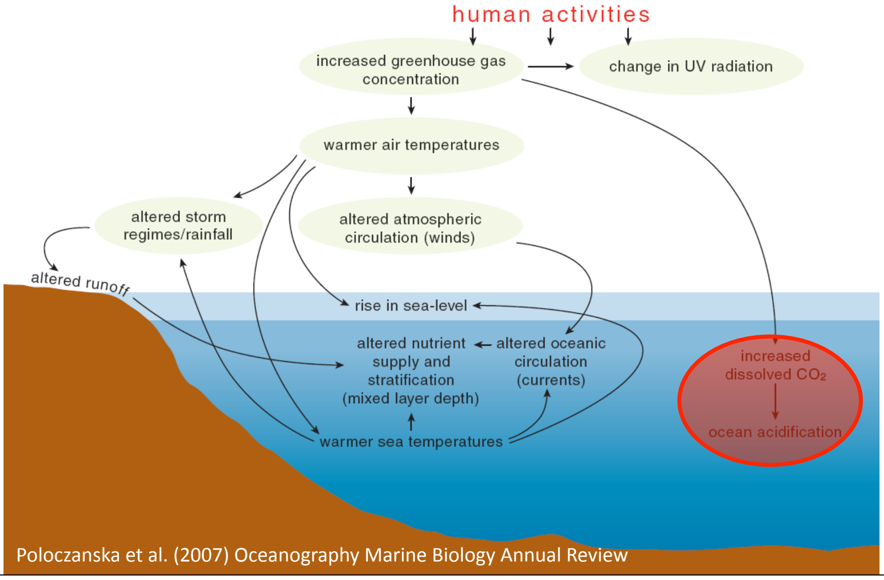
Complexity of Climate Change



human activities

increased greenhouse gas concentration

change in UV radiation

warmer air temperatures

altered storm regimes/rainfall

altered atmospheric circulation (winds)

altered runoff

rise in sea-level

altered nutrient supply and stratification (mixed layer depth)

altered oceanic circulation (currents)

warmer sea temperatures

increased dissolved CO_2

ocean acidification

Poloczanska et al. (2007) Oceanography Marine Biology Annual Review

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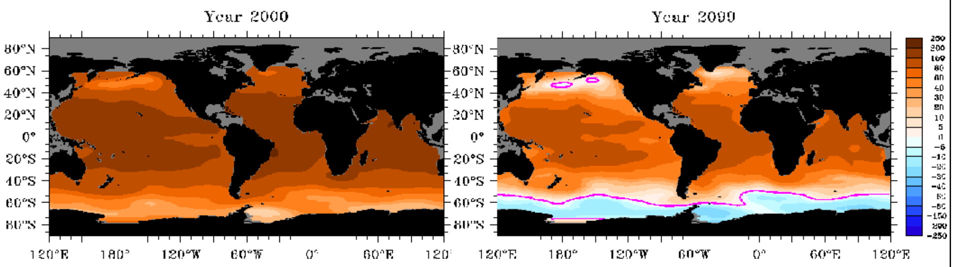
Ocean Acidification

Organisms	Photosynthetic or non-photosynthetic	Form of calcium carbonate	Habitat
Foraminifera	Some photosynthetic Non-photosynthetic	Calcite Calcite	Benthic Planktonic
Coccolithophores	Photosynthetic	Calcite	Planktonic
Macroalgae*	Photosynthetic	Aragonite or calcite	Benthic
Corals: warm water cold water	Photosynthetic Non-photosynthetic	Aragonite Aragonite	Benthic Benthic
Pteropod molluscs	Non-photosynthetic	Aragonite	Benthic
Non-pteropod molluscs*	Non-photosynthetic	Aragonite + calcite	Benthic or Planktonic
Crustaceans*	Non-photosynthetic	Calcite	Benthic or Planktonic
Echinoderms	Non-photosynthetic	Calcite	Benthic

**Not all members of the group are calcified.*

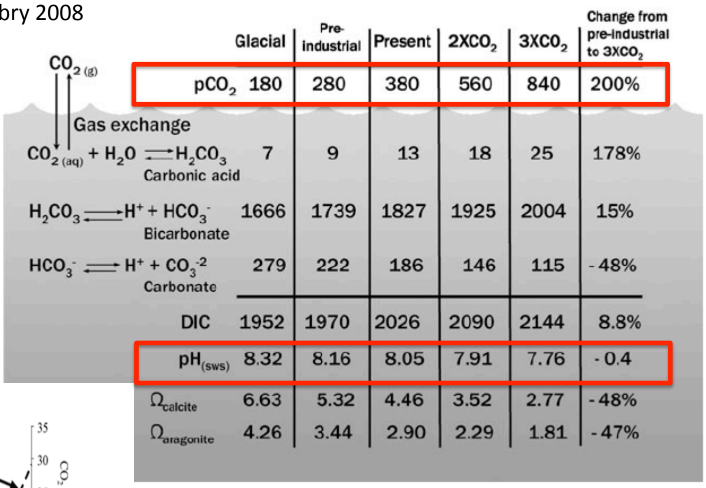


$CO_2 + CO_3^{2-} + H_2O \rightarrow 2HCO_3^-$

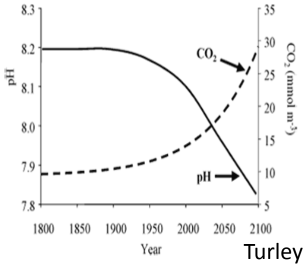
Orr et al. (2005) Nature

Royal Society Report (2005)

Fabry 2008



	Glacial	Pre-industrial	Present	$2XCO_2$	$3XCO_2$	Change from pre-industrial to $3XCO_2$
pCO_2	180	280	380	560	840	200%
$CO_{2\,(aq)} + H_2O \rightleftharpoons H_2CO_3$ Carbonic acid	7	9	13	18	25	178%
$H_2CO_3 \rightleftharpoons H^+ + HCO_3^-$ Bicarbonate	1666	1739	1827	1925	2004	15%
$HCO_3^- \rightleftharpoons H^+ + CO_3^{-2}$ Carbonate	279	222	186	146	115	- 48%
DIC	1952	1970	2026	2090	2144	8.8%
$pH_{(sws)}$	8.32	8.16	8.05	7.91	7.76	- 0.4
$\Omega_{calcite}$	6.63	5.32	4.46	3.52	2.77	- 48%
$\Omega_{aragonite}$	4.26	3.44	2.90	2.29	1.81	- 47%



Turley 2005

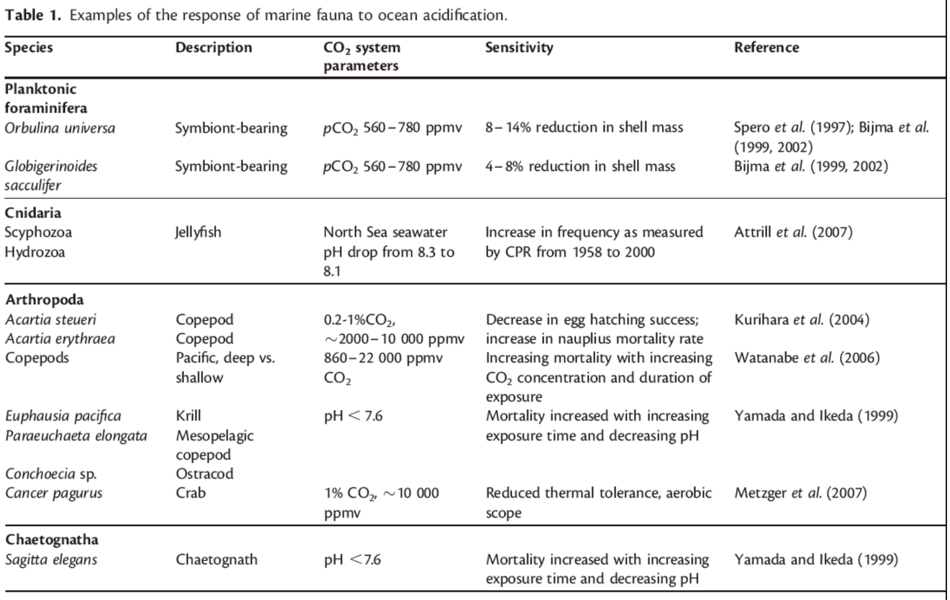
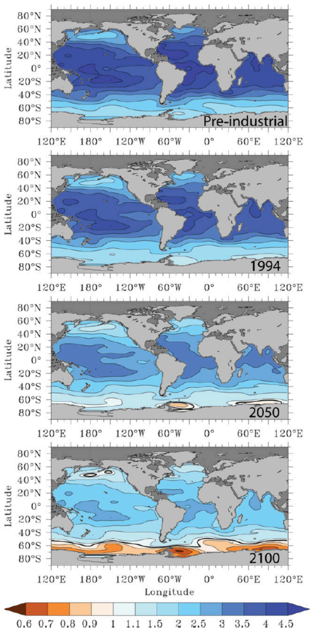


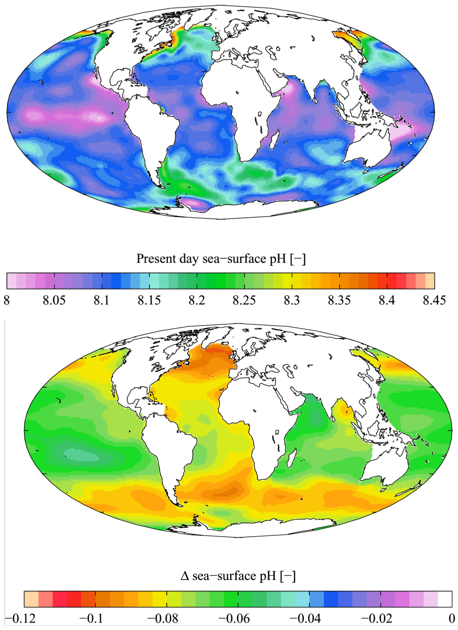
Table 1. Examples of the response of marine fauna to ocean acidification.

Species	Description	CO_2 system parameters	Sensitivity	Reference
Planktonic foraminifera				
Orbulina universa	Symbiont-bearing	pCO_2 560–780 ppmv	8–14% reduction in shell mass	Spero *et al.* (1997); Bijma *et al.* (1999, 2002)
Globigerinoides sacculifer	Symbiont-bearing	pCO_2 560–780 ppmv	4–8% reduction in shell mass	Bijma *et al.* (1999, 2002)
Cnidaria				
Scyphozoa Hydrozoa	Jellyfish	North Sea seawater pH drop from 8.3 to 8.1	Increase in frequency as measured by CPR from 1958 to 2000	Attrill *et al.* (2007)
Arthropoda				
Acartia steueri *Acartia erythraea*	Copepod Copepod	0.2-1%CO_2, ~2000–10 000 ppmv	Decrease in egg hatching success; increase in nauplius mortality rate	Kurihara *et al.* (2004)
Copepods	Pacific, deep vs. shallow	860–22 000 ppmv CO_2	Increasing mortality with increasing CO_2 concentration and duration of exposure	Watanabe *et al.* (2006)
Euphausia pacifica *Paraeuchaeta elongata* *Conchoecia* sp.	Krill Mesopelagic copepod Ostracod	pH < 7.6	Mortality increased with increasing exposure time and decreasing pH	Yamada and Ikeda (1999)
Cancer pagurus	Crab	1% CO_2, ~10 000 ppmv	Reduced thermal tolerance, aerobic scope	Metzger *et al.* (2007)
Chaetognatha				
Sagitta elegans	Chaetognath	pH <7.6	Mortality increased with increasing exposure time and decreasing pH	Yamada and Ikeda (1999)

Fabry 2008

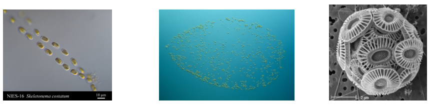


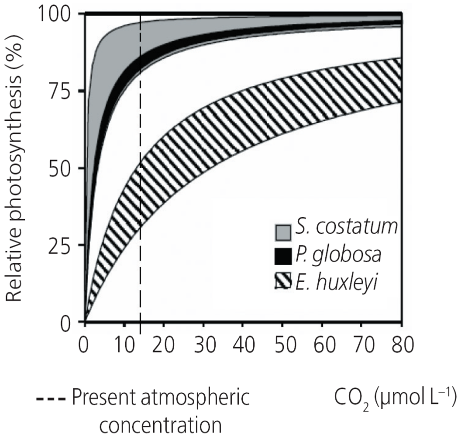
Surface water aragonite saturation state (Fabry 2008)



Change in sea surface pH between 1700s and 1990s

Dissolved CO_2





Photosynthesis of three different phytoplankton species (diatom Skeletonema costatum, haptophytes Phaeocystis globosa and Emiliania huxleyi) with respect to CO2 sensitivity (adapted from Rost and Riebesell 2004). Microalgal species differ in their responses to CO2, which implies that a high-CO2 ocean will induce shifts in phytoplankton species composition. (*Hallegraeff 2010*)

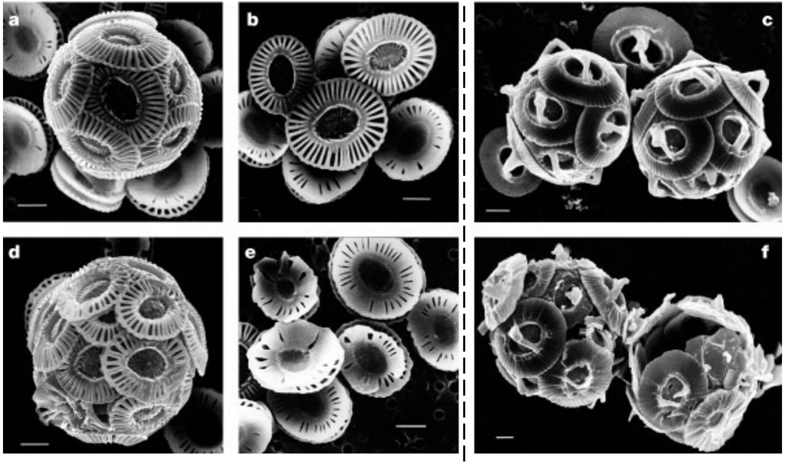
Royal Society Report (July 2005)

Acidification - Coccolithophores

SEMs *Emiliania huxleyi* | *Gephyrocapsa oceanica*

300 ppm

780–850 ppm



Potentially 60% decrease in calcification by end of 21st century

Riebesell et al. (1999) *Nature*

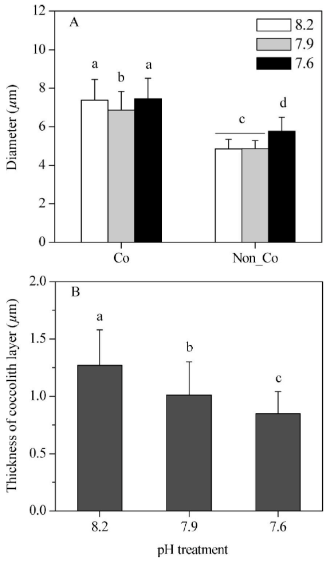
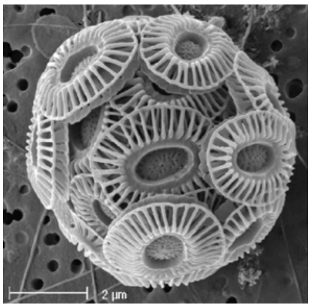


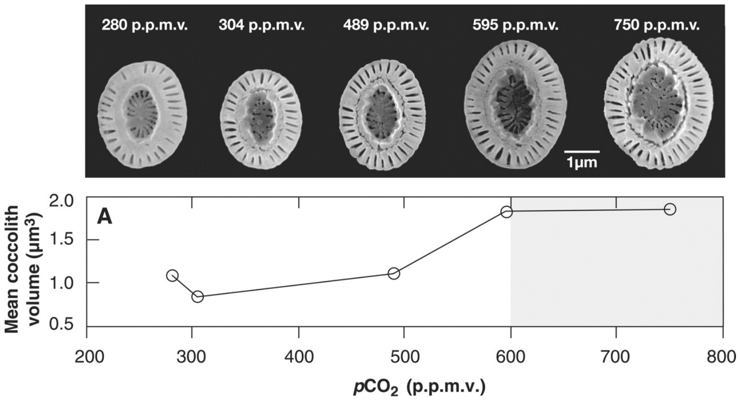
Fig. 3. (A) Diameter of *E. huxleyi* cells grown for 11 d at pH$_{NBS}$ levels of 8.2, 7.9, and 7.6, respectively. Diameters are shown for cells either with (Co) or without coccoliths (Non_Co). (B) Thickness of the coccolith layer, derived from half the difference in the diameter of cells with and without coccoliths. The letters on top of the bars indicate significant difference at $p = 0.05$, so for the same letters there are no significant differences among the data. Values are means ± SD ($n \geq 100$).



Decrease in cell size and calcification

Gao et al. 2009

Coccolithophores may respond by increasing carbonate contents!

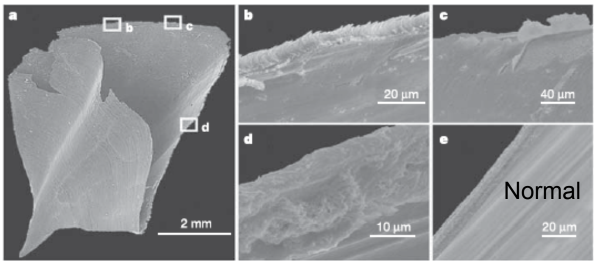


Iglesias-Rodriguez et al. 2008

Acidification - Mollucs

- *Clio pyramidata*, important pteropod in subpolar waters, kept in water undersaturated in aragonite for 48 h


hoto: Gilmer & Harbison




hoto: Russ Hopcroft

Limacina helicina dominant pteropod in polar waters

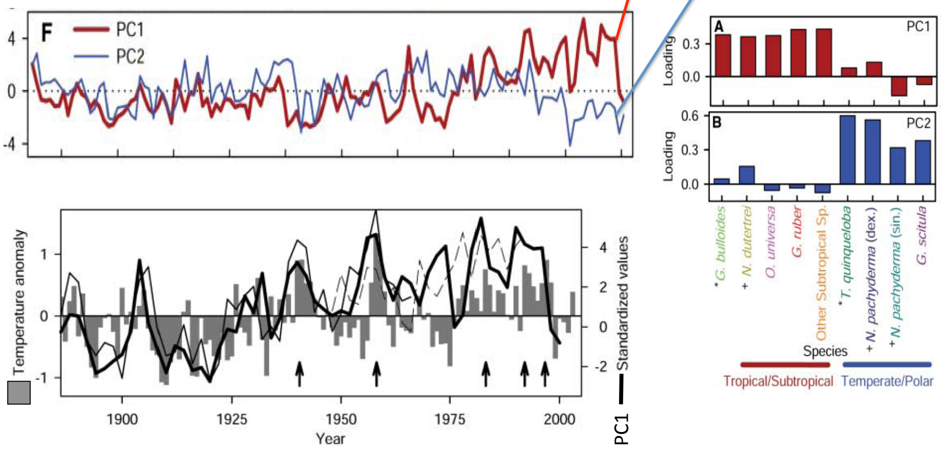
Orr et al. (2005) Nature

So, far warming more effective on Foraminifera than acidification

Tropical taxa

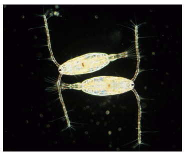
Temperate taxa

southern California



Field et al (2006) Science

Effects on copepods: no effect on mortality

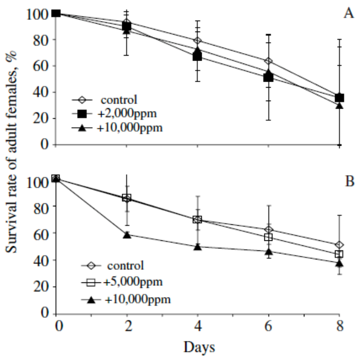


H. Kurihara et al. / Marine Pollution Bulletin 49 (2004) 721–727

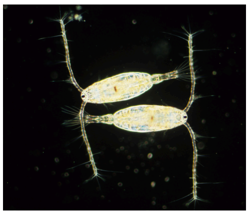
Table 2
pH and pCO_2 level of each CO_2 seawater at the experiment of hatch and nauplius mortality rate of *A. erythraea* eggs

Conditions	pCO_2	pH
Control	0.036	8.09 (0.06)
+2000	0.236	7.31 (0.08)
+5000	0.536	7.00 (0.05)
+10,000	1.036	6.82 (0.05)

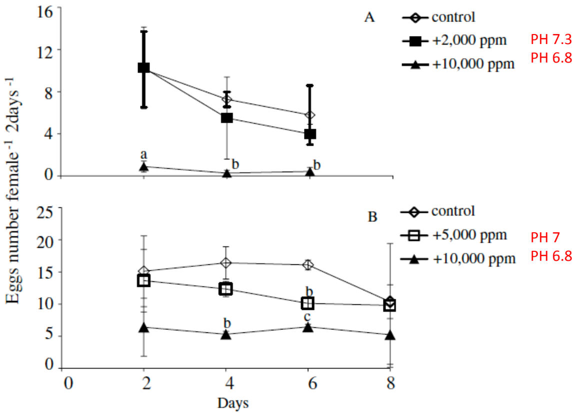
Fig. 1. Survival rate of adult female copepods (A) *A. steueri* and (B) *A. erythraea* incubated in increased CO_2 concentrations. Bars mean SD. Each value is the mean of three experiments for *A. steueri* and 2 for *A. erythraea*.



Effects on copepods: inconclusive on reproduction



H. Kurihara et al. / Marine Pollution Bulletin 49 (2004) 721–727



Effects

Kleypas 2008

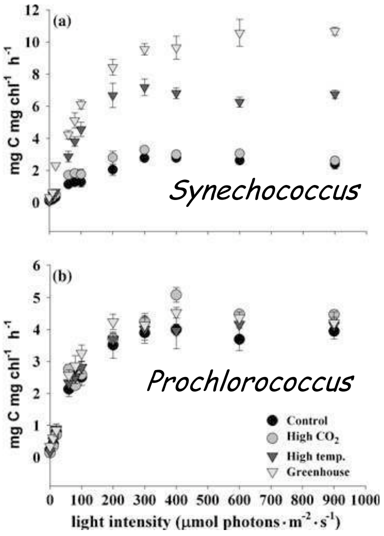
Cyanobacteria

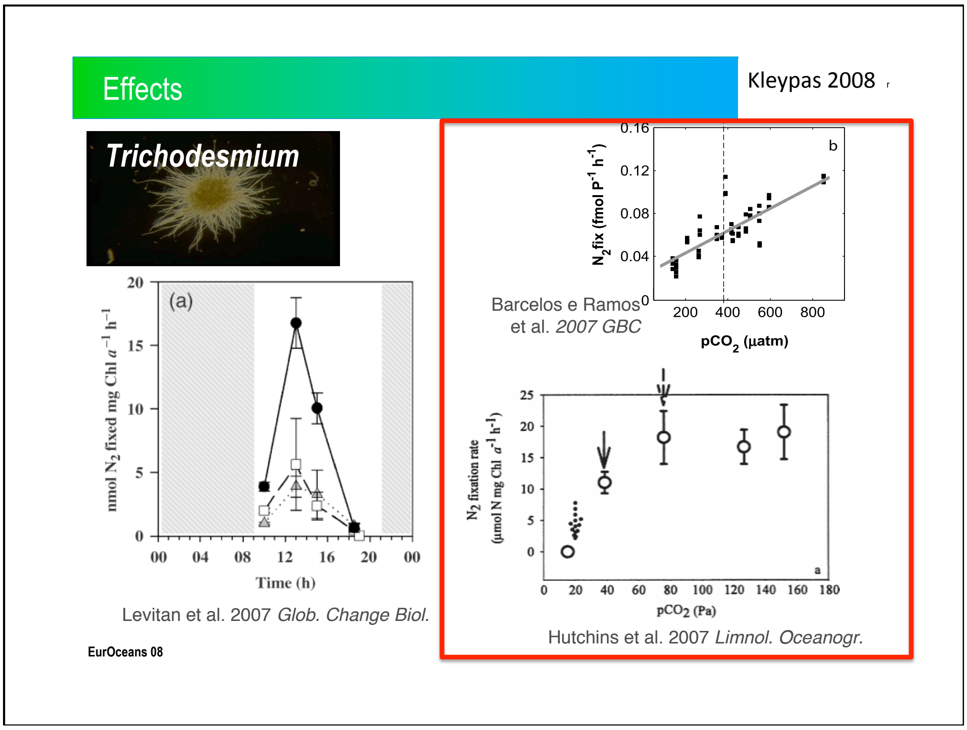
Photosynthesis versus irradiance curves:

Different responses of *Synechococcus* and *Prochlorococcus* to elevated pCO_2 and temperature

`Fu et al. 2007 J. Phycol.`

EurOceans 08





Effects

Kleypas 2008

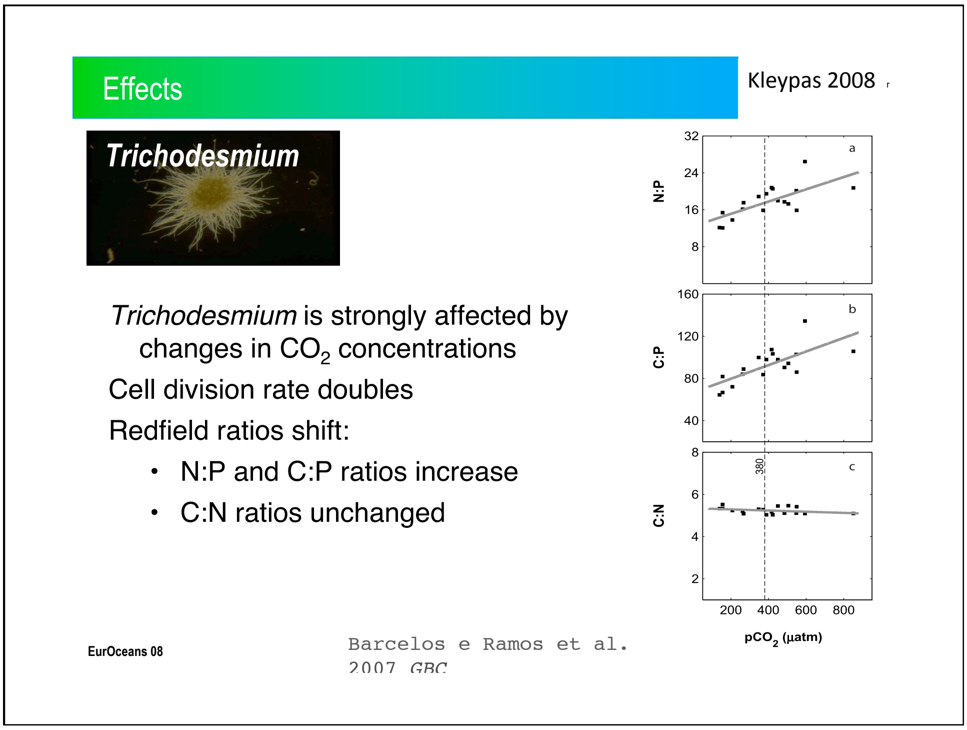
Trichodesmium

Levitan et al. 2007 *Glob. Change Biol.*

Barcelos e Ramos et al. *2007 GBC*

Hutchins et al. 2007 *Limnol. Oceanogr.*

EurOceans 08



Effects

Kleypas 2008

Trichodesmium

Trichodesmium is strongly affected by changes in CO_2 concentrations

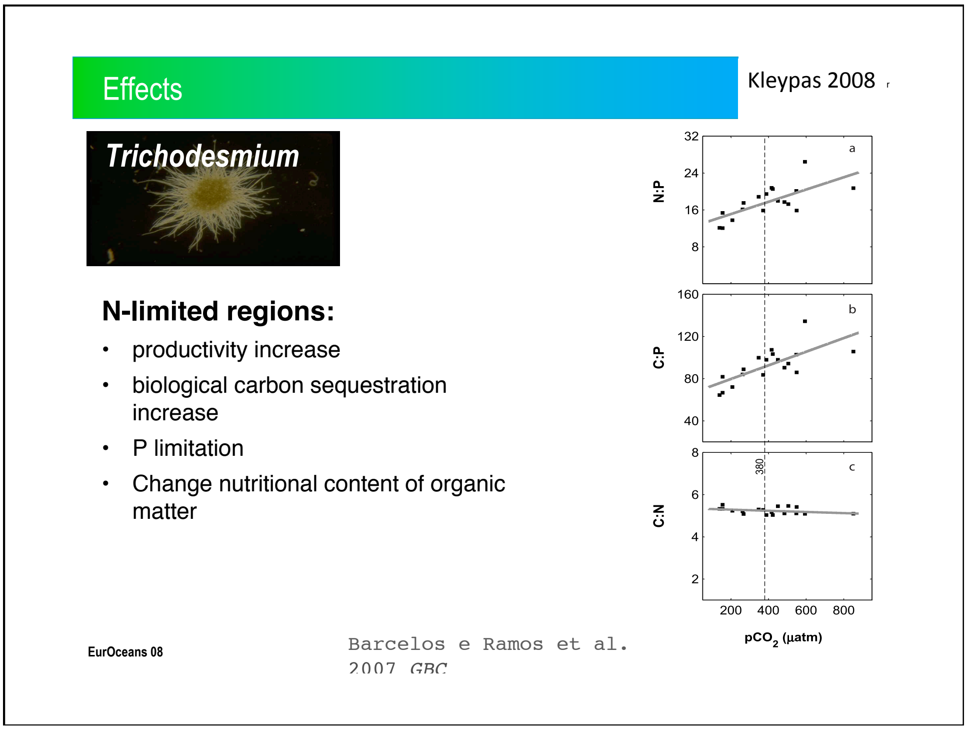
Cell division rate doubles

Redfield ratios shift:

- N:P and C:P ratios increase
- C:N ratios unchanged

EurOceans 08

`Barcelos e Ramos et al. 2007 GBC`



Effects

Kleypas 2008

Trichodesmium

N-limited regions:

- productivity increase
- biological carbon sequestration increase
- P limitation
- Change nutritional content of organic matter

EurOceans 08

Barcelos e Ramos et al. 2007 GBC

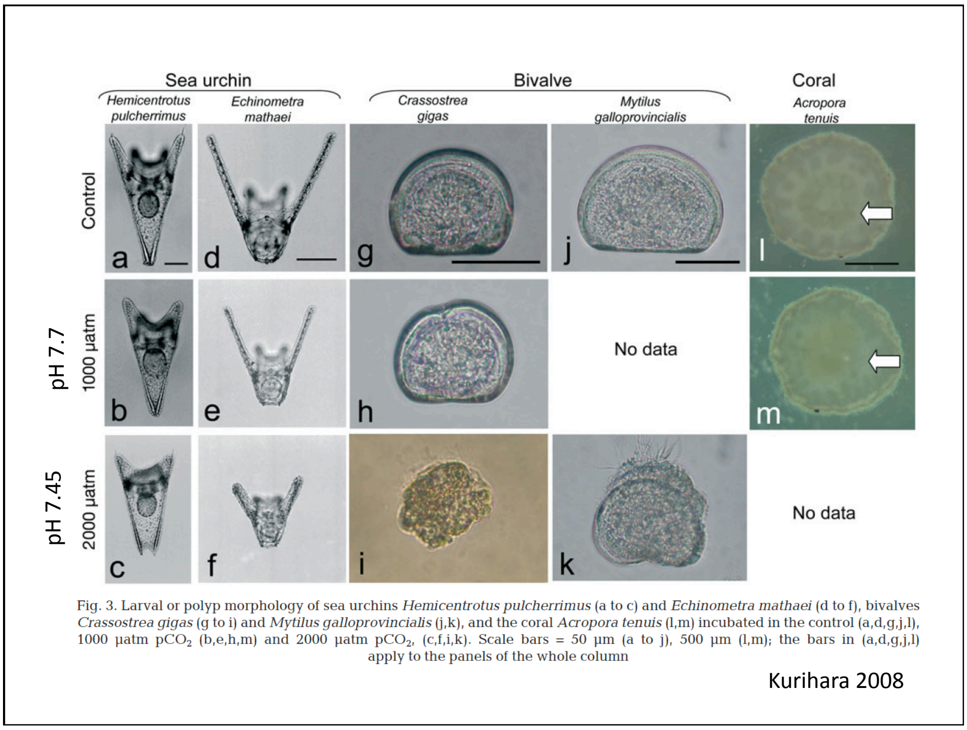
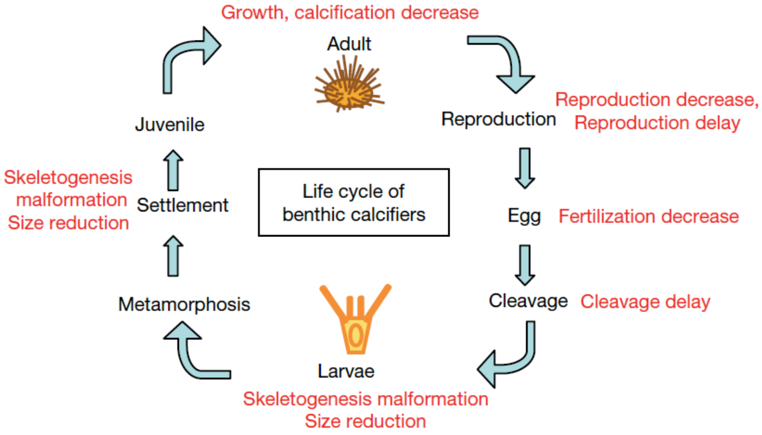


Fig. 3. Larval or polyp morphology of sea urchins *Hemicentrotus pulcherrimus* (a to c) and *Echinometra mathaei* (d to f), bivalves *Crassostrea gigas* (g to i) and *Mytilus galloprovincialis* (j,k), and the coral *Acropora tenuis* (l,m) incubated in the control (a,d,g,j,l), 1000 µatm pCO_2 (b,e,h,m) and 2000 µatm pCO_2, (c,f,i,k). Scale bars = 50 µm (a to j), 500 µm (l,m); the bars in (a,d,g,j,l) apply to the panels of the whole column

Kurihara 2008



Growth, calcification decrease

Adult

Reproduction

Reproduction decrease,
Reproduction delay

Egg

Fertilization decrease

Cleavage

Cleavage delay

Larvae

Skeletogenesis malformation
Size reduction

Metamorphosis

Settlement

Skeletogenesis
malformation
Size reduction

Juvenile

Life cycle of
benthic calcifiers

Fig. 5. Summary of CO_2 effects at different life cycle stages of benthic calcifiers under CO_2 concentrations that are expected to occur in the future ocean (380~2000 µatm pCO_2 / pH 8.2~7.3). Although the magnitude of CO_2 tolerance may differ between species and life stages, effects of high CO_2 are proposed for several different life stages, including reproduction, egg, cleavage, larva, settlement and adult stages

Kurihara 2008

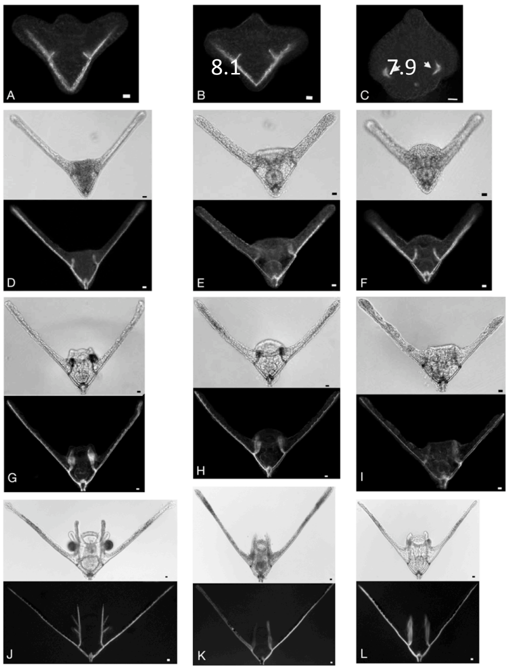


Fig. 3. *Ophiothrix fragilis*. Larval development at the 3 pHs used. First column (A, D, G, J), pH 8.1 (control); second column (B, E, H, K), pH 7.9; third column (C, F, I, L), pH 7.7. (A to C) Day 1, (D to F) Day 2, (G to I) Day 5, (J to L) Day 8. Dark panels: normal transmitted light; light panels: polarized light. Scale bars = 10 µm

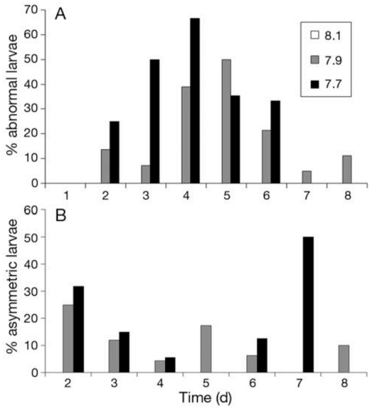


Fig. 7. *Ophiothrix fragilis*. Percentage of (A) abnormalities and (B) asymmetry in larvae raised at pH 8.1, 7.9 and 7.7 (data pooled from the different repetitions). By definition, no larva was asymmetric at pH 8.1 (controls). Note the absence of abnormalities at pH 8.1 (controls)

We lack long-term studies

Dupont et al. 2008

UV and acidification combined effects (Gao et al. 2009)

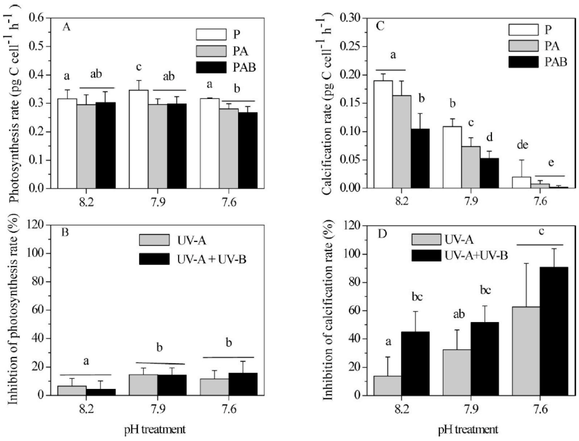
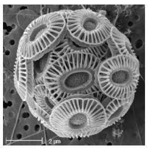
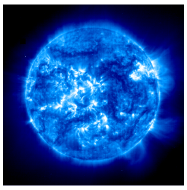


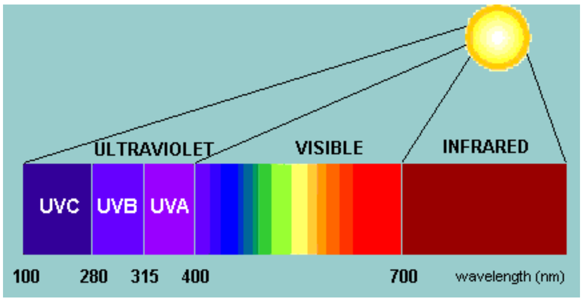
Fig. 4. (A) Effects of UVR on photosynthetic carbon fixation of *E. huxleyi* grown at 8.2, 7.9, and 7.6 pH_{NBS} levels. The cells were exposed to PAR only (P), PAR + UV-A (PA), or PAR + UV-A + UV-B (PAB). (B) UV-A–induced or UV-A + UV-B–induced inhibition of photosynthesis at pH levels of 8.2, 7.9, and 7.6. (C) Effects of UVR on calcification carbon fixation of *E. huxleyi* grown at 8.2, 7.9, and 7.6 pH_{NBS} levels. The cells were exposed to PAR only (P), PAR + UV-A (PA) or PAR + UV-A + UV-B (PAB). (D) UV-A–induced or UV-A + UV-B–induced inhibition of calcification at pH levels of 8.2, 7.9, and 7.6. The letters on top of the bars indicate significant difference at $p = 0.05$, so for the same letters there are no significant differences among the data. The values are means ± SD ($n = 9$; 3 measurements for each of the triplicate cultures at day 11).



P = PAR
PA = PAR+UV-A
PAB = PAR+UV-A+UV-B

UV may damage organisms, especially at high latitudes



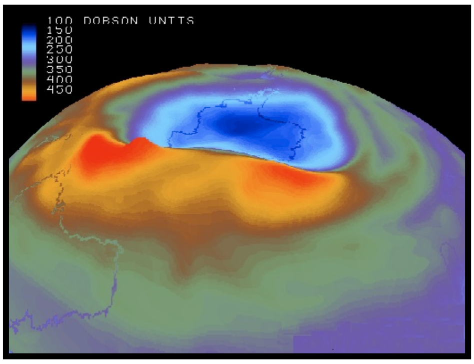


Ozone depletion

Reduction of Arctic and Antarctic ice cover

⇩

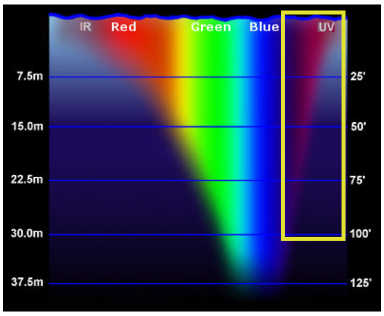
Higher doses of UVR in polar regions



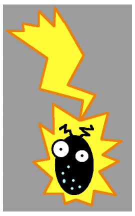
slide from C. Ruiz

UVR (280-400nm) affects microbial activity through:

- Photochemical transformations of DOM
- Cellular damage

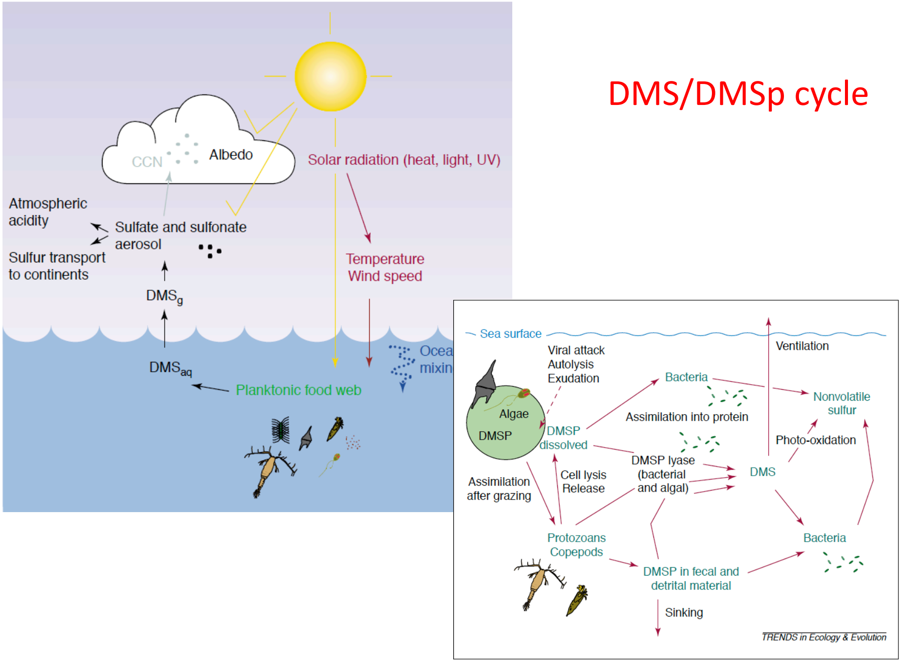


Direct damage	**Indirect damage**
Direct absortion by biological molecules	Formation of reactive oxigen species or free radicals



slide from C. Ruiz

DMS/DMSp cycle

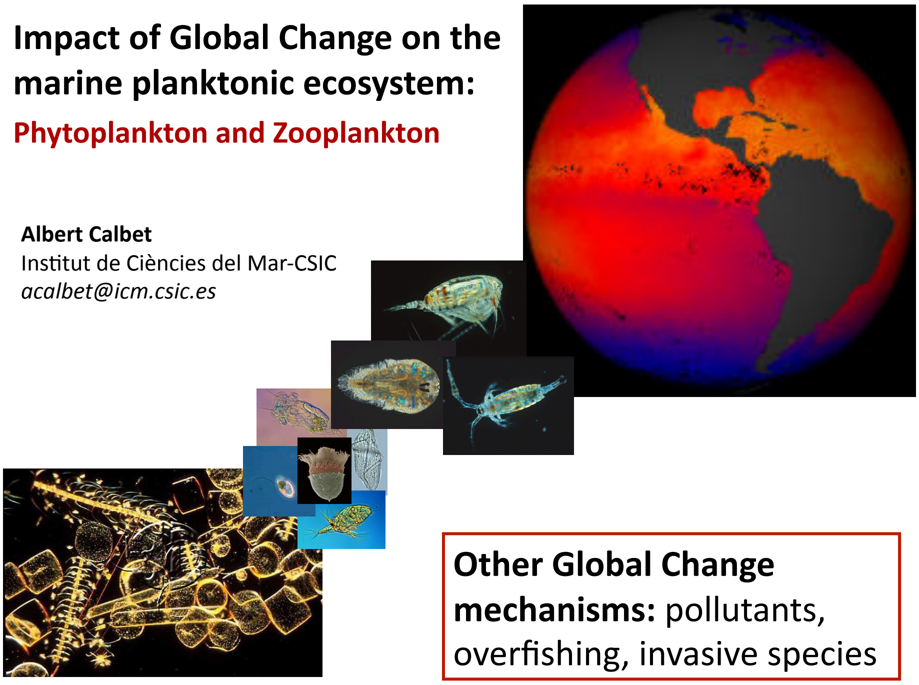


Simó 2001

Impact of Global Change on the marine planktonic ecosystem:

Phytoplankton and Zooplankton

Albert Calbet
Institut de Ciències del Mar-CSIC
acalbet@icm.csic.es



Other Global Change mechanisms: pollutants, overfishing, invasive species

POLLUTION

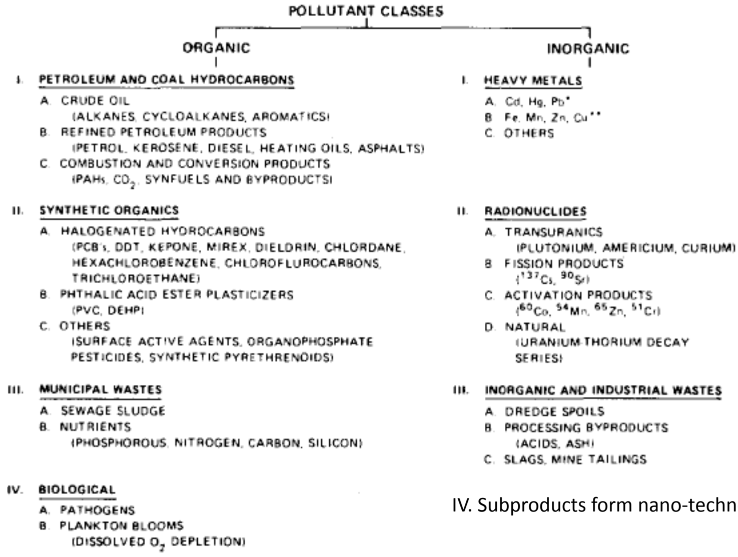
There are four main sources of aquatic (toxic) pollution:

- industrial wastes
- municipal wastes
- agricultural run-off
- accidental spillage

More than 2.8 billion gallons of industrial waste water per day are discharged directly into U.S. ocean waters (U.S. EPA, 1994)

Source	**Million gallons/year**
Large Spill Accidents	37
Routine Ship Maintenance	137
Drains and Urban Runoff	363
From Air Pollution	92
Natural seepage	62
Offshore Drilling	15

See the Sea.org



POLLUTANT CLASSES

ORGANIC

I. **PETROLEUM AND COAL HYDROCARBONS**
  - A. CRUDE OIL
    (ALKANES, CYCLOALKANES, AROMATICS)
  - B. REFINED PETROLEUM PRODUCTS
    (PETROL, KEROSENE, DIESEL, HEATING OILS, ASPHALTS)
  - C. COMBUSTION AND CONVERSION PRODUCTS
    (PAHs, CO_2, SYNFUELS AND BYPRODUCTS)

II. **SYNTHETIC ORGANICS**
  - A. HALOGENATED HYDROCARBONS
    (PCB's, DDT, KEPONE, MIREX, DIELDRIN, CHLORDANE, HEXACHLOROBENZENE, CHLOROFLUROCARBONS, TRICHLOROETHANE)
  - B. PHTHALIC ACID ESTER PLASTICIZERS
    (PVC, DEHP)
  - C. OTHERS
    (SURFACE ACTIVE AGENTS, ORGANOPHOSPHATE PESTICIDES, SYNTHETIC PYRETHRENOIDS)

III. **MUNICIPAL WASTES**
  - A. SEWAGE SLUDGE
  - B. NUTRIENTS
    (PHOSPHOROUS, NITROGEN, CARBON, SILICON)

IV. **BIOLOGICAL**
  - A. PATHOGENS
  - B. PLANKTON BLOOMS
    (DISSOLVED O_2 DEPLETION)

INORGANIC

I. **HEAVY METALS**
  - A. Cd, Hg, Pb*
  - B. Fe, Mn, Zn, Cu**
  - C. OTHERS

II. **RADIONUCLIDES**
  - A. TRANSURANICS
    (PLUTONIUM, AMERICIUM, CURIUM)
  - B. FISSION PRODUCTS
    (^{137}Cs, ^{90}Sr)
  - C. ACTIVATION PRODUCTS
    (^{60}Co, ^{54}Mn, ^{65}Zn, ^{51}Cr)
  - D. NATURAL
    (URANIUM-THORIUM DECAY SERIES)

III. **INORGANIC AND INDUSTRIAL WASTES**
  - A. DREDGE SPOILS
  - B. PROCESSING BYPRODUCTS
    (ACIDS, ASH)
  - C. SLAGS, MINE TAILINGS

IV. Subproducts form nano-technology

Olsen et al. 1982

GEOCHEMICAL PROCESSES AFFECTING PARTICLE-POLLUTANT DYNAMICS IN COASTAL MARINE ENVIRONMENTS

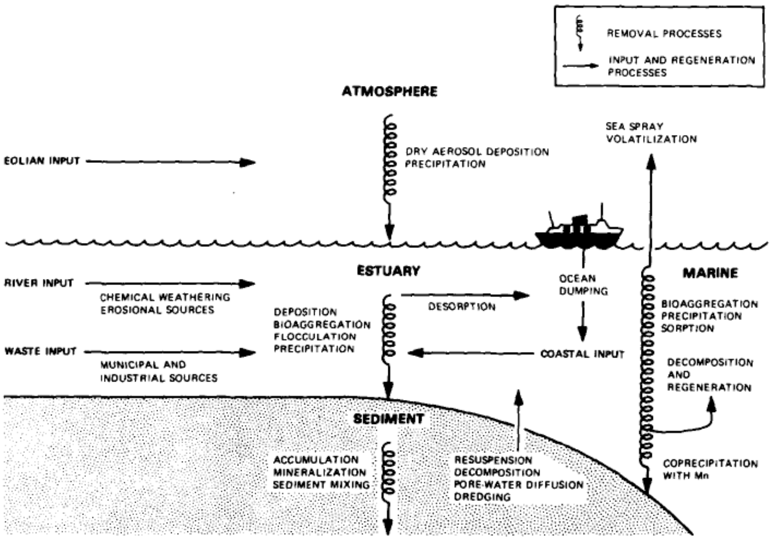
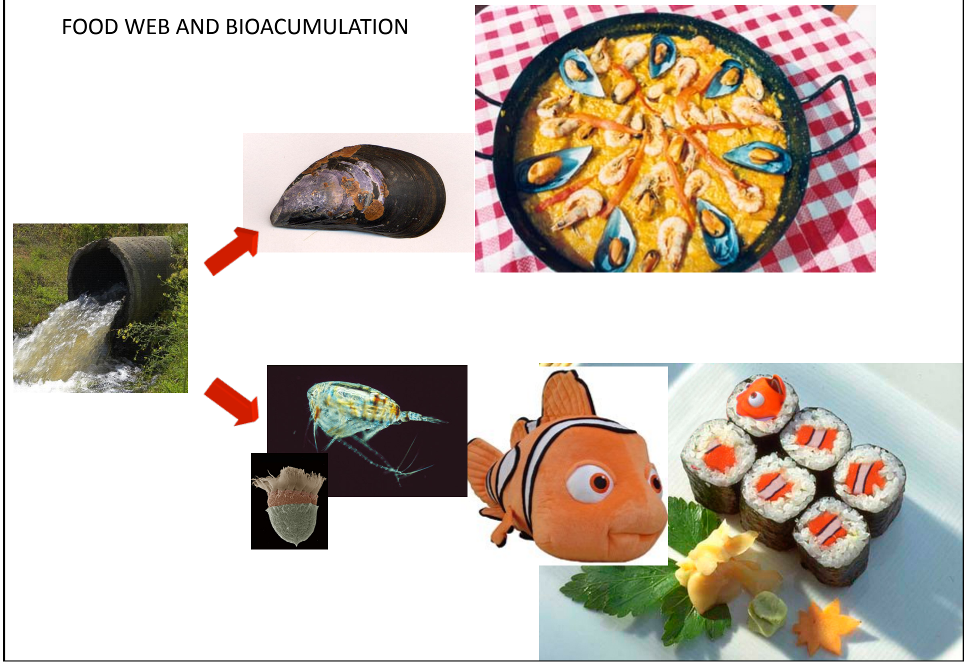
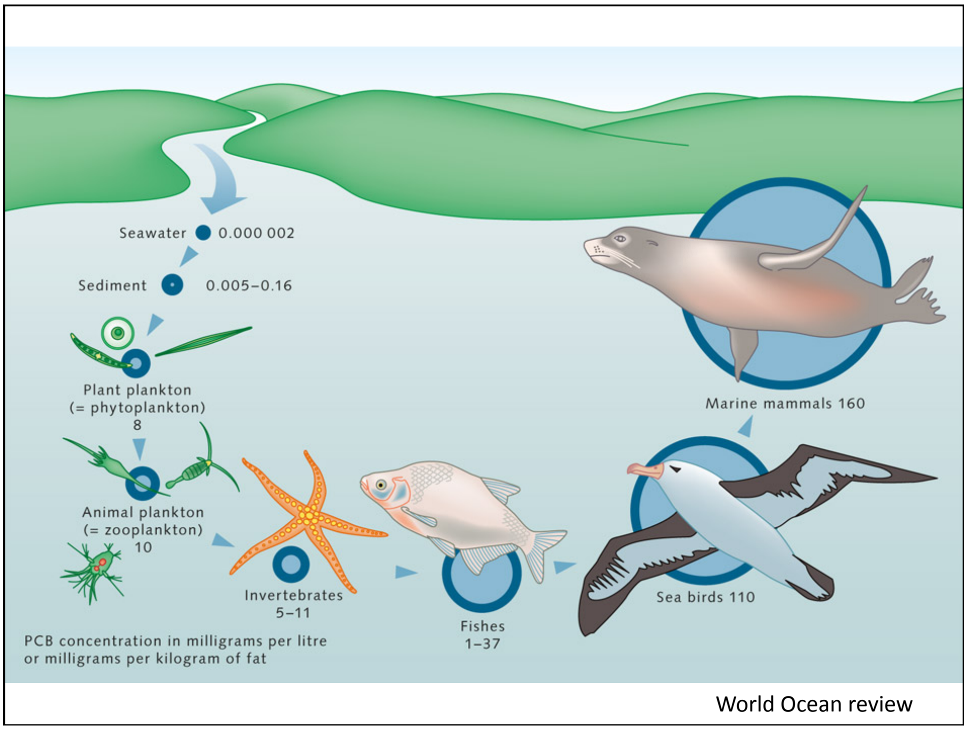


Fig. 1. Schematic illustration of the biogeochemical processes which affect pollutant—particle dynamics.

Olsen et al. 1982

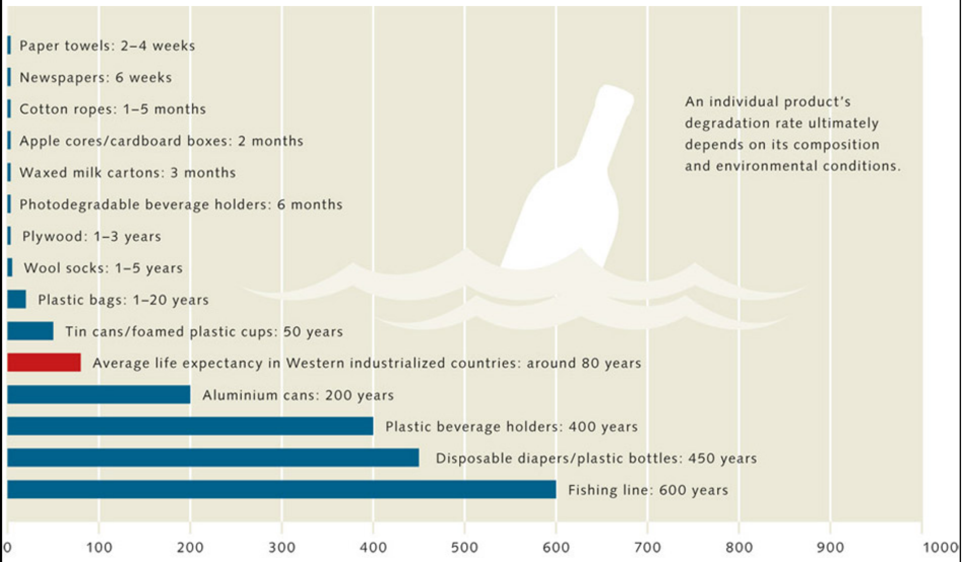
FOOD WEB AND BIOACUMULATION



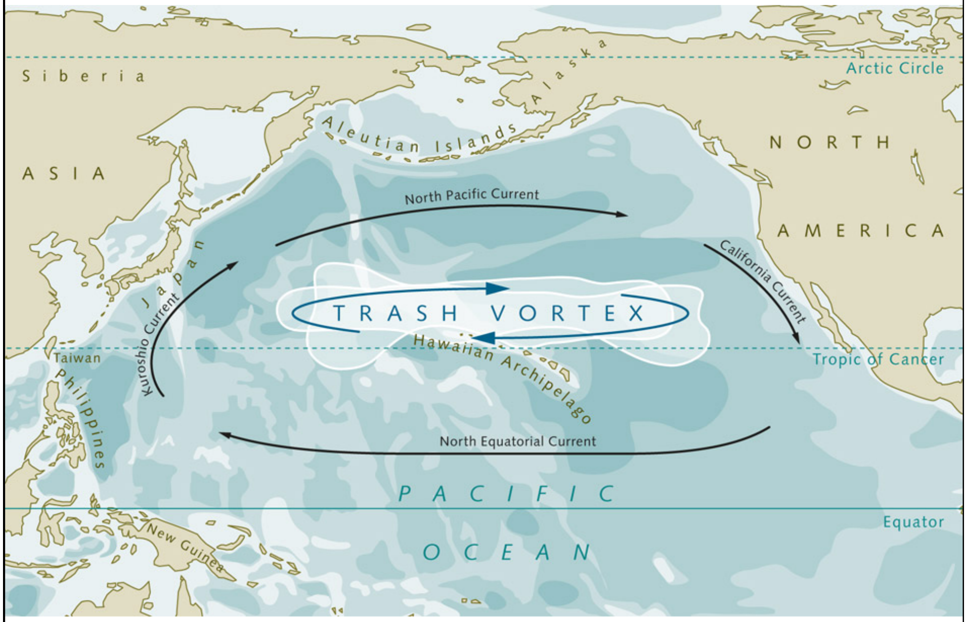


World Ocean review

Not only chemicals, also litter

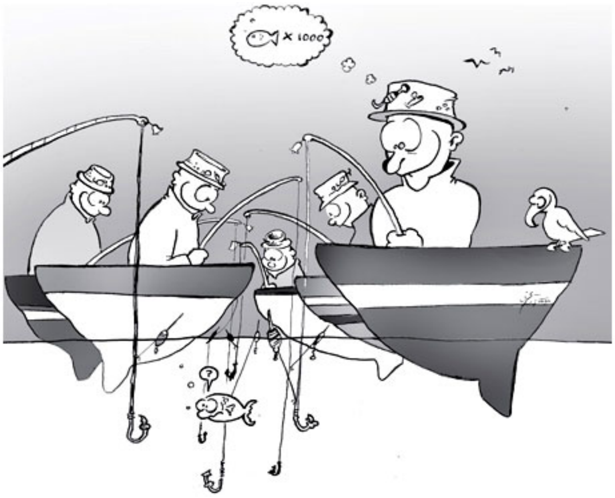


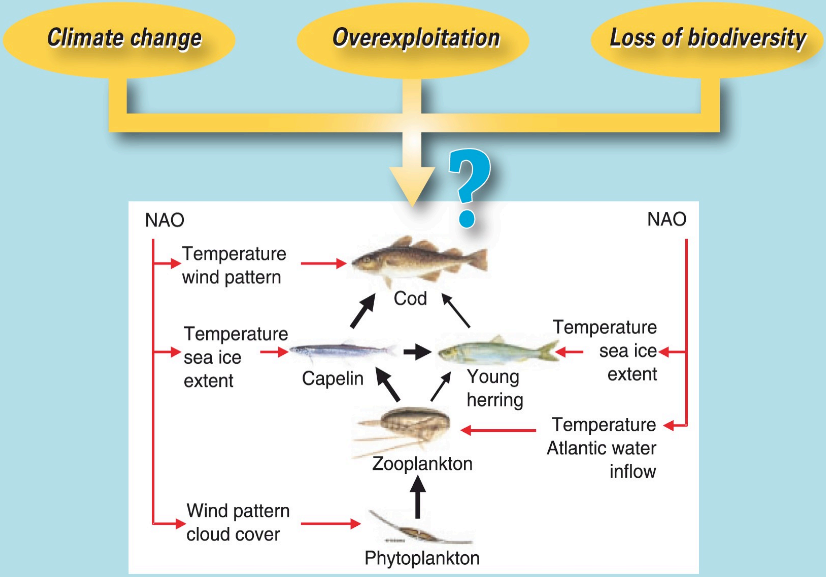
World Ocean review



World Ocean Review

OVERFISHING



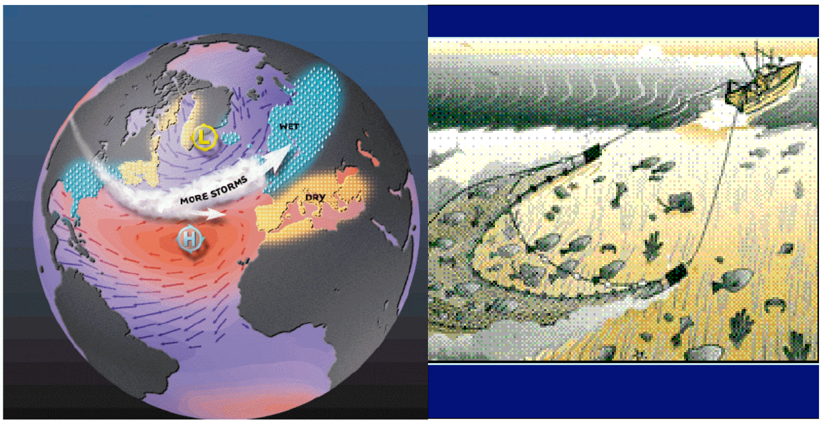


Climate change

Overexploitation

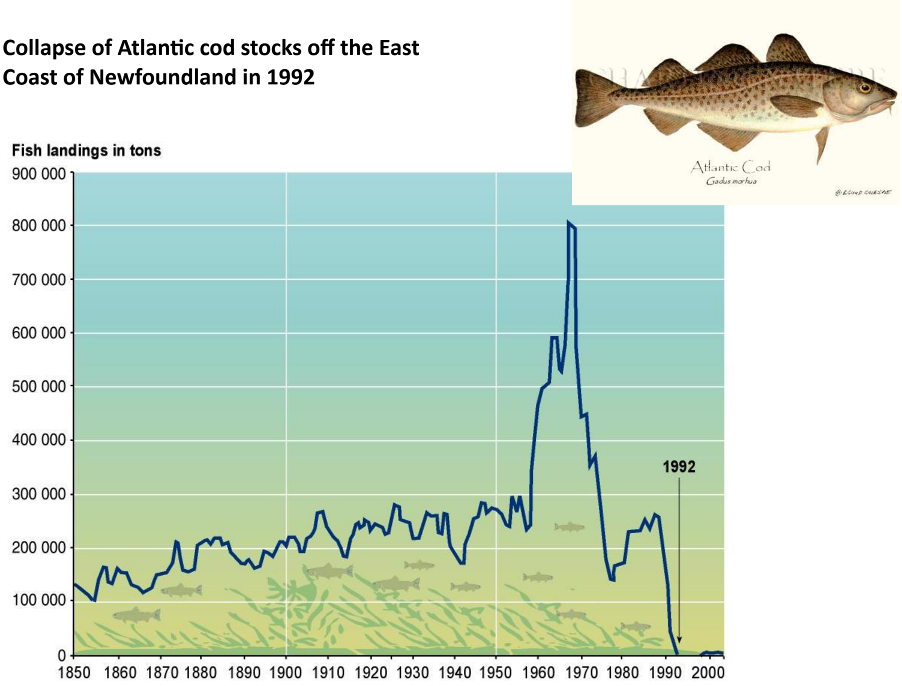
Loss of biodiversity

- Systems changing due to environmental forcing (natural and anthropogenic)

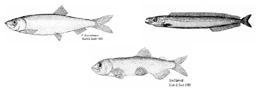


Kenneth et al. 2005

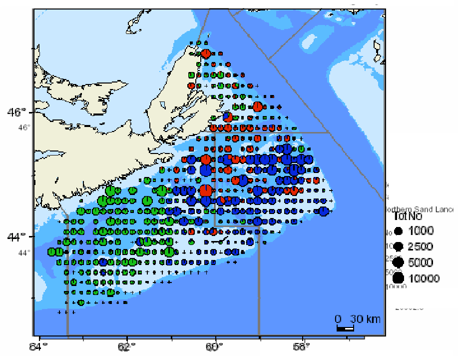
Collapse of Atlantic cod stocks off the East Coast of Newfoundland in 1992

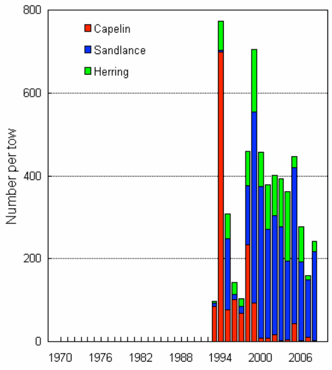


Source: Millennium Ecosystem Assessment



Response of major forage fish species (planktivores)

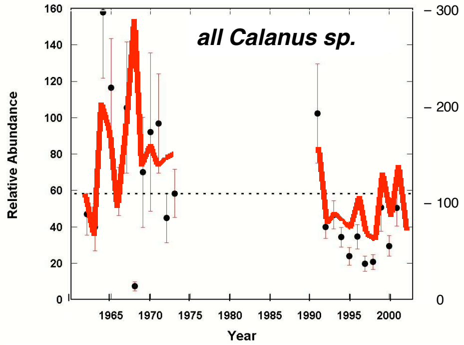




- Release from predation
- Similar increases in macroinvertebrates

Kenneth et al. 2005

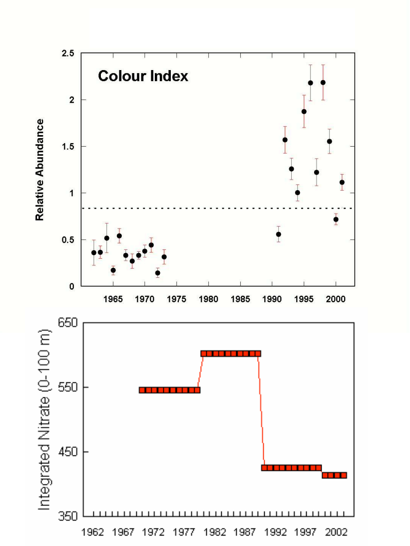
Response of Zooplankton



Decline in abundance of large-bodied species

Kenneth et al. 2005

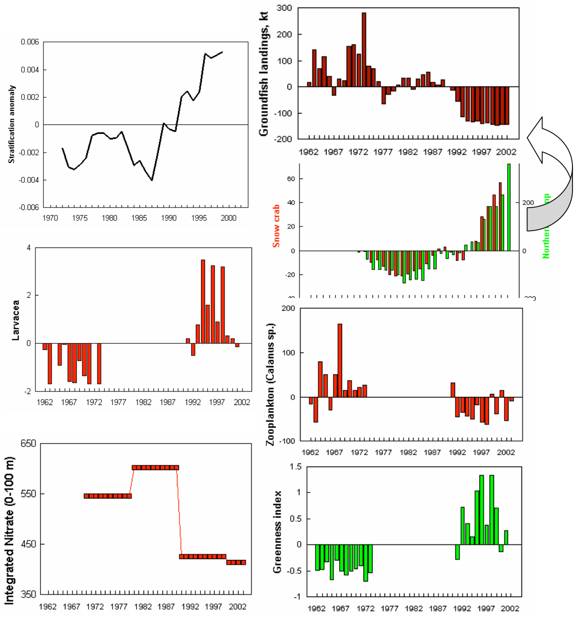
Phytoplankton and nutrients



Phytoplankton levels increased dramatically after 1992

Nutrients (decadal averages) steadily dropped

Kenneth et al. 2005



Side effects:

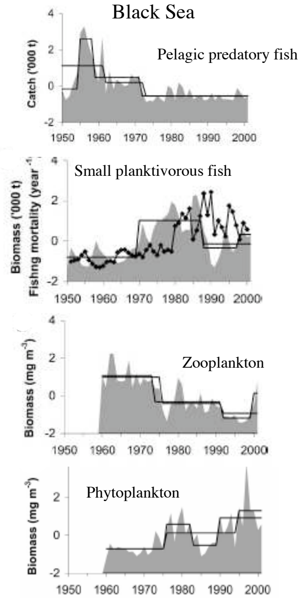
Quijon & Snelgrove (2005):

Crab predation reduces infaunal abundance of sedentary polychaetes and clams

Negative feedback – forage fish prey on early life stages of former predators

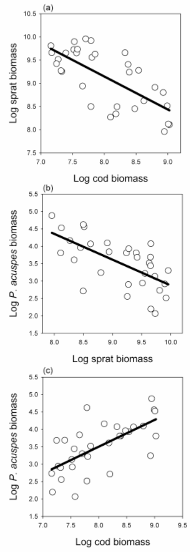
Non-predated mesozooplankton increase (e.g. larvacea) but can flourish at low nutrient levels

Black Sea



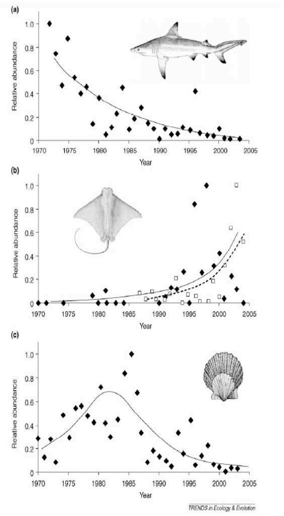
Daskalov et al 2007

Baltic Sea



(Möllmann et al. 2008)

SE US Coast



(Myers et al. 2008)

Invasive species

Introductory vectors on alien species

- **Ballast Water:** 1 of the 2 major unintentional mechanisms for aquatic introductions, the other: **hull-fouling**
- International **shipping**, followed by **aquaculture:** major means of introduction globally, also 2 main vectors for high levels of invasion in temperate regions of Europe, North America and Australia
- Regional differences, i.e. Eastern Mediterranean: Suez Canal, main mechanism
- Other important mechanisms: sediments in ballast tanks and attached to anchors/chains and commercial fishing nets and gear

From Quílez-Badia 2009

Other introductory vectors

aquaculture (intentional and unintentional)

stock enhancement purposes

use of living organisms as bait or packing material for bait

fish processing companies

remaining organisms left in fishnets and traps

import of live animals for human consumption

on or within recreational equipment

ocean and coastal currents transporting organisms attached to man-made floating objects

species introductions as fouling organisms on migrating non-indigenous host species

transport of sand and gravel as construction material

removal of barriers

research

ornamental trade

imports for hobby or public aquaria

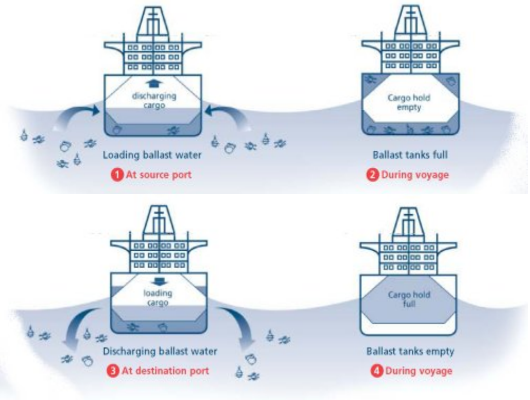
Smithsonian Environmental Research Center

From Quílez-Badia 2009

Seawater as ballast

- From 1880s ballast material changed: seawater easier to obtain, transport, get rid of, available everywhere => more efficient and economical than solid ballast

- When ship empty of cargo, BW taken in, when loaded with cargo, BW discharged => creating new type of transport to new environments, unattainable otherwise



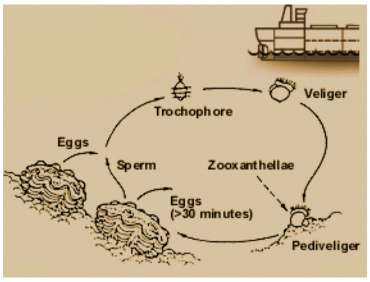
Source: GloBallast (http://globallast.imo.org/index.asp?page=problem.htm&menu=true)

From Quílez-Badia 2009

The ballast water (BW) problem

- It is expected global and local shipping will increase in future => can also generate potentially serious ecological, economical and health threat

- Organism small enough to go through ships' BW intake pumps and filters can be carried in BW => bacteria, other microbes, phytoplankton, small invertebrates, eggs, cysts and larvae of species (including of larger organisms (> 2 cm) and planktonic stages of benthic species)



Source: GloBallast (http://globallast.imo.org/index.asp?page=problem.htm&menu=true)

Examples of ballast water-mediated introductions

Zebra mussel (*Dreissena polymorpha*)


Source: USCG

- Originally from Black Sea
- First identified in US in 1988
- In Irish waters ,first noticed in 1997
- In Spain in 2001
- In US has infested > 40% of internal waterways and required US$1 billion on control measures between 1989 and 2000

Examples of ballast water-mediated introductions

Asian clam (*Corbula amurensis*)

- Native to Japan, China and Korea in cold temperatures.
- In San Francisco Bay, USA:
  - Major biological disturbance with significant ecological consequences. Large populations established (95% of biomass in some areas)
  - In the 1990s, so abundant that spring phytoplankton bloom virtually disappeared
  - Thought to be responsible for collapse of some commercial fisheries and decline in diversity and abundance of many benthic species


Photo: Luis A. Solórzano www.californiabiota.com

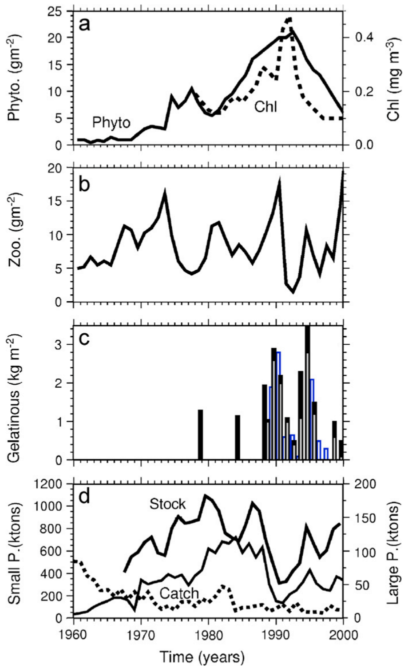
Examples of ballast water-mediated introductions

North American comb jellyfish (*Mnemiopsis leidyi*)

•Accidentally introduced in early 1980s to Black Sea:


Source: www.livt.net

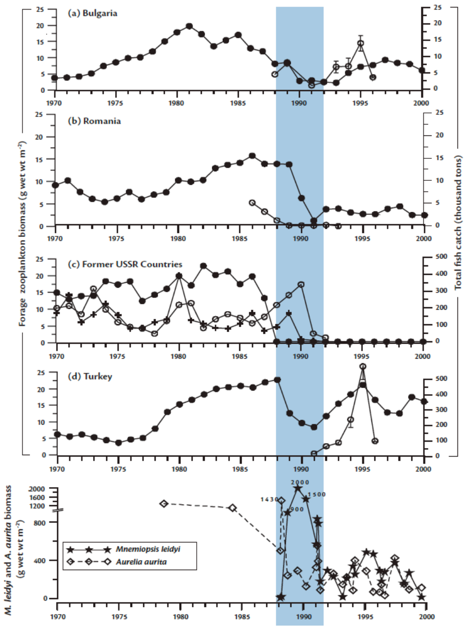
- ➢Population exploded: biomass of 1.5-2 kg · m^{-2} in summer of 1989, devastating food chain of entire Black Sea basin
- ➢Caused sharp decrease of anchovy (*Engraulis encrasicolus*) and other pelagic fish stocks in Black Sea.
- ➢Also similar effects on the Caspian Sea



BLACK SEA

Long-term changes of the (a) phytoplankton biomass integrated over the upper 50m of the water column (continuous line) (in g m^2) and surface chlorophyll concentration (broken line) (in mg m^3) during May–November period, (b) annual mean mesozooplankton biomass (in g m^2), (c) gelatinous carnivore biomass (in kg m^2) (*Mnemiopsis leidyi* in black color and Aurelia aurita in grey color), (d) annual mean small pelagic fish stock and catch, and large predatory pelagic catch (broken line) (in kilotons). They are given as the averages of all measurements within the interior basin.

Oguz et al. 2007



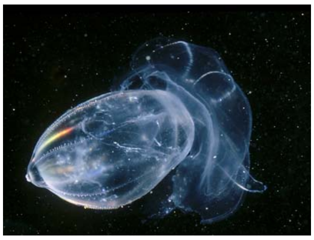
Only zooplankton, different areas

Long-term changes in the biomass of fish, forage zooplankton, and gelatinous macrozooplankton in the Black Sea. Fish catch data for each country is from www.seaaroundus. com. The forage zooplankton data (from Kideys et al. [2000], except for Romania) are for (a) from the off shore western Black Sea, (b) from the coastal waters off Romania (from A. Petran and M. Moldoveau, National Institute for Marine Research and Development "Grigore Antipa" Constanta, unpublished data, 2005), (c) from the coastal northwestern shelf (+) and off shore waters of the northeastern region, and (d) from off shore waters off Turkey. Gelatinous zooplankton data before 1991 belong to the northern Black Sea (Russian values), and after 1990 belong to the southern Black Sea (Turkish values, after Kideys et al. [2000]). Note the blue rectangular area where the first peak of *Mnemiopsis leidyi occurred, when there were* sharp decreases in the fish catches and forage zooplankton in different regions.

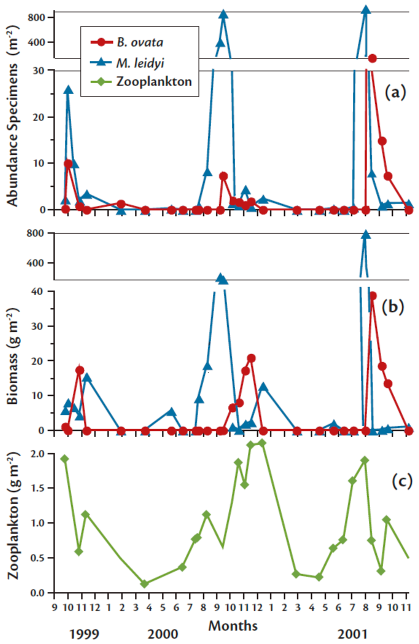
Kideys et al. 2005

Natural predator introduction (1998)

Beroe ovata



Beroe ovata feeding on *Mnemiopsis*



(a) Abundance and (b) biomass of *M. leidyi and B. ovata, and (c) zooplankton* biomass in Sevastopol Bay in 1999-2001 (from Finenko et al., 2003).

Note the predation impact of *B. ovata on M. leidyi and of M. leidyi on forage* zooplankton particularly in 2000 and 2001.

Kideys et al. 2005