Phytoplankton regime shifts and climate change

Philip Boyd

IMAS INSTITUTE FOR MARINE AND ANTARCTIC STUDIES

UTAS

translatingnatureintoknowledge

OCB July 2016

Anthropogenic climate change drives shift and shuffle in North Atlantic phytoplankton communities

Andrew D. Barton[a,1], Andrew J. Irwin[b], Zoe V. Finkel[c], and Charles A. Stock[a]

MARINE CALCIFERS

Multidecadal increase in North Atlantic coccolithophores and the potential role of rising CO_2

Sara Rivero-Calle,[1,2*] Anand Gnanadesikan,[1*] Carlos E. Del Castillo,[1,3] William M. Balch,[4] Seth D. Guikema[5]

PHYTOPLANKTON

Millennial-scale plankton regime shifts in the subtropical North Pacific Ocean

Kelton W. McMahon,[1,2*] Matthew D. McCarthy,[1] Owen A. Sherwood,[3] Thomas Larsen,[4] Thomas P. Guilderson[1,2,5]

Phytoplankton adapt to changing ocean environments

Andrew J. Irwin[a,1], Zoe V. Finkel[b], Frank E. Müller-Karger[c], and Luis Troccoli Ghinaglia[d]

Regime shifts – an abrupt change between contrasting persistent states in an ecosystem

Biota	Region	Reference
Phytoplankton – nitrogen fixers	NPSG	Karl et al. (1995, 1999); Karl (1999)
Phytoplankton	NE subarctic Pacific	Whitney et al. (1998)
Phytoplankton – pico to large diatoms	Equatorial Pacific	Chavez et al. (1999)
Small to large phytoplankton[a]	NE subarctic Pacific	Parslow (1981)
Coccolithophores	Bering Sea	Napp and Hunt Jr. (2001)
Phytoplankton	NE Atlantic and North Sea	Reid et al. (1998)
Euphausids	Bering Sea	Napp and Hunt Jr. (2001)
Zooplankton and salmon	NE subarctic Pacific	Beamish et al. (1999)
Calanoid copepods	North Sea	Heath et al (1999)
Krill and Salps	Polar Southern Ocean	Loeb et al. (1997)
Krill and Salps	Southern Ocean – East Antarctica	Nicol et al. (2000)
Penguin stocks	MIZ – Antarctic Peninsula	Smith et al. (1999)
Cod stocks	North Sea	O'Brien et al. (2000)
Elevated export to depth	NE subarctic Pacific	Boyd et al. (1998)
Fulmar populations	N Atlantic	Thompson and Ollason (2001)

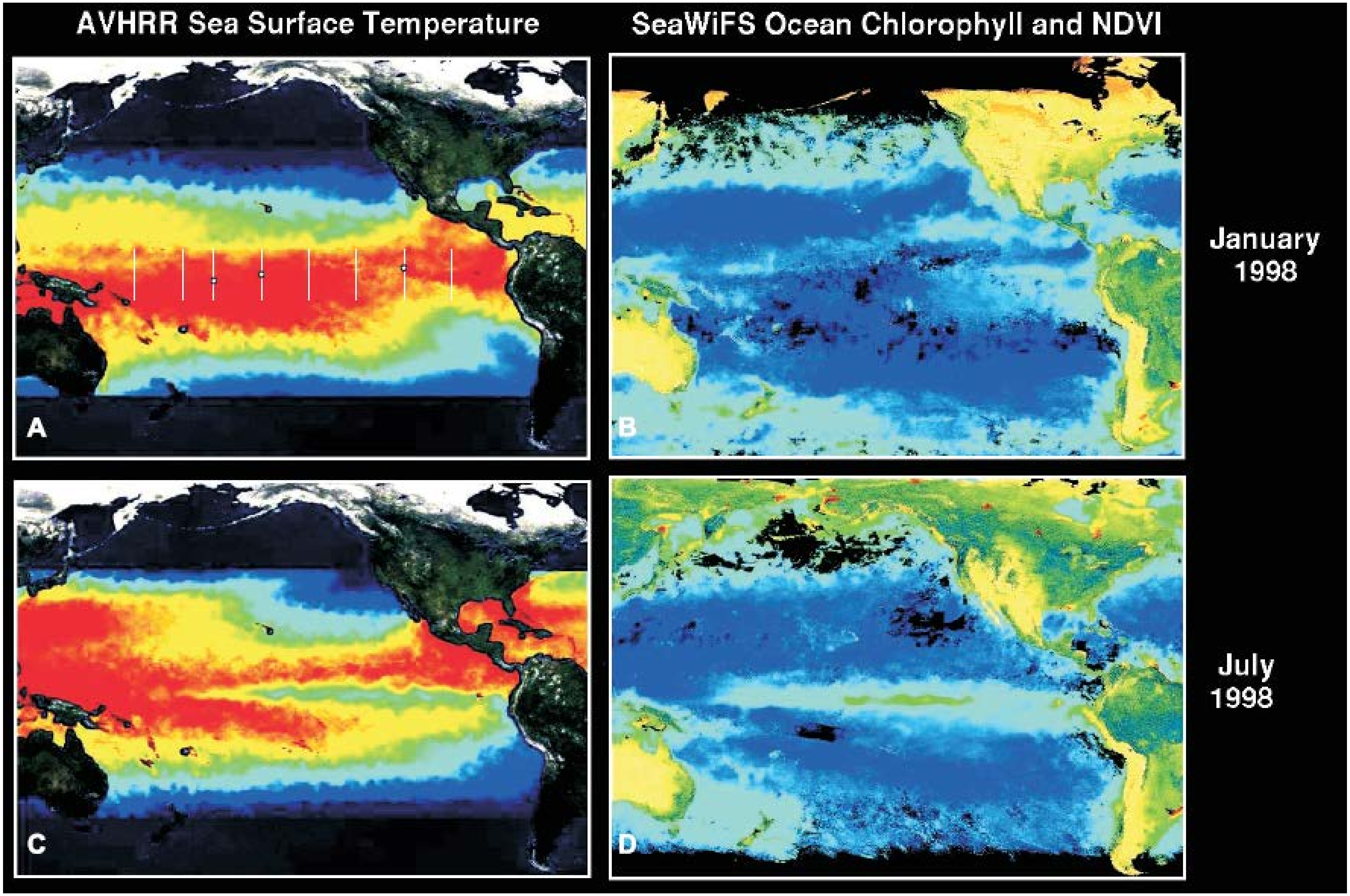
Boyd & Doney (2003)

Global Change Biology

Global Change Biology (2016) **22**, 2069–2080, doi: 10.1111/gcb.13229

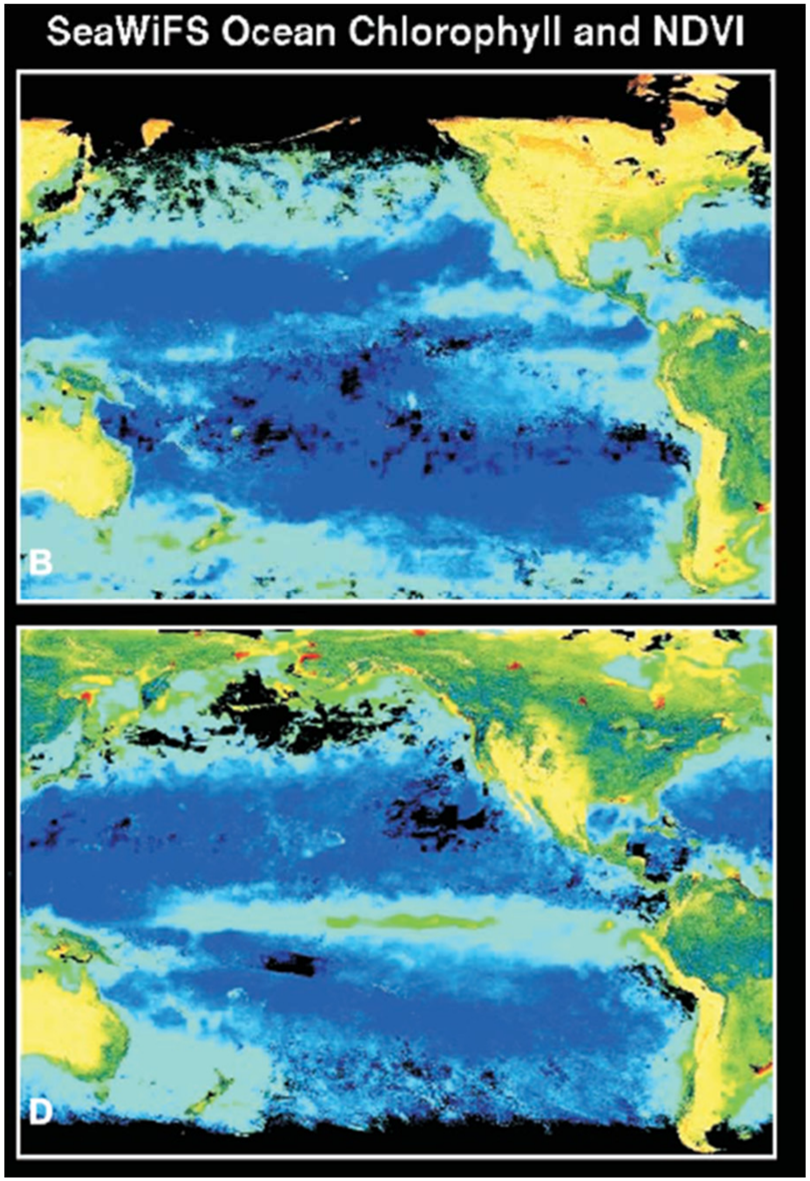
Climate change-related regime shifts have altered spatial synchrony of plankton dynamics in the North Sea

EMMA J. DEFRIEZ[1], LAWRENCE W. SHEPPARD[2], PHILIP C. REID[3,4,5] and DANIEL C. REUMAN[2,6]

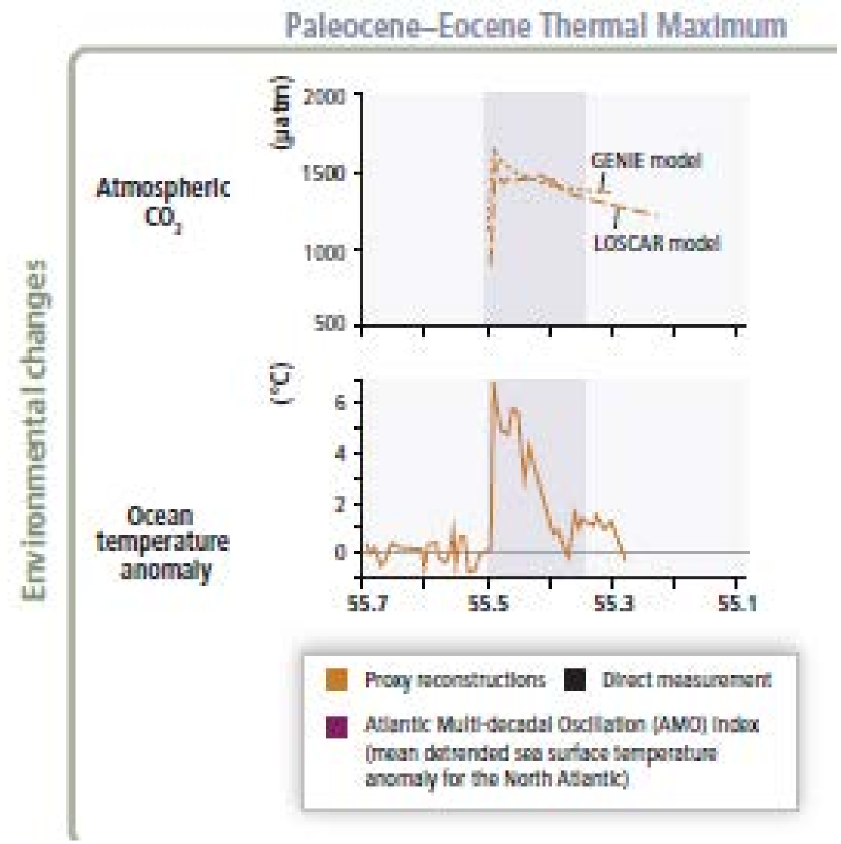


Chavez et al. (1999)

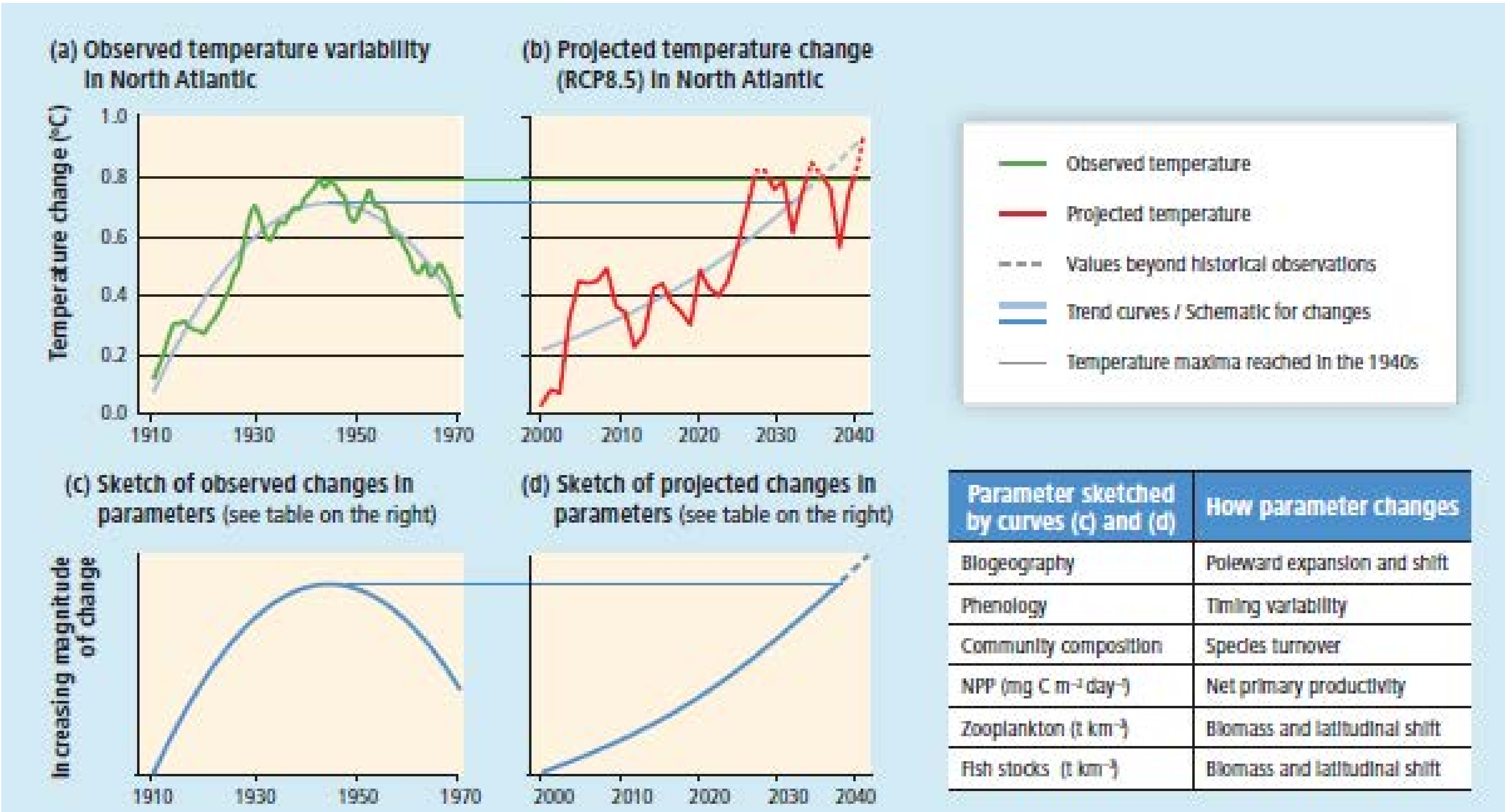
The search for climate change analogues



Versus



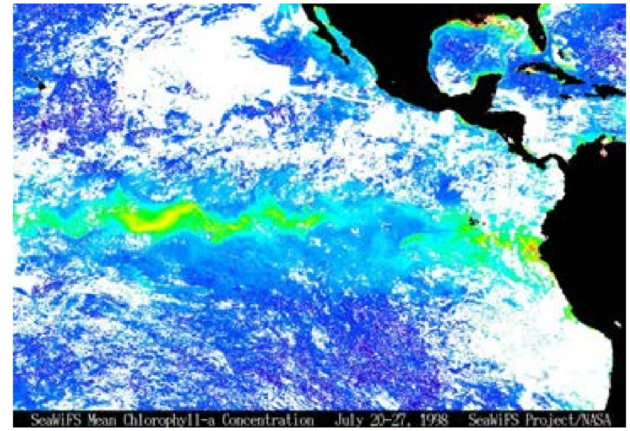
A few regime shifts are slow enough to match warming trends



Parameter sketched by curves (c) and (d)	How parameter changes
Biogeography	Poleward expansion and shift
Phenology	Timing variability
Community composition	Species turnover
NPP (mg C m^{-3} day^{-1})	Net primary productivity
Zooplankton (t km^{-3})	Biomass and latitudinal shift
Fish stocks (t km^{-3})	Biomass and latitudinal shift

Pörtner et al. (2015) IPCC WG2

However the clusters of environmental change do not match that for climate change



Chavez et al. (1999)

Seasonal progression

Temp	↑
Fe	↓
Nuts	↓
MLD	↑
CO2	↓
PAR	↑

La Niña

Temp	↓
Fe	↑
Nuts	↑
MLD	↑
CO2	↑
PAR	NC

Climate Change

Temp	↑
Fe	↓
Nuts	↓
MLD	↑
CO2	↑
PAR	??

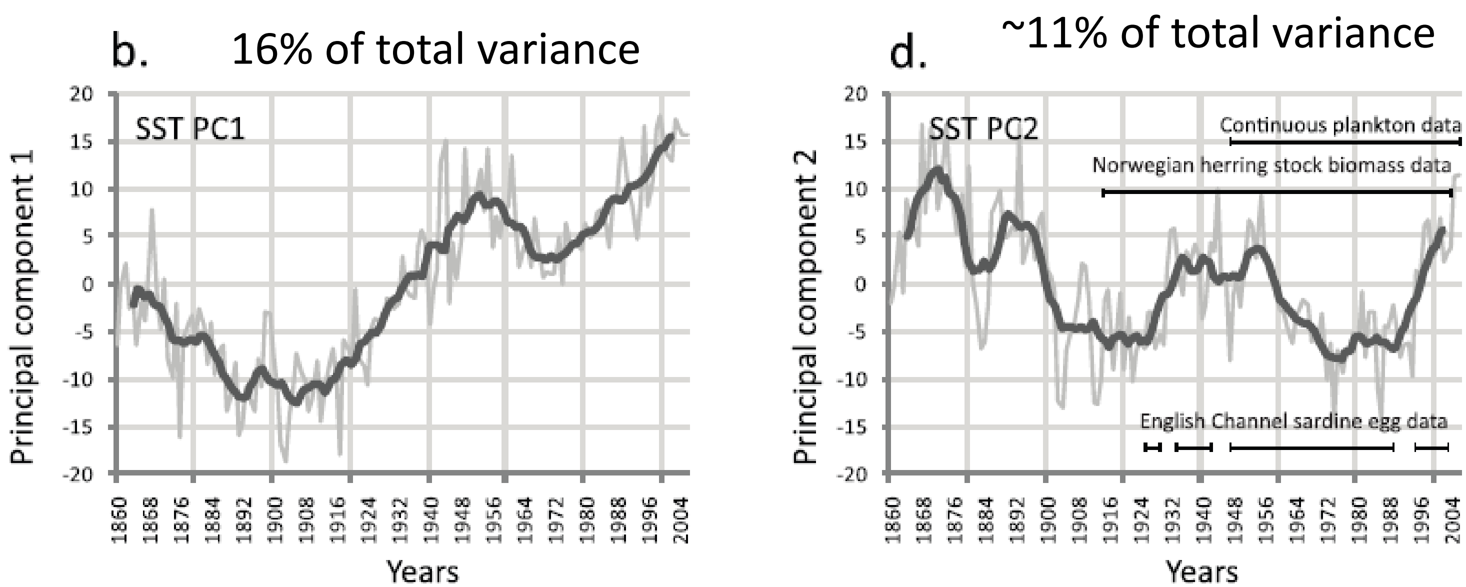
Boyd et al. (2010)

OPEN ACCESS Freely available online

PLOS | ONE

Marine Ecosystem Response to the Atlantic Multidecadal Oscillation

Martin Edwards[1,2]*, Gregory Beaugrand[3], Pierre Helaouët[1], Jürgen Alheit[4], Stephen Coombs[5]

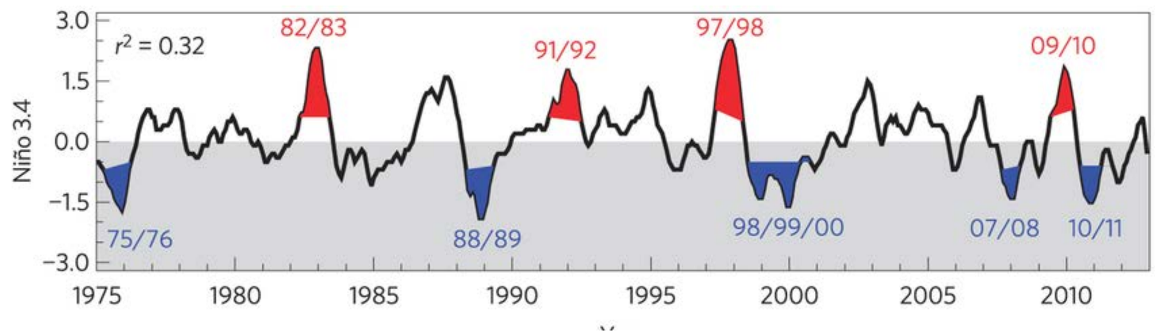


Our findings suggest that the AMO is far from a trivial presence against the backdrop of continued temperature warming in the North Atlantic and accounts for the second most important macro-trend in North Atlantic plankton records; responsible for habitat switching (abrupt ecosystem/regime shifts) over multidecadal scales.

Biological responses to environmental fluctuations

Phytoplankton encounter a mix of

natural climate variability



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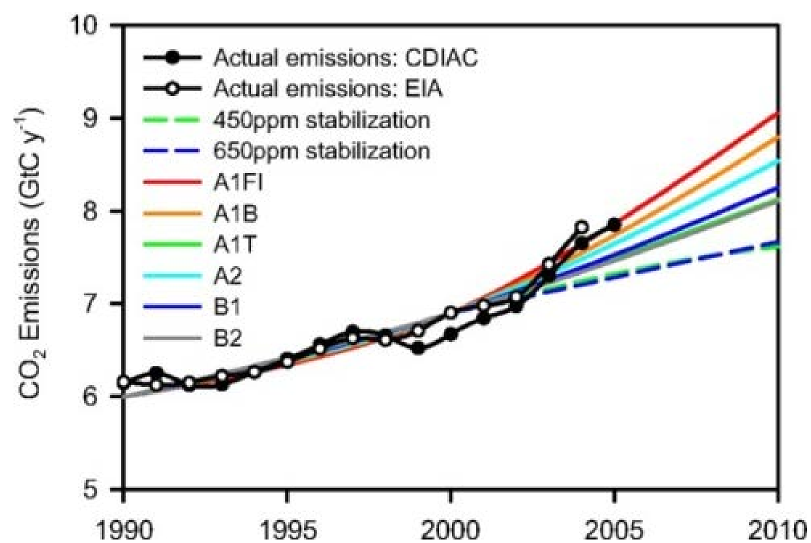

mean climate change

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PNAS

LETTER

Reply to Brun et al.: Fingerprint of evolution revealed by shifts in realized phytoplankton niches in natural populations

PNAS

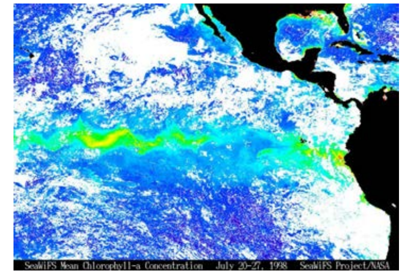
Measuring evolutionary adaptation of phytoplankton with local field observations

Irwin et al. recently published a study that investigates the capacity of phytoplankton to adapt their ecological niches to changing

Irwin et al. investigated local populations that may have evolved narrower thermal niches. However, isolated phytoplankton

We suggest instead that temperature is not a limiting factor for most species in the considered environment and that the changes

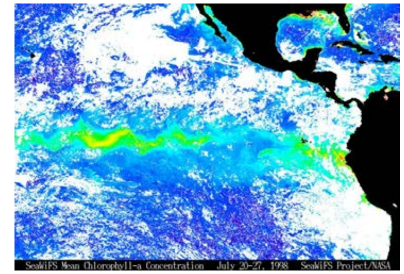
ISSUES



We know shifts in phytoplankton community structure propagate through foodwebs so a mechanistic understanding of environmental forcing/biological response is essential

Are these records long enough to detect altered phytoplankton communities (see Henson et al. 2010, Di Lorenzo & Ohman 2013)

Phytoplankton are passive drifters – how does drift influence their environmental trajectory and hence their response



ISSUES

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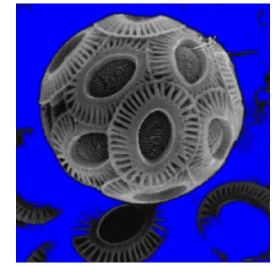
Phytoplankton are passive drifters – how does drift influence their environmental trajectory and hence their response

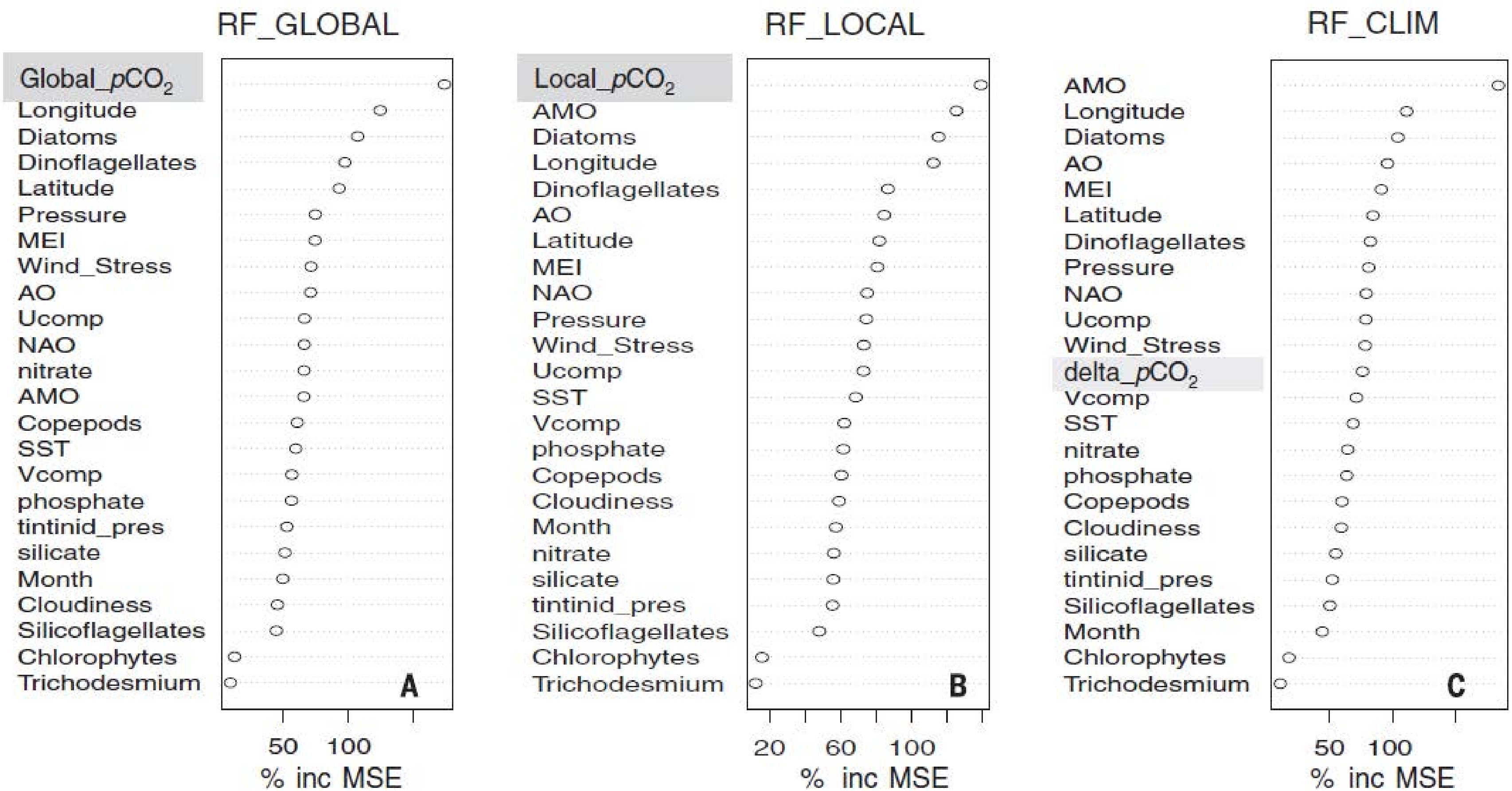
Drift in ocean currents impacts intergenerational microbial exposure to temperature

Martina A. Doblin[a,1] and Erik van Sebille[b,c]

The timescales of global surface-ocean connectivity
Bror F. Jönsson & James R. Watson
Nature Communications 7, Article number: 11239 doi:10.1038/ncomms11239

Rivero-Calle (2015) employed 3 random forest walk models
To explore the relative importance of properties to
Predicting coccolithophore occurrence



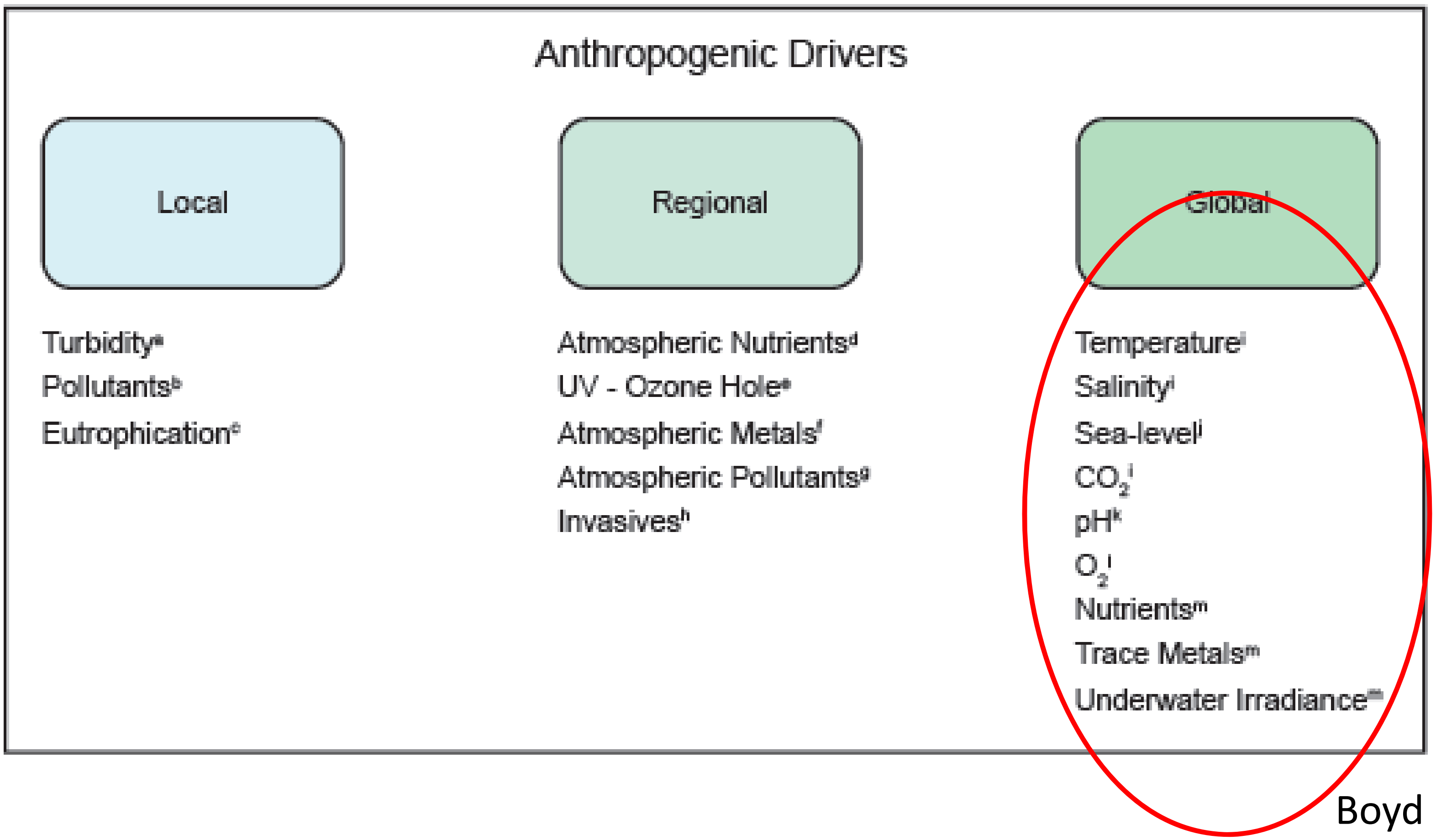


Mauna Loa

ML + Takahashi

Takahashi

Permutations of multiple stressors vary with locale



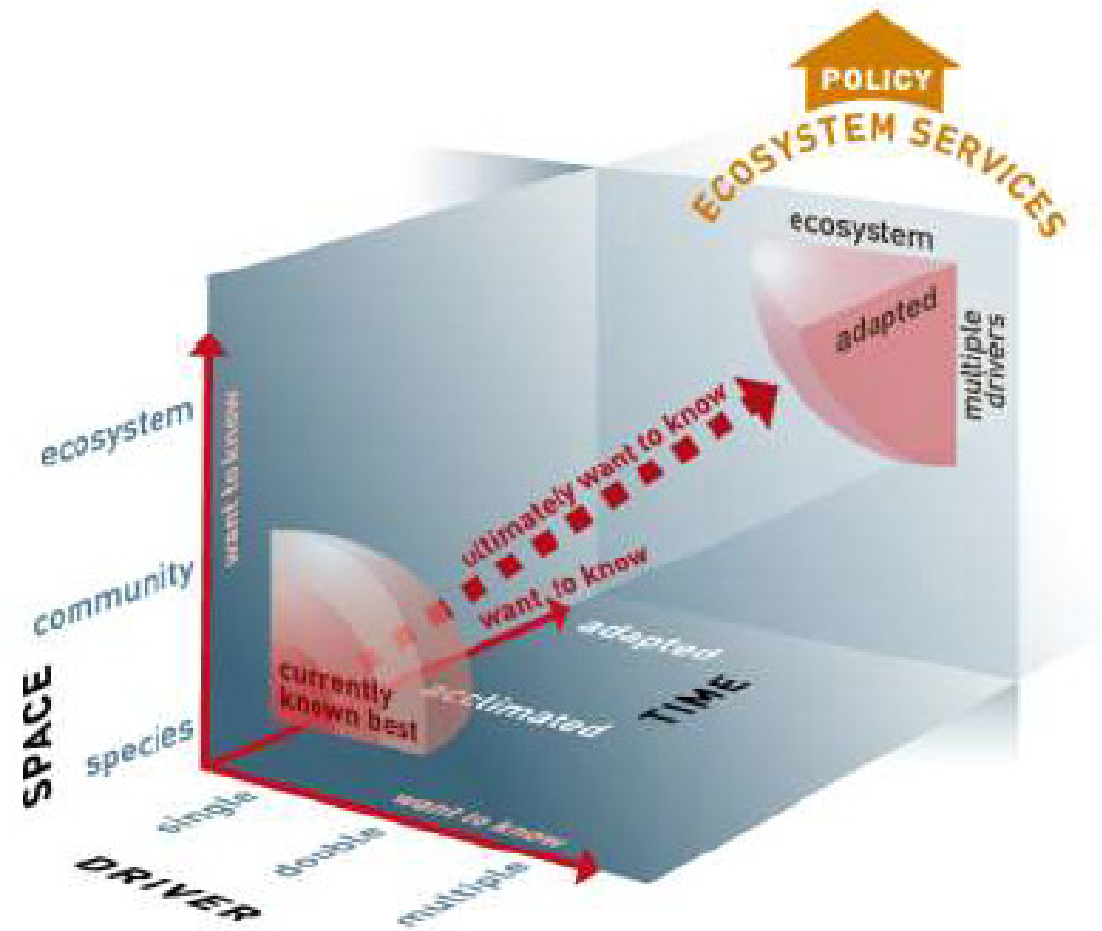
Boyd & Hutchins 2012 MEPS

The fledgling multi-stressors community has expertise to help shed light on drivers behind the observed floristic shifts

COMMENTARY:

Lessons learned from ocean acidification research

Ulf Riebesell and Jean-Pierre Gattuso



Moving along the axes

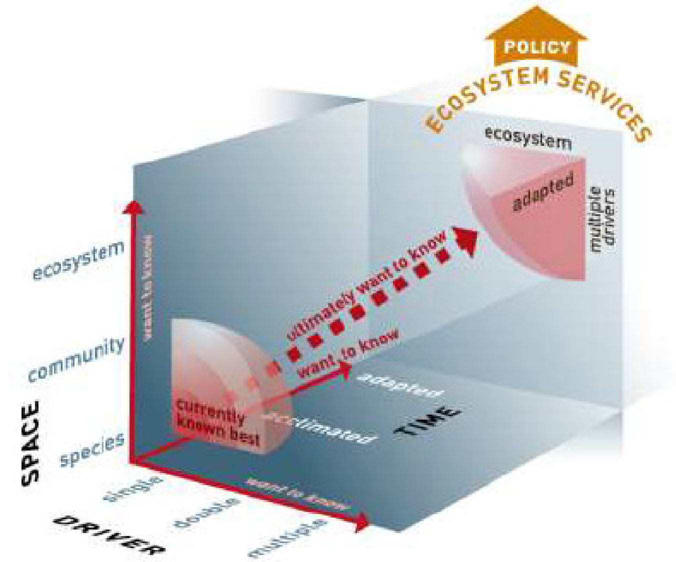
nature climate change

ARTICLES

PUBLISHED ONLINE: XX MONTH XXXX | DOI: 10.1038/NCLIMATE2811

Physiological responses of a Southern Ocean diatom to complex future ocean conditions

P. W. Boyd[1,2]*, P. W. Dillingham[3], C. M. McGraw[3,4], E. A. Armstrong[5], C. E. Cornwall [1,6], Y.-y. Feng[6], C. L. Hurd[1,6], M. Ringold-Gault[7], M. Y. Roleda[6†], E. Timmins-Schiffman[8] and B. L. Nunn[8]



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Ecology, 93(3), 2012, pp. 441–448
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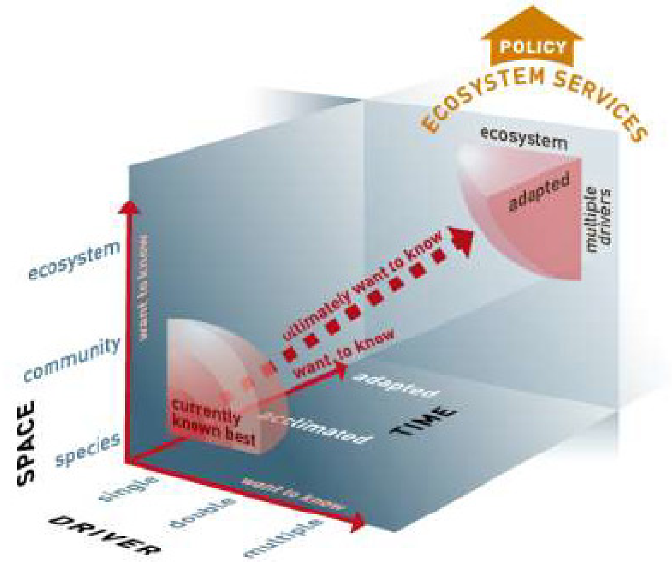
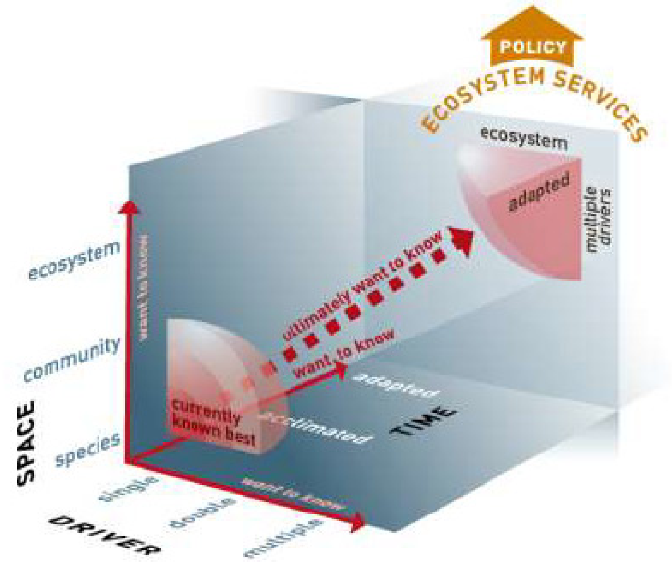
Multiple anthropogenic stressors and the structural properties of food webs

Eoin J. O'Gorman,[1,2,3] Jayne E. Fitch,[1] and Tasman P. Crowe[1]



Moving along the axes



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ARTICLES

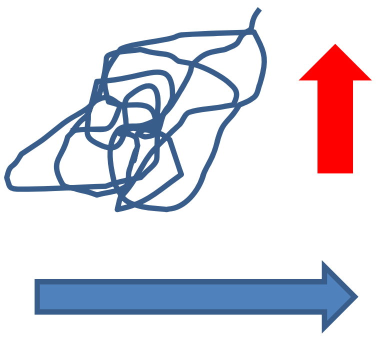
PUBLISHED ONLINE: 8 APRIL 2012 | DOI: 10.1038/NGEO1441

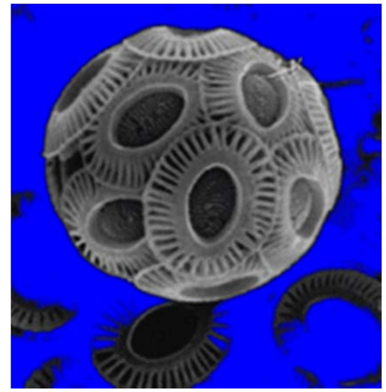
nature geoscience

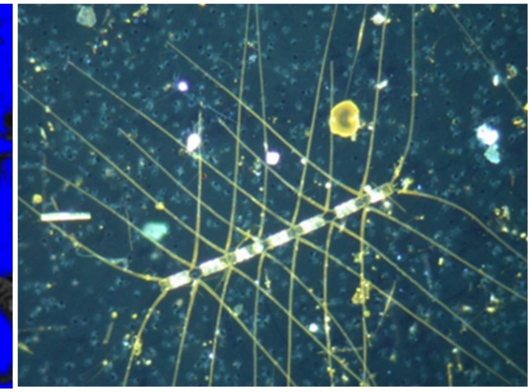
Adaptive evolution of a key phytoplankton species to ocean acidification

Kai T. Lohbeck[1,2], Ulf Riebesell[2] and Thorsten B. H. Reusch[1*]

Another approach to long Time-series datasets







10 km decade^{-1}

~40 km decade^{-1}

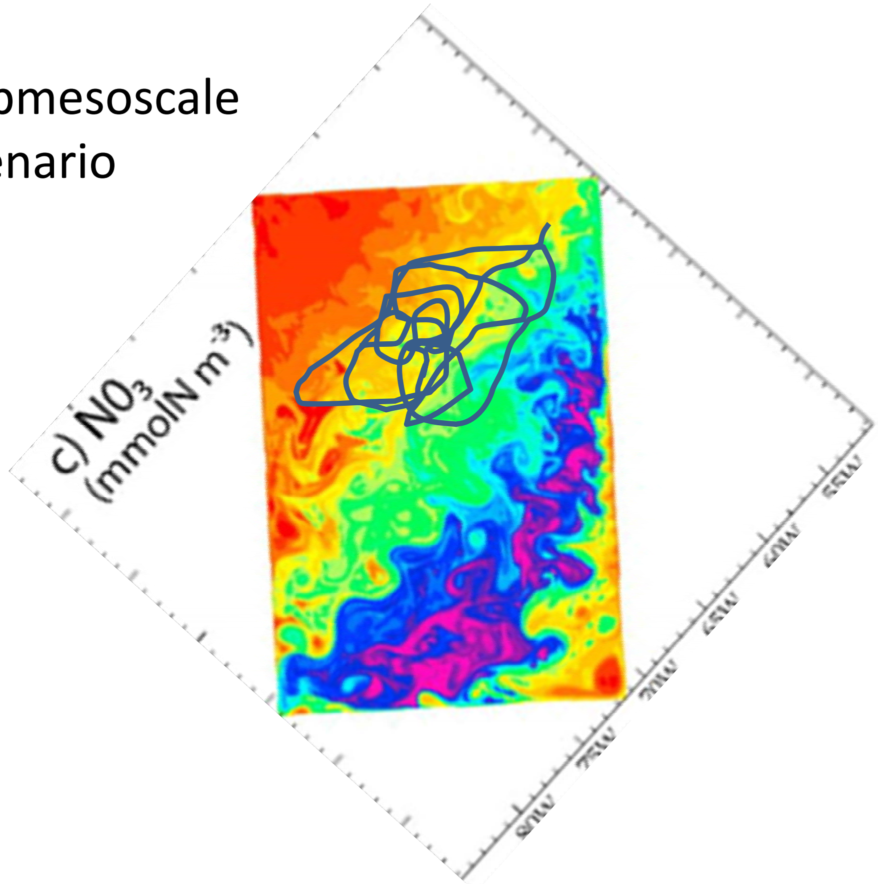
Climate velocities (Barton et al., 2016)

Assuming 150 day growth season at 0.5 d^{-1} growth rate
750 generations of a phytoplankter over this period

Overwintering? Scope for physiological change over 750 generations?

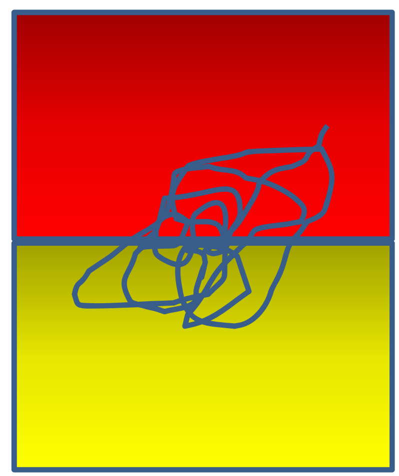
What conditions will the phytoplankton encounter over this period?

Submesoscale scenario



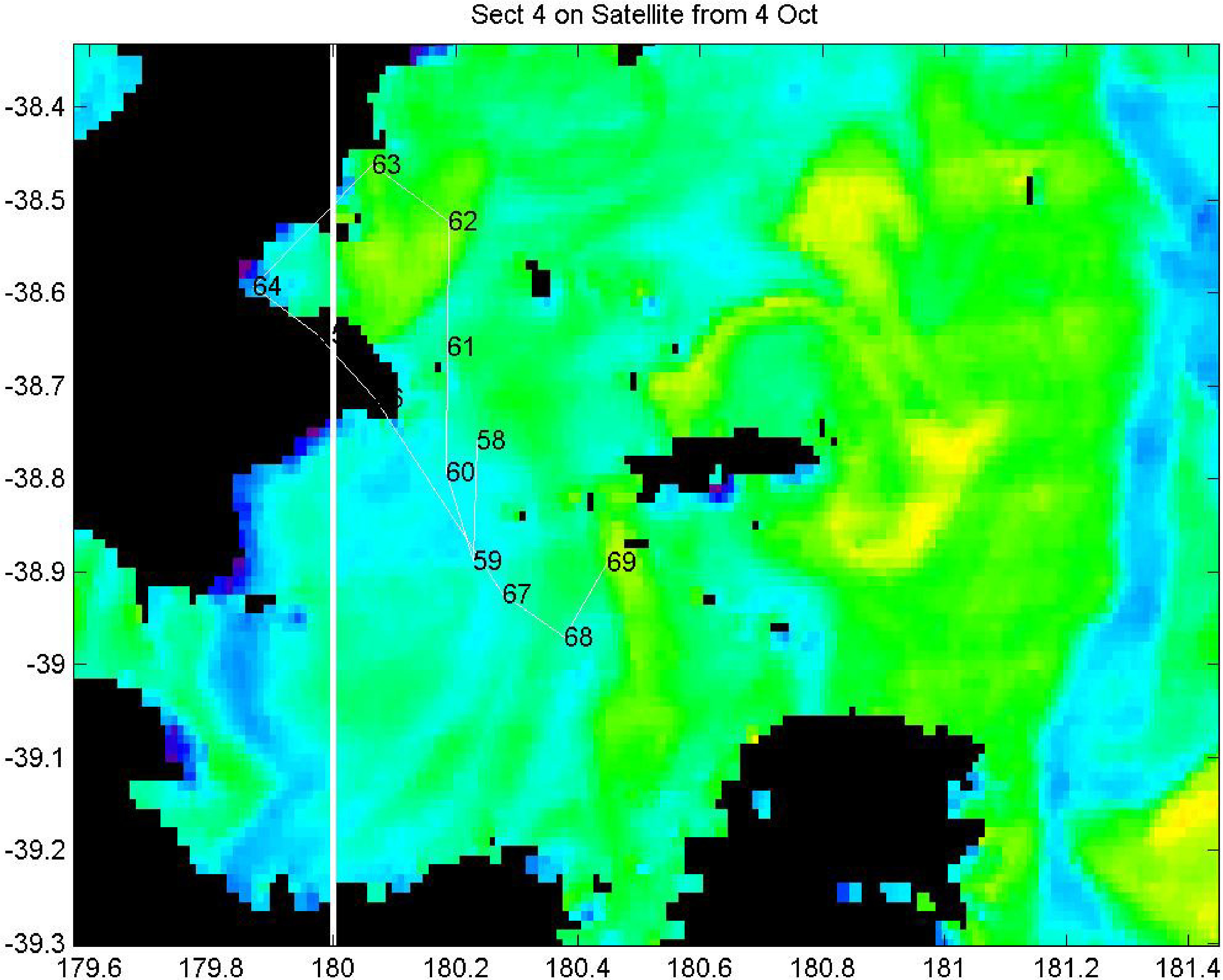
Levy et al. (2012)

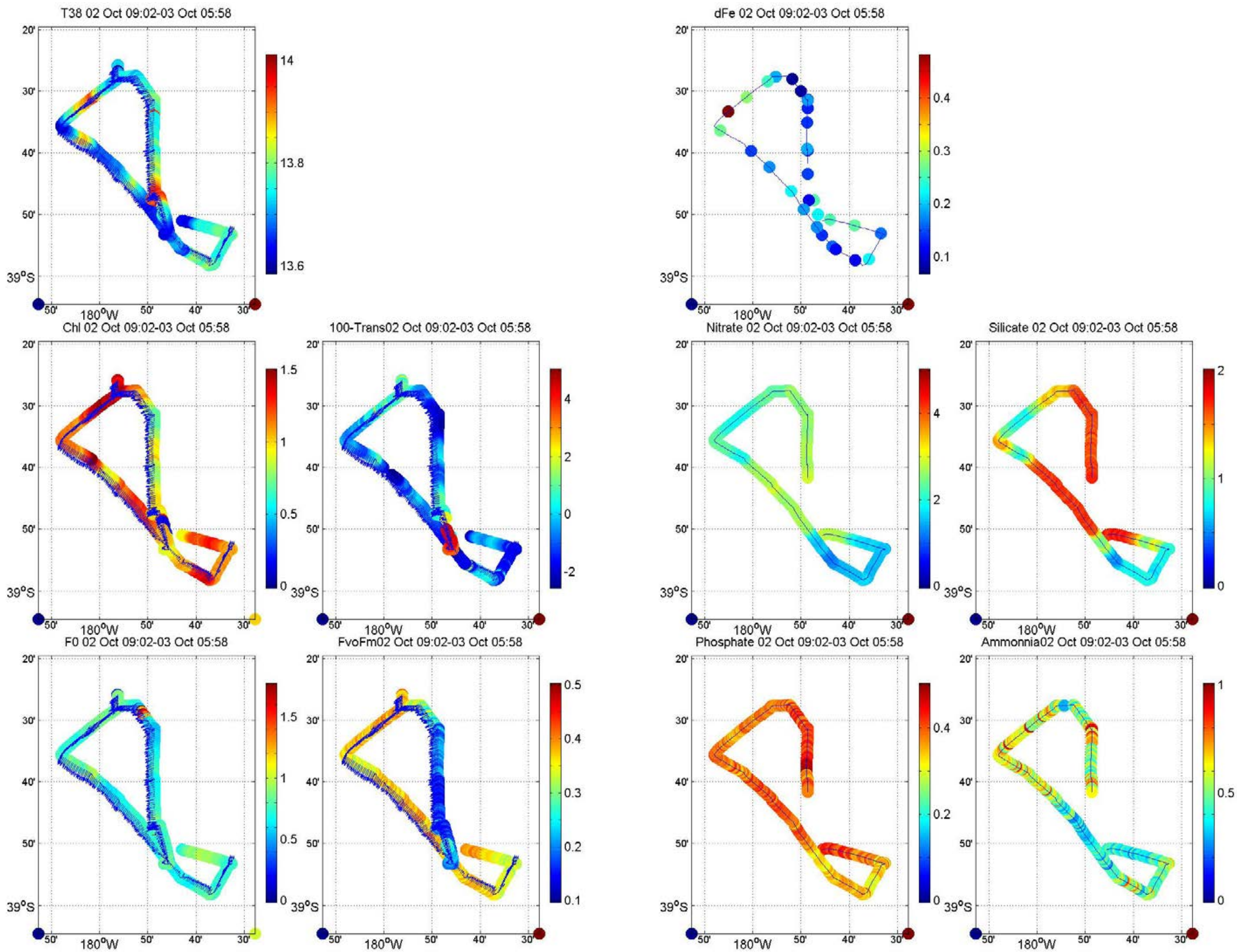
Simpler scenario

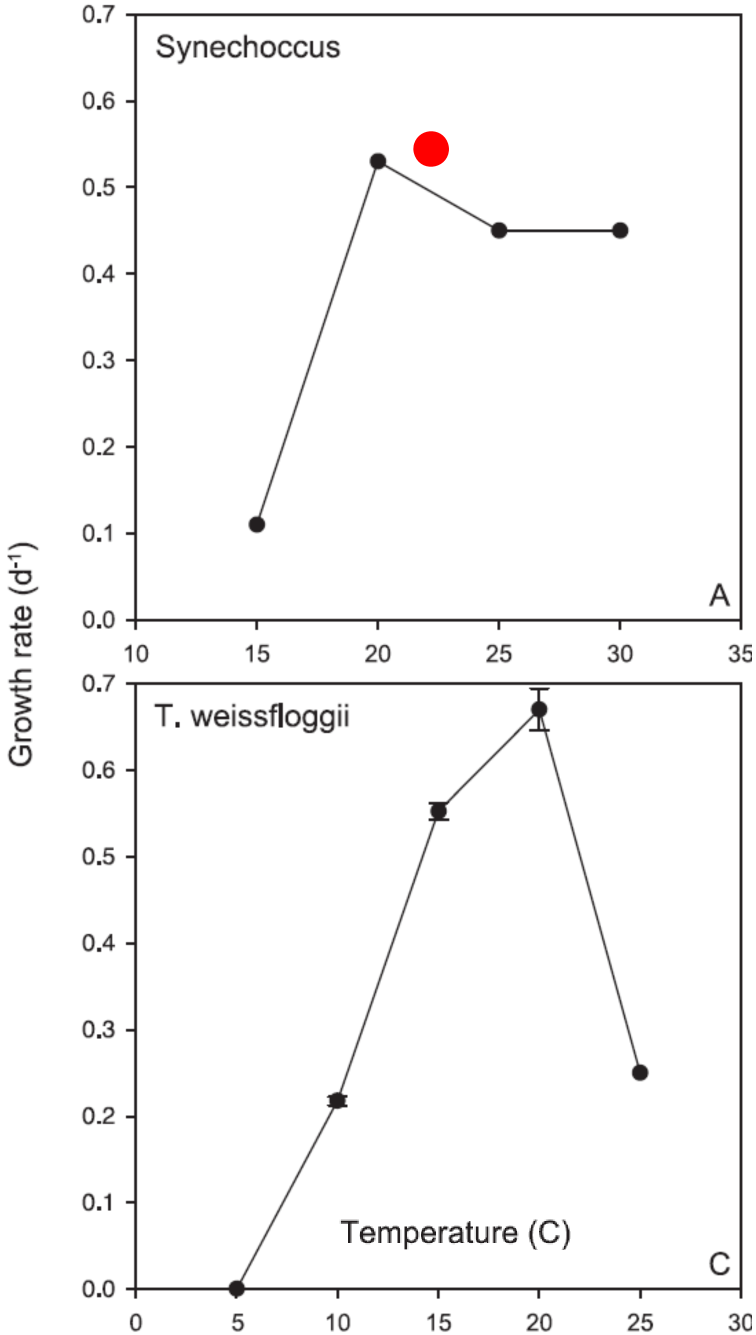


Abrupt gradient scenario

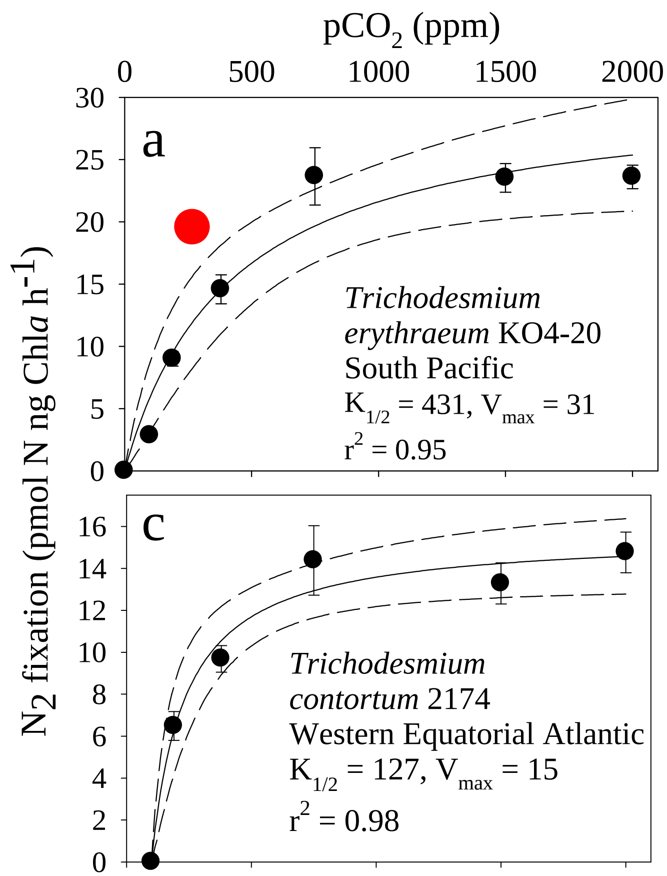
FeCycle III GEOTRACES process study (Boyd unpublished)




T38 02 Oct 09:02-03 Oct 05:58
dFe 02 Oct 09:02-03 Oct 05:58
Chl 02 Oct 09:02-03 Oct 05:58
100-Trans02 Oct 09:02-03 Oct 05:58
Nitrate 02 Oct 09:02-03 Oct 05:58
Silicate 02 Oct 09:02-03 Oct 05:58
F0 02 Oct 09:02-03 Oct 05:58
FvoFm02 Oct 09:02-03 Oct 05:58
Phosphate 02 Oct 09:02-03 Oct 05:58
Ammonia02 Oct 09:02-03 Oct 05:58
20'
30'
40'
50'
39°S
50'
180°W
50'
40'
30'

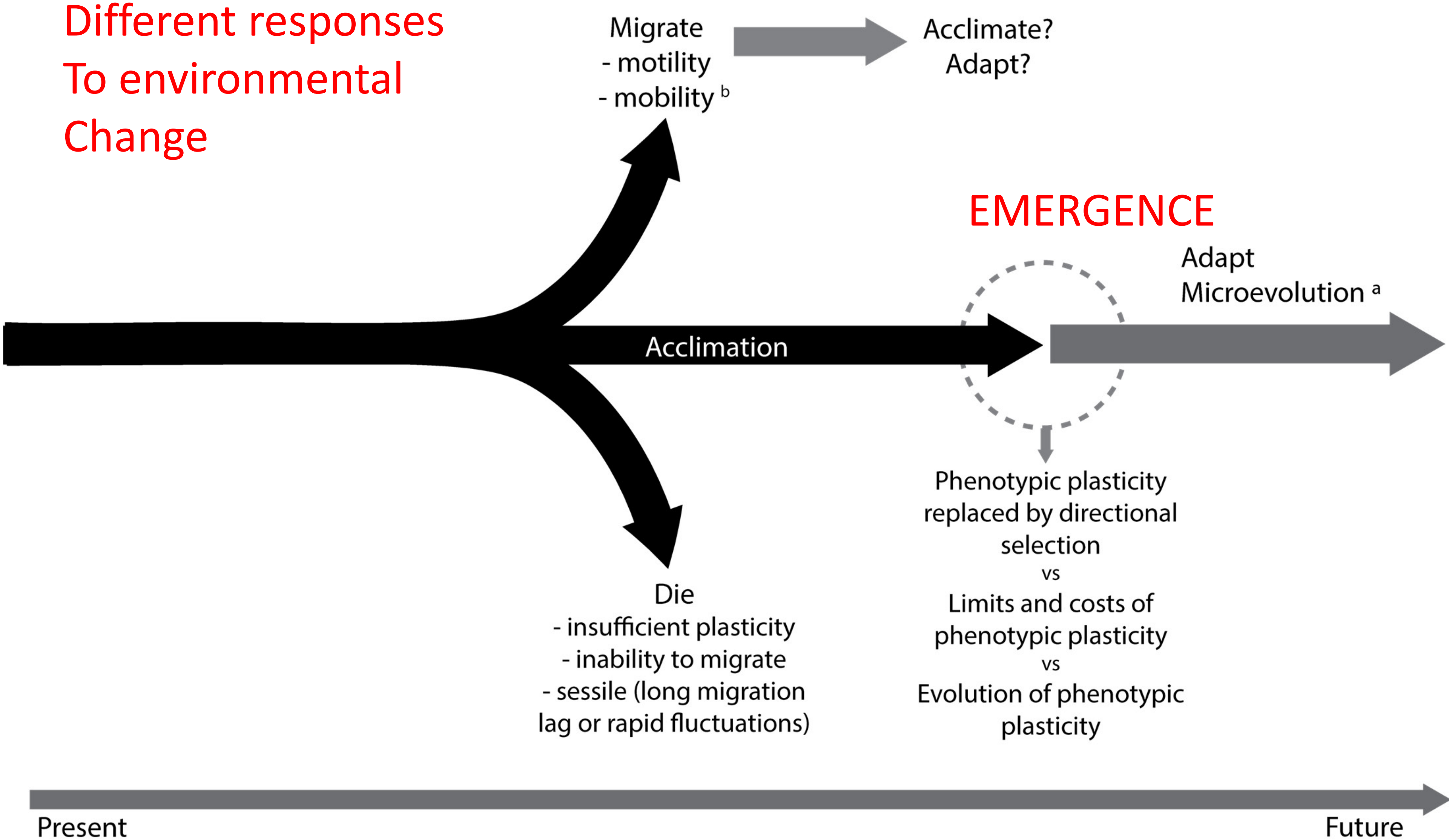


Boyd et al. (2013)



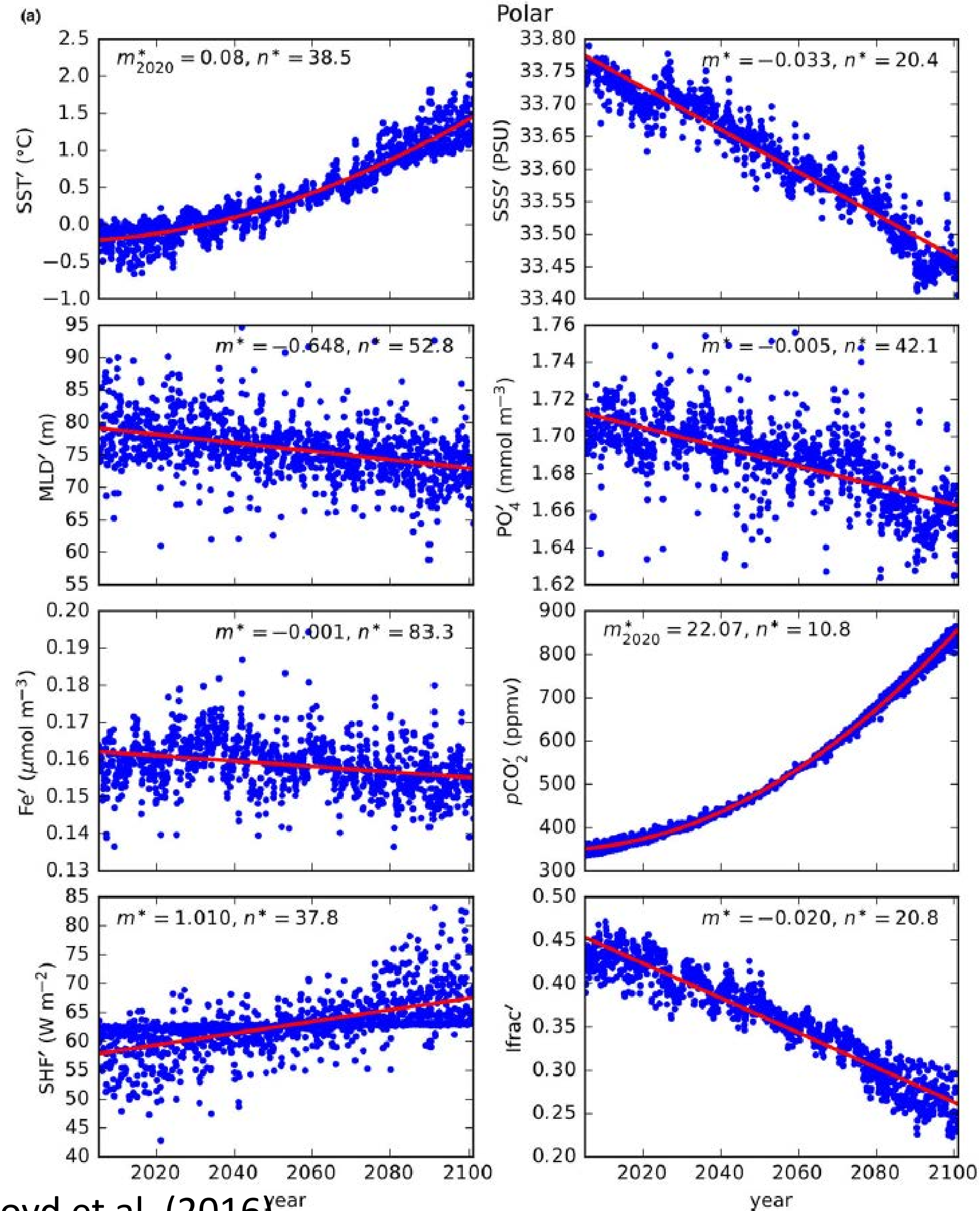
Hutchins et al. (2013)

Different responses To environmental Change



Closely linked with the Emergence

Boyd et al. (2016, GCBiology)



Boyd et al. (2016)

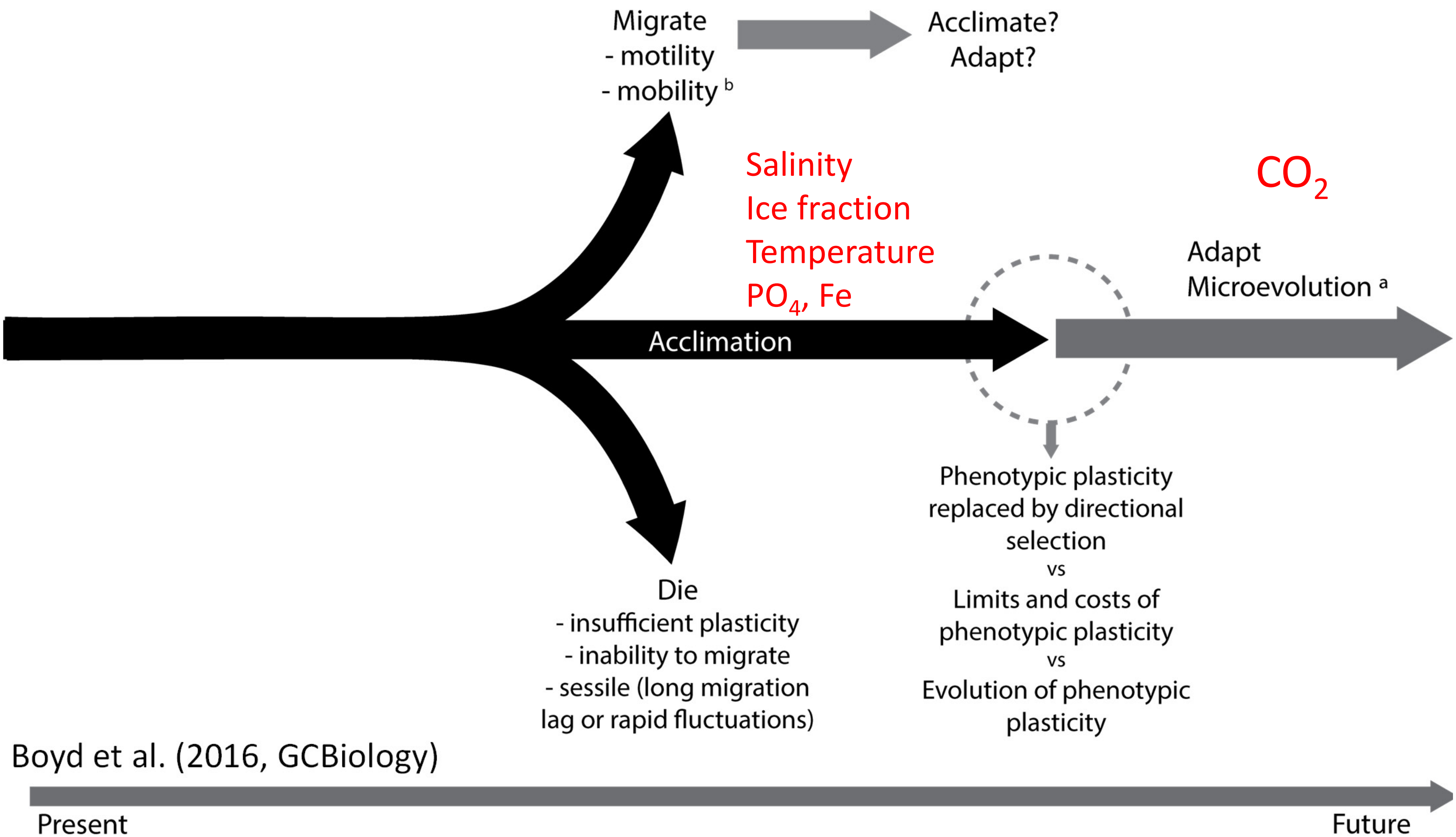
CESM1 RCP 8.5 run
Monthly anomalies from the mean annual cycle

Polar S. Ocean

CO_2 11 years
Salinity 20 years
Ice fraction 21 years
Temperature 37 years
u/w irradiance 38 years
Phosphate 42 years
ML depth 53 years
Iron 83.3 years

Increased variability in Properties by 2100

Environmental response strategies in 15 years in the Southern Ocean



Boyd et al. (2016, GCBiology)

Global Change Biology

Global Change Biology (2016), doi: 10.1111/gcb.13287

RESEARCH REVIEW

Biological responses to environmental heterogeneity under future ocean conditions

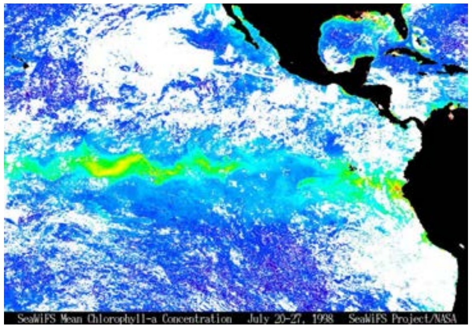
PHILIP W. BOYD[1,2], CHRISTOPHER E. CORNWALL[1,*], ANDREW DAVISON[3], SCOTT C. DONEY[4], MARION FOURQUEZ[1,2], CATRIONA L. HURD[1], IVAN D. LIMA[4] and ANDREW MCMINN[1,2]

We conclude that the strategies used by biota to respond to shifts in environmental heterogeneity may be complex.

They will have to physiologically straddle wide-ranging timescales in the alteration of ocean conditions.

For example, the need to adapt to rapidly rising CO_2 and also acclimate to environmental heterogeneity in more slowly changing properties such as warming.

Conclusions



- Regime shifts may be driven by a combination of climate variability and change
- Recent time-series studies have reported marked floristic shifts
- Powerful statistical approaches have been employed
- Candidate mechanisms range from adaptation to 'shift and shuffle'
- To further explore the validity of these candidate mechanisms each should be recast in terms of environmental variability and its influence on phytoplankton responses (acclimation/adaptation)
- In a changing climate the variance (including more regime shifts?) may be just as influential as the mean for marine life

Gordon Research Conferences

frontiers of science

Announcing the 2016 Gordon Research Conference on:

Ocean Global Change Biology

July 17-22, 2016
Waterville Valley Resort Waterville Valley, NH
USA
Chair: **Philip Boyd**
Vice Chair: **Gretchen E. Hofmann**

There is a growing awareness within the oceanographic and global environmental change communities that the various effects of a changing climate on oceanic properties will be both multi-faceted, and occur simultaneously. Furthermore, there is a growing body of evidence that our ability to predict the biological responses to these dramatic alterations of the oceanic environment is contingent on understanding the interactive effects between distinct ocean properties. In the last decade our research community has primarily focused on the biological effects of changes to individual ocean properties, such as pH (ocean acidification) or temperature (sea surface warming). This GRC brings these distinct but related research threads together by adopting a holistic approach to two pressing research questions - "How will ocean biota respond to fundamental and concurrent alterations of their environment?", and "How will their cumulative responses affect ocean productivity, biodiversity, and biogeochemistry?". The aim of this Gordon Research Conference is to bring together disparate research communities, from experimentalists to modelers, who are all tackling aspects of biological responses to ocean global change. This GRC brings together these diverse research communities who are addressing this common question, in order to devise a range of approaches to tackle this issue systematically.

Apply now at: **http://www.grc.org/programs.aspx?id=15856**

Talk
Slide title
Gtc thanx
Preamble. Time shorter than usual but more haste less speed
We are beyond OA
Multiple stressors b and h
R and g cube
3 papers nature get us up individual axes
Need all the help we can get
What happens in teal ocean
Holy grail too slow
Cv and or rs
Growth industry of late
And for many years b and d
High profile and high profile scalp
Angels and fools
Ipcc. Edwards calib uncertainty Lang
Expels of calib uncertain langiGe
Smart of phyto trends
Too short Henson and calcofi
Expt evil folks are I'm A Parnell universe
Shluter Hutchins Collins
Grc and OCB bring these together
Grc. Variance
Exports confounding model outputs temp example
Recent review on Ezh double stfs
So se examples. Climate vel Barton. Cell divisions what does cell encounter Landry trajectory
Overlld with 3 scenarios
Cv. Cc rs. Gmish
Pp versus directional selection. Andrew and zoe
Cc experiments overlay with cv
Respite curve !???? Add thermal reaction norm with Dot

We know with se confidence how mean will chamfered. Less do for cv
Pp betrays da figurehcb
Rs. Fools rush in but
Top down bottom cpntrs
Wet berg. Chaizez. Others
IniotL studies say cv wil increase
Others say rs will change
So is eh cube a busts. No rosette
Double stfs no
Fit other fprms of variance on as a stressor
Need yo better dissect out metrics
Clusters of MS 2010 somewhere?
Table GBC. Epileptic fits
End
Grc. Unifying approach

Since ~1850 CE, however, sea surface temperatures have increased, accompanied by a likely decrease in the tradewinds concomitant with gyre expansion, as a result of Northern Hemisphere warming. The resulting increase in stratification and decrease in nutrient availability may have selected for a N2-fixing cyanobacterial community, as observed in the instrumental record over

We find that individual species and entire communities move in space, or shift, and that communities internally reassemble, or shuffle.

Global Change Biology

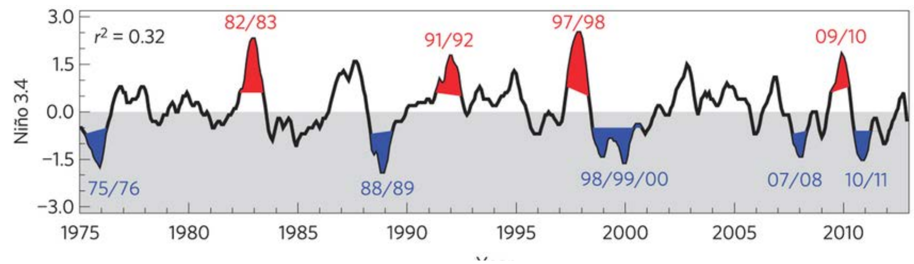
Global Change Biology (2016) **22**, 2069–2080, doi: 10.1111/gcb.13229

Climate change-related regime shifts have altered spatial synchrony of plankton dynamics in the North Sea

EMMA J. DEFRIEZ[1], LAWRENCE W. SHEPPARD[2], PHILIP C. REID[3,4,5] and DANIEL C. REUMAN[2,6]

Working definition: a regime shift is a relatively abrupt change between contrasting persistent states in an ecosystem

Biological responses to environmental fluctuations



- Taxa from environments characterised by greater heterogeneity may have greater phenotypic plasticity. Schaum *et al.* (2013)

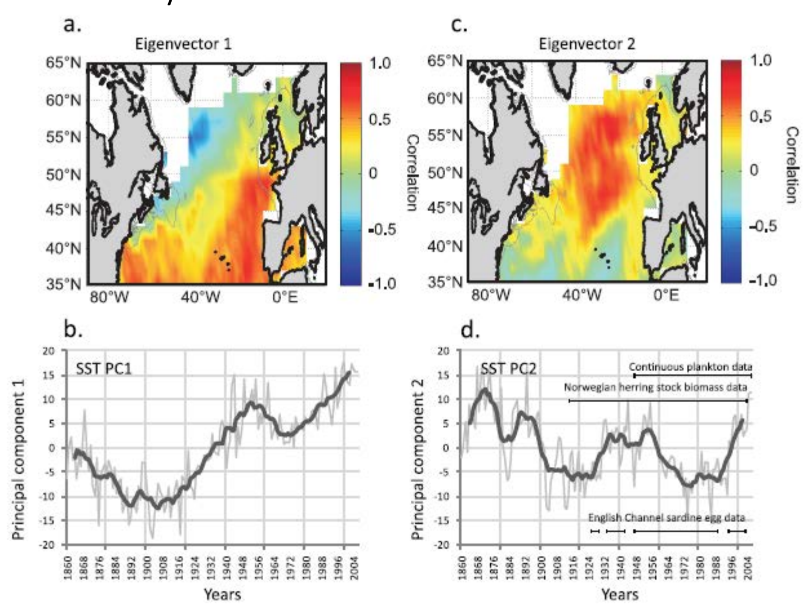
- Climate-change models report that environmental heterogeneity will increase in future decades (IPCC, 2014)

- Climate-change biological manipulation studies that include environmental fluctuations reveal different responses compared to climate change treatments (Cornwall et al. 2013)

Marine Ecosystem Response to the Atlantic Multidecadal Oscillation

Martin Edwards[1,2*], Gregory Beaugrand[3], Pierre Helaouët[1], Jürgen Alheit[4], Stephen Coombs[5]

Against the backdrop of warming of the Northern Hemisphere it has recently been acknowledged that North Atlantic temperature changes undergo considerable variability over multidecadal periods. The leading component of natural lowfrequency temperature variability has been termed the Atlantic Multidecadal Oscillation (AMO). Presently, correlative studies on the biological impact of the AMO on marine ecosystems over the duration of a whole AMO cycle (,60 years) is largely unknown due to the rarity of continuously sustained biological observations at the same time period. To test whether there is multidecadal cyclic behaviour in biological time-series in the North Atlantic we used one of the world's longest continuously sustained marine biological time-series in oceanic waters, long-term fisheries data and historical records over the last century and beyond. Our findings suggest that the AMO is far from a trivial presence against the backdrop of continued temperature warming in the North Atlantic and accounts for the second most important macro-trend in North Atlantic plankton records; responsible for habitat switching (abrupt ecosystem/regime shifts) over multidecadal scales and influences the fortunes of various fisheries over many centuries.



Climate-related phytoplankton habitat shifts. Colored scanning electron micrograph of the calcium carbonate shells of coccolithophores. Each plate is about ~2.5 μm wide. Ranges and abundances of this and other phytoplankton groups shift with changing ocean conditions.

ECOLOGY

Adrift in an ocean of change

Rising temperatures and ocean acidification drive changes in phytoplankton communities

By **Meike Vogt**

evidence is accumulating that phytoplank-

In the realm of phytoplankton, the Who Who is of critical importance to ecosys tem function. Different phytoplankto groups have evolved various physiologica strategies that allow them to thrive in ma rine environments ranging from freezin nutrient-rich polar waters to warm, nutr ent-poor subtropical ocean deserts. Thei extensive functional diversity allows ther to differentially influence global biogec

Our observations are consistent with the hypothesis that phytoplankton communities adapted to the changes in temperature and irradiance observed over a decade. This hypothesis should be tested with genomic and transcriptomic profiling of species from time-series studies

PNAS

Southern Ocean phytoplankton turnover in response to stepwise Antarctic cooling over the past 15 million years

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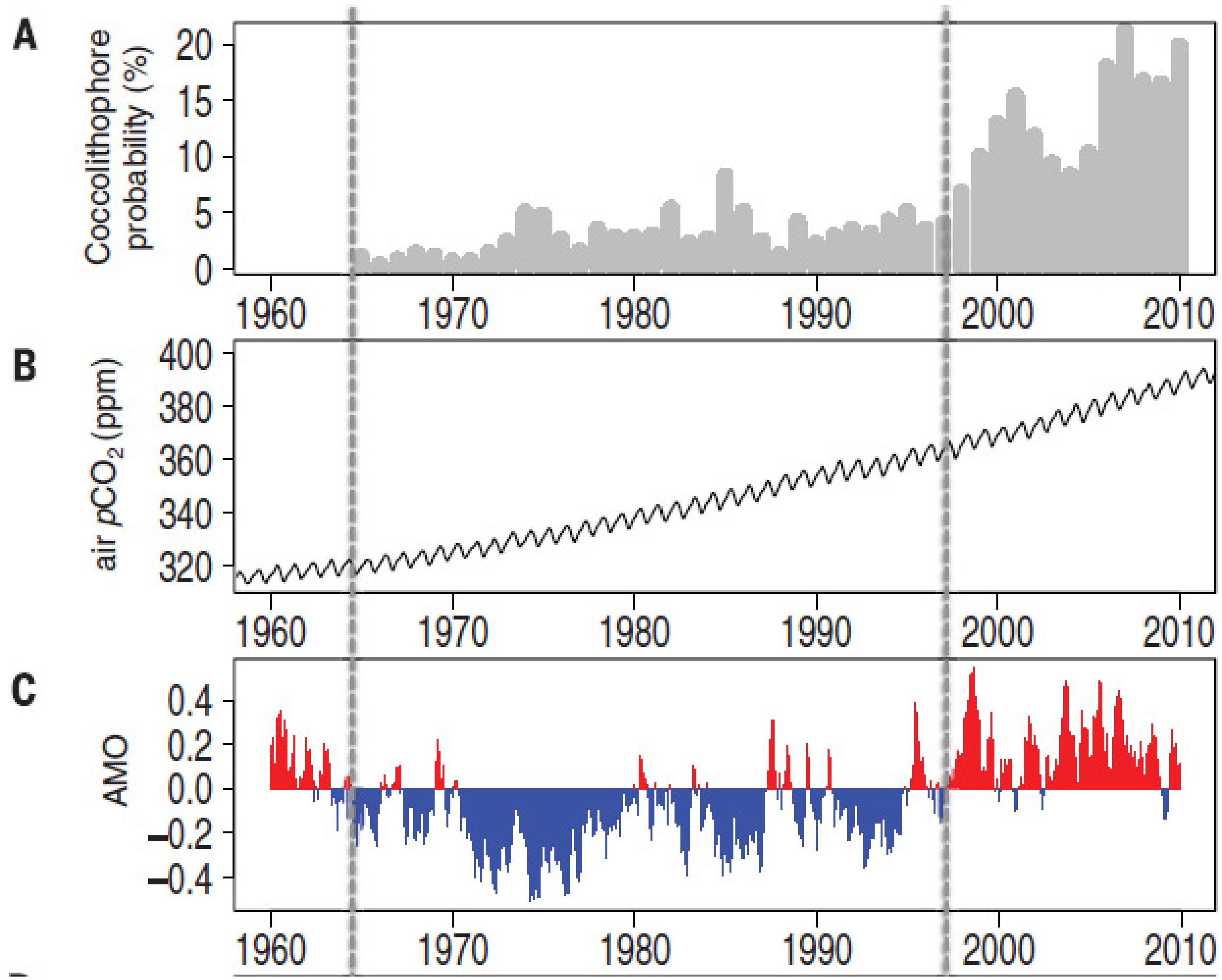
A
Coccolithophore probability (%)
20
15
10
5
0
1960
1970
1980
1990
2000
2010
B
air pCO_2 (ppm)
400
380
360
340
320
1960
1970
1980
1990
2000
2010
C
AMO
0.4
0.2
0.0
−0.2
−0.4
1960
1970
1980
1990
2000
2010

PNAS

Drift in ocean currents impacts intergenerational microbial exposure to temperature

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Edited by David M. Karl, University of Hawaii, Honolulu, HI, and approved March 28, 2016 (received for review October 29, 2015)

Here we show that upper-ocean microbes experience along-trajectory temperature variability up to 10 °C greater than seasonal fluctuations estimated in a static frame, and that this variability depends strongly on location. These findings demonstrate that drift in ocean currents can increase the thermal exposure of microbes and suggests that microbial populations with broad thermal tolerance will survive transport to distant regions of the ocean and invade new habitats.

Our findings also suggest that advection has the capacity to influence microbial community assemblies, such that regions with strong currents and large thermal fluctuations select for communities with greatest plasticity and evolvability, and communities with narrow thermal performance are found where ocean currents are weak or along-trajectory temperature variation is low.

Given that fluctuating environments select for individual plasticity in microbial lineages, and that physiological plasticity of ancestors can predict the magnitude of evolutionary responses of subsequent generations to environmental change [Schaum CE, Collins S (2014) Proc Biol Soc 281(1793):20141486], our findings suggest that microbial populations in the sub-Antarctic (∼40°S), North Pacific, and North Atlantic will have the most capacity to adapt to contemporary ocean warming.

Citation:Lindegren, M, Checkley DM, Ohman MD, Koslow JA, Goericke R. 2016. Resilience and stability of a pelagic marine ecosystem. Proceedings of the Royal Society B-Biological Sciences. 283

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Abstract:

The accelerating loss of biodiversity and ecosystem services worldwide has accentuated a long-standing debate on the role of diversity in stabilizing ecological communities and has given rise to a field of research on biodiversity and ecosystem functioning (BEF). Although broad consensus has been reached regarding the positive BEF relationship, a number of important challenges remain unanswered. These primarily concern the underlying mechanisms by which diversity increases resilience and community stability, particularly the relative importance of statistical averaging and functional complementarity. Our understanding of these mechanisms relies heavily on theoretical and experimental studies, yet the degree to which theory adequately explains the dynamics and stability of natural ecosystems is largely unknown, especially in marine ecosystems. Using modelling and a unique 60-year dataset covering multiple trophic levels, we show that the pronounced multi-decadal variability of the Southern California Current System (SCCS) does not represent fundamental changes in ecosystem functioning, but a linear response to key environmental drivers channelled through bottom-up and physical control. Furthermore, we show strong temporal asynchrony between key species or functional groups within multiple trophic levels caused by opposite responses to these drivers. We argue that functional complementarity is the primary mechanism reducing community variability and promoting resilience and stability in the SCCS.

Biological regime shifts and changes in predictability

Joachim W. Dippner,

Karin Junker,

Ingrid Kröncke

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DOI: 10.1029/2010GL045696View/save citation
Cited by: 9 articlesRefreshcitation countCiting literature

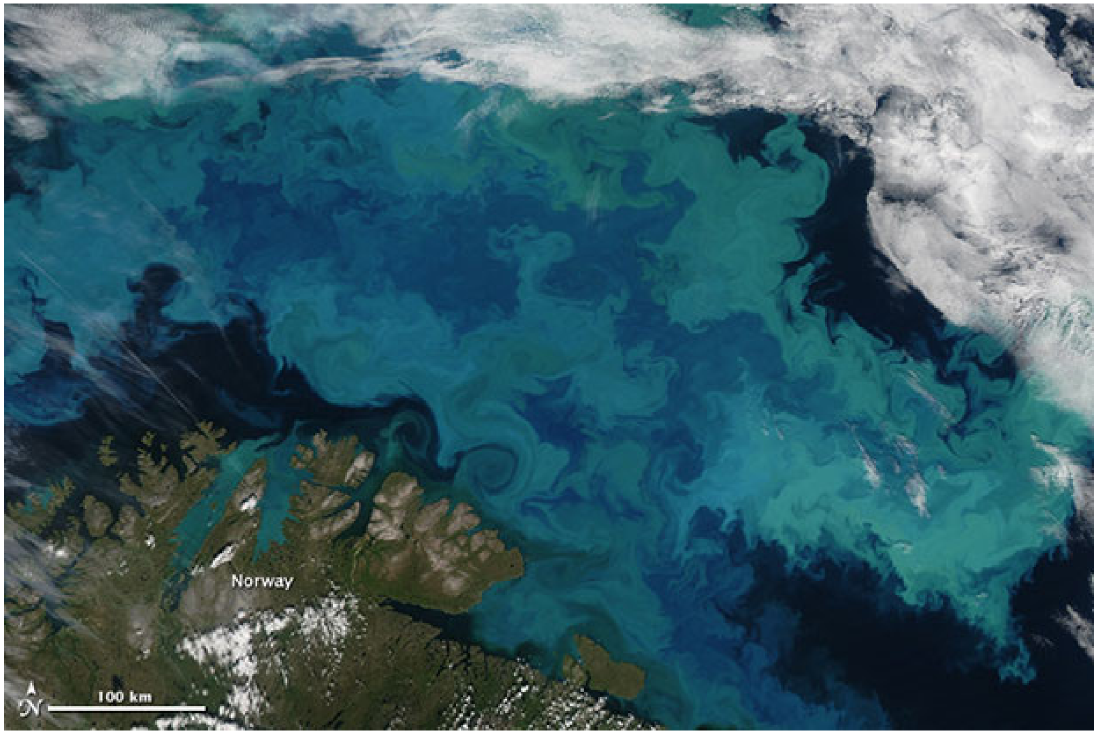
Abstract

[1] Time series of climate indices and of biomass, abundance, and species number of benthic macrofauna in the southern North Sea are related to each other to investigate the predictability of biological time series in presence of biological regime shifts in 1989/1990 and 2001/2002. The results indicate that a smooth biological regime shift occurred in 1989/1990 caused by positive climate feedback mechanisms. In this case, the benthic community structure remained predictable. In contrast, in 2001/2002 an abrupt biological regime shift caused by a climate regime shift occurred. Here became the biological time series inherently unpredictable.

Ocean time-series observations also point to environmental drivers on oceanic biota

Increases in spatial extent of coccolithophores in Bering & Barents Sea linked to warming and stratification (Smyth et al, 2004).

Likewise for Subantarctic waters (Cubillos et al. 2009)



Global Change Biology

Global Change Biology (2016), doi: 10.1111/gcb.13287

RESEARCH REVIEW

Biological responses to environmental heterogeneity under future ocean conditions

PHILIP W. BOYD[1,2], CHRISTOPHER E. CORNWALL[1,*], ANDREW DAVISON[3], SCOTT C. DONEY[4], MARION FOURQUEZ[1,2], CATRIONA L. HURD[1], IVAN D. LIMA[4] and ANDREW MCMINN[1,2]

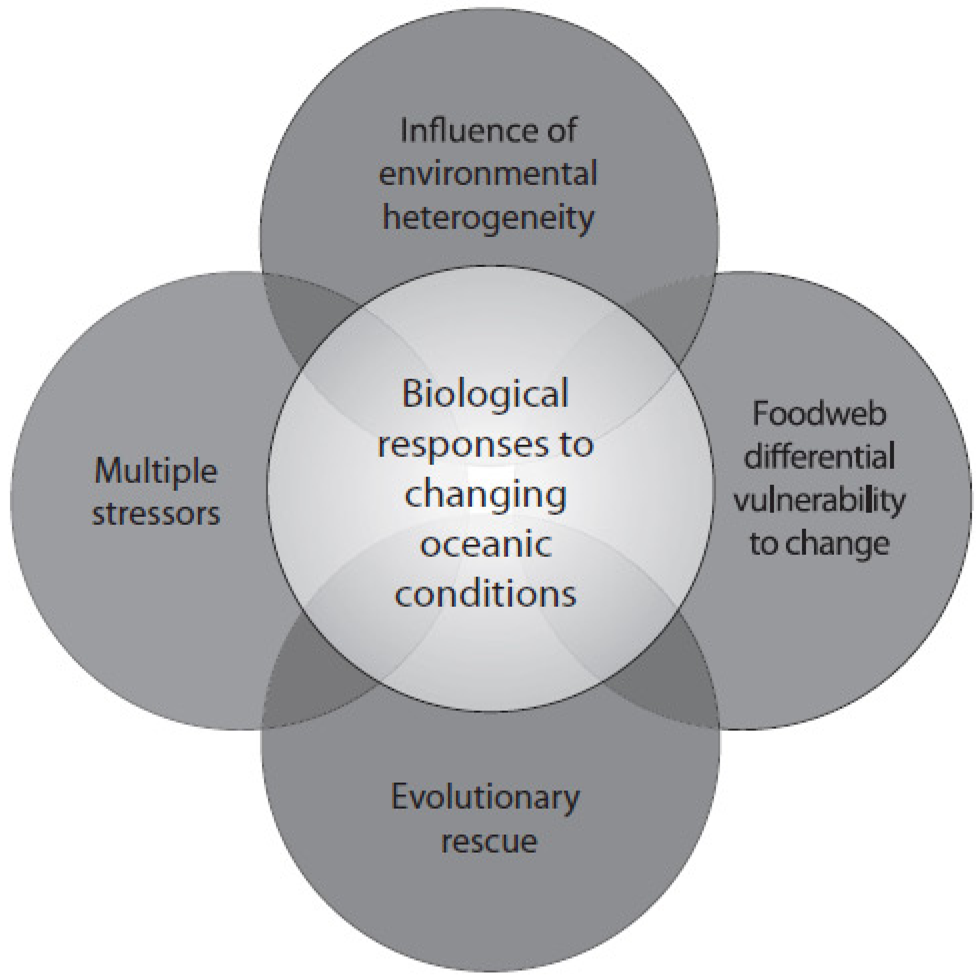

Influence of environmental heterogeneity
Multiple stressors
Biological responses to changing oceanic conditions
Foodweb differential vulnerability to change
Evolutionary rescue

Table 1 Metrics commonly used to define the components of environmental time series – such as the annual cycle of temperature at an ocean site (Karl *et al.*, 2003) that comprise its environmental heterogeneity

Metric	Analogous or inclusive terms
Average state	Mean, Median, Mode
Variability	Standard deviation, Variance
Magnitude of events	Range or amplitude, Minimum value, Maximum value
Rate of change	Abruptness, Sustained, Progressive, Step-wise
Duration of events	Prolonged, Transient
Frequency of events	Periodicity, Intermittency, Stochastic, Cyclic

Conceptual and experimental approaches

Limnol. Oceanogr., 55(3), 2010, 1353–1376
© 2010, by the American Society of Limnology and Oceanography, Inc.
doi:10.4319/lo.2010.55.3.1353

Environmental control of open-ocean phytoplankton groups: Now and in the future

Philip W. Boyd,[a,*] Robert Strzepek,[b] Feixue Fu,[c] and David A. Hutchins[c]

Reviewed conceptual approaches including Margalef's Mandala, resource ratio theory, functional traits & emergent biogeography

Compared & contrasted the projections of coupled ocean atmosphere climate models with results from experimental manipulation studies

Oceanic Regime Shifts Driven by Ocean Acidification and Climate Change

Seminar

May 18, 2016
12:15 PM
Collins Conference Room

Sante fe insttute

Brad deYoung (Memorial University)

Abstract. Oceanic regime shifts are the result of sudden, dramatic and persistent changes in the state of an ocean ecosystem. Except in some exceptional circumstances, such shifts are difficult to identify even after they have taken place. I will review some examples to identify key characteristics of regime shifts and outline a few different types of oceanic regime shifts. I will talk about how the characteristics of such shifts might change in the future, given climate change, in particular ocean acidification. Will they become more frequent or more significant? Is there any likelihood that we will be able to detect them earlier? The scale of anthropogenic ocean impacts is leading us ever deeper more directly into some form of ecosystem management. The possible management responses to an oceanic regime shift depend on the characteristics of the shift and when it is detected. Given an increase in the likelihood of regime shifts in the coming decades, as I will argue, what are the ocean environmental policies that we can or should consider to limit their frequency, scale or impact.

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There is a growing awareness within the oceanographic and global environmental change communities that the various effects of a changing climate on oceanic properties will be both multi-faceted, and occur simultaneously. Furthermore, there is a growing body of evidence that our ability to predict the biological responses to these dramatic alterations of the oceanic environment is contingent on understanding the interactive effects between distinct ocean properties. In the last decade our research community has primarily focused on the biological effects of changes to individual ocean properties, such as pH (ocean acidification) or temperature (sea surface warming). This GRC brings these distinct but related research threads together by adopting a holistic approach to two pressing research questions - "How will ocean biota respond to fundamental and concurrent alterations of their environment?", and "How will their cumulative responses affect ocean productivity, biodiversity, and biogeochemistry?". The aim of this Gordon Research Conference is to bring together disparate research communities, from experimentalists to modelers, who are all tackling aspects of biological responses to ocean global change. This GRC brings together these diverse research communities who are addressing this common question, in order to devise a range of approaches to tackle this issue systematically.

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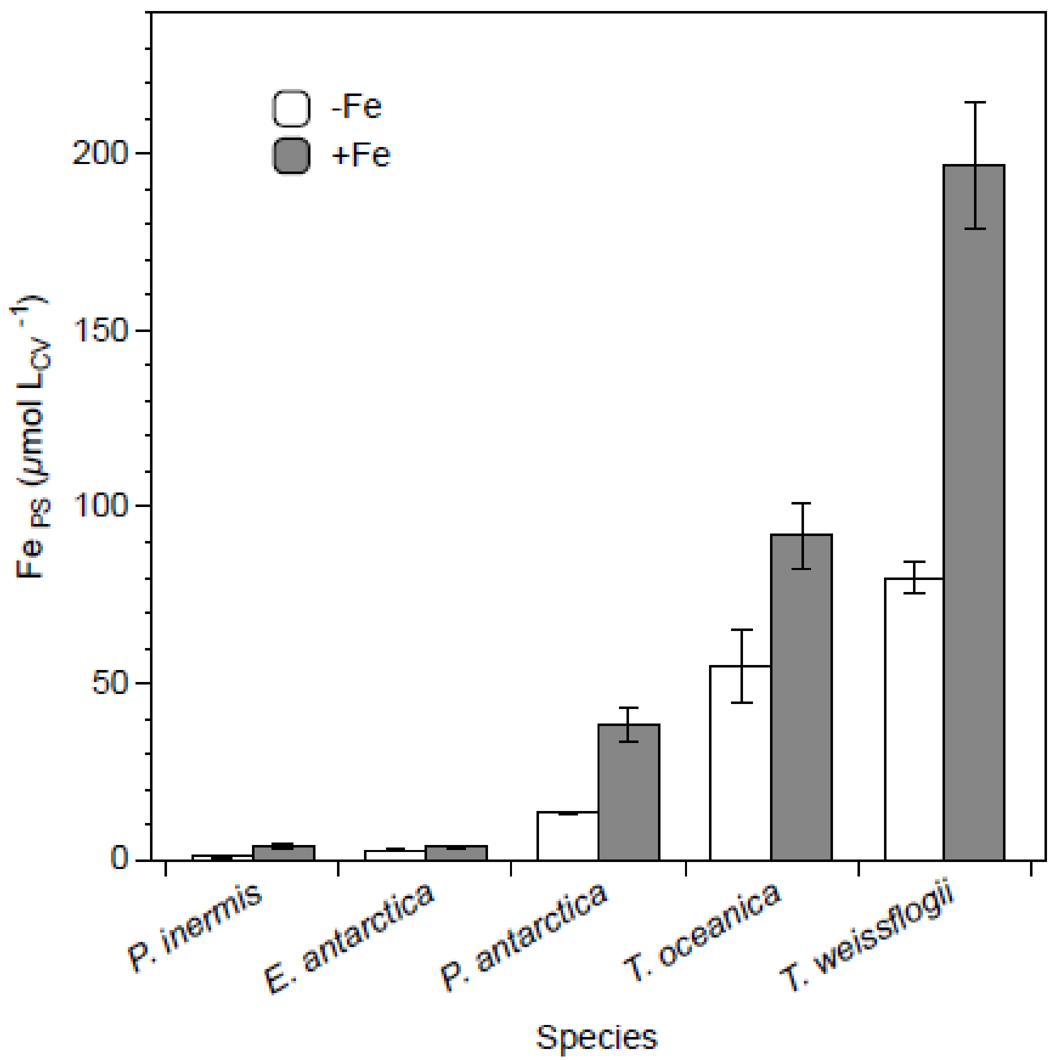
There are pronounced regional differences in phytoplankton physiology



Strzepek & Boyd (submitted)