRIBUTION
circa 2003

"producing excitement…"

and re-directing the next several decades of marine carbon cycle research

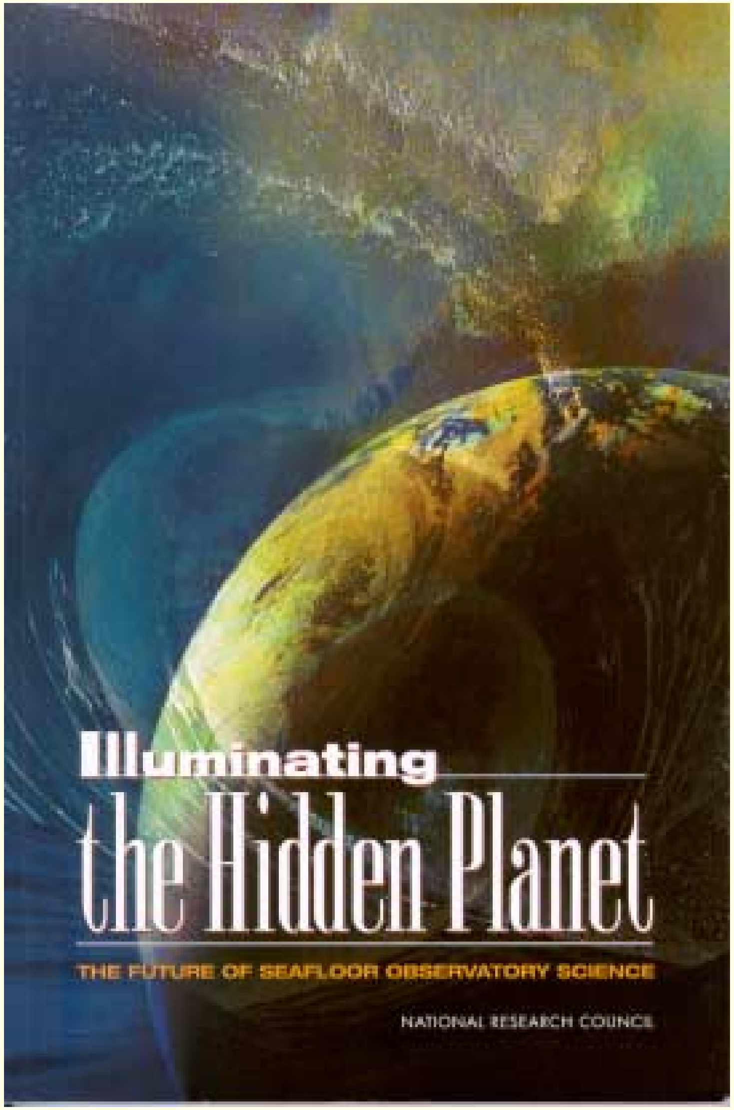


Global Models and Predictions

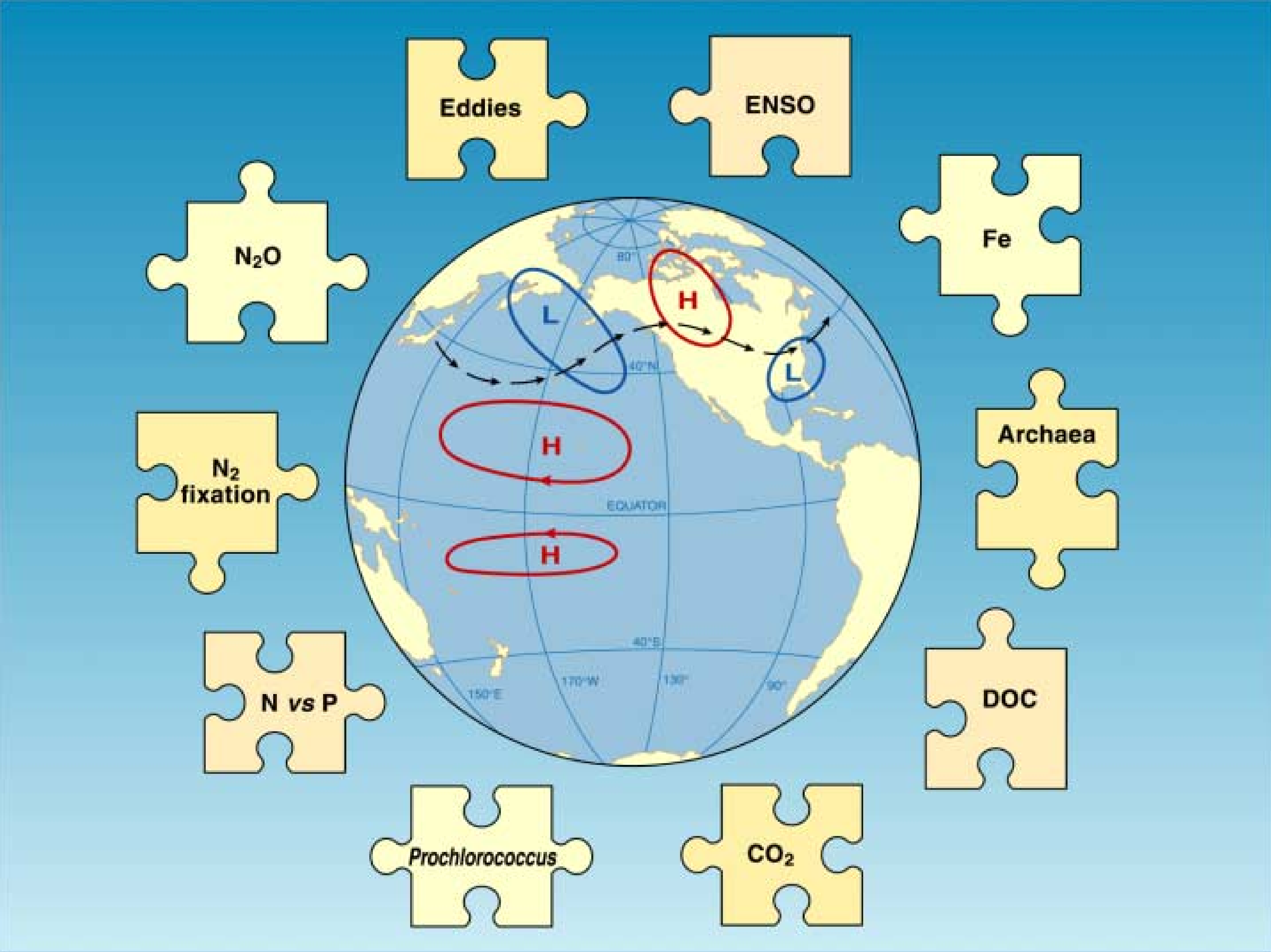
- Ocean circulation models coupled with biology
- Increased temperature will impact both CO_2 solubility and biological pump

POST-JGOFS CHALLENGES

- Expand coastal and open ocean observation programs including new sensors and data collection methods
- Develop a relevant, meaningful conceptual model of the ocean's carbon cycle and the role of marine microbes – the "unseen majority"
- Conduct meaningful ocean perturbation experiments to test our understanding of ecosystem processes
- Develop a mean climatology of ocean ecosystems to facilitate the detection of climate influenced change



- Preaching to the choir!
- Ocean Studies Board – National Research Council (2001)
- Be prepared for some significant scientific advances in the next few decades



Eddies
ENSO
N_2O
Fe
L
H
L
H
H
N_2 fixation
Archaea
EQUATOR
40°N
40°S
150°E
170°W
130°
90°
N *vs* P
DOC
Prochlorococcus
CO_2

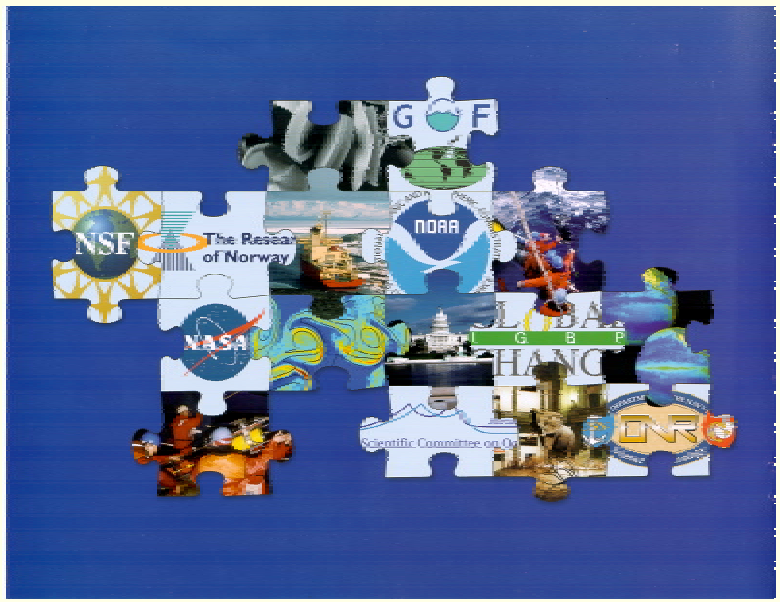
IN SUMMARY

“Study nature, not books”

“Strive to interpret what really exists”

… excellent advice from
Louis Agassiz (1807-1873)

JGOFS



To be continued!