Genomic-to-space measurements reveal global ocean nutrient stress

Adam Martiny

UCI University of California, Irvine
Oregon State University
BIO GO-SHIP
NASA MUREP

Acknowledgement

eDNA analysis:

Alyse Larkin, Lucas Ustick, Catherine Garcia, Nathan Garcia, Adam Fagan, Melissa Brock, Jenna Lee, Bio-GO-SHIP collaborators

Satellite analysis:

Amy Nuno, Toby Westberry, Mike Behrenfeld

Part 1: Bio-GO-SHIP

Sustained Global Scale Biological Observations

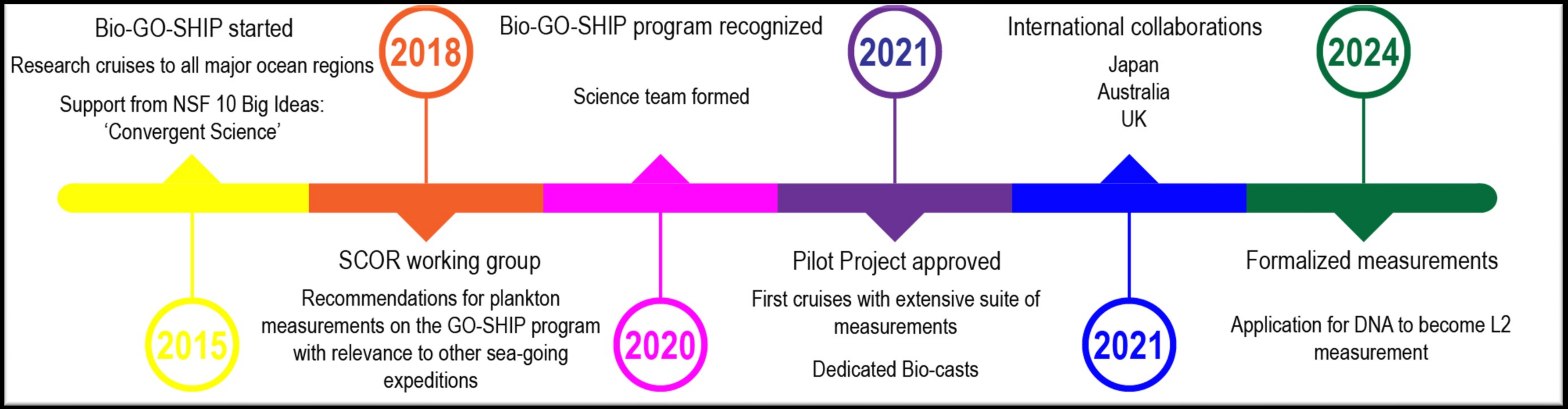
Are marine biodiversity and ecosystem functions affected by climate change?

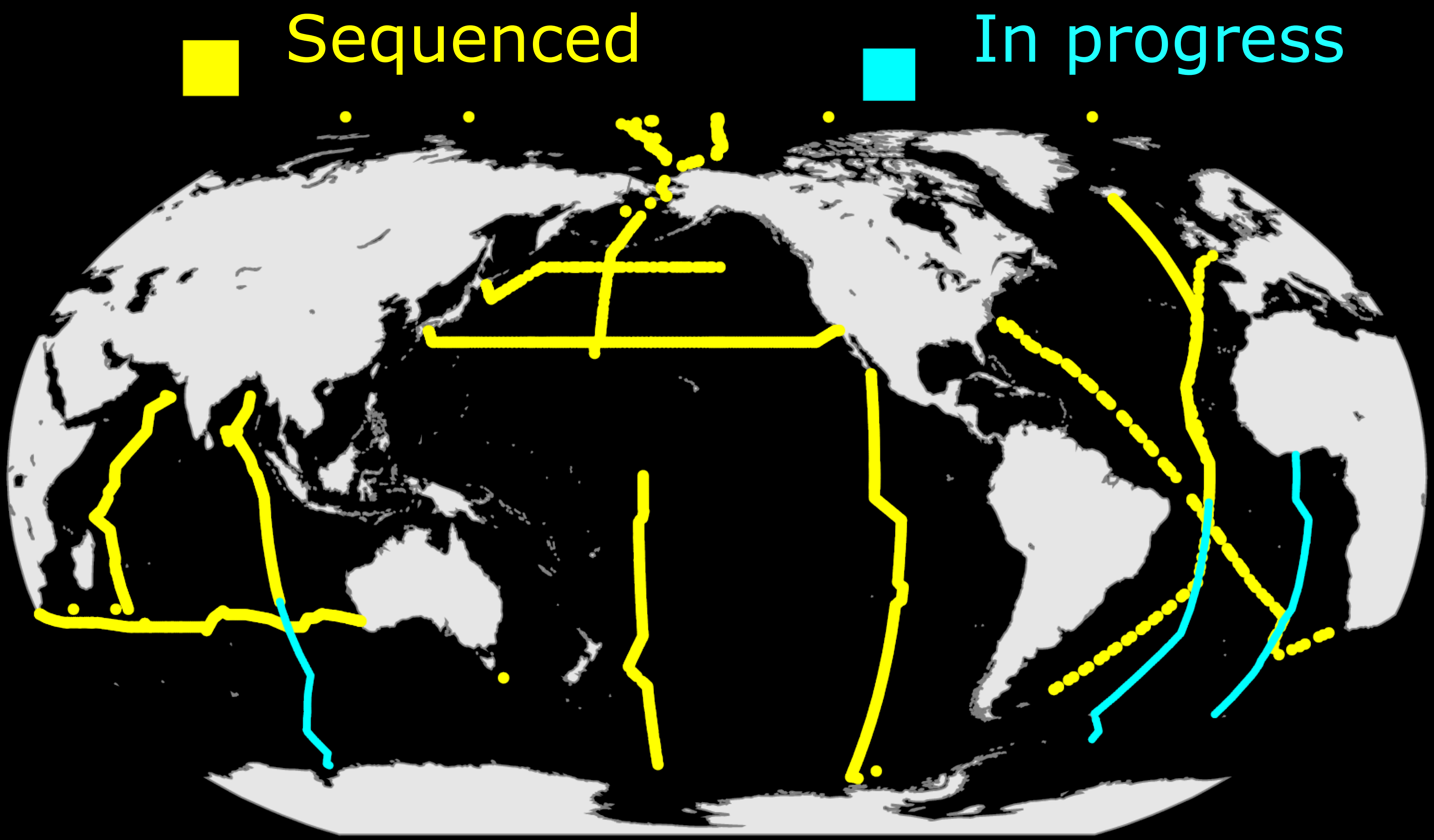
Bio-GO-SHIP = baseline + change

There are other groups that are doing physical and chemical measurements (GO-SHIP)

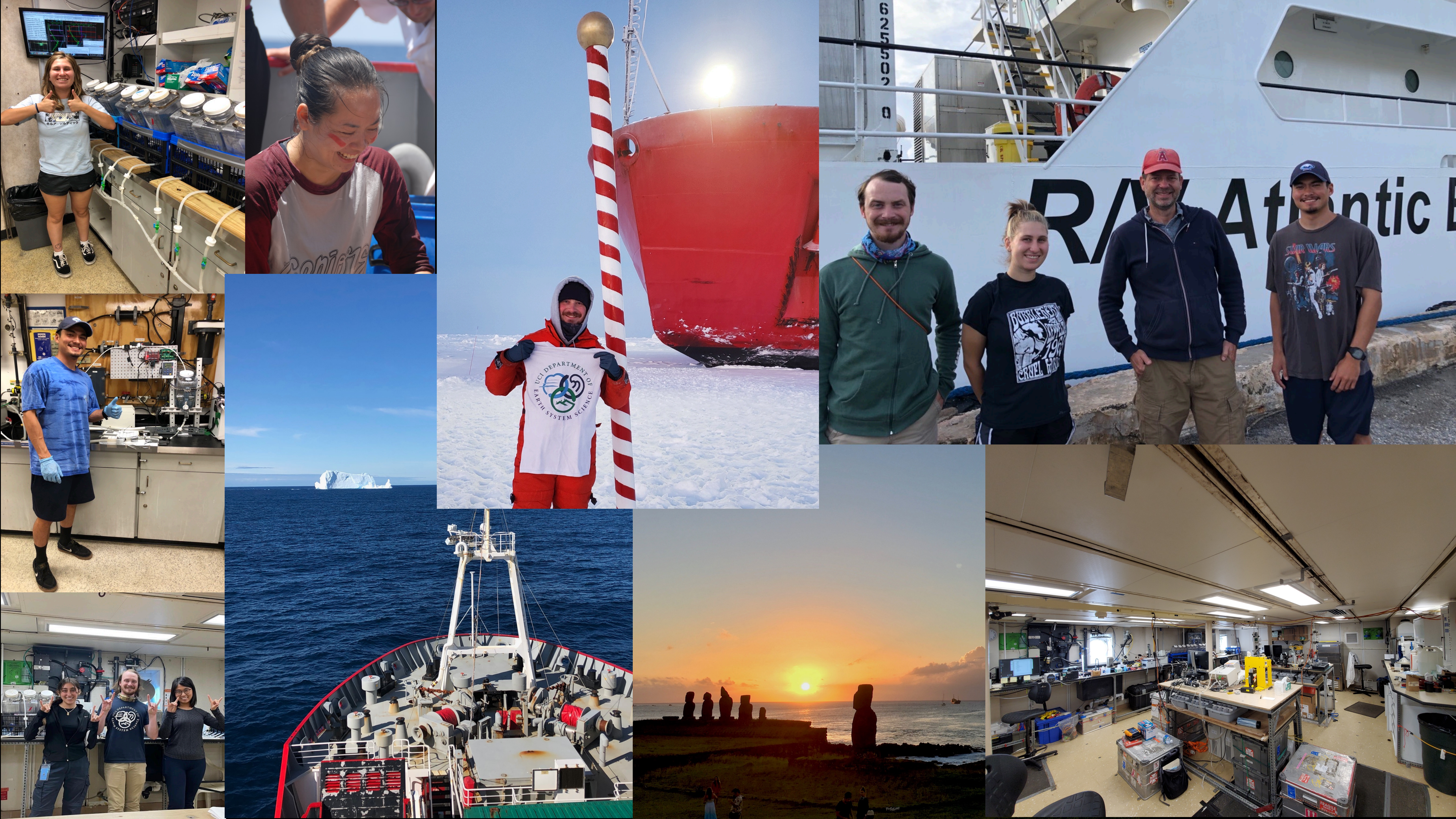
Website: biogoship.org

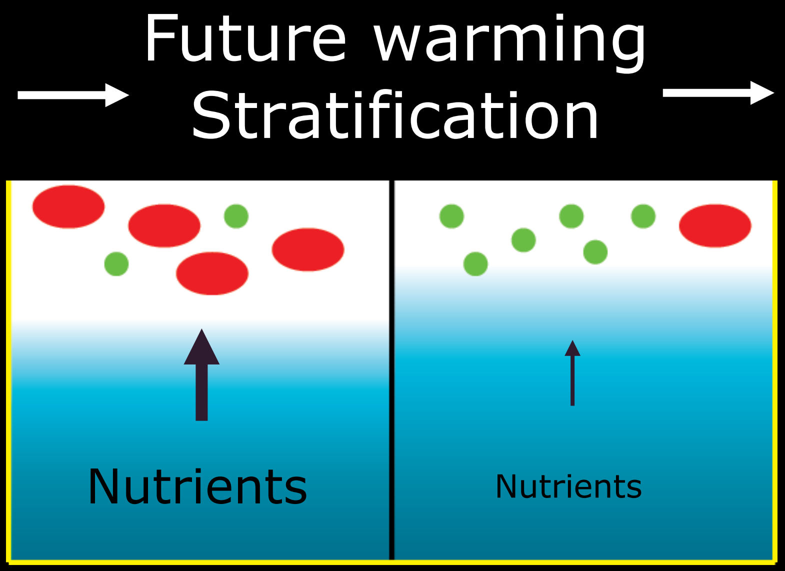
Bio-GO-SHIP – international program





Aim to cover the globe in 10 years – and then repeat!

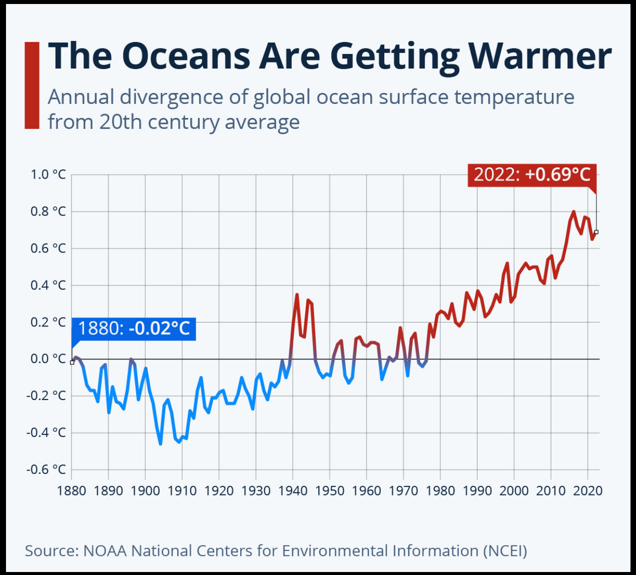

UCI DEPARTMENT OF EARTH SYSTEM SCIENCE
STAR WARS



Large potential impact on marine life and carbon sequestration

Uncertainty:
1. Physical link between warming and stratification
2. Ecosystem resilience

The ocean is changing



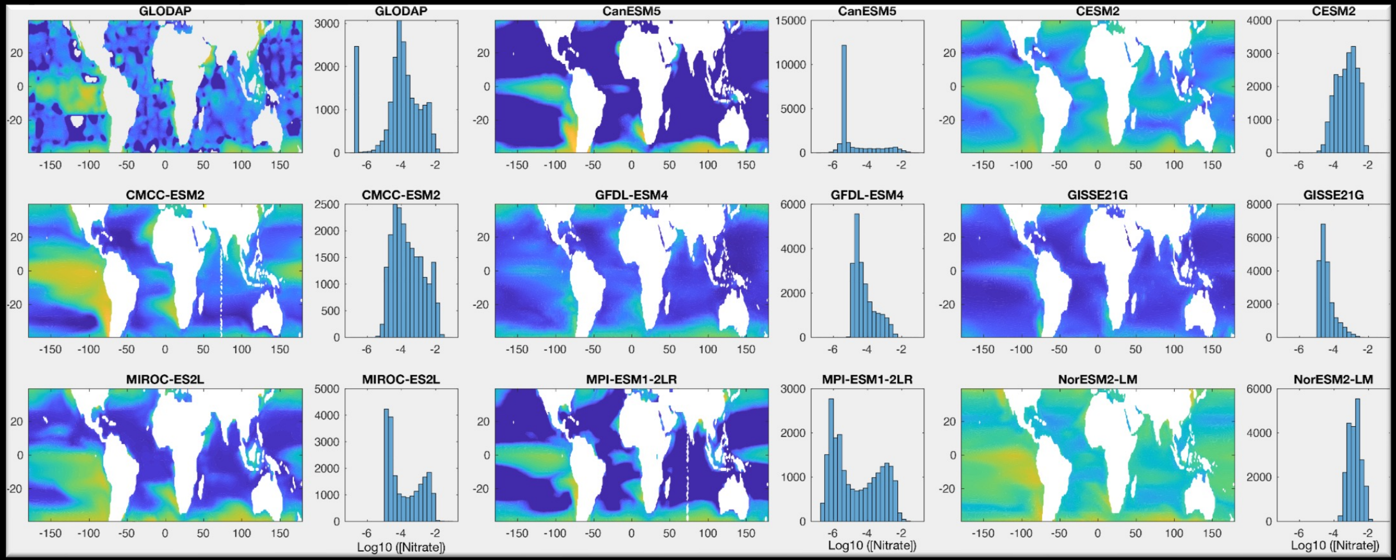
Microbial growth environment

- Temperature
- pH
- Light
- Oxygen
- **Nutrient**
- Carbon substrates

High uncertainty in changes to many environmental conditions

High uncertainty in changes to growth and production

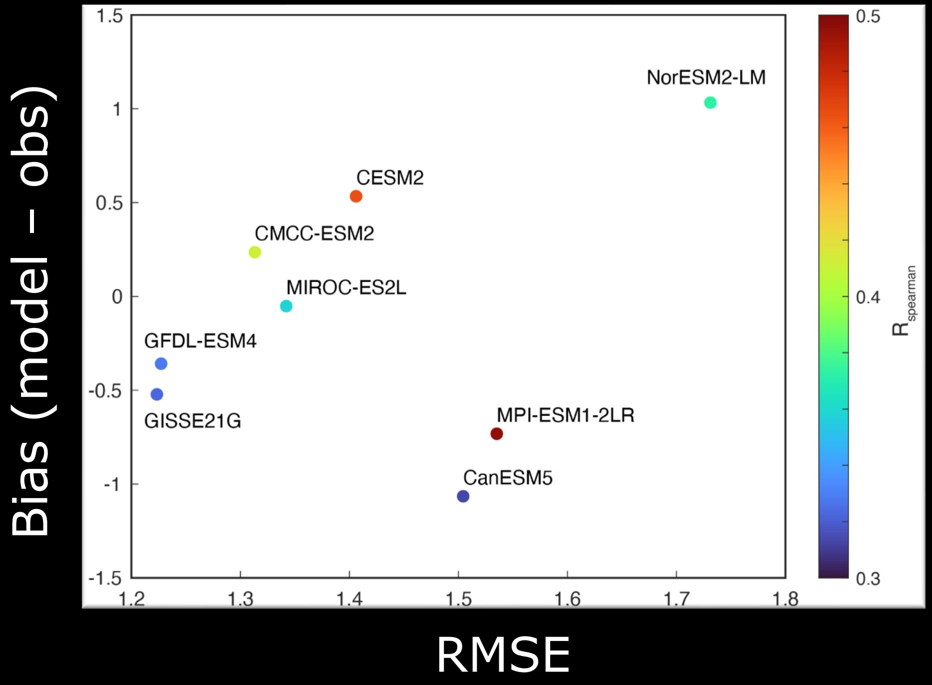
CMIP6 models
(historical run)
(log10 transformed)



Comparison between obs and models

RMSE~1.5 -> average 17x off

Bias =-1 -> Model 10x too low



Classic ideas about nutrient limitation

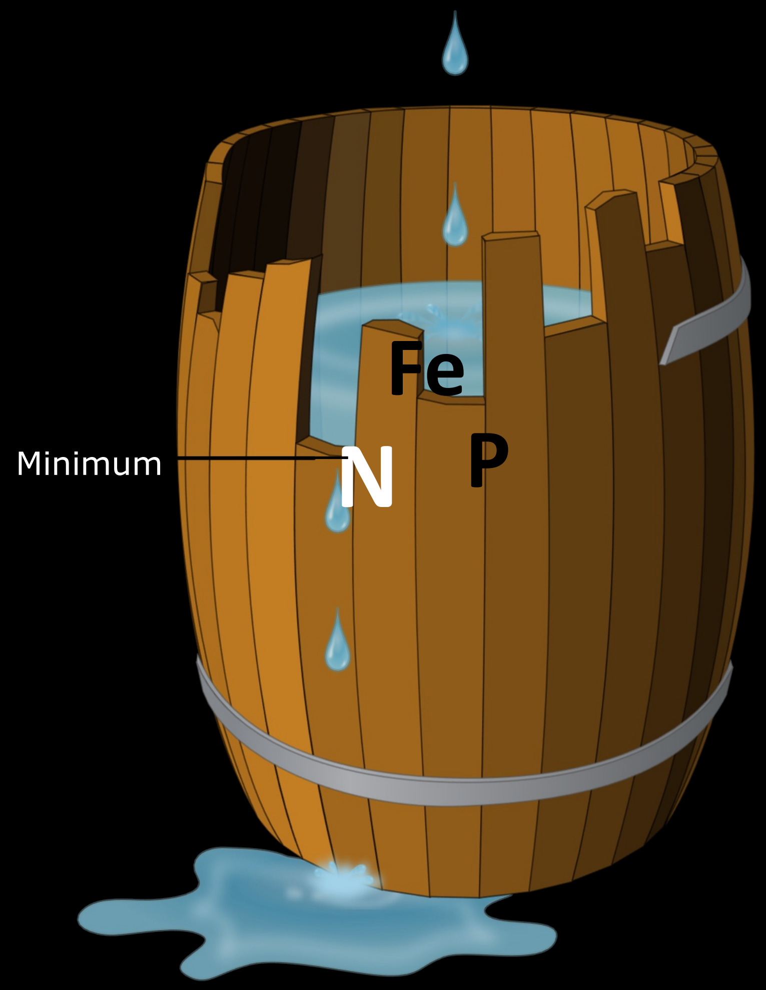
Surface phytoplankton growth is commonly limited by nutrients

- **N**itrogen, **P**hosphorus, or Iron (**Fe**)

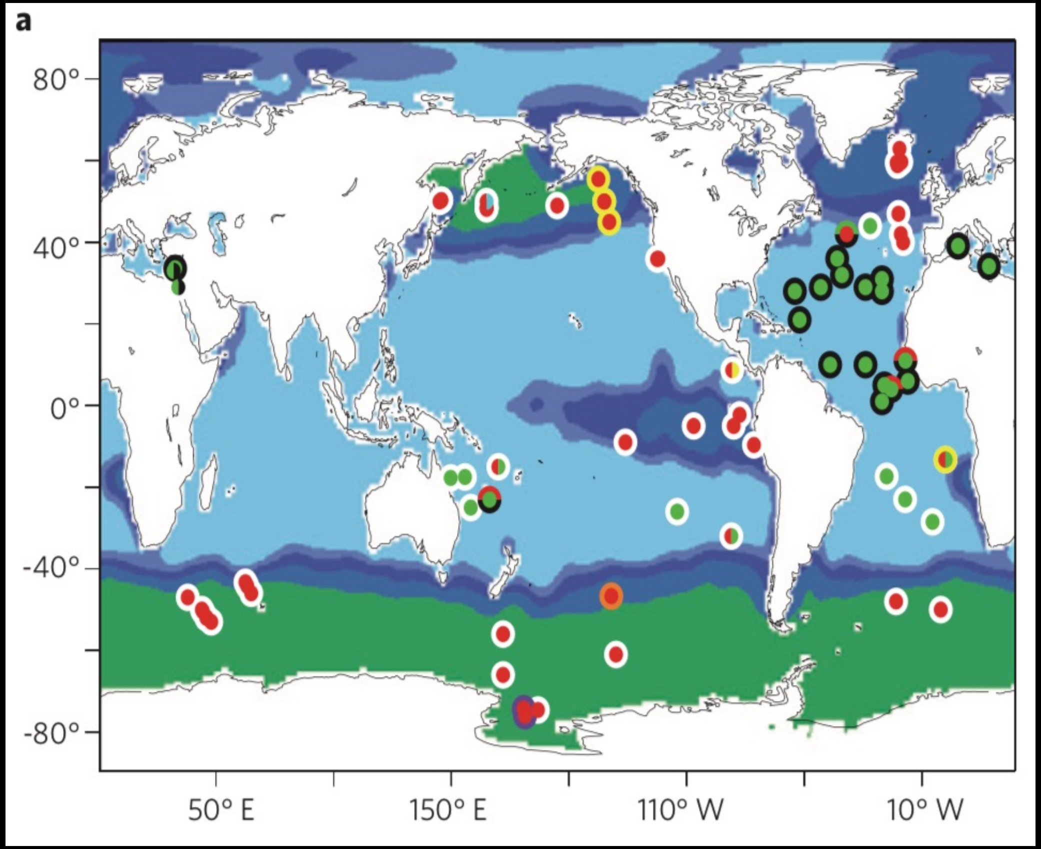
Liebig's Law of the Minimum

- One primary limiting nutrient

N is thought to be the primary limiting resource in most of the ocean



Nutrient addition experiments show complex variation in limiting nutrient



N limitation

P limitation

Fe limitation

Inner circle is 1° and outer is 2° limitation

Background is [nitrate]

1. Mostly N limitation
2. Fe limitation in places with high nitrate
3. P co-limitation in N Atlantic Ocean
4. Co-limitation is common but…

Moore et al, Processes and patterns of oceanic nutrient limitation. 2013.

Evolution and ecology of nutrient traits

Physiology and Evolution:

- Improved nutrient uptake affinity (overexpression of transporters)
- Access to alternative forms (organically bound)
- Frugal use to lower demand (loss of function requiring this resource)

Ecology:

- Invasion of species with less need or improved uptake
- New functional types (e.g., presence of N-fixers)

Short-term nutrient addition experiments may not capture the impact and trade-offs of these biological processes

Gene gain and loss important for adaptation to nutrient regimes

Phosphorus

Phosphate acquisition genes in *Prochlorococcus* ecotypes: Evidence for genome-wide adaptation

Populations switch from inorganic to organic forms (P_i, esters, phosphonates)

Nitrogen

PNAS

Widespread metabolic potential for nitrite and nitrate assimilation among *Prochlorococcus* ecotypes

Adam C. Martiny[a,b,1], Satish Kathuria[a], and Paul M. Berube[c]

Departments of [a]Earth System Science and [b]Ecology and Evolutionary Biology, University of California, Irvine, CA 92697; and [c]Department of Civil and Environmental Engineering, Massachusetts Institute of Technology, Cambridge, MA 02139

Edited by David M. Karl, University of Hawaii, Honolulu, HI, and approved May 1, 2009 (received for review March 8, 2009)

The marine cyanobacterium *Prochlorococcus* is the most abundant photosynthetic organism in oligotrophic regions of the oceans. The

coccus and *Prochlorococcus* suggests that the inability to use certain nitrogen species in *Prochlorococcus* is the result of past

Populations switch from using ammonia->urea->nitrite->nitrate

Iron

PNAS

Characterization of *Prochlorococcus* clades from iron-depleted oceanic regions

Douglas B. Rusch[a], Adam C. Martiny[b,c], Christopher L. Dupont[d], Aaron L. Halpern[a,1], and J. Craig Venter[d,2]

[a]J. Craig Venter Institute, Rockville, MD 20855; Departments of [b]Earth System Science and Ecology and [c]Evolutionary Biology, University of California, Irvine, CA 92697; and [d]J. Craig Venter Institute, San Diego, CA 92121

Contributed by J. Craig Venter, July 29, 2010 (sent for review February 21, 2010)

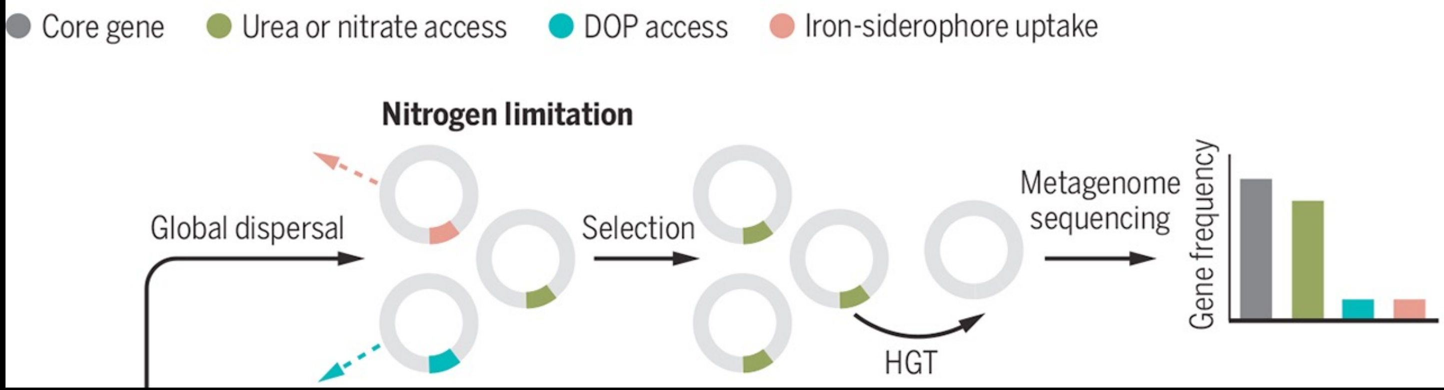
Prochlorococcus describes a diverse and abundant genus of marine

knowledge of genetic variation (15, 16). In addition, most se-

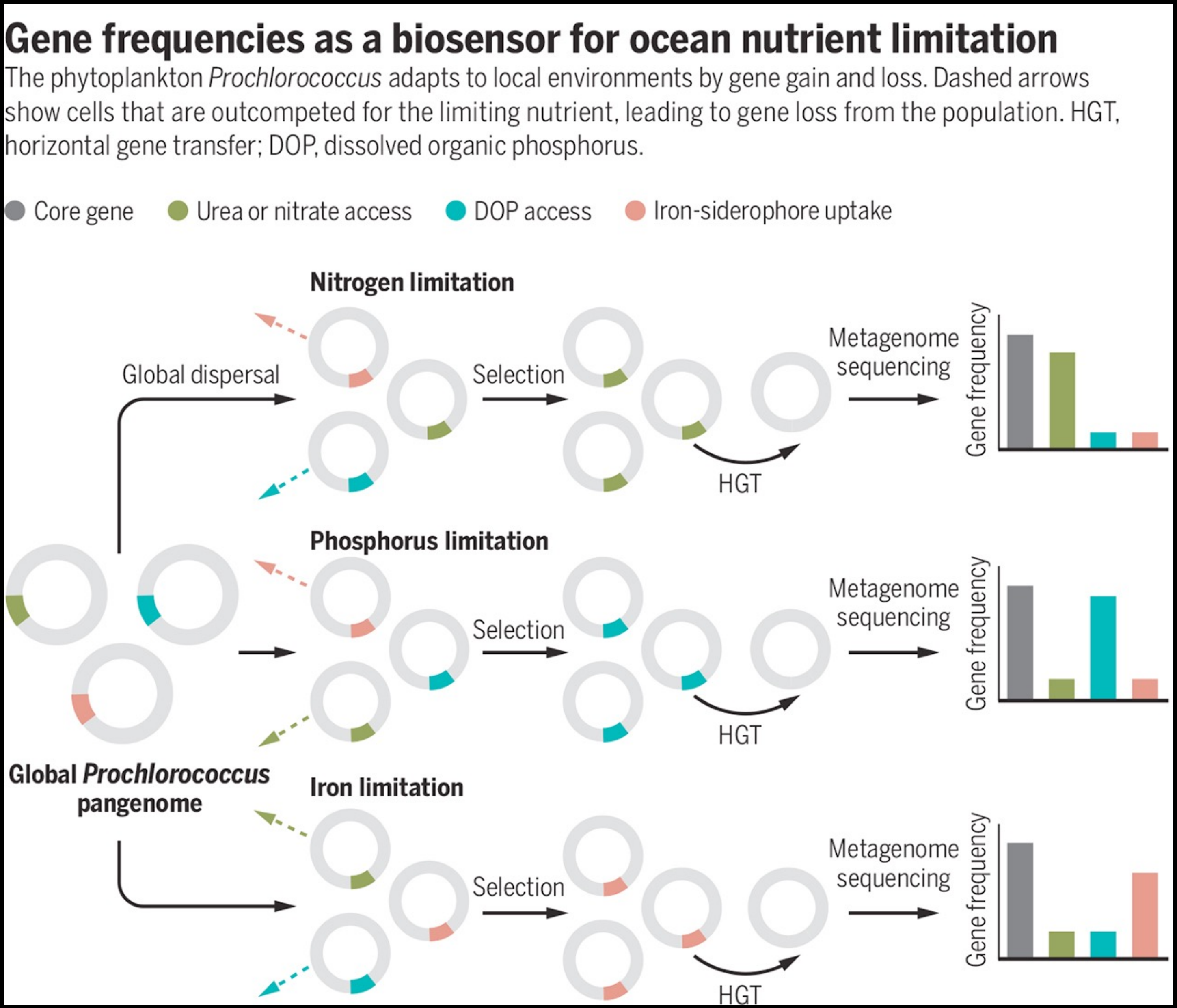
Populations have gained siderophore transporters or lost Fe containing proteins under Fe stress

Gene frequencies as a biosensor for ocean nutrient limitation

The phytoplankton *Prochlorococcus* adapts to local environments by gene gain and loss. Dashed arrows show cells that are outcompeted for the limiting nutrient, leading to gene loss from the population. HGT, horizontal gene transfer; DOP, dissolved organic phosphorus.



The frequency of genes reflects selection under local environmental conditions



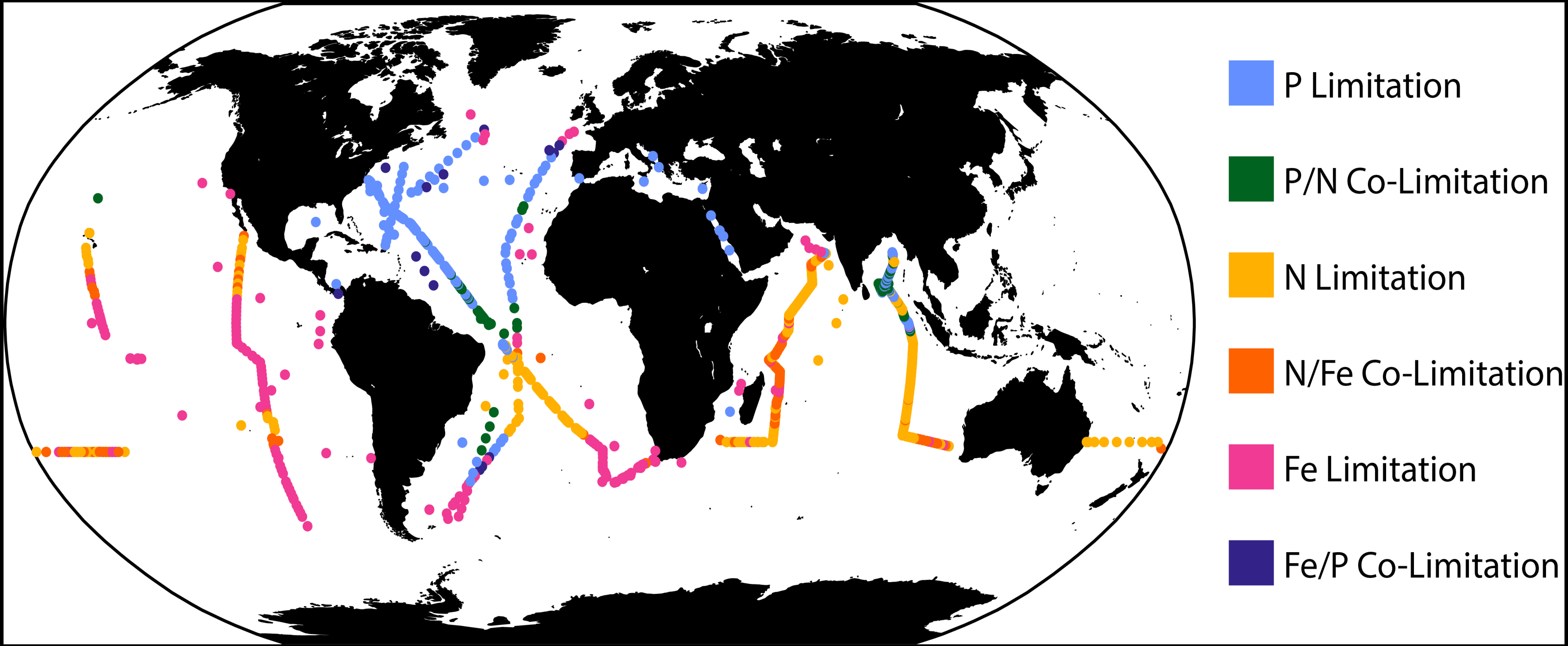
The frequency of genes reflects selection under local environmental conditions

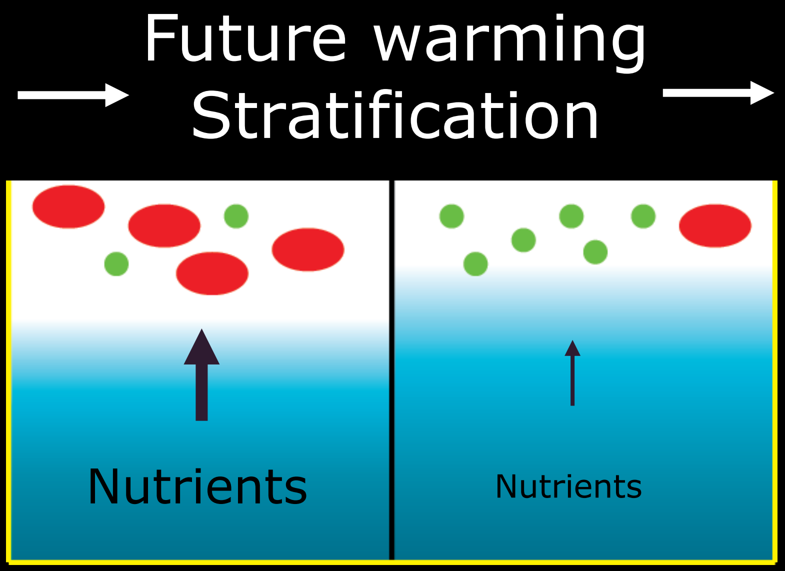
RESEARCH

OCEAN MICROBIOLOGY

Metagenomic analysis reveals global-scale patterns of ocean nutrient limitation

Lucas J. Ustick[1]†, Alyse A. Larkin[2]†, Catherine A. Garcia[2], Nathan S. Garcia[2], Melissa L. Brock[1], Jenna A. Lee[2], Nicola A. Wiseman[2], J. Keith Moore[2], Adam C. Martiny[1,2]*





Difficult to quantify nutrient stress over large spatial and temporal scales

Solution:

Combination of large-scale genomics +
Regulation of C:chlorophyll from remote sensing

Large potential impact on marine life and carbon sequestration

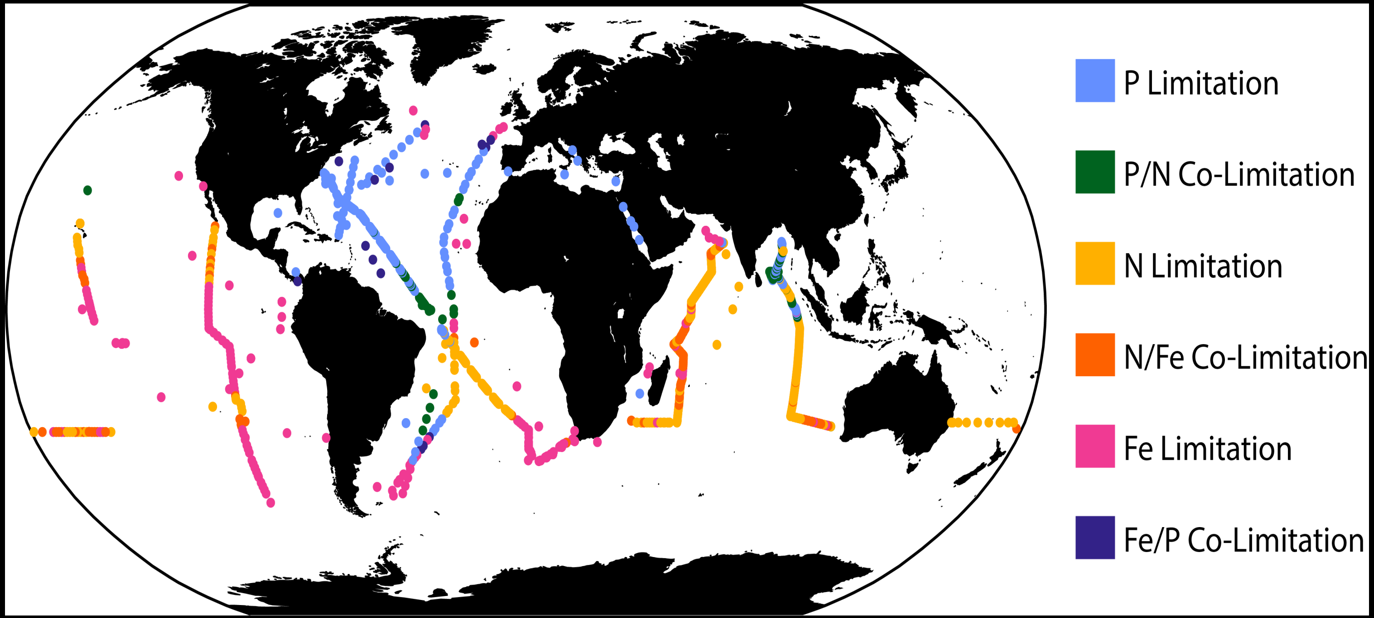
Uncertainty:

1. Physical link between warming and stratification
2. Ecosystem resilience

Diagnosing nutrient stress

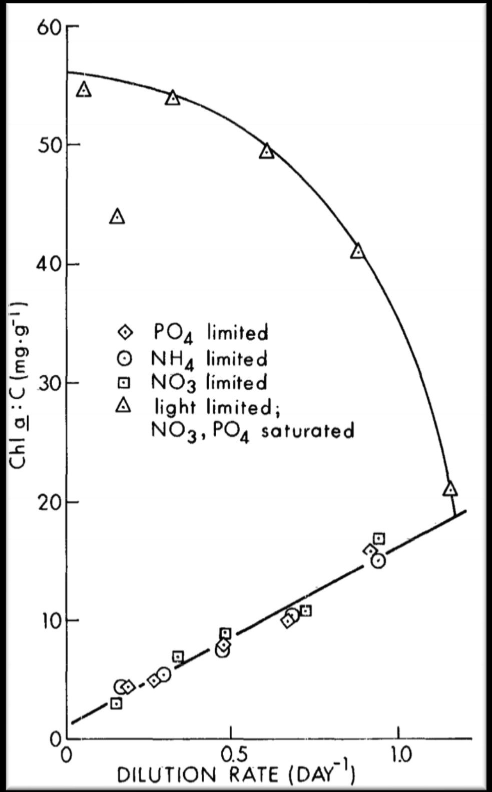
eDNA:

Biomarkers for type and severity nutrient stress



Physiology:

Cells adjust chlorophyll in response to light and nutrient stress



Laws and Bannister, 1980

Remote sensing of nutrient stress

Isolating nutrient stress signal

$\boldsymbol{\Theta_{obs}}$ = chl / C_{phyto}

$\boldsymbol{\mu \sim \Theta \times PAR}$

$\boldsymbol{\Theta'} = \boldsymbol{\Theta_{obs}} / \boldsymbol{\Theta_{photo}}$

$\boldsymbol{\Theta_{photo}}$ = f(PAR, K_d, MLD)
(i.e., photo-acclimation effect)

$\boldsymbol{\Theta'}$ ↓ with nutrient limitation

$\boldsymbol{\Theta_{photo}}$ is described in Behrenfeld et al., 2015

Remote sensing 'ingredients'

Chlorophyll

Backscattering -> C_{phyto}

PAR

Light attenuation (K_d)

\+ Mixed layer depth (HYCOM)

From MODIS
(can also use SeaWiFS - or PACE)

Remote sensing of nutrient stress

Isolating nutrient stress signal

Θ_{obs} = chl / C_{phyto}

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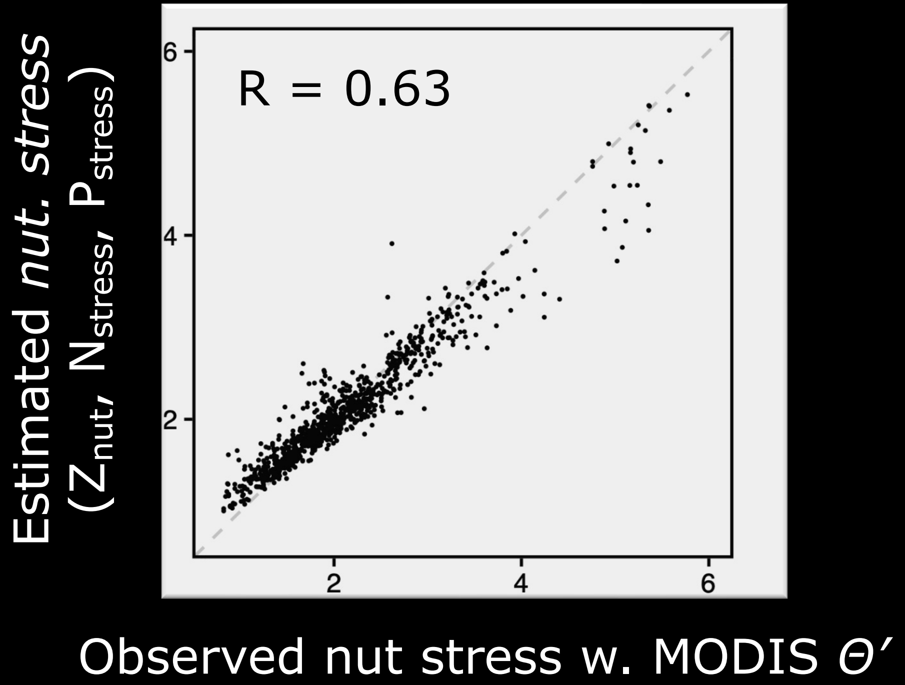
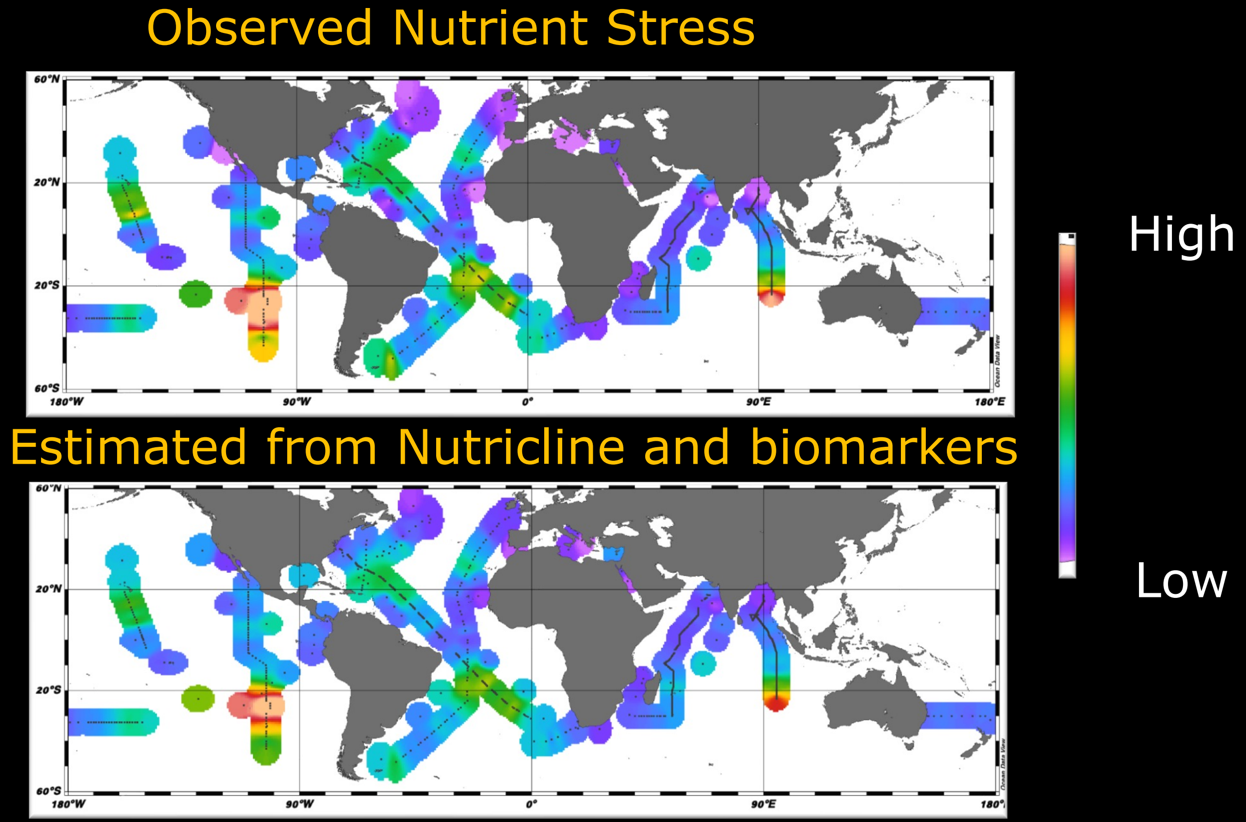
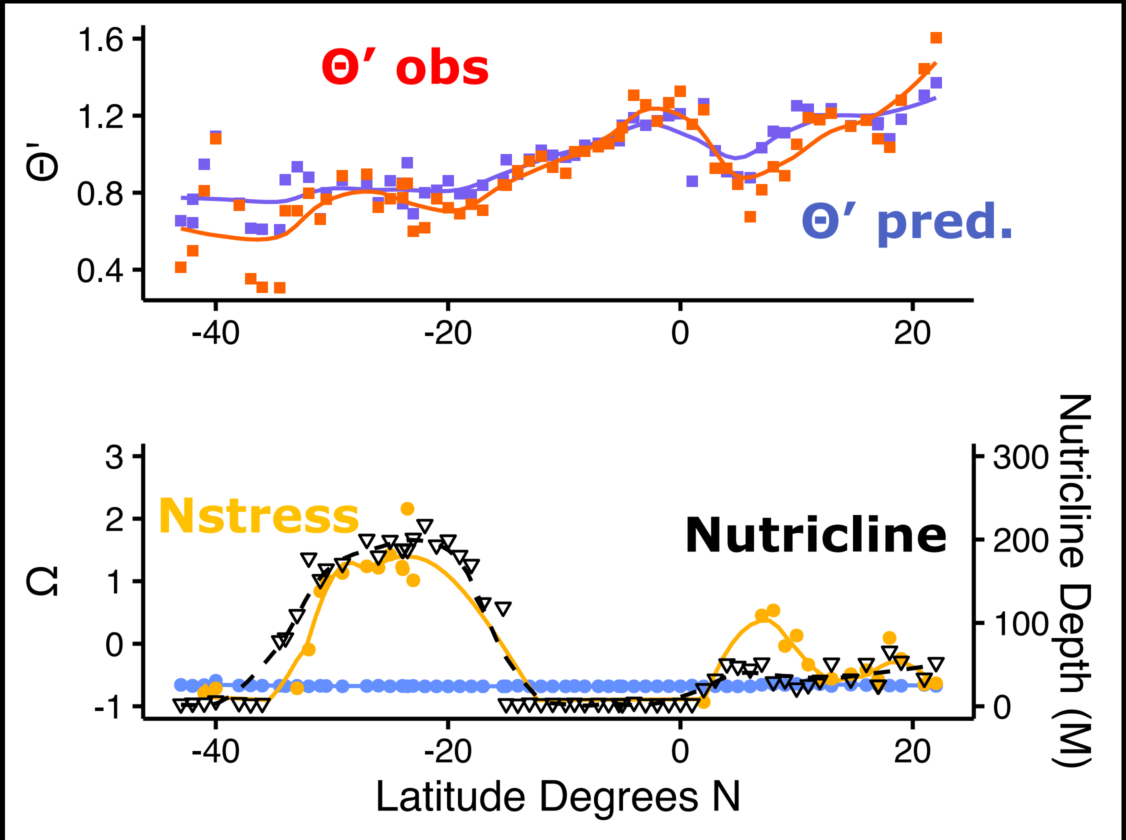
Strong correspondence between environment conditions, genomics, and remote sensing of nutrient stress





Type of nutrient stress important

Eastern Pacific section (P18)



Depressed growth

Fast growth

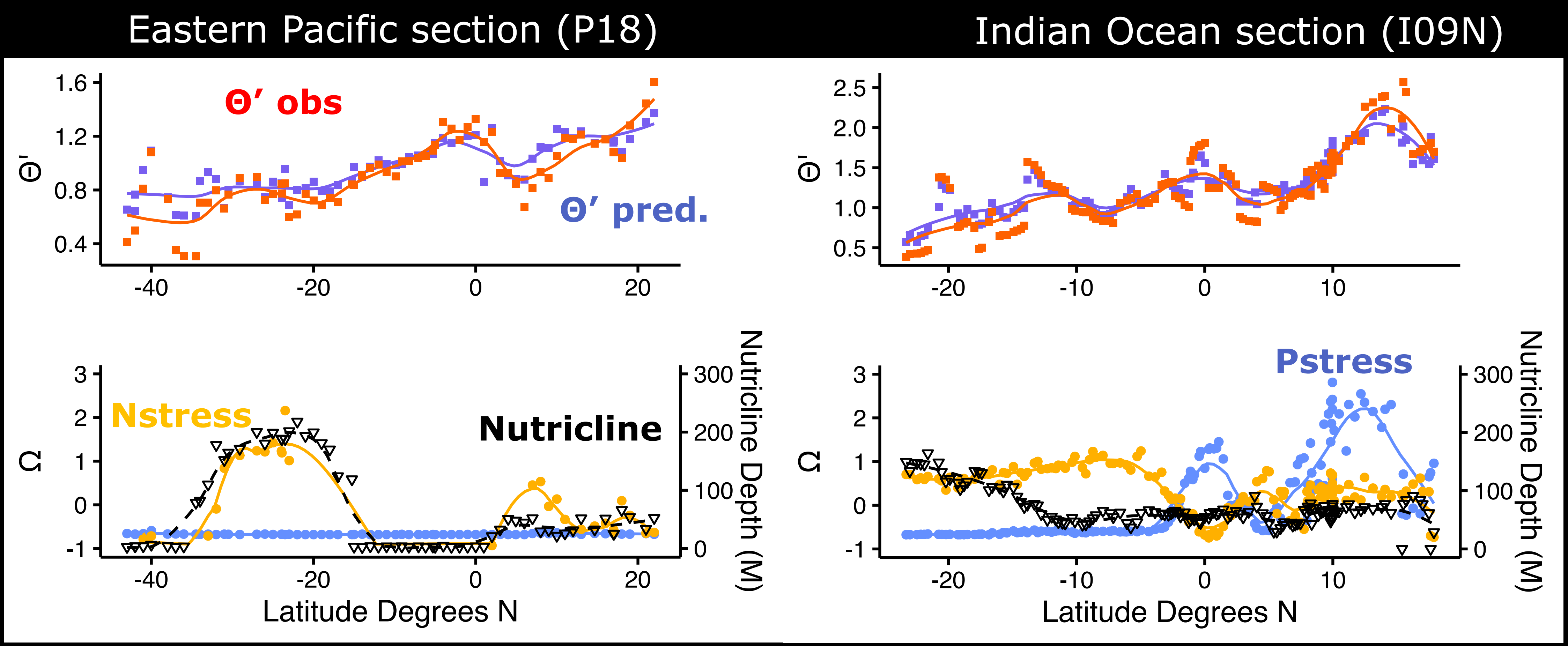
Θ′ pred. ~ environmental factors + genes

We tested the correlation between ~6000 genes vs. theta′

N stress genes consistent had highest (negative) correlation

A model with P stress genes improved fit

Type of nutrient stress important



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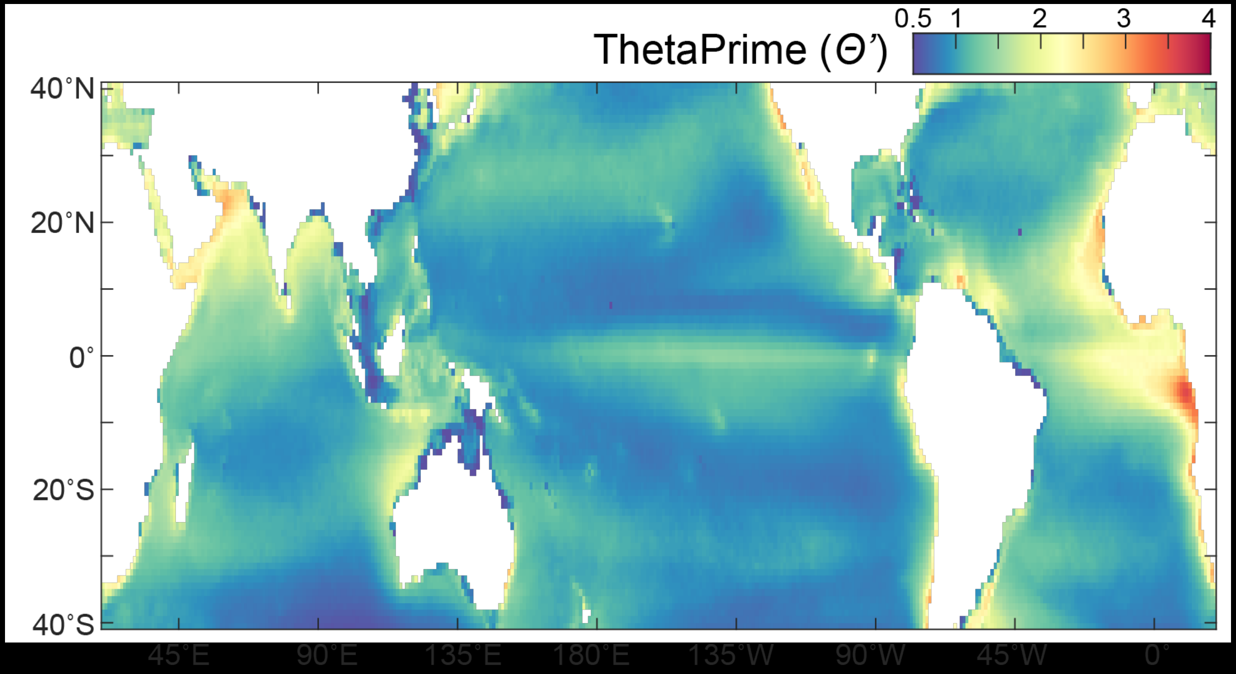
Fast growth

Θ′ pred. ~ environmental factors + genes

Mean global nutrient stress

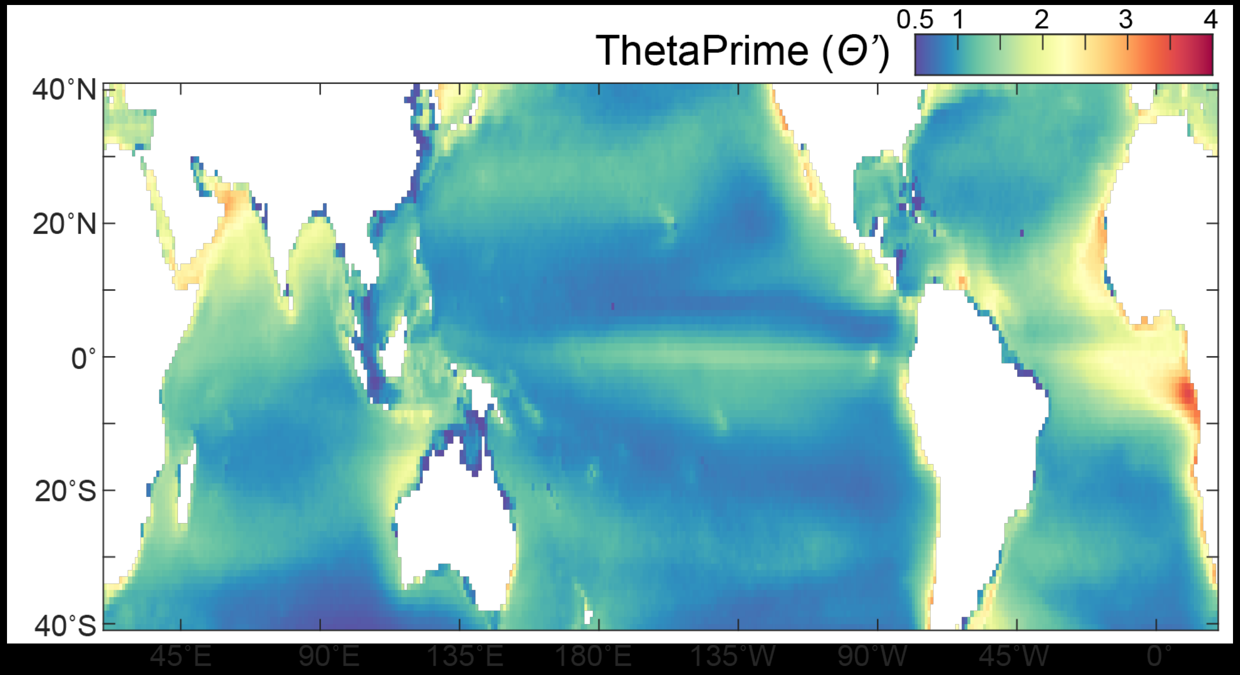


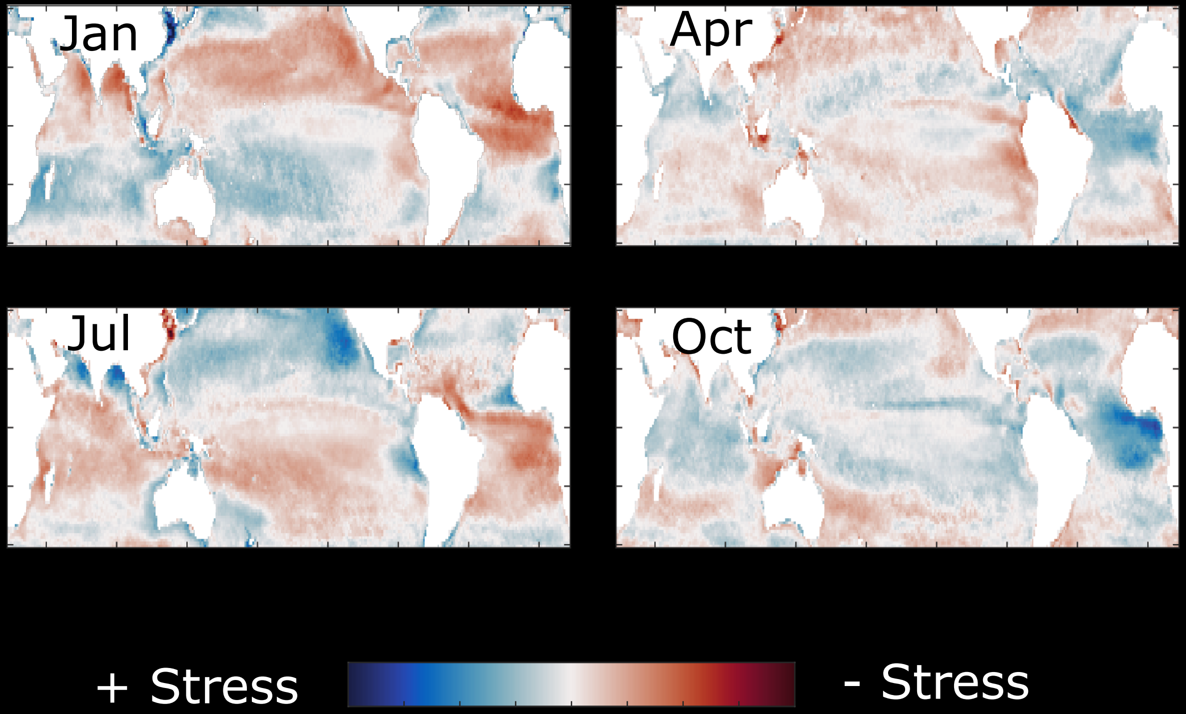
Higher nutrient stress in subtropical gyres

Lower nutrient stress in upwelling regions

Southern hemisphere bias

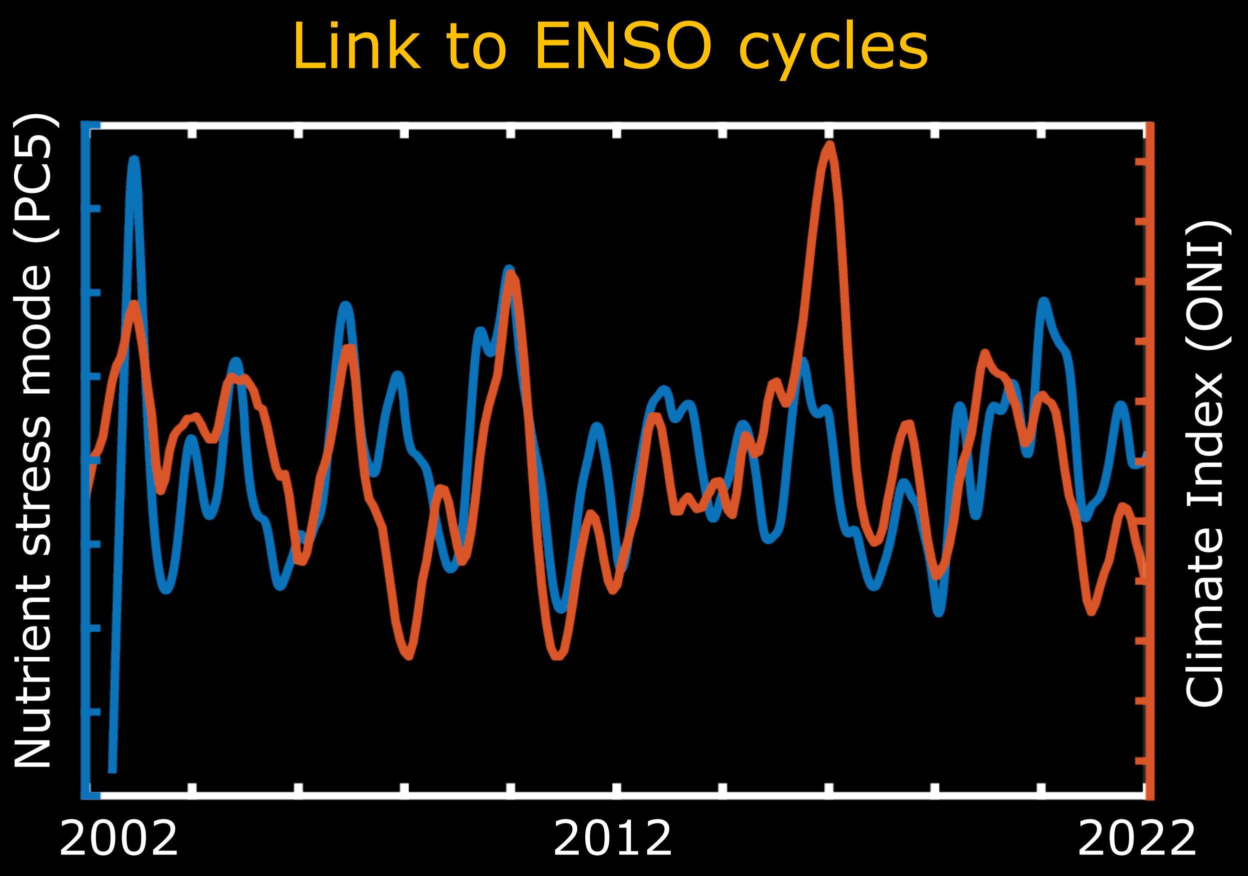
Mean and seasonal nutrient stress



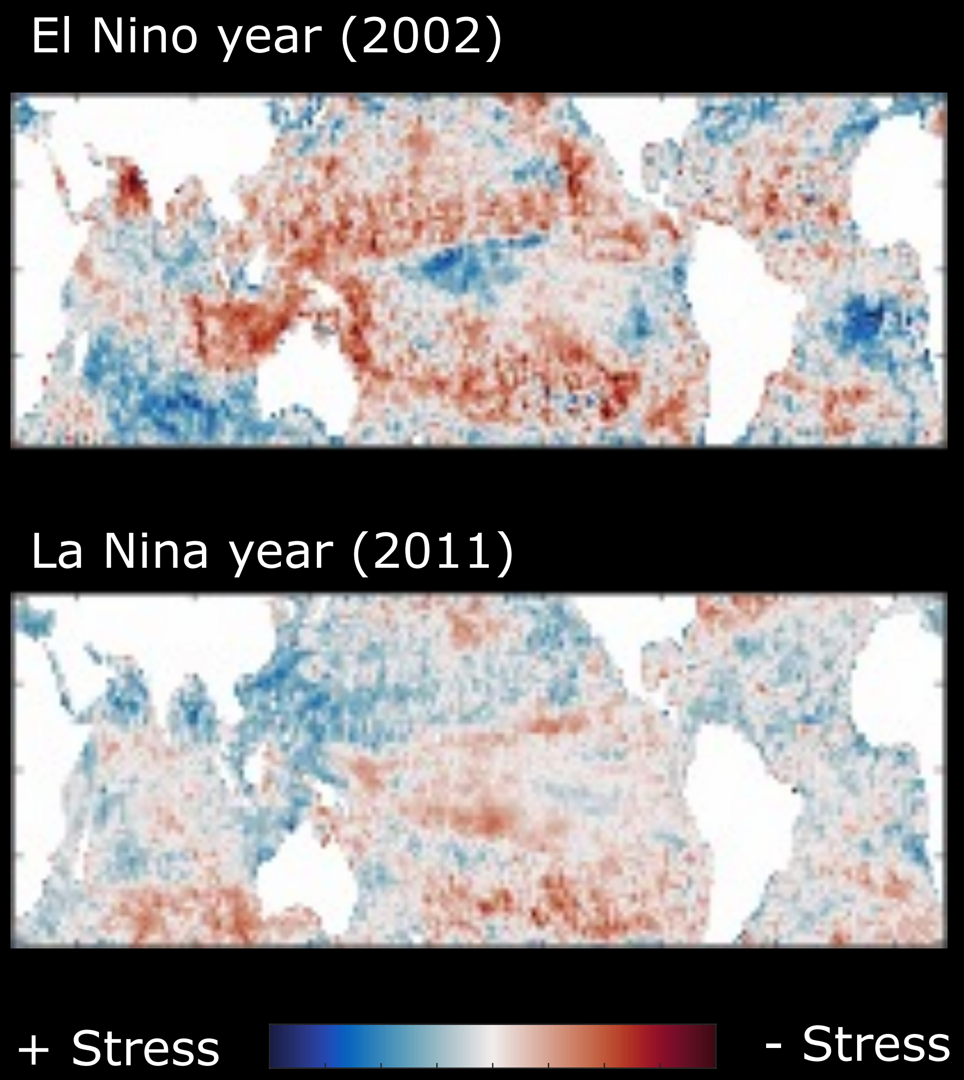


Clear seasonal cycles in thetaPrime - and nutrient stress

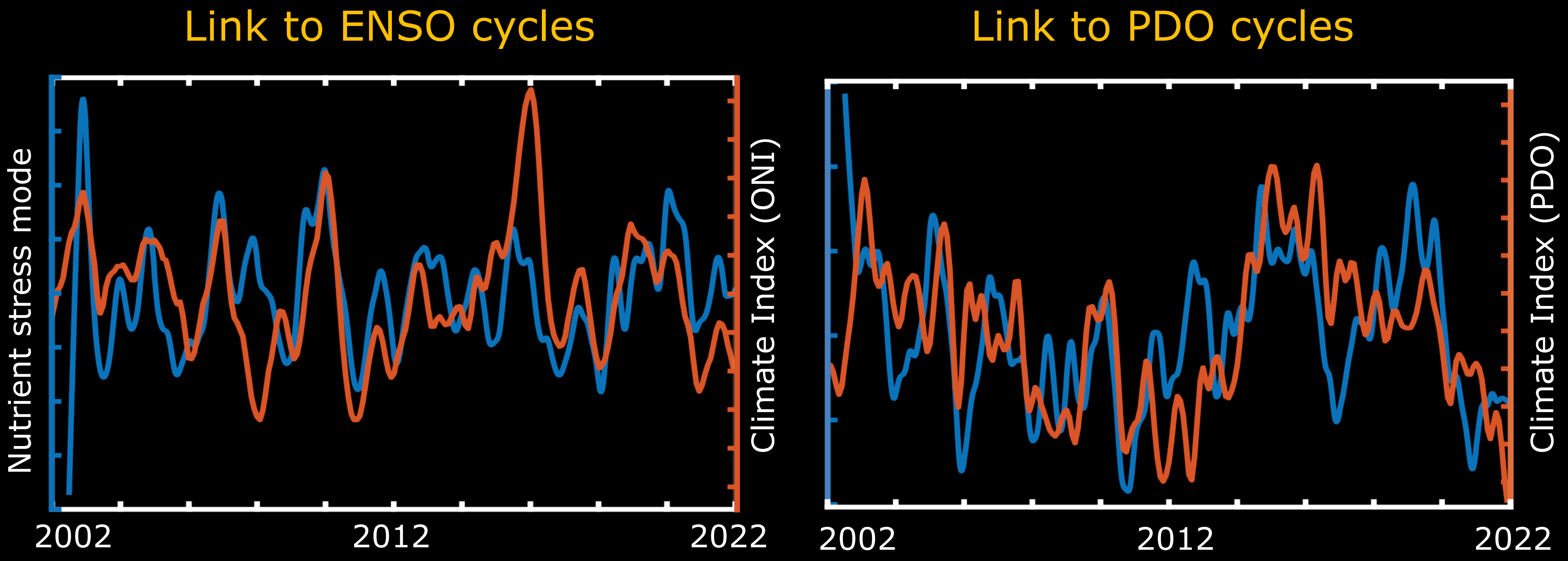
Climate cycles in nutrient stress



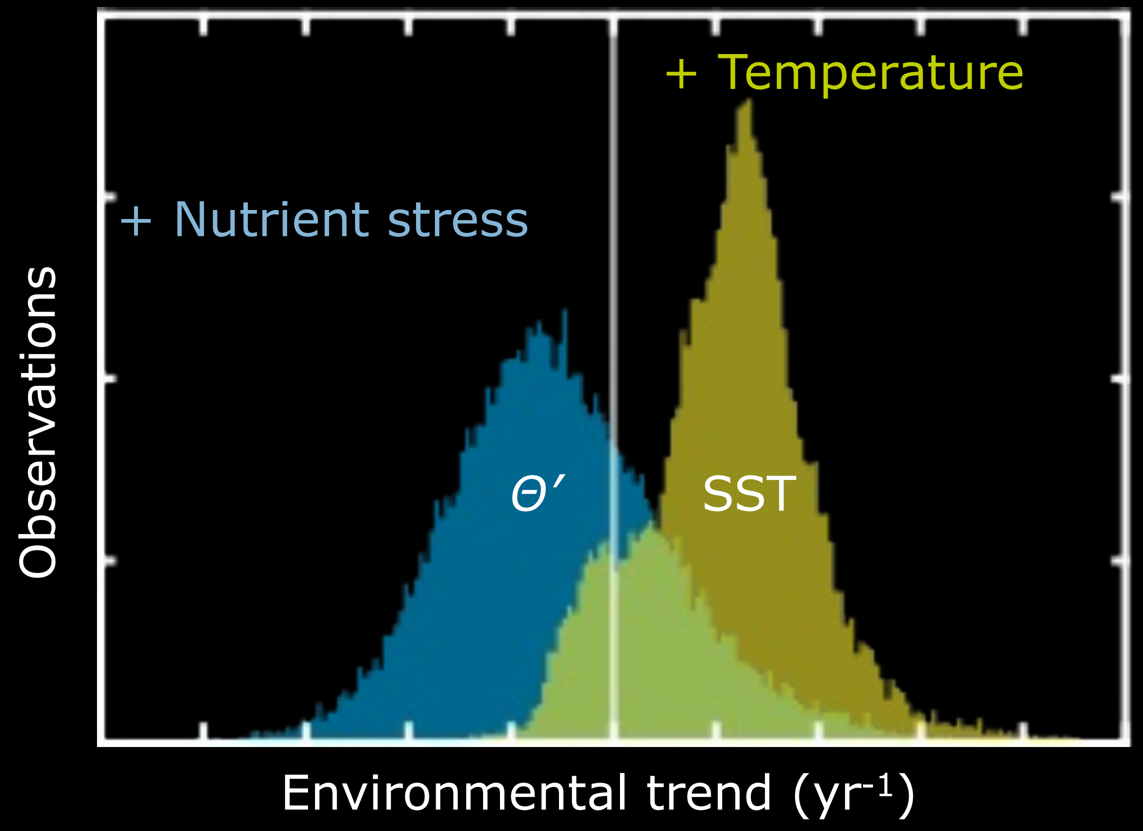
First interannual principal component from EOF analysis



Climate cycles in nutrient stress



Contemporary change in nutrient stress vs. temperature



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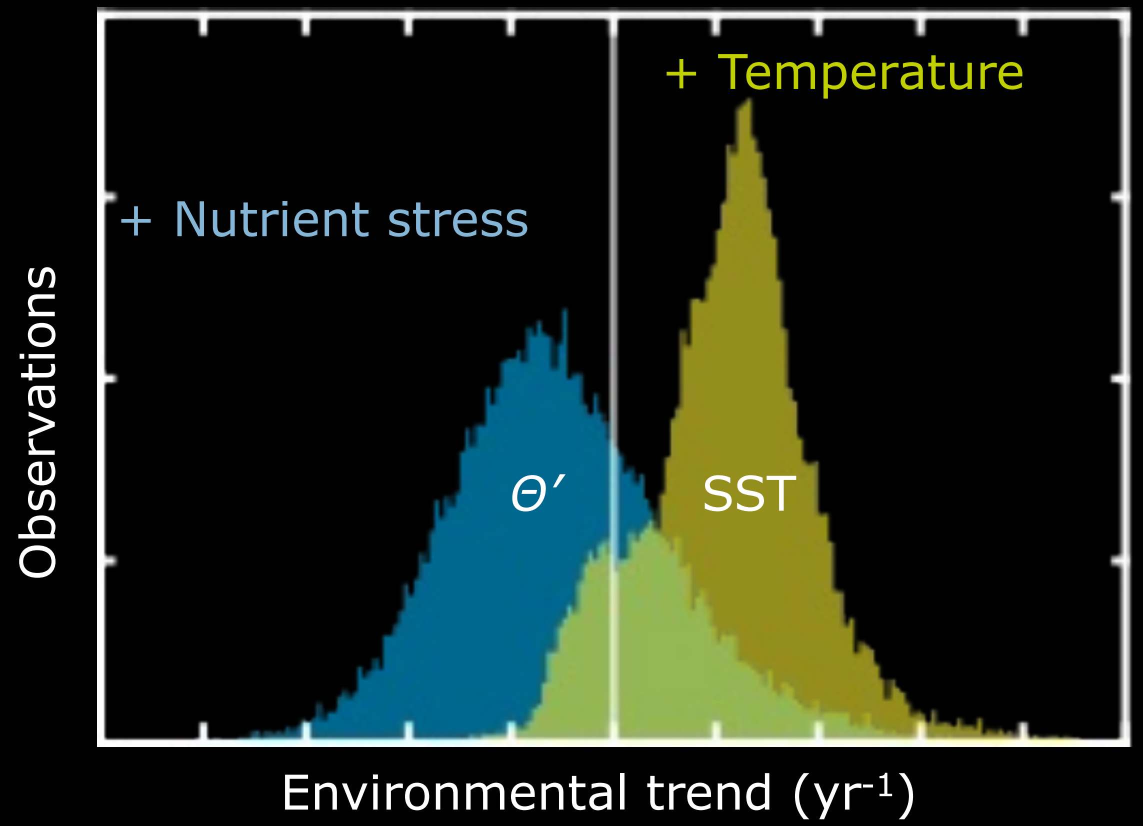
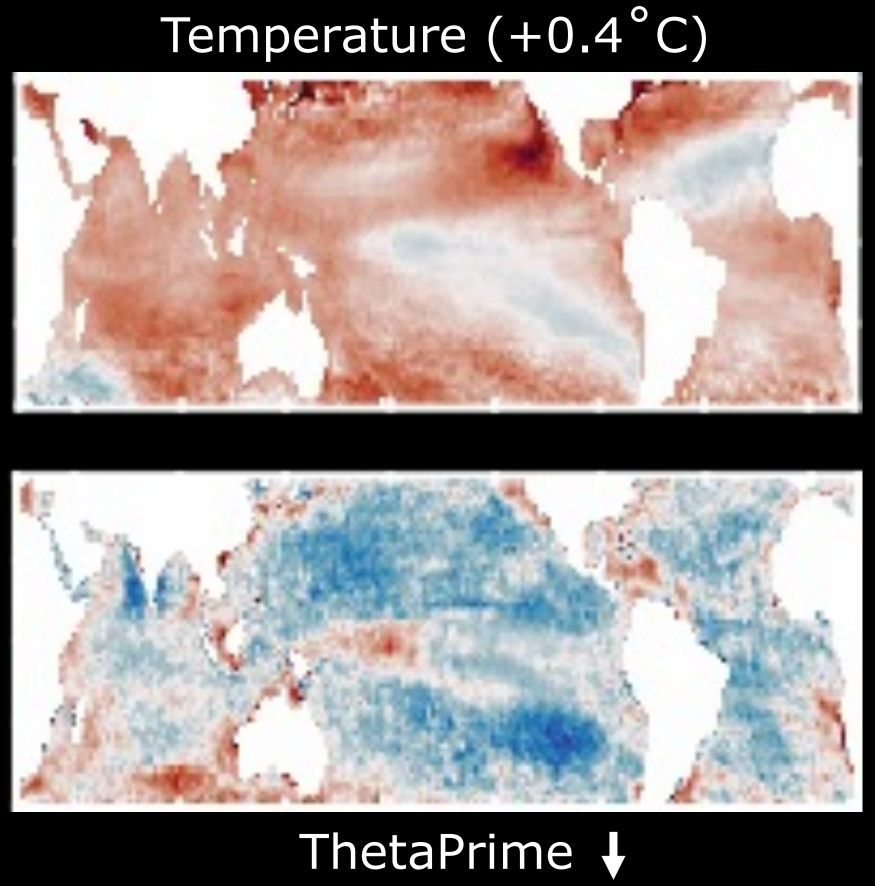
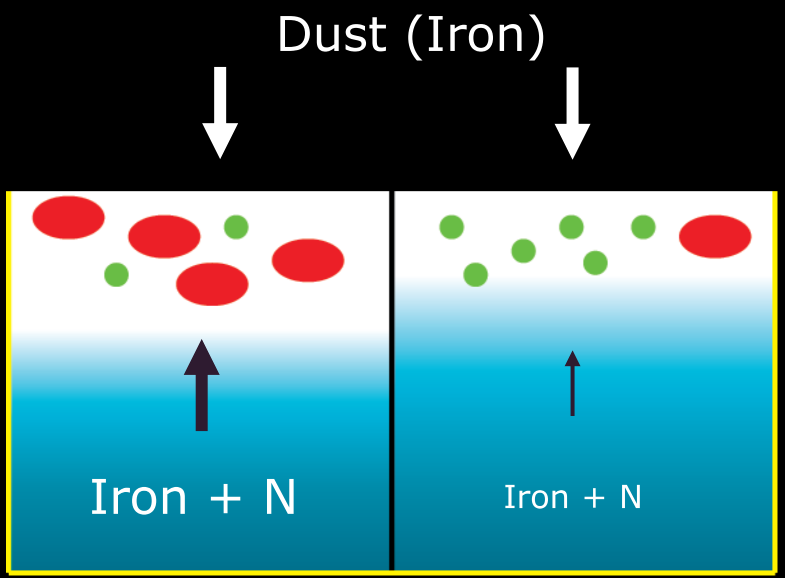




Lower growth rate linked to warming!!

→ Future warming Stratification →



Iron is also an important nutrient

Limits productivity in many regions (including upwelling/HNLC regions)

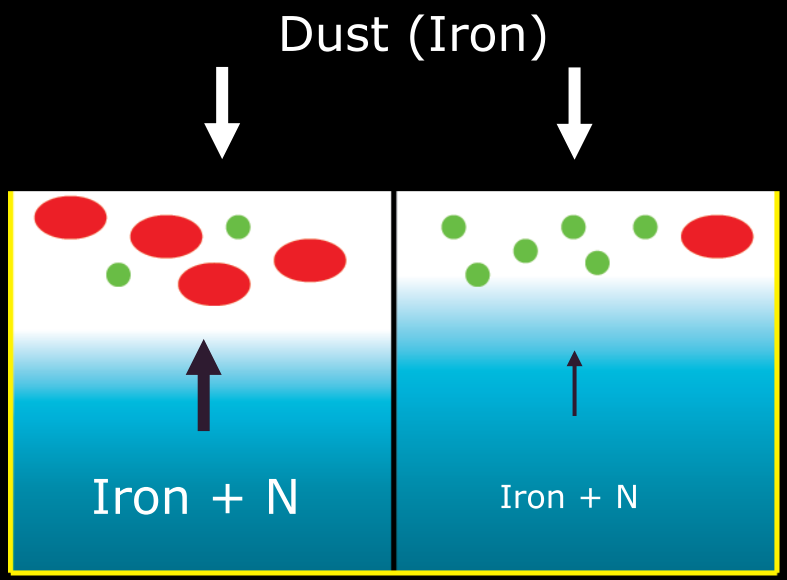
Vertical supply of iron will also decline

Some iron is also supplied via dust (aeolian)

Dust Fe is <u>**NOT**</u> regulated by stratification

Led by Amy Nuno
Student recruited for this project

→ Future warming Stratification →



Iron is also an important nutrient

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Dust deposition is **NOT** regulated by stratification

We can use ocean color fluorescence to detect iron stress

Biochemical mechanism linking Fe limitation with fluorescence

Iron is required for photosynthesis

photosystem Ⅰ (PSⅠ) and photosystem Ⅱ (PSⅡ)

PSⅠ has greater iron quota than PSⅡ

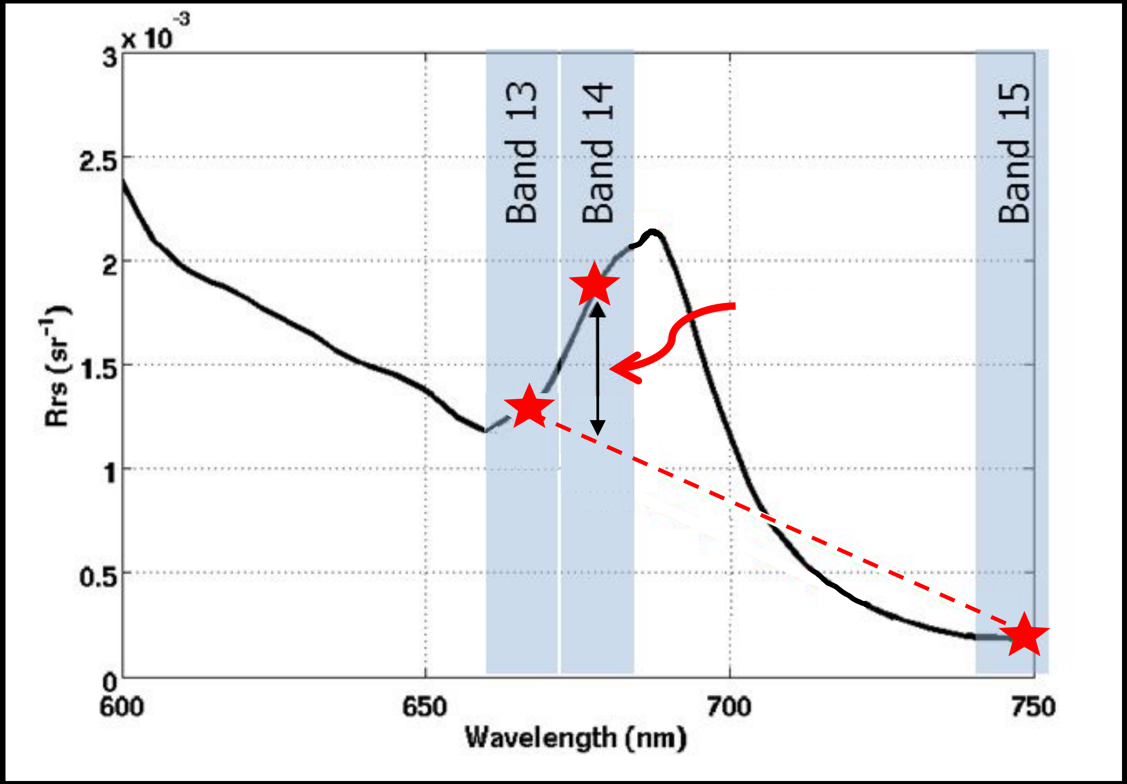
Laboratory studies have shown that under iron stress there is an increase in PSⅡ : PSⅠ ratio

PSⅡ emits most fluorescence

Fluorescence quantum yield (Φsat):

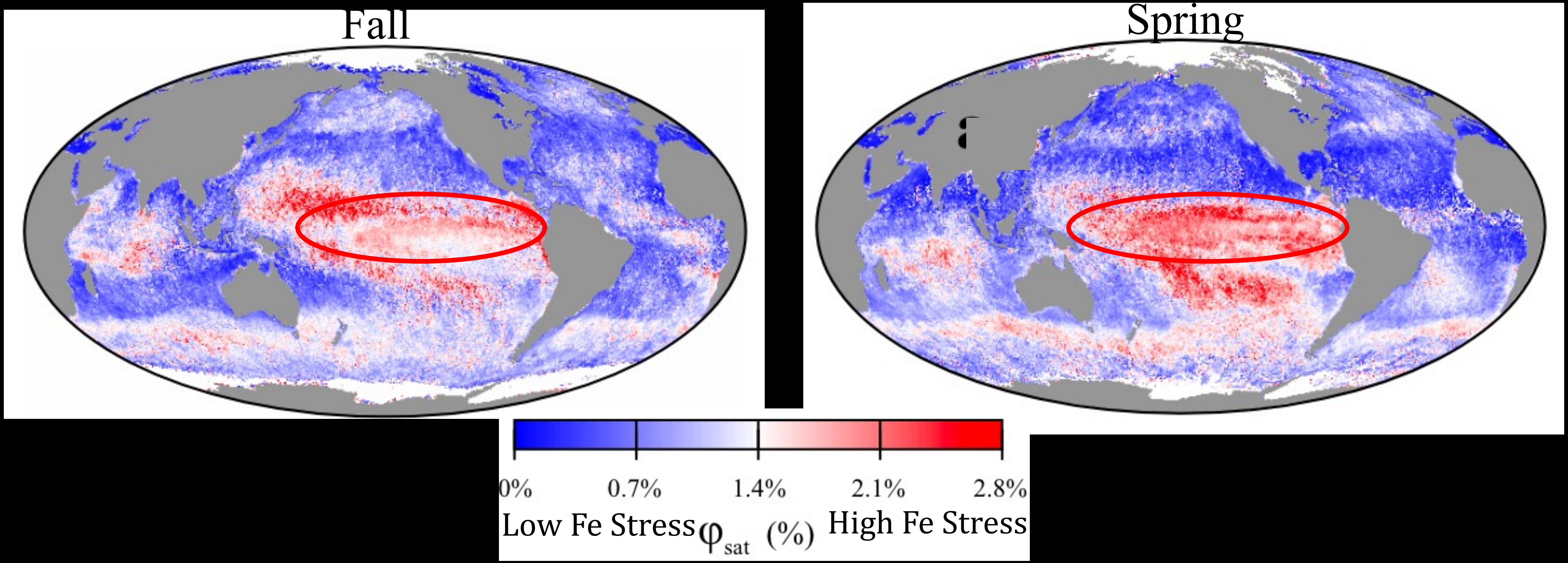
fluorescence / absorbed light

Φsat ~ Fe Stress



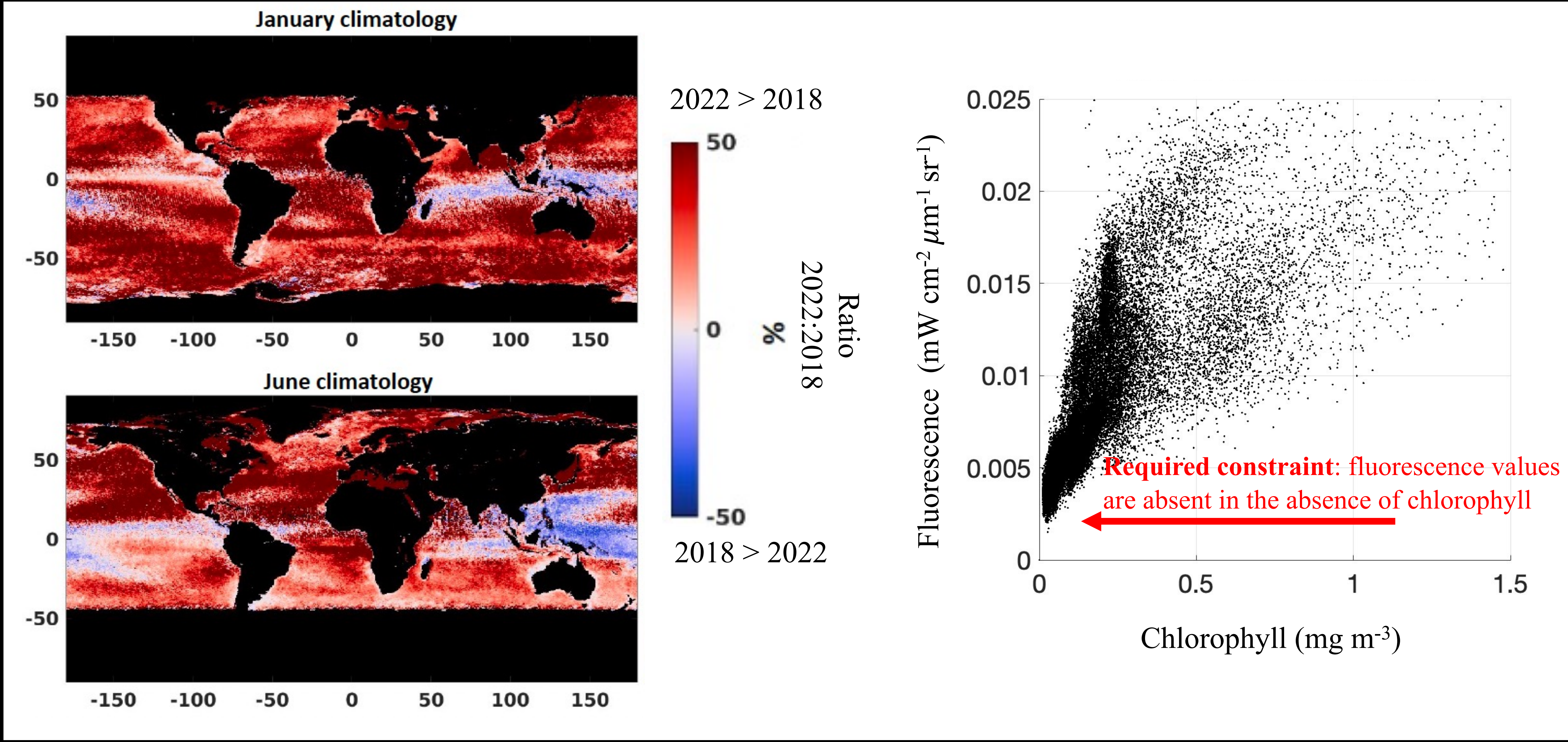
Behrenfeld et al., 2009

Behrenfeld et al (2009) study

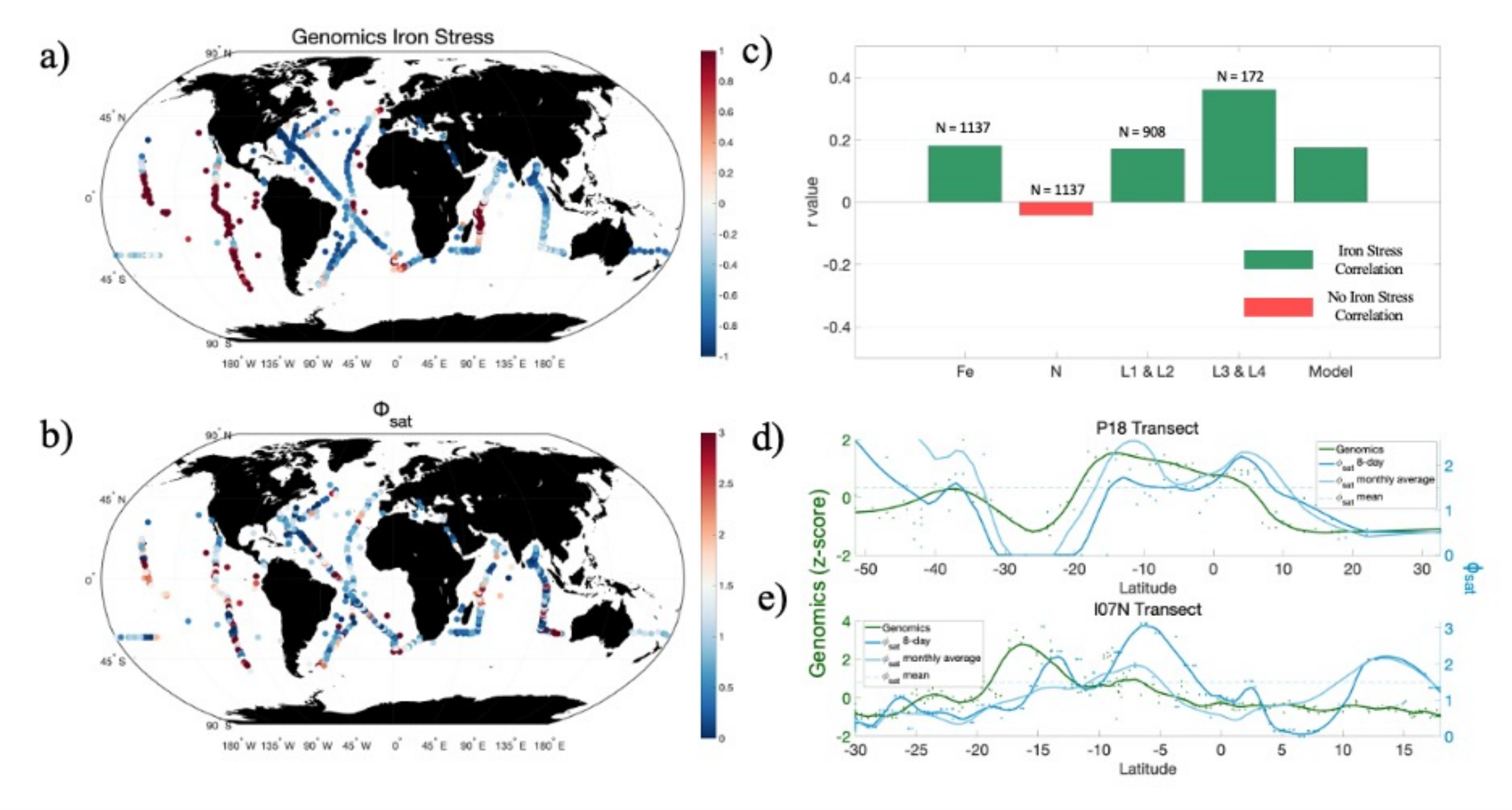


- Equatorial Pacific has elevated ϕ_{sat}
- Inconsistencies from what we know from *in-situ* iron limitation data
    - Expected elevated ϕ_{sat} values in the North Pacific and Southern Ocean
- Requires reevaluation

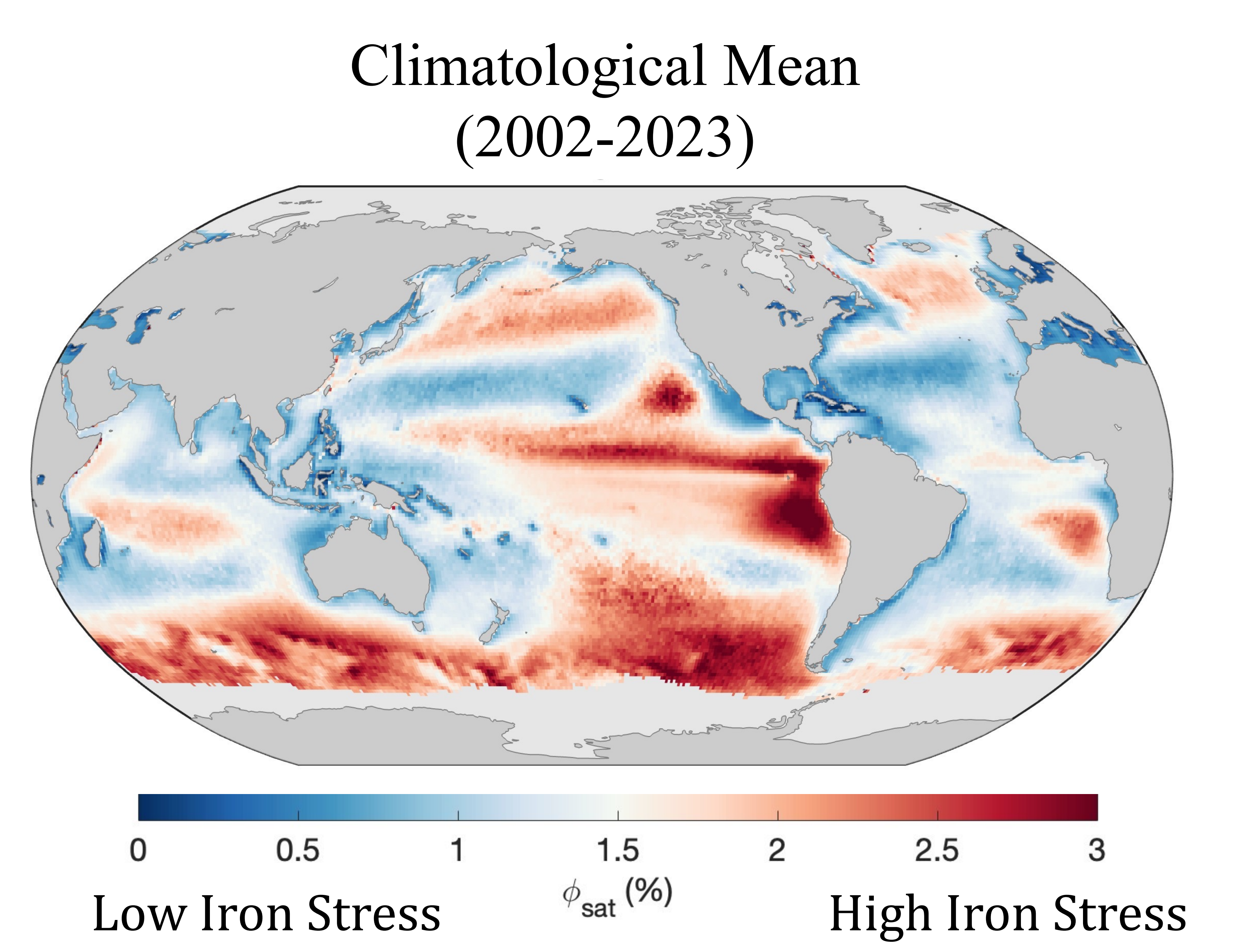
MODIS-Aqua reprocessing 2022 vs 2018 nFLH

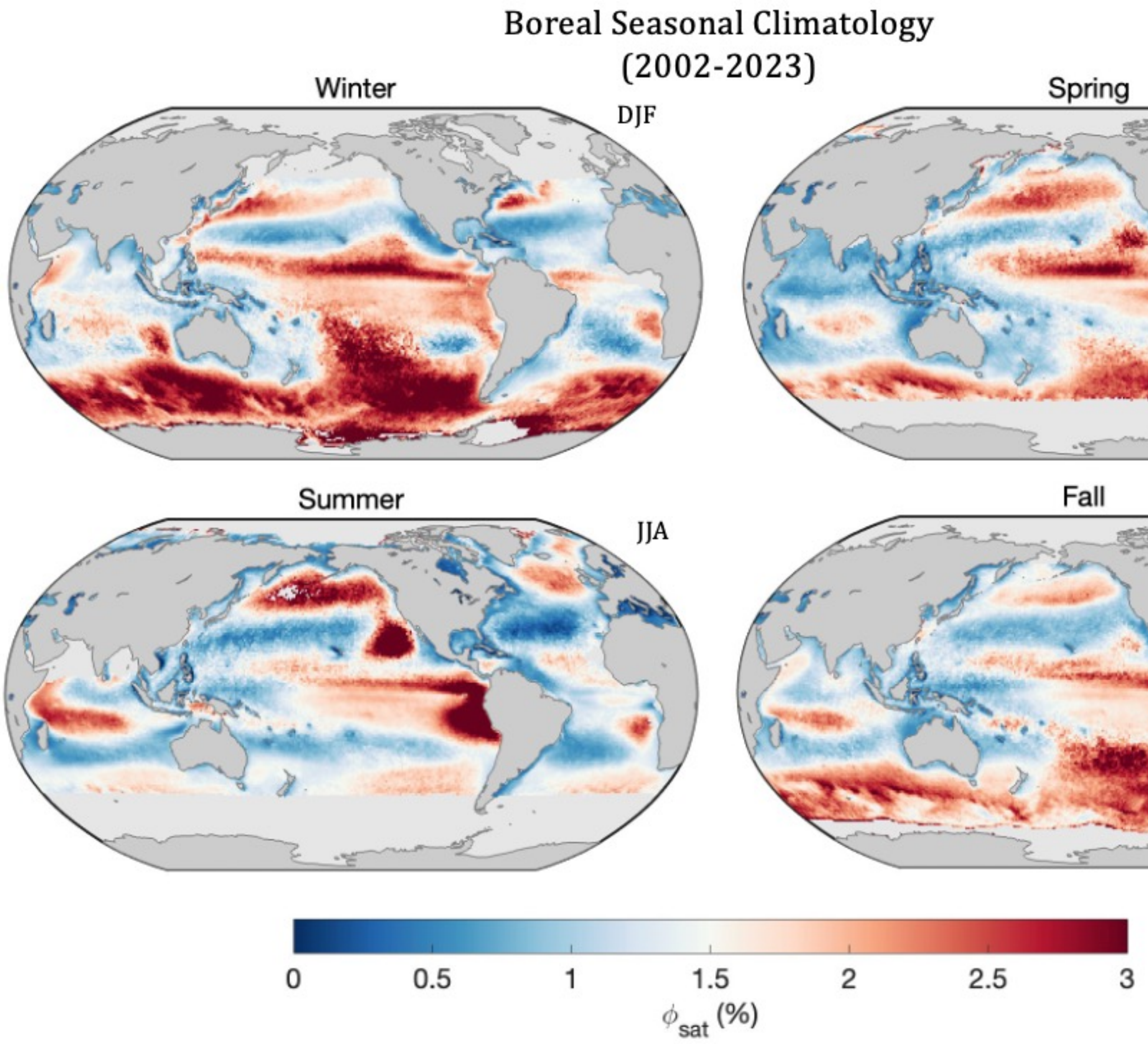


Genomic Validation



Iron Stress Proxy ϕ_{sat}

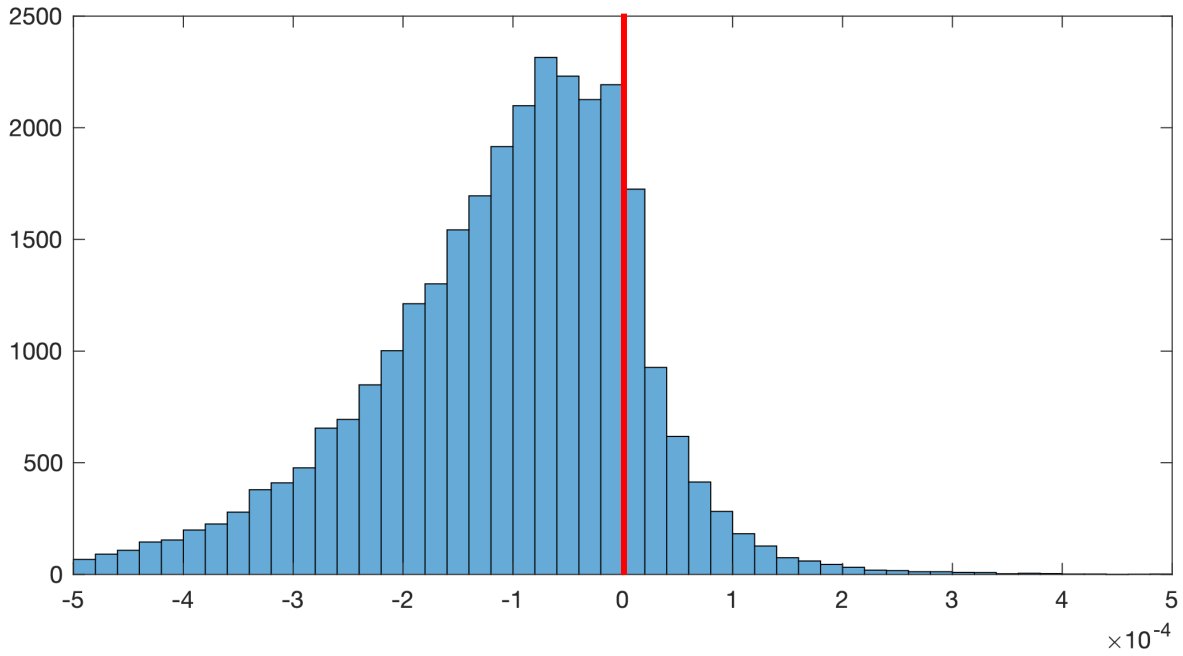




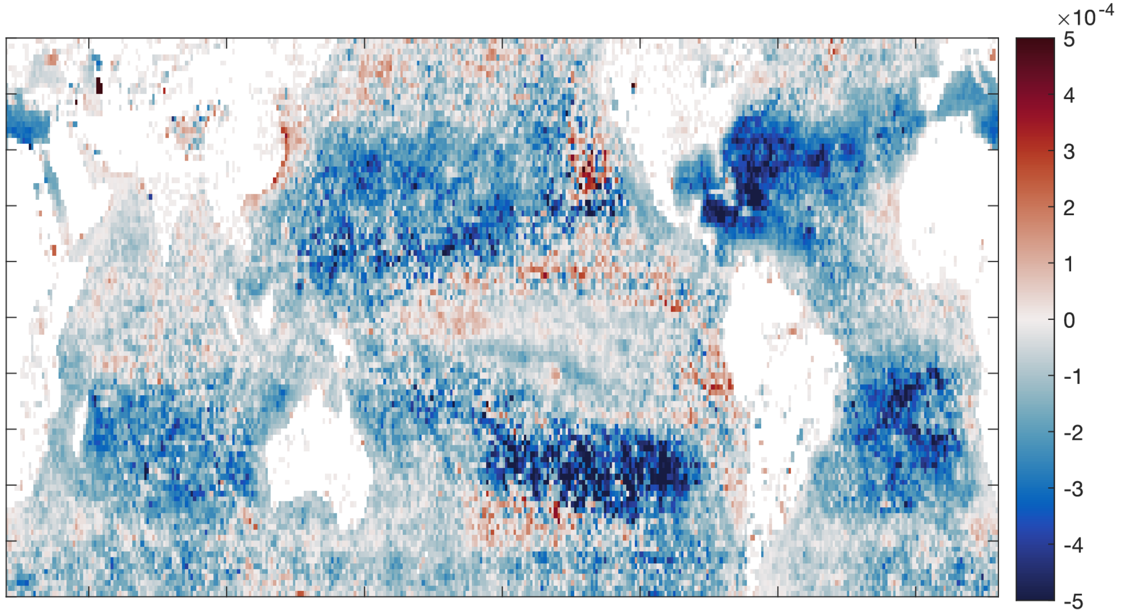
Boreal Seasonal Climatology
(2002-2023)
Winter
DJF
Spring
MAM
Summer
JJA
Fall
SON
0
0.5
1
1.5
2
2.5
3
ϕ_{sat} (%)

Long-term decline in Fe stress

86% show a decline in nutrient stress



Most of the decline is occurring in subtropical gyre regions



Summary

- Integration of ‘omics and remote sensing -> mechanistic understanding of phytoplankton growth regulation
- N stress leads to a stronger depression in theta’ compared to P
- Remote sensing of iron stress show new regions of high iron stress
- Reveals global spatio-temporal variation in nutrient stress
- Link to ENSO cycles with higher eastern equatorial macronutrient stress during El Nino
- Link to climate warming -> widespread **increase** in macronutrient stress
- Link to climate warming -> widespread **decrease** in iron stress

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Thank You

Questions?