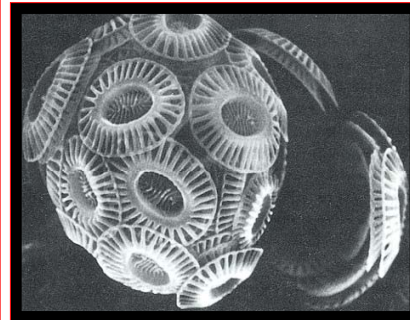
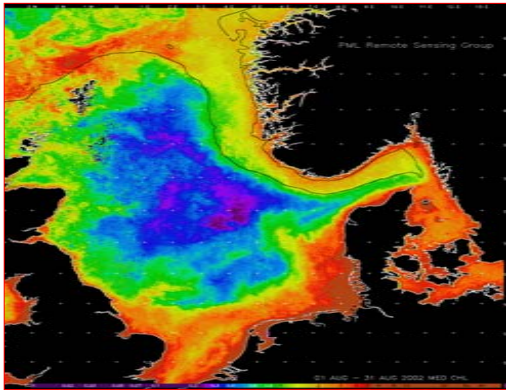


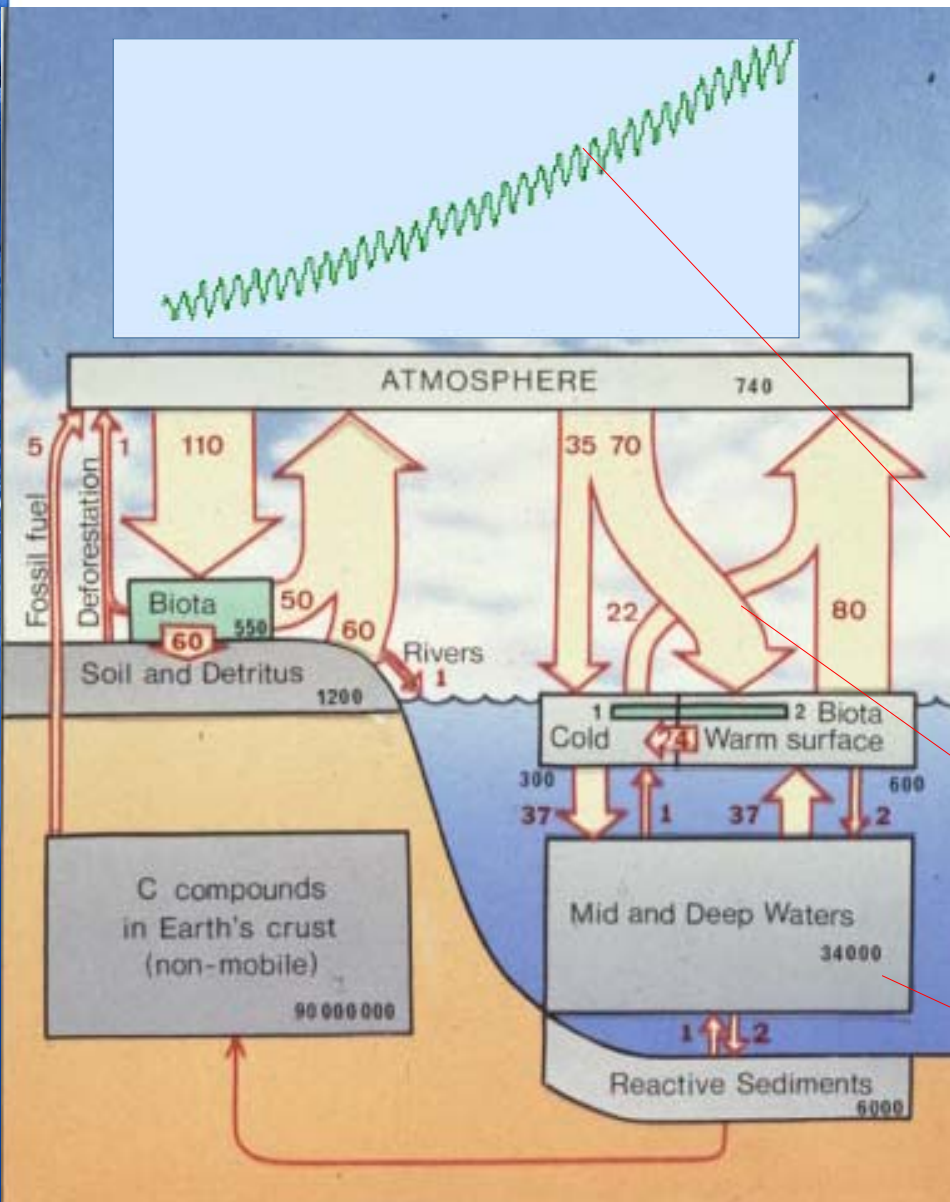
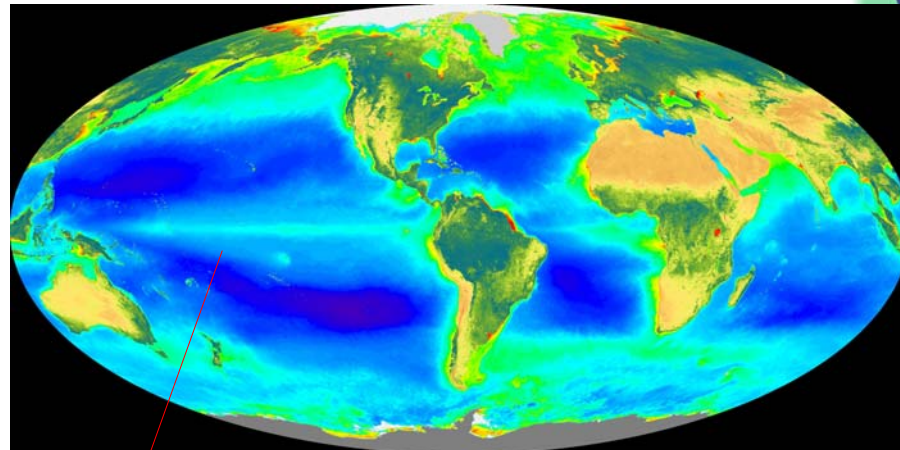
Ocean Acidification

Carol Turley

Plymouth Marine Laboratory, UK



Oceanic Role in the Global Carbon Cycle



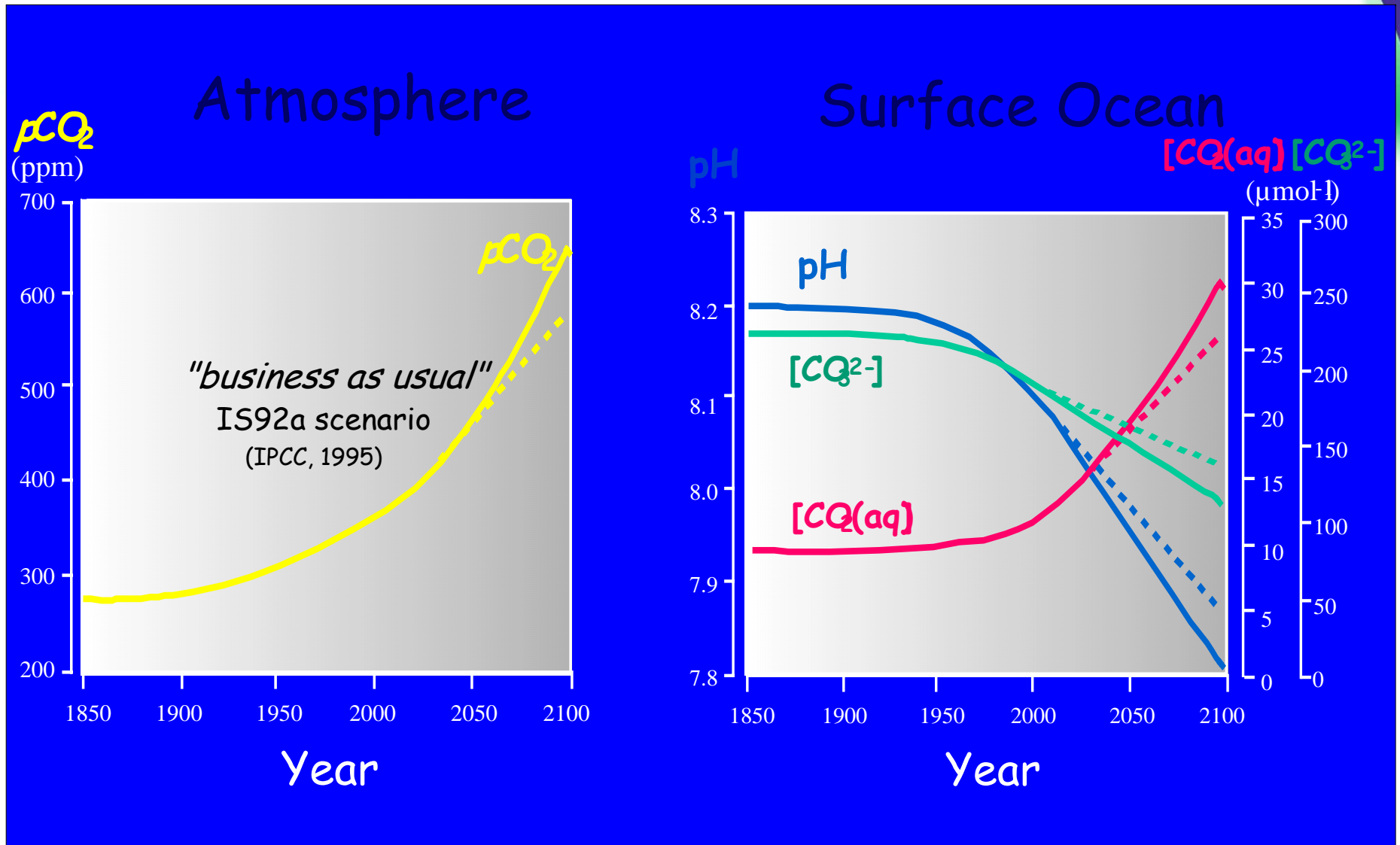
50% of global primary production is carried out in the oceans by plankton <math><10\mu\text{m}</math>

Anthropogenic CO_2 uptake is decreasing ocean pH

Fluxes of CO_2 in and out of the oceans are large

Oceans are an important reservoir for CO_2 with 50% of anthropogenic CO_2 taken up by oceans (Sabine et al. 2004 *Science*)

Oceanic Acidification



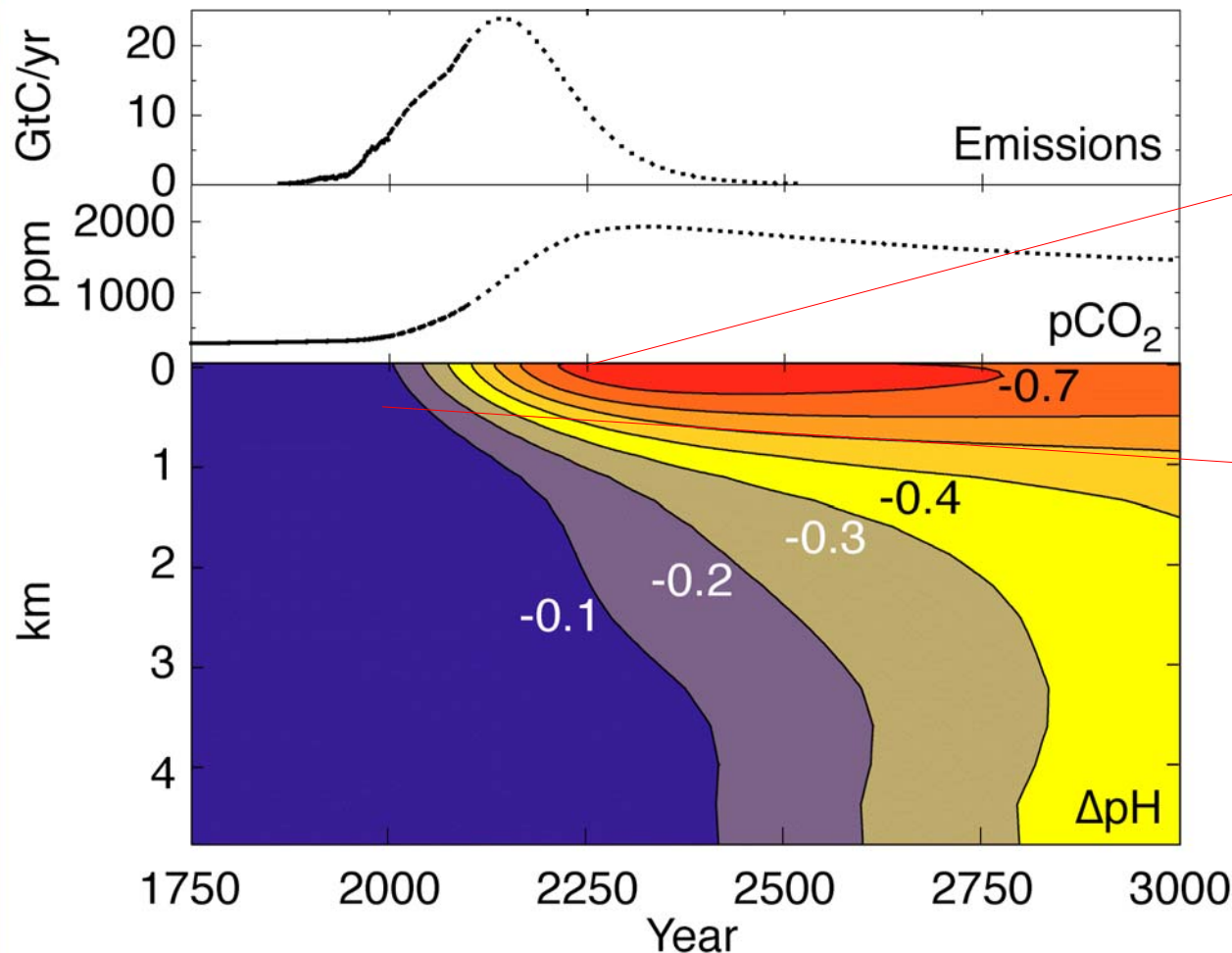
The Oceans are becoming more acid as they take up more CO_2

Wolf-Gladrow, Riebesell, Burkhardt, Bijma (1999) *Tellus* 51B, 461



Continued CO₂ Emissions and Ocean Acidification

While climate change has uncertainty, these geochemical changes are highly predictable. Only the time scale, and thus mixing scale length are really under debate.

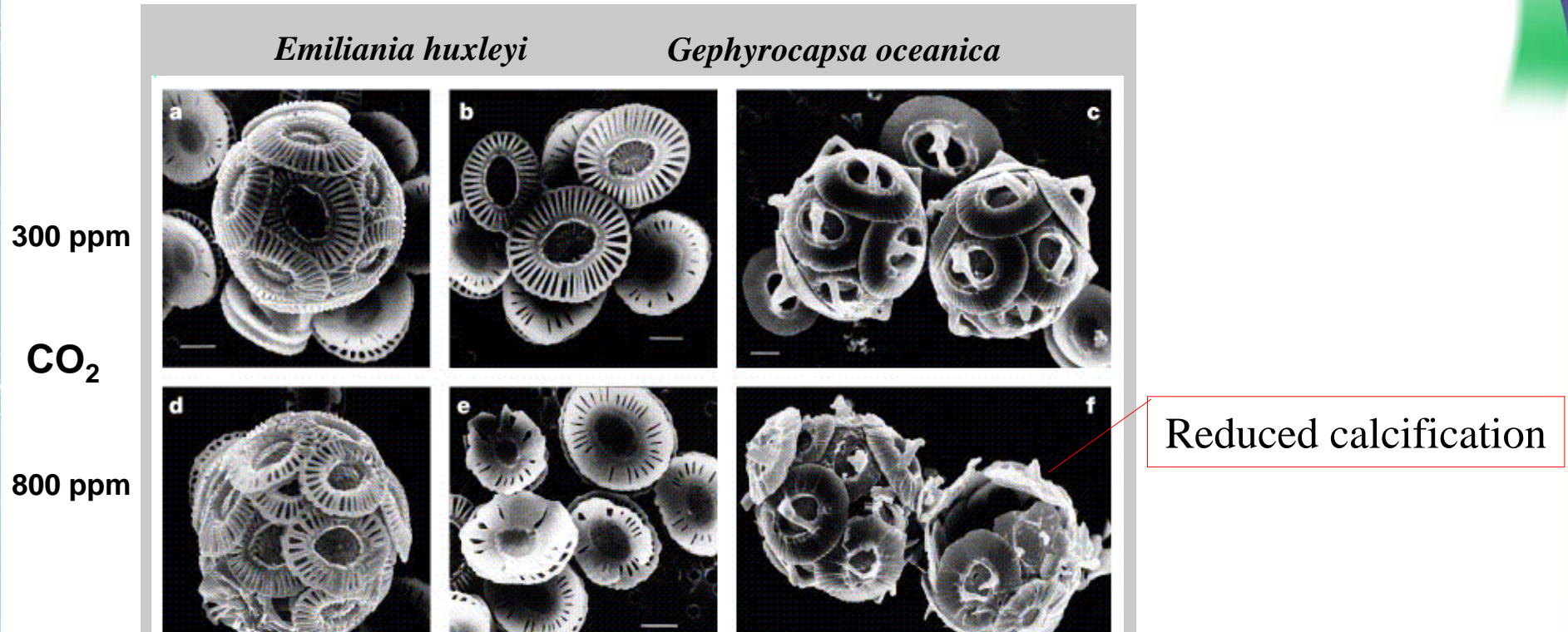


Anthropogenic CO₂ predicted to decrease surface ocean pH by 0.77

pH has probably already changed by 0.1 in surface waters due to absorption of anthropogenic CO₂

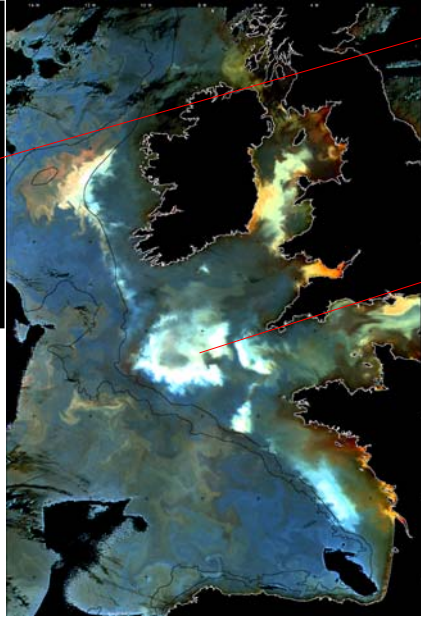
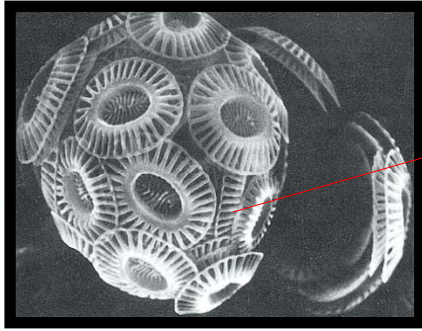
Caldeira & Wickett 2003, Nature: A simulation of changes in ocean pH assuming continued usage of known fossil fuel reserves.

Effects of CO₂ on Calcifying Phytoplankton - Coccolithophores



Riebesell et al. Nature (2000)

Coccolithophores: Important Primary Producers on European Shelf Seas



Largest current producer of **calcite** on Earth

Extensive blooms (often 100,000's km²) of these calcite forming phytoplankton occur on shelf seas

Important role in the global carbon cycle through the **transport of calcium carbonate** to deeper waters and sediments



Coccolithophores are major producers of dimethyl sulphide (**DMS**) to the atmosphere – thought to be important in cloud formation

Reduction in coccolithophores could change phytoplankton **biodiversity**

Change in biogeochemistry and ecosystem

Holligan (1993), Archer et al.

Increased CO₂/Decreased pH: Effect on Corals



Increased CO₂ may have a direct effect on hard corals to build reefs

Corals cannot secrete stable forms of calcium carbonate (especially aragonite) at lower pH

BIOSPHERE-2: Coral calcification rates may be **reduced** by 21% - 40% during 1880 – 2065 due to changes in atmospheric CO₂



Knock on effect on whole coral ecosystem

Extensive cold water corals have recently been discovered on the European Shelf

Effects on Calcareous Invertebrates

Commercial shellfish may suffer from:

- reduced feeding
- reduced growth
- respiratory distress
- destruction of chemosensory systems
- increased susceptibility to infection
- decalcification of shells
- narcosis
- decrease in population size
- mortality



100% mortality of scallop at pH 7

Spat and juveniles **more sensitive**, recruitment may be effected

Harris et al. 1999; Bamber 1990; Smith 1979; Yuan et al. 2000; Knutzen 1981; Morris et al. 1989; Lorentz & Taylor 1992; Dwyer & Burnett 1996; Burnett et al. 1997; Tamburri et al. 2000 Shiramura 2002

Effect of pH on Benthic Ecosystem Engineers



"Ecosystem engineers" modify, maintain and/or create habitats



These key species have calcium carbon shells or skeletons and are important in European shelf sediments

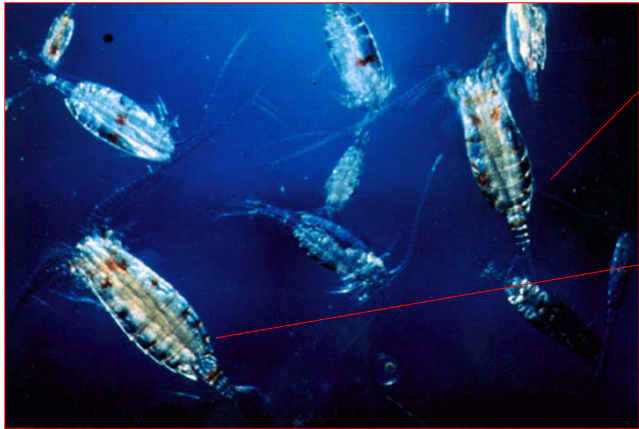


Large, long lived organisms are very important for maintaining benthic diversity and regulating biogeochemical processes



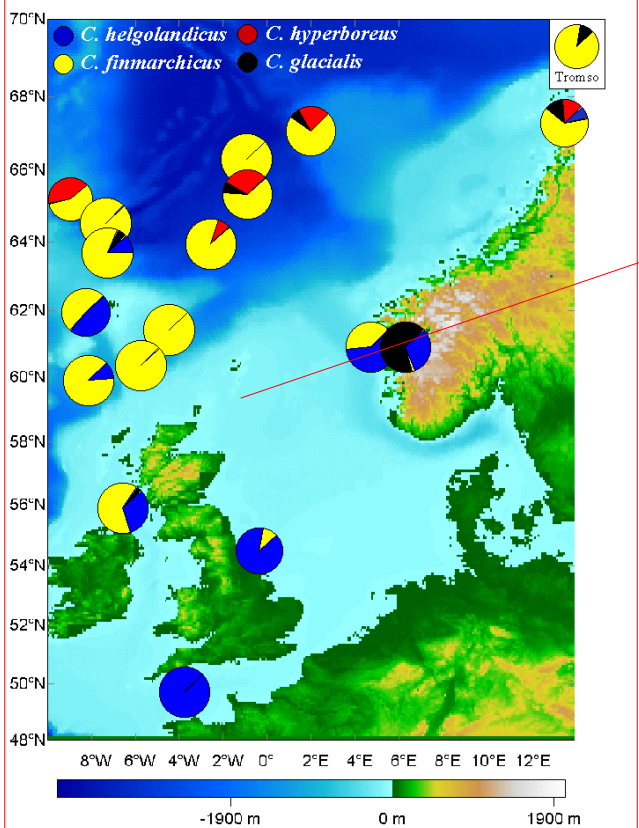
Unknown vulnerability to CO₂ induced pH change

Effects of Low pH on Zooplankton



Evidence to indicate that marine zooplankton (crustacea) passing through plumes of CO₂ enriched seawater suffer high mortalities – but very little research

Some zooplankton have calcium carbonate shells (molluscs) or skeleton others are chitinous (crustacea), the latter may be less sensitive to pH



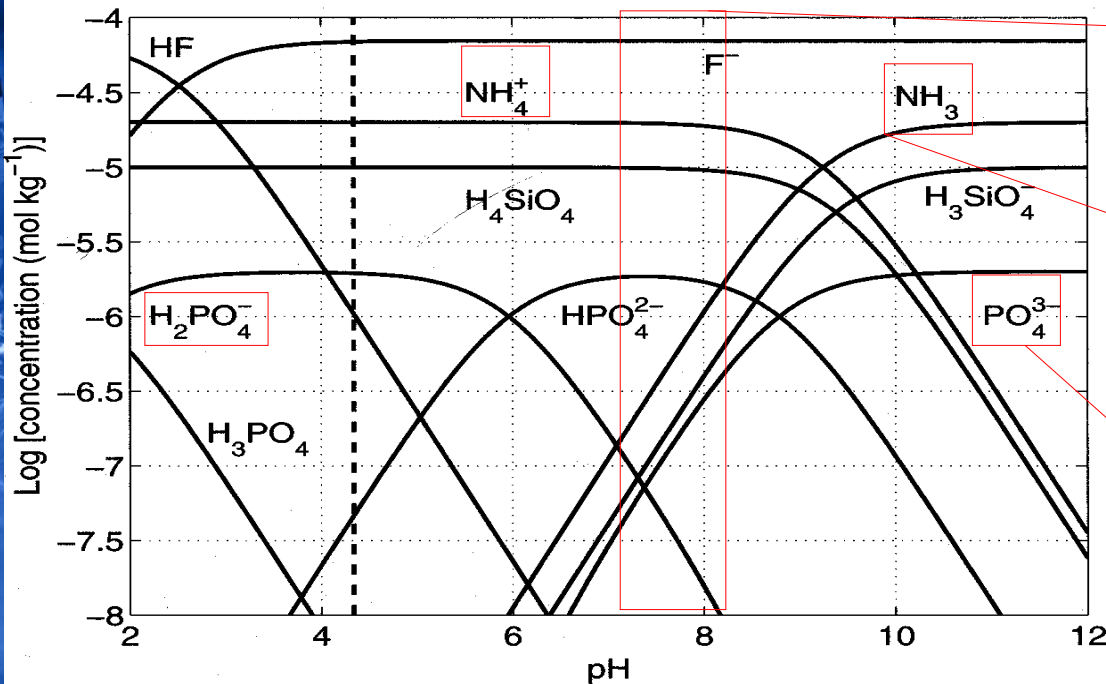
Reduced fertilization of copepod eggs at CO₂ levels beyond 1000 ppm

Zooplankton are a key part of the food chain and species vary with water mass



A change in species diversity may change the size of faecal pellets and the biological pump

Effect of Reducing pH on Key Nutrients



Speciation: of key nutrients for phytoplankton and bacterial growth are pH dependent

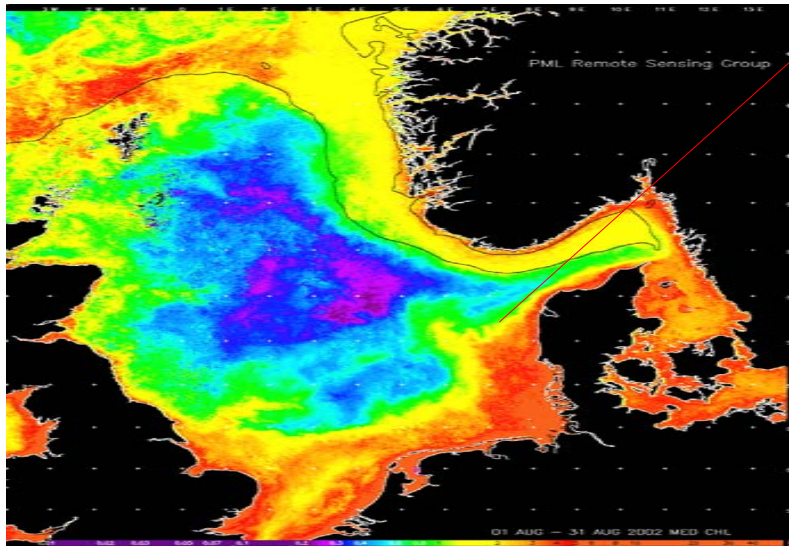
Nitrogen: in particular ammonia-ammonium, is pH dependent, with the concentration of NH₃ (Aq) decreasing as pH declines

Inorganic phosphate: as pH falls to 7.8, the concentration of H₂PO₄⁻ rises as that of PO₄³⁻ decreases

Consequences: for nutrient availability to phytoplankton and bacteria is not clear

Changes in speciation of phosphate, silicate and ammonia with pH (from Reebe and Wolf-Gladrow 2001)

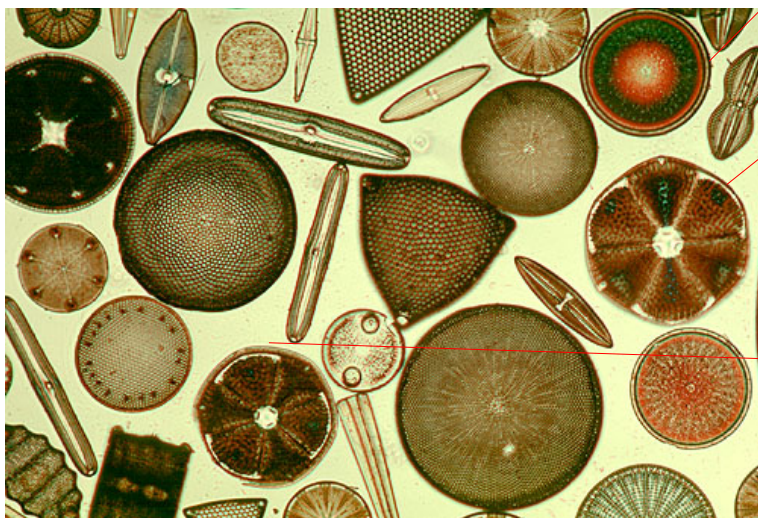
Effect of pH Induced Changes in Nutrient Speciation on Phytoplankton



August 2002 mean chlorophyll concentration from SeaWiFS

Nutrients are an important control on the evolution of the spring phytoplankton bloom in surface waters of the shelf seas

- At pH 7.8 NH_3 may be reduced by c. 50%
- Phytoplankton use active transport mechanisms to acquire it i.e. use energy
- Will this impose an ecological deficit?



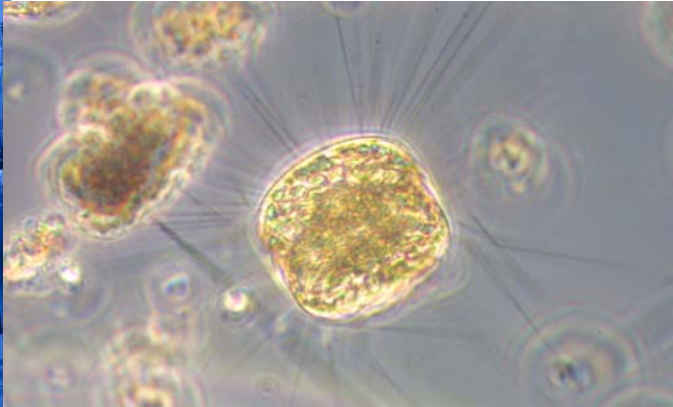
Diatoms

Also need to consider effect of:

- Phosphorus species and membrane transport
- Trace metals and elements on phytoplankton

Changes in the relative proportions of phosphorus, nitrogen and trace metal species may have an effect on plankton diversity

CO₂ effects on Carbon Fixation by Phytoplankton



The enzyme involved in carbon fixation is ribulose biphosphate carboxylase/oxygenase (RUBISCO)

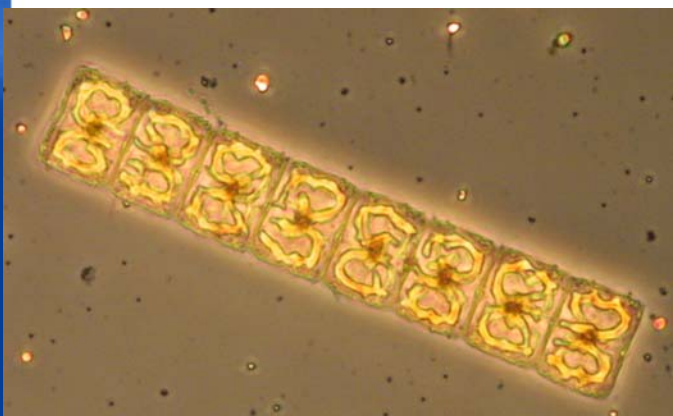
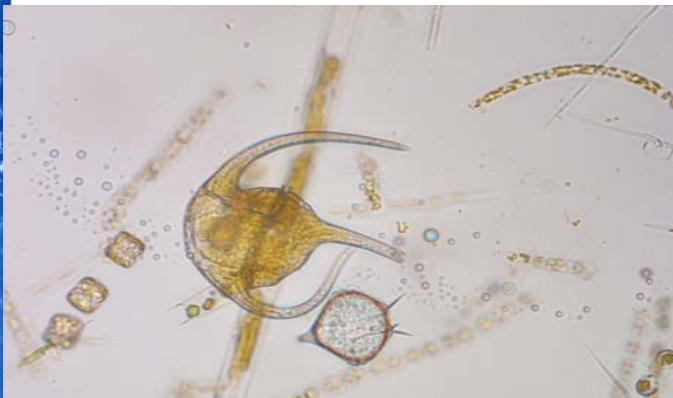
The affinity of the enzyme for CO₂ is low and marine phytoplankton are thought to have CO₂ concentrating mechanisms

Different groups of phytoplankton have different CO₂ affinity

Could increased CO₂ obviate the need for CO₂ concentrating mechanisms?

Would competitive advantage be lost? We do not know — and there will almost certainly be interspecies effects

One study showed a small but significant increase in photosynthesis occurred with an increase in CO₂ to 850 ppm



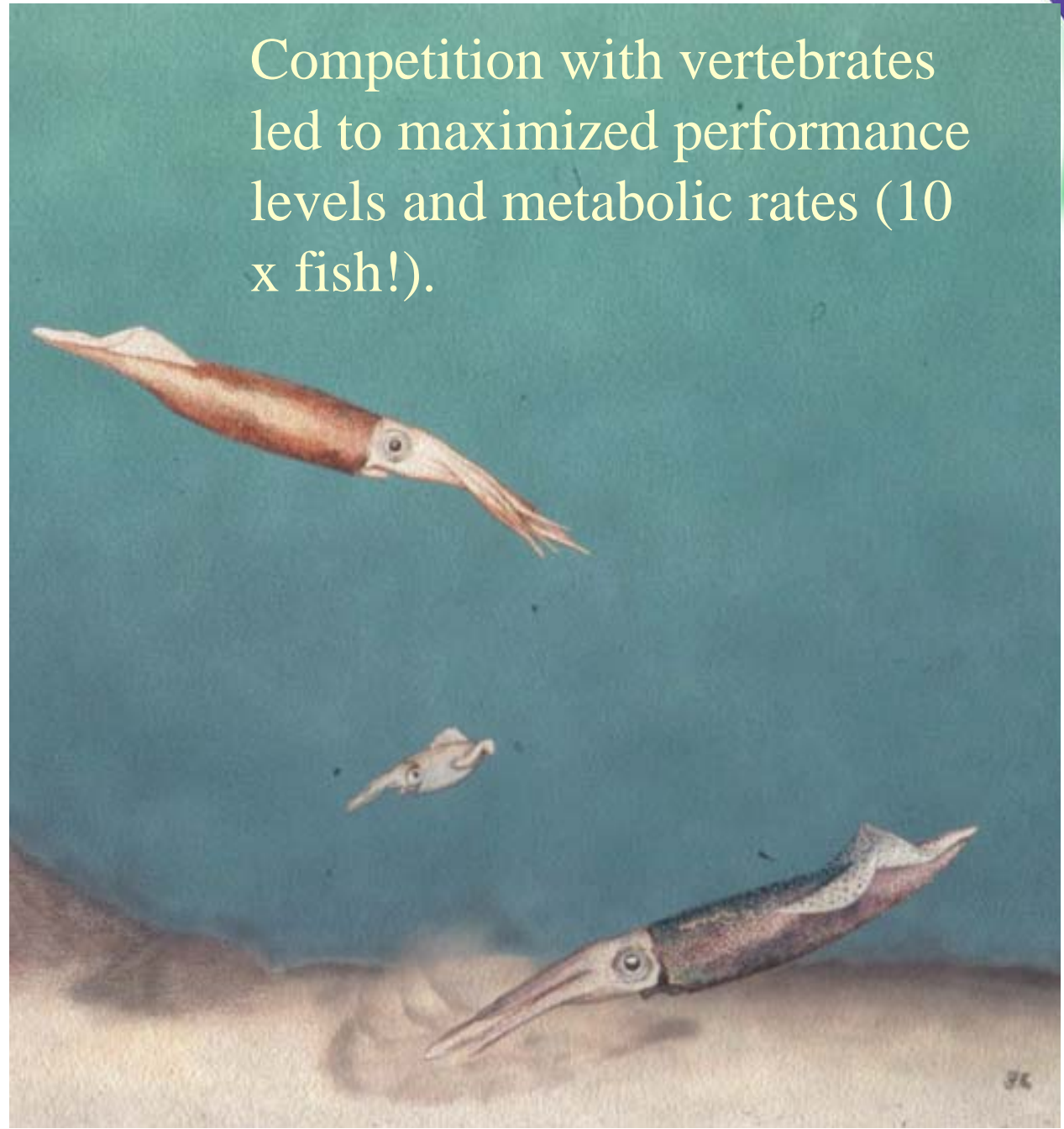
Acute effects of high CO₂ levels on Squid – the elite athletes of the ocean

Illex illecebrosus

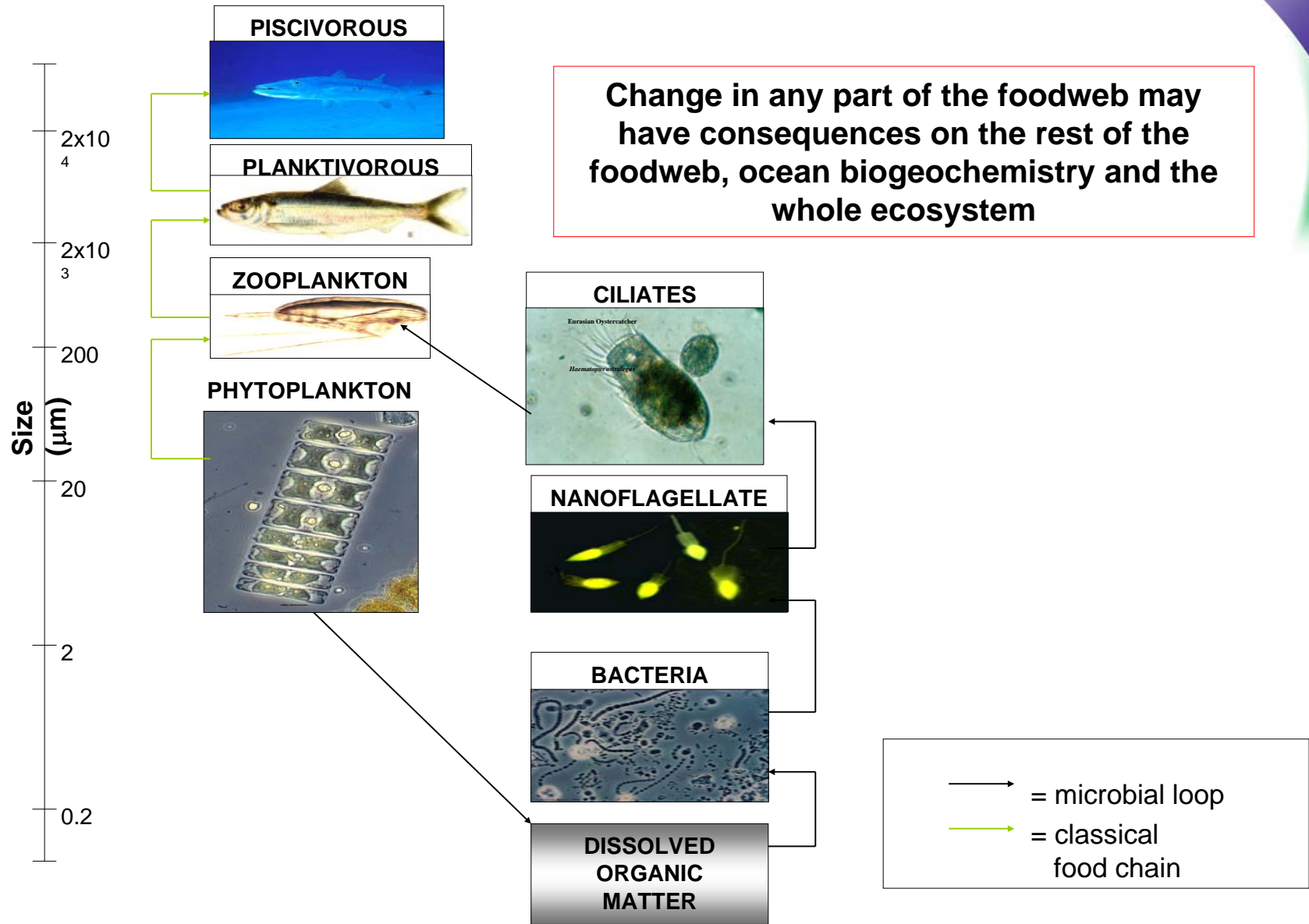
Lolliguncula brevis

Loligo pealei

Competition with vertebrates led to maximized performance levels and metabolic rates (10 x fish!).



Whole Ecosystem Effects: Pelagic



Another pressure on sediment ecosystems?



Who is paying attention to ocean acidification?

- International Panel on Climate Change (**IPCC**): formed a WG on ocean acidification
- International Global Biosphere Programme (**IGBP**): reduced pH is a key issue in its new international programmes:
- Integrated Marine Biogeochemistry and Ecosystem Research (**IMBER**) & the Surface Ocean-Lower Atmosphere Study (**SOLAS**)
- International Council for Science (**ICS**), **IGBP** & **SCOR** funded an international conference at **UNESCO**, Paris 2004 The Ocean in a High- CO₂ World
- **The Royal Society** Working Group on Ocean Acidification
- **OSPAR** and **The London Convention** Environmental Impact of Placement of Carbon Dioxide in in the Maritime Area
- **DEFRA**, **DTI** and **NERC** through funded programmes
- **Nature** and **Science** – many articles over last 3 years
- **Media**: TV, radio, newspapers – large interest in last 6mth

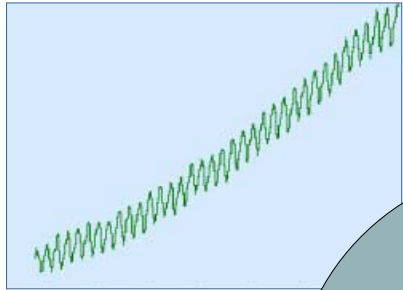
PML Objectives

- 1: To facilitate and promote **integration** of international and national R & D on ocean acidification through networking, collaboration and advice.
- 2: To create a UK **modelling** capacity for exploring the effects of high CO₂ (including lowered pH) on the marine ecosystem of UK shelf waters and to make an initial exploration of marine ecosystem response to elevated CO₂.
- 3: Develop a **UK facility** within the Plymouth Marine Laboratory to enable experiments examining the environmental impacts of CO₂ induced seawater acidification.
- 4: Determine the **impact** of pH change, as a result of CO₂ acidification, on:
 - a) the health and function of key benthic organisms.
 - b) the biodiversity and community structure of subtidal soft sediment communities.
 - c) nutrient cycling and the geochemical environment within the sediment.

Funded by NERC, DEFRA and DTI

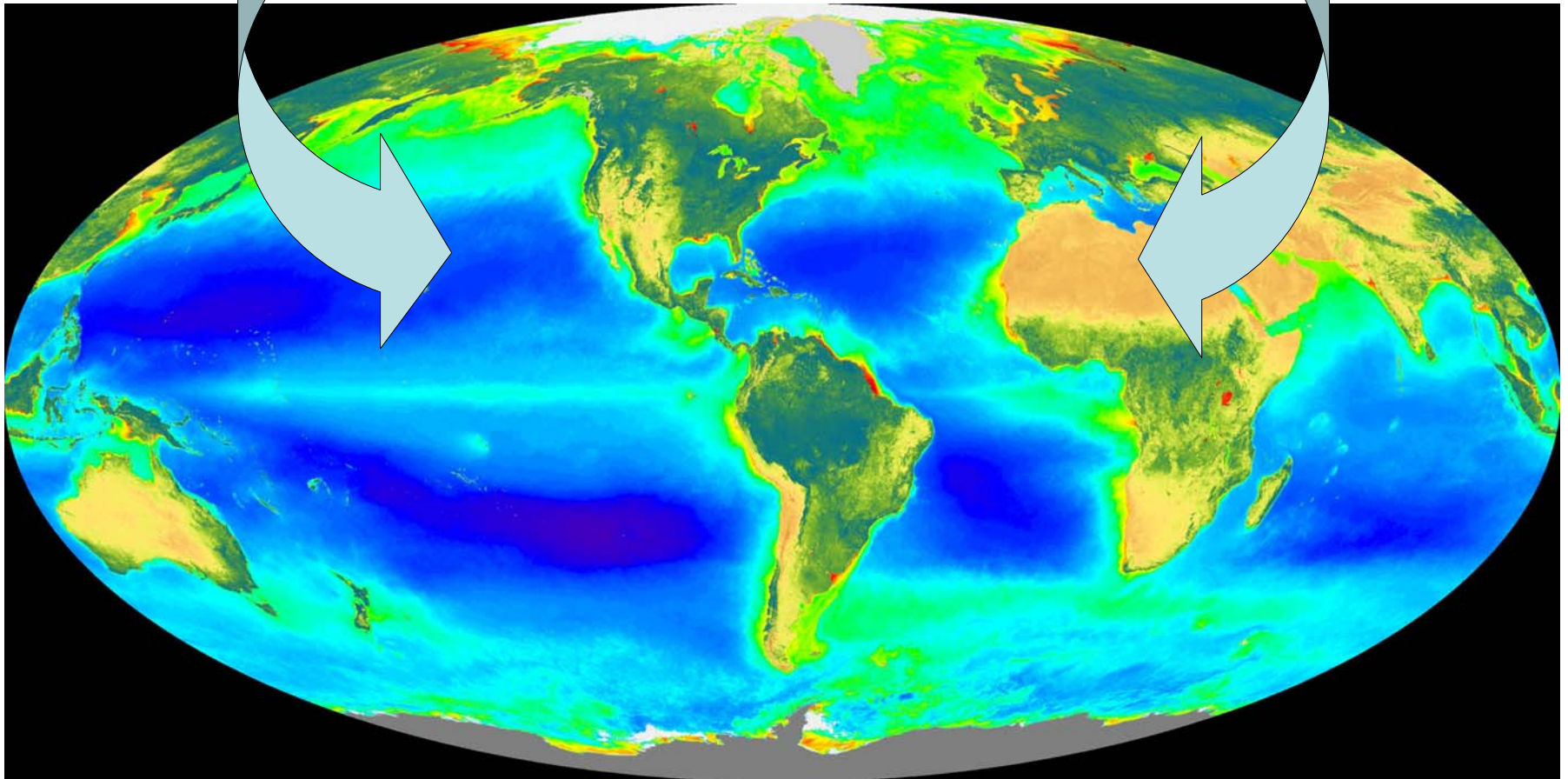
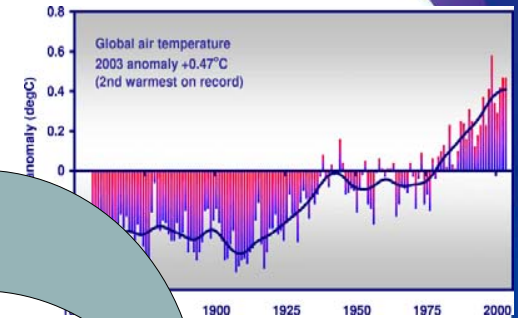
Global Feedbacks and Synergistic Impacts

Changes that may accompany increased seawater CO₂ and reduced pH include increased temperature, changes in availability of nutrients, salinity, O₂, ocean mixing, circulation and wind.



What are the combined effects on the oceans?

What are the feedbacks to the whole Earth system?



Sunset over a warming ocean now > 0.1 pH units lower than pre-industrial and which contains about 400 billion tons of fossil fuel CO₂



Ocean acidification: another argument for control of CO₂ emissions



Potentially Important Factors for the Future Oceanic Uptake of CO₂

Physical and chemical processes:

- CO₂ buffering capacity of the oceans: reduced CO₂ uptake
- Increased vertical stratification:
 - reduce CO₂ uptake
 - reduced nutrient supply to photic zone
 - changes in rain ratio
 - reduction in O₂
- CO₂ is less soluble in warm water:
 - increase sea-air flux as oceans warm
 - increase atmospheric CO₂

Summary of Potential Biological Effects

Shifted ecosystem equilibria caused by:

- Significant shift in speciation of key nutrients
- Shift in phytoplankton diversity due to different affinities for CO₂
- Increased bioavailability of toxic chemicals
- Reduced calcification rates
- Higher ratios of non-calcifiers over calcifiers
- Reduced behavioural capacity, growth, production and life span
- Reduced tolerance to thermal extremes
- Enhanced geographical distribution shifts
- Reduced distribution ranges
- Food chain length and composition
- Reduced population densities Increase in other species?
- Regime shifts.....biodiversity?