Part 1 : Physical and ecological impacts of climate change relevant to marine and inland capture fisheries and aquaculture

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1. **Climate Change: the physical basis in marine and freshwater systems**
   - Heat content and temperature
   - Salinity and stratification
   - Ocean circulation and coastal upwelling
   - Sea level rise
   - Acidification and other chemical properties
   - Atmosphere-Ocean and Land-Ocean exchanges
   - Low frequency climate variability patterns

2. **Effects of climate variability and change on ecosystem and fish production processes**
   - Summary of physiological, spawning, and recruitment processes sensitive to climate variability
   - Primary production
   - Secondary production
   - Distribution changes
   - Abundance changes
   - Phenological changes
   - Species Invasions and diseases
   - Food web impacts from zooplankton to fish
   - Regime shifts and other extreme ecosystem events

3. Anticipated impacts of climate change on ecosystems and fish production

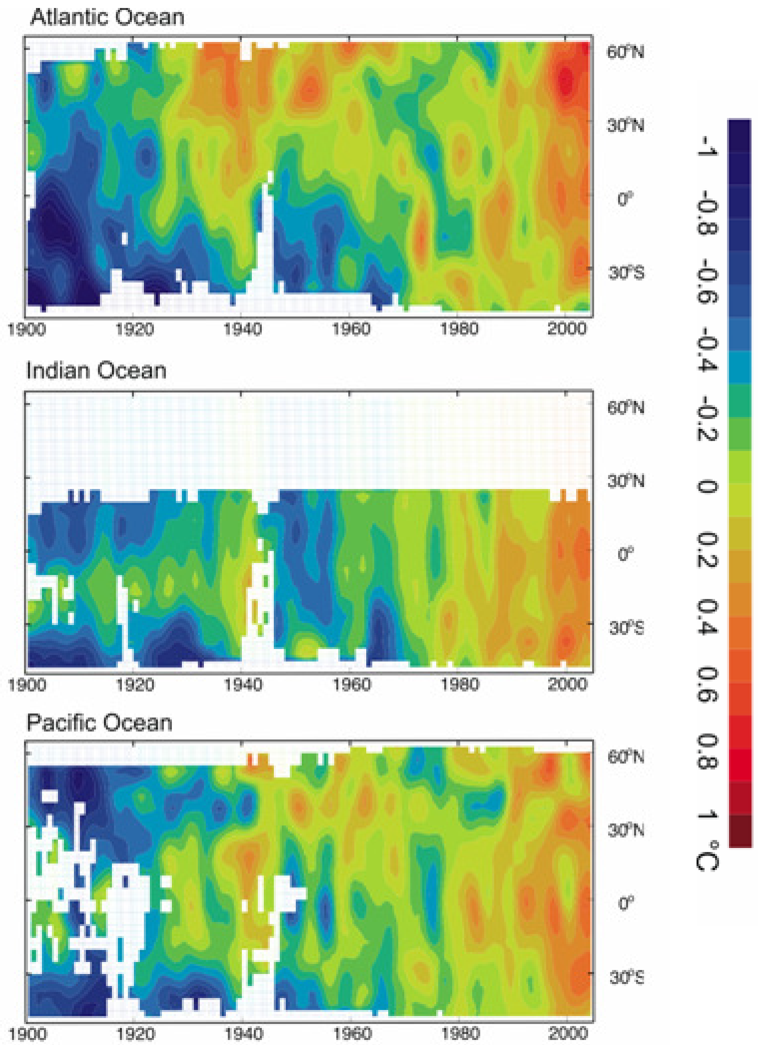
- General impacts:
  - *Rapid time scales*
  - *Intermediate time scales*
  - *Long time scales*
- Case studies:
  - *Arctic*
  - *North Atlantic*
  - *North Pacific*
  - *Wind-driven coastal upwelling systems*
  - *Tropical and sub-tropical seas*
  - *Coral reef systems*
  - *Freshwater systems*
  - *Aquaculture systems*
- Uncertainties and research gaps

1. **Climate Change: the physical basis in marine and freshwater systems**

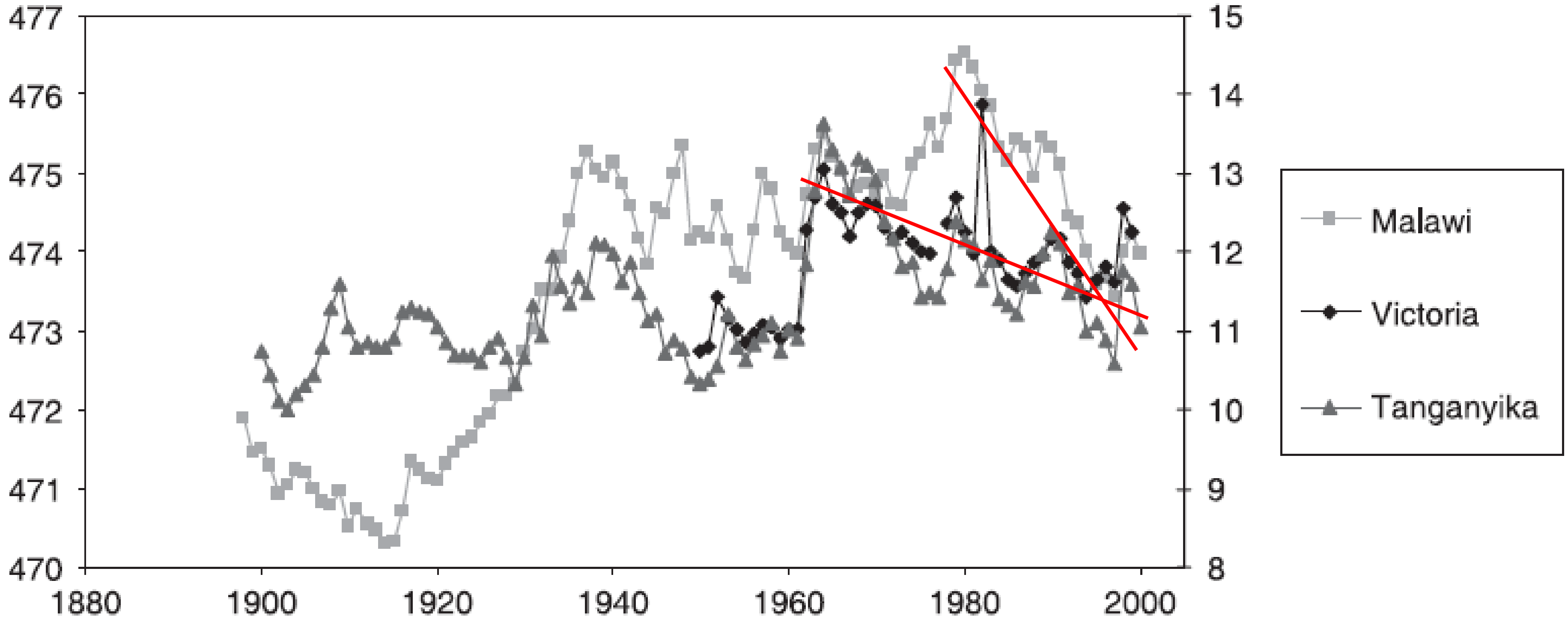
2. **Effects of climate variability and change on ecosystem and fish production processes**

3. **Anticipated impacts of climate change on ecosystems and fish production**

•*Oceans are warming, and the warming is more intense in surface (0-700m) waters but also in deeper waters of the Atlantic Ocean*

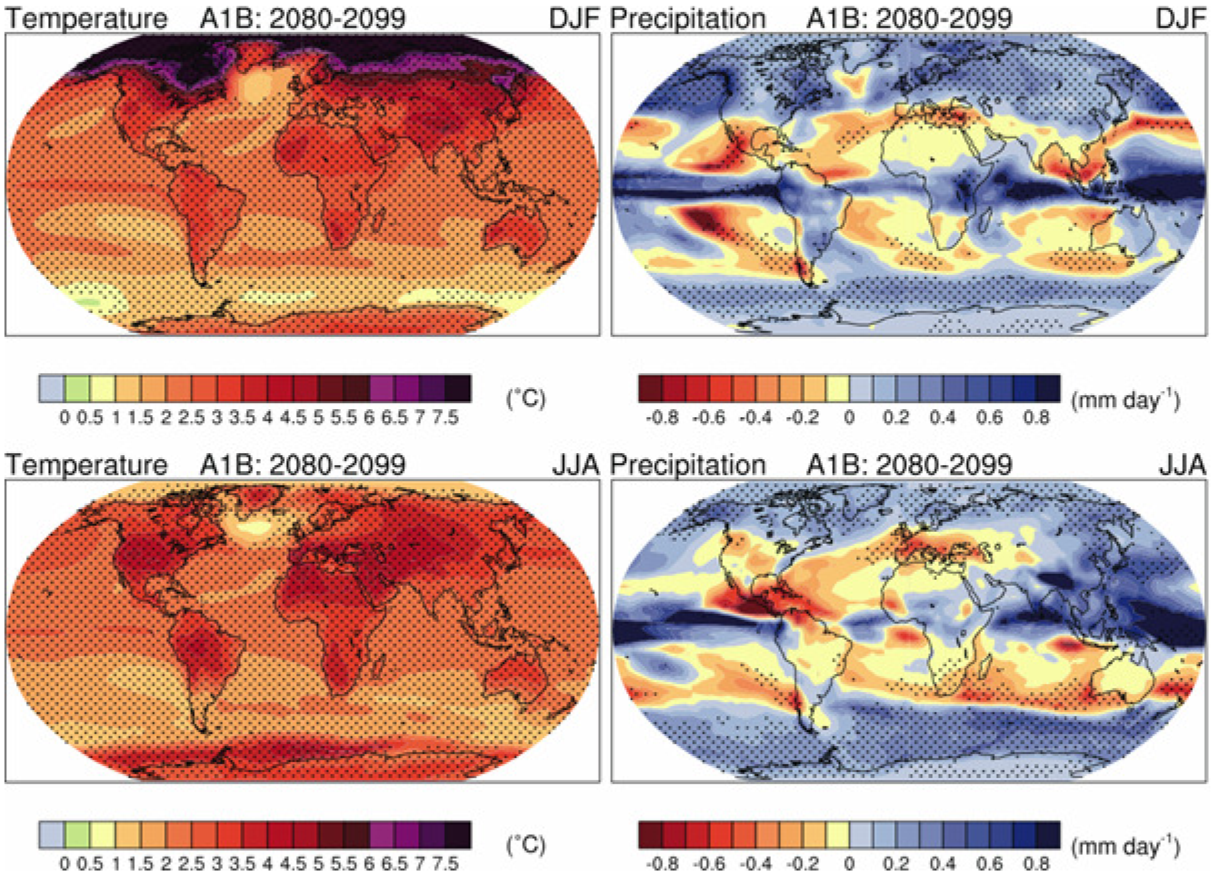


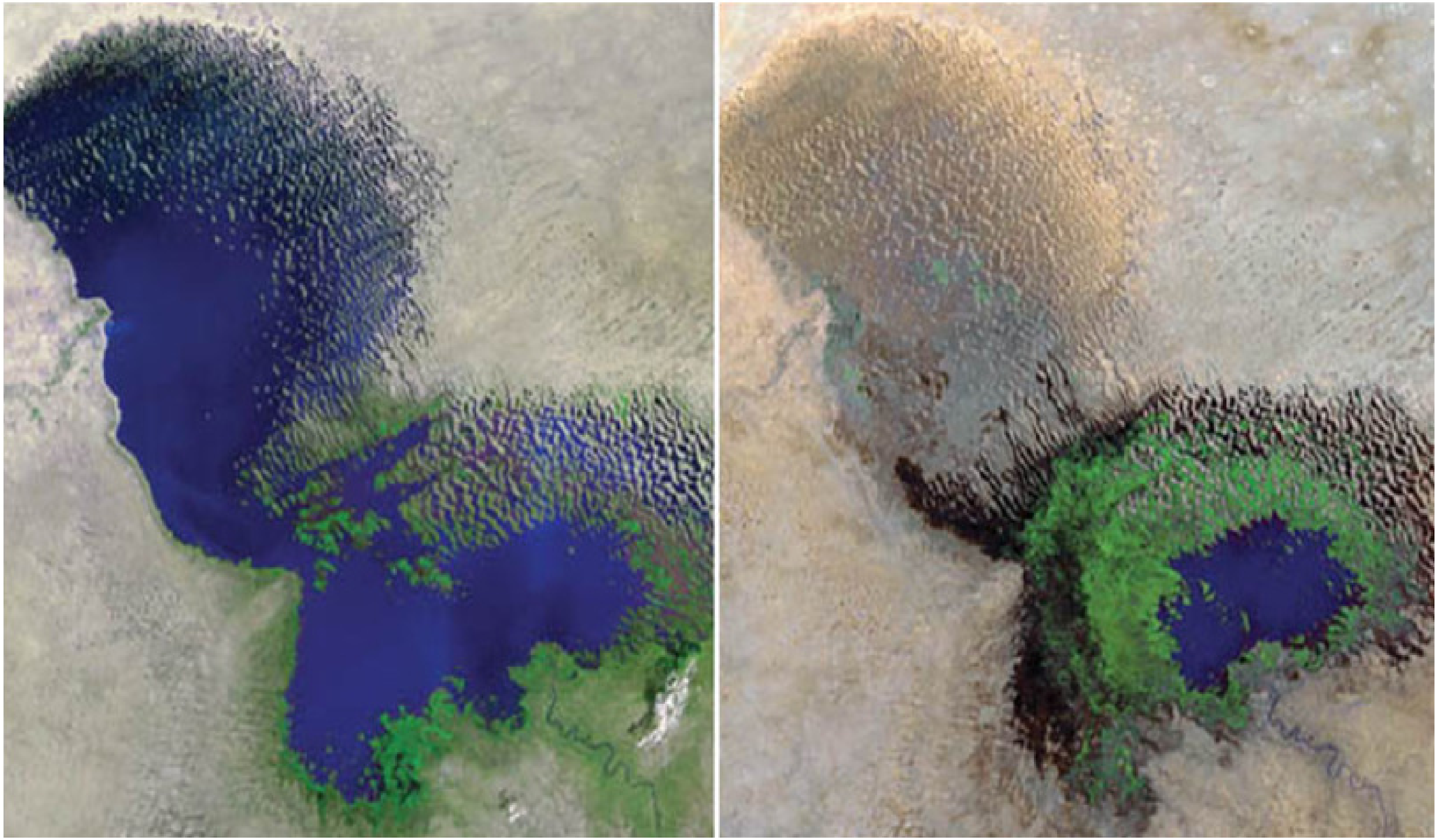
•***Many lakes have experienced warming, and levels are decreasing in many areas as a result of human use and precipitation changes***



Annual mean water levels for the African Great Lakes (as m a.s.l.) relative to Lake Malawi elevations (left) or Victoria lake (right) from Hecky et al. (2006)

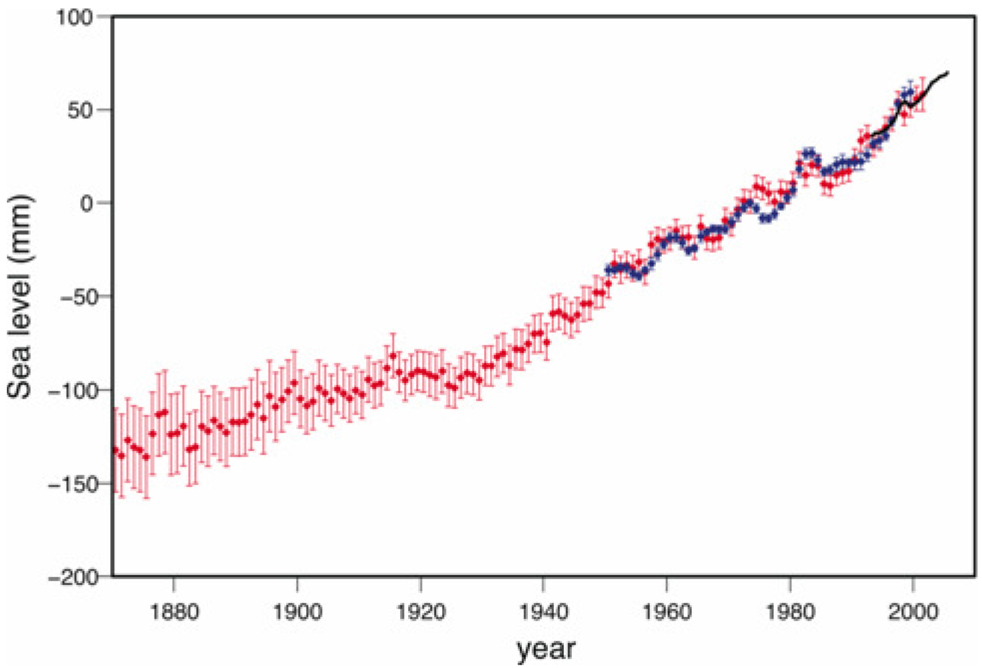
•*River run-off is expected to increase at higher latitudes and decrease in parts of West Africa, southern Europe and southern Latin America. Overall a 4% increase in river run off is associated with a 1°C global increase in temperature*





•***Global average sea level has been rising at an average rate of 1.8 mm per year since 1961. The rate has accelerated since 1993 to about 3.1 mm per year***

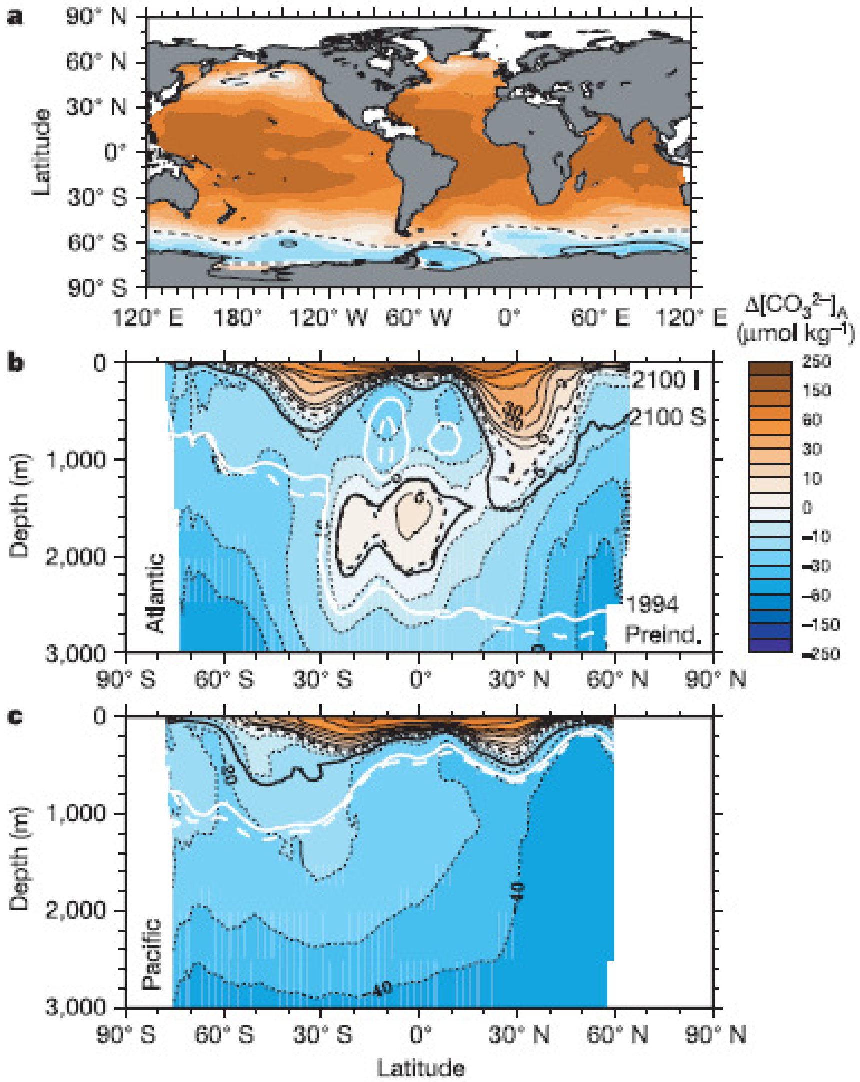
https://www.cresis.ku.edu



•Surface seawater pH has decreased by 0.1 units in the last 200 years. Model estimates predict further reduction of 0.3-0.5 pH units over the next 100 years

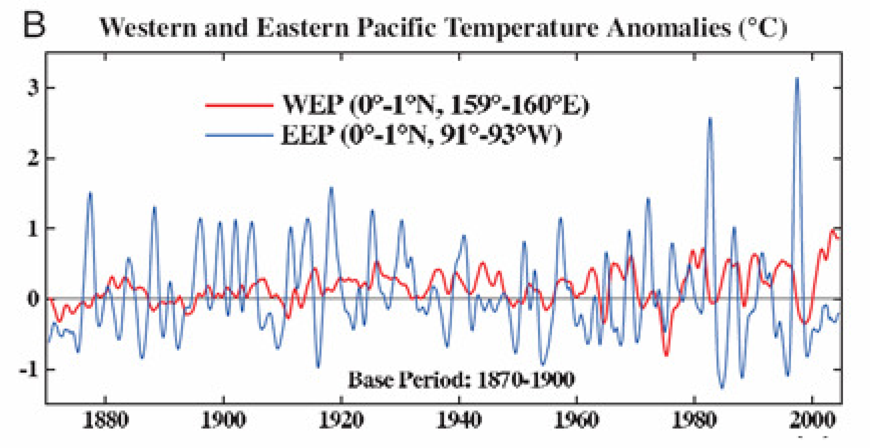
Atlantic

Pacific

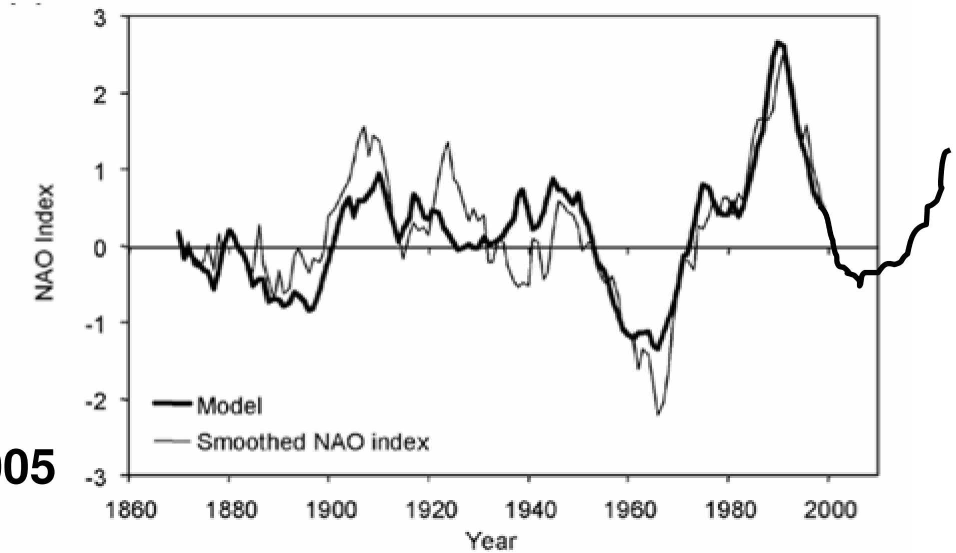


Orr et al. 2005

•*Some studies indicate an increase in the intensity and frequency of particular atmospheric patterns (eg. NAO, ENSO), but in general climate models predict a rather spatially uniform warming trend throughout the ocean basins combined with the continued presence of decadal variability similar to that of the 20th century*



ENSO
Hansen et al. 2006



NAO
Taylor et al 2005

1. Climate Change: the physical basis in marine and freshwater systems

2. **Effects of climate variability and change on ecosystem and fish production processes**

3. Anticipated impacts of climate change on ecosystems and fish production

- ***Climate warming would lead to a contraction of the highly productive marginal sea ice biome and the seasonally stratified subtropical gyre, and an expansion of the low productivity permanently stratified subtropical gyre biome and the subpolar gyre biome***

Table 6. Average Response of Biogeographical Province Areas to Global Warming Averaged Over the Period 2040 to 2060[a]

	Indian Ocean			Pacific Ocean			Atlantic Ocean				Global	
	Control	Δ	%Δ	Control	Δ	%Δ	Control	Δ	%Δ	Control	Δ	%Δ
Northern Hemisphere												
Marginal sea ice				3.8	−1.7	−45.3	3.2	−1.2	−37.5	7.0	−2.9	−41.7
Subpolar				8.5	1.2	13.9	5.5	1.1	19.7	14.0	2.3	16.2
Subtropical seasonal				4.9	−0.7	−13.4	8.8	−0.8	−9.4	13.6	−1.5	−10.9
Subtropical permanent	3.3	0.1	2.3	35.4	1.0	2.9	12.5	0.9	7.4	51.2	2.0	4.0
Low-latitude upwelling	2.1	−0.1	−6.8	10.9	0.2	1.6	4.4	0.0	0.8	17.3	0.1	0.4
5°S to 5°N												
Upwelling	4.5	0.5	10.1	14.6	0.2	1.3	4.6	0.1	2.4	23.7	0.7	3.2
Downwelling	2.3	−0.5	−19.5	4.4	−0.2	−4.3	1.3	−0.1	−10.9	7.7	−0.8	−9.7
Southern Hemisphere												
Low-latitude upwelling	7.9	−0.1	−0.7	8.7	−0.6	−7.3	3.8	0.2	4.8	20.4	−0.5	−2.5
Subtropical Permanent	15.0	1.1	7.3	37.4	3.6	9.7	13.9	1.5	10.8	66.3	6.2	9.4
Subtropical seasonal	13.8	−0.5	−3.3	12.1	−1.8	−14.7	6.4	−1.2	−18.4	32.3	−3.4	−10.6
Subpolar	8.2	1.5	18.7	12.5	0.4	3.3	7.1	0.2	3.4	27.8	2.2	7.9
Marginal sea ice	8.8	−2.1	−23.7	8.8	−1.5	−16.9	7.8	−0.8	−10.3	25.3	−4.4	−17.2
Total	65.8			161.9			79.3			306.7		

[a]Areas are given in 10^{12} m^2. Δ is the difference between the model average warming minus control; %Δ is the per cent change of the averages shown in the table. The averages are taken over all the AOGCMs except MPI, which was not included because its prognostic mixed layer generally gives much shallower mixed layers than the potential density-dependent definition used by the remaining models. The basin and global totals of the control simulation are smaller than the observed areas due to the coarse grid resolution of the models. There is no Atlantic downwelling province in the GFDL model. The following provinces disappear in the warming scenarios: Pacific downwelling in the GFDL model, Southern Hemisphere Atlantic subtropical seasonal in the GFDL model, and Northern Hemisphere Pacific marginal sea ice in the CSIRO model.

Sarmiento et al. 2004

•*Increased vertical stratification and water column stability in oceans and lakes is likely to reduce nutrient availability to the euphotic zone and thus primary and secondary production in a warmed world. However, in high latitudes the residence time of particles in the euphotic zone will increase, extending the growing season and thus increasing primary production. Overall a small global increase in primary production will be expected, with very large regional differences.*

Table 9. Predicted Response of Primary Production (mg carbon m^{-2} d^{-1}) to Global Warming for the Period 2040 to 2060[a]

	Indian Ocean			Pacific Ocean			Atlantic Ocean			Global		
	Control	Δ	%Δ	Control	Δ	%Δ	Control	Δ	%Δ	Control	Δ	%Δ
B&F Model												
Northern Hemisphere												
Marginal sea ice				667	99	14.9	655	80	12.2	650	85	13.2
Subpolar				477	97	20.5	934	46	4.9	609	101	16.5
Subtropical seasonal				579	9	1.6	647	26	4.0	626	25	3.9
Subtropical permanent	528	−34	−6.4	282	−3	−1.1	352	−25	−7.2	309	−9	−2.9
Low-latitude upwelling	417	−16	−3.9	222	−4	−1.7	448	−38	−8.5	286	−11	−4.0
5°S to 5°N												
Upwelling	375	−23	−6.0	477	−58	−12.2	540	−50	−9.3	465	−49	−10.5
Downwelling	355	−9	−2.5	413	−26	−6.4	468	−47	−10.0	395	−21	−5.4
Southern Hemisphere												
Low-latitude upwelling	280	−18	−6.6	254	−9	−3.4	873	−73	−8.4	326	−9	−2.8
Subtropical permanent	334	−15	−4.5	327	−14	−4.2	406	−7	−1.7	343	−12	−3.4
Subtropical seasonal	523	23	4.3	340	16	4.8	547	16	3.0	444	25	5.7
Subpolar	283	17	5.9	317	21	6.7	356	88	24.6	314	33	10.6
Marginal sea ice	158	28	17.9	233	29	12.6	159	58	36.3	179	40	22.2

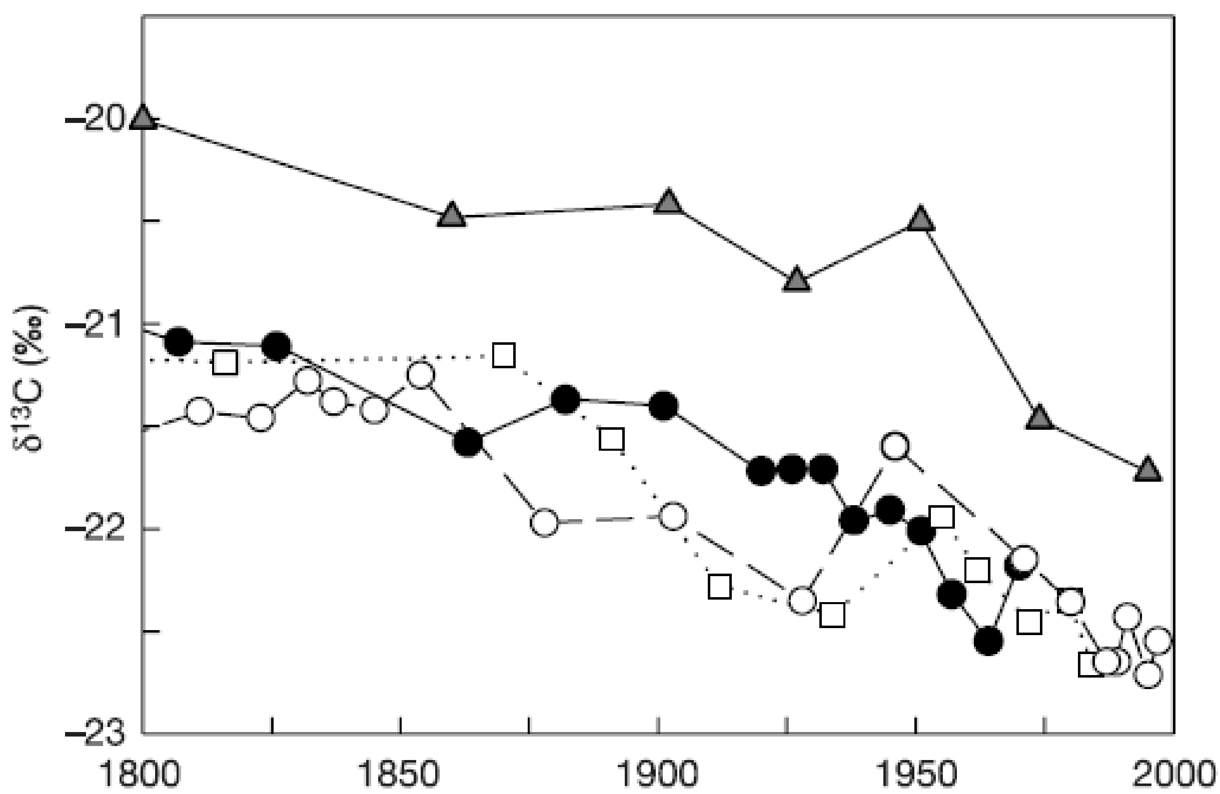
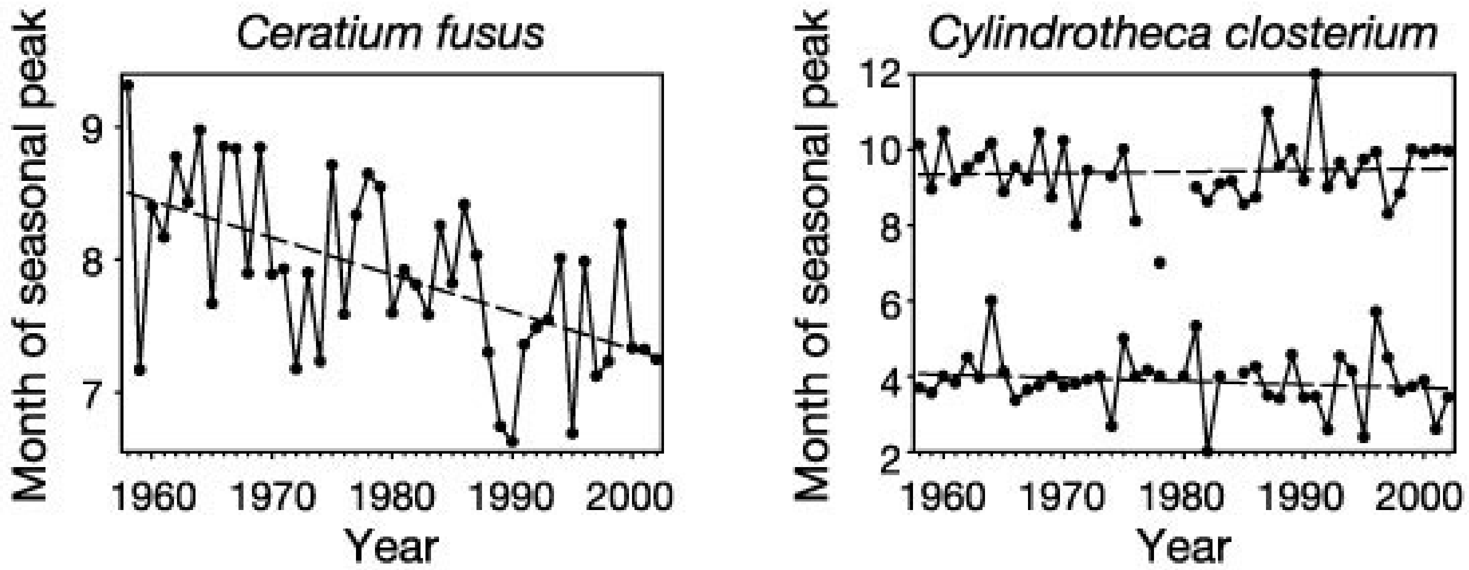


Figure 3 Carbon isotope records in sediment cores. $\delta^{13}C$ values indicate a post- 1950s trend towards more negative values in all cores. Filled symbols represent cores from relatively undisturbed watersheds (filled circles, LT-98-58M; grey triangles, LT-97-56V), and open symbols represent cores from developed watersheds (squares, LT-98-37M; circles, LT-98-82M).

Lake Tanganyika. O'Reilly et al. 2003

•***Plankton community structure is changing: dinoflagellates have advanced their seasonal peak in response to warming, while diatoms have shown no consistent pattern of change.***



Edwards and Richardson 2004

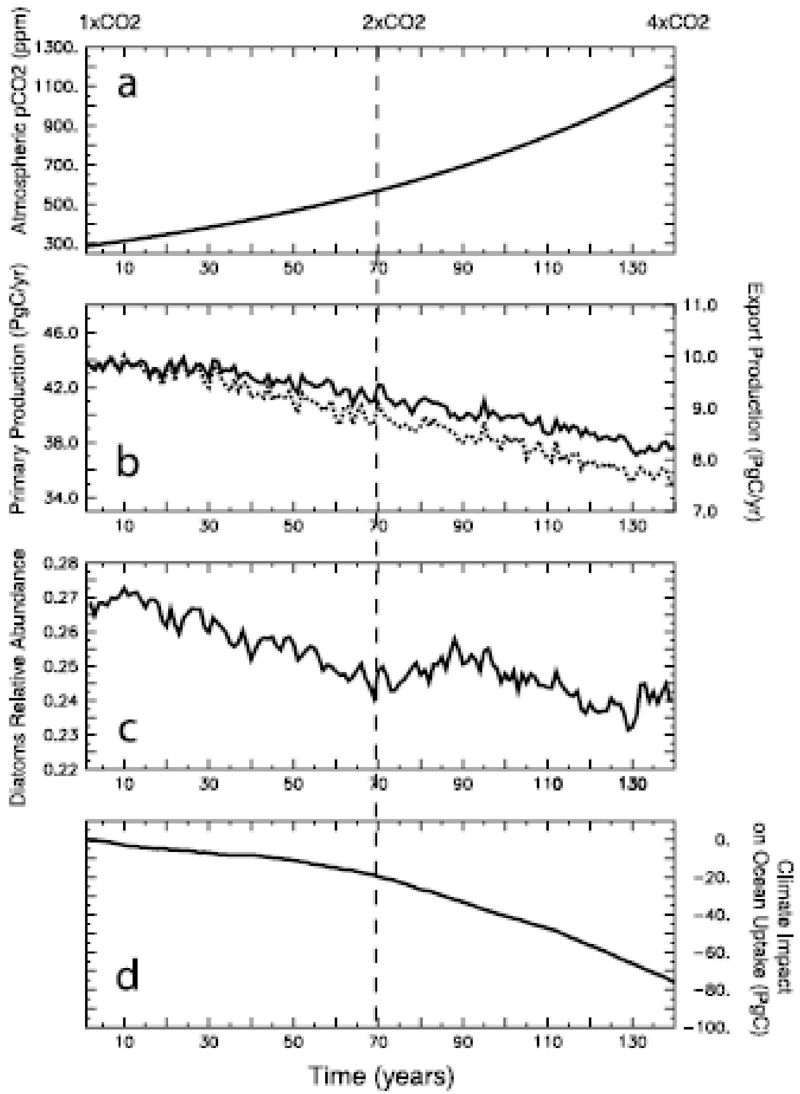


Figure 2. Time series of (a) atmospheric CO_2 (ppm) which increases at a rate of 1% y^{-1}, (b) global primary productivity (full line) in PgC y^{-1} (left axis) and global particulate export production at 100 m (dotted line) in PgC y^{-1} (right axis), (c) global mean contribution of diatoms to total chlorophyll and (d) climate change cumulative effect on oceanic carbon uptake (PgC).

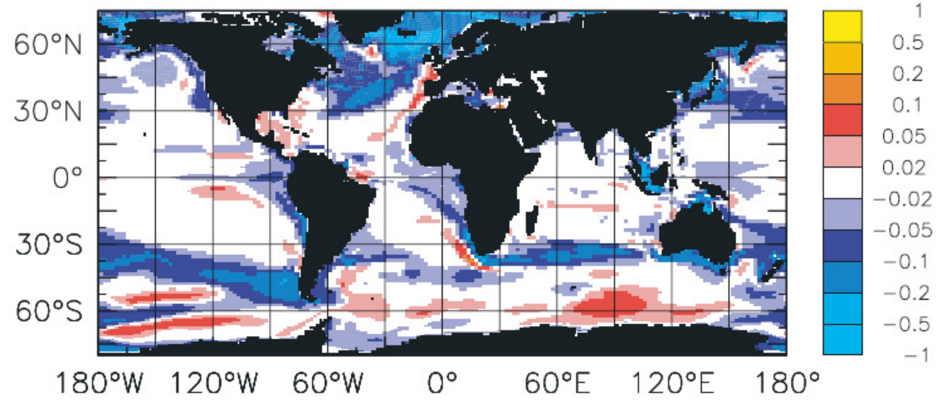
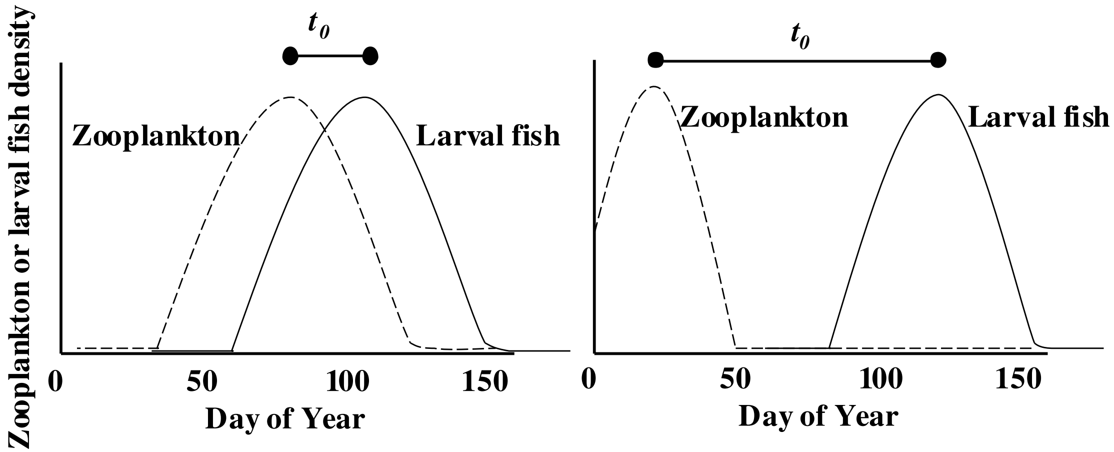


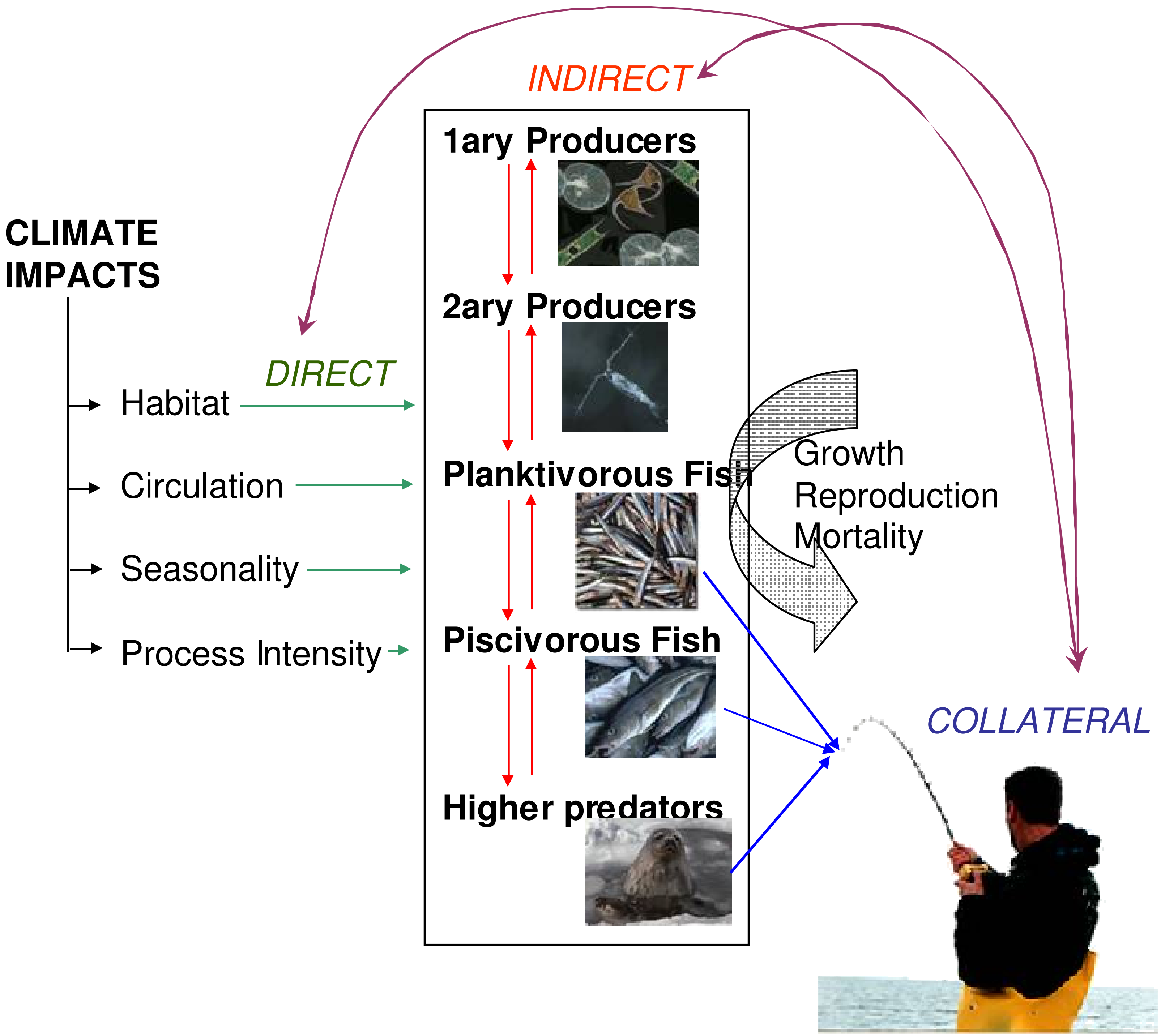
Figure 3. Simulated changes ($4xCO_2$ – $1xCO_2$) in the relative abundance of diatoms.

Bopp et al. 2005

•***Observations in many European and North American lakes suggests that the spring phytoplankton bloom has advanced due to warming, but that zooplankton has not responded similarly, and their populations are declining because their emergence no longer corresponds with high algal abundance. There is concern that marine and freshwater trophodynamics may have already been radically altered by ocean warming through predator-prey mismatch.***

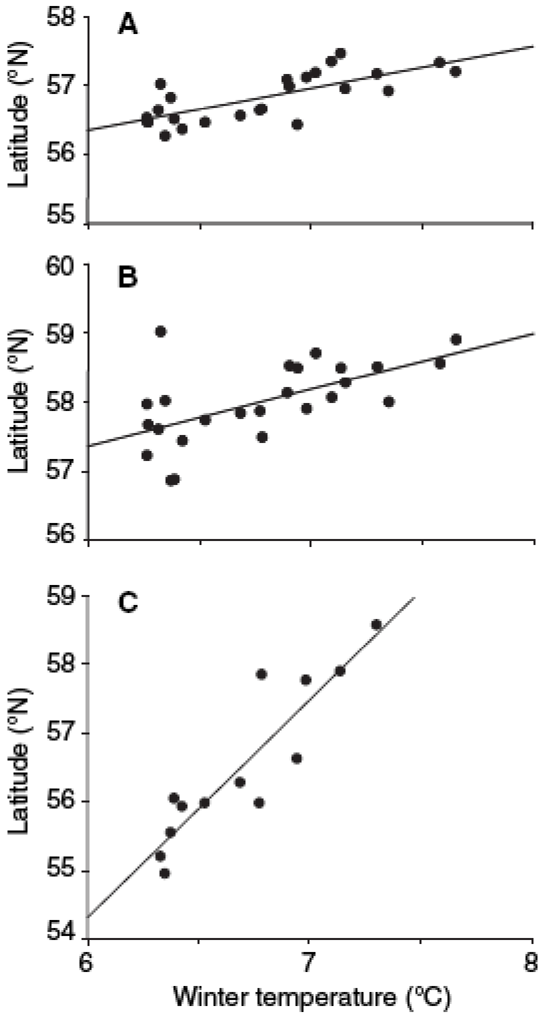


Cushing 1990



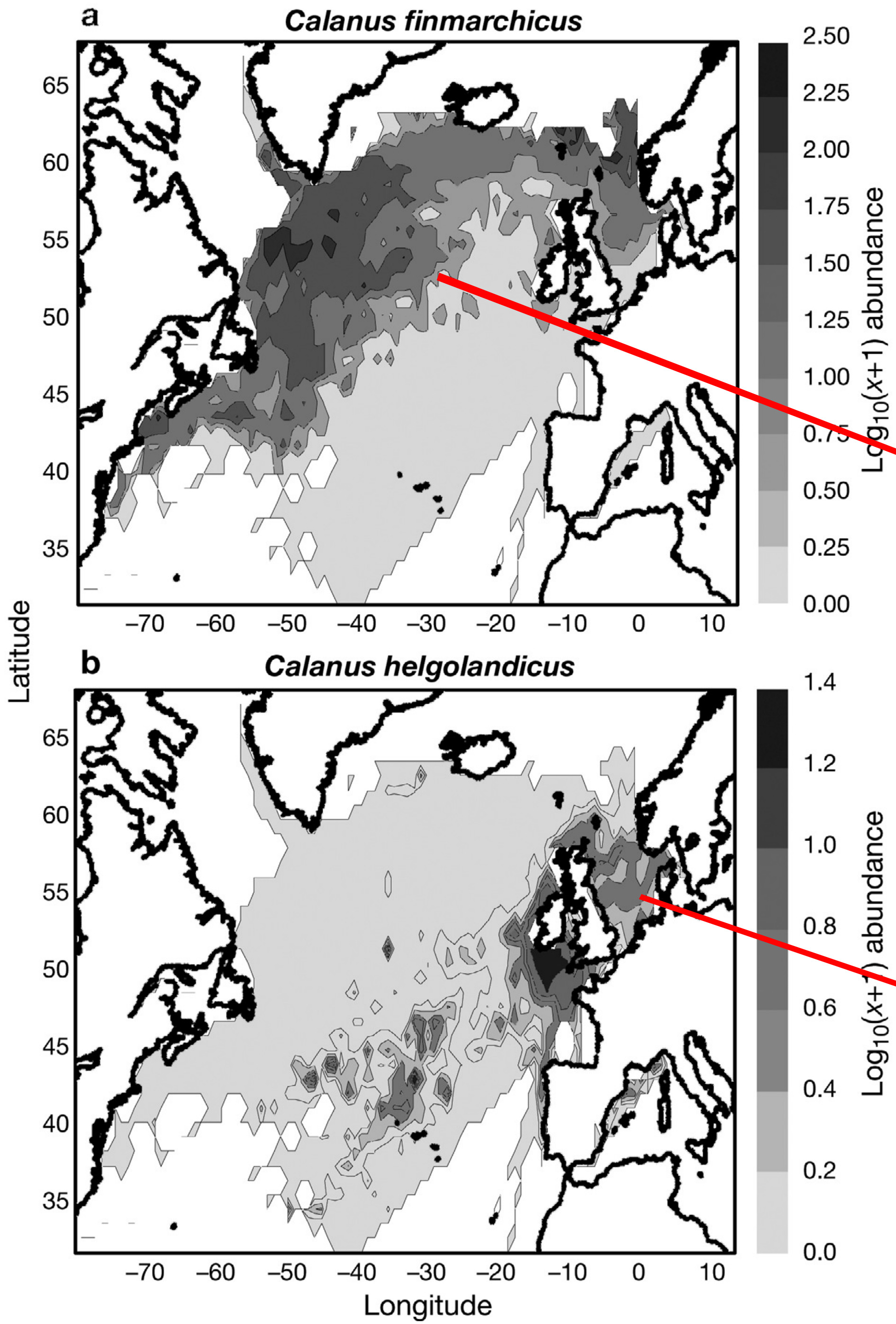
INDIRECT
CLIMATE IMPACTS
Habitat
Circulation
Seasonality
Process Intensity
DIRECT
1ary Producers
2ary Producers
Planktivorous Fish
Piscivorous Fish
Higher predators
Growth
Reproduction
Mortality
COLLATERAL

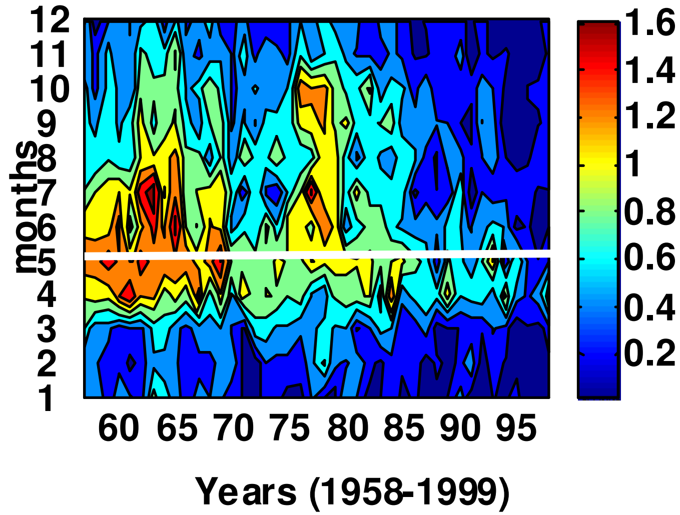
•***Climate change is expected to drive most terrestrial and marine species ranges toward the poles, expanding the range of warmer-water species and contracting that of colder-water species***

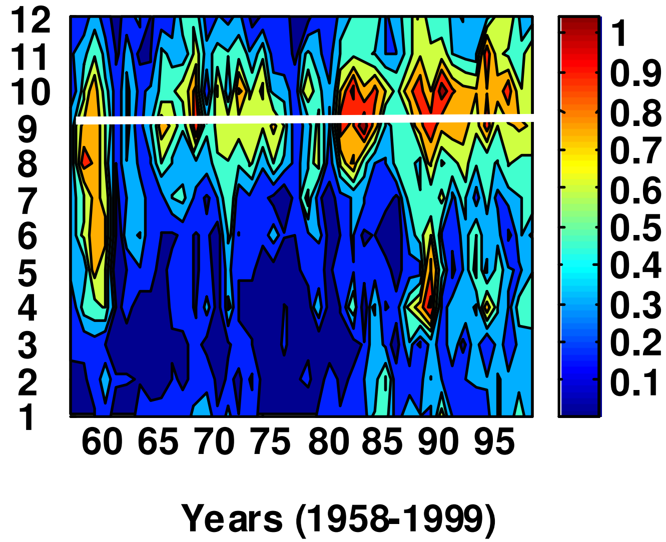


Examples of North Sea fish distributions that have shifted north with climatic warming. Relationships between mean latitude and 5-year running mean winter bottom temperature for (A) cod, (B) anglerfish, and (C) snake blenny are shown (from Perry et al. 2005).

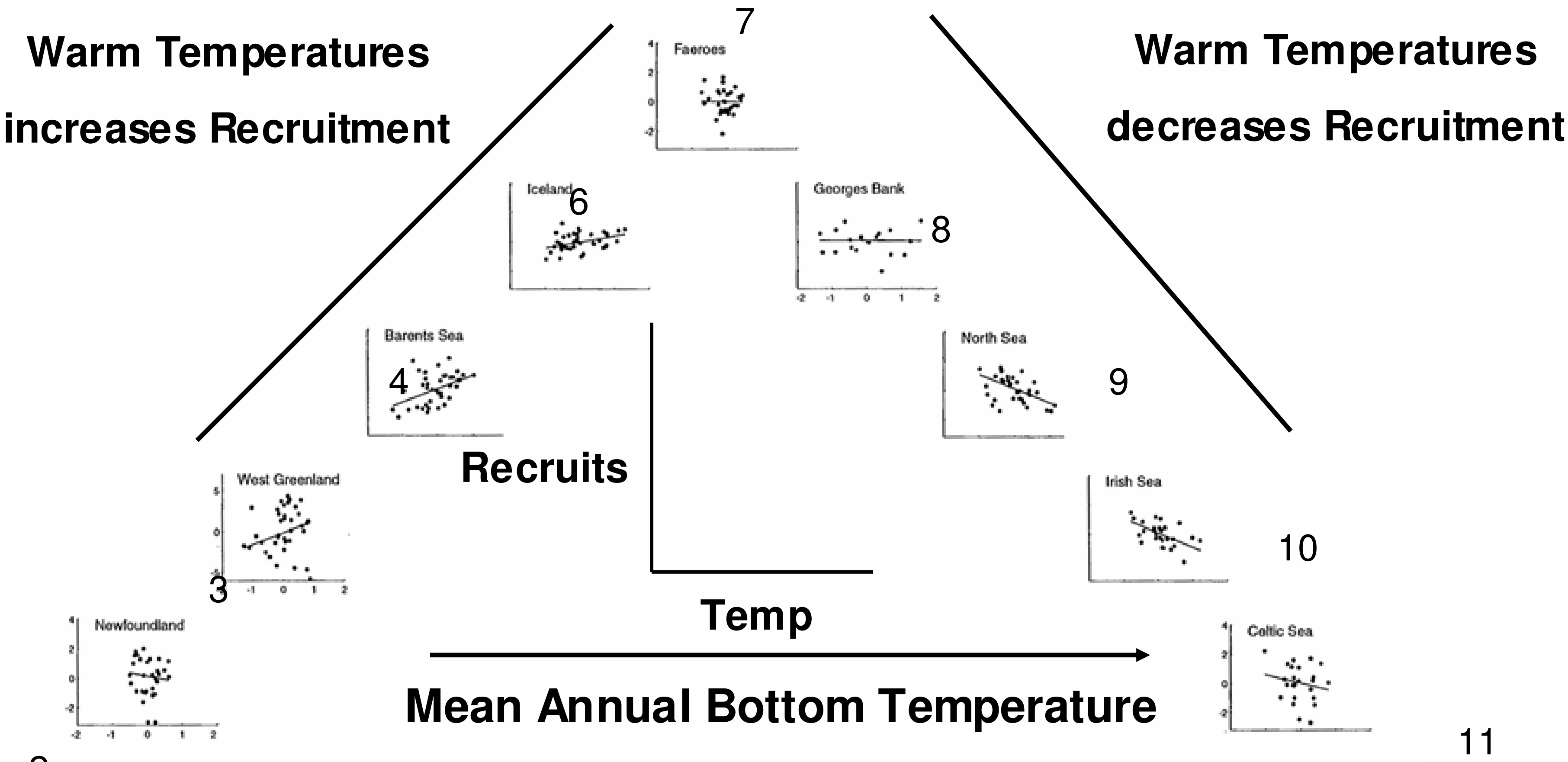
Beaugrand et al 2004 and
Helaouet and Beaugrand 2007







- *Populations at the poleward extents of their ranges tend to increase in abundance with warmer temperatures, whereas populations in more equatorward parts of their range tend to decline in abundance as temperatures warm.*



Planque and Fredou (1999)

- ***The sensitivity of ecosystems to amplify climatic signals suggests that gradual (or even linear stochastic) changes in climate can provoke sudden and perhaps unpredictable biological responses as ecosystems shift from one state to another.***

Table 1 | Analyses of key North Pacific physical time series

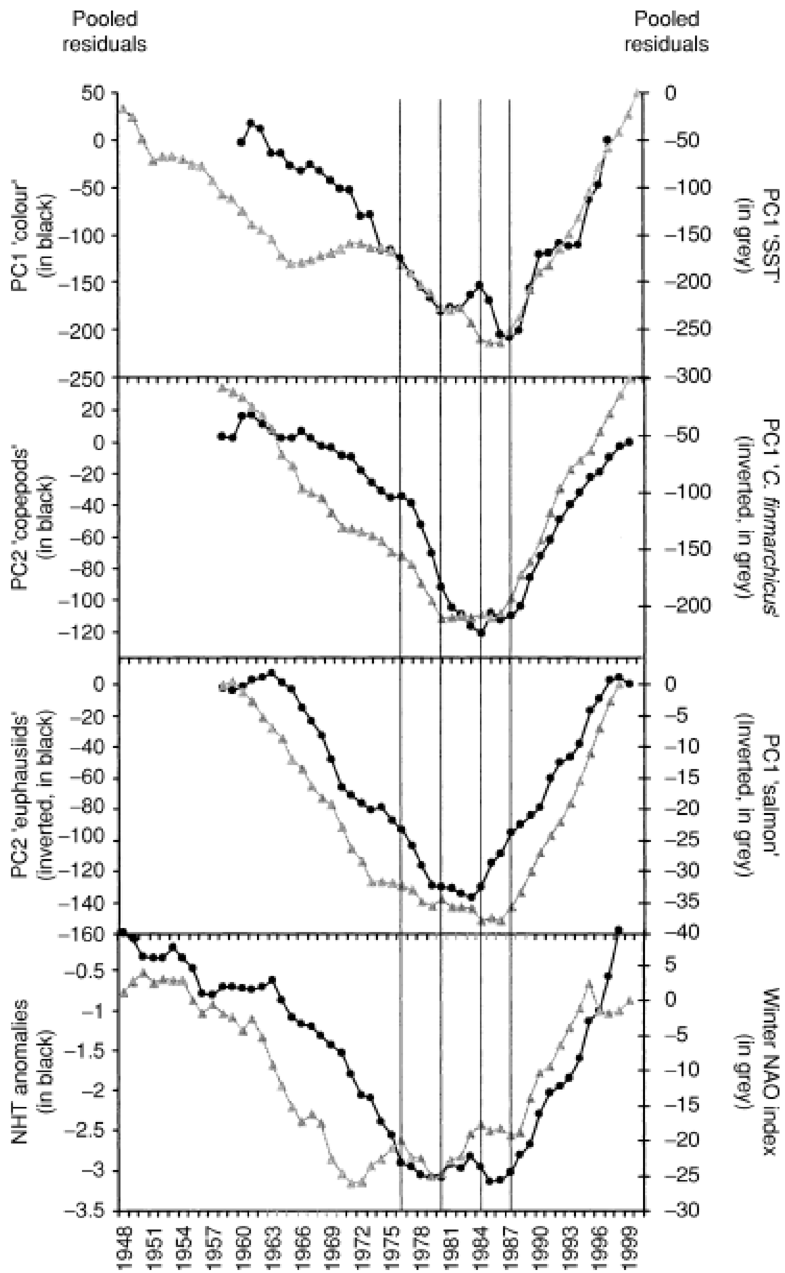
Timescale	Physical data	Best E	Best θ	Best ρ	$\Delta\rho$	Nonlinear?
Weekly	SIO SST	20 +	0	0.252	0	No
Monthly	SIO SST	20 +	0	0.787	0	No
Monthly	Pacific Grove SST	20 +	0	0.524	0	No
Monthly	Farallones SST	20 +	0	0.486	0	No
Monthly	PDO	20 +	0	0.255	0	No
Monthly	NPI	20 +	0	0.636	0	No
Monthly	SOI	20 +	0	0.380	0	No
Quarterly	SIO SST	20 +	0	0.958	0	No
Quarterly	PDO	20 +	0	0.376	0	No
Quarterly	NPI	20 +	0	0.497	0	No
Quarterly	SOI	20 +	0	0.328	0	No
Annual	SIO SST, composite	20	0	0.770	0	No
Annual	PDO, composite	10	0	0.547	0	No
Annual	NPI, composite	16	0	0.674	0	No
Annual	SOI, composite	13	0	0.640	0	No

Table 2 | Analyses of key North Pacific biological time series

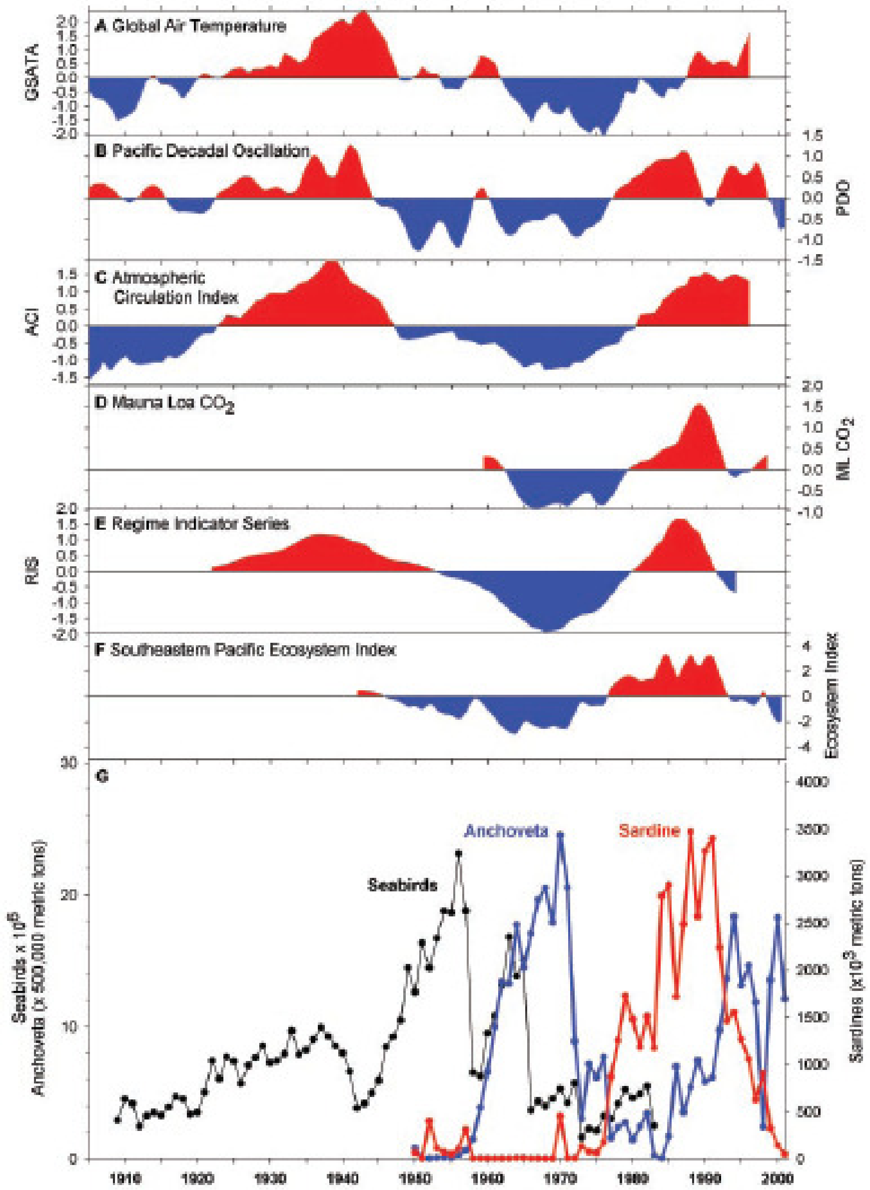
Timescale	Biological data	Best E	Best θ	Best ρ	$\Delta\rho$	Nonlinear?
Weekly	Scripps Pier diatom	3	0.3	0.539	0.139*	Yes
Monthly	Scripps Pier diatom	4	0.05	0.542	0.083	Yes
Quarterly	CalCOFI coastal larval fish	7	1.6	0.715	0.031*	Yes
Quarterly	CalCOFI coastal-oceanic larval fish	8	0.6	0.744	0.017	Yes
Quarterly	CalCOFI oceanic larval fish	8	1.4	0.678	0.020*	Yes
Biannual	CalCOFI copepod	6	1.2	0.677	0.027	Yes
Annual	CalCOFI copepod	5	0.4	0.566	0.015	Yes
Annual	CalCOFI coastal larval fish	5	0.6	0.603	0.060*	Yes
Annual	CalCOFI coastal-oceanic larval fish	4	0.2	0.502	0.092	Yes
Annual	CalCOFI oceanic larval fish	7	0.6	0.576	0.017	Yes
Annual	Chinook salmon	3	0.4	0.448	0.440*	Yes
Annual	Coho salmon	7	0.3	0.656	0.117	Yes
Annual	Chum salmon	4	0.18	0.634	0.767*	Yes
Annual	Steelhead trout	3	0.2	0.281	0.272	Yes
Annual	Sockeye salmon	4	0.7	0.484	0.168	Yes
Annual	Composite salmon and trout	4	0.3	0.464	0.078	Yes

Hsieh et al 2005

Beaugrand et al. 2003



Chavez et al. 2003



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Anticipated impacts of climate change on ecosystems and fish production

- *At “**rapid” time scales** (a few years) there is high confidence that increasing temperatures will have negative impacts on the physiology of fish because limited oxygen transport to tissues at higher temperatures. This physiological constraint is likely to cause significant limitations for aquaculture. These constraints on physiology will result in changes in distributions of both freshwater and marine species, and likely cause changes in abundance as recruitment processes. Changes in the timing of life history events are expected with climate change (high confidence). Short-life span rapid turnover species, for example plankton, squid, and small pelagic fishes, are those most likely to experience such changes.*

- *At **intermediate time scales** (a few years to a decade), temperature-mediated physiological stresses and phenology changes will impact the recruitment success and therefore the abundances of many marine and aquatic populations (high confidence). These impacts are also likely to be most acute at the extremes of species’ ranges, and for shorter-lived species. Changes in abundance will alter the composition of marine and aquatic communities, with possible consequences to the structure and productivity of these marine ecosystems. Predicting net community impacts (e.g. total biomass or productivity) has intermediate confidence because of compensatory dynamics within functional groups. Increasing vertical stratification is predicted for many areas, and is expected to reduce vertical mixing and decrease productivity (intermediate confidence). It will drive changes in species composition.*

- *At* ***long time scales*** *(multi-decadal), predicted impacts depend upon changes in net primary production in the oceans and its transfer to higher trophic levels. Models show high variability in their outcomes so any predictions have low confidence. Regional predictions may have improved confidence because of better knowledge of the specific processes involved. Most models do show decreasing primary production with changes of phytoplankton composition to smaller forms, although with high regional variability.*

Predicted Regional Impacts

- ***Arctic***
- ***North Atlantic***
  - NE Atlantic:
  - NW Atlantic:
- ***North Pacific***
- ***Wind-driven coastal upwelling systems***
- ***Tropical and sub-tropical seas***
- ***Coral reef systems***
- ***Freshwater systems***
- ***Aquaculture systems***

Arctic

- 5 °C increase in air temperature,
- 6% increase in precipitation,
- 15 cm rise in sea level,
- 5% increase in cloud cover,
- 20 day reduction in sea ice duration, and
- 20% reduction in winter ice with substantial ice-free areas in summer.

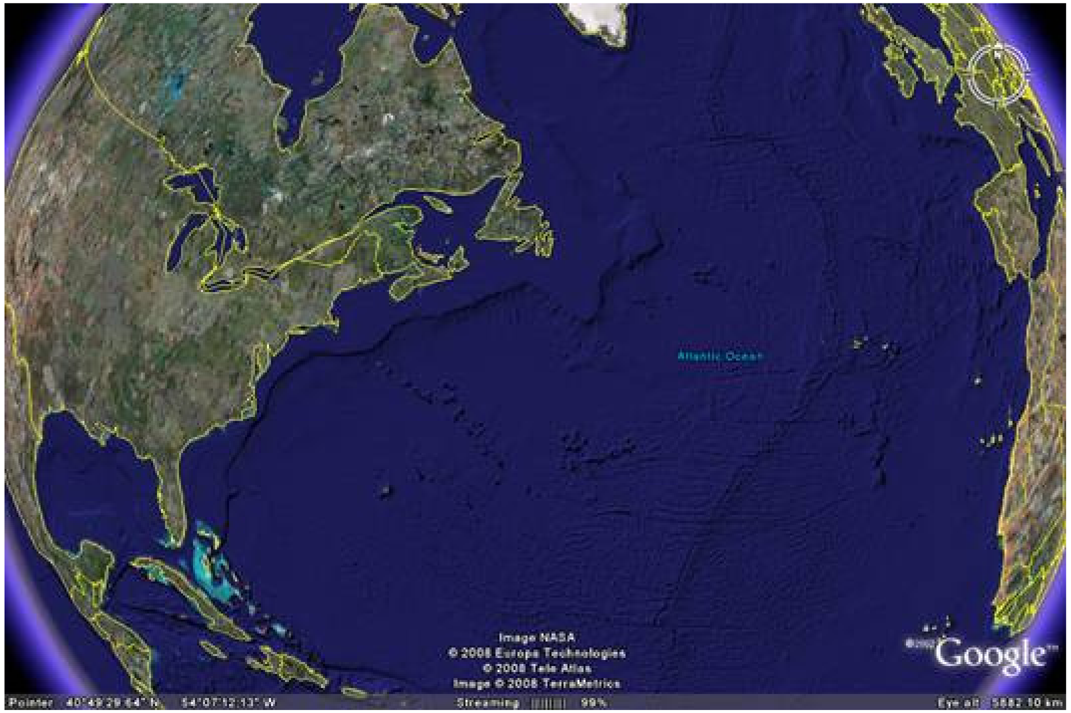
- primary production to 2-5 times over present conditions,
- reduced ranges of cold water fish and benthic species but expanded ranges of Atlantic and Pacific species northwards.
- long-lived Arctic species with narrow temperature tolerances and with late reproduction are likely to be first to disappear from more southerly habitats;
- changes to migration timing are likely, as are increases in growth rates;
- non-native species are likely to increase in Arctic waters
- extinction of any present Arctic fish species unlikely.

North Atlantic

NE Atlantic:

1. Climate change impacts likely to continue to vary with state of the NAO
2. sea temperatures in the North, Nordic and Barents Seas likely to increase by 1-3 °C over the next 50 years.
3. increased wind-induced fluxes of warm Atlantic waters
4. increased vertical stratification and reduced ice cover.

5. primary production is likely to increase in the Barents Sea,
6. zooplankton production is likely to decrease
7. northward shifts of the distributions of all species,
8. increase biomass production of species in Arcto-boreal regions,
9. introduce southern invaders into the southern North Sea
10. Spawning areas for capelin in the Barents Sea shift eastwards.
11. North Sea become dominated by pelagic species, although the total system productivity may not be too different than today
12. Baltic Sea is predicted to become warmer and fresher and more stratified
13. B.S. more dominated by species tolerant of low salinities.



North Atlantic

Northwest Atlantic:

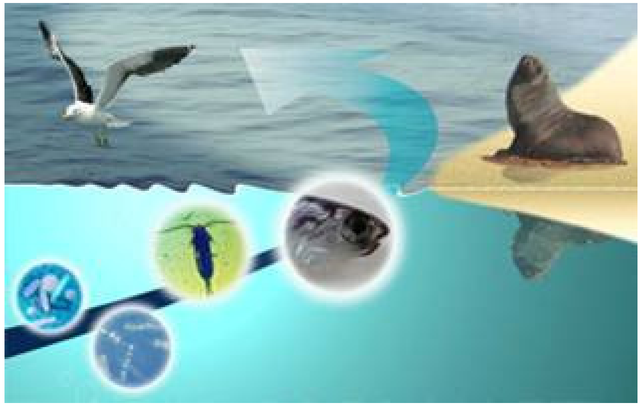
- predictions of distributions and migration changes similar to NE Atlantic
- Populations at their range limits will be most affected,
- In some locations and at some times decreased temperatures may occur as a result of increased glacial melting in Greenland. This may provide refuges for some cold water species, or may provide lethal cold shocks to other species such as Atlantic cod.
- Species adapted to cool and narrow temperature conditions, such as Atlantic salmon, may be extirpated from their present habitats

North Pacific

- anthropogenic warming in 30-50 years likely to be as large as natural climate variability today.
- climate-ecosystem-fisheries relationships developed during the latter half of the 20th century may not be robust in the 21st century.
- PDO pattern of decadal variability will continue into the 21st century, but will occur on top of persistent upward trend in sea surface temperature
- changes in mixed layer depths (shoaling) and temperature (increasing).
- expect sub-polar planktonic system to change from strong variability and winter lows to more constant annual values and decreased yearly-averaged primary productivity.
- Other areas (e.g. coastal) may experience higher growth rates as temperatures warm. Conditions to cause seasonal changes in 1ary production in the NW Pacific.
- west coast of North America, northward shifts of fish populations are predicted
- Pacific sockeye salmon may be restricted to Bering Sea
- Bering Sea: extensive retreats of sea ice, losses of cold-water species and increasing abundances of species from the North Pacific
- N. Pacific sensitive to the effects of increasing acidification.
- Various species are negatively impacted by low pH concentrations

Wind-driven coastal upwelling systems

- Responses of coastal wind systems that drive upwelling ecosystem contradictory
- primary production model of Sarmiento et al. (2004) showed no consistent global response of upwelling regions to climate change.
- Intensified Benguela upwelling may increase nutrient inputs, primary production, and low-oxygen events
- Such may also occur in other upwelling systems
- Considerable local variability among systems



Tropical and sub-tropical seas

- Highly diverse habitats and biology; poorly studied
- not resolved whether tropical Pacific will become more “El Niño-like” (east-west gradient in time-mean SST is reduced), or more “La Niña-like” character (increased east-west SST gradient)
- primary production in the tropical Pacific expected to decline because of increased stratification and decreased nutrient supply
- combined effects of changes in circulation, temperature, nutrients, primary production cascade up the food web to influence prey availability and habitat conditions for tuna
- Tuna habitat conditions east of the date line could improve, similar to El Niño-events
- Australia and New Zealand - greatest impacts likely on coastal species and sub-tidal nursery areas, temperate endemic species rather than tropicals, and coastal and demersal species rather than pelagic and deep-sea species.
- Models for Australia predict physical changes similar to other regions: ocean warming, increased vertical stratification, strengthening of poleward coastal currents, increasing ocean acidification, sea level rise, and altered storm and rainfall regimes
- warming and increasing stratification will alter plankton community composition, alter their distributions polewards, and change the timing of their bloom dynamics so that transfers to higher trophic levels may be impaired.
- Benthic and demersal fishes will shift their distributions southward, and may decline in abundance. Pelagic species will also shift their distributions southwards, and some species may benefit from increased local upwelling

Coral reef systems

1. at risk from climate change impacts related to increasing temperatures, acidity, storm intensity and sea levels and non-climate factors such as over-exploitation, non-native species introductions, and increasing nutrient and sediment loads.
2. risks to coral reefs not distributed equally: increasing temperatures significant issue for warm-water systems; increasing acidity and decalcification a significant issue for both warm- and cold-water systems; direct human impacts a significant issue in more populous regions.
3. Three different time scales can be identified for climate change-related impacts to coral reef systems:
   - -years: increased temperature effects on coral bleaching,
   - -decades: increasing acidification and dissolution of carbonate structures;
   - -multi-decades: weakening of structural integrity, increasing susceptibility to storms and erosion events
4. Increasing acidity (decreasing pH) is a significant and pervasive longer-term threat to coral reefs. potential for coral reef systems to adapt to these environmental stresses is uncertain: symbiotic zooxanthellae may adapt to be more tolerant of high temperatures; Migrations of corals to higher latitudes is unlikely
5. Declines in corals have negative impacts to reef fish biodiversity in at least one study
6. However, to date little evidence for a link between climate warming and bleaching events with impacts on coastal fisheries

Freshwater systems

- anticipated response is for cold-water species to be negatively affected, warm-water species to be positively affected, and cool-water species to be positively affected in the northern but negatively affected in the southern parts of their range
- general shift of cool- and warm-water species northward is expected in North America and likely the rest of the northern hemisphere.
- However, responses of particular lake ecosystems to climate change depend on size, depth, and trophic status of the lake.
- modelling study concluded cold-water fish would be most affected because of losses of optimal habitats in shallow, eutrophic lakes.
- Growth conditions for cool- and warm-water fishes should improve in well-mixed lakes, small lakes, and those with oligotrophic nutrient conditions.
- rates of change of freshwater system to climate will depend on ability of freshwater species to ‘move across the landscape’, i.e. use of dispersal corridors;
- Most affected are likely to be fish in lowland areas that lack northward dispersal corridors, and cold-water species generally (Poff et al., 2002).
- River ecosystems particularly sensitive to changes in the quantity and timing of water flows, which are likely to change with climate change .
- Exacerbated by human efforts to retain water by reservoirs and irrigation channels;
- abundance and species diversity of riverine fishes particularly sensitive to these disturbances, since lower dry season water levels reduce the number of individuals able to spawn successfully and many fish species are adapted to spawn in synchrony with the flood pulse to enable their eggs and larvae to be transported to nursery areas on flood plains

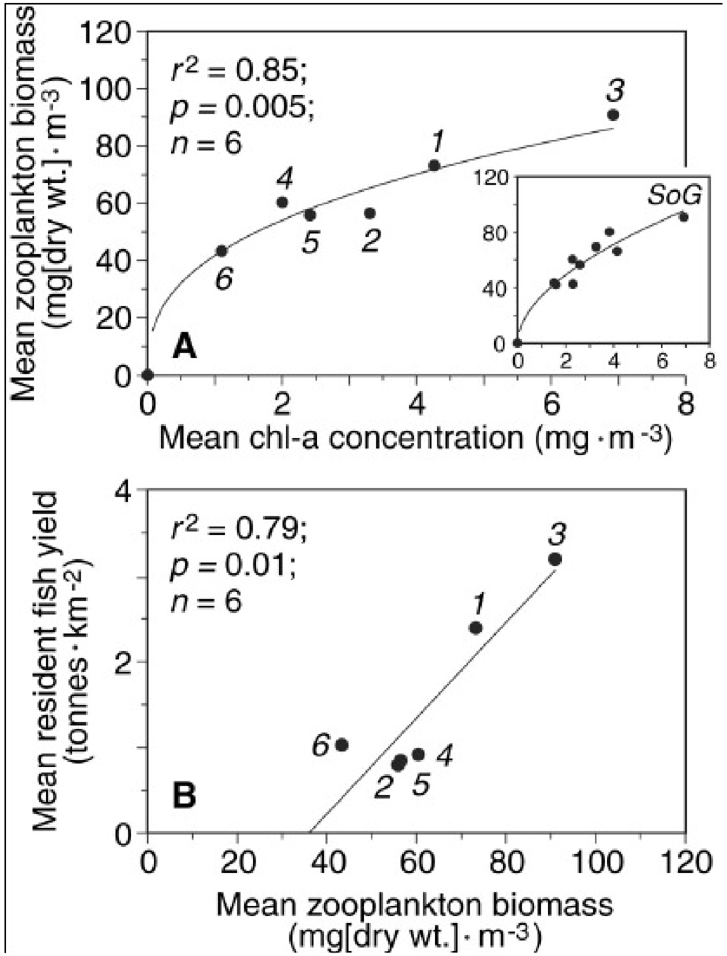
Aquaculture systems

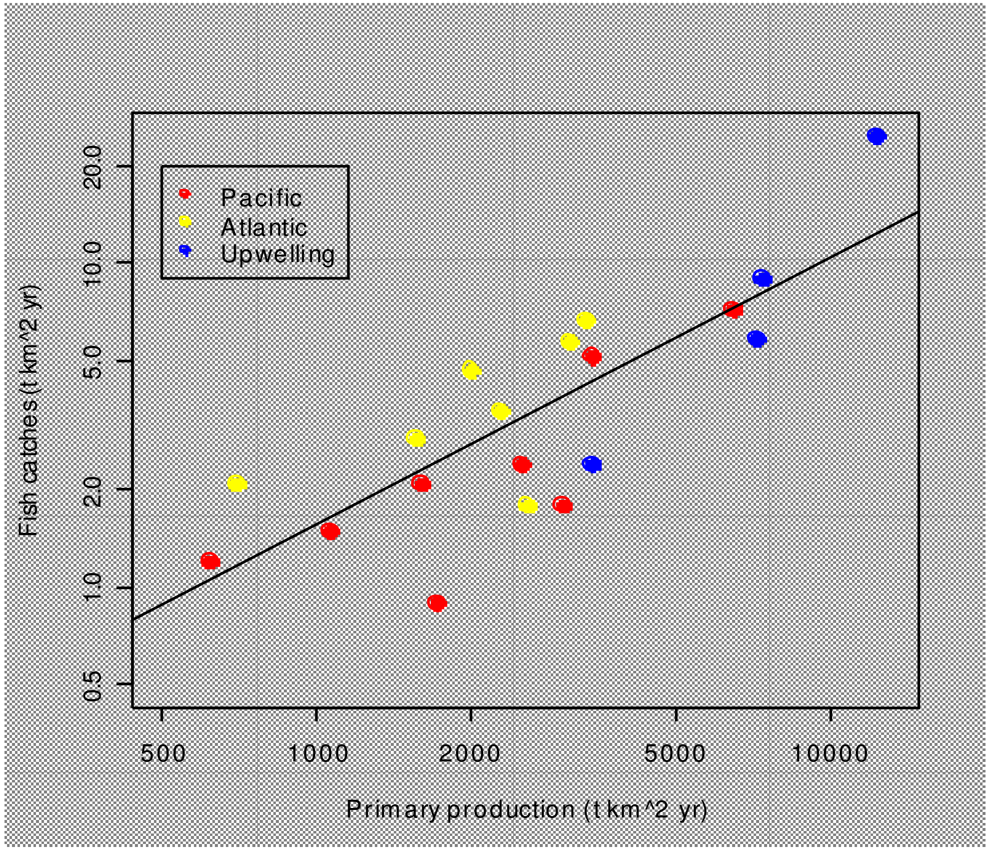
- Direct impacts: changes in availability of freshwater, temperature, sea level, and increased frequencies of extreme events (such as flooding and storm surges)
- Negative impacts include (Table 4): stress due to increased temperature and oxygen demands; uncertain supplies of freshwater; extreme weather events; sea level rise; increased frequency of diseases and toxic events; uncertain supplies of fishmeal from capture fisheries.
- Positive impacts of climate change include: increased food conversion efficiencies and growth rates, increased length of the growing season, and range expansions polewards due to decreases in ice.
- If primary production increases - more food for filter-feeding invertebrates
- may be problems with non-native species invasions, declining oxygen concentrations, and possibly increased blooms of harmful algae
- Local conditions in traditional rearing areas may become unsuitable for many traditional species,
- Temperature stress will affect physiological processes such as oxygen demands, food requirements,
- For aquaculture activities to realise benefits of increased temperature, will need to increase food supplies,
- Freshwater aquaculture activities will have to compete with changes in availability of freshwater due to human use, riverine requirements, as well as changes in precipitation regimes
- increases in precipitation could also cause problems such as flooding
- Sea level rise also has the potential to flood coastal land areas, mangrove and sea grass regions which may supply seed stock for aquaculture species

Research needs

- Regional impacts, particularly those leading to non-linear dynamics (e.g. lakes drying, regime shifts)
- Global impacts on fish production based on bottom up ecosystem processes as driven by climate change
- Compounded impacts across food production systems

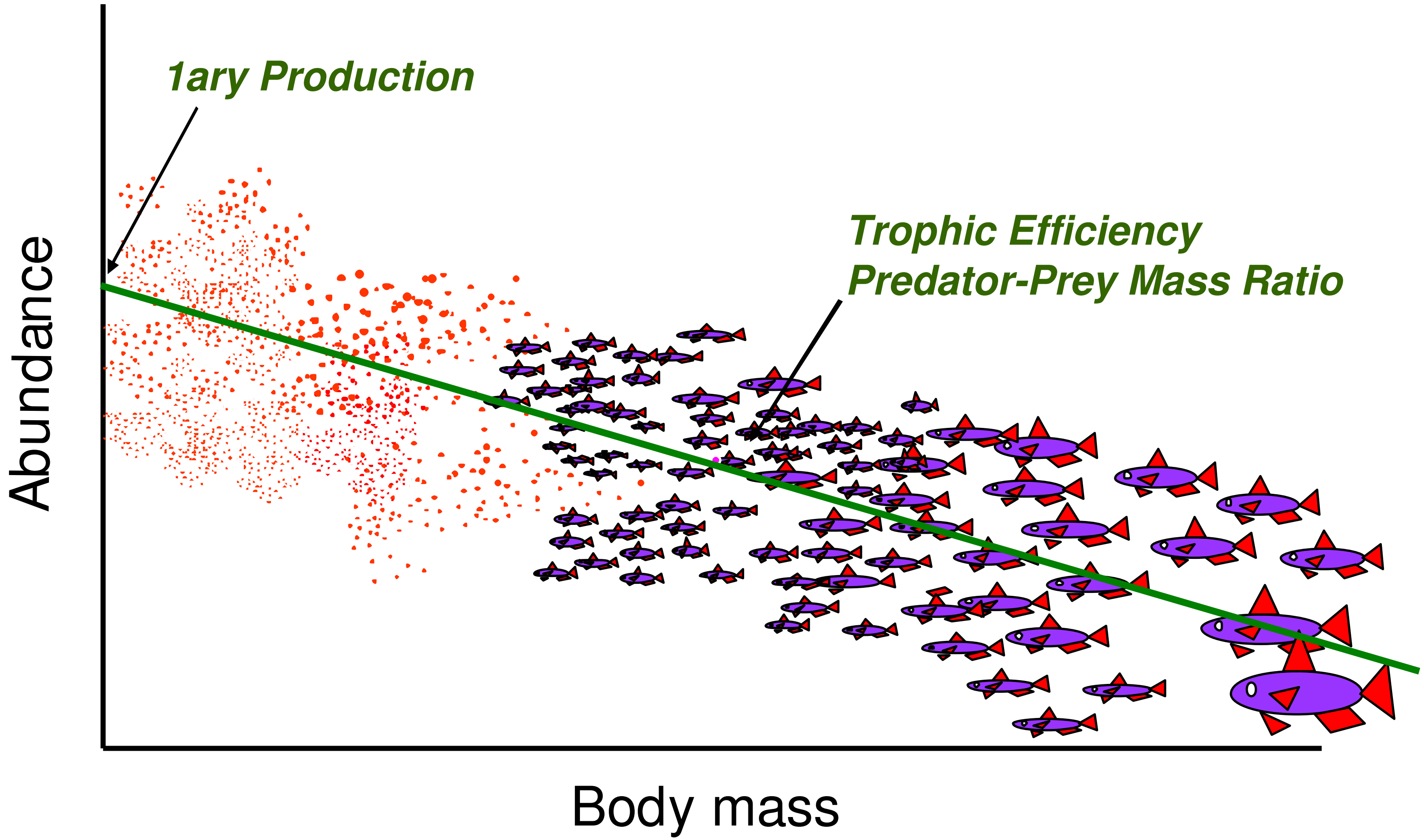
From primary production to fish





Ware and Thomson 2005. Science

Estimate fish production based on metabolic theory



Jennings et al. 2008

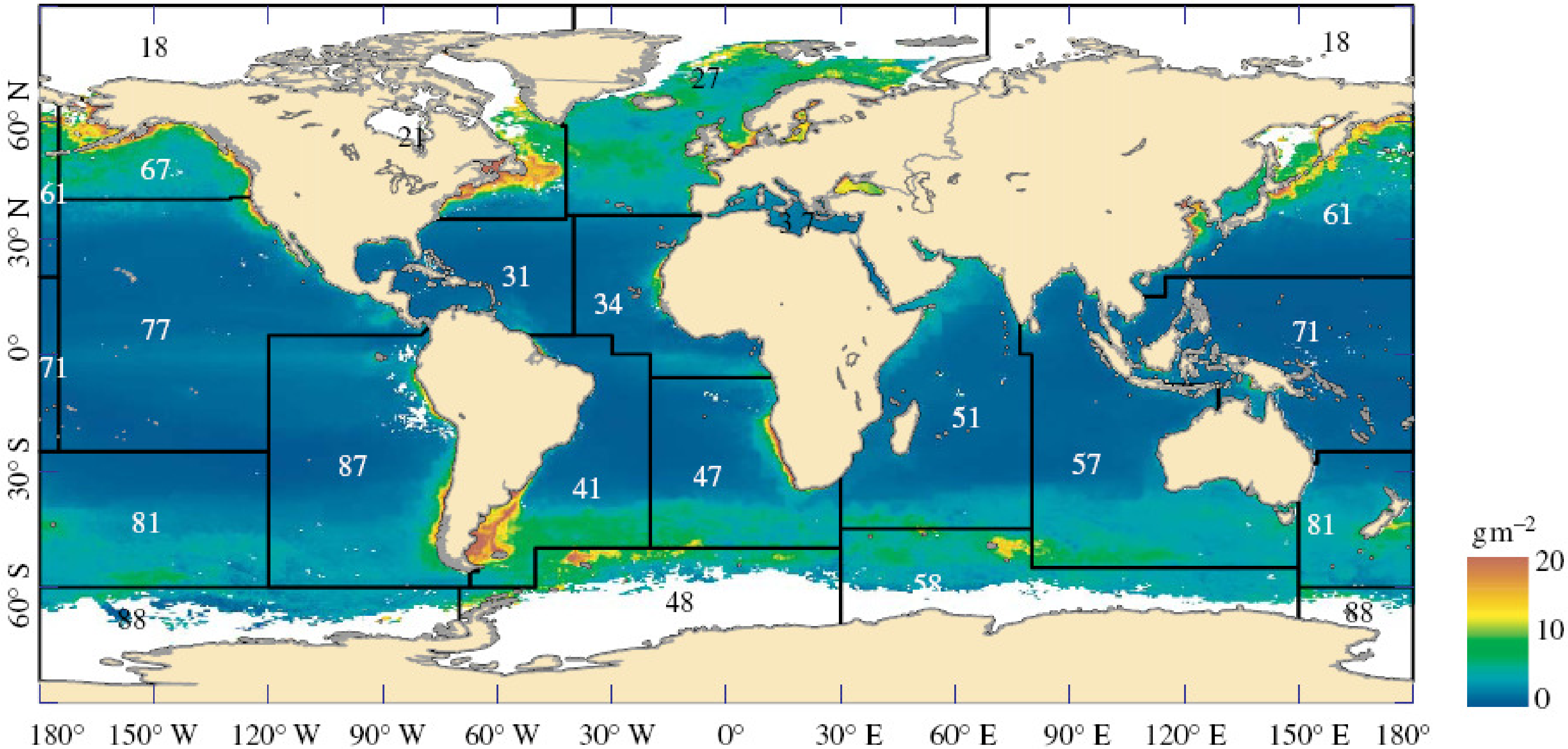
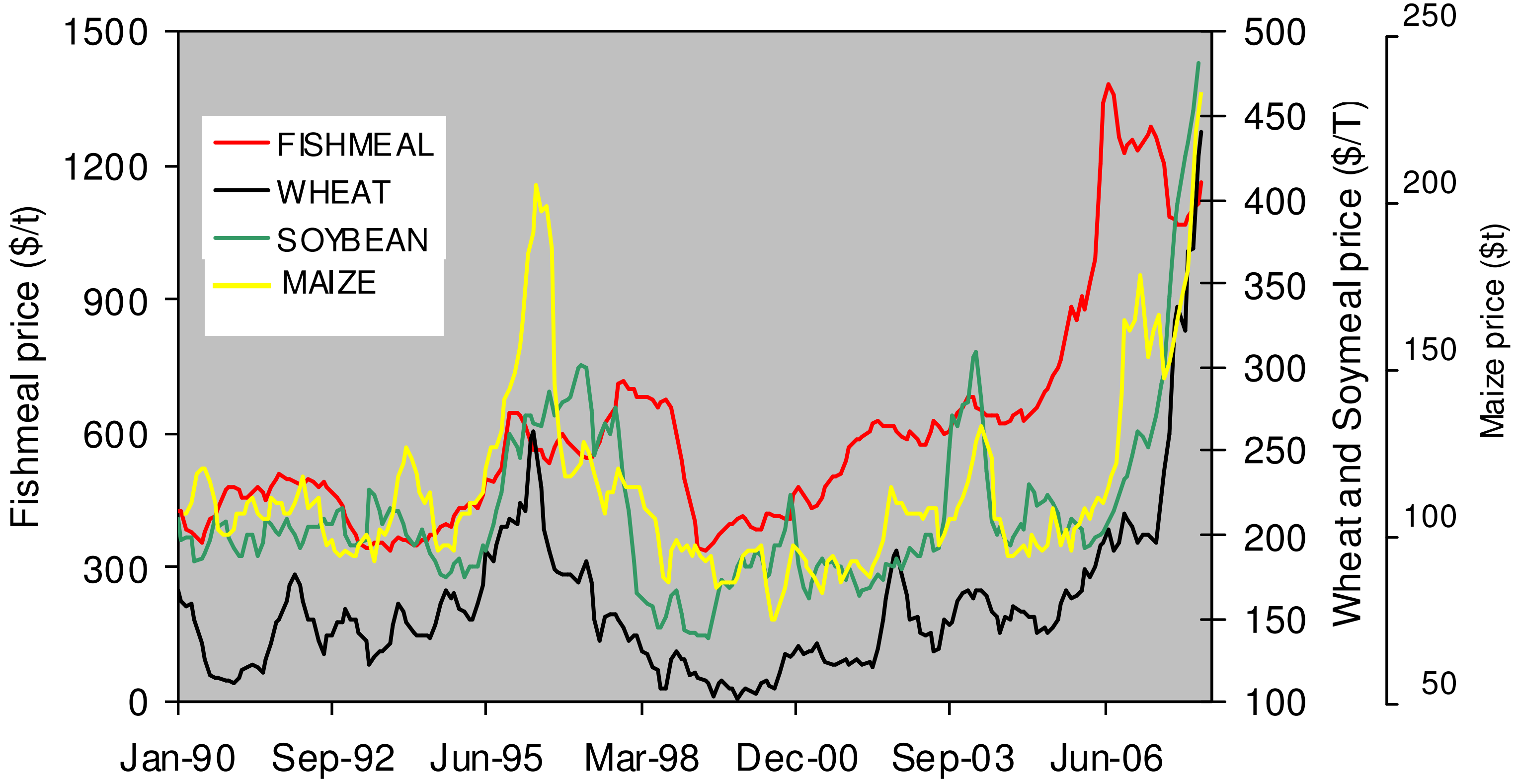
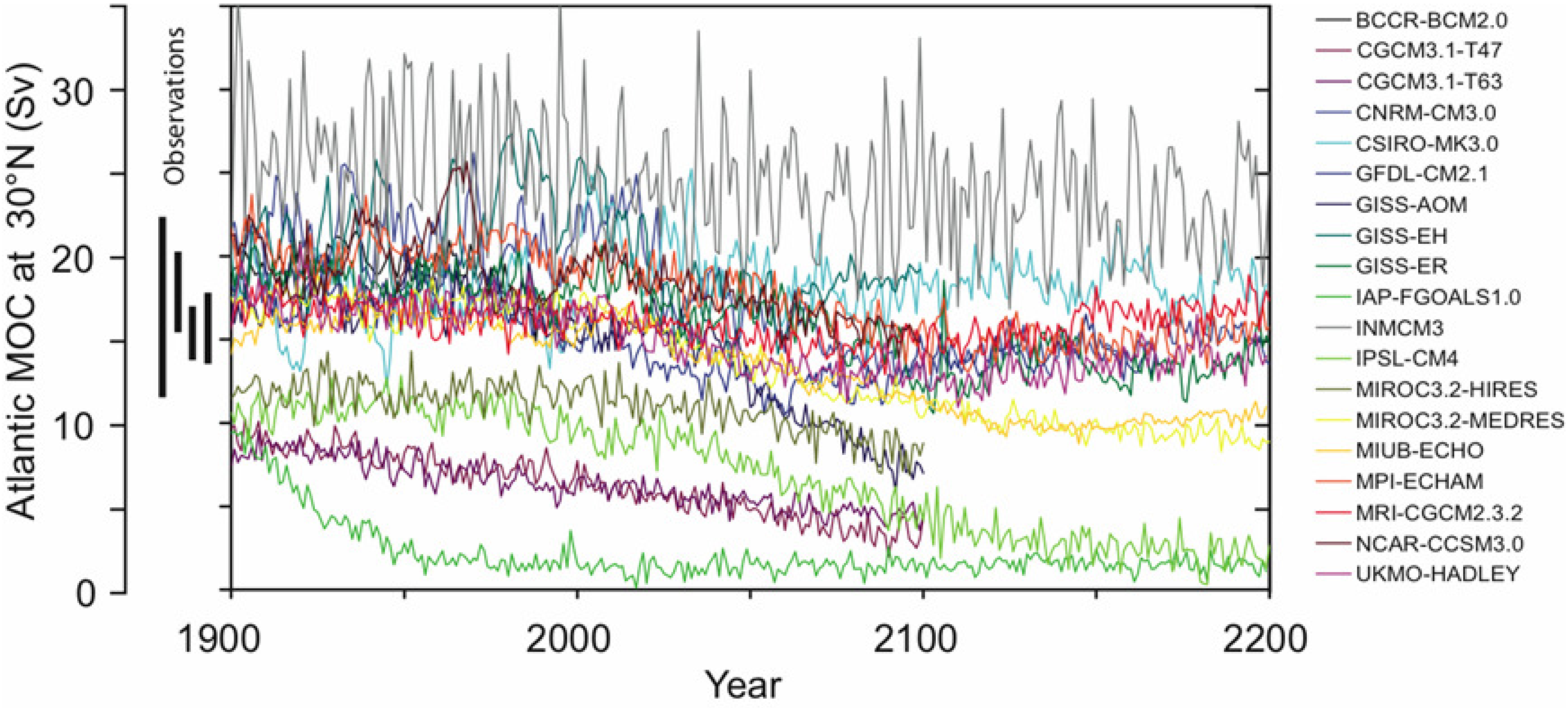


Figure 3. The distribution of teleost biomass. The overlays show the FAO fishing areas and their corresponding codes (see electronic supplementary material for further details). PP estimates were not available for the areas shown in white.

Global commodity markets



•***A reduction of about 30% in the MOC has been observed in the 2nd half of the 20th century. Further reductions are expected as a result of increased freshwater input in the Arctic and sub-Arctic, increased stability of the surface mixed layer, reduction in salt flux, reduced ocean convection, and less deepwater formation***



•***Ecosystem simulations indicate that there is no clearly discernable pattern of upwelling response to global warming at the global scale. However, there are indications that upwelling seasonality may be affected, with important food web consequences.***

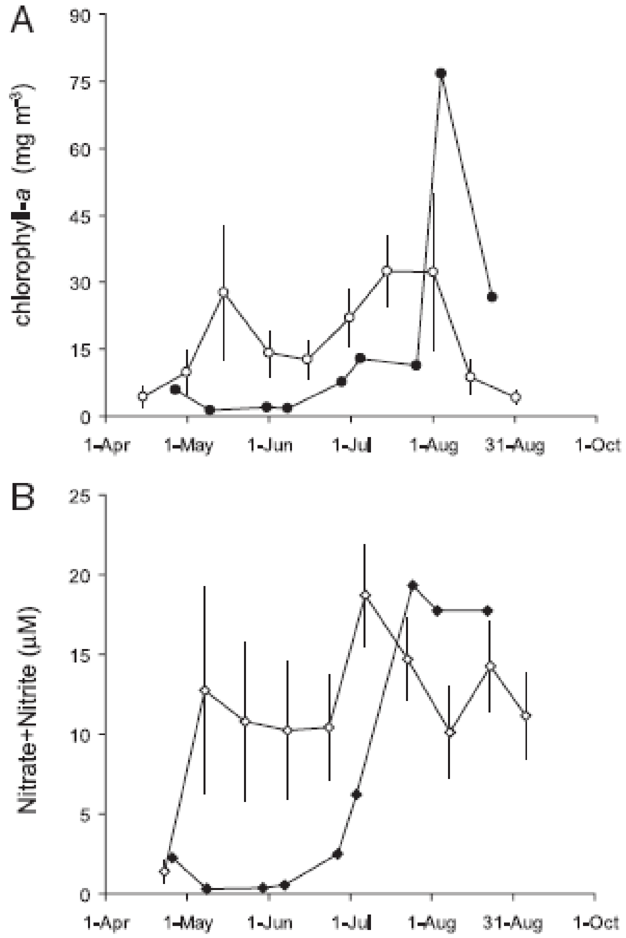


Fig. 5. Time series of surf-zone chlorophyll and nutrients off the central Oregon coast. (*A*) Time series of chl-a (circles) measured at the coast off of central Oregon (44.25°N): 2005 (filled symbols); 1993–2004 climatological mean (open symbols) with 95% C.I. (bars). (*B*) As in *A*, but for nitrate plus nitrite (diamonds).

Barth et al. 2007