Microbes in Motion:
A Sea of Change

HOT Team
USA

ACKNOWLEDGMENTS

- PICES-13 Scientific Committees and local organizers
- P. Harrison, K. Lee, C. Sabine
- My lab and the National Science Foundation

OUTLINE: A SEA OF CHANGE

- Microbes: The “silent majority”
- North Pacific Subtropical Gyre (NPSG): Paradigms ca. 1985 (pre-JGOFS)
- Shifting regimes and paradigms
- Climate-driven, decade-scale habitat variability: N_2 fixation, Fe-P syntrophy, N:P stoichiometry and ecological consequences
- Critical knowledge gaps and future prospectus

MICROBIAL OCEANOGRAPHY

- Application of general ecological principles to microbial communities in nature
- Comparative ecosystem analysis
- Biodiversity, biomass and productivity
- C-N-P cycling and energy flow
- Methods development and technology transfer
- Education and training

ROLE OF MICROBES IN GLOBAL OCEAN ECOLOGY

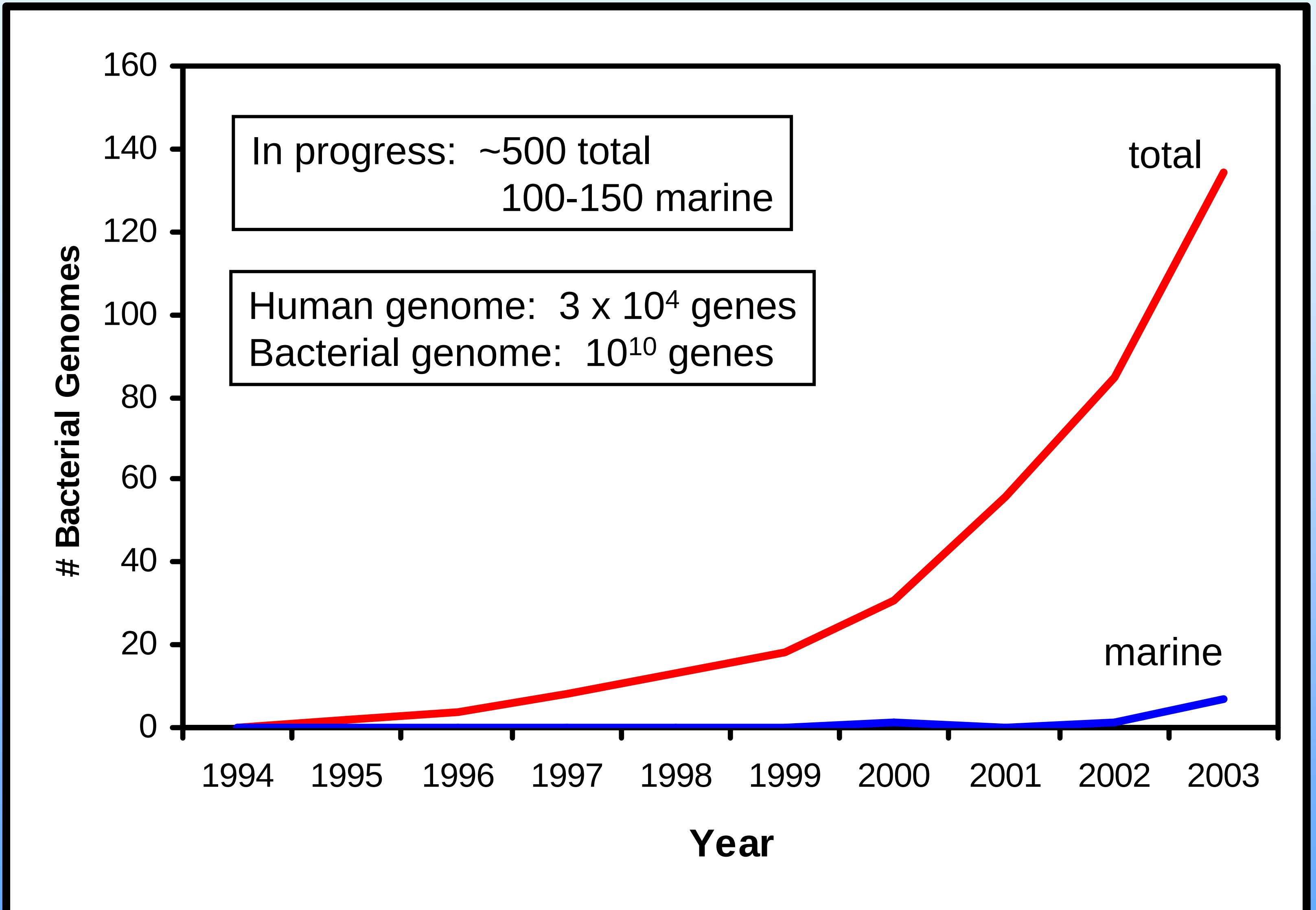
- Control production and consumption of organic matter
- Control O_2 concentration, pH and redox levels
- Production and consumption of “greenhouse” gases (CO_2, CH_4, N_2O)
- Control N availability: N_2 fixation, nitrification and denitrification

Microbes make things happen!

POST-1978: NOTHING SHORT OF A MARINE MICROBIOLOGICAL REVOLUTION!

- 1979: Discovery of *Synechococcus* (Waterbury)
- 1988: Discovery of *Prochlorococcus* (Chisholm)
- 1990: Discovery of SAR-11 (Giovannoni)
- 2003: Full genome sequences of the same

not to mention: *planktonic crenarchaeota (DeLong/Fuhrman), rhodopsin-containing photobacteria (Béjà/DeLong), A-An-P (Kolber/Béjà),* N_2*-fixers (Zehr), new picoeukaryotes and viruses, and other novel marine microbes*



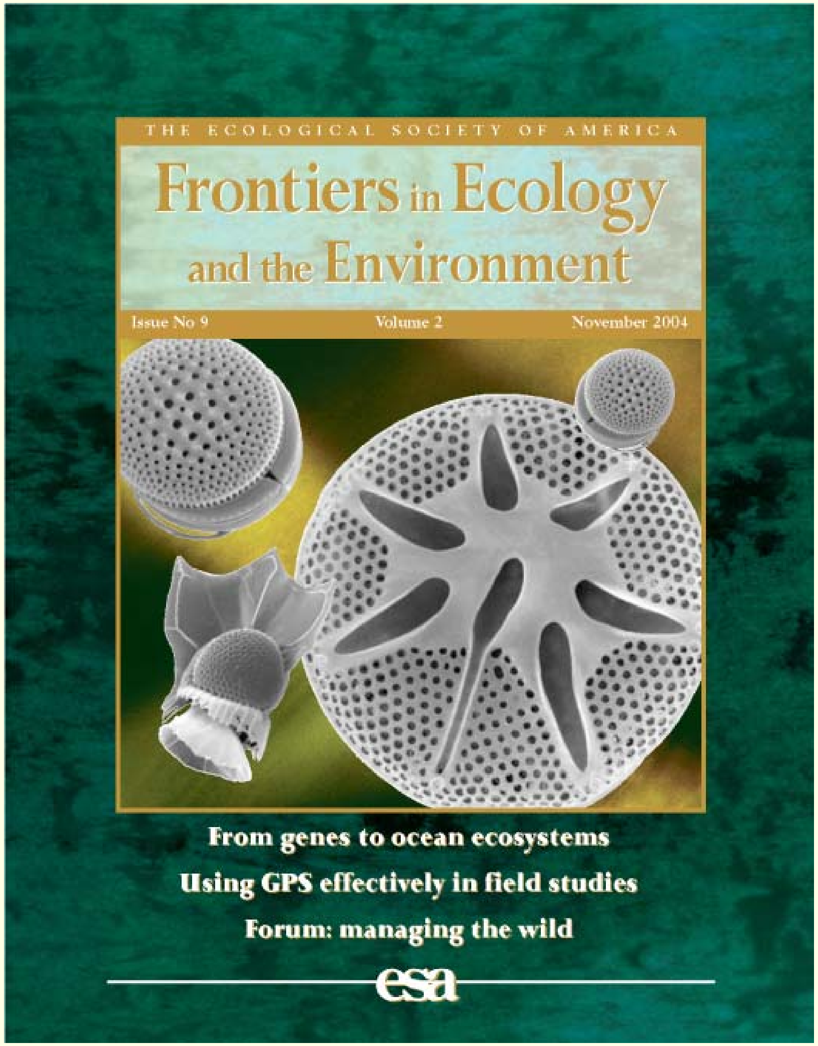
In progress: ~500 total
100-150 marine
Human genome: 3 x 10^4 genes
Bacterial genome: 10^10 genes
total
marine
Bacterial Genomes
Year
0
20
40
60
80
100
120
140
160
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003

J.C. Venter (2003)
“Unleashing the power of genomics: Understanding the environment and biological diversity”
The Scientist 17: 8

- Sargasso Sea (200 *l*), shotgun sequencing approach
  - Few thousand new species
  - More than 1,000,000 new protein-coding genes (10x the total # discovered to date)
  - Hundreds of new photoreceptors that may capture energy from sunlight

Paradigm Shift
(S. W. Chisholm)

A Sea of Creatures



- Hot off the press: Doney et al. (2004)
- "From Genes to Ecosystems: The Ocean's New Frontier"
- Bottom line: Gene sequence information has added value when joined with oceanography, biogeochemistry and modeling
- Let's get to work!

A FEW CONTEMPORARY RESEARCH TOPICS

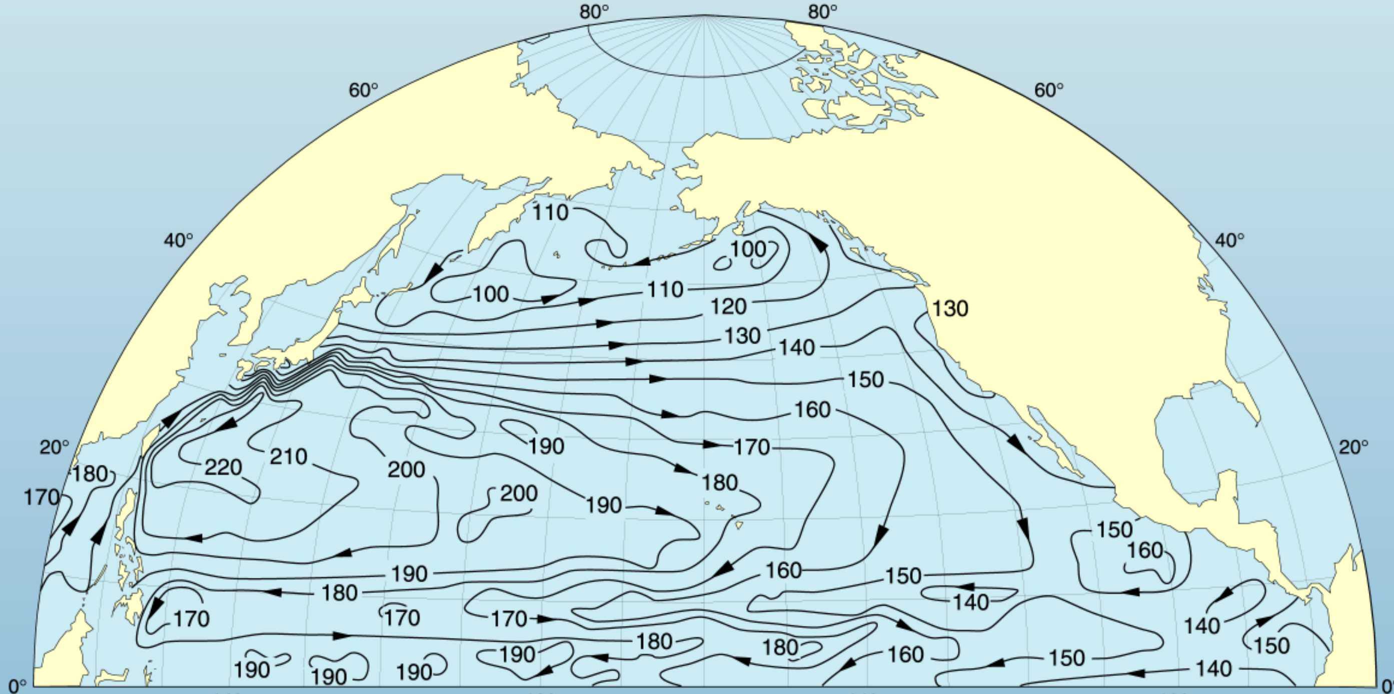
- Role of sunlight: *The world beyond oxygenic photosynthesis*
- Metabolic balance of the sea: *Is the open ocean net heterotrophic?*
- Competition and selection: *How is the resource (e.g., nutrient) spectrum divided?*
- Time domains in microbial oceanography: *snapshots vs. motion pictures*

“In the absence of time-series data sets, contemporary field observations are hidden in the ‘invisible present’”

John Magnuson
1990 Bioscience 40: 495

HAWAII OCEAN TIME-SERIES PROGRAM (1988-PRESENT)

- Description of the NPSG and how it functions using a multidisciplinary approach
- Characterization of microbial community structure and dynamics
- 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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0°
140°
180°
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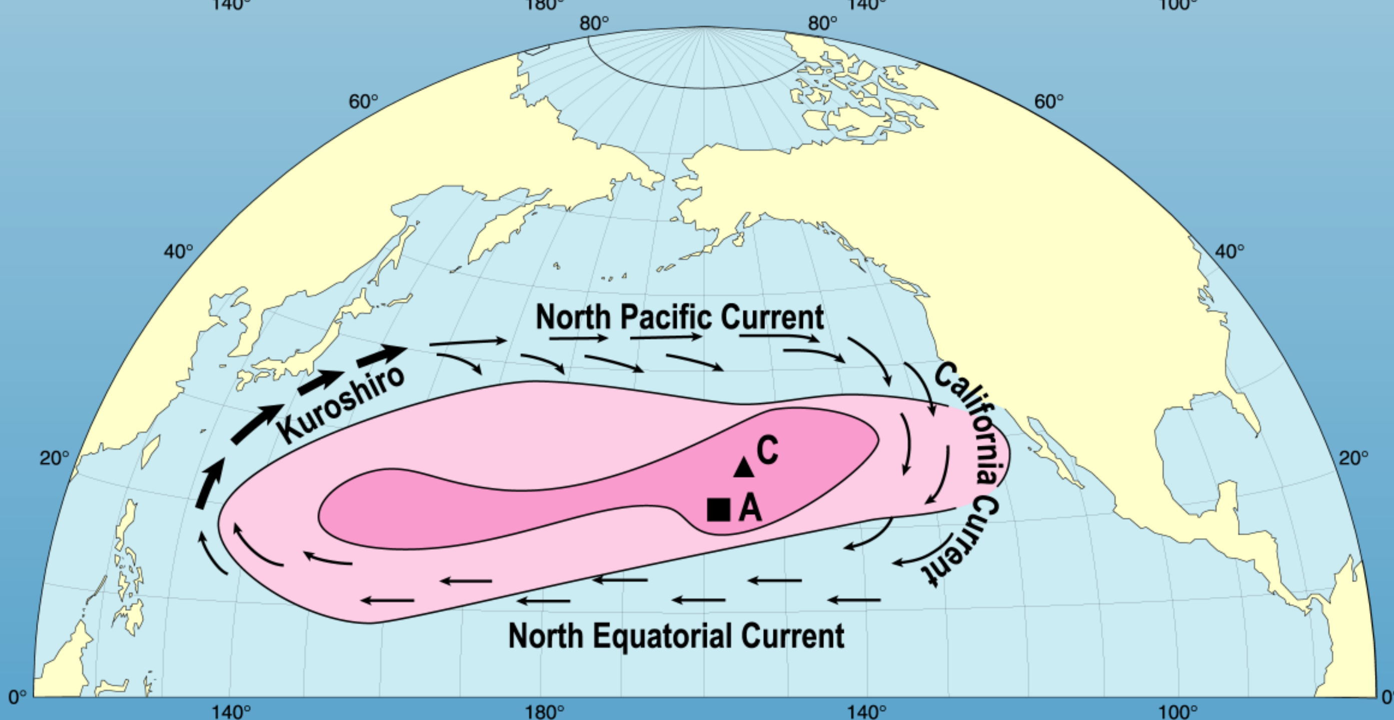

80°
80°
60°
60°
40°
40°
20°
20°
0°
0°
140°
180°
140°
100°
North Pacific Current
Kuroshio
California Current
C
A
North Equatorial Current

NPSG CHARACTERISTICS (CA. 1985)

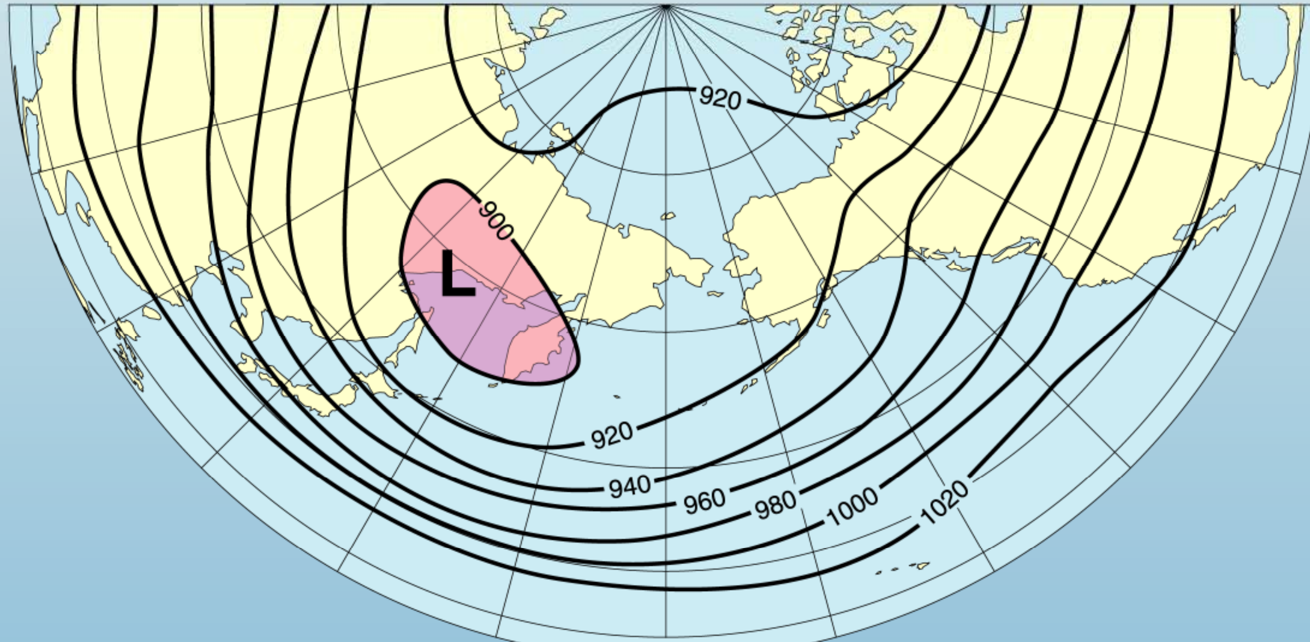
- *Habitat:* Very old, very large and very isolated
- *Oligotrophy:* low biomass, nutrients, primary production and export
- *Climax community:* time/space invariant
- *Biogeochemistry and Eco-dynamics:* Well characterized, easily modeled

CLIMAX COMMUNITY THEORY (Clements 1916, Whittaker 1953)

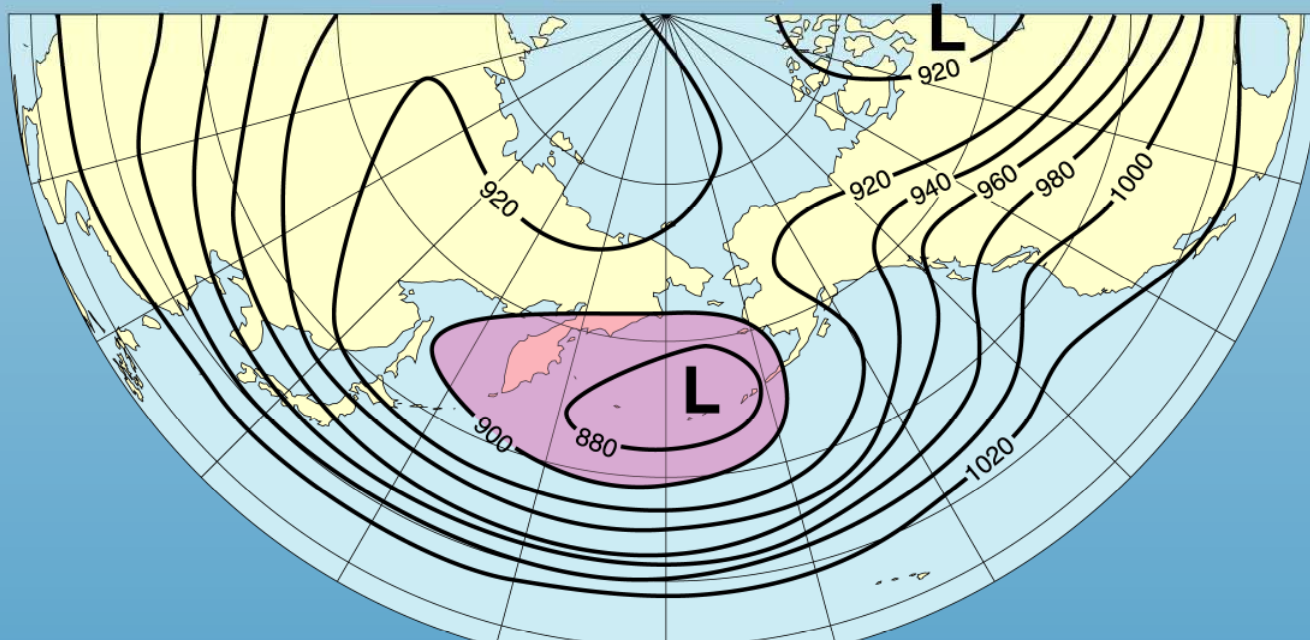
- Succession - orderly process of community development involving changes in community structure, function and dynamics - reasonably directional and predictable
- Driven by changes in physical environment - i.e., climate
- Culminates in a stable, terminal ecosystem - the Climax community - maximum utilization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

BARRIERS TO LINKING CLIMATE CHANGE TO OCEAN BIOLOGY

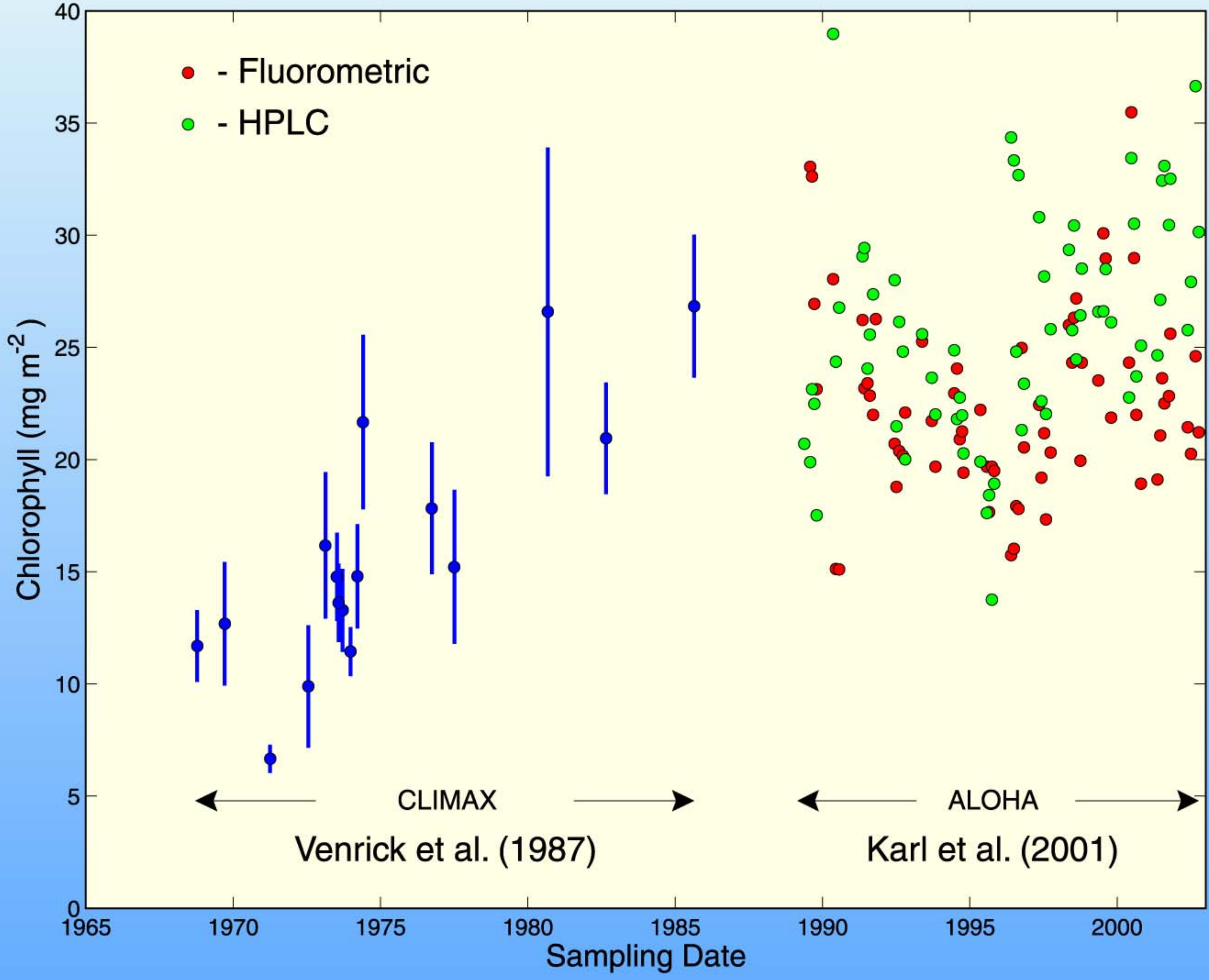
- Natural habitat variability
- Lack of consistent, long-term ocean observations (lags, thresholds, feedbacks)
- Changing bio-ocean paradigms
- Other ($$, motivation, human resources, technology)



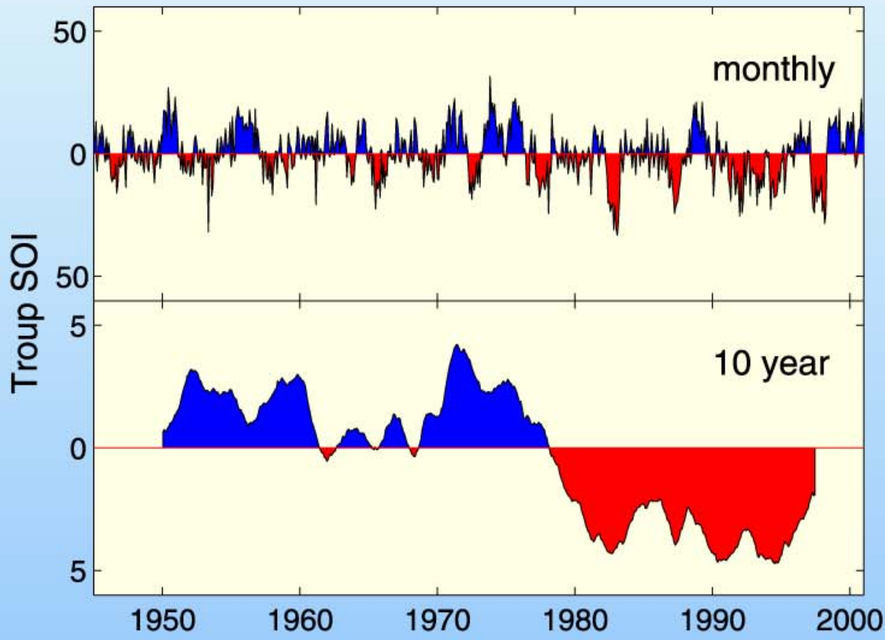
1947–1972



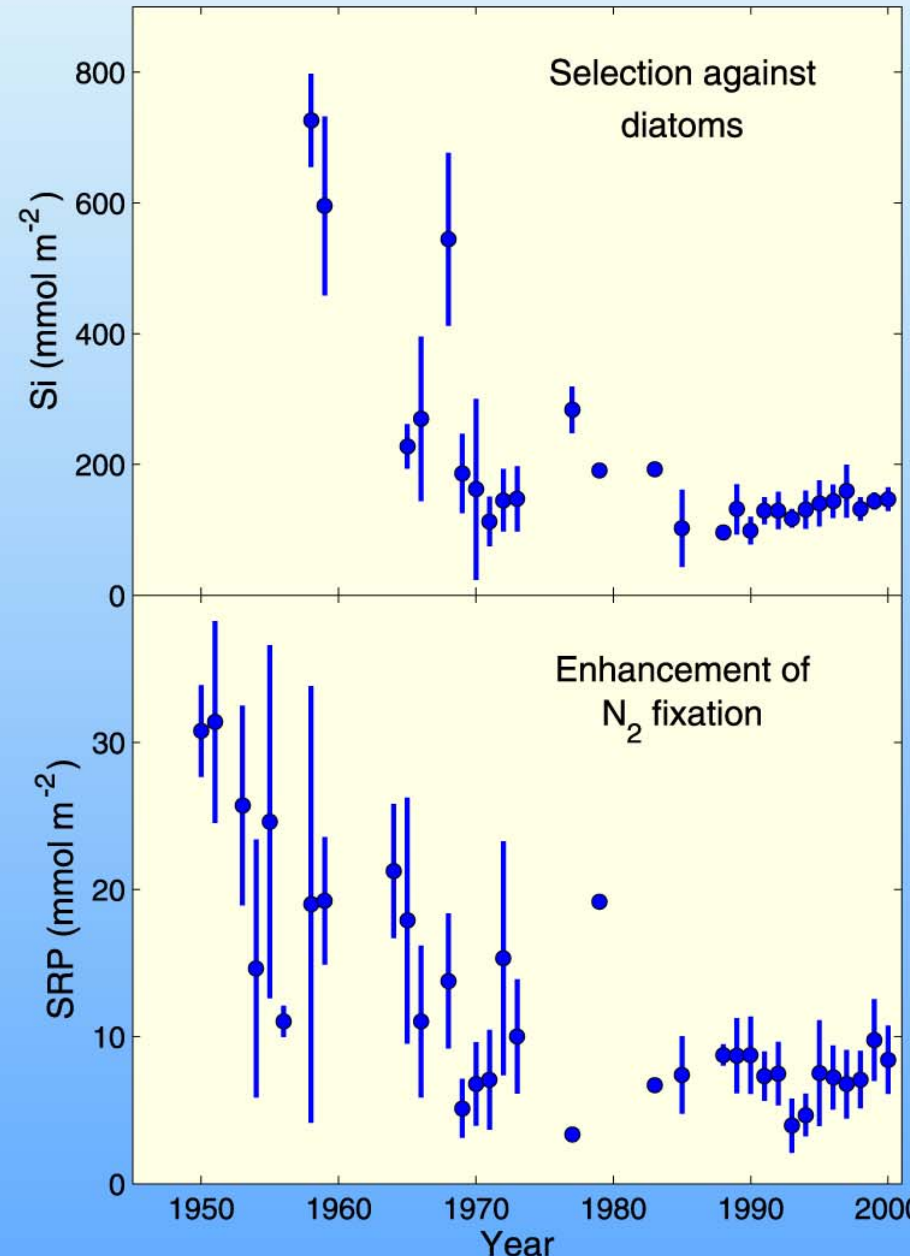
1976–1977

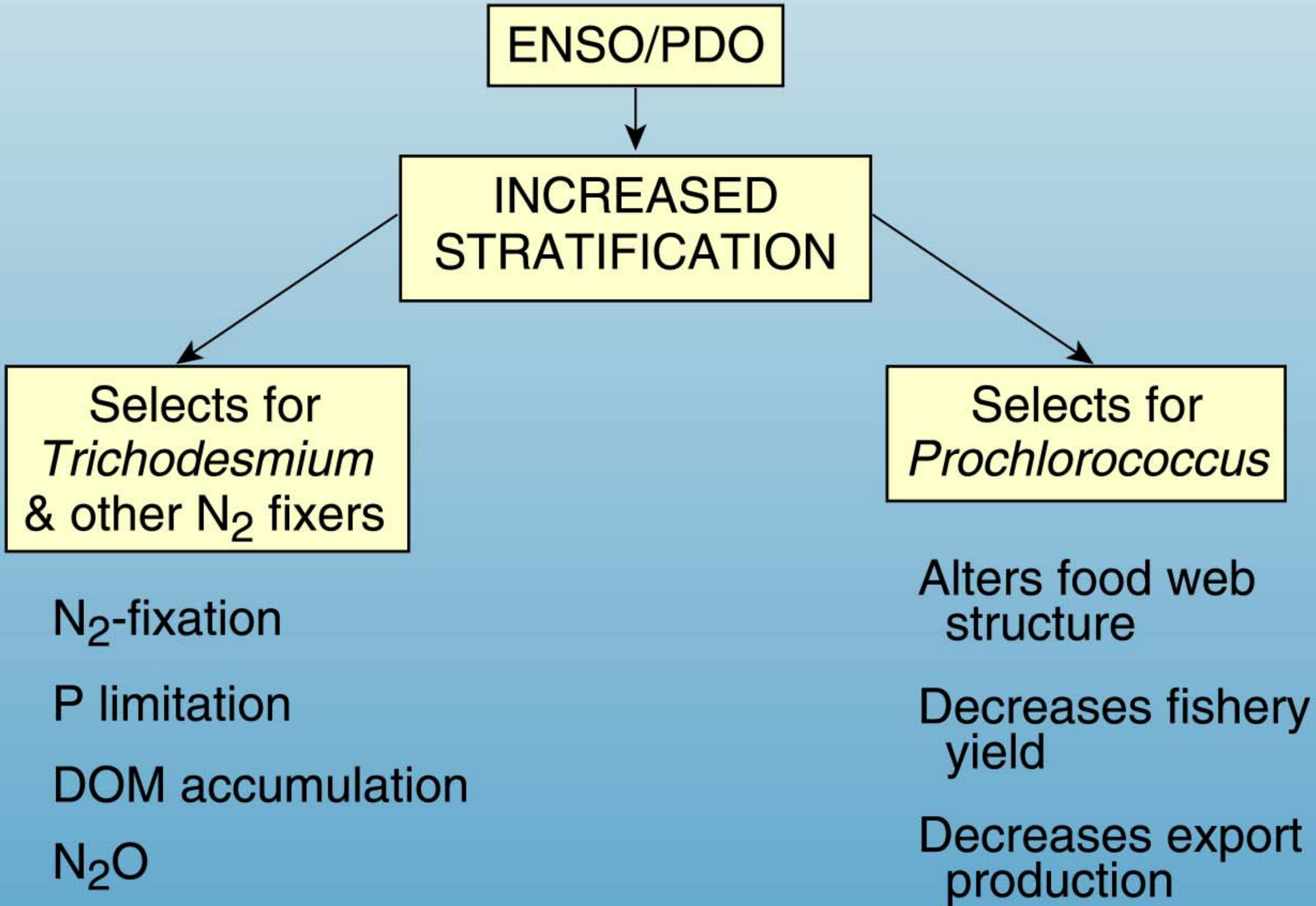


- Fluorometric
- HPLC
Chlorophyll (mg m^{-2})
Sampling Date
CLIMAX
ALOHA
Venrick et al. (1987)
Karl et al. (2001)
0
5
10
15
20
25
30
35
40
1965
1970
1975
1980
1985
1990
1995
2000



NUTRIENT DYNAMICS IN THE NORTH PACIFIC SUBTROPICAL GYRE



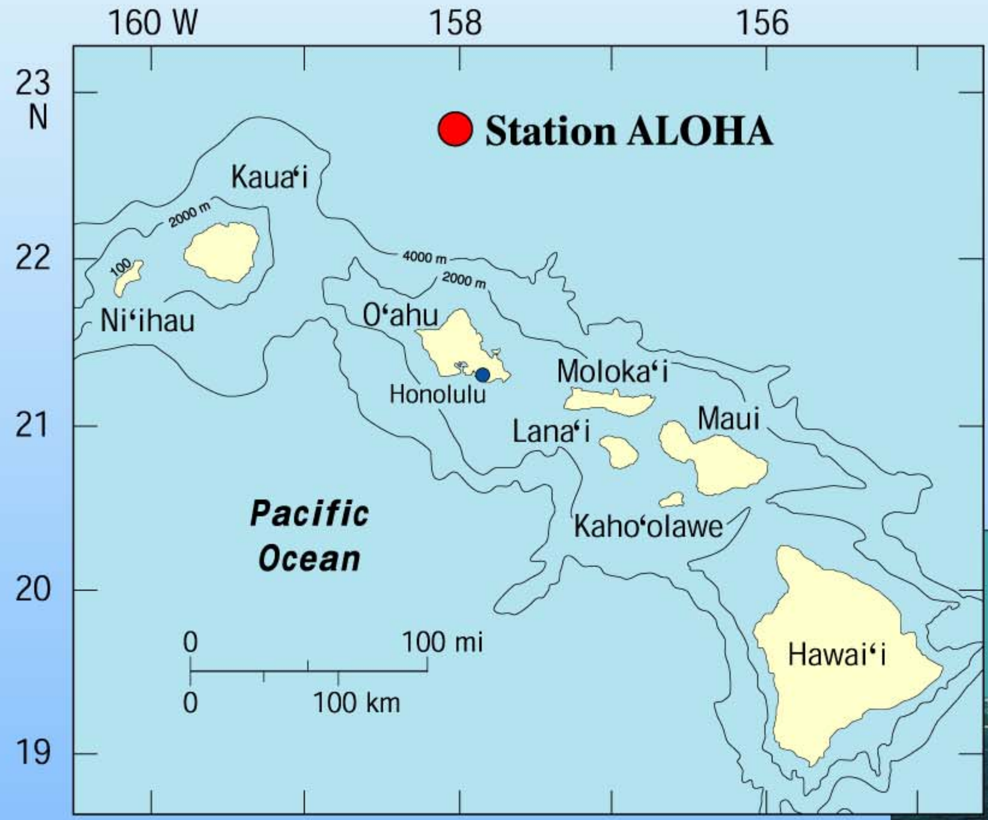

ENSO/PDO
INCREASED STRATIFICATION
Selects for *Trichodesmium* & other N_2 fixers
Selects for *Prochlorococcus*
N_2-fixation
P limitation
DOM accumulation
N_2O
Alters food web structure
Decreases fishery yield
Decreases export production

ECOSYSTEM VARIBILITY AND REGIME SHIFTS

- Abrupt, large-scale ecosystem change punctuates longer periods of modest variability – called regimes
- While regimes, or ecosystem states, probably are not truly stable, they are persistent and, perhaps, resilient
- Detection of the processes that cause regimes to persist, and those that cause them to break down pose challenges for ecosystem research and management
- Ecosystem change is usually not reversible, or can be reversed only with a long time delay (oscillation or alternation of ecosystem states, or regime shifts)

“Climate-induced regime shifts are phenomena often at the edge of statistical significance, yet are at the forefront of significance to ecologists and the public”

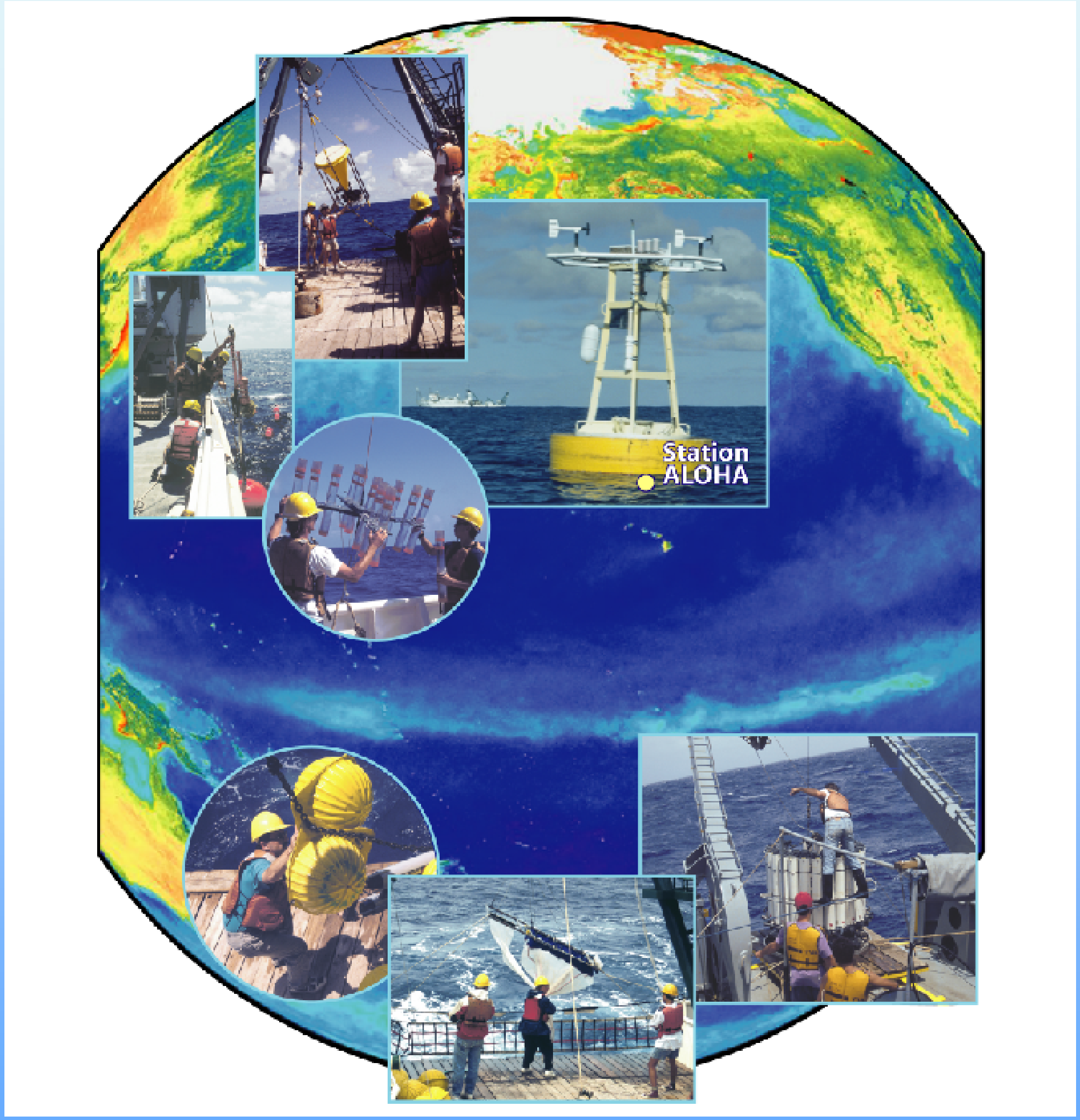
S. R. Carpenter, 2003
Regime Shifts in Lake Ecosystems: Pattern and Variation



Hawai'i Ocean Time-series (HOT)

Data availability:
http://hahana.soest.hawaii.edu

Contact:
D. Karl (dkarl@hawaii.edu)

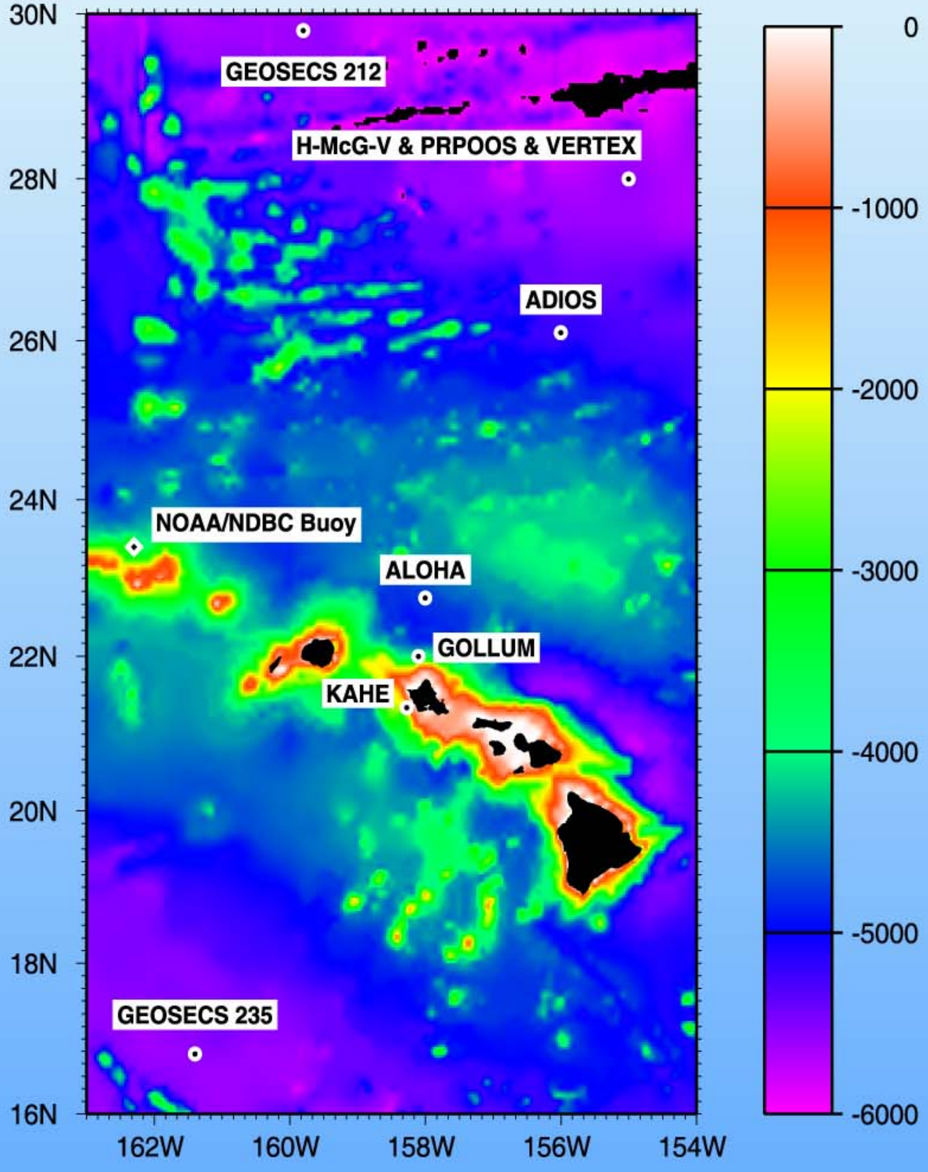


Hawaii Ocean Time-series: It's HOT!

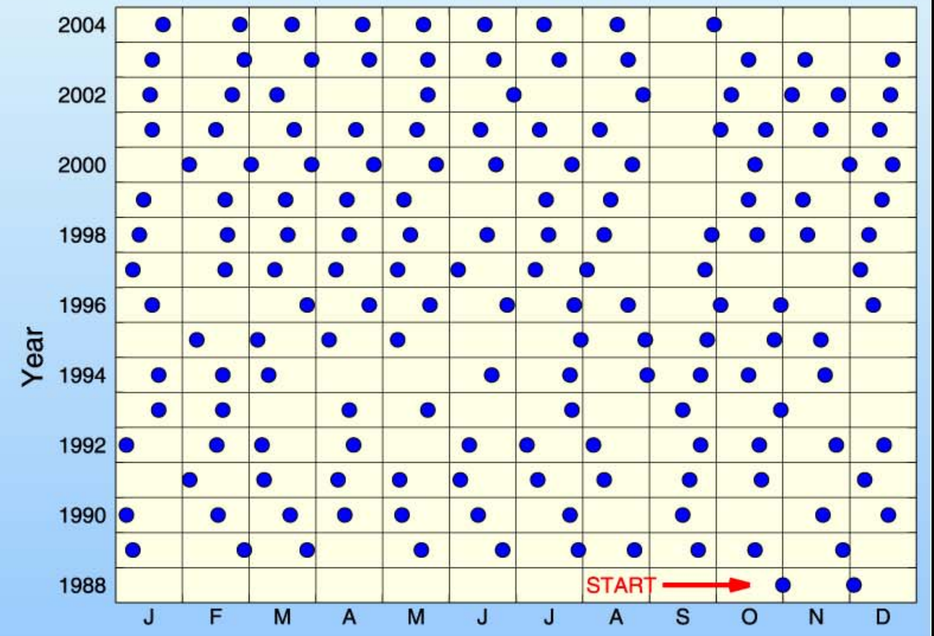
- Approximately monthly cruises to Sta. ALOHA (22°45'N, 158°W) since Oct 1988
- Core physical, chemical and biological measurements (e.g., CTD, DIC-alk, nutrients, DOC-N-P, POC-N-P) and bio-optics
- Rate measurements (e.g., primary production and particulate matter export)

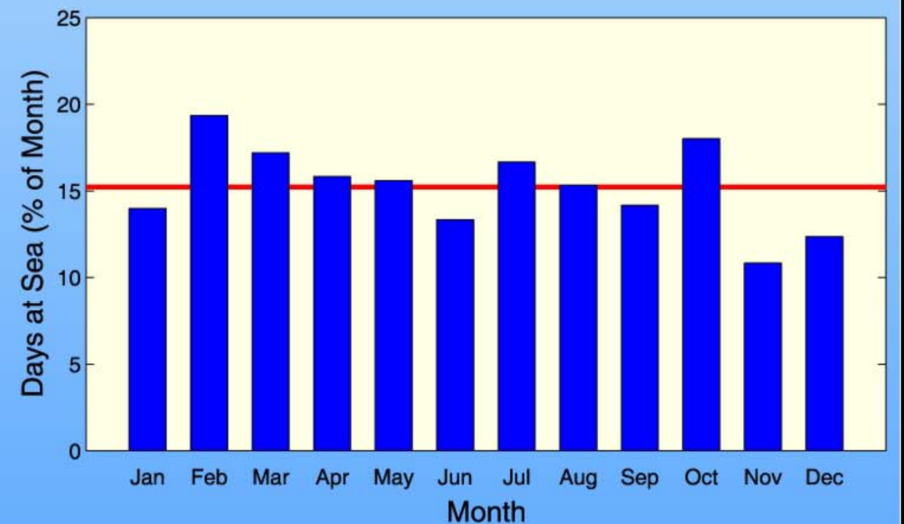
http://hahana.soest.hawaii.edu

THE TWO FACES OF THE NORTH PACIFIC GYRE



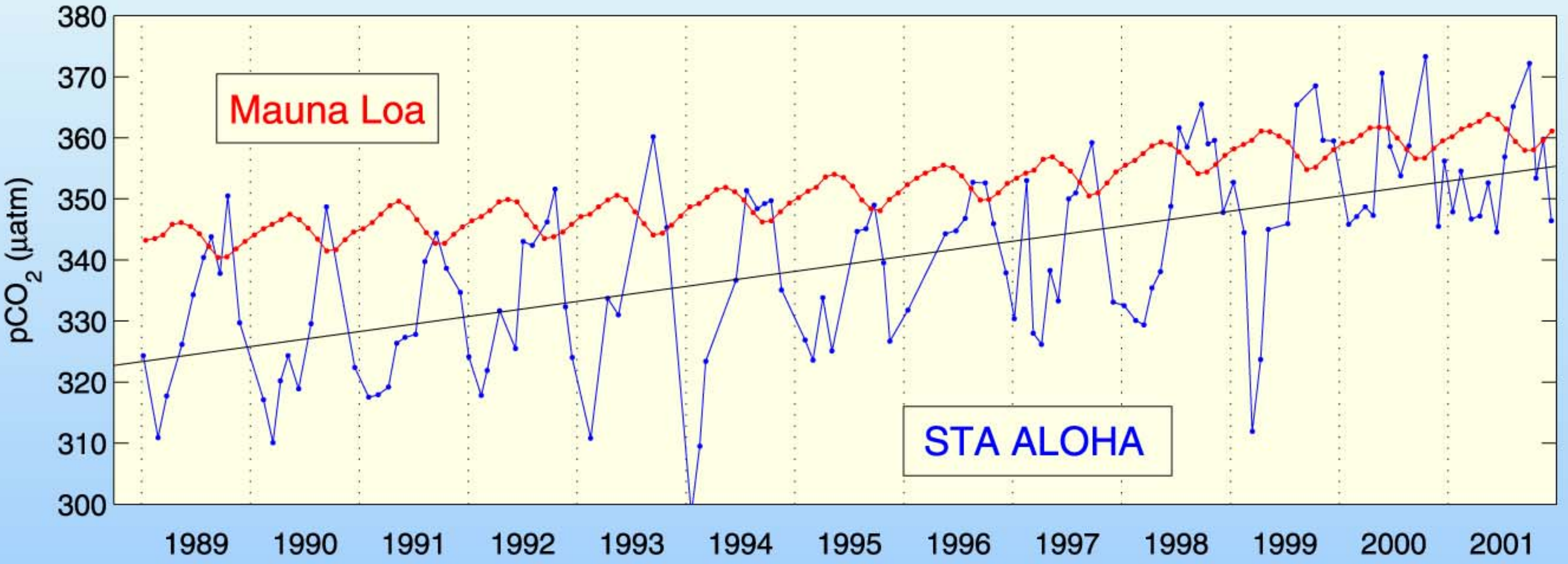
HAWAII OCEAN TIME-SERIES





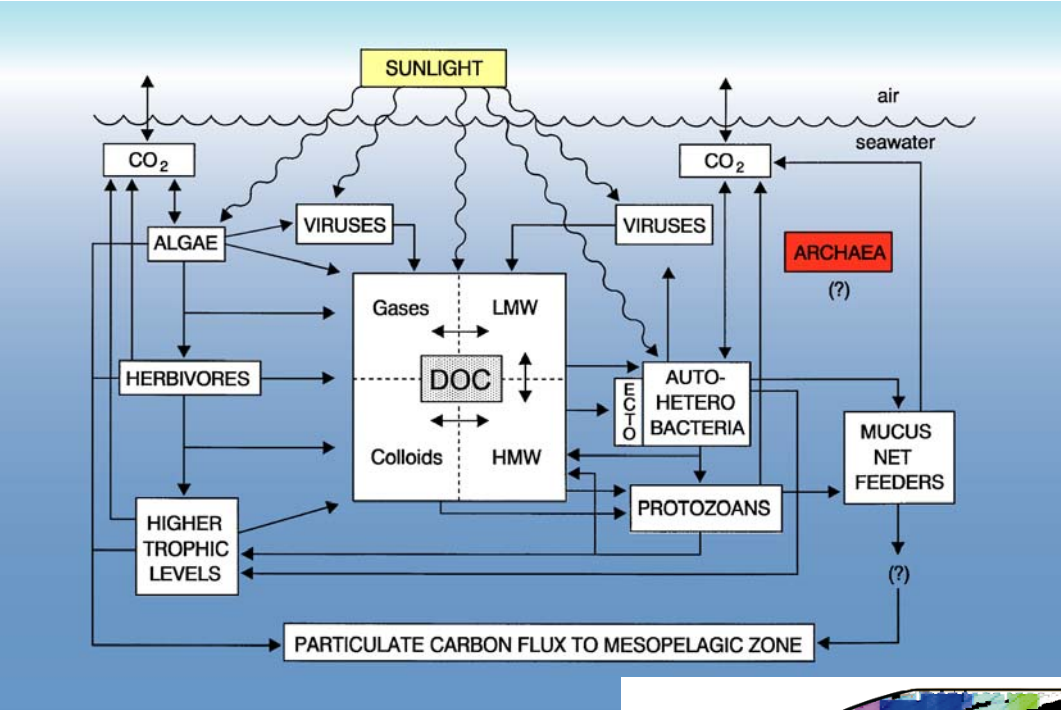
HOT BIOGEOCHEMICAL ENIGMAS: SELECTED EXAMPLES

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

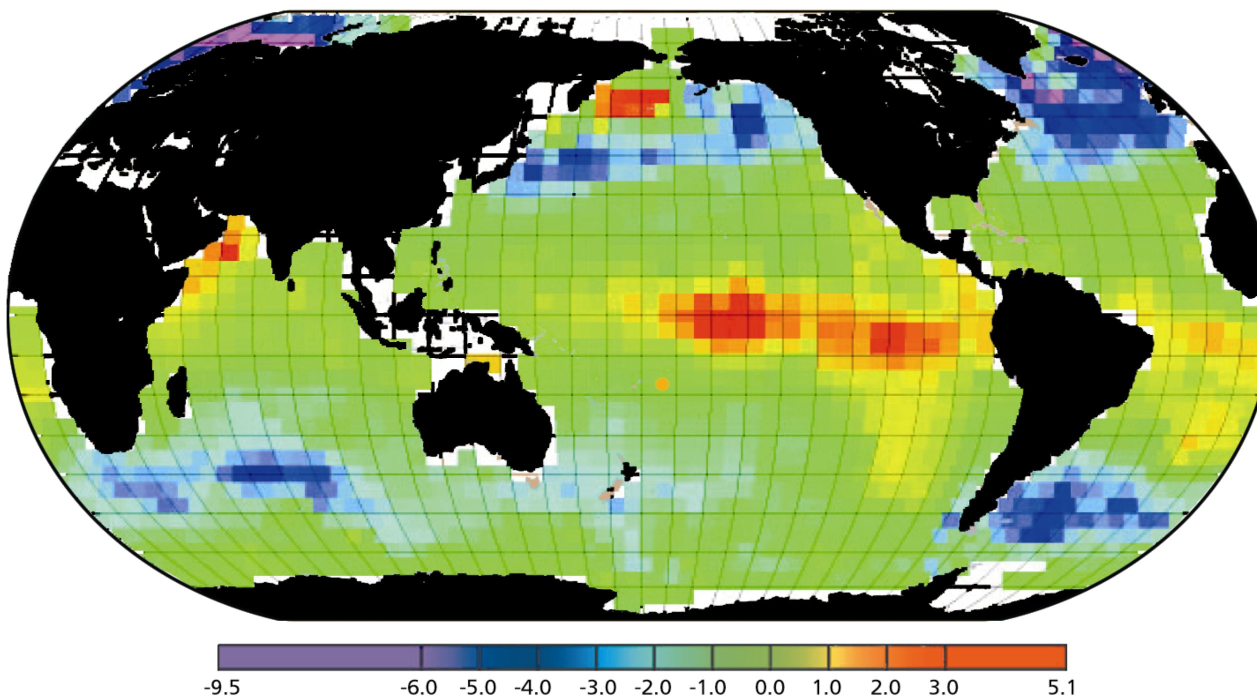


- The Subtropical North Pacific habitat is a net sink for atmospheric carbon dioxide
- The strength of the net sink ($\triangle pCO_2$) is seasonally variable and, perhaps, getting weaker with time over the past decade
- These variations may be the direct result of climate (e.g., E vs. P) or climate effects on the biological pump

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



With great difficulty!



CO_2 Flux (moles carbon dioxide per square meter per year)

U.S. JGOFS

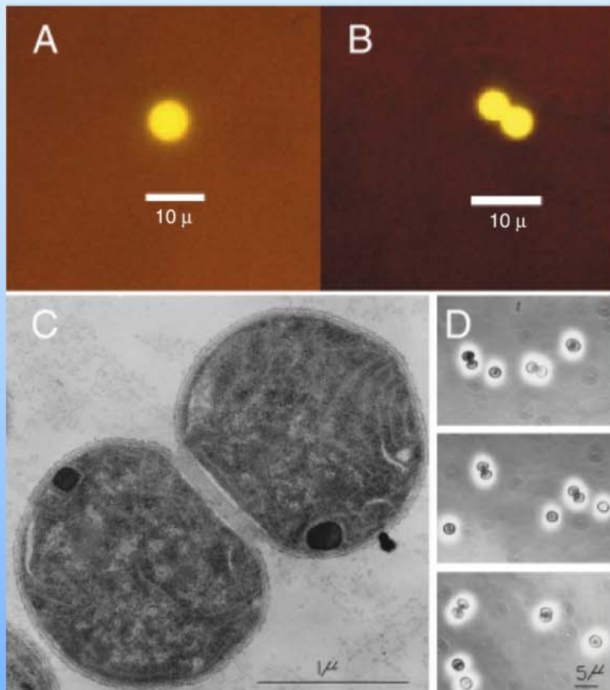
SHIFTING PARADIGMS

- 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

N_2 FIXATION AT STATION ALOHA (1990-2000)

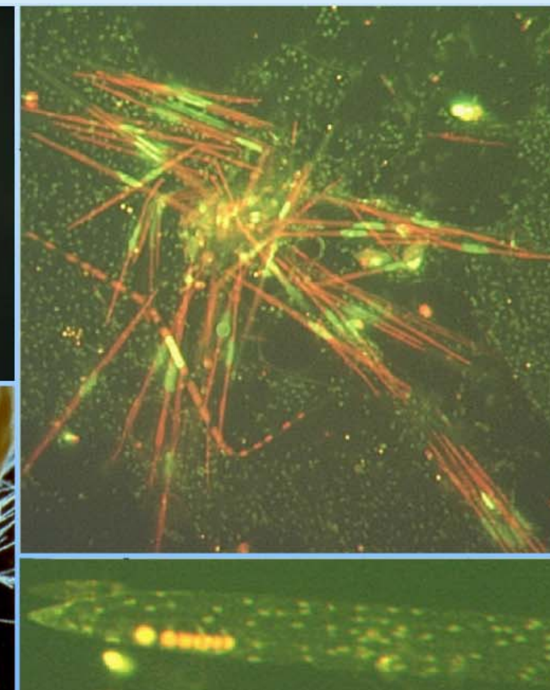
- N_2 accounts for 47±9% of “new” N
- Large interannual variations:
  36% in 1993 vs. 69% in 1999
- Relative importance of N_2 vs. NO_3^- as a source of new N has increased since 1995

The Diazotroph Rogues Gallery



Pico

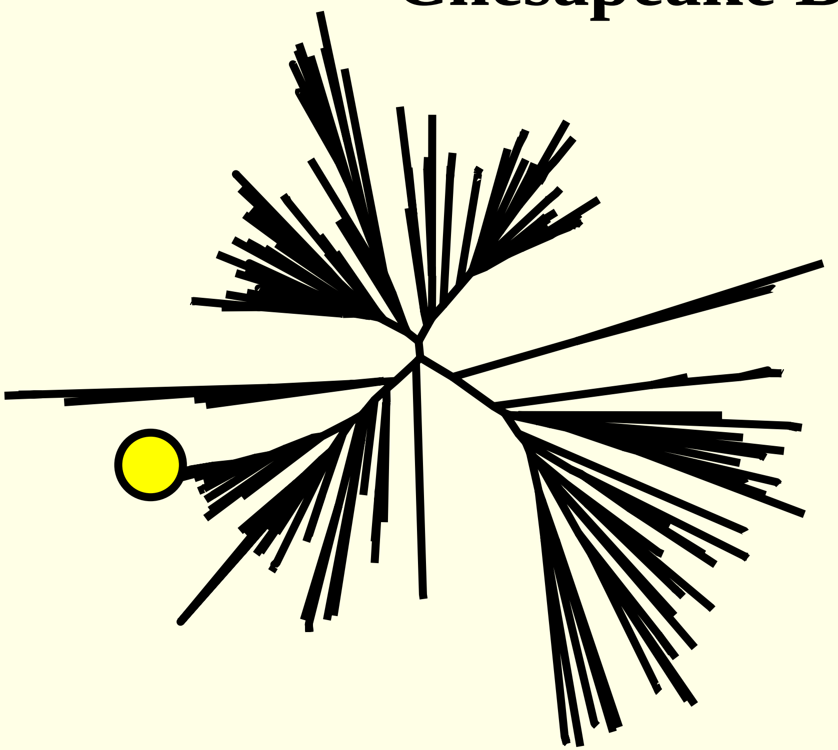
Tricho



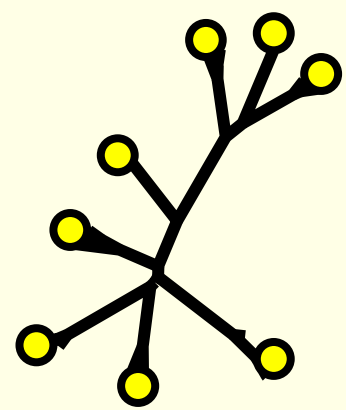
Diatomic
diatom

DIVERSITY OF NITROGENASE GENES AND THEIR EXPRESSION

Chesapeake Bay

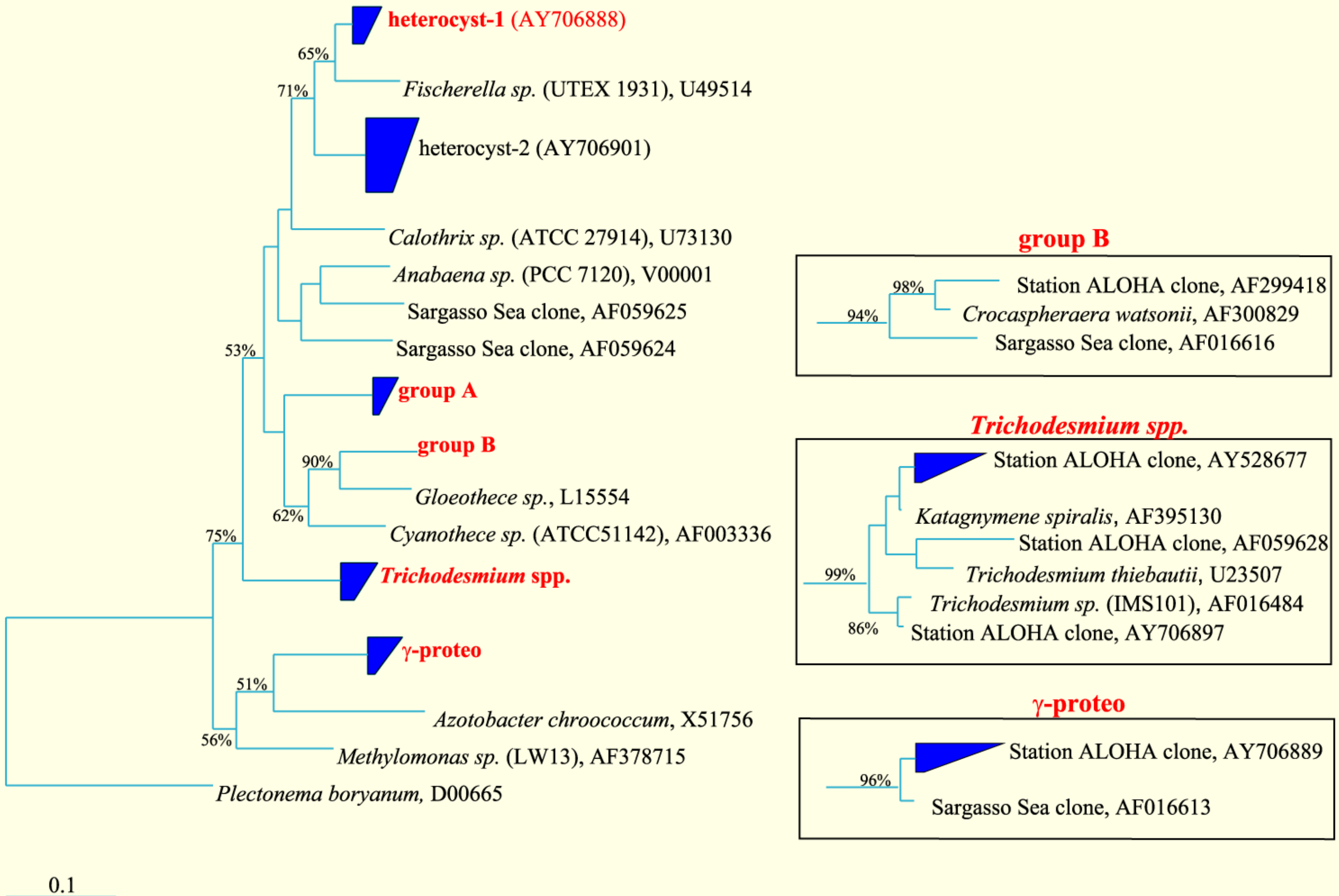


North Pacific Subtropical Gyre



J. Zehr, unpublished

Diazotroph Diversity

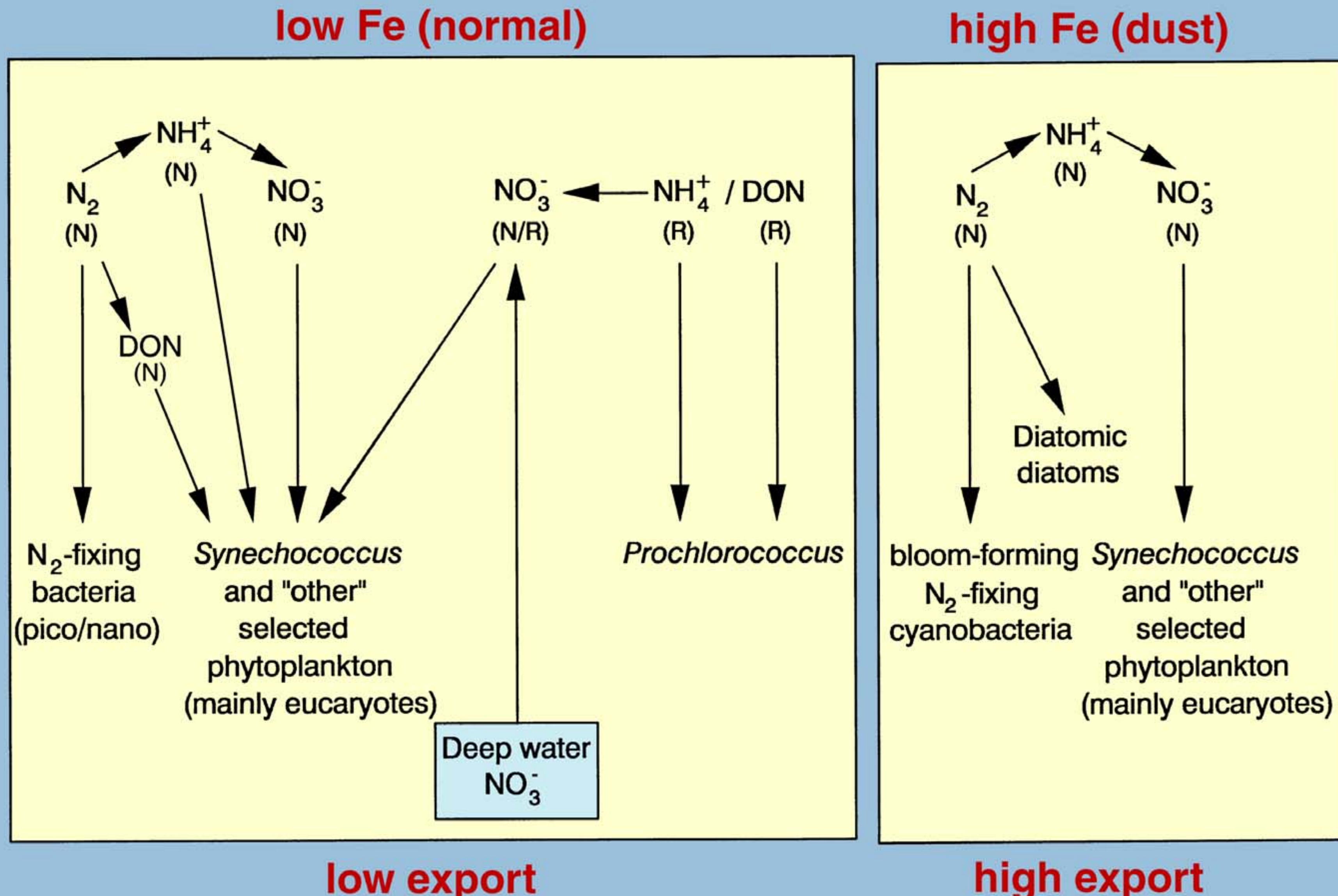


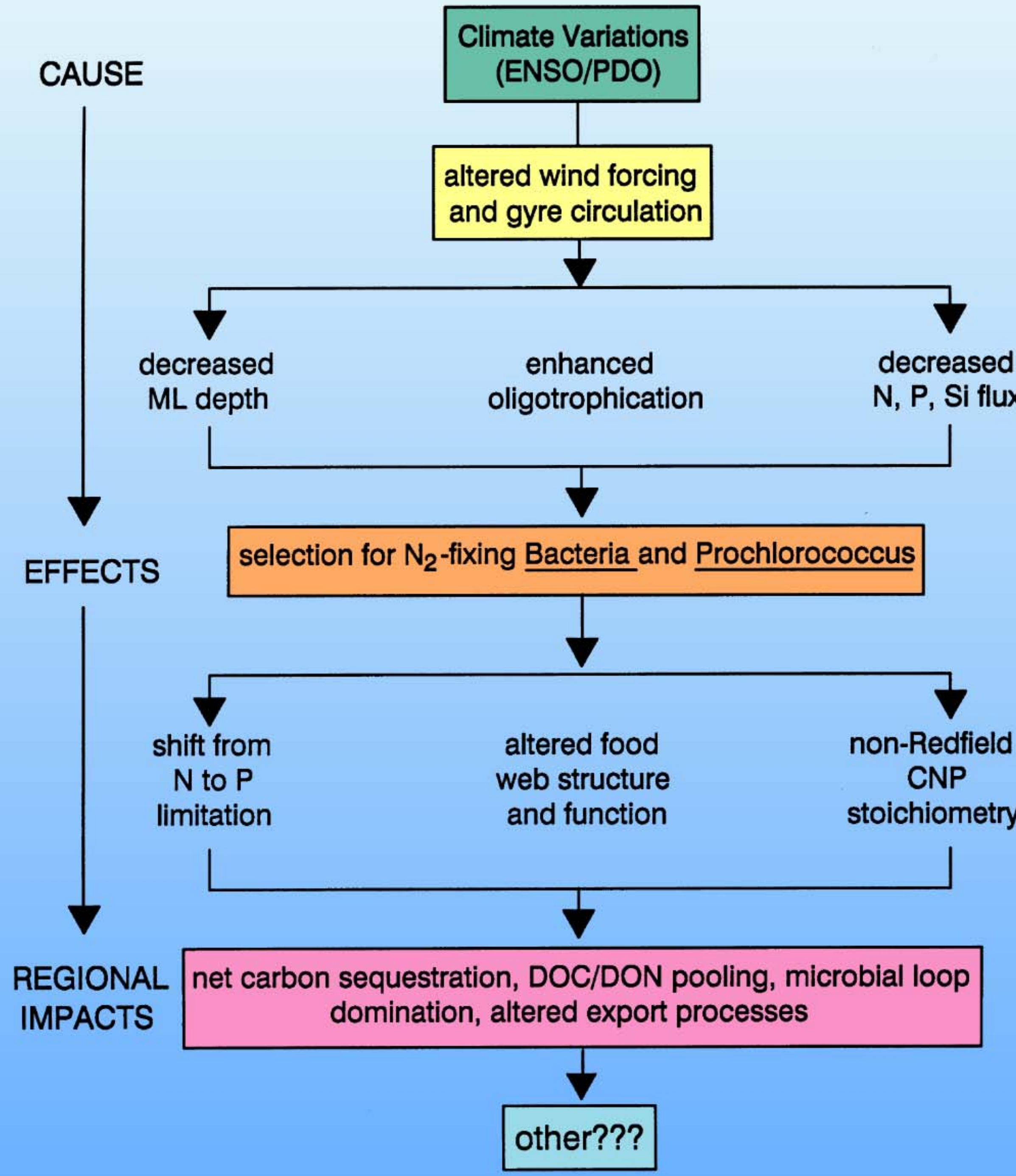
Church et al., submitted

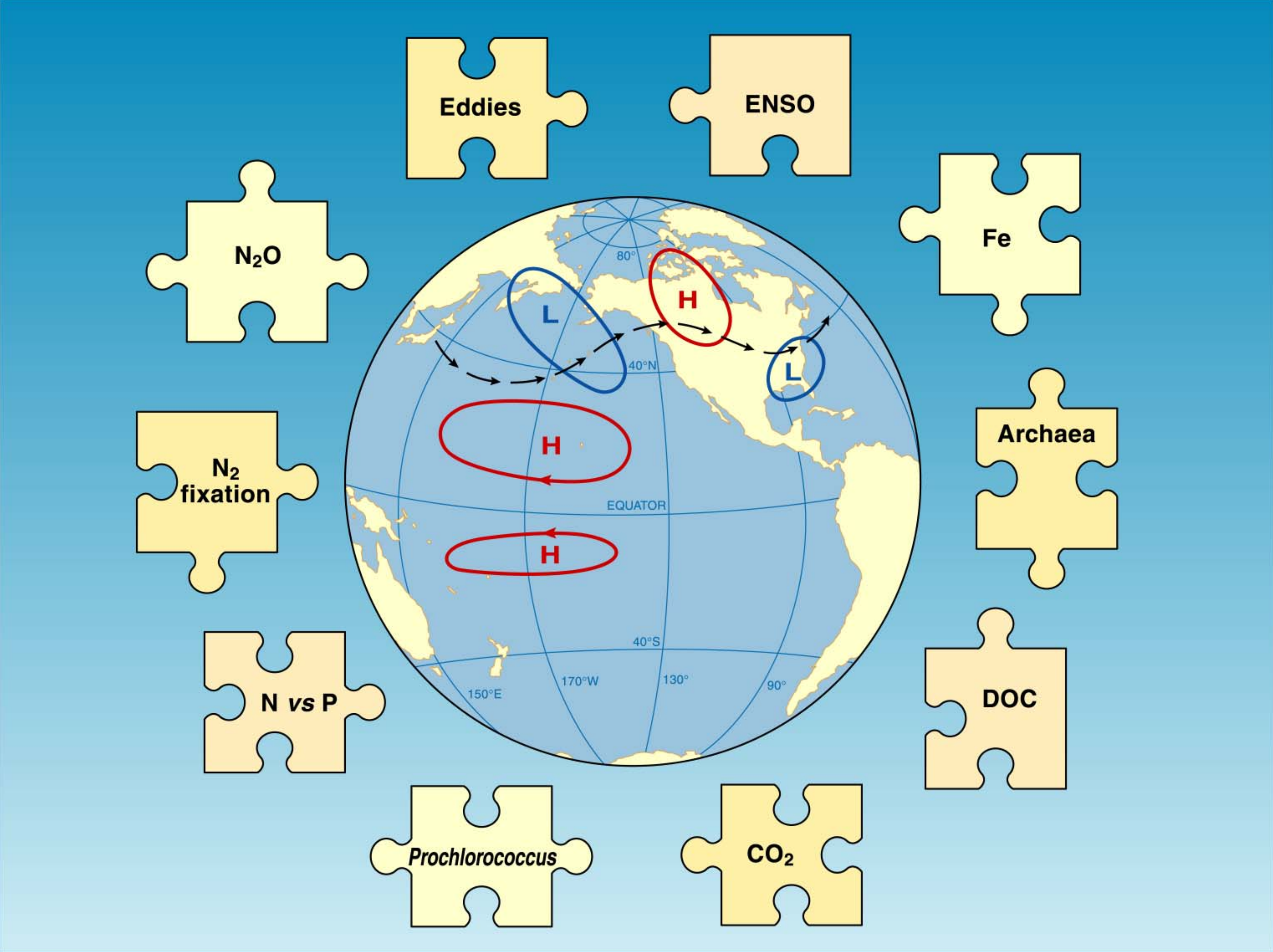
MICROBE-DUST CONNECTIONS

- 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

STATION ALOHA: New vs. Regenerated N Revisited




CAUSE
Climate Variations (ENSO/PDO)
altered wind forcing and gyre circulation
decreased ML depth
enhanced oligotrophication
decreased N, P, Si flux
EFFECTS
selection for N2-fixing Bacteria and Prochlorococcus
shift from N to P limitation
altered food web structure and function
non-Redfield CNP stoichiometry
REGIONAL IMPACTS
net carbon sequestration, DOC/DON pooling, microbial loop domination, altered export processes
other???



Eddies
ENSO
N_2O
Fe
N_2 fixation
Archaea
N *vs* P
DOC
Prochlorococcus
CO_2
L
H
L
H
H
80°
40°N
EQUATOR
40°S
150°E
170°W
130°
90°

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!

CONCLUSIONS

- 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