Phytoplankton regime shifts and climate change

Philip Boyd

OCB July 2016
Anthropogenic climate change drives shift and shuffle in North Atlantic phytoplankton communities

Andrew D. Barton\textsuperscript{a,1}, Andrew J. Irwin\textsuperscript{b}, Zoe V. Finkel\textsuperscript{c}, and Charles A. Stock\textsuperscript{a}

MARINE CALCIFERS

Multidecadal increase in North Atlantic coccolithophores and the potential role of rising CO\textsubscript{2}

Sara Rivero-Calio,\textsuperscript{1,2} Anand Gnanadesikan,\textsuperscript{1} Carlos E. Del Castillo,\textsuperscript{1,3} William M. Baleh,\textsuperscript{4} Seth D. Guikema\textsuperscript{a}

PHYTOPLANKTON

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

Kelton W. McMahon,\textsuperscript{1,2} Matthew D. McCarthy,\textsuperscript{1} Owen A. Sherwood,\textsuperscript{3} Thomas Larsen,\textsuperscript{4} Thomas P. Guilderson\textsuperscript{1,2,5}

Phytoplankton adapt to changing ocean environments

Andrew J. Irwin\textsuperscript{a,1}, Zoe V. Finkel\textsuperscript{b}, Frank E. Müller-Karger\textsuperscript{c}, and Luis Troccoli Ghinaglia\textsuperscript{d}
Regime shifts – an abrupt change between contrasting **persistent** states in an ecosystem

<table>
<thead>
<tr>
<th>Biota</th>
<th>Region</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phytoplankton</td>
<td>NE subarctic Pacific</td>
<td>Whitney et al. (1998)</td>
</tr>
<tr>
<td>Phytoplankton – pico to large diatoms</td>
<td>Equatorial Pacific</td>
<td>Chavez et al. (1999)</td>
</tr>
<tr>
<td>Small to large phytoplankton³</td>
<td>NE subarctic Pacific</td>
<td>Parslow (1981)</td>
</tr>
<tr>
<td>Coccolithophores</td>
<td>Bering Sea</td>
<td>Napp and Hunt Jr. (2001)</td>
</tr>
<tr>
<td>Phytoplankton</td>
<td>NE Atlantic and North Sea</td>
<td>Reid et al. (1998)</td>
</tr>
<tr>
<td>Euphausids</td>
<td>Bering Sea</td>
<td>Napp and Hunt Jr. (2001)</td>
</tr>
<tr>
<td>Zooplankton and salmon</td>
<td>NE subarctic Pacific</td>
<td>Beamish et al. (1999)</td>
</tr>
<tr>
<td>Krill and Salps</td>
<td>Polar Southern Ocean</td>
<td>Loeb et al. (1997)</td>
</tr>
<tr>
<td>Krill and Salps</td>
<td>Southern Ocean – East Antarctica</td>
<td>Nicol et al. (2000)</td>
</tr>
<tr>
<td>Penguin stocks</td>
<td>MIZ – Antarctic Peninsula</td>
<td>Smith et al. (1999)</td>
</tr>
<tr>
<td>Cod stocks</td>
<td>North Sea</td>
<td>O’Brien et al. (2000)</td>
</tr>
<tr>
<td>Elevated export to depth</td>
<td>NE subarctic Pacific</td>
<td>Boyd et al. (1998)</td>
</tr>
<tr>
<td>Fulmar populations</td>
<td>N Atlantic</td>
<td>Thompson and Ollason (2001)</td>
</tr>
</tbody>
</table>


---

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

**Emmanuel Defriez**, **Lawrence W. Sheppard**, **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

Pörtner et al. (2015) IPCC WG2
However the clusters of environmental change do not match that for climate change.

Chavez et al. (1999)

<table>
<thead>
<tr>
<th>Seasonal progression</th>
<th>La Niña</th>
<th>Climate Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temp</td>
<td>↑</td>
<td>↑</td>
</tr>
<tr>
<td>Fe</td>
<td>↓</td>
<td>↑</td>
</tr>
<tr>
<td>Nuts</td>
<td>↓</td>
<td>↑</td>
</tr>
<tr>
<td>MLD</td>
<td>↑</td>
<td>↑</td>
</tr>
<tr>
<td>CO2</td>
<td>↓</td>
<td>↑</td>
</tr>
<tr>
<td>PAR</td>
<td>↑</td>
<td>NC</td>
</tr>
</tbody>
</table>

Boyd et al. (2010)
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 &

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

Andrew D. Barton\textsuperscript{a,1}, Andrew J. Irwin\textsuperscript{b}, Zoe V. Finkel\textsuperscript{c}, and Charles A. Stock\textsuperscript{a}

MARINE CALCIFERS

Multidecadal increase in North Atlantic coccolithophores and the potential role of rising CO\textsubscript{2}

Sara Rivero-Callo,\textsuperscript{1,2} Anand Gnanadesikan,\textsuperscript{1} Carlos E. Del Castillo,\textsuperscript{1,3} William M. Balleh,\textsuperscript{4} Seth D. Guikema\textsuperscript{3}

PHYTOPLANKTON

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

Kelton W. McMahon,\textsuperscript{1,2} Matthew D. McCarthy,\textsuperscript{1} Owen A. Sherwood,\textsuperscript{3} Thomas Larsen,\textsuperscript{4} Thomas P. Guilderson\textsuperscript{1,2,5}

Phytoplankton adapt to changing ocean environments

Andrew J. Irwin\textsuperscript{a,1}, Zoe V. Finkel\textsuperscript{b}, Frank E. Müller-Karger\textsuperscript{c}, and Luis Troccoli Ghinaglia\textsuperscript{d}
Phytoplankton adapt to changing ocean environments

Andrew J. Irwin\textsuperscript{a,1}, Zoe V. Finkel\textsuperscript{b}, Frank E. Müller-Karger\textsuperscript{c}, and Luis Troccoli Ghinaglia\textsuperscript{d}

LETTER

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

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

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

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?

---

**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-Calles (2015) employed 3 random forest walk models to explore the relative importance of properties to predicting coccolithophore occurrence.
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

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

P. W. Boyd1,2*, P. W. Dillingham3, C. M. McGraw3,4, E. A. Armstrong5, C. E. Cornwell1,6, Y.-y. Feng6, C. L. Huret1,6, M. Ringold-Gault7, M. Y. Roleda6, E. Timmins-Schifman8 and B. L. Nunn9
Physiological responses of a Southern Ocean diatom to complex future ocean conditions

Multiple anthropogenic stressors and the structural properties of food webs
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. Cornwell\(^1,6\), Y.-y. Feng\(^6\), C. L. Hurd\(^1,6\), M. Ringold-Gault\(^7\), M. Y. Rolle\(^a\)\(^6\), E. Timmins-Schiffman\(^8\) and B. L. Nunn\(^9\)

Multiple anthropogenic stressors and the structural properties of food webs

Eoin J. O’Gorman\(^1,2\), Jayne E. Fitch\(^1\), and Tasman P. Crowe\(^1\)

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

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

Simpler scenario

Abrupt gradient scenario

Levy et al. (2012)
FeCycle III GEOTRACES process study (Boyd unpublished)

Sect 4 on Satellite from 4 Oct
Trichodesmium erythraeum KO4-20
South Pacific
$K_{1/2} = 431$, $V_{\text{max}} = 31$
$\rho^2 = 0.95$

Trichodesmium contortum 2174
Western Equatorial Atlantic
$K_{1/2} = 127$, $V_{\text{max}} = 15$
$\rho^2 = 0.98$

Boyd et al. (2013)

Hutchins et al. (2013)
Different responses To environmental Change

- Migrate
  - motility
  - mobility
- Acclimate?
- Adapt?

Acclimation

- Die
  - insufficient plasticity
  - inability to migrate
  - sessile (long migration lag or rapid fluctuations)

EMERGENCE

- Adapt
- Microevolution

- Phenotypic plasticity replaced by directional selection
  - vs
  - Limits and costs of phenotypic plasticity
  - Evolution of phenotypic plasticity

Present

Future

Closely linked with the Emergence

Boyd et al. (2016, GCBiology)
Increased variability in Properties by 2100

Boyd et al. (2016)

CESM1 RCP 8.5 run
Monthly anomalies from the mean annual cycle

Polar S. Ocean

CO₂ 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)

- Migrate - motility - mobility
- Acclimate?
- Adapt?
- Salinity
- Ice fraction
- Temperature
- $PO_4$, Fe
- Die
  - insufficient plasticity
  - inability to migrate
  - sessile (long migration lag or rapid fluctuations)
- Phenotypic plasticity replaced by directional selection
  - Limits and costs of phenotypic plasticity
  - Evolution of phenotypic plasticity

Adapt Microevolution

$CO_2$

Present

Future
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
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

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.
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)
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.
ECOLOGY

Adrift in an ocean of change
Rising temperatures and ocean acidification drive changes in phytoplankton communities

By Melike Vogt

In the realm of phytoplankton, the WHO is of critical importance to ecosystem function. Different phytoplankton groups have evolved various physiological strategies that allow them to thrive in marine environments ranging from freezing, nutrient-rich polar waters to warm, nutrient-poor subtropical ocean deserts. The extensive functional diversity allows them to differentially influence global biogeo...
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.
Southern Ocean phytoplankton turnover in response to stepwise Antarctic cooling over the past 15 million years

James S. Crampton, Rosie D. Cody, Richard Levy, David Harwood, Robert McKay, and Tim R. Naish

GNS Science, Lower Hutt 5040, New Zealand; School of Geography, Environment and Earth Sciences, Victoria University of Wellington, Wellington 6140, New Zealand; Antarctic Research Centre, Victoria University of Wellington, Wellington 6140, New Zealand; and Department of Earth and Atmospheric Sciences, University of Nebraska-Lincoln, Lincoln, NE 68588
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.
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

First published: 17 December 2010
Full publication history
DOI: 10.1029/2010GL045696
View/save citation
Cited by: 9 articles

Abstract

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)
RESEARCH REVIEW

Biological responses to environmental heterogeneity under future ocean conditions

PHILIP W. BOYD\textsuperscript{1,2}, CHRISTOPHER E. CORNWALL\textsuperscript{1,*}, ANDREW DAVISON\textsuperscript{3}, SCOTT C. DONÉY\textsuperscript{4}, MARION FOURQUEZ\textsuperscript{1,2}, CATRIONA L. HURD\textsuperscript{1}, IVAN D. LIMA\textsuperscript{4} and ANDREW MCMINN\textsuperscript{1,2}
Biological responses to changing oceanic conditions

- Influence of environmental heterogeneity
- Multiple stressors
- Food web 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

<table>
<thead>
<tr>
<th>Metric</th>
<th>Analogous or inclusive terms</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average state</td>
<td>Mean, Median, Mode</td>
</tr>
<tr>
<td>Variability</td>
<td>Standard deviation, Variance</td>
</tr>
<tr>
<td>Magnitude of events</td>
<td>Range or amplitude, Minimum value, Maximum value</td>
</tr>
<tr>
<td>Rate of change</td>
<td>Abruptness, Sustained, Progressive, Step-wise</td>
</tr>
<tr>
<td>Duration of events</td>
<td>Prolonged, Transient</td>
</tr>
<tr>
<td>Frequency of events</td>
<td>Periodicity, Intermittency, Stochastic, Cyclic</td>
</tr>
</tbody>
</table>
Conceptual and experimental approaches

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
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.
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
There are pronounced regional differences in phytoplankton physiology.

Strzepek & Boyd (submitted)