Background and context for observational approaches to benthic dynamics

When considering long-term observational programmes benthic ecosystems are often not considered or only included as a low priority. This is probably a result of the fact that many of the services provided by benthic marine ecosystems are externalities, in other words their value to humankind is not reflected in market prices. This is by no means true of all of them however. Coral reefs are amongst the most valuable marine ecosystems to humankind providing goods and services with an estimated annual value of $172 – 375 billion per annum (Moore and Best 2001; Wilkinson, 2002; Fischlin et al. 2007; Martínez et al. 2007). Time series of benthic observations are significant, especially as changes in benthic communities can act as early indicators of the ecosystem impacts of climate change, overexploitation in fisheries or of other human disturbances of ecosystems such as runoff of agrochemicals or sewage resulting in eutrophication. It is a sobering thought that globally it is a marine ecosystem, tropical coral reefs, that is likely to be the first to collapse as a result of climate change through the combined impacts of rising sea surface temperatures and ocean acidification (Veron et al., 2009). Even deep-sea ecosystems have been shown to be highly sensitive to climatic variability with changes in surface productivity, temperature or small scale hydrographic phenomena resulting in significant changes in the abundance, biodiversity, population dynamics and ecosystem functioning in benthic communities (Wigham et al., 2003; Company et al., 2008; Danavaro et al., 2008; Ruhl et al., 2008). However, marine ecosystems rarely appear as a significant component of policy documents related to climate change.

The need for systematic long-term measurements over large scales

There are a variety of human activities that have a negative impact on benthic marine ecosystems. Some of these occur in the oceans, some originate on the land and primarily affect coastal ecosystems. These impacts include:

- Climate change
    - Changes in temperature
    - Changes in vertical mixing
    - Changes in oxygenation
    - Changes in surface productivity
    - Changes in currents
    - Changes in seasonality
    - Ocean acidification
    - Changes in frequency of extreme weather events
- Fisheries
    - Removal of target and by-catch species
    - Habitat destruction
    - Food web alterations
    - Regime shifts
- Pollution

Increased nutrients causing eutrophication, increased frequency of harmful algal blooms, hypoxia or anoxia of marine ecosystems
Sedimentation
Introduction of toxic substances including heavy metals, oil, PCBs, PAH, organochlorine compounds, TBT and other hormone mimics

- Oil and gas exploration
  - Oil
  - Drilling muds and associated chemicals
  - Habitat destruction
  - Sedimentation
- Marine mining, aggregate extraction, dredging
  - Habitat destruction
  - Sedimentation
- Biotic invasions
  - Food web alterations
  - Regime shifts
  - Competitive exclusion
- Disease and plagues
  - Food web alterations
  - Regime shifts
  - Habitat destruction
- Habitat destruction
  - Regime shifts
- Noise
  - Changes in movement / behaviour
  - Mortality of affected species

Most of these impacts are common across all benthic ecosystems but exposure, vulnerability and resilience may differ markedly amongst benthic communities. For example, some deep-sea coral communities are very fragile and have a high vulnerability to physical impact damage and are extremely slow growing, individual corals living to more than 4000 years. Such communities show a much lower resilience to physical impacts from, for example, bottom trawling than shallow-water communities where recovery may be much more rapid. In the case of physical disturbance to the environment, in general, habitats with high levels of natural variability or disturbance are less vulnerable and more resilient to impacts than those that typical show little variability over time (e.g. deep sea).

It is also important to note that benthic marine ecosystems often face multiple impacts. There may be interactions between impacts that mean the affects are additive or even synergistic whereby exposure to one impact increases vulnerability and lowers resilience to others.

There is also a large disparity in our knowledge of different benthic marine ecosystems. Some shallow-water marine ecosystems are relatively well studied and the impacts of human disturbance well characterised whilst only a fraction of the deep-sea has been explored and little is understood with regards to the significance of disturbance.

Mapping

One of the primary obstructions to interpreting the impacts of human activities on marine ecosystems is a lack of understanding of the distribution of marine populations, species and habitats. This is critical in determination of exposure of benthic communities to different human disturbances, and contributes to our understanding of their vulnerability and resilience. This is also a major impediment to ecosystem-based management of marine ecosystems as well as the selection of the location, number and area of networks of marine protected areas that will effectively conserve populations, species and habitats on the coasts and in the oceans. Identification of the location, spatial distribution and number of benthic observatories to achieve research objectives is also severely hampered without accurate bathymetry and maps of distribution of substrata and habitats. Whilst it is recognised that mapping the entire seabed is impractical, efforts should be made to improve on current levels of knowledge, especially where data are already present but perhaps require synthesis or just need to be made publically available. Certainly, it will be important to place observatories into context by mapping their immediate surroundings at a high resolution.

What can be measured, the known, unknown and unknowable?

Physical measurements

Temperature	Yes	High	CTD
Salinity	Yes	High	CTD
Oxygen	Yes	High	Optodes and other sensors
Currents	Yes	High	ADCP
Chlorophyll-a	Yes	High	Fluorimeters
Other pigments	Yes	Medium	?
Nitrate	Yes	Medium	Wet chemistry or UV (ISUS)
Phosphate	Yes	Medium	Wet chemistry
Silicate	Yes	Medium	Wet chemistry
Sulphate	Yes	Medium	Wet chemistry
pCO_2	Yes	Medium	SAMI & PROOCEANUS, MAP Moored autonomous pCO_2[1]
pH	Yes	Poor/medium	Microelectrodes (subject to drift), spectrophotometer (ULPGC – in development)
Alkalinity	No		
Methane	Yes	Poor	Prototype stage. Bubbles can Be detected with acoustics
Hydrogen sulphide	Yes	High	Wet chemistry, all species;

[1] Uncertain as to what depth current CO_2 sensors can operate

			Also microelectrodes.
Light	Yes	High	Short term only. Spectroradiometer. Problems with drift and biofouling.
Organic carbon	Yes	Medium	Raman spectroscopy
Pollutants	Yes	High	Mostly GC, ICPMS but electrochemical methods in development
Ambient sound	Yes	High	Hydrophones
Particles	Yes	High	Transmissometry, particle counters
Sediment grain size	Yes	Poor	Only manual, lab-based.
Hard substrata – size	Yes	High	Video, multibeam, TOAD, LIDAR
Biological measurements			
Species richness	Yes/No	Medium	Taxonomic microarrays for microbial or meiofaunal communities. Larger size fractions – periodic sampling or video (epifauna). Colonisation of artificial substrata
Biomass	Yes/No	Poor	Periodic sampling or video (epifauna). Colonisation of artificial substrata
Abundance	Yes/No	Poor	Periodic sampling or video (epifauna). Colonisation of artificial substrata. Sediment profiling camera or x-ray (shelled fauna only). Particle counts combined with FISH (microorganisms)
Population parameters (growth rates, longevity, death rates)	Yes/No	Poor	Periodic sampling or video (epifauna only). Colonisation of artificial substrata.
Fecundity	Yes/No	Poor	Periodic sampling.
Fertilisation success	Yes/No	Poor	Periodic sampling and laboratory experiments
Timing of reproduction	Yes/No	Poor	Video (epifauna), settlement panels or sediment trays, biochemical methods, sampling of larvae in water column

Recruitment	Yes/No	Poor	Video (epifauna), settlement panels or sediment trays
Respiration	Yes	High	Incubation chambers
Genetic diversity or structure	Yes	High	For metazoans only by Sampling. Microorganisms – taxonomic chips
Physiological condition	Yes/No	Medium	Colour or fluorescence is Useful in some cases (coral), biochemical methods, sampling and lab measurements of condition. Experimental chambers (max swimming speed, respiration)
Primary production	Yes	High	PAM, FRRF
Disease	Yes	High	FISH or arrays to detect specific taxa. Also qPCR etc.
Activity	Yes	High	Video (epifauna, surface bioturbation), sediment profiling cameras
Species interactions	Yes	High	Video (epifauna only)
Trophic structure	Yes	Medium	Video (epifauna only), periodic sampling (isotope, lipid, biomarker, stomach contents)
Calcification/decalcification	Yes	Medium	Measurements of growth, sampling to determine skeletal density
Bioerosion	Yes	Medium	Presence of bioeroding organisms
Import and export production			
Invasive species	Yes	High	Direct observation or Sampling, genetic detection
Biogeochemistry (microbially mediated nitrification etc.)	Yes	Medium	Ecogenomic chips

Priority observational programme

Carbon cycling in benthic ecosystems

There is very little understanding of the role of benthic ecosystems in the uptake and storage of carbon. Some marine ecosystems have a large potential for the storage of carbon including wetlands, extreme oxygen minimum zones and polar ecosystems. Understanding the fate of carbon in benthic ecosystems is key to understanding the impacts of climate change. There are potential positive and negative feedbacks to climate change from benthic ecosystems as a result of disturbance in the physical environment and biological communities of the ocean surface and water column. In addition, other human activities, such as deep-sea fishing also affect the function of benthic ecosystems through mechanical disturbance of the seafloor as well as removal of biomass from ecosystems. Studying the cycling of carbon in fished and non-fished systems is again and effective way to understand the ecosystem impacts of fishing. Finally, there has been wide discussion of the use of geoengineering as a means to draw CO2 out of the atmosphere. Many of these schemes have a large potential to affect benthic ecosystems with knock on impacts on key functions such as carbon cycling.

Studying variation and change in carbon cyling requires observatories producing a time-series of surface to seafloor measurements. Many of these measurements are of physical aspects of the environment but they also include measurements of biological communities because of their important role in mediating the uptake and ultimately storage of carbon (or not) in marine ecosystems. Species are important. Many of the human impacts on the oceans have the potential to change the diversity, abundance and biomass of marine organisms in ecosystems and such changes can result in significant shifts in the cycling of carbon in the benthos.

Such a science programme would have obvious policy relevance in terms of informing the IPCC and policymakers with respect to critical issues such as geoengineering and fishing.

In addition this project would target several key related issues and specific target ecosystems on the basis of their urgency with respect to the threat posed by current environmental change.

These include: coral reef ecosystems, ocean acidification, hypoxia, and ecosystem impacts of fishing.

Core set of measurements for seafloor observatories (complemented with water column measurements)

Available now:
Autonomous: Temperature, Salinity, pH, pCO_2, PAR, O_2, nutrients, chl-a (fluorescence), flux (sediment trap/SAPS – automated preservation of samples for DNA), PIC, DIC, optics (photo and video), acoustics, respiration and growth, H_2S, Si, Microbial genetic samplers, gene expression (e.g. nitrification), microarrays for analyses of expression of genes related to specific ecosystem functions (e.g. nitrification).

Note that it is currently not possible to sample many of the components of biological communities, especially the infauna, using remote observatories. Thus biological observatories would require, at least in the short-term, repeated sampling to assess species richness, biomass and abundance of benthic communities.

Repeat sampling: biomass, remineralisation, diversity, abundance to species level + others (see spreadsheet)

Future (within next 10 years): automated samplers for:
Full carbonate system, genetic profiler (mass sequencing), sediment profiler/in situ X-ray, automated habitat mapping, benthic fauna sampler including hard substrata (corer/drill and

suction for epifauna) + preservation for faunal analyses e.g. abundance/diversity; DNA) (NB. Require spatial sampling), pollutant sampler, CH_4,

Long-term
Mid-size benthic taxa: Image recognition of sediments for meio- macro- fauna
Shallow water: More accessible so less drive for funding/developing automated technology?

Benthic observatories would need to operate over multiple-scales and would require a multidisciplinary approach.

Combinations of:
-Moorings with fixed horizontal sensors + profilers (seafloor up)
-Seafloor stations: Landers (multidisciplinary core + guest experiments), Docking stations for mobile platforms e.g. AUVs, ROVs, gliders,

Infrastructure requirements
- Cables e.g. where r-t data, bi-directional flow (intelligent sampling) is essential and where cost-efficient e.g. shallow waters
- Harnessing power in deep-sea less accessible areas e.g. thermal power (chemosynthetic), current, redox
- More links/collaboration with other marine users for infrastructure/power? e.g. telecommunications cables (hubs/nodes for ocean observation)? E.g. oil/gas industry?

Distribution of observatories, key environments and issues

Where possible the aim would be to integrate with existing or already planned observatories. However, in some cases the science will demand development of new observatories.

Corals (Jessica Morgan)
Tropical (shallow): There is a planned network of coral observatories across the Pacific and in some parts of the Caribbean. However, some areas, notably the Indian Ocean require investment in new observatories. Examples would include the Chagos Archipelago and Reunion.

Global observation need to increase biological remote sensing: e.g. add a hyperspectral sensor to a government satellite for overview of coral bleaching and other environmental remote sensing applications.

Oxygen minimum and dead zones
The aim here would be to further explore carbon cycling in natural EOMZs as well as expanding dead zones. There would be a requirement for observatories to be placed along a transect from the surface to below the OMZ to investigate variation in the OMZ size at short to long timescales.

Target areas include: Man-made coastal regions e.g. Gulf of Mexico, Baltic, Marmara Sea
Natural e.g. N Arabian Sea, Peru/Chile margin,

Fishing
The aim would be to investigate the impacts of fishing on benthic marine ecosystems but with some focus on impacts on ecosystem function.

Observatories could be placed in existing protected areas and results compared with observations or observatories placed in fished areas (note the problem of fishing interactions with gear).

Areas may include: Rockall Bank vs. adjacent fished areas. Emperor Seamounts (Pacific) e.g. Koko seamount. Condor seamount (Azores), Corner Rise Seamounts, Graveyard seamount complex (N Zealand) – enhance/utilise existing time-series? Coral Seamount SW Indian Ocean (VPA)

Also key fisheries regions on continental shelves such as the NE and NW Atlantic, N Pacific.

Polar areas

Southern Ocean – key focus for geoengineering (Fe fertilisation) need a T-S observatory to inform? Address science Q's e.g. How will thermohaline circulation change
Central Arctic Ocean – key transition zone ice cover to open ocean
Irminger Basin/Labrador Sea/S. Ocean: key areas as CO2 sinks

Deep Sea

Chemosynthetic communities

- Chemosynthetic sites: Papua New Guinea, MAR, Fortuna SW Pacific, Endeavour (NE Pacific). Vulnerable/sensitive to environmental change e.g. O_2 and T concs.
- Cold seeps: Haakon Mosby Volcano, Gulf of Mexico, Gulf of Guinea

Abyssal plain

- Thermohaline circulation
  e.g. Antarctic changes in deep ocean
  e.g. Irminger Basin
- Monitoring of nodule areas likely to be mined – Clarion-Clipperton Fracture Zone.

Ocean acidification

-California current, Oregon: Ocean acidification issues
-Coral hotspots:
- Tropical: Great Barrier Reef, Chagos, Taiwan, Caribbean, Reunion (Corals: Tropical)
- Cold water: N. MAR (MPAs), Mediterranean, Florida (Oculina reefs), Rockhall (MPA) too shallow? Comparison site for deeper water, Porcupine Bank, NW Atlantic Gulley Corals: Deep/cold)

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Wetlands

Pristine vs. impacted areas including salt marshes, estuarine mud flats, mangrove forests. Many issues related to habitat destruction, pollution etc.

Other points

Such an observer programme would address many issues over a variety of timescales including:

Relationships between biodiversity and ecosystem function
Specific impacts of a variety of human disturbances
Identification of the ecosystem services provided by marine ecosystems
Specific policy advice related to ecosystem management.
Feed into discussions on the benefits of marine protected areas.

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