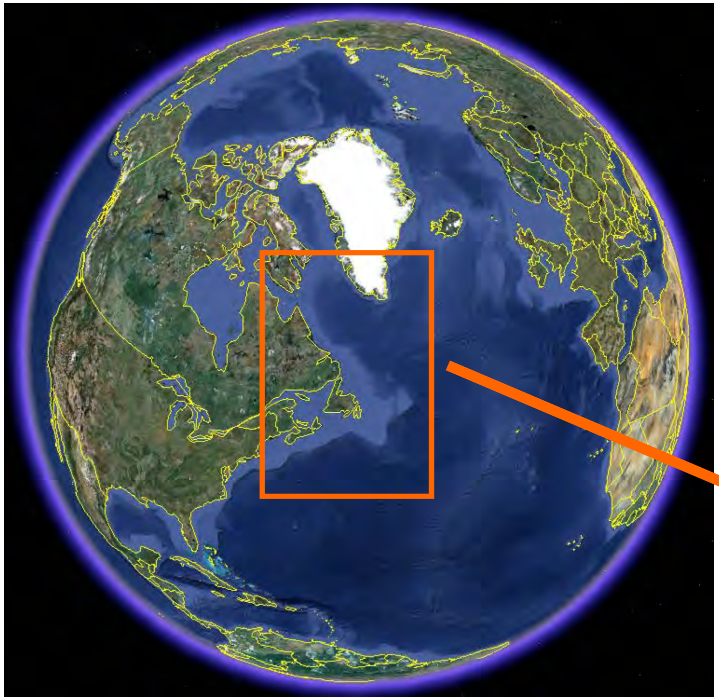
Ecosystem change in the North Atlantic: Impacts, Vulnerabilities and Opportunities

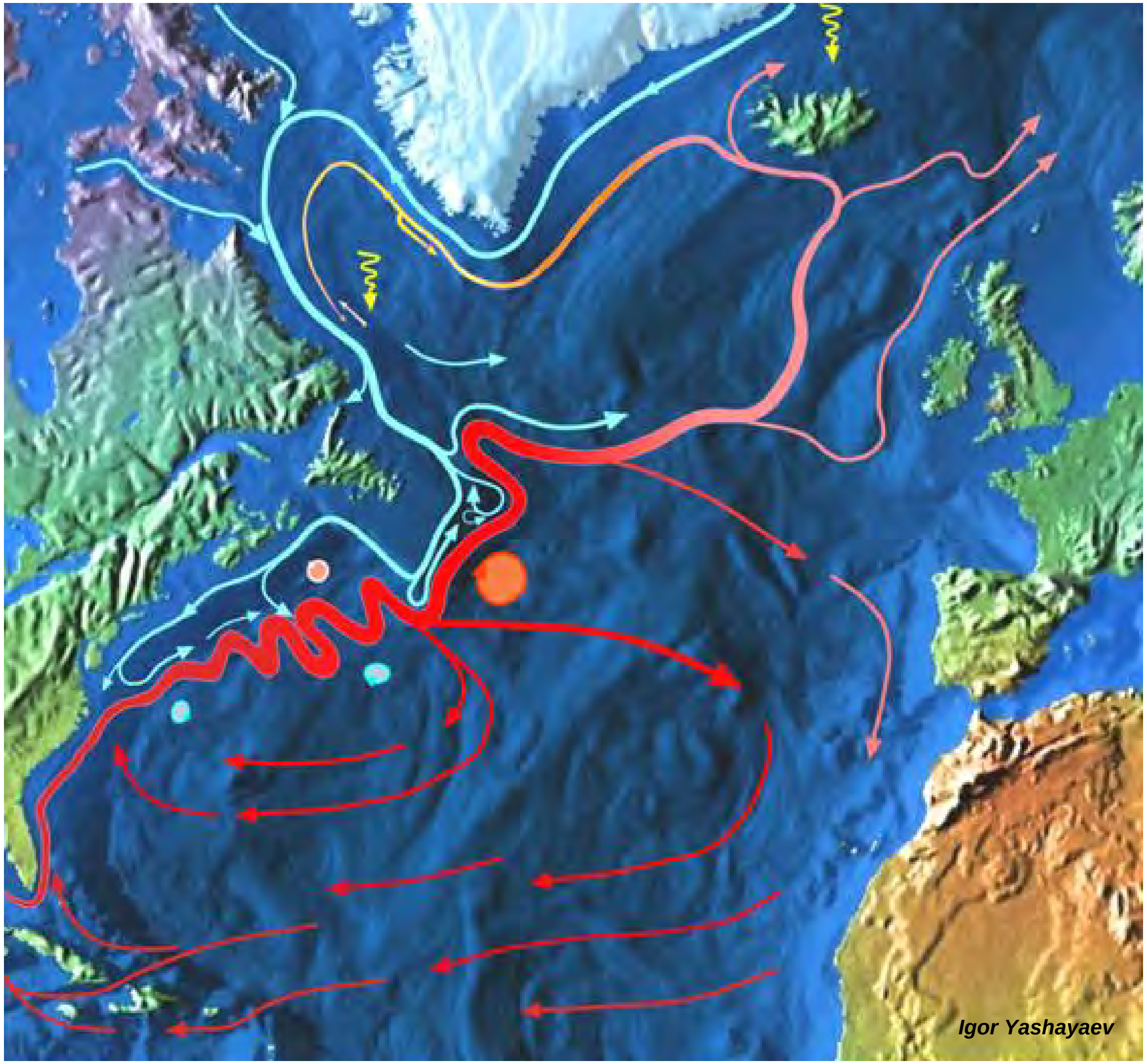
William Li ***and*** **Nancy Shackell**

Fisheries and Oceans Canada
Bedford Institute of Oceanography

Atlantic Canada : Scotian Shelf, Gulf of St. Lawrence, Gulf of Maine, Grand Banks, Labrador Sea …



North Atlantic Ocean



Northwest Atlantic is characterized by general southward flow of cold, fresh sub-polar water and northward flow of warm, salty sub-tropical water (Gulf Stream).

Scotian Shelf - Gulf of Maine is a transition zone for these 2 water masses.

The Tail of Grand Banks is a "choke point" in this system.

Atlantic Canada : "Preliminary Reports"

1986 Wright et al.

Oceanic Changes Associated with Global Increases in Atmospheric Carbon Dioxide: A Preliminary Report for the Atlantic Coast of Canada

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Canadian Technical Report of Fisheries and Aquatic Sciences No. 1426

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Changes in the Fisheries of Atlantic Canada Associated with Global Increases in Atmospheric Carbon Dioxide: A Preliminary Report

K.T. Frank[1], R.I. Perry[2], K.F. Drinkwater[3], and W.H. Lear[4]

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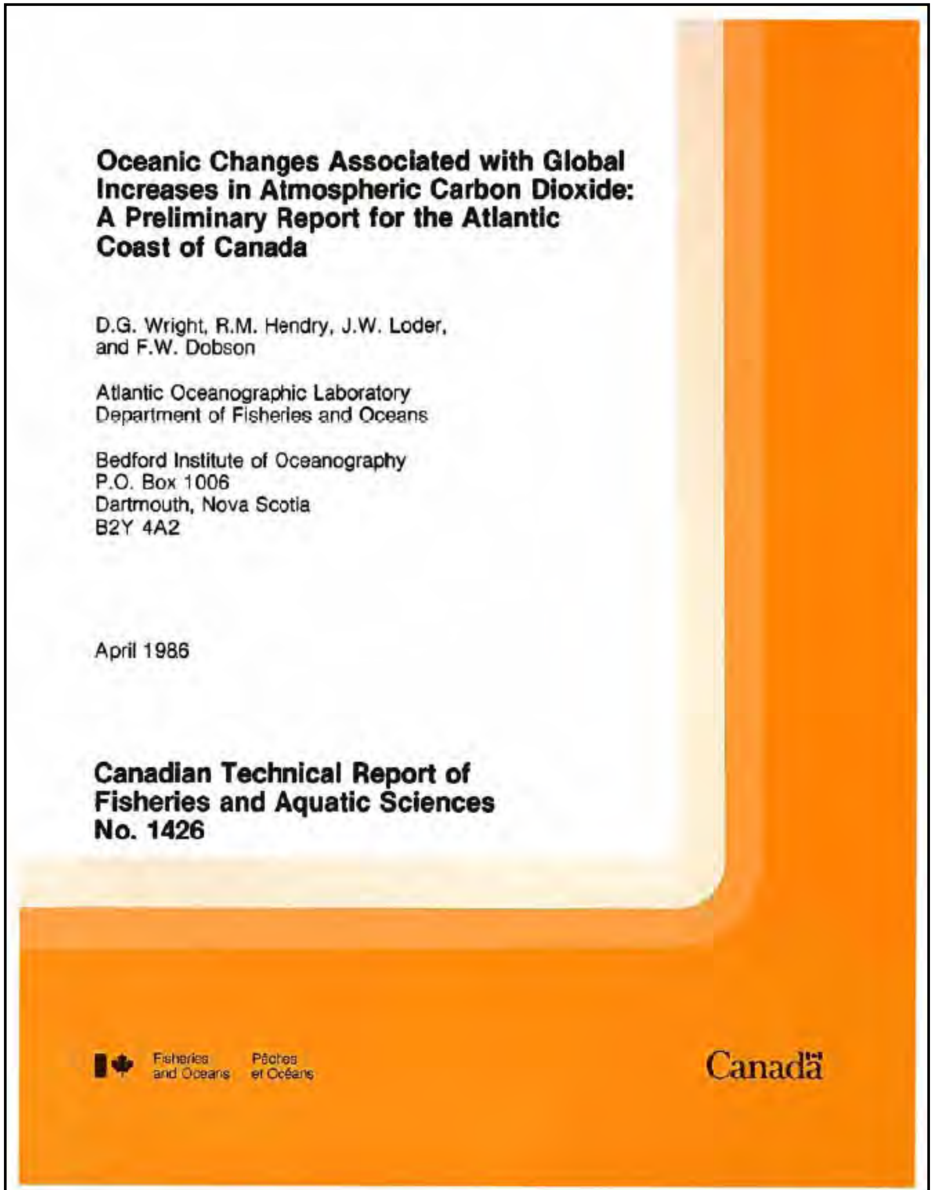
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In the waters off eastern Canada, we expect that the primary changes will be:

1. Warmer ocean temperatures;
2. Reduced surface salinities;
3. Increased along-shelf residual currents associated with a stronger Labrador Current and increased freshwater discharge into the Gulf of St. Lawrence;
4. Increased stratification and thinner surface mixed layers, except in regions of reduced ice cover where mixed layers may deepen in winter and spring;
5. Reduced areal extent of ice cover on the Labrador Shelf and in the Gulf of St. Lawrence;
6. Earlier seasonal snow melt and ice break-up;
7. Later seasonal freeze-up;
8. Reduced Gulf Stream eddy activity;
9. More northward excursion of the North Atlantic Current into the southern Labrador Sea.

Wright et al. 1986 Oceanic Changes Associated with Global Increases in Atmospheric Carbon Dioxide: A Preliminary Report for the Atlantic Coast of Canada

Atlantic Canada : "Preliminary Reports" - *fisheries*

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Fisheries and Oceans   Pêches et Océans   Canada

In the waters off eastern Canada, we expect that the primary changes will be:

1. Northward and possibly shoreward displacement of several commercially important, resident groundfish stocks (the length scale of change cannot be specified).

2. Expansion of warmer-water species currently uncommon in our waters from localities south of the Gulf of Maine.

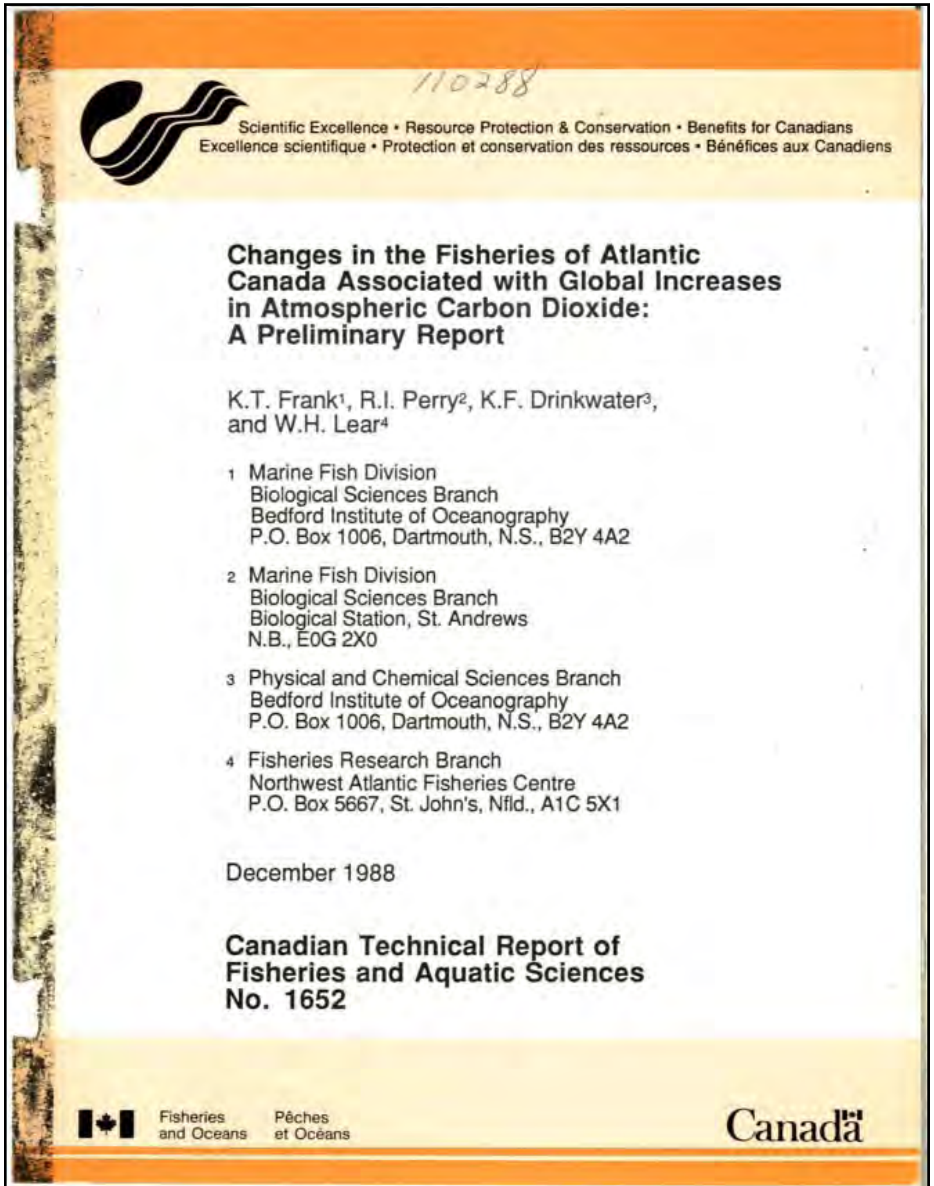
3. Earlier arrival and later departure times at northern boundaries for species (mainly pelagic) which undergo extensive seasonal migrations; year-round feeding in overwintering areas is a distinct possibility.

4. A tendency for changes in fish species composition from groundfish to pelagics due to the anticipated reduction in the amount of organic material reaching the bottom that fuels the benthic food web.

5. Changes in the time of arrival and location of offspring relative to their nursery grounds for those fish stocks that rely on advective dispersal of eggs and larvae for successful reproduction.

Frank et al. 1988 Changes in the Fisheries of Atlantic Canada Associated with Global Increases in Atmospheric Carbon Dioxide: A Preliminary Report

1988 Frank et al.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Fisheries and Oceans   Pêches et Océans   Canada

In the waters off eastern Canada, we expect that the primary changes will be:

6. Less frequent episodes of poor recruitment for those fish stocks inhabiting Georges Bank, Scotian Shelf and the southern Grand Banks.

7. Reduction in total fish production due to changes in phytoplankton species composition (diatom to dinoflagellates) and the associated increase in the numbers of steps in the food chain.

8. Decreased production of the cod stock complex of southern Labrador Shelf, northern Newfoundland and the northern Grand Bank (i.e. NAFO Div. 2J3KL).

9. Reduction in the mean abundance levels of stocks whose spawning locations are associated with tidally-mixed regions.

10. Increased development of nearshore regions for aquaculture activities.

Summary of climate projections for Atlantic Canada - 2012

- SEA LEVEL
- SEA ICE
- TEMPERATURE
- ACIDITY
- SALINITY
- STRATIFICATION
- DISSOLVED OXYGEN
- RIVER RUNOFF
- NUTRIENTS

SEA LEVEL can be expected to continue to rise associated with the global trends of ocean expansion due to heating and melting glaciers, and with regional factors such as continental subsidence.

- Extreme events (e.g. intense storms) are expected to increase, with associated coastal hazards.

SEA ICE can be expected to continue to decrease in sea ice coverage

- Spatial extent
- Ice volume

OCEAN TEMPERATURE and **OCEAN ACIDITY** can be expected to increase associated with a warmer overlying atmosphere with increased CO_2 concentrations:

- Increases should be largest in the upper layers, but are also expected at all depths over the shelf and upper slope as waters ventilated elsewhere and earlier move into the region.
- The increased ocean acidity can be expected to result in a lowering of calcium carbonate saturation in the upper ocean, with effects on calcareous organisms and other aspects of the ecosystem.

OCEAN WARMING can be also be expected on the Scotian Shelf/GoM due to a northward shift of the Gulf Stream:

- Based on expected tendency for more positive NAO (and slowing of the AMOC)
- Leading to higher salinity in the slope water off the SS/GoM
- And perhaps changes in chemical properties at depth such as nutrients and dissolved oxygen.

Summary of climate projections for Atlantic Canada - 2012

- SEA LEVEL
- SEA ICE
- TEMPERATURE
- ACIDITY
- **SALINITY**
- **STRATIFICATION**
- **DISSOLVED OXYGEN**
- **RIVER RUNOFF**
- **NUTRIENTS**

Net regional **SALINITY CHANGES** expected on the mid-century time scale are uncertain due to opposing tendencies:

- Melting arctic ice (reduces S) and more precipitation in northern regions (fresher water flowing into Maritime Canada region) versus northward shift of more saline subtropical waters.

STRATIFICATION can be expected to generally increase:

- MIXED LAYER DEPTHS in the near-surface may be shallower, due to combined influences of temperature and salinity changes
- Magnitudes will probably vary seasonally and spatially

DISSOLVED OXYGEN can be expected to be reduced in the subsurface waters over the Atlantic Canadian shelf and slope:

- Due to increased stratification and reduced depths of winter convection.

RIVER RUNOFF into Maritime Canada Seas:

- No significant change in freshwater volume flux expected (based on CCCMA simulations)
- Difference in timing of freshwater pulse could change if river regulation changes

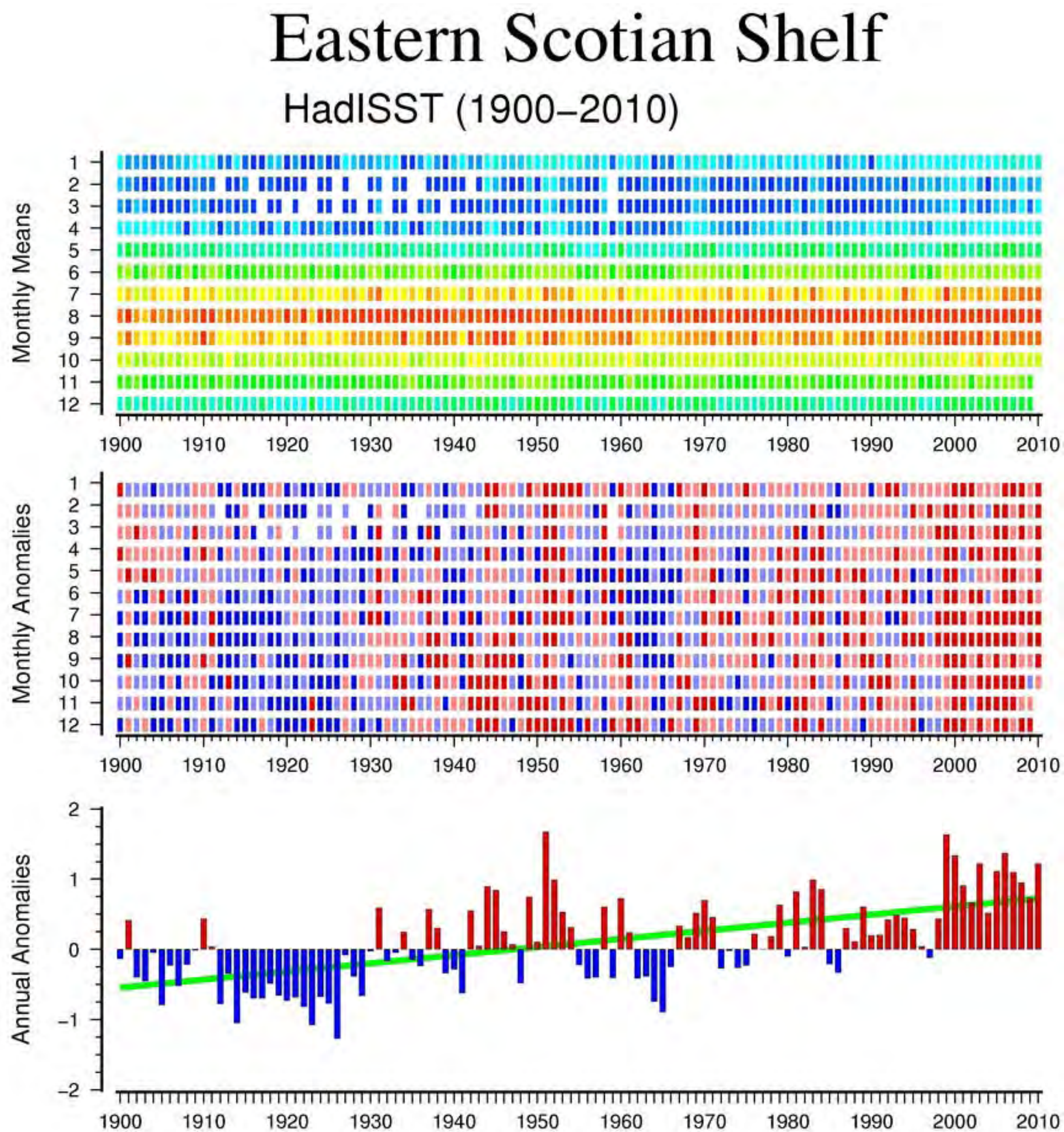
NUTRIENT CONCENTRATIONS: may change on the Scotian Shelf.

- With the increased contribution of subtropical slope water, there should be a tendency towards increased nutrient concentrations, at least at depth.
- However, nutrient concentrations are influenced by multiple factors including complex biogeochemical processes, such that it is difficult to project the net effects of climate change and other factors.

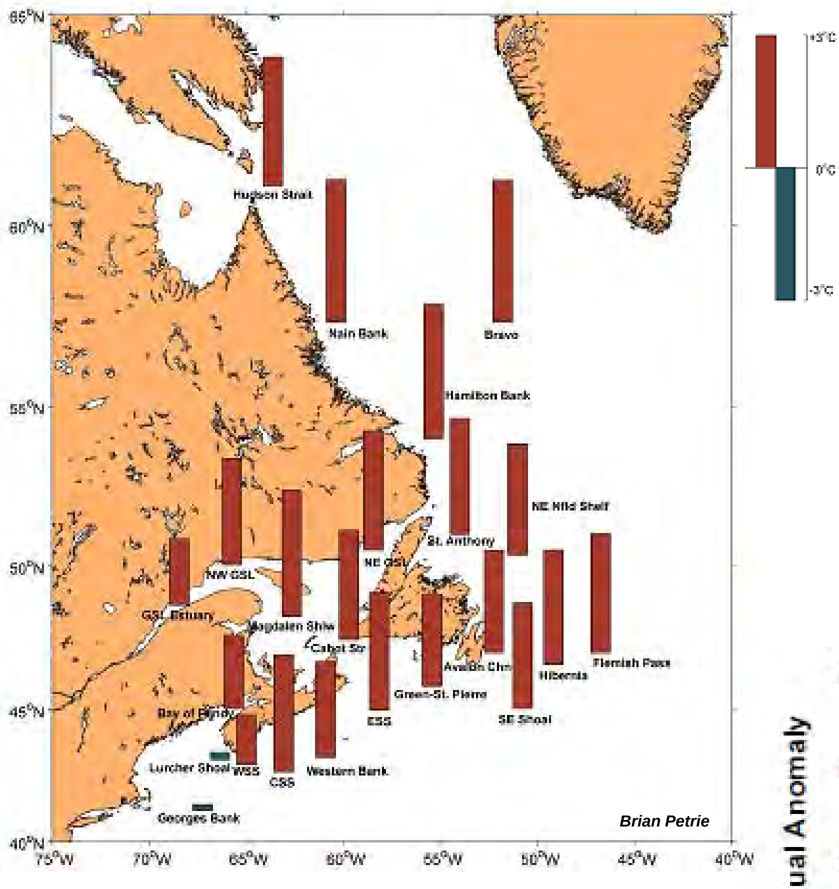
Summary of climate projections for Atlantic Canada

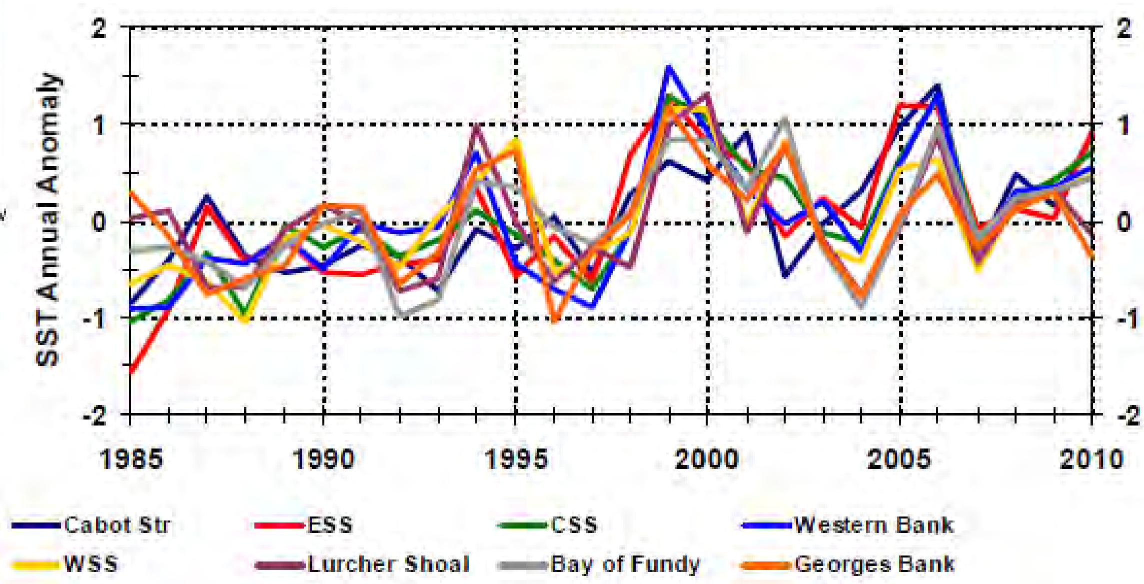
IMPORTANT POINT

- On the 10-20 year timescale, climate-related changes could be swamped by natural variability.
- Climate-related changes will be more evident on the 50+ year timescale.

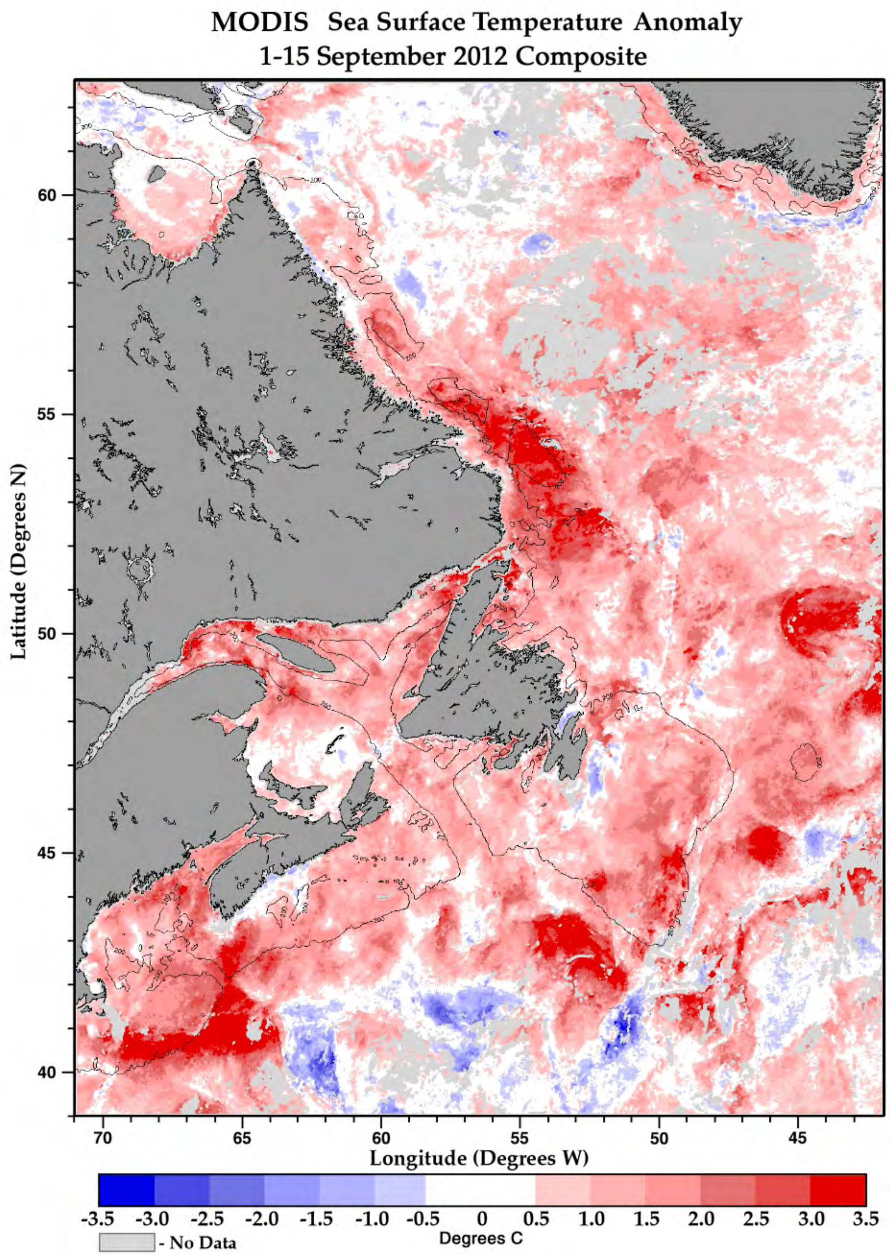


Annual Sea Surface Temperature Trends *(Atlantic Canada)*

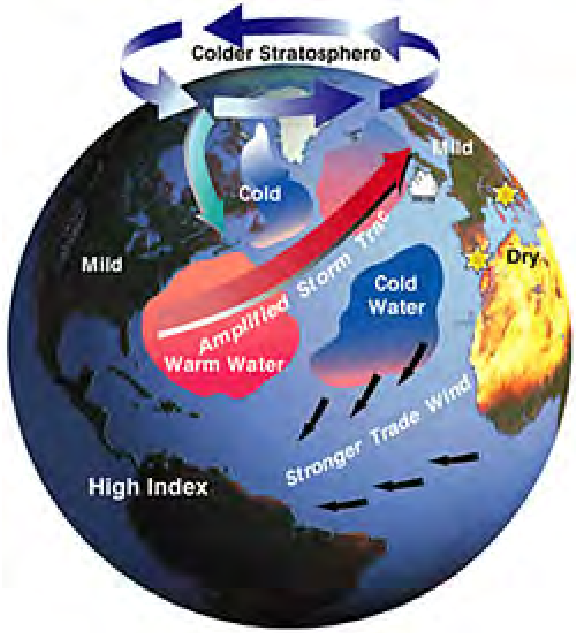


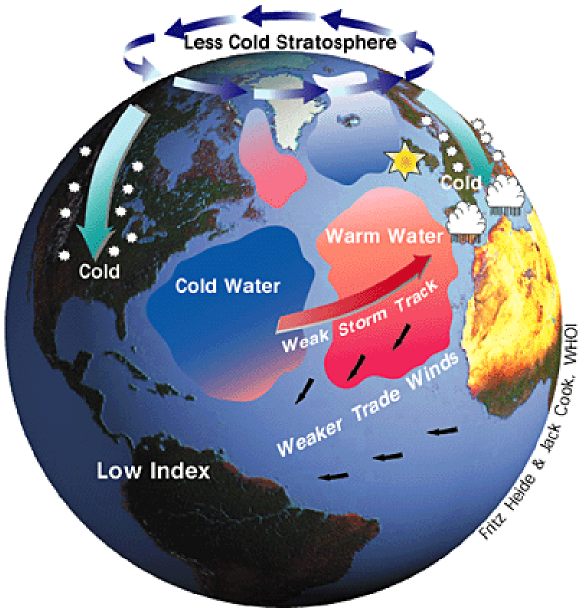


Sea Surface Temperature Anomaly 2012 *(2 week composite)*



North Atlantic Oscillation



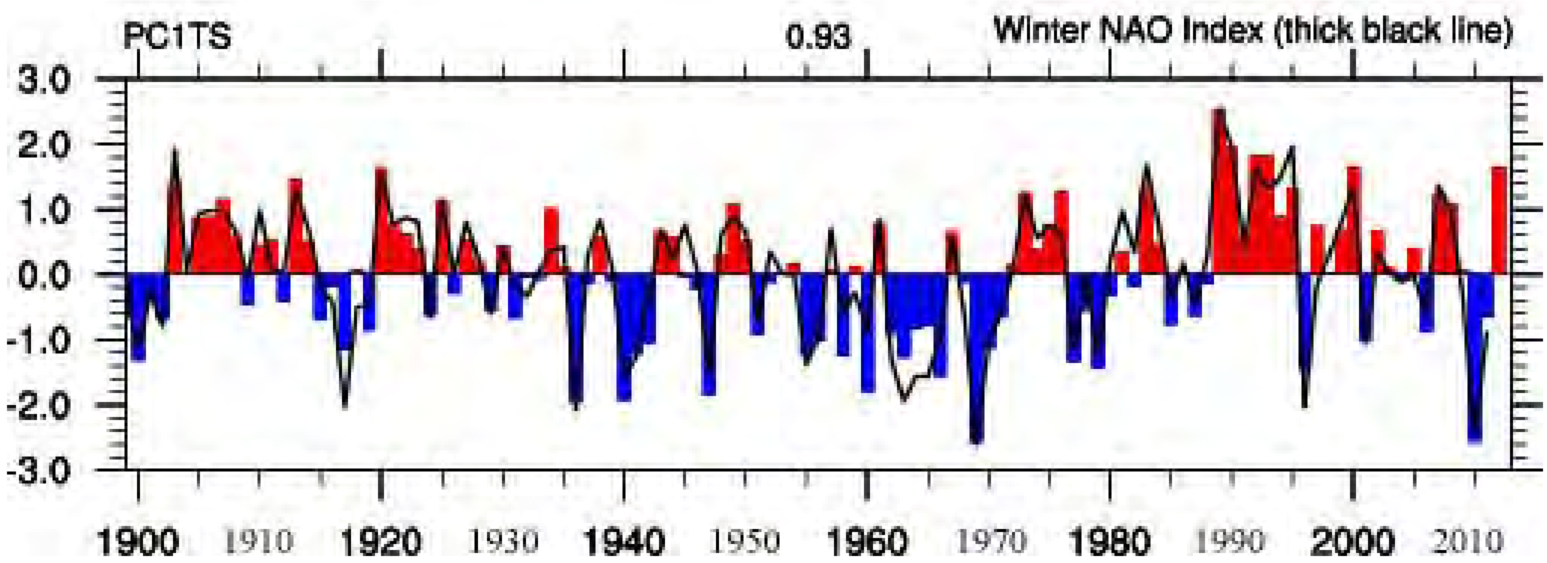


NAO is the dominant meteorological pattern driving North Atlantic climate

NAO = Sea Level Atmospheric Pressure Difference between the Azores and Iceland

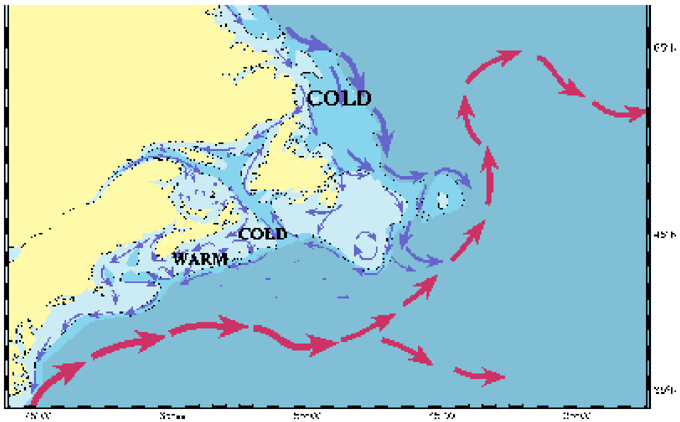
Positive NAO leads to severe winters over the Labrador Sea, Shelf and Grand Banks

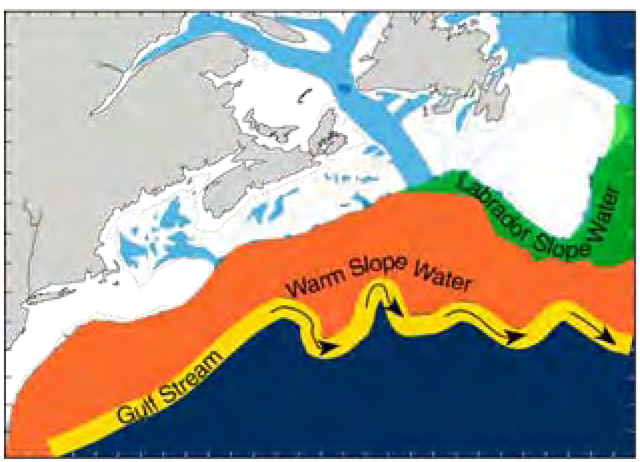
Negative NAO leads to mild winters over the Labrador Sea, Shelf and Grand Banks



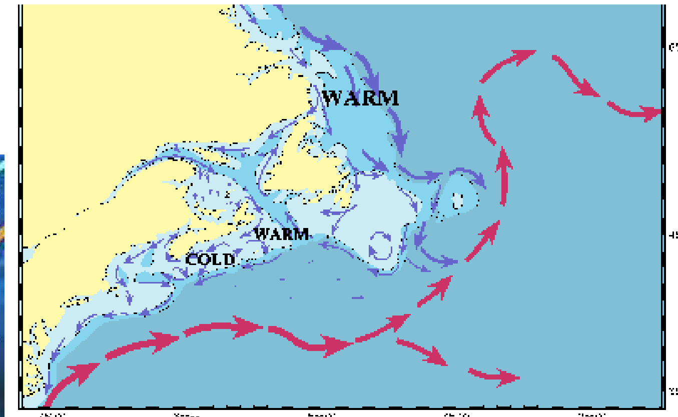
North Atlantic Oscillation

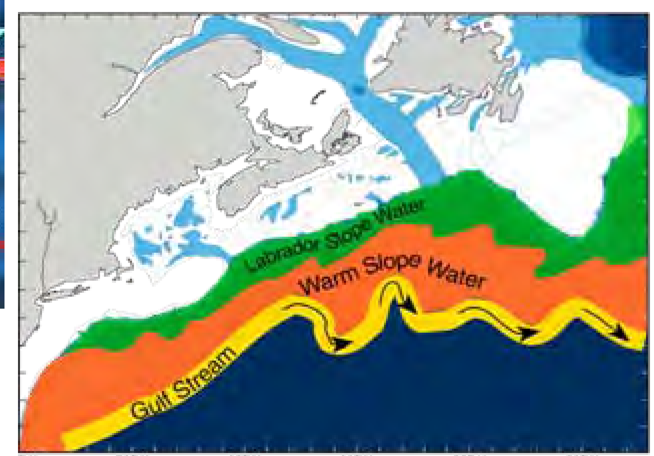
High NAO		Low NAO
Increase	Cold air outbreaks over Labrador Sea	Decrease
Increase	Deep convection in Labrador Sea	Decrease
Tighter	Labrador Sea gyre	More diffuse
Stronger	Eastward flowing branch	Weaker
Less flow	Flow around Tail of the Grand Banks	More flow





High NAO



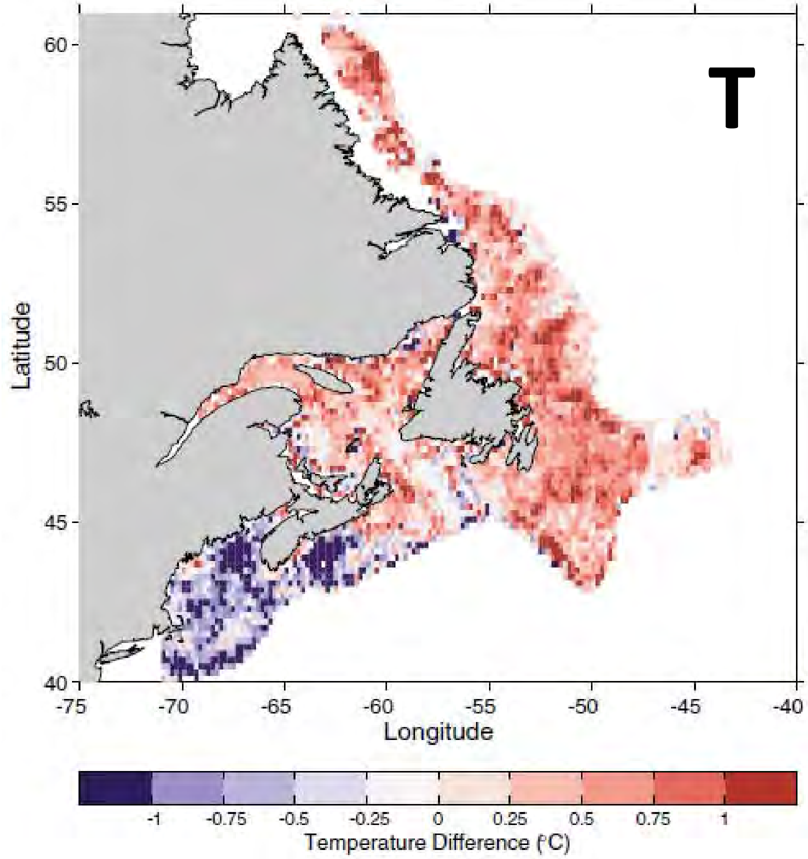


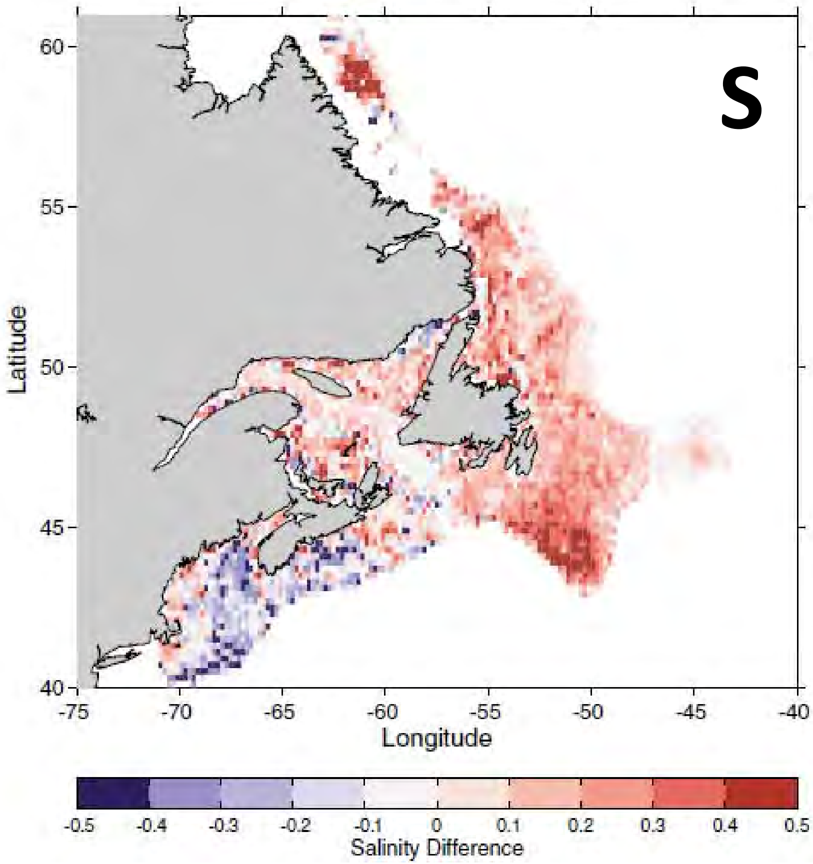
Low NAO

David Brickman

Spatial structure of temperature and salinity change in response to NAO

The temperature and salinity differences (negative minus positive NAO winter anomalies) for the years from 1970–2004 when the NAO anomalies had the same sign as at least the two preceding years

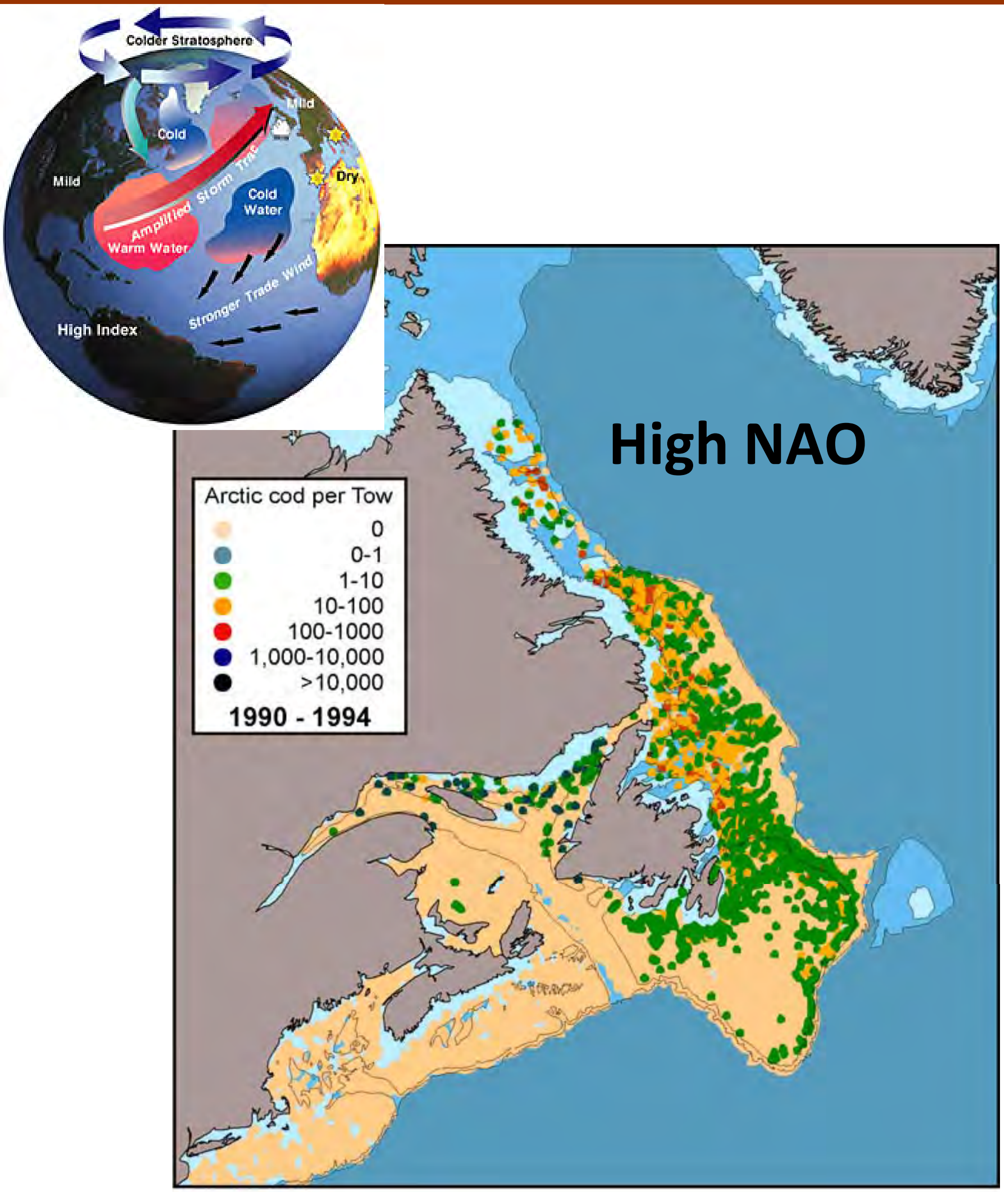


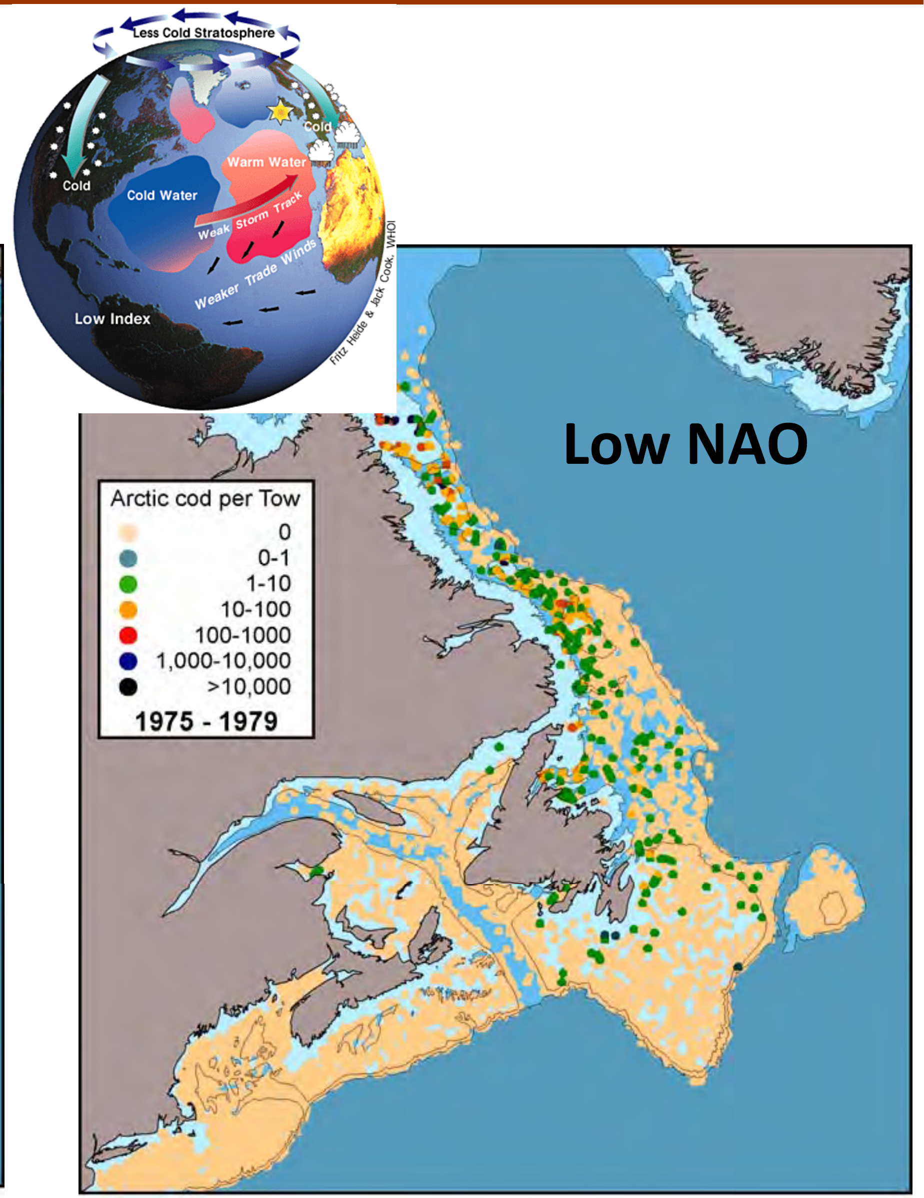


Warm, salty (cold, fresh) conditions prevail on the Newfoundland-Labrador Shelf, the eastern Scotian Shelf and the Gulf of St. Lawrence during periods of negative (positive) NAO anomalies. The opposite response is seen on the central and western Scotian Shelf and in the Gulf of Maine.

Petrie B 2007. Does the North Atlantic Oscillation affect hydrographic properties on the Canadian Atlantic continental shelf? Atmosphere-Ocean 45:141-151

Distribution of Arctic cod



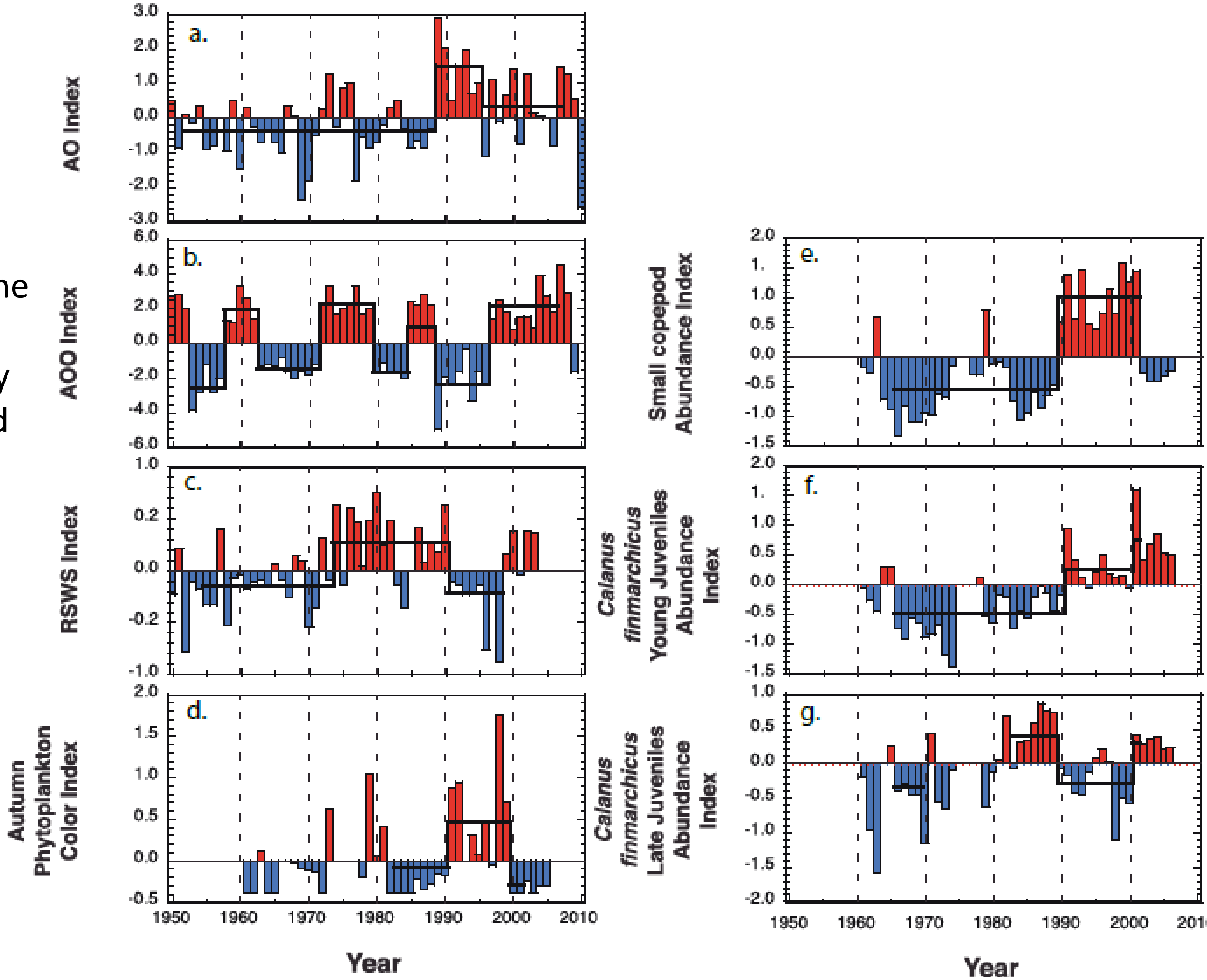


Brian Petrie, Ken Drinkwater

Recent Arctic climate change and remote forcing of Northwest Atlantic shelf ecosystems?

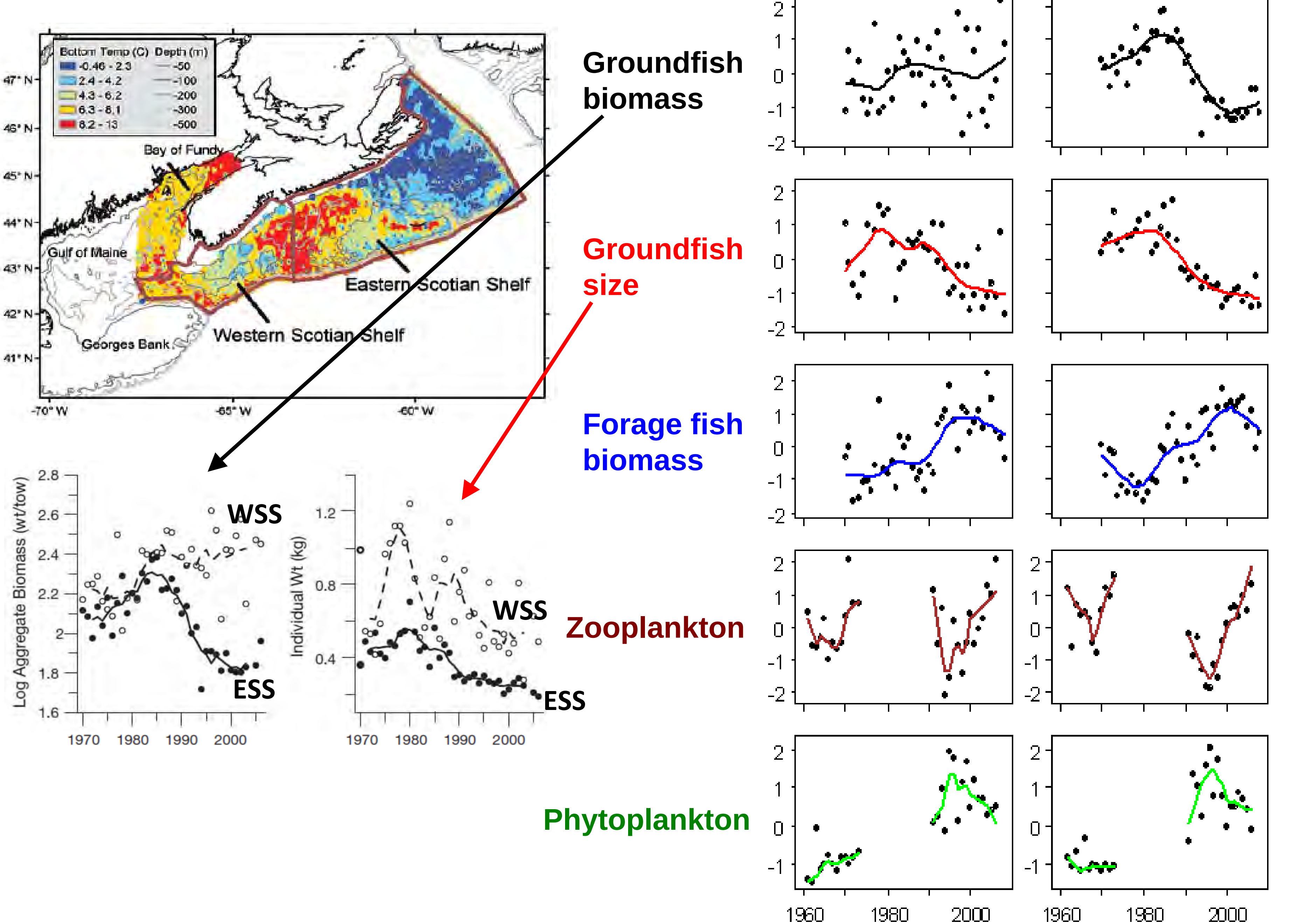
Variable patterns of freshwater export from the Arctic Ocean are linked to regime shifts in Northwest Atlantic shelf ecosystems.

Salinity anomalies, both negative and positive, alter the timing and extent of water-column stratification, thereby impacting the production and seasonal cycles of phytoplankton, zooplankton, and higher-trophic-level consumers.



Marine Ecosystems Response to Climate in the North Atlantic (MERCINA) working group 2012. Oceanography 25(3):208-213

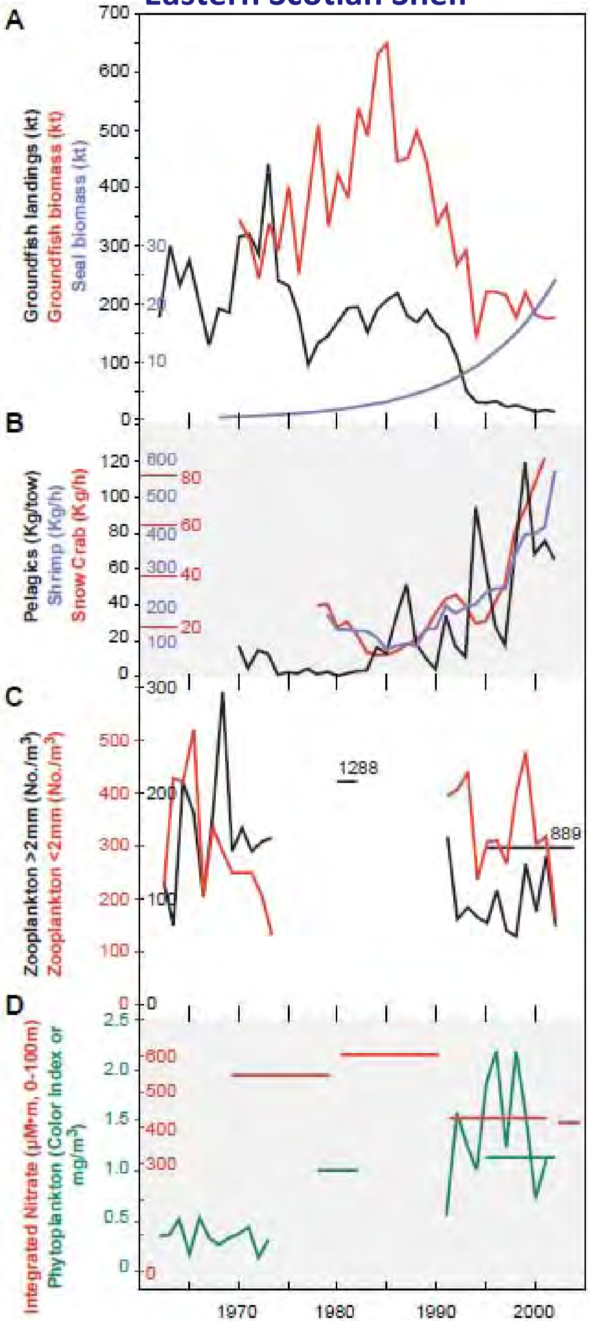
Or trophic cascade on Scotian Shelf ecosystems?

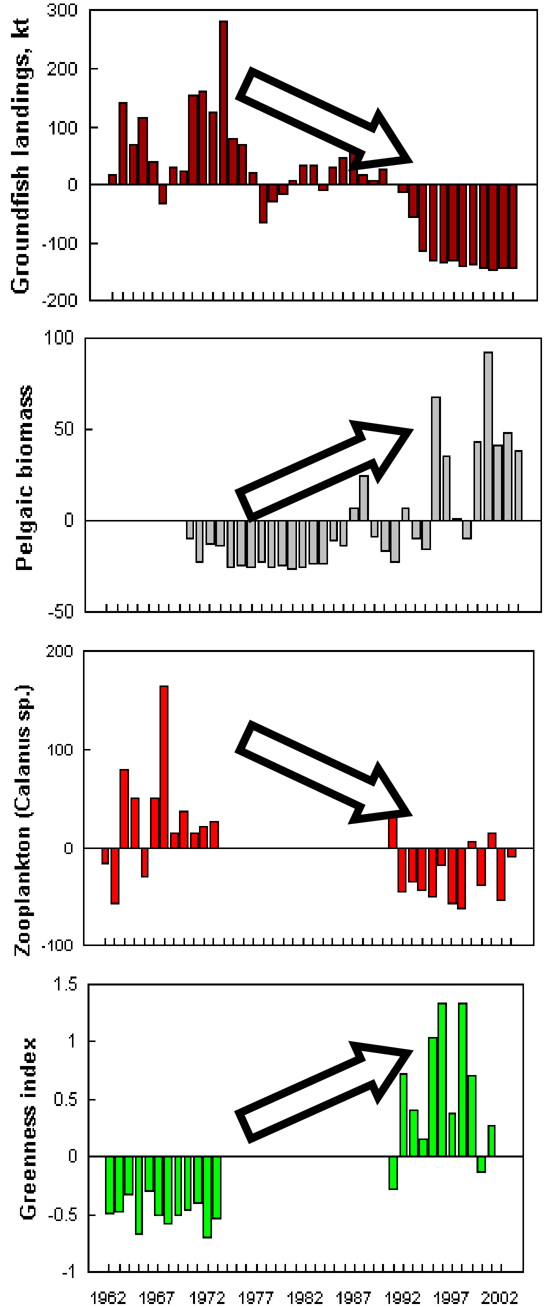


Decline in top predator body size and changing climate alter trophic structure in an oceanic ecosystem (Shackell et al. 2010. Proc. R. Soc. B 277:1353-1360)

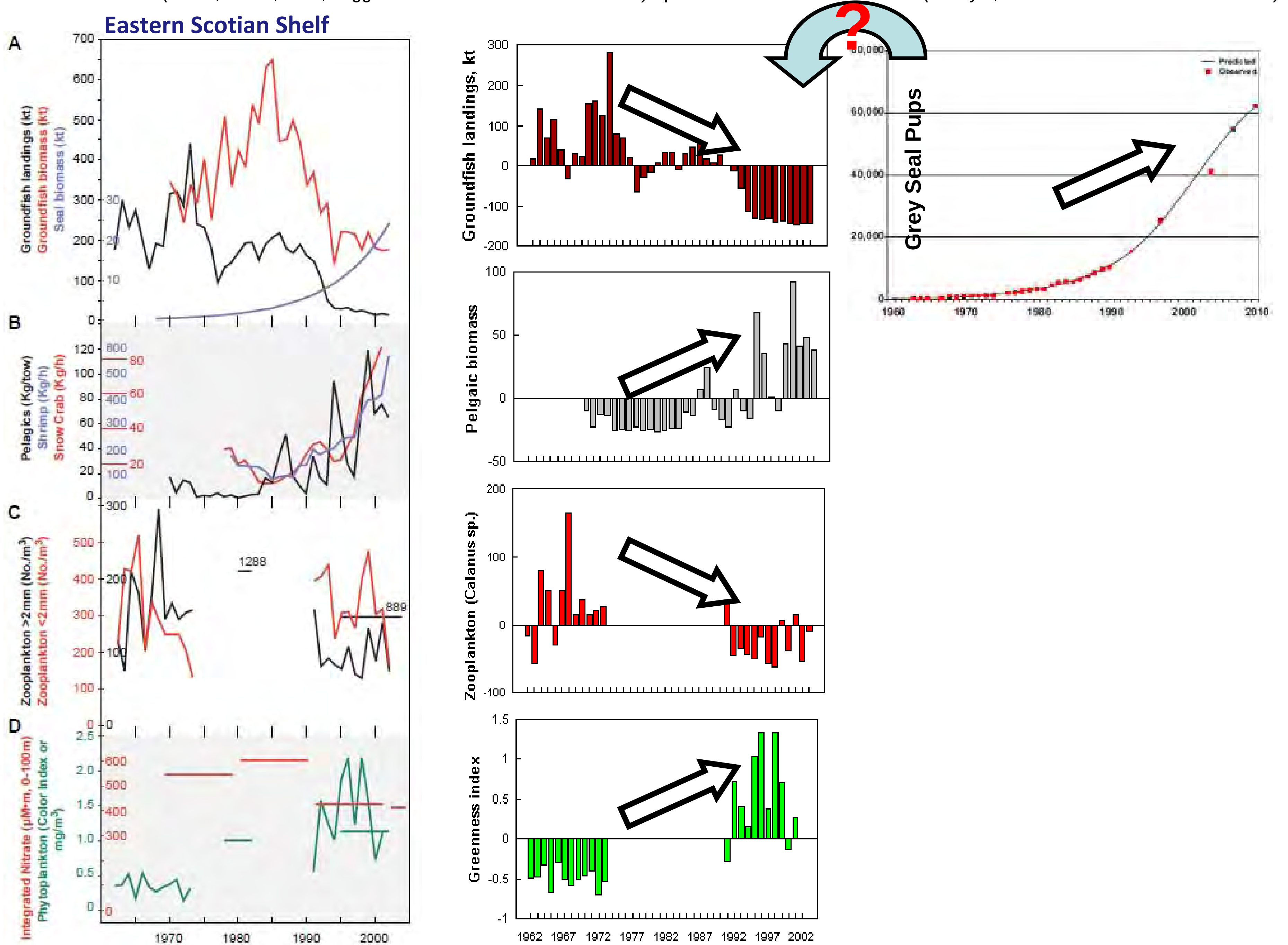
TROPHIC CASCADE *(Frank, Petrie, Choi, Leggett 2005. Science 308:1621-1623)*

Eastern Scotian Shelf



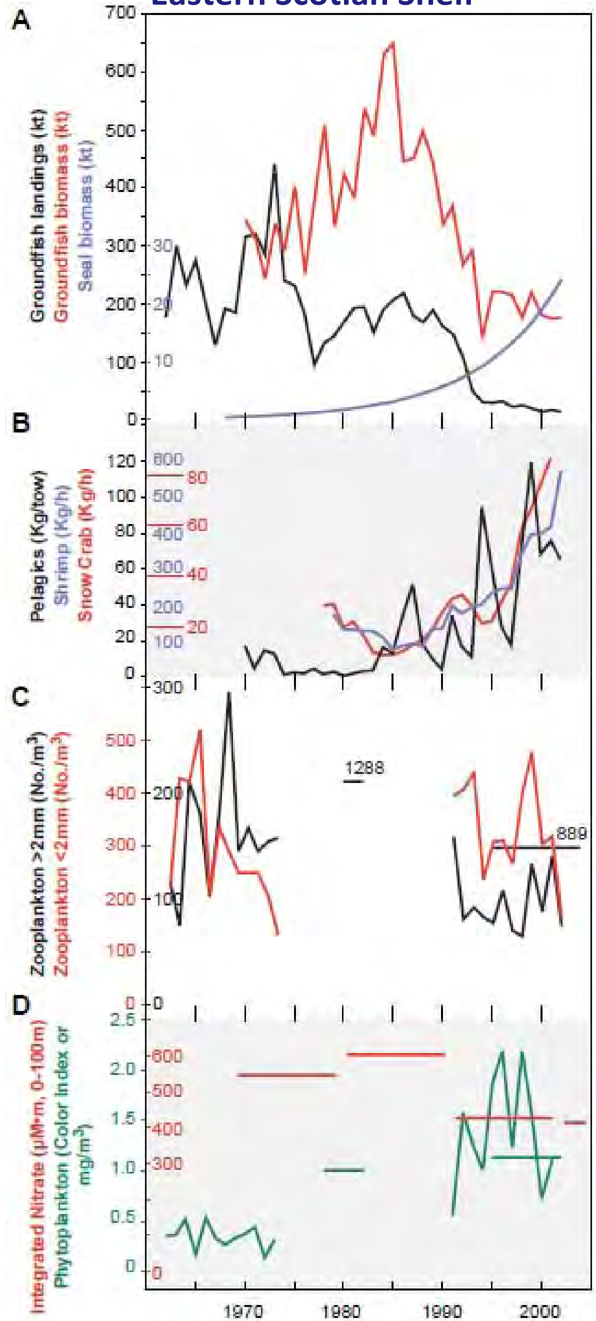


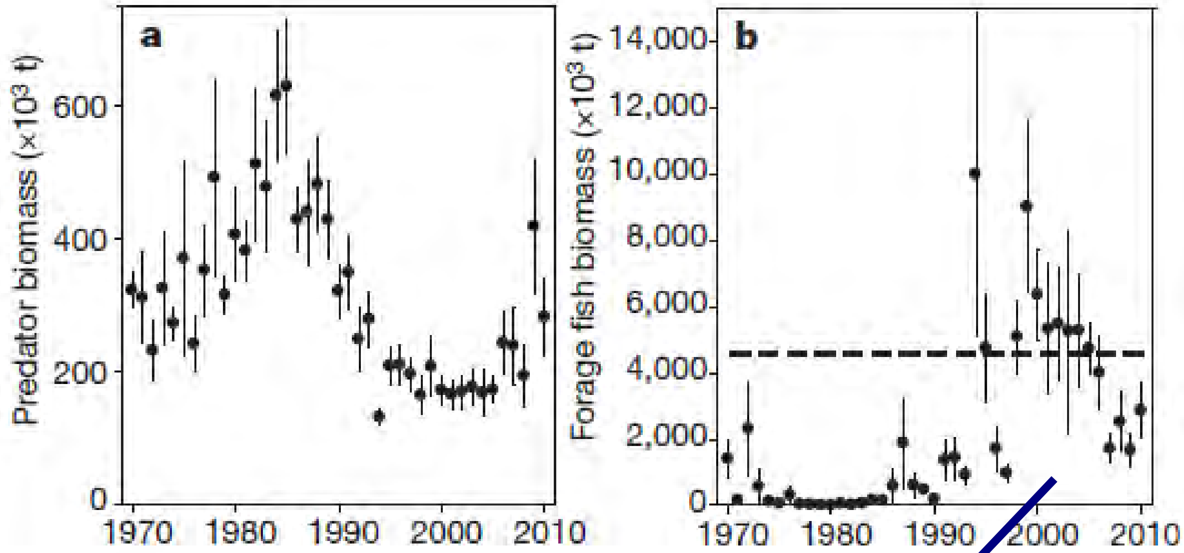
***TROPHIC CASCADE** (Frank, Petrie, Choi, Leggett 2005. Science 308:1621-1623)* **|** ***SEAL-COD INTERACTIONS** (O'Boyle, Sinclair 2011 Fisheries Research)*



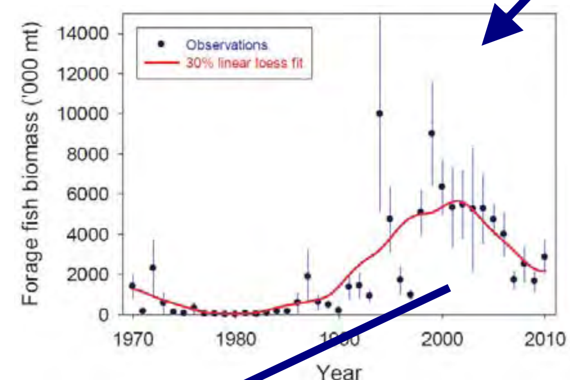
DAMPED HARMONIC OSCILLATION *(Frank. Petrie, Fisher Leggett 2011. Nature 477:86-89)*

Eastern Scotian Shelf

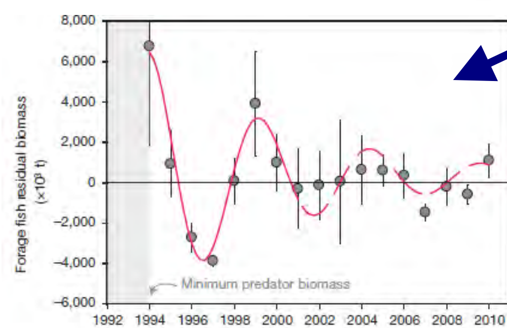




Loess fit

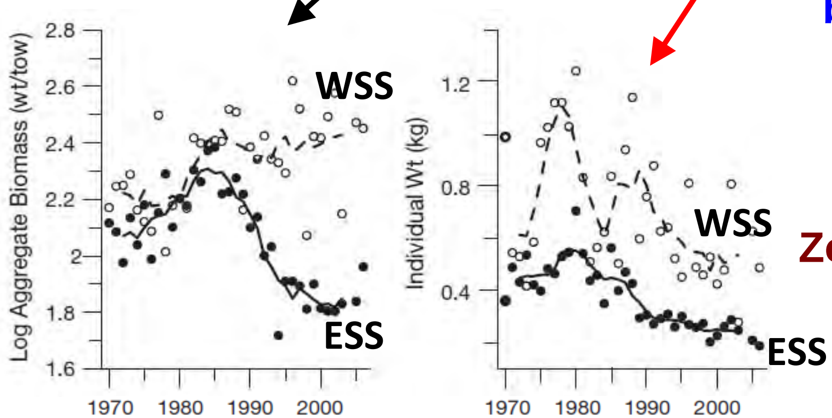


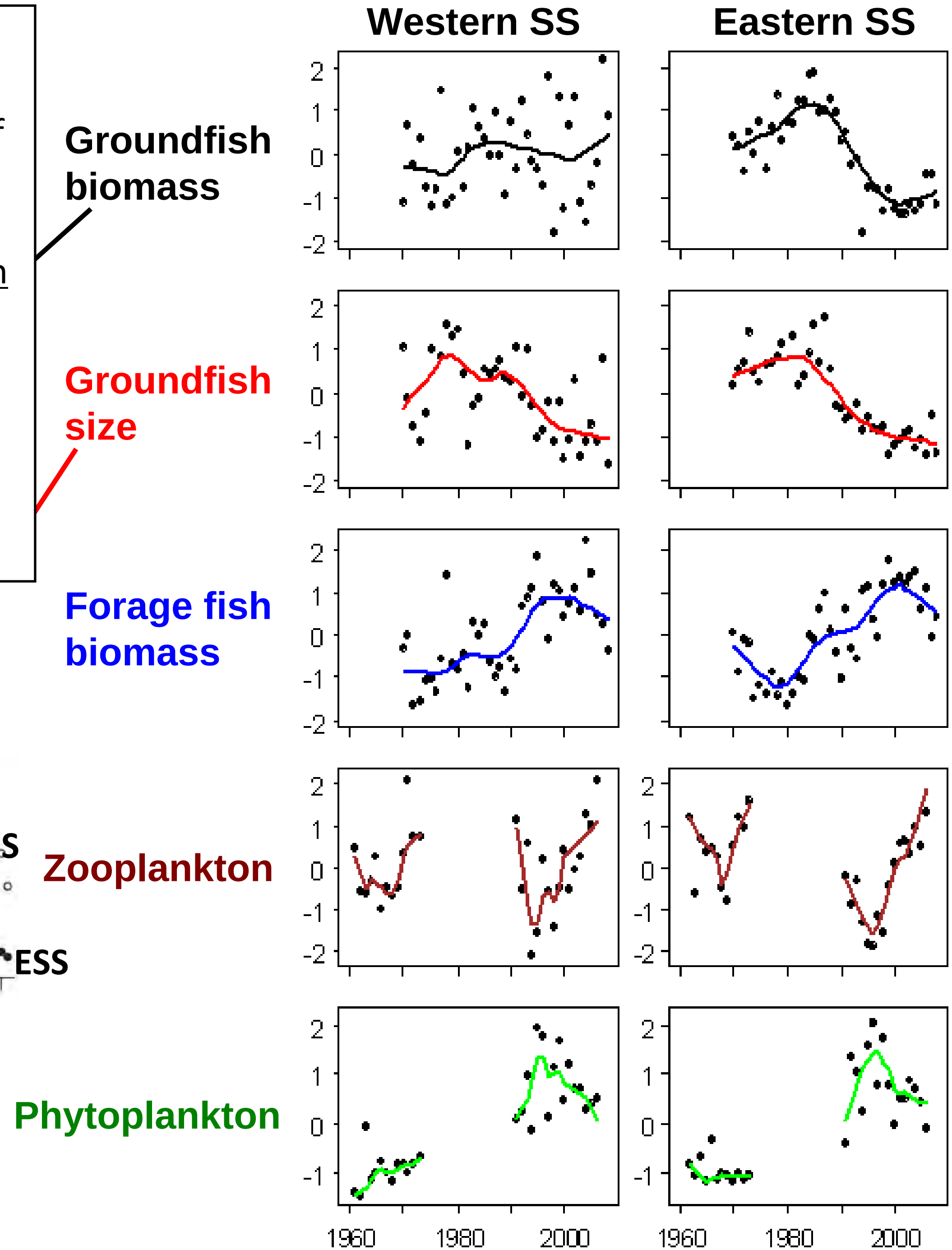
Anomaly



On the **Eastern Scotian Shelf**, the response of lower trophic levels can be primarily attributed to the absolute loss of biomass of large fish.

On the **Western Scotian Shelf**, the decline in body size of large fish may have led to different predator/prey dynamics In other words, the indirect effects of size-selective fishing can result in a similar, but less extreme, trophic response as the direct removal of biomass of top predators.





Decline in top predator body size and changing climate alter trophic structure in an oceanic ecosystem (Shackell et al. 2010. Proc. R. Soc. B 277:1353-1360)

State of the Scotian Shelf Ecosystem – Report Card of 85 variables

1	Grey seal numerical abundance
2	Human population (Nova Scotia)
3	Landed value / total landings
4	Specific metabolic rate
5	Pelagic numerical abundance
6	Pelagic:demersal ratio (biomass)
7	Invertebrate landed value
8	Pelagic:demersal ratio (numbers)
9	Pelagic biomass
10	Species-area intercept
11	Diatoms (CPR)
12	Pelagic landed value
13	Grey seal pups
14	Colour index (CPR)
15	Size-abundance r-squared
16	Macroinvertebrate biomas (CPUE)
17	Groundfish diversity (Margalef)
18	Dinoflagellates (CPR)
19	No. seismic tracks (3D)
20	Gulf Stream front position
21	Stratification anomaly (0-50m)
22	Diatom:dinoflagellate ratio (CPR)
23	Landed value
24	Volume CIL source water
25	Sea level anomaly
26	Invertebrate landings
27	Species-area slope
28	NAO anomaly (6 yr interval)
29	Calanus hyperboreus (CPR)
30	Sable Is. Temperature
31	SST anomaly (satellite)
32	Mixed layer temperature
33	Species richness predicted
34	Paracalanus, Pseudocalanus (CPR)
35	NAO anomaly
36	Emerald bottom temperature
37	No. of storms
38	Shelf front position
39	Fish species diversity (Shannon)
40	Misaine bottom temperatures
41	No. seismic tracks (2D)
42	Groundfish numerical abundance
43	Species composition 1
44	Nitrate concentrations
45	No. wells drilled
46	fecundity
47	Sable Is. tau y
48	Mixed layer salinity
49	Ice coverage
50	Groundfish landed value
51	Bottom temperature
52	Sable Is. total stress
53	Sable Is. tau a
54	Mixed layer sigma-t
55	Oxygen concentrations
56	Sable Is. tau x
57	Halifax SST
58	Bottom area >3 Celsius
59	Relative area (fish condition>0)
60	RIVSUM
61	Mixed layer depth
62	Physiological condition
63	Stratification anomaly (50 to 0m)
64	Bottom temp. anomaly (6yr)
65	Bottom temperature (6yr)
66	Length age 6 Silver Hake
67	Pelagic landings
68	Groundfish biomass
69	Species composition 2
70	Calanus finmarchicus (CPR)
71	Relative fish mortality
72	Size-abundance slope
73	Length age 6 Pollock
74	PCB concentrations in seals
75	Groundfish mean weight
76	Metabolic rate
77	Fish community similarity
78	Landings total
79	Length age 6 Cod
80	Trawled surface area
81	Size-abundance intercept
82	Length age 6 Haddock
83	Groundfish landings
84	Mean body mass
85	Total fisheries landings

1	Grey seal numerical abundance
2	Human population (Nova Scotia)
5	Pelagic numerical abundance
7	Invertebrate landed value
9	Pelagic biomass
11	Diatoms (CPR)
16	Macroinvertebrate biomas (CPUE)
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20	Gulf Stream front position
21	Stratification anomaly (0-50m)
29	Calanus hyperboreus (CPR)
31	SST anomaly (satellite)
35	NAO anomaly
37	No. of storms
42	Groundfish numerical abundance

Below Normal

Normal

Above Normal

48	Mixed layer salinity
49	Ice coverage
50	Groundfish landed value
55	Oxygen concentrations
61	Mixed layer depth
66	Length age 6 Silver Hake
68	Groundfish biomass
70	Calanus finmarchicus (CPR)
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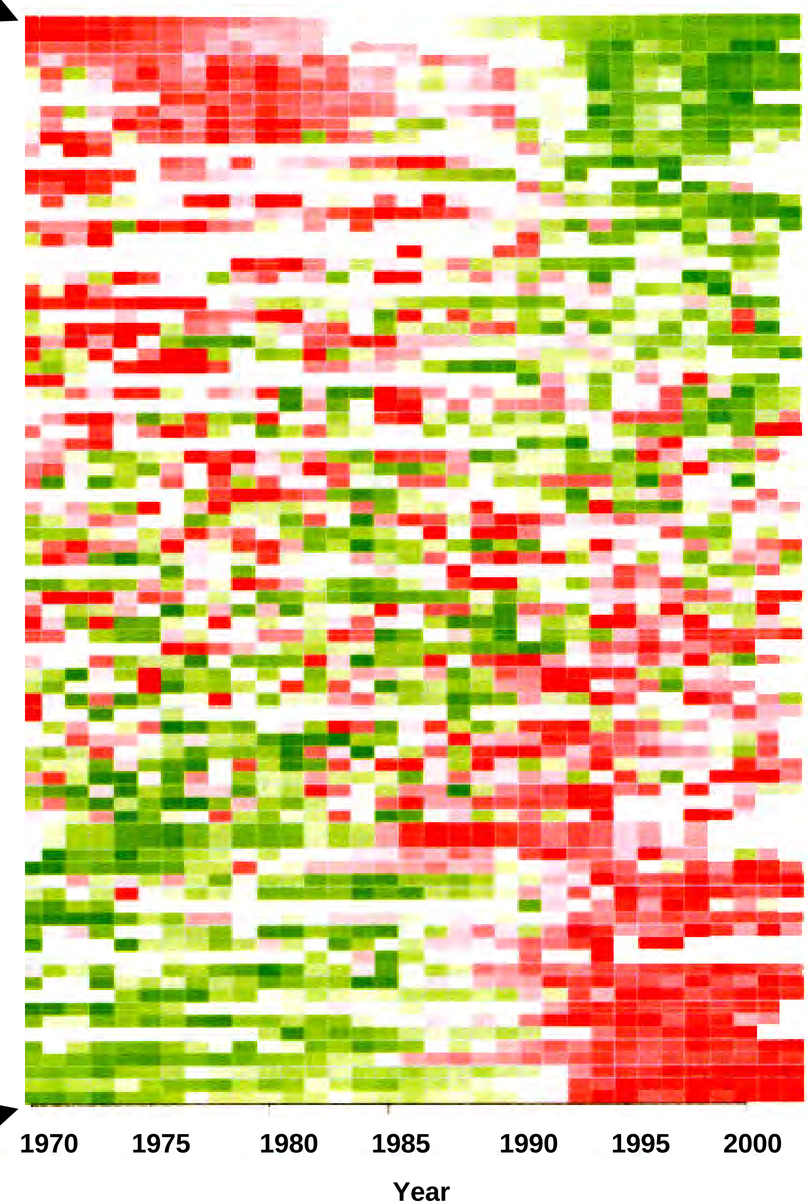
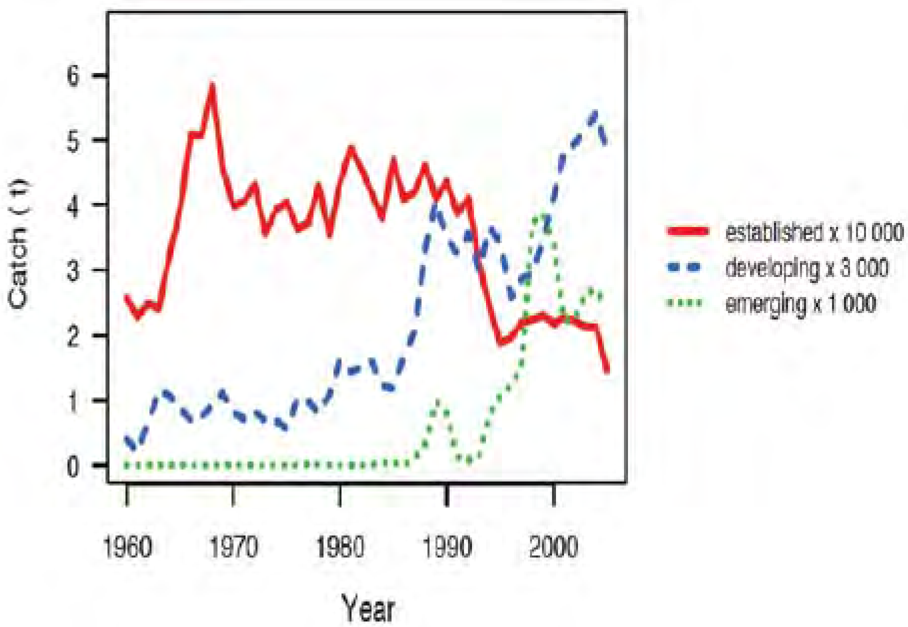
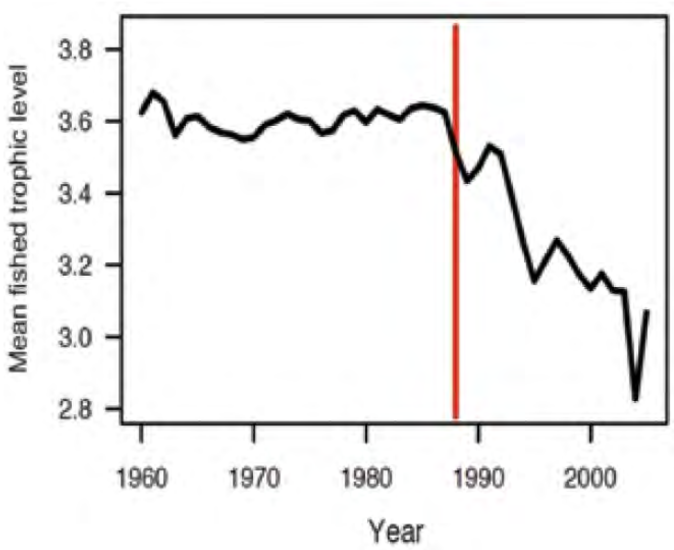


Frank, Choi, Petrie 2006. Proceedings of the Nova Scotian Institute of Science 43(2):185-198

Socio-economic shift: *from groundfisheries to lower trophic level fisheries*





Mean annual catch of fisheries divided into those that are:

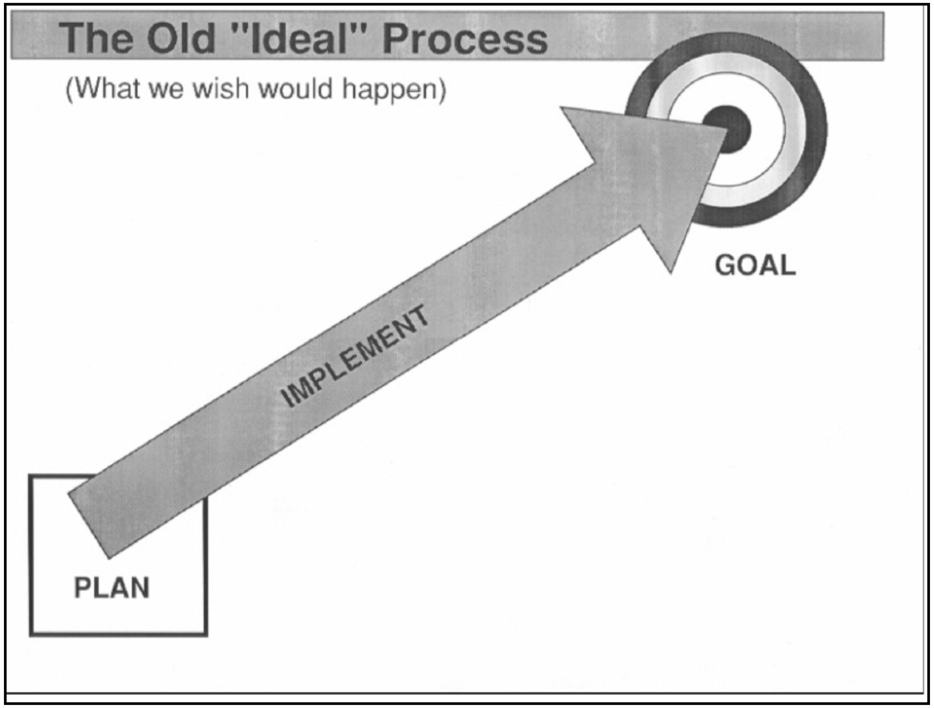
1) **established**: *cod, haddock, halibut, redfish, yellowtail flounder,herring;*

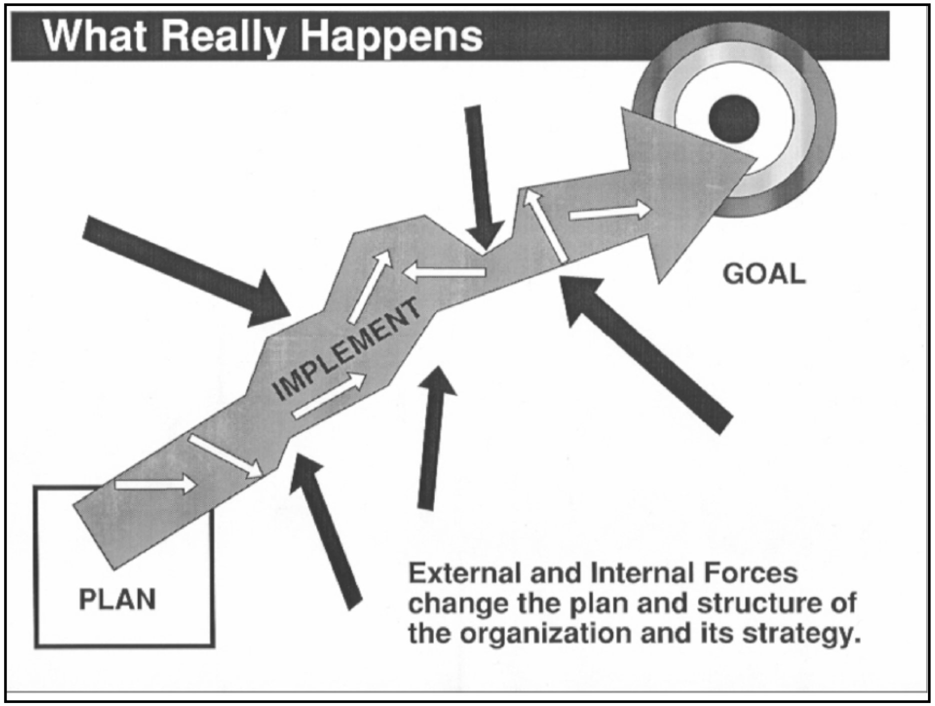
2) **developing**: *dogfish, lobster, snow crab, shrimp, scallop, periwinkles, rockweed*;

3) **emerging**: *red crab, rock crab, Jonah crab, quahog, Arctic surf clam, Altantic surf clam, sea urchin, sea cucumber*

Anderson SC, Lotze HK, Shackell NL 2008. Evaluating the knowledge base for expanding low trophic level fisheries in Atlantic Canada. CJFAS 65: 2553–2571

Ecological Futures: Predictions, Forecasts, Projections, Scenarios

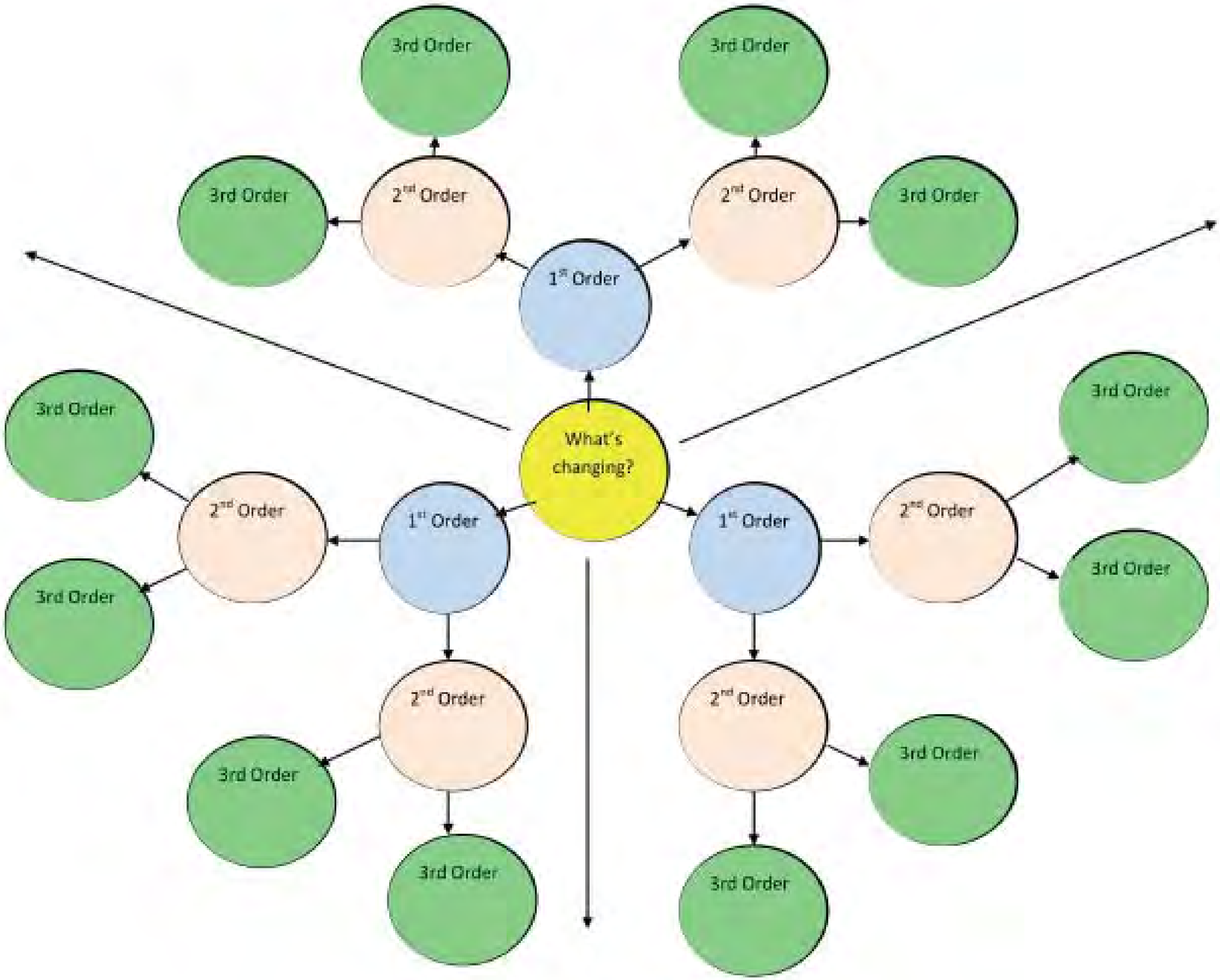




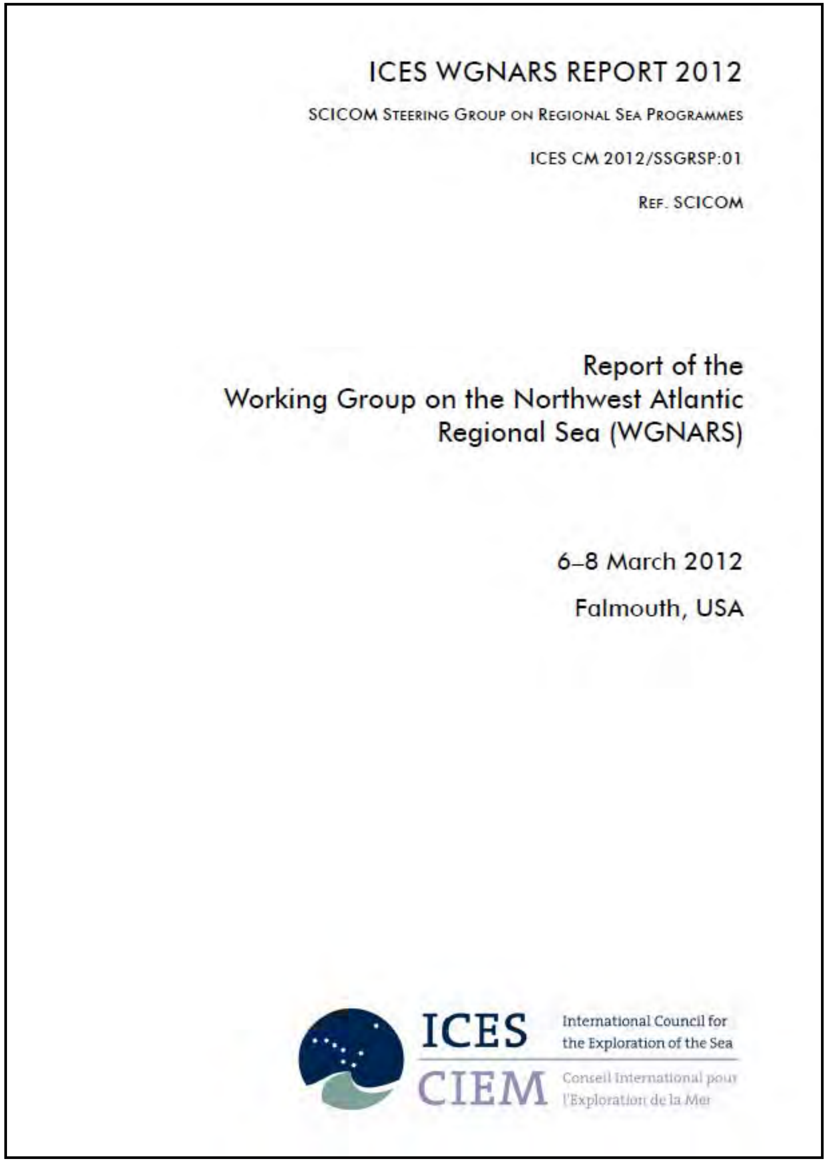
Source: Lloyd Walker, Precurve LLP

Ecological Futures: Predictions, Forecasts, Projections, Scenarios

"Futures Wheel" for impact assessment



Integrated Ecosystem Assessment



ICES WGNARS REPORT 2012

SCICOM Steering Group on Regional Sea Programmes

ICES CM 2012/SSGRSP:01

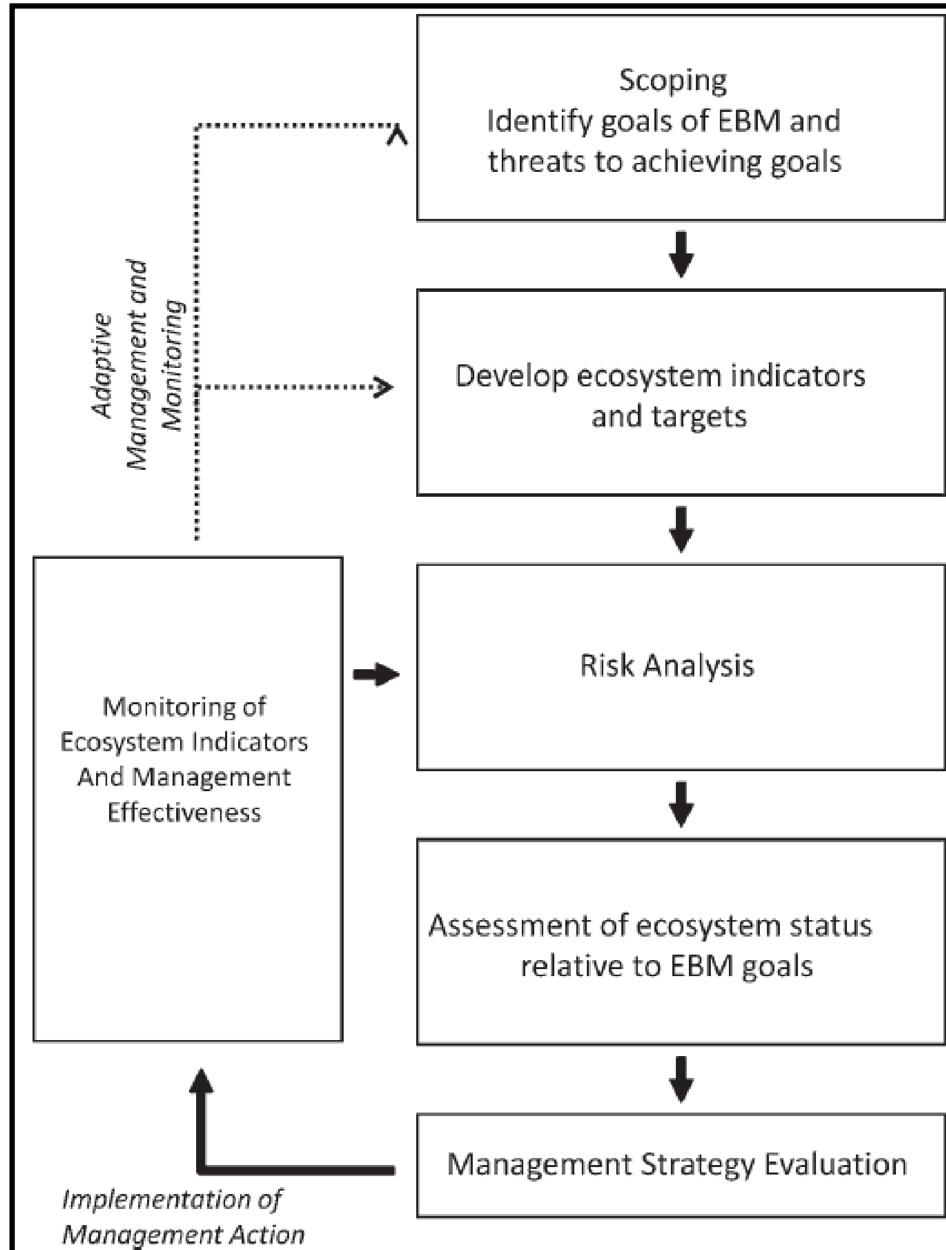
Ref. SCICOM

Report of the
Working Group on the Northwest Atlantic
Regional Sea (WGNARS)

6–8 March 2012

Falmouth, USA

ICES CIEM
International Council for the Exploration of the Sea
Conseil International pour l'Exploration de la Mer



Levin PS, Fogarty MJ, Murawski SA, Fluharty D 2009 Integrated ecosystem assessments: Developing the scientific basis for ecosystem-based management of the ocean. PLoS Biology 7(1):e1000014

Integrated Ecosystem Assessment

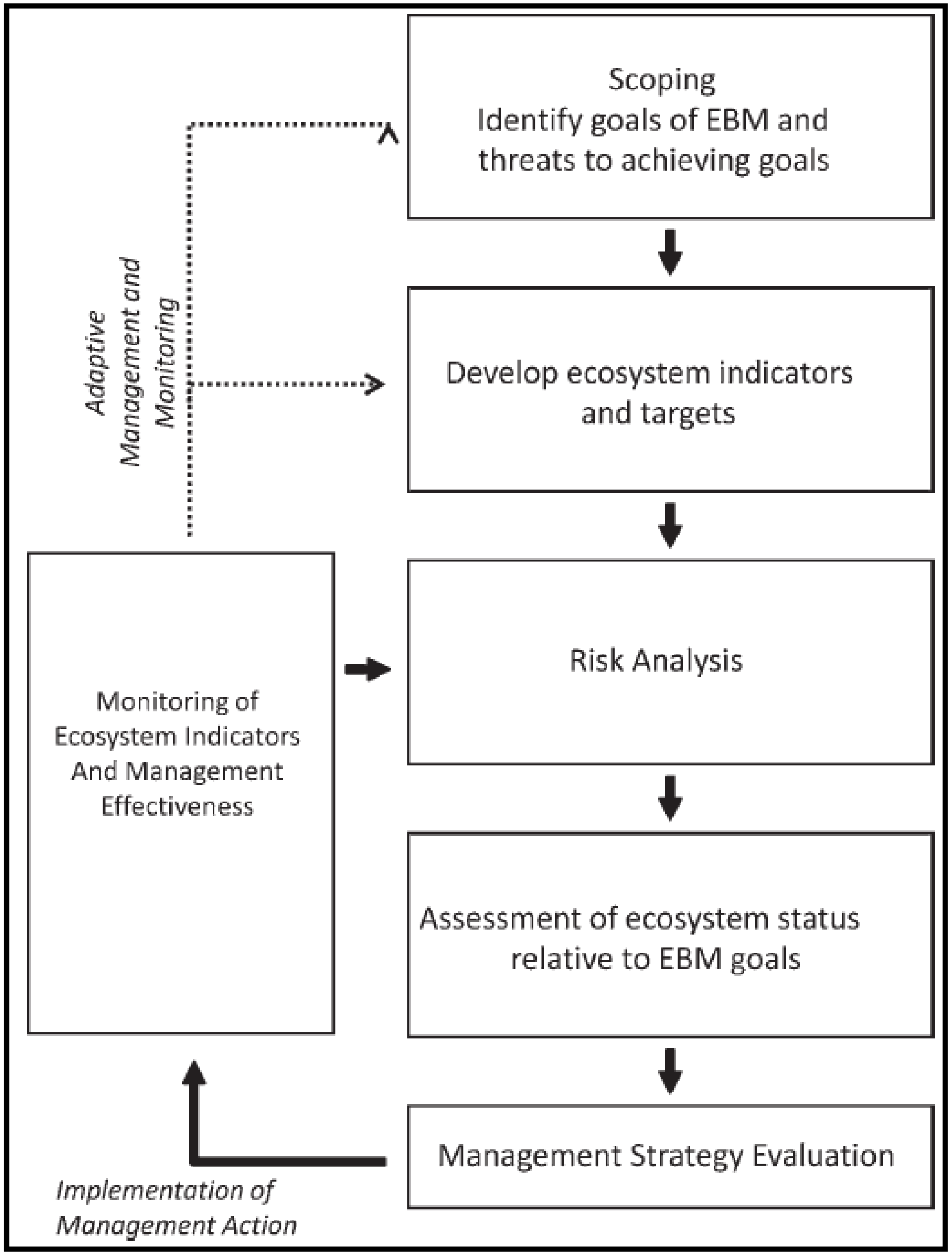
1. SCOPING
Begin with a scoping process to identify key management objectives and constraints.

2. INDICATOR DEVELOPMENT
Identify appropriate indicators and management thresholds.

3. RISK ANALYSIS
Determine the risk that indicators will fall below management targets; and combine risk assessments of individual indicators into a determination of overall ecosystem status.

4. MANAGEMENT STRATEGY EVALUATION
Evaluate the potential of different management strategies to alter ecosystem status.

5. MONITORING AND EVALUATION
Implement management actions and monitor their effectiveness. Repeat the cycle in an adaptive manner.



Levin PS, Fogarty MJ, Murawski SA, Fluharty D 2009 Integrated ecosystem assessments: Developing the scientific basis for ecosystem-based management of the ocean. PLoS Biology 7(1):e1000014

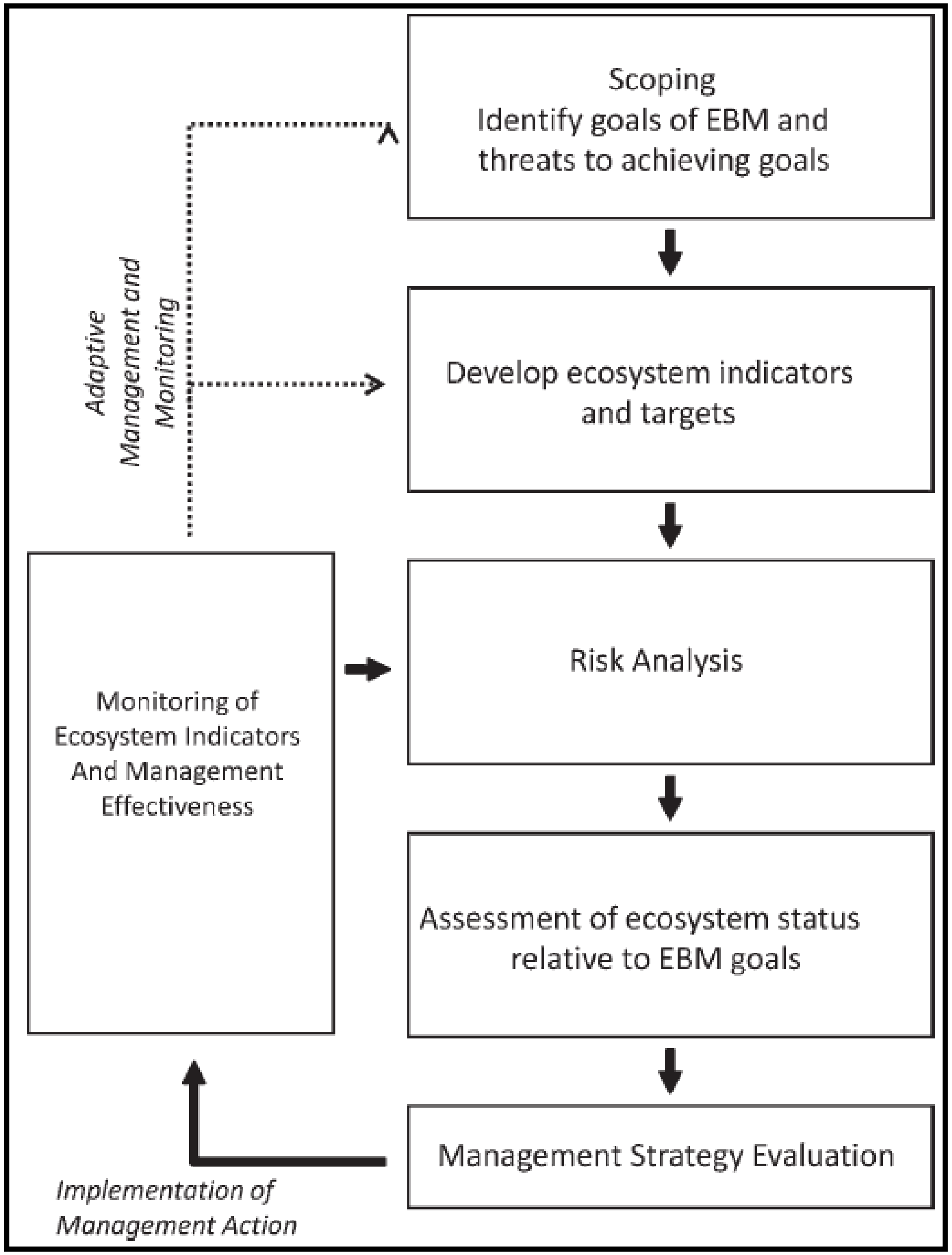
Integrated Ecosystem Assessment

Simply tallying the status and trends of various components of the ecosystem cannot inform Ecosystem-Based Management.

Instead, there is a clear need to actively integrate diverse physical, biological, and socioeconomic data

And to think critically about the ways in which decisions affect tradeoffs among ecosystem goods and services valued by society.

GOVERNANCE STRUCTURES are critical because in their absence, scientists are left to debate the causes and consequences of ecosystem-level impacts without an appropriate management authority to inform, or a mechanism to effect needed changes.



Levin PS, Fogarty MJ, Murawski SA, Fluharty D 2009 Integrated ecosystem assessments: Developing the scientific basis for ecosystem-based management of the ocean. PLoS Biology 7(1):e1000014

Ecosystem change: impacts, vulnerabilities, opportunities

OBJECTIVES (*what you want*)

1. Economically prosperous maritime sectors and fisheries
2. Sustainable aquatic ecosystems

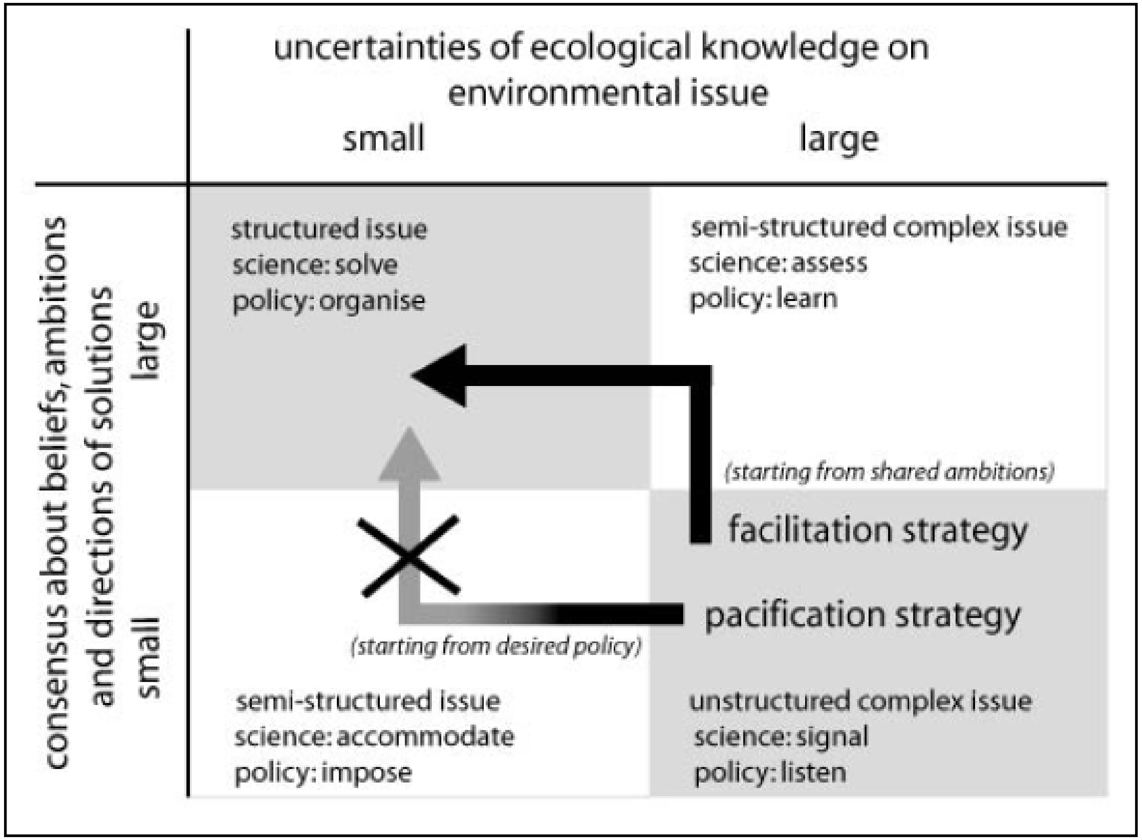
RISKS (*what may happen – vulnerabilities and opportunities*)

1. Ecosystem and fisheries degradation and damage
2. Changes in biological resources
3. Species reorganisation and displacement

ASSESSMENT FACTORS (*how to consider risks*)

1. Impact on the ecosystem (*extreme*, *very high*, *medium*, *low*, *negligible*)
2. Likelihood of the impact to occur (*almost certain*, *likely*, *moderate*, *unlikely*, *rare*)
3. Uncertainty of the analysis (*very high*, *high*, *moderate*, *low*, *very low*)

The Role of Ecological Science in Environmental Policy Making: from a Pacification toward a Facilitation Strategy



Before policy making can take place, **complex environmental issues** need to become more structured by **reducing either scientific uncertainty or societal dissent**: the "pacification strategy" and the "facilitation strategy," respectively.

A **pacification strategy**, in which science is expected to pacify stakeholders, is not an answer, as uncertainties are likely to remain high due to a different pacing of scientific progress and policy-making demands.

Instead, a **facilitation strategy** in which stakeholders formulate shared ambitions and directions for solutions at an early stage, and ecological scientists extend their participation in the process by scientifically assessing policy alternatives.

To support the creation of consensus between stakeholders including researchers, but also to ensure that knowledge is optimally used and assumptions are well founded, stakeholders' knowledge and solutions should be elicited, and confronted with the standards adhered to in a **scientific framework**.

DPSIR – A Scientific Framework for the Scotian Shelf

DRIVING FORCES
- Climate change (GHG emissions & natural variability)
- Population growth
- Increased demand for natural resources

RESPONSES
- National actions
- Provincial actions
- Trans-boundary responses
- Adaptation

PRESSURES
Changes in:
- Temperature
- Circulation
- pH
- Oxygen
- Salinity
- Ocean currents
- Sea level

IMPACTS
- Ecosystem productivity
- Spatial distribution
- Species composition
- Timing of seasonal events
- Trophic interactions
- Acidification
- Hypoxia
- Ecosystem buffering ability
- Adaptive ability of exploited species

STATE
- Thermal habitat changes
- Chemical habitat changes
- Hydrographic changes

DPSIR represents a systems analysis view:- social and economic developments exert pressure on the environment and, as a consequence, the state of the environment changes.

This leads to impacts on e.g. human health, ecosystems and materials that may elicit a societal response that **feeds back** on the driving forces, on the pressures or on the state or impacts directly, through adaptation or curative action.

Shackell & Loder "Climate Change and its Effects on Ecosystems, Habitats and Biota. State of the Scotian Shelf Report"

TROPHIC S

Table 1: Biophysical and socio-economic impacts of trophic imbalance

Table 1: Biophysical and socio-economic impacts of trophic imbalance

Table 2: Key Legislation that is applicable to managing species at risk on the Scotian Shelf.

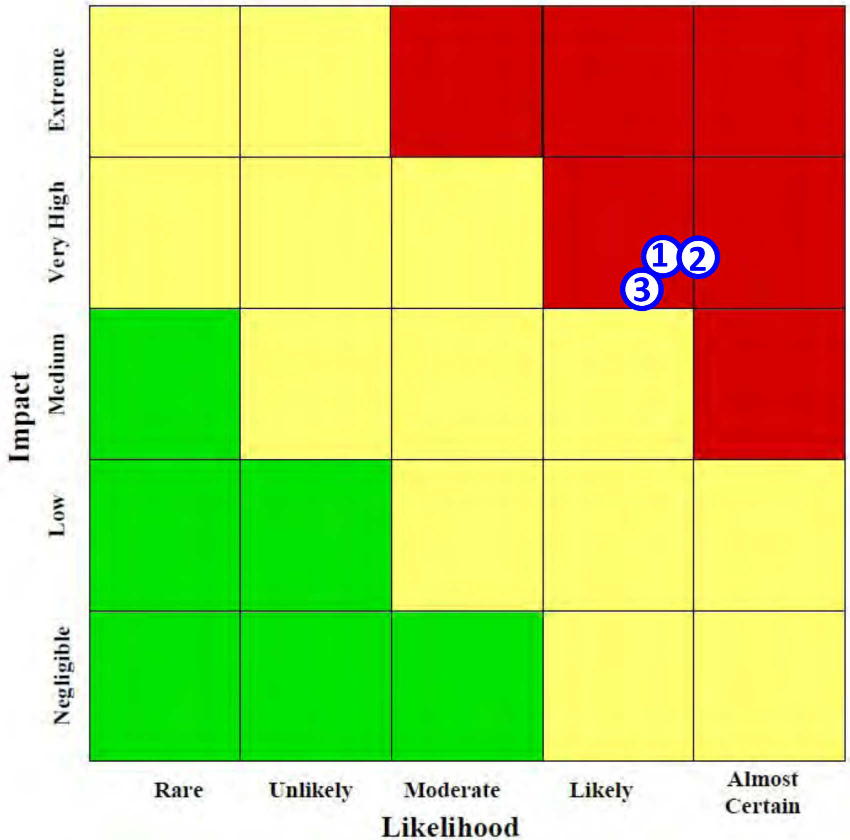
INDICATOR SUMMARY

INDICATOR	POLICY ISSUE	DPSIR	ASSESSMENT	TREND
Climate Change				

INDICATOR SUMMARY

INDICATOR	POLICY ISSUE	DPSIR	ASSESSMENT	TREND
Coastal Communities				
Fishery jobs	Employment levels in fishing industry	Impact	Poor	Unclear / Neutral
Health of Coastal Communities	Economic vibrancy and well-being	Impact	Poor	Negative
Fish Plants	Number of operational fish plants has declined	Impact	Poor	Unclear / Neutral
Fisheries Management				
Policy and legislation	All relevant policy and legislation are in place	Response	Fair	Unclear / Neutral
Practice	Implementation of policy is lagging	Response	Poor	Unclear / Neutral

Summary (*from science*)



1. Ecosystem and fisheries degradation and damage
2. Changes in biological resources
3. Species reorganisation and displacement

CLIMATE CHANGE RISK ASSESSMENT REPORT Fisheries and Oceans Canada

Perspective (*from economics*)

THE GLOBE AND MAIL

SATURDAY, SEPTEMBER 29, 2012 — SECTION B

Report on Business

Designed to deliver consistent returns + yield — Sprott Flatiron Yield Trust www.sprott.com/flatiron

EDITOR: DEREK DeCLOET

S&P/TSX 12,317.46 (-21.39) | DOW 13,437.13 (-48.84) | S&P 500 1,440.67 (-6.48) | DOLLAR 101.71 (-0.24) | GOLD 1,773.90 (-6.60) | OIL 92.19 (+0.34) | GCAN 10-YR 1.723% (-0.03)

DEBT CRISIS

A world on thin ice, an economy in peril and a dose of perspective

ERIC REGULY
ereguly@globeandmail.com

ROME

Climate change skeptics, from the ultra-conservative think tanks to oil company executives, have spent years attacking climate change scientists and politicians who dared to believe that man-made carbon-dioxide emissions were accelerating global warming. The scientists were pilloried if they got the slightest thing wrong. Guess what? The scientists did get one huge thing wrong – they vastly underestimated the rate of the Arctic ice melt.

The economic effects are still largely unknown, but evidence is building that it will not be sweet. Makes you wonder why so much energy and money is being devoted to far lesser crises.

Eric Reguly, The Globe and Mail
September 29, 2012

Perspectives on FUTURE (Forecasting & Understanding Trends, Uncertainty and Responses)

PERSPECTIVES

THE ROBERT H. MACARTHUR AWARD LECTURE

Ecology, 83(8), 2002, pp. 2069–2083

ECOLOGICAL FUTURES: BUILDING AN ECOLOGY OF THE LONG NOW[1]

Stephen R. Carpenter

Center for Limnology, 680 North Park Street, University of Wisconsin, Madison, Wisconsin 53706 USA

Stephen R. Carpenter, MacArthur Award Recipient, 2000

Abstract. Ecosystem dynamics unfold into the future but are understood by examining the past. A forward-looking ecology, which assesses a broad range of possible future ecosystem states, is the complement of long-term, historical approaches to ecology. Together they are the ecology of the long now. The "long now" of ecosystems includes historical influences that shape present ecologies, and the future consequences of present events.

As a step in testing theories by their consequences, prediction is widely used in ecology. Ecologists have developed, criticized, and improved many predictive theories. Ecologists also have developed many empirical relationships that are potentially useful in forecasting. Eutrophication is an example of a problem for which ecologists created fundamental understanding, predictive capability, and new options for management.

Ecologists frequently justify their research funding through appeals to improved predictability. This goal is sometimes attainable and in any case motivates a considerable body of insightful research. However, in many cases of environmental decision making, what ecologists cannot predict is at least as important as what can be predicted. It is important to assess the full range of changes in ecosystems that may plausibly occur in the future, and the implications of these changes. The paper discusses some ways that ecological information can be used to improve understanding of the future consequences of present choices.

Key words: adaptive management; alternate states; Bayesian analysis; ecological economics; eutrophication; fishery; forecast; long-term research; optimal control; prediction; resilience; uncertainty.

Manuscript received 17 August 2001; accepted 10 December 2001; final version received 22 January 2002.

[1] Presented 7 August 2001 in Madison, Wisconsin, USA.

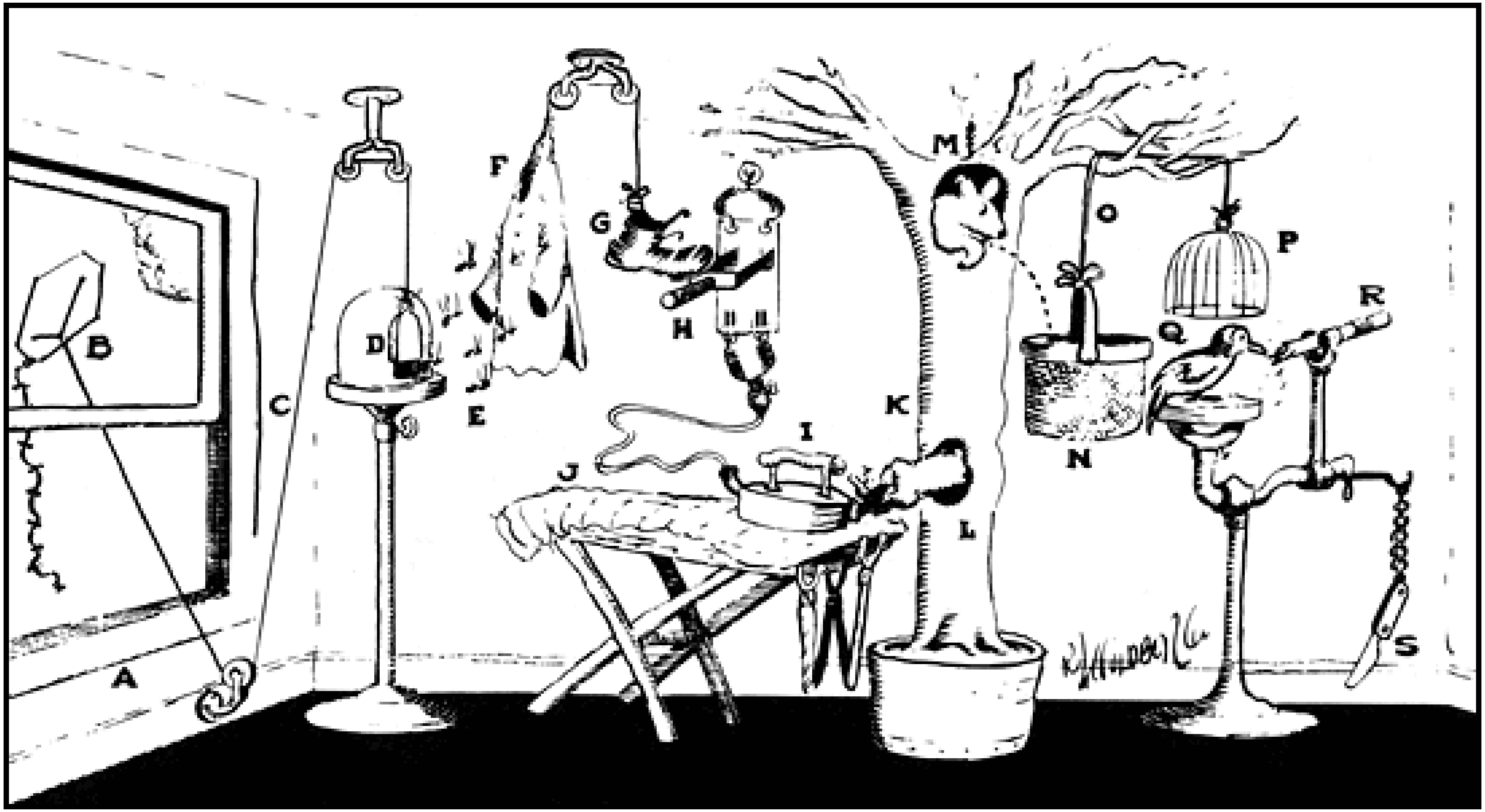
Despite the usefulness of prediction as a tool for advancing ecological research, **the future of integrated systems of people and nature is beyond the traditional scope of ecology**. This calls for new forms of ecological research as well as creative ways of coping with an ever-changing environment

Ecologists must embrace a bipolar stance toward prediction.

At one pole, ecologists strive to expand our capabilities to forecast ecological change for spatial extents and time horizons of human action. A culture of prediction and rigorous assessment of probabilities will improve the science of ecology.

At the opposite pole, ecologists must acknowledge the shortcomings of ecological predictions and frankly admit when prediction is inappropriate.

Cause and effect in a mechanistic worldview: will this pencil sharpener work?



Open window (A) and fly kite (B). String (C) lifts small door (D) allowing moths (E) to escape and eat red flannel shirt (F). As weight of shirt becomes less, shoe (G) steps on switch (H) which heats electric iron (I) and burns hole in pants (J). Smoke (K) enters hole in tree (L), smoking out opossum (M) which jumps into basket (N), pulling rope (O) and lifting cage (P), allowing woodpecker (Q) to chew wood from pencil (R), exposing lead. Emergency knife (S) is always handy in case opossum or the woodpecker gets sick and can't work.