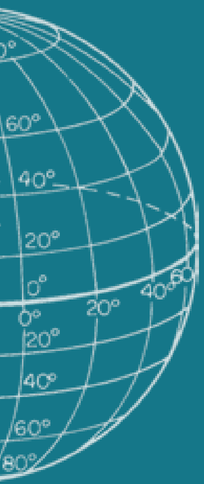
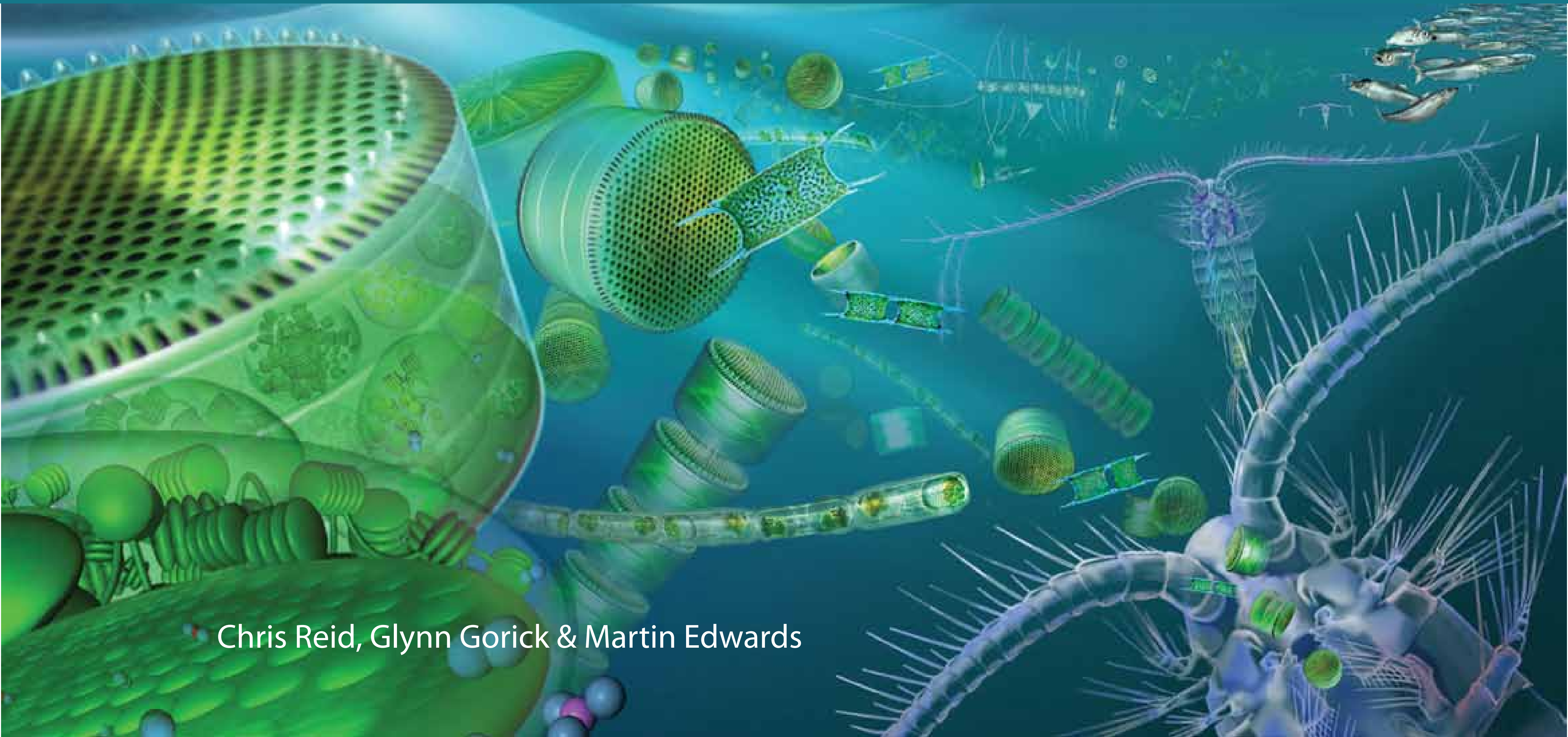


Climate Change and European Marine Ecosystem Research

European Commission's Seventh Framework Programme: *Climate Change and European Marine Ecosystem Research (CLAMER)*

Sir Alister Hardy Foundation for Ocean Science



Chris Reid, Glynn Gorick & Martin Edwards

Citation: Reid, P.C., Gorick, G. & Edwards, M. 2011. Climate change and European Marine Ecosystem Research. 53p. Sir Alister Hardy Foundation for Ocean Science, Plymouth, UK.

Illustrations: ©Glynn Gorick

Design, layout and other images: Martin Edwards
Printer: Kingfisher, Totnes, Devon, UK
Published by: Sir Alister Hardy Foundation for Ocean Science. ©SAHFOS
ISBN No: 978-0-9566301-1-7

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www.clamer.eu

CLAMER is funded under the European Commission's Seventh Framework Programme. Contract number 244132

Sir Alister Hardy Foundation for Ocean Science

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Acknowledgements:
Special thanks are given to Jan Seys, coordinator of CLAMER Work Package 3, and Karen Rappé, Flanders Marine Institute, Ostend, Belgium for their encouragement and advice in the preparation of this book and for the suggestions and improvements made to the text by our freelance copyeditor, Nigel Jonas. We are also grateful for advice and comments received from the following: Jürgen Alheit, Leibniz Institute for Baltic Sea Research, Warnemünde, Germany. Manuel Barange, Plymouth Marine Laboratory, UK. Keith Brander, Danish Institute of Aquatic Resources, Technical University of Denmark, Charlottenlund, Denmark. Jan-Bart Calewaert, Marine Board, European Science Foundation, Ostend, Belgium. Roberto Danovaro, Polytechnic University of Marche, Ancona, Italy. Marion Gehlen, Laboratoire des sciences du climat et de l`environnement, Gif–sur-Yvette, France. Stephan Gollasch, GoConsult, Hamburg, Germany. Dave Kulka, Fisheries and Oceans Canada, Newfoundland and Labrador Region, Waverley, Nova Scotia, Canada. Priscilla Licandro, SAHFOS, Plymouth, UK. Dan Minchin, Marine Organism Investigations, Ballina, Ireland. Kalliopi A. Pagou, Hellenic Centre for Marine Research, Athens, Greece. Leif Toudal Pedersen, DMI, Copenhagen, Denmark. Benjamin Planque, Institute of Marine Research, Tromsø, Norway. Robin Raine, The Martin Ryan Institute, National University of Ireland, Galway. Paul Tréguer, University of Brest, Brest, France. Luigi Vezzulli, University of Genoa, Genoa, Italy. Rachel Warren, Tyndall Centre, UEA, UK. Philip Weaver, National Oceanography Centre, Southampton, UK.



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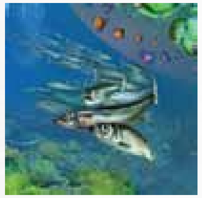
   

There is no doubt that rapid global warming and ocean acidification are real, and very high confidence that both are forced by human activities and emissions of carbon dioxide. Climate change effects are especially evident in the oceans, with European regional seas showing some of the most pronounced and rapid impacts.

The EU has funded many research projects and regional sea programmes on the effects of climate change on marine ecosystems. Scientists are producing world-leading research, but the perception persists that they have not transmitted their findings effectively to policy-makers and the public. The 7th Framework Programme project '*Climate Change and Marine Ecosystem Research*' (CLAMER) addresses this, with 17 marine research institutions cooperating to provide a synthesis of understandable science, helping European citizens and policy-makers recognise the gravity of climate change's effects on the oceans and their socio-economic consequences. This will make it easier for the public to change habits and accept expensive mitigation and adaptation policies.

CLAMER has reviewed and summarised past research, organised a pan-European awareness and perception poll, examined socio-economic implications and produced outreach products like the film Living with a Warming Ocean – and this book.

The book starts with three short contributions by collaborating colleagues from CLAMER summarising the poll results, public understanding and communication of marine climate change issues. Twelve chapters follow, each describing a different issue, illustrated with a commissioned image by Glynn Gorick.

Levels of atmospheric CO_2 are accelerating, reaching a global average of 392 ppm (NOAA ESRL) in May 2011. Concentrations are close to – some believe have already passed – a level that will lead to a global temperature rise of 2°C ("dangerous" human interference with the climate system). Humanity needs to change direction and find alternative energy sources to carbon. Failure to do so is likely to have grave consequences for security and global socio-economic welfare.

Public attitudes towards climate change and the oceans

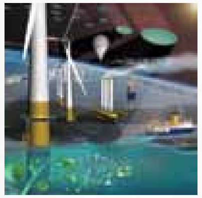
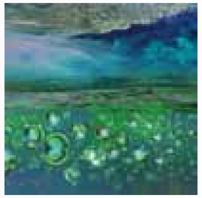
Geraldine Terry, Tyndall Centre, University of East Anglia, Norwich, UK. Jason Chilvers, School of Environmental Sciences, University of East Anglia, UK.

In industrialised countries, responding to climate change requires a transformation of economies, societies and individual lifestyles. It is vital that the public engage with efforts to curb and adapt to climate change and that scientists and policy makers understand the basis of their opinions. Previous studies have focussed on attitudes to sea level rise and coastal flooding and show that few people feel personally at risk, even in vulnerable locations. While sea level rise and harm to wildlife have visibility and immediacy other issues such as ocean acidification do not and are seen as remote and scientific with little relevance to people's lives.

A review of social science research concerning public views on climate change and its impacts on marine environments was carried out in CLAMER, alongside a study exploring public responses in greater depth. The studies showed that people prioritise environmental problems based on their experience, with pollution as the priority marine issue. Marine climate change, sea level rise, coastal flooding and erosion were regarded as important because they affect human populations on land and in some instances are already visible. However, the salience of impacts on wildlife in the survey responses plus public campaigns on the protection of the marine environment, show that concern is not solely driven by self-interest.

The public see scientifically defined climate change impacts as remote in space and time and often irrelevant to their daily lives. This is compounded by alarmist stories from some journalists, which are shown to be counter-productive, promoting psychological 'denial'. The most effective messages combine authoritative scientific information about climate impacts on local scales with simple advice on how to respond. Any attempt to involve the public should start from an understanding of how they understand, experience and engage with marine climate change issues in their own terms.

The thoughts of 10,000 European citizens on marine climate change

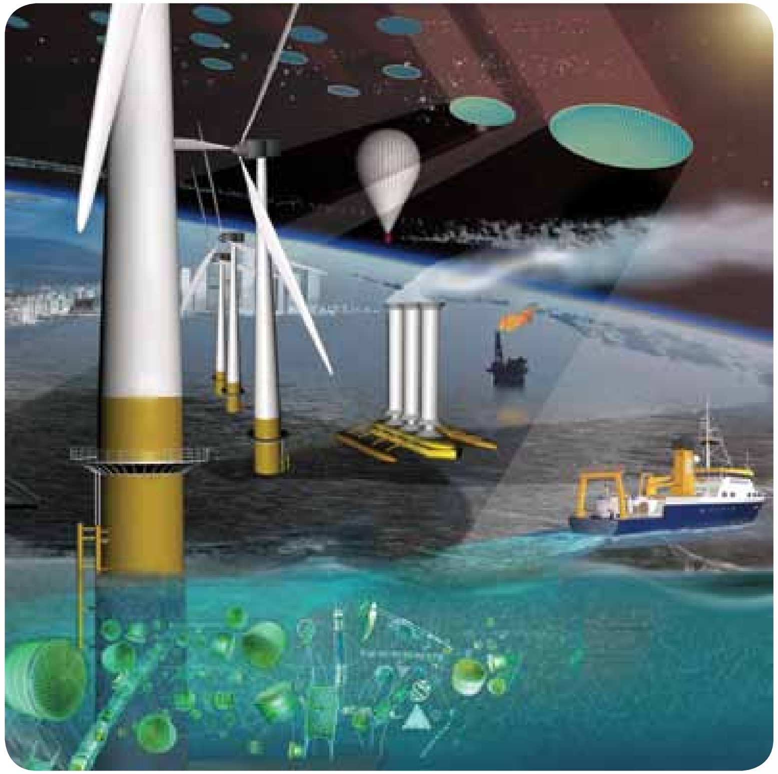





Paul Buckley, CEFAS, Lowestoft, UK

A public poll as part of the CLAMER project was organised to find out what European citizens know and care about in relation to climate change impacts at the coast and in our seas. As the first survey to focus on marine climate change issues in Europe, over 10,000 people were polled in 10 countries, from the Arctic to the Mediterranean. The poll provided statistically robust data at European and national levels for age, gender, proximity to the coast and interaction with European seas. Public concerns about marine climate change issues (such as sea level rise and coastal erosion) were examined against other issues such as overfishing, pollution and habitat destruction. Gathering information on the public's views of marine environmental issues is important for the EU to help improve scientific communication to citizens and enhance its standing as a trusted source of knowledge.

The survey shows the public cares about climate change, ranking it second in a list of major global threats. Mitigation measures (international agreements on cutting CO_2 and technological fixes) were preferred over adaptation (such as coastal management). Awareness was linked to perceived research priorities, with melting sea-ice coming out on top. Other issues such as disease, pests or non-native species were rated high, despite limited awareness of these subjects. Knowledge of social and economic research was low with support for policies that help communities cope with climate change against those that focus on economic cost.

The EU is regarded as 'effective in tackling climate change' by twice as many people in some countries than others, whilst females, older people and those living near the coast are typically more 'concerned' about all issues. The poll revealed that some scientists and media are trusted more than others (e.g. scientists from universities compared to those supported by industry or government).



Communicating EU marine science to the public

John Pinnegar, CEFAS, Lowestoft, UK

The CLAMER initiative was instigated because of a perception within the European Commission that scientific messages on climate change and the marine environment were not being heard and there was low awareness of these issues by European citizens. To examine this thesis the outreach activities of 64 EU and national research projects that focussed on marine climate change were examined to determine and highlight examples of 'good practice', innovation and success in communicating with the public. Most EU projects engaged in an information campaign or public outreach activity, although rarely as an integral part of the wider programme of work. In most cases, outreach did not extend beyond a one-way transfer of knowledge through project websites, factsheets, or scientific papers although a quarter generated media interest with mention in newspapers, magazines or on television and radio. More imaginative ways of engaging the public have started to emerge, including public expeditions, web blogs or Twitter feeds, explanatory videos or films and use of online video repositories like 'YouTube'. Projects have involved celebrities to put across their message and increase media coverage.

A new development, 'citizen science', is the active involvement of members of the public in scientific data gathering or analysis. Examples include projects that use home computer power when PCs are sitting idle and a global project that is digitising historic maritime weather observations from the 18th to 20th centuries. Other schemes use members of the public to record sightings or strandings of unusual or 'charismatic' species such as whales, sea turtles and seahorses.

Outreach and engagement should be viewed as an integral part of scientific programmes and not simply an afterthought. Large scale public engagement programmes are not always appropriate, but more thought should be directed towards two-way approaches, involving the public – rather than simply informing them.

Changes to temperature, the thermohaline circulation and ice

Background

All European seas have warmed over the last few decades at 4 to 7 times the global rate, due to natural variation and global warming. Both surface and deeper temperatures in the North Atlantic have increased, but below that of the global mean. The timings of sea temperature maxima and minima show considerable variability, with strong impacts on food web interactions and seasonal processes in marine ecosystems. Decadal changes are thought to be related to the large-scale Atlantic Meridional Overturning Circulation (AMOC) that is part of what is commonly known as the 'Global Conveyor Belt'. Formation and sinking of cold dense water in the northern North Atlantic is a major driver of the deep cell of the AMOC, reinforced by global density gradients created by surface heat and freshwater fluxes. The enclosed, brackish and layered Baltic is dominated by irregular sub-surface saline intrusion events. These oxygenate stagnant deep basins and have shown a marked change in their occurrence over the last 30 years, and the picture is complicated by variability in river inflows at the surface.

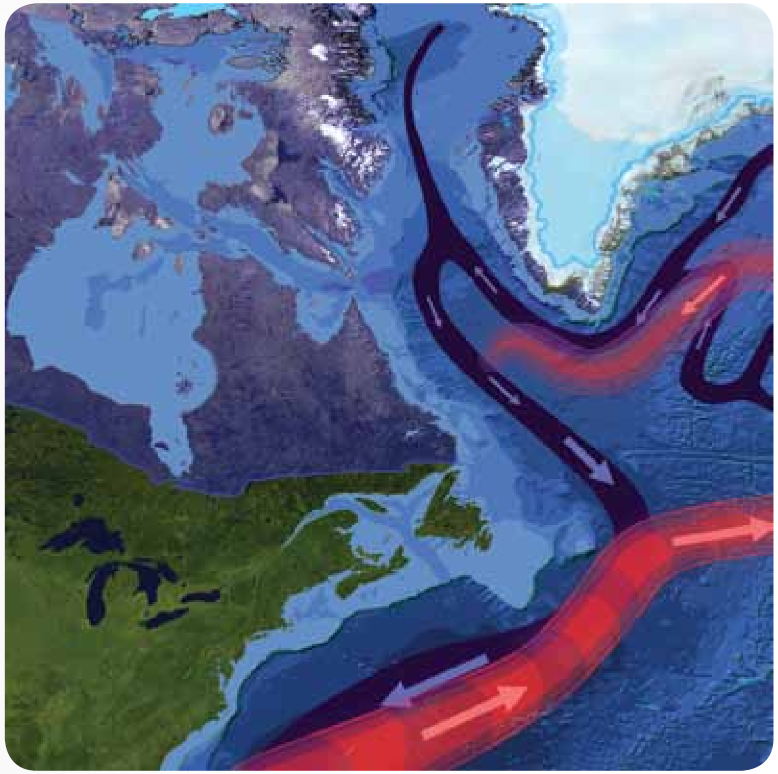
Warming in the Arctic is by far the fastest on Earth, due to amplification from feedbacks such as the albedo effect (reduced reflection of sun rays as ice melts), intrusion of pulses of warm water from the North Atlantic and Pacific and changes in atmospheric circulation. All these have had a pronounced effect on the Arctic cryosphere (the part of the Earth where water exists as ice or snow), causing a decline in sea-ice cover and of the volume of the Greenland ice sheet. An associated intensification of the hydrological cycle, with thawing permafrost and increased river runoff, is changing the density of surface waters with consequences for global ocean circulation.

The main engine for the Earth's ocean circulation is found in the northernmost North Atlantic. Here the warm North Atlantic current, that ensures the warmth of Europe, cools at the edge of the Arctic, becomes denser (heavier) and sinks to return south as a deep counter-current along the eastern edge of North America. Rising temperatures are melting the Greenland ice sheet, permafrost and sea-ice, producing greater freshwater flows into the Arctic and changing these currents.


N
© Glynn Gorick

The present

Warming of European regional seas has accelerated over the last 25 years, with the Baltic North and Black Seas showing the greatest increases of temperature. From the limited data available, the AMOC shows considerable variability even on a daily scale and there is no evidence at present for any long-term change. In contrast, sea-ice in the Arctic has shown pronounced changes in coverage and thickness with declines in extent averaging 11% per decade over the last 30 years, with a possible recent acceleration. Since 1980, the ice thickness has reduced by almost a half to 1.75 m in 2008 and old multiyear ice is now found only to the north of Greenland. In Greenland, warming has occurred at twice the global average rate – a phenomenon comparable with similar events during the Holocene.



The future

Warming will continue even if greenhouse gas emissions reduce and if the AMOC slows down as predicted by some models. The relative proportion of 'natural' and global warming drivers of temperature rise is still unclear. The Arctic is projected to warm especially rapidly, 2.8 to 7.8°C by 2100, and it is estimated that it may be free of summer sea-ice within 20 to 30 years.

The Baltic is projected to become increasingly brackish, warming by between 2 and 4°C by 2100 and the North Sea by 0.8°C by 2040, while the Mediterranean is predicted to gain salinity as warm tropical water flows in from the Red Sea. Future changes in the Black Sea are less clear.

Projection Confidence

There is a high probability that sea temperatures will continue to rise. As processes behind changes in ocean gyres, slope currents, the AMOC and atmospheric circulation modes are unclear, projected temperature patterns for all European Seas have a large error bar. There is poor confidence in the modelling of sea-ice cover and changes in the Greenland ice sheet.

The message

Major consequences for the weather, water cycle and socio-economics of Europe and the Arctic are expected if sea temperatures, as predicted, continue to rise. There is an urgent need to improve understanding of ocean/atmosphere interactions during the current rapid warming and of the processes driving an associated reduction in the large North Atlantic sink for atmospheric CO_2. Improved data collection, assimilation and modelling are needed.

CLAMER Chapter 2

Sea level, coastal erosion and storms

Background

Approximately 41% of the world's population lives within 100 km of the coast, many in coastal cities vulnerable to sea-level rise. Satellite measurements show a rapid increase in level from ~1993, higher than at any time in the last two millennia. Contributing processes include: 1) expansion of seawater as it warms, 2) melting of land ice, 3) melting of the Greenland and Antarctic ice sheets, 4) gravity and 5) human activities. Like the moon, ice sheets have a gravitational attraction. As the Greenland ice sheet melts, the gravity change reduces sea levels in Northwest Europe while melting of the West Antarctic ice sheet would have the opposite effect. Human contributions to sea-level rise derive from draining wetlands, groundwater withdrawal, dam construction and land use change.

Absolute sea level is the surface height of the ocean relative to the centre of the Earth. Relative sea level is the height of the sea relative to land – some land is rising, some static and some sinking. In areas of subsidence, such as the palaeo Rhine delta, problems of sea-level rise are exacerbated. The reverse applies to northern Europe, where land is rising due to the isostatic rebound of the Earth's crust caused by the removal of the weight of Pleistocene ice sheets.

Shoreline retreat and erosion over accretion have been widely reported and attributed to global sea-level rise. Changes in the magnitude and frequency of storms and relative sea-level change due to climate change have important implications for coastal sedimentary systems that are strongly influenced by local geology. Note, however, that no past trend has been detected in storm activity in northern Europe that can be attributed to climate change, but these effects cannot be ignored because associated storm surges present serious risks.

As warm seas expand and glacial ice melts, sea levels are rising. The image shows the potential effect of a sea level rise of 1m by 2100 for the coastline between Zeebrugge and Calais. Developing appropriate sea defences will prevent flooding.


Calais
Dunkerque
Nieuwpoort
Oostende
De Haan
Wenduine
Blankenberge
Zeebrugge
©Glynn Gorick

The present

Global sea-level rise has accelerated since 1993 to 3.1 mm per year, a rate faster than the IPCC scenarios for 2100, and almost double the 20th century average, with regional rates in Europe ranging from 3.6 to 1.8 mm per year. The acceleration has been caused by thermal expansion of seawater and a large increase in volume caused by melting land ice. Land in northern Europe is rising due to ice-sheet rebound (isostasy) and sinking or stable to the south.

Increasing human occupation of the coast, sea-level rise, and (in some regions of Europe) higher storm activity, have led to more coastal protection engineering, reductions in sediment supply due to dam construction (particularly in the Mediterranean and Black Seas), shoreline armouring and nourishment of beaches from offshore sand deposits.

The future

New estimates that add the contribution of melting land ice and ice sheets, give a maximum sea level increase of about 1m by 2100, with likely considerable geographical variability and possible, though unlikely, extreme values up to 2m. The net response, including expected land movements, means that coastal regions of the southern North Sea, Italy and Poland, with large areas of land less than 1m above present sea level, are vulnerable to flooding.

The rate and extent of coastal erosion and land retreat from sea level rise is likely to increase, but there is little support from historical observations or projections for a systematic change in the frequency or intensity of storms in Europe.

Projection Confidence

Confidence in historical measurements of sea level is high, as the data have been subjected to rigorous quality control, but medium to low for future projections as the contributions of melting land ice, the behaviour of ice sheets and the role of decadal versus long-term change and regional variability are still unclear. Regional variability is especially important for planning and managing coastal protection where modelling and prediction of coastal behaviour at relevant spatial and temporal scales give unreliable results.

The message

The tropics, low-lying islands in Oceania, the Netherlands and the coastal strip of Belgium are all especially vulnerable to relative sea-level rise. Continuing urbanisation of the coastline is likely to increase the demand for sea defence as a response to erosion. Research priorities include improving understanding of the processes behind rapid reductions in ice sheets and of factors that contribute to spatial variability of sea-level rise.

CLAMER Chapter 3

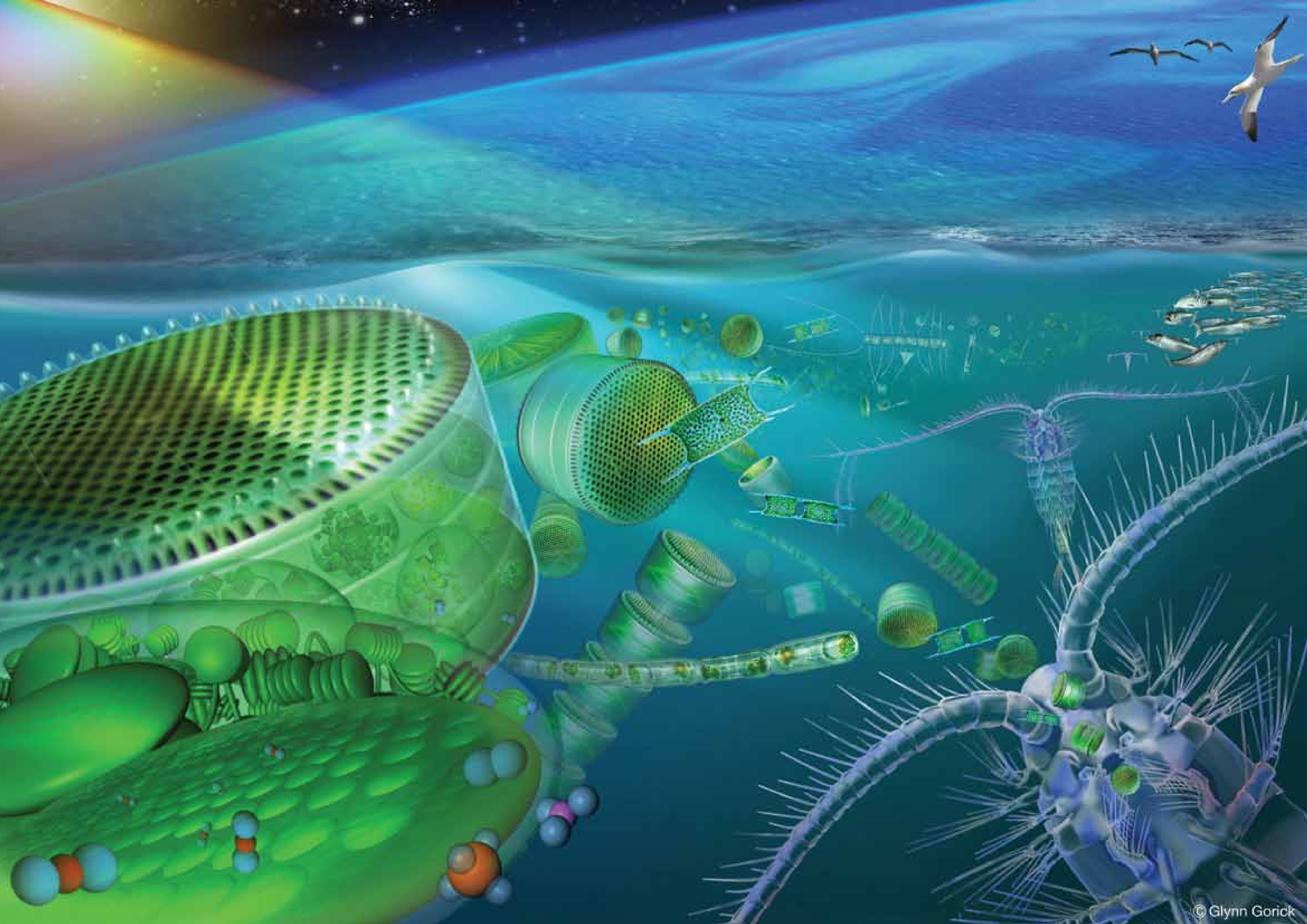
Primary production

Background

Half of the Earth's photosynthetic carbon fixation forms in the oceans. The productivity and fish-carrying capacity of European seas depends on this photosynthesis by microscopic phytoplankton. Fuelled by light and regulated by water temperature, plant growth requires nutrients to construct the cellular building blocks that drive phytoplankton physiological processes. Plant nutrients, such as nitrate, phosphate and trace elements like iron, are primarily supplied from deeper waters underlying the sunlit euphotic zone. In shallow shelf seas, they are mainly sourced from the adjacent ocean and from riverine inputs. Colder nutrient-rich waters are transferred to the euphotic zone through mixing by tides and wind or by upwelling caused by other processes. The availability of nutrients is often limited by a vertical gradient in water density in the upper 50 to 100 m. This gradient in what is called stratification is caused by vertical differences in temperature and salinity (warmer and fresher waters are less dense).

The stronger the stratification, the more difficult it is to mix deeper nutrient-rich waters into the euphotic zone, resulting in an upper bound on the primary productivity of surface waters. Temperature also regulates the microbial loop (see Chapter 7) that recycles nutrients in the stratified layer. In warm tropical and subtropical waters, strong stratification may lead to nutrient 'deserts' and low phytoplankton growth. Global patterns measured from satellites show that European seas, other than the Mediterranean, are amongst the most productive in the world. Changes in primary production and in the size and composition of phytoplankton cells, due to warming seas, have important implications for the ability of pelagic systems to capture and store carbon dioxide. Multiple biological interactions are involved in the breakdown of organic detritus as it sinks, as carbon, to the deep ocean through what is known as the biological pump.

Microscopic marine plants (phytoplankton) make the oxygen in every second breath we take. Packed with chlorophyll, they harvest the red and blue photons in sunlight to drive their photosynthesis. Fuelled by CO_2 and nutrients derived from deeper water, their growth provides food for virtually all living organisms in the sea, including the fish we eat. Satellites provide a bird's eye view of how global patterns of chlorophyll are responding to climate change.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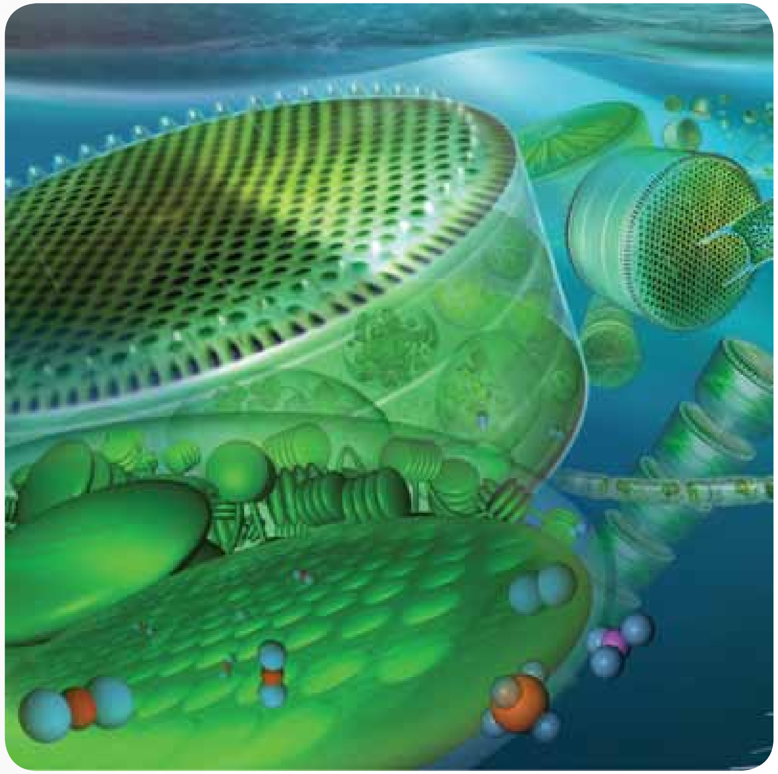
The present

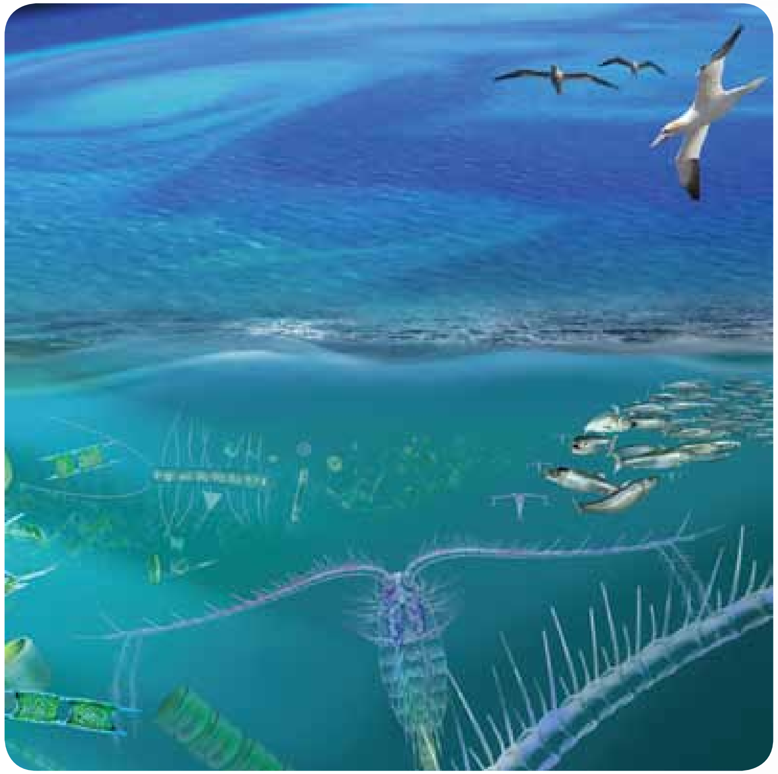
Satellite data and modelling are used to estimate global patterns of primary production as *in situ* measurements are rare. Chlorophyll a (phytoplankton biomass) is often used as a proxy for primary production. Chlorophyll declined in the Mediterranean and Black Seas but increased in the Baltic and much of northern Europe between 1998 and 2009. The chlorophyll index also increased after ~1988 in the North Sea, a phenomenon correlated with improved water transparency and linked to an exceptional influx of oceanic nutrients onto the shelf.

Climate variability associated with climate modes such as El Niño and the North Atlantic Oscillation have caused changes in the circulation of the Atlantic and Pacific oceans over the last decade, with a 15% expansion of the nutrient-poor 'ocean deserts' in the central basins with consequences for chlorophyll patterns and ocean productivity.



The future

Observations of decadal trends and model output suggest that climate change is likely to lead to increased stratification, especially in the tropics and mid-latitudes, reducing nutrient availability to the euphotic zone and primary production. In these regions small phytoplankton (picoplankton) are likely to be favoured at the expense of larger diatoms, so that transfer of carbon to the deep ocean will be reduced. In higher latitudes, stronger mixing means that productivity is likely to be enhanced. The net global impact has been estimated at not larger than 10%.



Projection Confidence

Low confidence exists in the future extrapolation of present trends in chlorophyll and primary production as estimated from satellite data, because natural variability is larger than the global warming trend and the models' spatial resolution is too coarse to capture shelf-sea biological processes. Satellite sea-surface measurements use algorithms with large uncertainties; calibration is also a problem, given the limited number of *in situ* measurements of pelagic primary production and the paucity of data on benthic primary production in shallow seas.

The message

Present patterns of marine primary production may continue or the system may undergo unpredictable change in response to global warming. Both have profound implications for carbon sequestration and fish-carrying capacity. The identification of future change relies on maintaining continuous satellite missions to measure chlorophyll fluorescence, *in situ* time-series of primary production and phytoplankton time-series in general, as well as broad-scale surveys such as the Continuous Plankton Recorder survey.

CLAMER Chapter 4

Microorganisms and the microbial loop

Background

New advances in molecular and biogeochemical tools have revolutionised understanding of the importance of microbial communities and of their fundamental role in biogeochemical cycles and the health of the oceans. Estuarine, coastal and oceanic waters as well as sediments, harbour a huge diversity of viruses, bacteria, archaea, fungi, protists and micro-algae. There are 100 million times more bacteria in the ocean than stars in the universe and 10 to 100 times more viruses than bacteria. Microbes transform and cycle carbon, oxygen, nitrogen, phosphorus, sulphur and other compounds. Importantly for climate they can take up CO_2 from the atmosphere and regulate carbonate systems. The balance of these processes controls the dynamics of ocean biomes. Some microorganisms have negative effects – disease, toxicity, harmful algal blooms (see Chapter 11); others provide novel bioactive compounds and essential services to human society.

Two main pathways, herbivore zooplankton and microbial detrital, are involved in the transfer of C, N and P through different levels of the food web and in the transport from the surface to the bottom by the 'biological pump'. In the former, large phytoplankton cells such as diatoms are grazed by zooplankton such as copepods, with a flux of dead cells and particulate organic carbon to the bottom. The second pathway, the microbial loop, using dissolved organic matter fuels higher trophic levels, and this is more important in oligotrophic (low nutrient) surface waters where recycled ammonium supports new photosynthesis, and the flux to the deeper ocean is negligible. At the same time viruses, by infecting microorganisms, convert their biomass to cell debris and dissolved organic matter. This process, the viral shunt, can profoundly influence the pathways of organic carbon and nitrogen in the oceans and alter global biogeochemical cycles. A similar assemblage of specialist microbial organisms is involved in the deep ocean interior.

Huge numbers of diverse microbe species, including ciliates, bacteria and viruses, rule the oceans. They provide a vital service by processing waste and dead material, with bacteria for example grazed on by ciliates, which in turn become a secondary food source for larger animals in the sea. Predatory viruses burst infected cells to release nutrients, making them available again for phytoplankton growth.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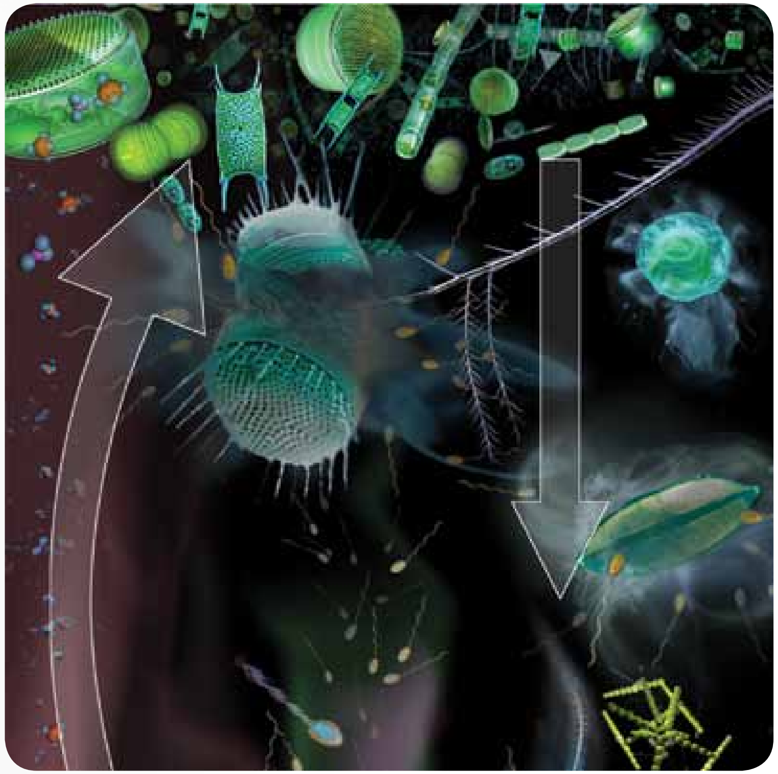
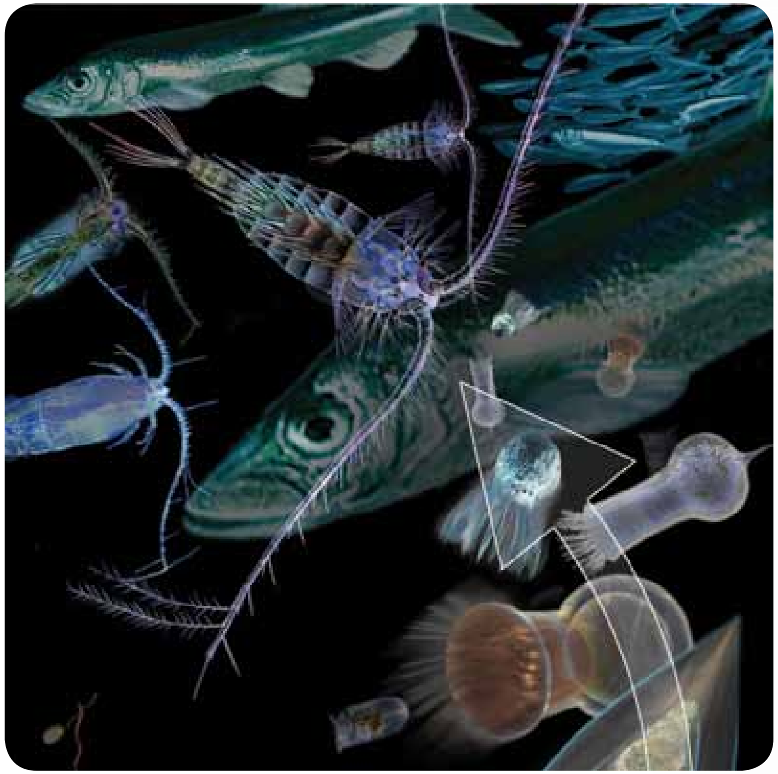
The present

Within the last two decades, understanding of oceanic microbial diversity and ecology has been revolutionised by the discovery and application of new genomic, geochemical, isotope and membrane lipid technologies, and fluorescent microscopy. For the first time it is possible to determine the true microbial biomass, biodiversity and composition in seawater samples and discover the biogeochemical roles of a number of different microbes. While these new findings demonstrate the crucial importance of microbes to climate variability and change, the roles of only a very small fraction of the microbial food web have been resolved so far and there is poor knowledge of spatial and temporal variability, especially at a global scale.



The future

The extent to which newly-discovered complex microbial systems and the microbial loop will change biogeochemical cycles and feedback to climate change in a warming world is difficult to forecast as we still know so little about the processes involved, but some general points can be made. Metabolic rates and primary production are likely to increase with faster nitrogen fixation and recycling of carbon, and with a less efficient biological pump. Oxygen minimum zones are expected to expand with enhanced anaerobic microbial reactions. There may also be a poleward shift in microbial communities and altered microbial diversity related to the freshening of seawater related to climate change. The potential of microorganisms as micro-engineers for the future benefit of mankind is only beginning to be explored and awaits our imagination and discovery.



Projection Confidence

A mechanistic understanding of the vast range of microbial processes and ecosystem interactions involved in global biogeochemical cycles and those that impact atmospheric composition e.g. nitrous oxide (N_2O), cloud nuclei forming dimethylsulfide (DMS) and methane (CH_4), is needed before it will be possible to predict their future role in climate change. As knowledge of the influence of microbes (including viruses) on climate change is poor, confidence in future projections is low.

The message

The role of microbial processes in climate variability and change is crucially important, but little understood and poorly quantified, particularly in their contribution to biogeochemical cycling, microbial diversity and feedbacks. While microbial assemblages will adapt to global change, the direction of change is presently unclear as are possible effects on ecosystems and the services they provide. Improving our understanding of critical microbial processes is a major challenge for future research.

CLAMER Chapter 5

Ocean acidification

Background

Close to one third of the carbon dioxide (CO_2) produced by humans from burning fossil fuels and other sources has been absorbed by the oceans since the beginning of industrialisation and has buffered the cause and effects of climate change. Reacting with seawater to form a weak acid, this large addition of CO_2 is causing ocean acidification with potentially profound effects on ocean chemistry. At the end of the 21st century, the rate of acidification might reach levels that marine organisms have not experienced for 55 million years. A resulting lowered pH and saturation states of the carbonate minerals that form the shells and body structures of many marine organisms makes these groups especially vulnerable.

Substantial reductions in the calcification rates of both pelagic and benthic organisms over the next century are expected based on historical extrapolation and experiments. Many of these organisms are key members of marine food webs and some, such as shellfish for human consumption, are economically important. Tropical corals are expected to be especially vulnerable with an average 30% reduction in calcification for a doubling of preindustrial levels of CO_2. Deep-water corals off the western margins of Europe are likely to be strongly impacted as their skeletons are made of the more easily dissolvable carbonate mineral aragonite. The growth of individual coral skeletons and the ability of reefs to remain structurally viable are likely to be severely affected. Continuing acidification may also affect the ability of the oceans to take up CO_2, so that atmospheric concentrations may increase even faster.

Atmospheric carbon dioxide, dissolving in seawater and reacting with it, produces more hydrogen ions, raises acidity, and reduces the availability of calcium carbonate for plants and animals to make hard shells. Ocean acidification is expected to have severe consequences for many marine organisms, especially for planktonic pteropod molluscs in the Arctic and cold water corals.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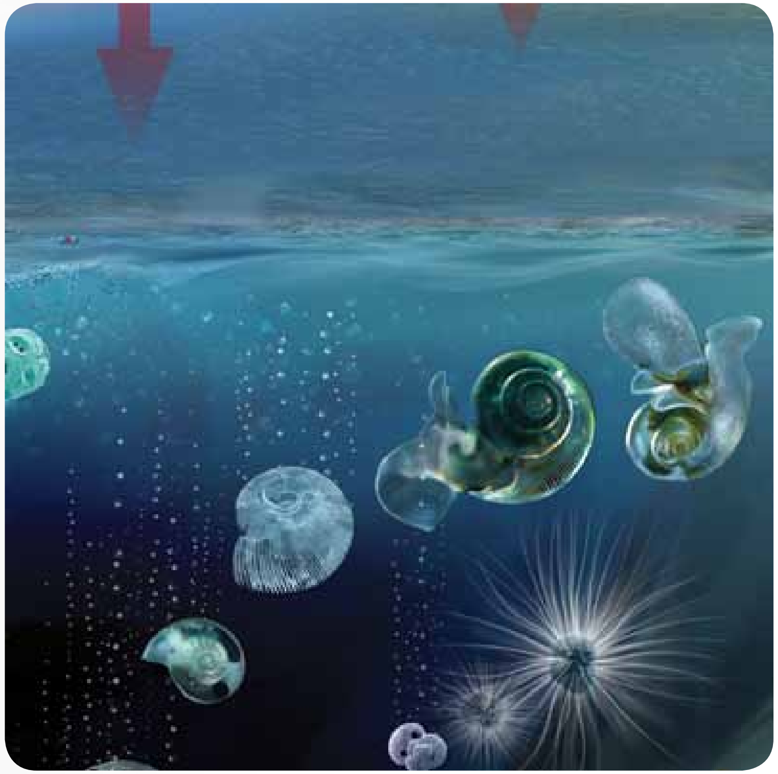
The present

In the modern ocean, many organisms in contact with water oversaturated with calcium carbonate precipitate skeletal material made from this chemical. At present, the response of marine carbonate producing organisms to reducing pH and saturation states of $CaCO_3$ is unclear, with planktonic and benthic biota showing both increasing and reducing calcification. Other physiological processes may also be altered and there is evidence for an increase in photosynthesis in some phytoplankton. In the Southern and Arctic Oceans, where cold temperatures favour CO_2 dissolution and the carbonate saturation state is low, marine calcifiers are especially vulnerable.



The future

The mean pH of ocean surface waters is already 0.1 units (30%) lower than it was in pre-industrial times and a decrease by a further 0.4 units (120%) is projected by the end of this century if emissions continue to follow a business-as-usual pathway. If these levels are reached, the whole of the Arctic Ocean will be undersaturated by 2100 with respect to calcium carbonate, with potential serious consequences for marine life and especially for calcifying organisms such as pteropods. The scale of these changes means also that the buffering capacity of the ocean (its ability to absorb CO_2) will be severely reduced.

Projection Confidence

The inorganic chemistry of carbonate systems is well understood and modelled using biogeochemical ocean general circulation models, so that there is high confidence in future projections of the level of ocean acidification for different CO_2 emission scenarios. In contrast, understanding of the response of marine biota to acidification is still at an early stage.

The message

There is considerable concern over the potential impacts of ocean acidification on biogeochemical cycles and especially that marine biota may not be able to adapt to the speed of change. Research is needed to improve understanding of the response to ocean acidification of benthic and pelagic biota (calcareous and non-calcareous), biogeochemical cycles; and of interactions and feedbacks with global warming, sea-ice and freshwater runoff in polar regions.

CLAMER Chapter 6

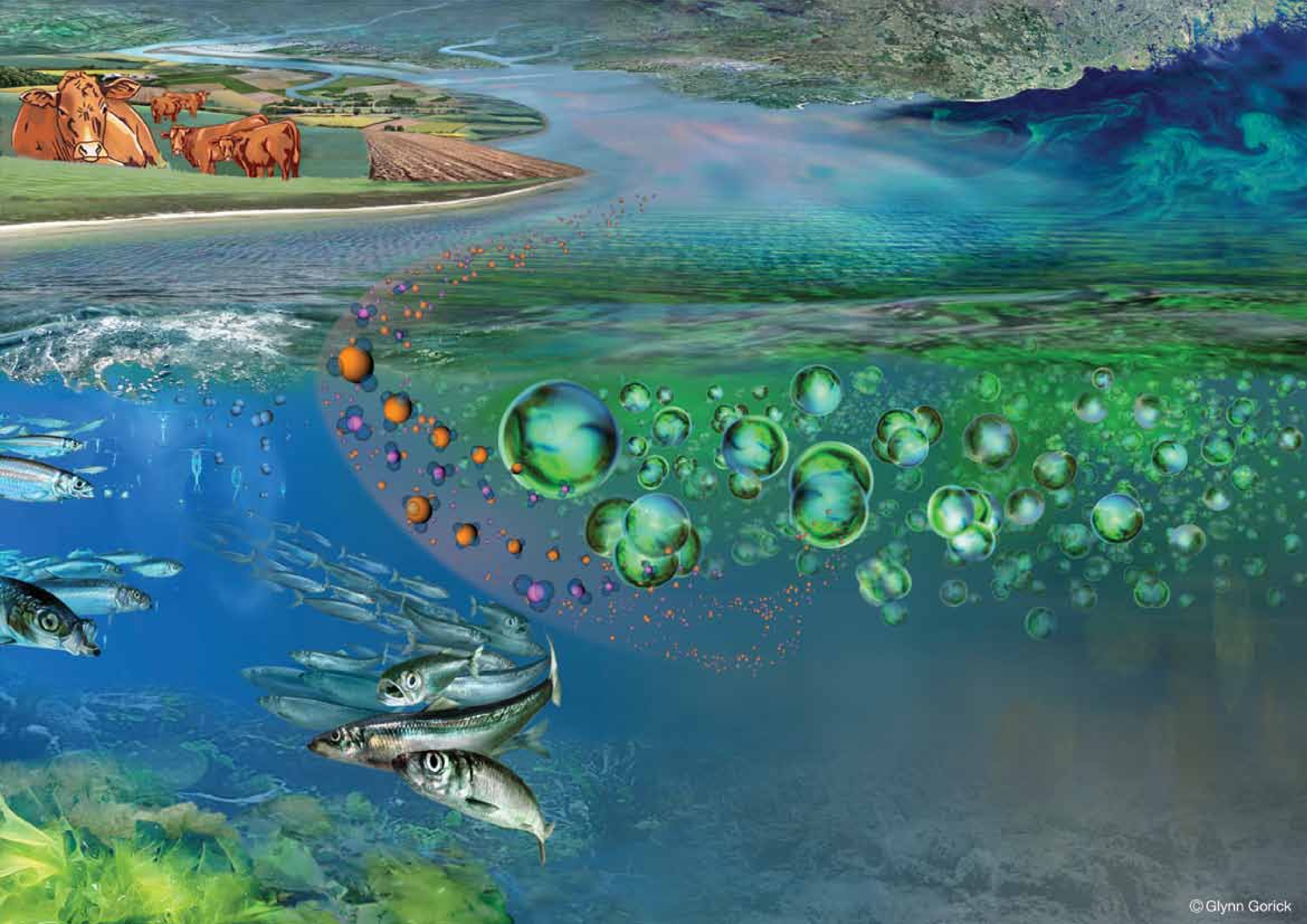
Marine eutrophication and coastal hypoxia

Background

Symptoms that have been attributed to human-induced eutrophication from excessive inputs of nutrients are a recognised problem in many European estuaries and coastal waters. They include enhanced primary production (high chlorophyll), low levels of dissolved oxygen and massive growth of nuisance algae. Note, however, that low subsurface levels of oxygen may be generated by naturally high biological productivity in the overlying water and other symptoms of eutrophication may also be caused by natural processes. Riverine inputs to European seas of nitrogen (N) phosphorus (P) and carbon (C) have increased substantially over the last century, as has atmospheric input of nitrogen. Except in enclosed seas like the Baltic, eutrophication is limited to the near-coastal zone, as the ocean is the main source of nutrients in offshore waters.

Eutrophication symptoms have been observed in the Baltic and Black seas, the Kattegat and eastern Skagerrak, the Wadden Sea, the German Bight, some near coastal and estuarine areas of the North Sea, part of the Irish Sea and lagoons and estuaries of the Bay of Biscay, Iberian and Mediterranean coasts including the Adriatic, Gulf of Lion and northern Aegean Sea. Locally, fish farming may also cause eutrophication problems. On average across Europe, 50–80% of the total N pollution drains from agricultural land, deriving from animal waste and fertilisers, whereas households and industry are the most important sources of P pollution. In the Mediterranean especially, discharge of raw or poorly treated wastewater is an important source of N and P. Atmospheric deposition of biologically available nitrogen is an additional source that may contribute to phytoplankton production, but it is widely dispersed and small compared to the oceanic inputs to coastal seas.

Nitrate and phosphate nutrients seeping into rivers from farm animal waste, fertilisers and sewage plants boost excessive growth of phytoplankton plant cells such as Phaeocystis in coastal and estuarine waters. These large blooms disrupt the food web, potentially impact tourism and can severely damage aquaculture systems.

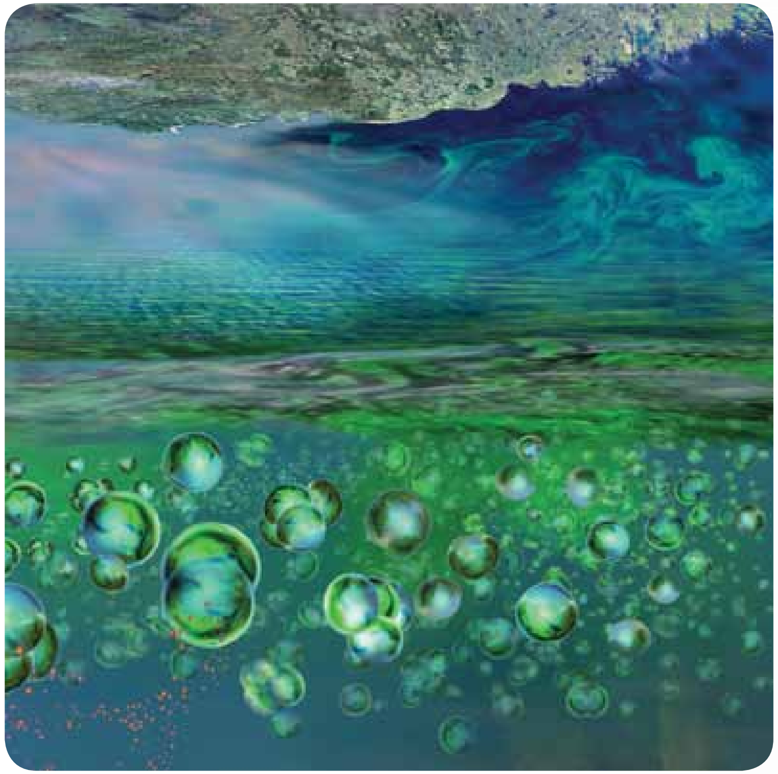


The present

Nutrient loads in northern European rivers reached a maximum in the mid 1980s and have reduced since, especially for phosphate, as a response to improvements in sewage treatment and the use of phosphate-free detergents. Rivers flowing into the Mediterranean and Black Seas have moderate nutrient loads compared to northern rivers, even though discharge of raw or poorly treated wastewater is still a major problem; they show similar trends for phosphate reduction since the 1980s, while nitrates have remained the same (or may have reduced a little) since the 1990s. Against this background, eutrophication symptoms (chlorophyll levels) have shown little improvement, although the timing and extent of blooms has changed since the late 1980s and has been linked to a combination of rising temperature, increased grazing pressure from the benthos and zooplankton, reducing nutrient inputs and changes in freshwater discharge.

The future

Climate change may exacerbate or ameliorate eutrophication. Changes – in circulation, river runoff, stratification, upwelling, in ecosystems (step changes or regime shifts), structure and functioning of the planktonic food web, parasitism and other anthropogenic forcing – all interact, and it is currently impossible to forecast which changes will predominate. Political decisions to clean up nutrient pollution in rivers, especially nitrogen from agriculture, and achieve a better balance in the ratios of nitrogen to phosphate to silica to carbon as part of the Marine Strategy Framework Directive are likely to have a much greater impact than will climate-induced effects.



Projection Confidence

Despite a sizeable scientific literature, the science of eutrophication is still poorly understood. To improve confidence in projections, there is a need for improved understanding of nutrient enrichment and the functioning of local and regional ecosystems. Better assessment and modelling tools are required and an integrated, standardised Europe-wide monitoring system implemented.

The message

There is a priority need to clarify the linkages between eutrophication symptoms and nutrients and to minimise undesirable effects that degrade the sustainability and health of ecosystems or affect living marine resources. Further reduction of nutrient inputs to the sea, especially agricultural sources of nitrogen, are needed to achieve a more balanced ratio between different nutrients and help ensure that any exacerbation due to climate change is minimised.

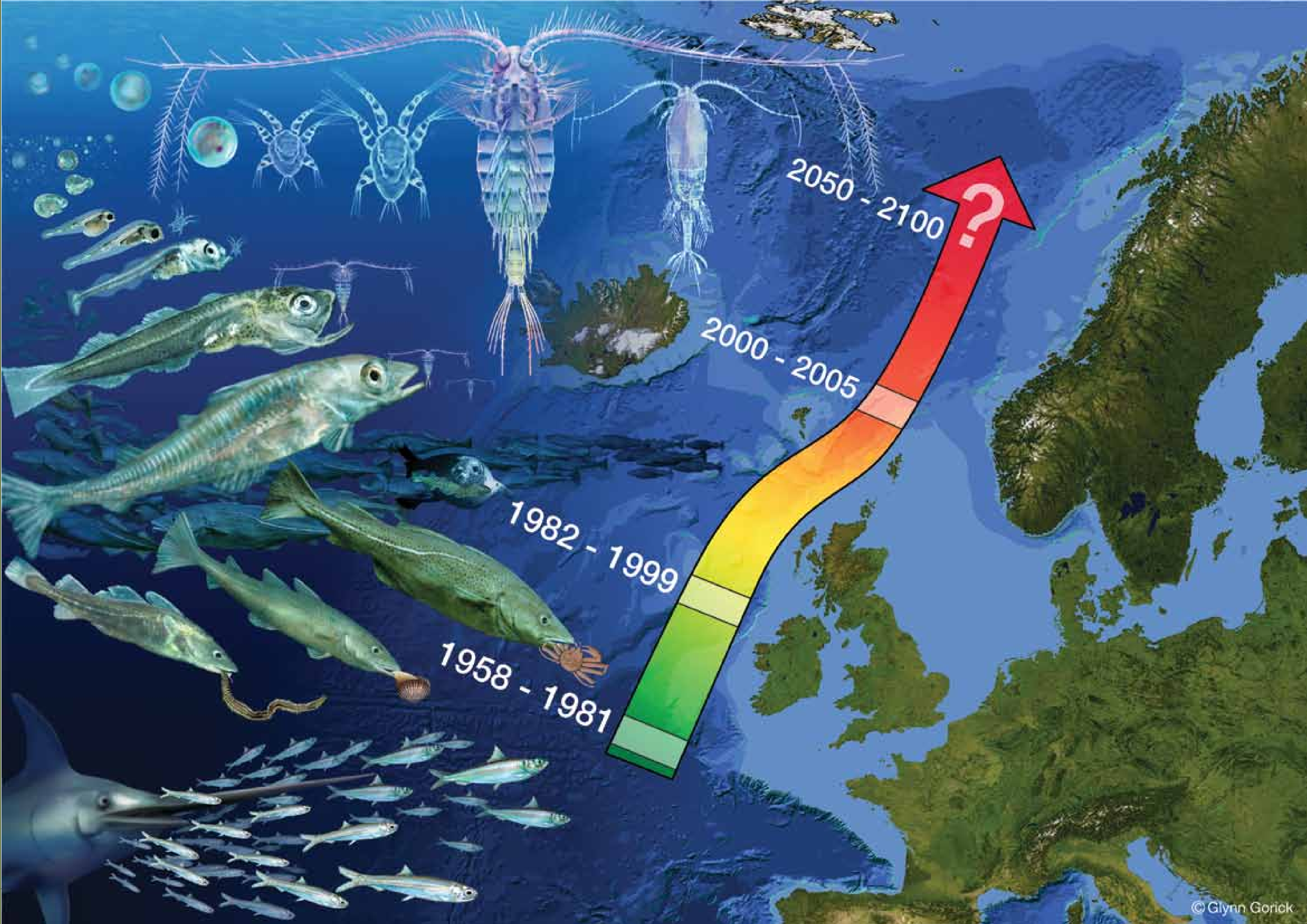
Shifts in species composition and biodiversity

Background

The biology of marine species is strongly governed by temperature through its effect on their physiology, abundance, community structure, biodiversity and the timing (phenology) of their seasonal cycle. Secondary effects, such as changes to the path of currents, may contribute to expansions and contractions of ranges. Many changes may be associated with movement of a critical thermal biogeographic boundary of ~9-10°C. Poleward range shifts of marine biota in the Northeast Atlantic during periods of warming (e.g. the 1920/30s and recent decades) and retraction in cooler periods are well documented and correlated with climate variability represented by the Atlantic Meridional Oscillation. There is clear evidence for changes in the seasonal timing (phenology) of many plankton groups – timing is crucial for the recruitment of many fish species, as their larvae can survive and develop only if their planktonic food is available to them when they need it.

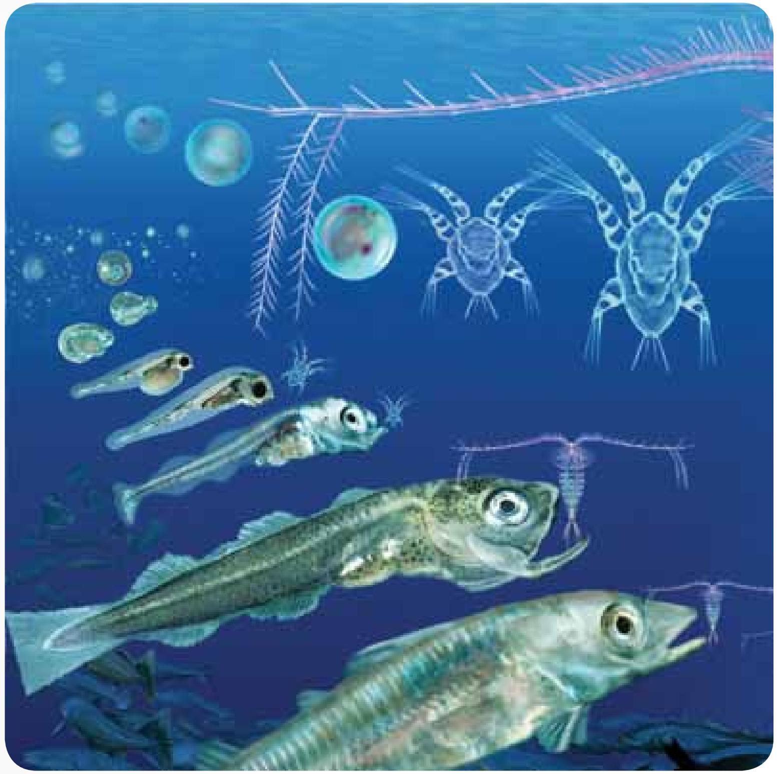
The effect of warming on ecosystems may not be gradual, as ecosystems may amplify climatic signals and exhibit step changes in structure, termed 'regime shifts' (see Chapter 8). In the temperate Northeast North Atlantic, planktonic biodiversity has increased with a parallel reduction in zooplankton size. This may negatively influence ecosystem function, as smaller zooplankton have a lower biomass and poorer food value for higher trophic levels. The Mediterranean is a biodiversity hotspot, combining winter cold and summer warm faunas. In recent decades biodiversity has increased substantially, especially for fish – more than 100 new species have been recorded, the majority as warm introductions from the North Atlantic and Red Sea via the Suez Canal (see Chapter 9).

Higher temperature and changes in currents at the edge of the European shelf have caused plankton more characteristic of warmer water to extend their range to the north of Shetland, a shift of 1000 km between the 1970s and 2000/2005. At the same time, the shrimp-like Calanus finmarchicus, abundant in colder water and an important food for fish – especially the larval stages of cod – has retreated towards the pole.


2050 - 2100
?
2000 - 2005
1982 - 1999
1958 - 1981
© Glynn Gorick

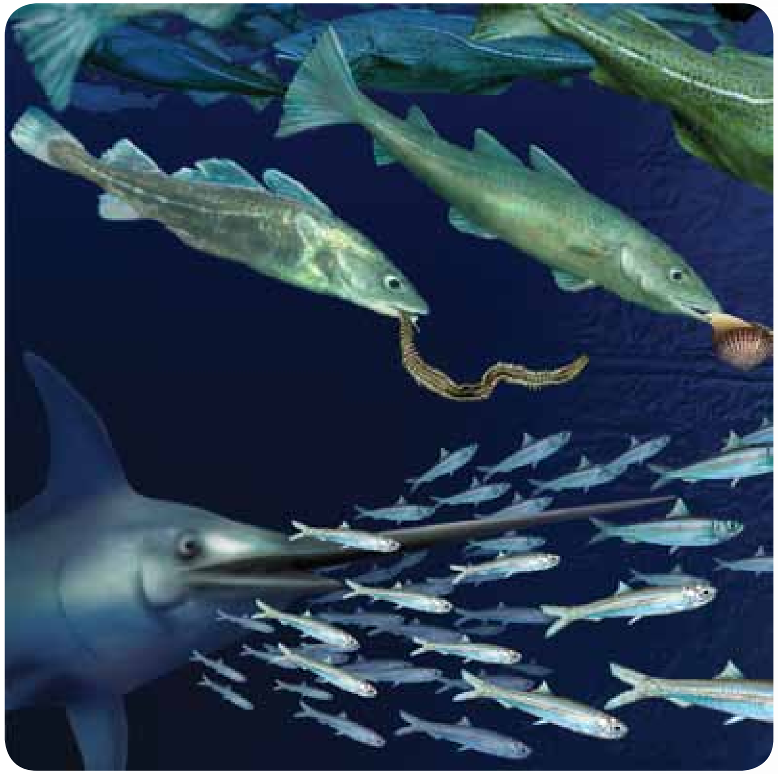
The present

Poleward range shifts in warm water plankton, attributed to rising temperature and enhanced flows in the shelf edge current at the western margin of Europe, have extended more than 1000 km over the last 5 decades. Plankton adapted to colder water have retreated to the north over a similar period. Over two-thirds of North Sea fish have shown shifts to the north in mean latitude or depth and parallel changes have occurred in the benthos. Similar, but less pronounced poleward movements and associated changes in biomass have been seen in the Mediterranean and other European seas. In the North Sea, some plankton have moved their seasonal timing forward by over a month.



The future

The copepod *Calanus finmarchicus* is an important food for fish in the North Atlantic, where its biomass is said to weigh more than the global human population. This species has reduced its abundance in the North Sea by ~70% since the 1960s, and while it has been replaced by its 'sister' species *C. helgolandicus*, the change has had important consequences for fish resources. Projected poleward movement of *C. finmarchicus* at one degree of latitude per decade will have pronounced consequences for Northeast Atlantic and Arctic ecosystems. Expected higher precipitation in the Baltic will increase the dominance of freshwater biota. Northward movement of warm Mediterranean water will favour the accelerated spread of non-native species in a warmer saline sea and the Black Sea will show a continuing increase in Mediterranean immigrants.



Projection Confidence

It is accepted that observed biogeographic shifts and phenology are related to regional climate warming and that rising sea temperature in European seas is partly caused by anthropogenic global warming. There is moderate confidence in the future projection of these changes. The mechanisms behind warming at the shelf edge are unclear and difficult to model. Linkages with atmospheric modes such as the Atlantic Multidecadal Oscillation (AMO) are poorly understood.

The message

Over the last 30 years, ecosystems in all European seas have changed substantially, in large part due to warming sea temperature linked to climate variability and change. The changes are reflected in shifts of distribution, seasonal timing, regime and biodiversity with many appearing to accelerate. The prognosis is for continuing change as temperatures rise (and Baltic salinity reduces) with likely important effects on biogeochemical cycles and living marine resources.

CLAMER Chapter 8

Jellyfish blooms and regime shifts

Background

The frequency and size of 'jellyfish' blooms have been increasing throughout the world in recent decades and have been linked to overfishing, eutrophication and climate change. Jellyfish – Cnidaria (medusae), Ctenophora (comb jellies) and Tunicata (salps) – can grow rapidly to form large 'blooms' as seasonal predators of plankton and fish eggs/larvae. Cnidaria (with stinging nematocysts in their tentacles) with the other 'jellies', can have a substantial socioeconomic impact on fisheries, aquaculture, tourism and marine industries by, for example, reduced recruitment and net damage, fish kills in growing cages, bather stings and blocked power station cooling water intakes. More positively, medusae may enhance fisheries by protecting the young stages of some gadoid species from predation between their tentacles. Time-series studies show strong statistical links between jellyfish and sea surface temperature, oceanic advection, climatic indices and abundance of zooplankton prey. Jellyfish may actively search for prey, as shown by recent evidence, and may enhance ability to increase their dominance in perturbed ocean ecosystems.

There is no standard definition of the term *regime shift*; here, such shifts are considered as rapid transitions in ecosystems from one semi-permanent state to another. The mechanism typically involves climate forcing although shifts may also result from overfishing, pollution or a combination of factors. Biological responses to shifting climatic conditions, as represented in a change in regime, may be non-linear and amplify the underlying linear abiotic climatic changes. This sensitivity implies that future gradual climate changes may provoke sudden biological responses (tipping points) with unpredictable consequences for the function and resilience of ecosystems, as well as for the carrying capacity of living marine resources. There is already substantial evidence from all European seas of historical, regional regime shifts that have had major impacts on all trophic levels and wide socioeconomic consequences.

In recent decades, the increasing occurrence of jellyfish blooms has been correlated with rising sea temperature. They have caused major problems for fisheries, aquaculture and tourism. A complete collapse of the Black Sea fishery in the late 1980s has been attributed, along with overfishing, to massive blooms of the comb jelly Mnemiopsis leidyi vacuuming up zooplankton, eggs, and fish larvae.

The present

Medusae occurrence in the Northeast Atlantic and North Sea has oscillated over 5 decades, increasing in warm years from the early 1980s, with abundance of some species reducing. Mediterranean blooms, especially of toxic *Pelagia noctiluca*, may have increased in recent years. Bloom outbreaks in the Black Sea, especially of the non-native comb jelly *Mnemiopsis leidyi*, have caused pronounced ecosystem changes and a decline in fish stocks.

Clear regime shifts, involving many trophic levels in the plankton, with evidence for associated changes in the benthos (suspension feeders to detritivores), hydrography and biochemistry have been well described from close to 1988 in the North and Baltic Seas with similar events in the Mediterranean at about the same time.

The future

If, as predicted, European seas continue to warm over the next century, warmer water species and boreal species respectively are likely to expand and retract their distributions. Patterns of abundance are less easy to forecast, but if overfishing and environmental degradation contribute to blooms and override climatic factors, high jellyfish populations may persist in competition with fish.

Limited understanding of the extent to which climate change, anthropogenic or intrinsic biological drivers may contribute to the development of regime shifts, plus a lack of appropriate spatiotemporal data, make it impossible at present to predict or model their future occurrence. Such knowledge has high relevance to the management of fisheries.

Projection Confidence

Understanding of environmental factors governing interannual and long-term variability of jellyfish is too limited to predict future patterns of bloom frequency. There is especially poor knowledge of the biology of the polyp stage of shelf-sea medusae.

Ability to predict the direction or occurrence of regime shifts is poor, especially as most past events have not been detected until well after their initiation. New statistical and modelling tools have been applied to try to improve detection and understanding of driving forces.

The message

Improved knowledge of how climate change, human impacts, ecology of benthic polyps and their interaction enhance jellyfish blooms is needed, as are better methods to estimate jellyfish abundance and map distributions. Regime shifts affect the carrying capacity, composition and distribution of fish, so new approaches to fish management are needed to maintain sustainable fisheries, as are improved techniques to identify, model and predict regime shifts and assess their impact on ecosystem resilience.

CLAMER Chapter 9

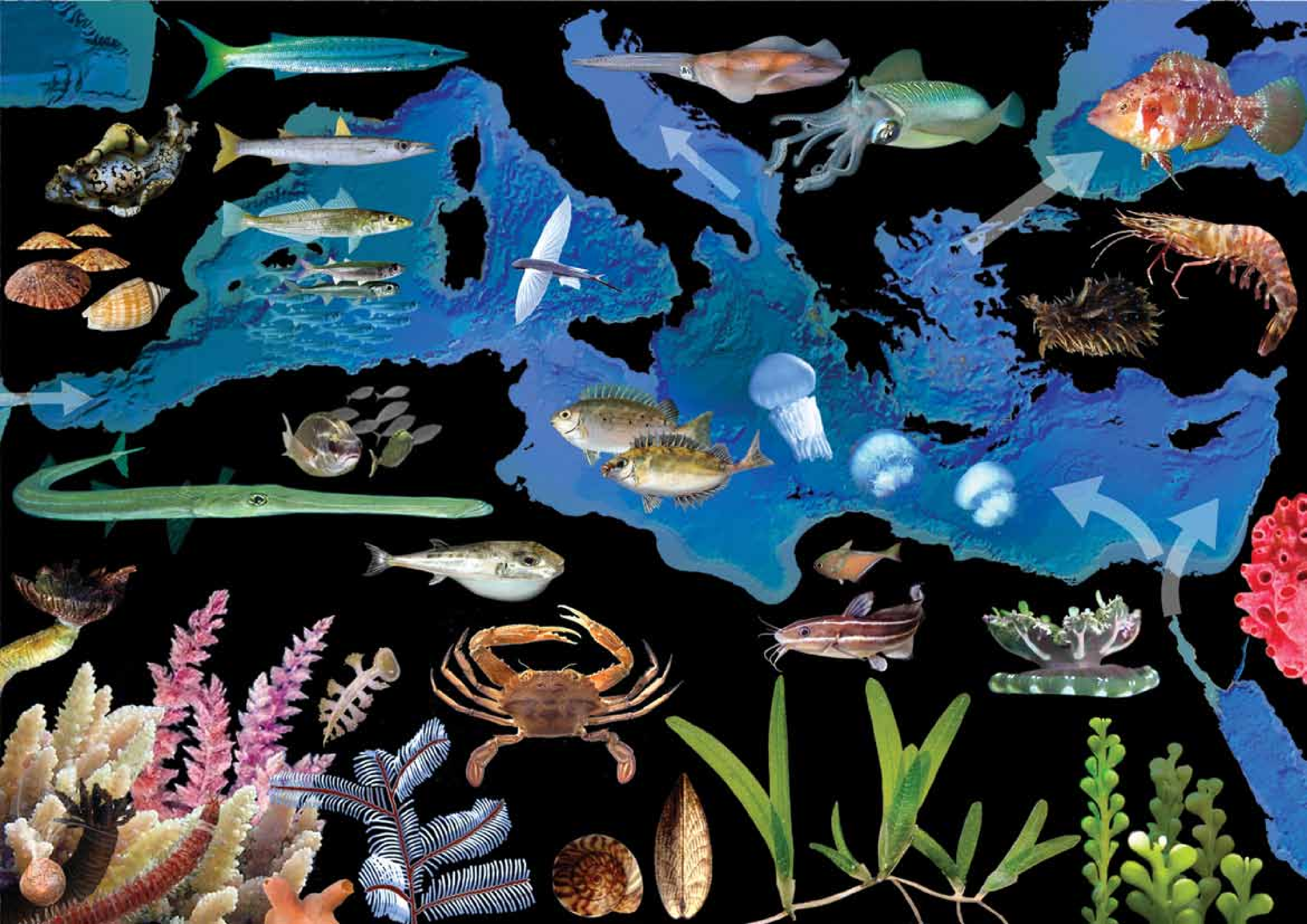
Non-native species

Background

Introduced non-native marine species are invasive if they spread and cause economic or environmental harm, or impact human health. Most introductions arrive via human intervention, intentional or otherwise (e.g. aquaculture, ballast water and hull fouling). Some native and established non-native species with previous historically static distributions are expanding their ranges polewards, and increasing their abundance in marginal areas of their range. These may relate to rising seasonal temperatures and changing hydrographic (e.g. currents) and meteorological conditions. Species that prefer warmer water may out-compete cold-adapted relatives through their greater growth and recruitment and/or colder species may simultaneously retreat to the north, tracking their temperature niche.

The spread of both native and non-native introductions has the potential to impact biological systems profoundly and may lead to a complete restructuring of food webs. The rate of spread of the ranges of natives would appear to be slower than that of introduced species, but an order of magnitude higher in marine compared to terrestrial environments. The Mediterranean is unique due to immigration from the Red Sea via the Suez Canal (termed, the Lessepsian migration after the builder of the canal) and in recent decades from the tropical Atlantic via the Strait of Gibraltar. The Baltic has been impacted by northward transfer of some brackish-water invasive species from the Black Sea along the European canal network, and periodic effects in the Black Sea have been partially linked to massive growth of the non-native comb jelly *Mnemiopsis*.

Tropicalisation of the Mediterranean has led to a rapid increase in invasions of non-native species from the Red Sea via the Suez Canal. More than ten new species arrive each year. Recent finds include the white stinger hydroid (Macrorhynchia philippina) and a poisonous puffer fish (Lagocephalus sceleratus).



The present

Records of non-native and invasive marine species have markedly increased at both global and European scales. These species may cause substantial damage to the diversity and abundance of native populations as well as to ecosystem function, thus impacting the livelihood of fishermen and at times affecting human health. For example, the comb jelly *Mnemiopsis leidyi*, whose abundance is correlated with higher temperature, partially contributed to a decline, by almost an order of magnitude, in Black Sea fish landings, with estimated losses to the industry of ~€240 million in the 1990s. Impacts on aquaculture include sporadic poisoning or smothering of farmed organisms, clogging of nets and fouling of structures. Until recently, most invasive species were introduced via human activities and spread naturally – a spread that has accelerated in recent decades, due to warmer temperature and physical responses linked to climate change.

The future

If recent patterns are maintained, it is predicted that both the number and spread of non-native species may increase due to climate change (plus ocean acidification) with consequences that are difficult to predict. On the western margins of Europe, rates of spread for planktonic warm water invasives and retreat of cold water natives may be as high as one degree of latitude per decade for typical mid-range IPCC scenarios and half this rate for benthic intertidal species. Enclosed seas such as the Mediterranean and Black Sea are vulnerable to the spread of invasives from adjacent seas as temperatures rise. Transarctic migrations from the Pacific to the North Atlantic (due to melting Arctic sea-ice) and fresh and warmer water invasions in the Baltic are expected to become more prevalent.

Projection Confidence

Taxonomic expertise, especially for microbial parasites and to some extent plankton, is poor. Historical and spatial coverage of systematic monitoring programmes is limited. Future projections vary among regions and seas, and have medium confidence as modelling of catalogued invasives is improving. There is poor confidence, however, for the ecosystem consequences of the arrival of new, yet to be identified and recorded, non-native arrivals.

The message

Impacts from the spread of non-native species may be enhanced by climate change. New preventative measures need to be devised, especially for species migrations via the Suez Canal and Arctic as well as by human vectors such as ballast water. A coordinated monitoring programme for invasive species should be established in European regional seas and main ports. Improved understanding of the ecology of invasions is needed to improve mitigation measures.

CLAMER Chapter 10

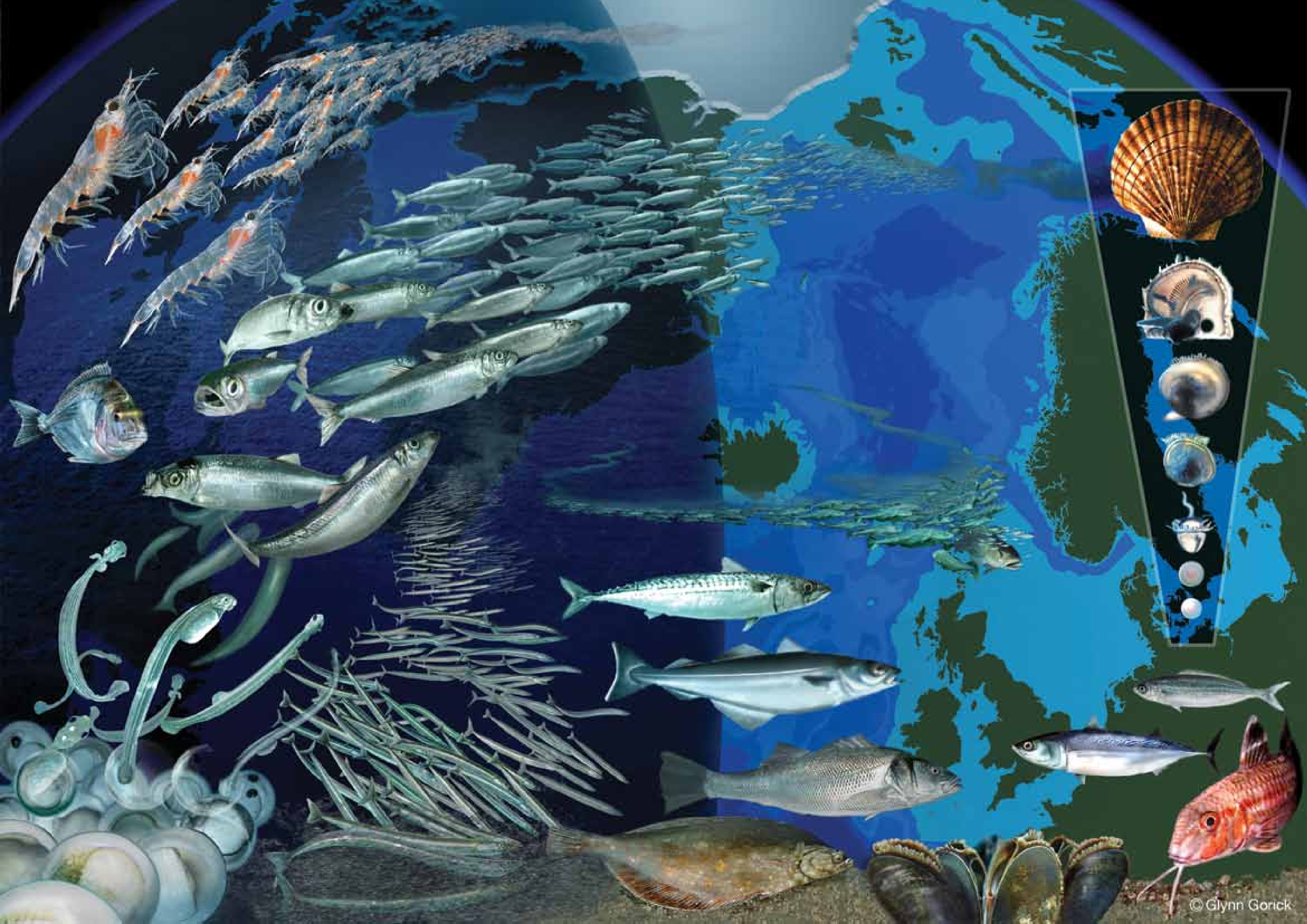
Food: Fisheries and Aquaculture

Background

In rapidly-warming areas of the northernmost Northeast Atlantic and further south (North Sea – extending to the Iberian coast), fisheries yields since 1981 have respectively increased and declined. The northern increase has been ascribed to pelagic fish responding to warming-induced higher food availability and the reverse situation to more stable water and lower zooplankton biomass. These observations reinforce the message that carrying capacity (production) of fish depends on primary production levels and the resulting biomass/composition of zooplankton. Primary production (see Chapter 3) is governed by light, nutrients, temperature and water stability and thus by climate, with strong feedbacks to fisheries. However, climate and fishing interact by a) climate fluctuation limiting the effectiveness of the management of exploited populations and b) fishing reducing the resilience of populations and their ability to adapt to climatic fluctuations. Interactions may also occur at the species level – in the Barents Sea, for example, cod, capelin and herring interact strongly and are all influenced by differential harvesting.

At European and global levels, production of fish and shellfish from wild stocks has levelled out, with landings from EU fleets declining. Maintaining fish and shellfish production has only been possible by a continuing growth in aquaculture. To maintain fish supplies at levels that will feed a growing European population, it is estimated that an additional 3.7 million tonnes of fish/shellfish will be needed by 2035, 35% more than the 2006 supply. Achieving these levels will be difficult, given that most wild fisheries are either fully- or over-exploited. Potential climate impacts on European aquaculture include: increases in pathogens and parasite range expansions, due to rising temperatures stimulating their growth, transmission and survival; reduced production of forage fish stocks, produced outside the North Atlantic and vulnerable to climate variability; increased frequency of jellyfish/harmful algal blooms and non-native introductions.

There is clear evidence from all European seas that rising temperatures, along with overfishing, are causing substantial changes to fish stocks such as herring, sand eels and cod, as well as to their ranges and migration routes. Warmer water fish species are gradually moving north so that unfamiliar fish species are now appearing on fish market stalls.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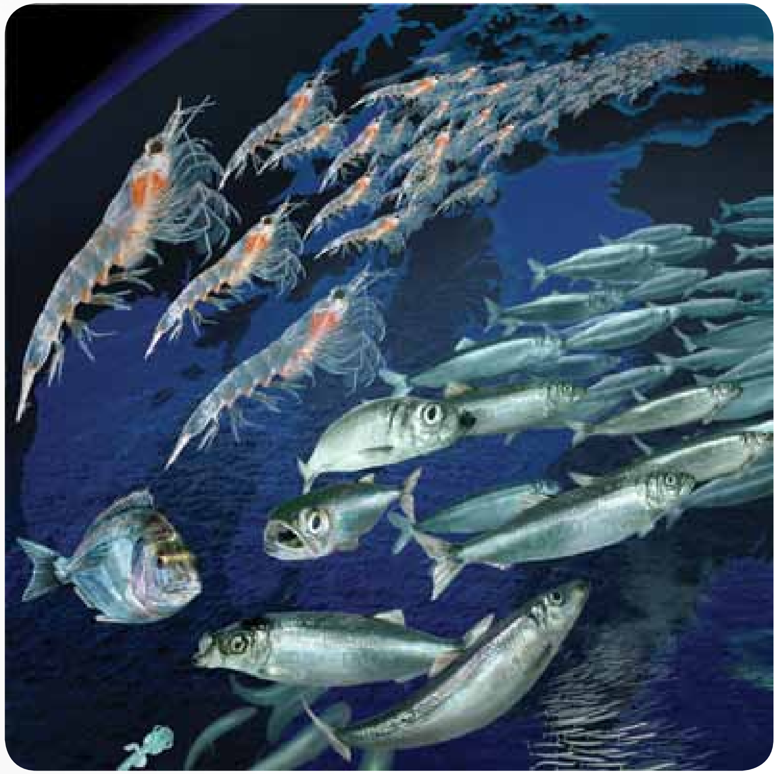
The present

Discriminating between fishery- and climate-related impacts on fish stocks is difficult. However, there is now clear evidence from all European seas that changes in sea temperature and other environmental factors have already altered fish population structure, recruitment, distribution (range extensions, retractions), phenology (timing) and migration routes. Fish like salmon and eels that live partly in rivers, partly in the sea have been strongly affected. Fishing, however, is still the dominant factor governing the status of exploited stocks.

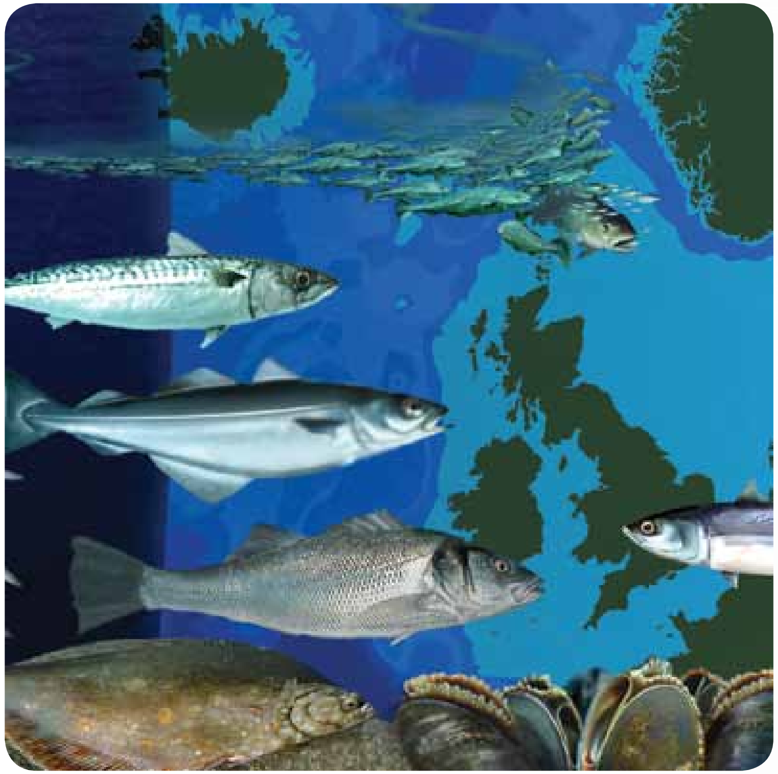
There is no evidence for any impact from climate change on existing aquaculture facilities, but that might be disguised by the rapid global growth of the industry.



The future

Northerly extension of warmer-water fish is expected to continue, with development of new exploitable populations. Stocks of cold-adapted species are projected to decline in, for instance, the North Sea, but to benefit from higher temperatures in areas such as the Barents Sea. Fish production is sensitive to the combined effects of climate, ocean acidification and plankton community changes, and heavily exploited fish stocks are likely to be especially vulnerable.

In coming decades, aquaculture is likely to be the main source of increased fish and shellfish production. Cultivation ranges will change and greater stock and infrastructure losses from changing weather patterns can be expected. A lesser but still critical dependency on forage fish used for fish oil/meal feed is likely for carnivorous aquaculture, even though increasing catches will be difficult. Ocean acidification may have indirect and direct effects on shellfish production.



Projection Confidence

Different models predict both positive and negative future changes in net global primary production (and thus fishery production) with a consensus for a decline in mid-latitudes and possible increase in high latitudes. However, there is great uncertainty and thus low confidence in the predictions, as many processes are poorly constrained in the models. Furthermore, the extent to which latitudinal range changes are attributable to regional climate variability (for example, the Atlantic Multidecadal Oscillation) or global warming is presently unclear.

The message

To ensure sustainable future fish stocks, it is important that management schemes take into consideration distributional changes and the potential for sudden step changes (regime shifts) by reducing fishing mortality, thus providing stocks with a buffer against years with poor recruitment and reducing their vulnerability to climate fluctuations. Aquaculture needs to reduce its dependency on wild fish by developing new food sources that are not made from forage fish.

CLAMER Chapter 11

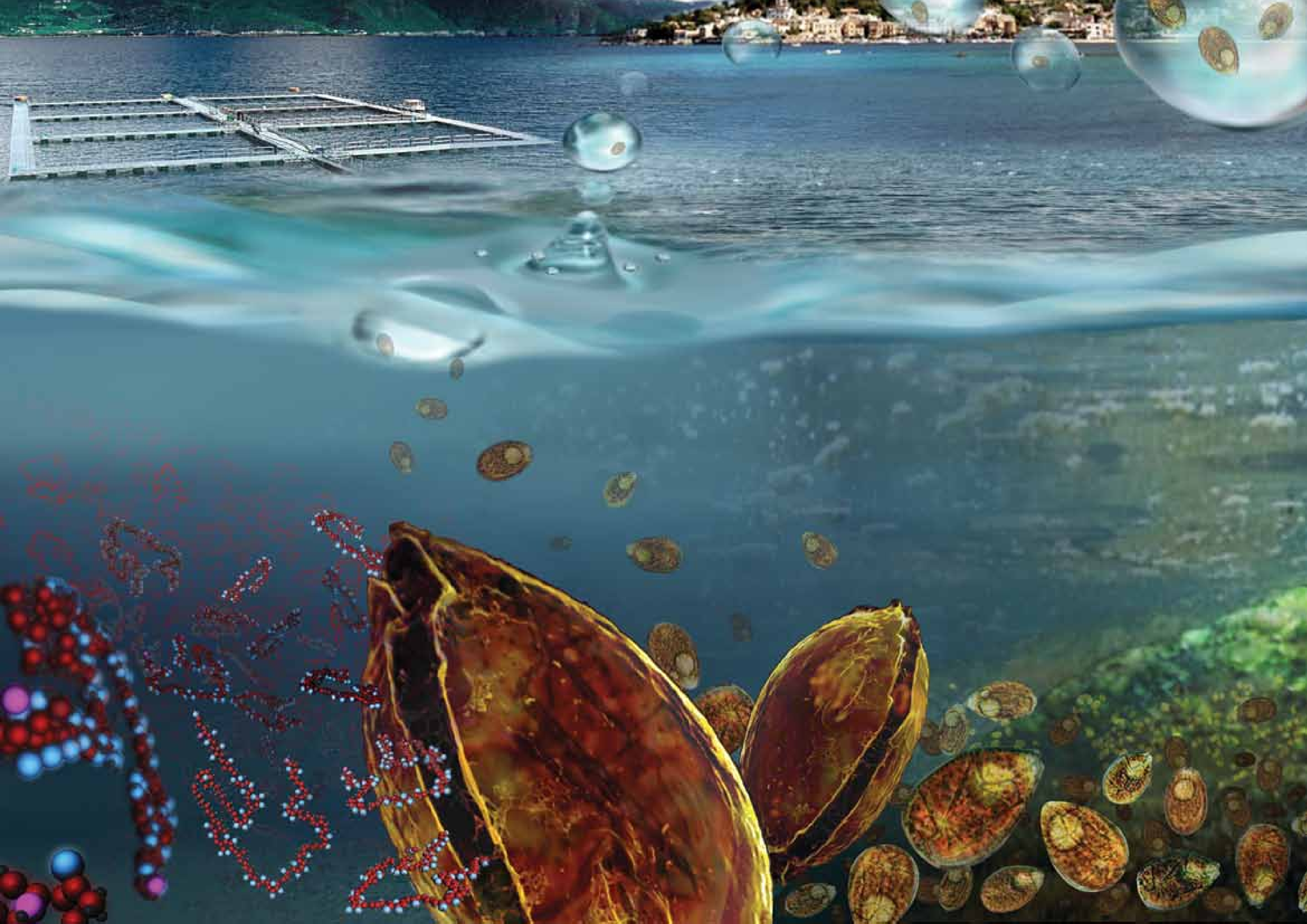
Human health, disease in marine organisms and harmful algal blooms

Background

There is concern that climate change may contribute to further introductions and dissemination, in Europe, of diseases in both marine organisms and humans. This viewpoint is based on observations of latitudinal and temporal associations between climate variability and the occurrence and intensity of respiratory and infectious diseases, parasitism and gastroenteritis. The response is likely to be complex, as higher sea temperatures affect the physiology of hosts, vectors and contributing parasite/pathogens and interact with other factors, including human and aquaculture disease abatement programmes and drug resistance. Changes in sea temperature and salinity will alter biogeographic ranges, affect abundance, rates of reproduction and growth, extend transmission seasons and change ecological interactions. Aquaculture is vulnerable to increasing levels of disease and parasites caused by rising temperature, with potential serious economic consequences for the industry.

Many phytoplankton groups are known to form harmful algal blooms (HAB), including: dinoflagellates, diatoms, haptophytes, raphidophytes and cyanobacteria. The species within these different groups show variable abundance/biomass and toxicity patterns, ranging from: high to low toxicity to humans and marine organisms with high or low abundance to non-toxic nuisance taxa. There is some evidence to link HAB events to rising temperature and climate change. Many bloom-forming species are sensitive to mixing and the intensity of stratification as they are able to utilise regenerated nitrogen and migrate vertically, and may be favoured by more intensive future stratification (see Chapter 5). A progressive global increase in aquaculture has led to an increase in the recording of paralytic, diarrhetic, neurotoxic, amnesic and azaspiracid shellfish poisoning and ciguatera fish poisoning has been recorded outside the subtropics. Globally, approximately 2,000 cases of food poisoning from consumption of contaminated fish or shellfish are reported each year, of which ~15% are fatal with another estimate suggesting 50,000 to 500,000 ciguatera intoxications per year alone.

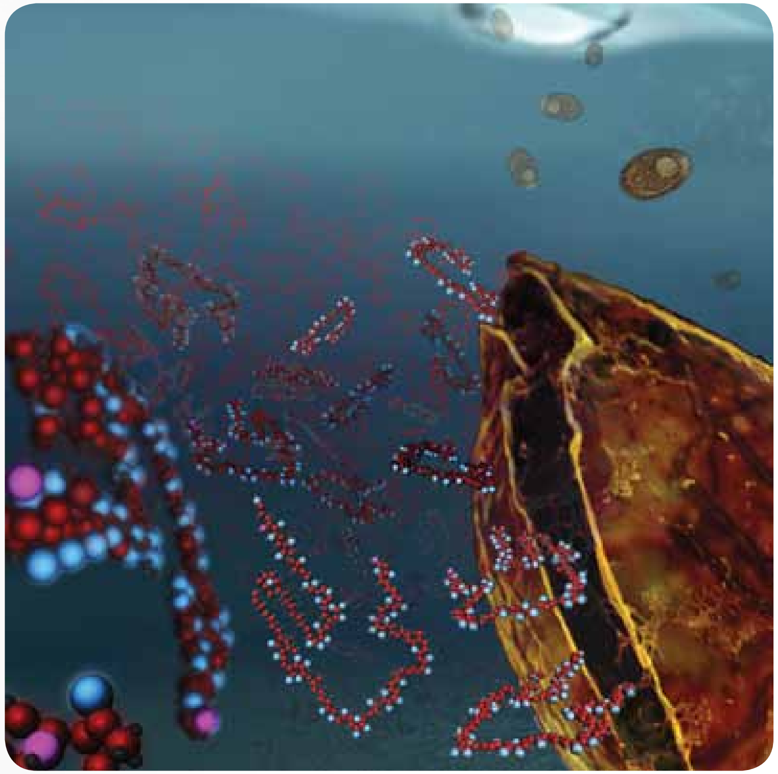
Harmful algal blooms, some of which produce poisons can have serious economic consequences for aquaculture and beach tourism. No clear relationship has been found between their occurrence and climate change, but some subtropical species such as Ostreopsis are now found in the Mediterranean. Toxins from this species may cause dermatitis in bathers and respiratory problems for tourists on beaches when released in aerosols.



The present

The prevalence and severity of a wide range of disease/parasite infections in marine organisms, e.g. corals and fish, have been linked to high sea surface temperature. Increases in plankton-associated *Vibrio* bacteria in the southern North Sea coincided with exceptional outbreaks of Vibrio wound infections in bathers in the Baltic and North Seas in recent unusually hot summers.

There is no clear pattern to the occurrence of HAB and toxic algal events in European waters in recent decades other than a change from west to east distribution patterns in the North Sea. Of note are exceptional records of tropical ciguatera fish poisoning in the Canaries, for the first time in 2004. 'Tropical' dinoflagellates linked to ciguatera, *Gambierodiscus* and *Ostreopsis*, now occur in the Mediterranean, in the latter case causing severe problems on Italian beaches from toxic aerosols and bathing impacts.



The future

The geographical ranges of some diseases and parasites have already increased as a response to warming temperatures, a pattern that is likely to extend to other taxa in the future. Human activities and many other factors may affect infectious and parasitic diseases and may overshadow effects from climate change.

Changes in the abundance, distribution, composition and timing of HABs are expected due to climate change. Outbreaks of toxic events in new areas, that affect humans, seafood or aquaculture, are likely to have serious social and economic consequences. Intensification of stratification and exceptional precipitation events may favour an increase in some HAB species. Tropicalisation of the Mediterranean and a trend to greater imports of wild and farmed fish may lead to a rise in the occurrence of ciguatera poisoning in Europe.

Projection Confidence

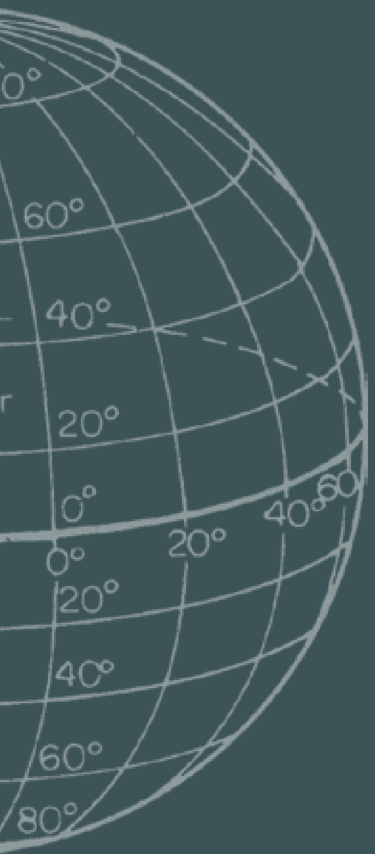
The intensity and future distribution of marine diseases in a warming and more acidic ocean are subject to considerable uncertainty. This is because of a poor understanding of potential natural and human forcing on their ecology and virulence.

Predictions of the response of HABs to climate change have a low level of confidence due to limited knowledge of the response of marine ecosystems to multifactorial drivers and the adaptability of phytoplankton to rapid change.

The message

Climate-induced changes to the prevalence and potency of marine pathogens, parasitism, HABs and biotoxins may have severe consequences for human and ecosystem health and may lead to a decline in consumer confidence in sea food, coastal recreation and tourism. Ingestion of water-borne pathogens, consumption of contaminated seafood and exposure to marine diseases may lead to higher medical costs.

Marine energy and geoengineering

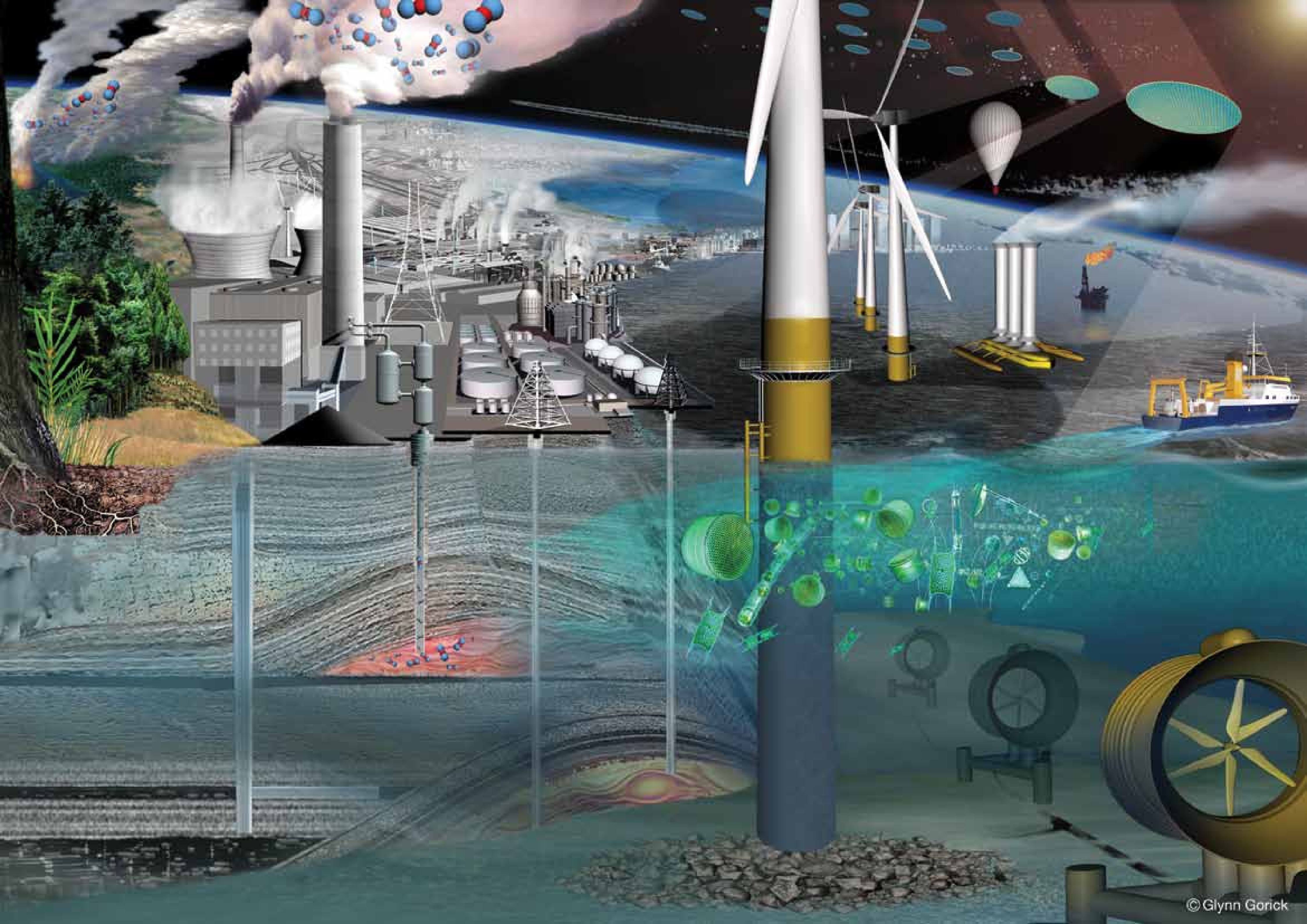


Background

Except for oil and gas, the exploitation of marine energy resources is in its infancy. Renewable sources of marine power include offshore wind generation, tides, waves, currents, deepwater thermal gradients, biomass and density differences between fresh and seawater. Offshore wind, tide and power generation represent a vast untapped source of renewable energy. Yet by 2009, offshore wind generation made up only a small fraction (2.5%) of the total wind power produced in Europe, itself only a small percentage of all renewables. The energy produced by other renewable marine sources is very small. The technologies needed to harness other sources of power from the sea, presently largely limited to tide and waves, are still in an early stage of development, with some operational test facilities and links to national grids now in place.

Geoengineering is the deliberate, large-scale manipulation of the Earth's climate to counteract the effects of global warming. This may be achieved by either removing the greenhouse gas carbon dioxide from the atmosphere or by reducing the incoming energy from solar radiation by reflecting it back into space to compensate for the increase in CO_2. Capture and storage of CO_2 in sedimentary deposits is feasible as demonstrated by operational systems in two Norwegian gas fields. It could also be pumped into deep ocean basins, although the resulting increased acidification would have negative consequences for deep sea organisms. The controversial procedure of 'ocean fertilisation' adds limiting nutrients such as iron to the surface ocean to enhance planktonic production. The aim is to increase oceanic drawdown of CO_2 from the atmosphere and increase export of carbon to the deep ocean via the biological pump. Enhancing cloud brightness by spraying them with seawater droplets from ships is proposed as a means of increasing the reflectivity of clouds to sunlight.

The oceans provide a vast and untapped resource of renewable energy production from offshore wind and tidal turbines, wave-energy harvesting devices and algal production, all developing rapidly to help reduce our carbon footprint. A range of global scale engineering projects has been proposed as a stopgap to counteract the effects of rising CO_2 by reducing the energy absorbed by the Earth from the sun or by harvesting and long-term storage of CO_2.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The present

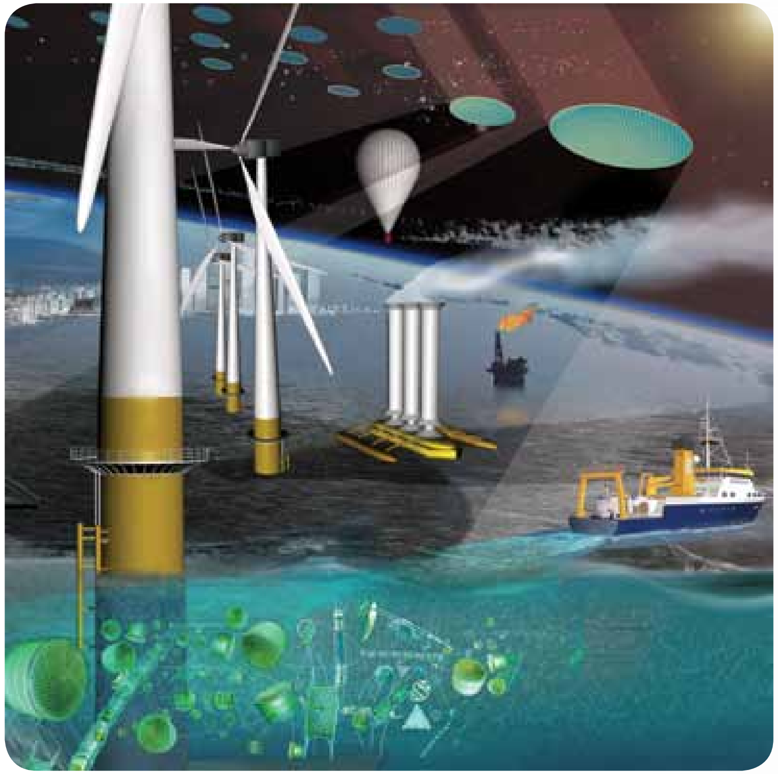
The Rance 240 MW tidal power station, is the world's largest marine energy plant, but only a minor contributor to French electricity. The total European capacity of all operational pilot tidal- and wave-power plants reached only 2.8 MW in 2009, with offshore wind generation achieving 1924 MW. Ocean Thermal Energy Conversion (OTEC) plants that use a heat engine to exploit the difference between cool deep and shallow warm water are operational outside Europe.

There are currently no effective and practical ocean geoengineering schemes other than capture and storage of CO_2 in sedimentary reservoirs. Experimental studies have been carried out to test the feasibility of ocean fertilisation and show that it is ineffective, costly and has low efficiency. Large scale expansion of OTEC schemes to stimulate primary production is impractical and inefficient as they contribute CO_2 to the atmosphere from the upwelled deep water.

The future

The EU has set a new renewable energy target of 20% by 2020. To achieve this target a rapid development of marine energy installations and an offshore energy electricity grid is needed. Development of offshore wind farms is expected to expand with a projection of up to 40 times the current installed capacity by 2020 and 150 GW by 2030. While other sources of offshore energy are less developed, they too are expected to grow rapidly.

As the practicality, efficiency, economics and ecosystem consequences of ocean fertilisation are far from clear, the Convention of Biological Diversity prohibited further applications of the technique until a stronger scientific justification is made through a regulatory framework that is currently under development. Expansion of CO_2 capture and storage in sedimentary basins is expected.



Projection Confidence

Considerable logistical, engineering, planning and financial issues need resolving to ensure smooth development of a range of different offshore energy sources. Sites of production are far from the regions of high energy use and supply bottlenecks may form in existing grids.

Geoengineering has a high risk with possible unintended and irreversible side effects and impacts on ecosystems that may negatively affect regions distant from the deployment. Solar reflection techniques would allow ocean acidification and its effects to continue unabated.

The message

A proactive European policy backed by appropriate environmental protection and funding is necessary to ensure that offshore energy production systems develop at the rate needed to fulfil renewable energy targets. Experiments on ocean fertilisation should be allowed to proceed with international guidelines and controls to improve knowledge of the functioning of ocean ecosystems and determine if manipulation of the oceans might be an effective means of reducing rising atmospheric CO_2.

The Sir Alister Hardy Foundation for Ocean Science (SAHFOS) is an internationally funded charity (Canada, Ireland, Norway, UK and the USA) that operates the Continuous Plankton Recorder (CPR) survey. The Foundation has been collecting data from the North Atlantic and the North Sea on biogeography and ecology of plankton since 1931. More recently, work has been expanded to include other regions around the globe including the Arctic and Southern Ocean. The results of the survey are used by marine biologists, scientific institutes and in environmental change studies across the world. The CPR team is based in Plymouth, England and consists of analysts, technicians, researchers and administrators, who all play an integral part in the running of the survey.

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