Regime Shifts in the Ocean: From Detection to Prediction?

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(and many others: M. Barange, G. Beaugrand, R. Harris, C. Moloney, I. Perry and M. Scheffer)
DEFINITION OF REGIME SHIFT

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


“Simple” example
Jamaican coral reef systems

Fig. 3. Degradation of Jamaican coral reefs over the past two decades. Small-scale changes in (A) coral cover and in (B) macroalgal cover over time at four depths near Discovery Bay (32).
Sequence of events

Removal of fish & Eutrophication

Sea urchins #'s increase

Hurricane in ‘81 (urchins recolonized)

Pathogen

Fleshy brown algae took over
“Complicated” explanation
Loss of resilience

Overfishing

Nutrient loading

Healthy state

Parasite infection

Stressed state

Sea urchin collapse

Rock
- Loss of resilience
- Irreversibility
- Triggered shifts

Can we anticipate how biological and ecological systems will respond?

(a) and (b): one equilibrium state
(c): three equilibrium states; two stable, one unstable

NATURE
For a system on the upper branch, close to the $F_2$ bifurcation point, a slight incremental change may bring it beyond the bifurcation and induce a catastrophic shift to the lower alternative stable state.

A perturbation, if sufficiently large, may also induce a shift the lower alternative stable state.

Scheffer, Carpenter, Walker, Foley and Folke 2001. NATURE
How can we demonstrate that there are alternative attractors in real ecosystems?

<table>
<thead>
<tr>
<th>Shifts in time series</th>
<th>Multimodal distributions</th>
<th>Dual relationships</th>
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<tbody>
<tr>
<td>(Spatial analogue to jumps in time series)</td>
<td>(Response to control factor best described by 2 separate fxns)</td>
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Figure 3. Three types of hints of the existence of alternative attractors from field data: (a) shift in a time series, (b) multimodal distribution of states, and (c) dual relationship to a control factor. The specific examples are (a) regime shift in the Pacific Ocean ecosystem (shaded) (modified with permission from [4]), (b) bimodal frequency distribution of free floating plants in a set of 158 Dutch ditches (modified with permission from [6]), and (c) different relationships between underwater shade and the total phosphorus concentration for shallow lakes dominated by Cyanobacteria (blue circles) and lakes dominated by other algae (open circles) (modified with permission from [62]).

Scheffer, et al. (2003) TREE.
Review of a few other oceanic examples

- **Scotian Shelf** – driven primarily by fishing, cascading trophic impacts
- **North Sea** – combined drivers: natural=biogeographic shift and human=fishing
- **North Pacific** – complex natural state change(s)
Fish community condition (1970-1982)

Scotian Shelf – Frank et al. 2005
Colour display of 60+ indices for Eastern Scotian Shelf

Grey seals, pelagic fish abundance, invertebrate landings, fish species richness, phytoplankton

Bottom temp., exploitation, groundfish biomass & landings, growth-CHP, avg. fish weight, copepods

Red – below average
Green – above average
North Sea: Long-term changes in the ecology (hydro-climate + biology)

Principal component 1 (30.08%)

Years


(G. Beaugrand)

‘cold’ episodic event

Regime shift

‘warm’ episodic event

(G. Beaugrand)
Shifts in copepod distributions in the North Atlantic:

Warm-water species have extended their distribution northward by more than 10° of latitude, while cold-water species have decreased in number and extension.

(Beaugrand et al., Science, 2002)
Second principal component (31.36%)

Gadoid species (cod)

plankton change

SST

NHT anomalies

Years (1958-1999)

Mean number of species per assemblage

Gadoid species (cod) and plankton changes in the central North Sea (1958-1999). The figure shows the relationship between Gadoid species (cod) and plankton changes across the years, with temperature anomalies (SST) and NHT anomalies also plotted. The Gadoid species and plankton changes are depicted as a function of years from 1958 to 1999.
Long-term changes in the abundance of two key species in the North Sea

C. finmarchicus

C. helgolandicus

Reid et al. (2003)
Consequences of plankton changes on higher trophic level

Mismatch between the timing of calanus prey and larval cod

Abundance of *C. finmarchicus*  

Abundance of *C. helgolandicus*

But there is also an influence from fishing – how much?
North Sea - dynamics

Meteorological/oceanographic forcing

Ocean circulation

Biogeographic shift

Fishing

Ocean conditions

Ecosystem status and function
North Pacific regime shift – Hare and Mantua (2000)

Fig. 1. Numeric and alphabetic abbreviations for the 100 time series used in this study. Geographical arrangement gives a general indication of where each variable is measured or has influence. See Table 1 for a definition of each abbreviation.
Physical forcing – air temperature - but there are dozens of other such time series
Fig. 4. Results from two regime shift analyses of a composite of the 100 environmental time series. The step passes through the mean standard deviate within each regime. The standard error of the 100 time series is illustrated for each year. After Hare and Mantua (2000).
Winter PDO

Euphausiid

Pink salmon (solid) lagged one year

Chinook (dashed) lagged 3 years

deYoung et al. (2007)
deYoung et al. (2007)
How predictable are regime shifts?

• Coral reefs (the “simplest” case)
  – We understand the causal links
  – We can’t predict disease outbreaks

• Fishing-dominated systems
  – Although fishing can be the dominant driver, its consequences are not predictable without understanding the foodweb dynamics
  – Shifts may not be easily reversible

• North Pacific
  – We have not been able to separate drivers or where different states are occurring
  – Accurate prediction not currently possible
Can we model regime shifts?

Example North Pacific model
Observations - Biological and Physical

NCEP 6 hourly data
1948-2002
(includes interannual variability)

COCO – Tokyo
3-D Nemuro

Zooplankton and temperature time series

Validation

Nemuro Pacific herring model

Time series output
Modeled the basin-scale response in physics and lower trophic levels...

... and forced the upper trophic levels...
Obtained “shifts” in weights of individual fish at various locations in the North Pacific...
Summary

- Clear evidence for regime shifts in the ocean
- More regime shifts are likely – decreased resilience
- Limited data, systemic complexity, range of different structures
- Need sustained monitoring, experimental work, models, etc.
Resolving the impact of climatic processes on ecosystems of the North Atlantic basin and shelf seas.

BASIN is an initiative to develop a joint EU/North American ocean ecosystem research program.
Biological consequences expected under climatic warming **or** changes in water mass structure.

- Changes in the range and spatial distribution of species.
- Shifts in the location of biogeographical boundaries, provinces, and biomes.
- Change in the phenology of species (e.g. earlier reproductive season).
- Modification in dominance (e.g. a key species can be replaced by another one).
- Change in diversity.
- Change in other key functional attributes for marine ecosystems.
- Change in structure and dynamics of ecosystem with possible regime shifts.

**Expected Result:** Major impact for marine exploited resources and biogeochemical processes (e.g. sequestration of CO$_2$ by the ocean).
Research Goals

• Integrate and synthesize existing basin-wide data sets from previous programs in Europe and North America,
• Improve the current state of the art in bio-physical modelling,
• Develop hindcast modelling studies to understand the observed historical variability of the North Atlantic ecosystem,
• Construct scenarios of possible ecosystem changes in response to future climate variability,
• Identify data gaps that limit process understanding and contribute to uncertainty in model results,
• Specify new data needed to assess the performance of forecasts,
• Provide relevant information to resource managers and decision makers.
What did we learn about marine food webs during the GLOBEC era?
We learnt that...

1. marine food webs are special
Food web supporting herring in the North Sea

Hardy (1924), adapted from Elton (1927)
Food web supporting herring in the North Sea

Hardy (1924), adapted from Elton (1927)
We learnt that...

1. marine food webs are special

2. population-level processes are important in food web dynamics (target-species approach)
Population-level processes: adaptability

Neocalanus plumchrus

Neocalanus flemingeri (small form)

Neocalanus flemingeri (large form)

Species show remarkable flexibility in patterns of growth and reproduction.
We learnt that...

1. marine food webs are special
2. population-level processes are important in food web dynamics (target-species approach)
3. long time series allow(ed) patterns to be identified (and processes inferred)
Changes in seasonal timing: pattern to process

Dates at which *Neocalanus plumchrus* reaches its annual biomass maximum

*Alaska gyre (biomass)*

*Alaska gyre (stage ratio)*

*VI cont. margin (stage)*

Warm water = early biomass peak

Changes in timing have unknown effects through the food web
We learnt that...

1. marine food webs are special
2. population-level processes are important in food web dynamics (target-species approach)
3. long time series allow(ed) patterns to be identified (and processes inferred)
4. food web structure varies on different scales
Changes in structure: alternative food web pathways

Scotia Sea

krill abundant

seals  penguins  other predators

icefish  myctophids

krill  amphipods  copepods

phytoplankton

krill scarce

seals  penguins  other predators

icefish  myctophids

krill  amphipods  copepods

phytoplankton

Murphy et al. (2007) Phil. Trans. R. Soc. B 362: 113
Changes in structure: regime shifts

Regions for which ecosystem regime shifts have been documented

Jarre and Shannon (in press) GLOBEC synthesis
We learnt that...

1. marine food webs are special
2. population-level processes are important in food web dynamics (target-species approach)
3. long time series allow(ed) patterns to be identified (and processes inferred)
4. food webs can change from one state to another
5. food web dynamics vary among regions
Food web dynamics: trophic controls

Mackas (in press, GLOBEC synthesis), based on Cury et al. (2001) and McQueen et al. (1986)
Bottom-up trophic control

Continental margin areas, NE Pacific

Large scale

- $r^2 = 0.87$
- $p < 0.0001$
- $n = 11$

Small scale

- $r^2 = 0.79$
- $p = 0.01$
- $n = 6$

Mean resident fish yield (metric tons.km$^{-2}$) vs. Mean chl a concentration (mg.m$^{-3}$)

Mean zooplankton biomass (mg [dry wt].m$^{-3}$) vs. Mean chl a concentration (mg.m$^{-3}$)

Ware and Thompson (2005) *Science* 308: 1280-1284
Food web dynamics: trophic controls

Mackas (in press, GLOBEC synthesis), based on Cury et al. (2001) and McQueen et al. (1986)
Top-down control – trophic cascades

Myers et al. (2008)
Science 315: 1846-1850

Daskalov et al. (2007)
PNAS 104: 10518-10523
Food web dynamics: trophic controls

Trophic level (taxa)

IV Top Predator (large fish)

III Level 1 Predator (small fish)

II Herbivore (copepod)

I Primary producer (phytoplankton)

'BOTTOM-UP' 'TOP-DOWN' 'WASP-WAIST'

Time after perturbation

Mackas (in press, GLOBEC synthesis), based on Cury et al. (2001) and McQueen et al. (1986)
Trophic controls are situation-dependent

• they vary in space...

• and they vary in time...
Latitudinal gradient in trophic controls
Analysis of 47 systems

Oscillating control – Bering Sea

We learnt that...

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2. population-level processes are important in food web dynamics (target-species approach)
3. long time series allow(ed) patterns to be identified (and processes inferred)
4. food webs can change from one state to another
5. food web dynamics vary among regions
6. food webs should be understood from end to end
Why study marine food webs end to end?

- Planktivore fish
- Juvenile fish
- Larval fish
- Piscivore fish
- Zooplankton
- Phytoplankton
- Microbial loop
- Carbon sequestration
- Marine biogeochemistry
- Top predators
- Marine conservation
- Maintenance of biodiversity
- Fisheries production
- Marine living resource management
- Marine fisheries production
We learnt that...

1. marine food webs are special
2. population-level processes are important in food web dynamics (target-species approach)
3. long time series allow(ed) patterns to be identified (and processes inferred)
4. food webs can change from one state to another
5. food web dynamics vary among regions
6. food webs should be understood from end to end
7. innovation is needed to deal with the complexity of marine food webs
Research framework for end-to-end food webs

Moloney, St John et al. (submitted)
<table>
<thead>
<tr>
<th></th>
<th>North Pacific</th>
<th>Coral - Jamaica</th>
<th>North Sea</th>
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<tbody>
<tr>
<td><strong>Drivers</strong></td>
<td>Complex physical climate (AO, PDO, ENSO)</td>
<td>Fishing</td>
<td>Oceanic (circulation temperature) atmospheric (NAO), fishing</td>
</tr>
<tr>
<td><strong>Response</strong></td>
<td>Zooplankton to fish and mammals</td>
<td>Eutrophicication</td>
<td>Phytoplankton to fish</td>
</tr>
<tr>
<td><strong>Time scale</strong></td>
<td>Shift – 1-5 years Persistence – 10-20 years</td>
<td>Shift: 1-5 years Regime: &gt; 10 years</td>
<td>Shift 1-5 years (NAO) Oceanic persistence – 10 years Erosion of resilience – &gt; 10 years - fishing</td>
</tr>
<tr>
<td><strong>Spatial scale</strong></td>
<td>10,000 km (basin) 1,000-2,000 km (regional)</td>
<td>10-100 km</td>
<td>1000-2000 km (extends beyond North Sea)</td>
</tr>
<tr>
<td><strong>Detect</strong></td>
<td>2 years</td>
<td>3-5 years</td>
<td>&lt; 1 year</td>
</tr>
<tr>
<td><strong>Predict</strong></td>
<td>Little skill</td>
<td>Following from detection</td>
<td>Little skill, Erosion - fishing impact is predictable</td>
</tr>
<tr>
<td><strong>Manage</strong></td>
<td>Not possible</td>
<td>Fishing management after detection - adaptation</td>
<td>Fishing management after detection - adaptation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Marine management of resilience and trigger &gt;&gt; prevention</td>
<td>Climate – not possible Fishing - prevention</td>
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