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Societal need for improved understanding of climate change, anthropogenic impacts, and geo-hazard warning drive development of ocean observatories in European Seas

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Abstract:

Society's needs for a network of *in situ* ocean observing systems cross many areas of earth and marine science. Here we review the science themes that benefit from data supplied from ocean observatories. Understanding from existing studies is fragmented to the extent that it lacks the coherent long-term monitoring needed to address questions at the scales essential to understand climate change and improve geo-hazard early warning. Data sets from the deep sea are particularly rare with long-term data available from only a few locations worldwide. These science areas have impacts on societal health and well-being and our awareness of ocean function in a shifting climate.

Substantial efforts are underway to realise a network of open-ocean observatories around European Seas that will operate over multiple decades. Some systems are already collecting high-resolution data from surface, water column, seafloor, and sub-seafloor sensors linked to shore by satellite or cable connection in real or near-real time, along with samples and other data collected in a delayed mode. We expect that such observatories will contribute to answering major ocean science questions including: How can monitoring of factors such as seismic activity, pore fluid chemistry and pressure, and gas hydrate stability improve seismic, slope failure, and tsunami warning? What aspects of physical oceanography, biogeochemical cycling, and ecosystems will be most sensitive to climatic and anthropogenic change? What are natural versus anthropogenic changes? Most fundamentally, how are marine processes that occur at differing scales related?

The development of ocean observatories provides a substantial opportunity for ocean science to evolve in Europe. Here we also describe some basic attributes of network design. Observatory networks provide the means to coordinate and integrate the collection of standardised data capable of bridging measurement scales across a dispersed area in European Seas adding needed certainty to estimates of future oceanic conditions. Observatory data can be analysed along with other data such as those from satellites, drifting floats, autonomous underwater vehicles, model analysis, and the known distribution and abundances of marine fauna in order to address some of the questions posed above. Standardised methods for information management are also becoming established to ensure better accessibility and traceability of these data sets and ultimately to increase their use for societal benefit. The connection of ocean observatory effort into larger frameworks including the Global Earth Observation System of Systems (GEOSS) and the Global Monitoring of Environment and Security (GMES) is integral to its success. It is in a greater integrated framework that the full potential of the component systems will be realised.

Highlights

► Societies increasingly depend on timely information on ecosystems and natural hazards. ► Data is needed to improve climate-related uncertainty and geo-hazard early warning. ► Observatory networks coordinate and integrate the collection of standardised data. ► Ocean observatories provide opportunity for ocean science to evolve.

Keywords: geological hazards, climate change, biological pump, biogeochemical cycles, ecosystem function, long-term changes, ocean observatory

1. Introduction

European researchers are developing a means to address a growing set of earth science questions that require a broad and integrated network of ocean and seafloor observation. The need to resolve patterns and processes across many time and space scales has pushed development of several earth and ocean observing programmes worldwide that integrate a variety of tools. Earth and ocean processes indeed operate on scales from a fraction of a second to decades or more (Fig. 1) and extend from the atmosphere to the sub-seafloor (Fig. 2). There is now wide recognition that research addressing science questions of international priority, such as understanding potential impacts of climate change or geo-hazards such as earthquakes and tsunamis, should be done in a framework that can effectively address questions across those scales (NRC 2000, Priede et al., 2003, 2005, Favali and Beranzoli 2006, Barnes et al. 2008).

In situ observation is essential to forming and revising experimental and model frameworks. Maintaining observation of key ocean science variables over long timescales with adequate temporal resolution has been challenging with many only lasting a few years or less. Marine time-series data constitute a minor fraction of existing data sets available for studying the climatic influences with very little data available from the deep sea (Glover et al. 2010). Measurements by research ship provide valuable information, but are limited to fairer weather conditions, and are too infrequent to characterise most processes, often neglecting important extremes. Even where time-series data sets have been available, between-site comparisons and larger-scale assessments have rarely been straightforward. Industrial activities and their impacts are nonetheless progressing into deeper waters where even basic processes are poorly understood. Estimating future ocean conditions requires improved scientific assessment of process limiting factors, particularly for ephemeral features. Enhanced integration of spatial and temporal process resesrch is also needed.

It is clear that more vigilant monitoring is necessary over longer durations and with greater continuity. The Intergovernmental Panel on Climate Change estimates that global warming will continue for centuries and will have pervasive impacts for society (IPCC 2007a, b). The international Group on Earth Observing (GEO), Global Earth Observation System of Systems (GEOSS), Global Ocean Observing System (GOOS), and OceanSITES are organisations and programmes that aim to bridge governmental, planning, and knowledge gaps. Existing European ocean observatories have begun to contribute to GEOSS and the Global Monitoring of Environment and Security (GMES) programme. Partnerships with industries already operating in European seas are also beginning to add breadth and quality to observation and logistical support. Site activity stretches from the Arctic Ocean near Svalbard to the mid Atlantic Ridge, and eastward through the Mediterranean to the Black Sea. Through hierarchical connections to GEOSS, observatories in these areas can integrate with coastal and terrestrial systems. Planning is now progressing in several areas with projects underway demonstrating how researchers, institutes, and industrial partners can work together on various network facets. The efforts include outlining objectives and design requirements, conducting research, standardising and augmenting existing systems, and addressing the logistical and governance challenges of developing the needed systems.

Human societies depend more and more on accurate and timely information on climate, weather, water, ecosystems, biodiversity, energy resources, and natural disasters. Here we outline major international science priorities in the four interconnected fields of geoscience, physical oceanography, biogeochemistry, and marine ecology, which will be advanced through observatory science. Efforts to outline relevant science objectives and design requirements have included the European Seafloor Observatory NETwork Concerted Action (ESONET CA; Priede et al. 2005), ESONET Network Implementation Model

(ESONIM), the Deep-Sea Frontier initiative (European Commission 2007), European Seas Observatory NETwork Network of Excellence (ESONET NoE), EuroSITES, and European Multidisciplinary Seafloor Observatory (EMSO) Preparatory Phase (Favali and Beranzoli, 2009), and the outputs of several other national and international ocean science projects and programmes (Table 1). These activities have been organising science requirement, logistical, fiscal, and legal aspects of building and operating dispersed ocean observatory networks.

With improved availability and consistency in measurements taken across European seas there will be a transformative shift in the ability to conduct cross-cutting science over a wide range of marine habitats. Proposed or active sites include those in abyssal plains, open slopes, seamounts, canyons, ridges, faults, fluid seeps, hydrothermal vents, gas hydrates, mud volcanoes, deep-sea corals, carbonate mounds, and potential geo-hazard zones. The sites also span the major biogeochemical provinces found in European waters (Fig. 3) with each site having more specialised science objectives depending on the setting.

Science objectives guide observatory design. *In situ* infrastructures include various arrangements like seafloor cables, moorings, landers, and vehicle systems. The modular designs being considered have two fundamental aspects with one addressing ‘core’ services like supply of data on temperature, salinity (conductivity), depth (pressure), and ocean currents and another that incorporates ‘specific’ data like seismicity, biogeochemical fluxes, and faunal abundances. The modular and expandable network can support highly specialised monitoring and experimental systems as needed. In order to address some objectives, fixed point systems will need support from satellites, climatic models, drifting floats, sea gliders, autonomous underwater vehicles, or the known distribution and abundances of marine fauna. Together these platforms provide a wide-ranging view of ocean dynamics over time and space.

Here we review science areas that relate to ocean observatory research and introduce some of the design concepts being considered. The broad-based approach to assessing the science objectives resulted in a vision of ocean observatories with substantial scope that is evolving ocean science in Europe. The integration of data from ocean observatory networks and other seismic, climatic and ecological systems in GEOSS and GMES has great potential to change the way in which researchers approach issues of great societal importance like climate change, natural resource utilisation, and environmental hazards.

2. Science Objectives

2.1 Geosciences

2.1.1 Seismicity

The solid earth holds many natural resources and its dynamics release massive amounts of energy in unpredictable ways. Intense geologic activity can result in catastrophic impacts on citizens, damage to offshore industry infrastructure, and ecosystem perturbations. Both earthquakes and submarine landslides can result in tsunamis with heights well above spring tide levels causing rapid flooding of coastal areas.

Earthquakes like those in Sichuan China in 2008 (M_w 8) and offshore Sumatra in 2004 (M_w 9.3) resulted in hundreds of thousands of lost lives and millions more displaced (Lay et al. 2005, Stone 2008). Tsunamis have also struck American Samoa in September 2009 killing more than one thousand people and displacing thousands more, and Chile in 2010 with loss of life and displacement. European earthquakes at the Western Hellenic Trench (365 AD), Eastern Hellenic Trench (1303 AD), Catania (1693 AD), Lisbon (1775 AD), and Messina (1908 AD) and their resulting tsunamis are among the most destructive in recorded history

(Boschi et al. 1997, Babtista et al. 1998, Piatanesi and Tinti 1998, Yalçiner et al. 2002, Tinti et al. 2004, Chester 2008).

The meeting of the Eurasian tectonic plate with African (Nubian) and Arabian plates along the southern Mediterranean, as well as the Eurasian and North American plates along the Mid Atlantic Ridge offer an opportunity to study solid earth processes across Europe (Fig. 4, Kreemer et al. 2003, Sgroi et al. 2007). In the Marmara Sea region there have been several recent earthquakes with the last of which was in 1999 that resulted in about 20,000 lost lives. The nature of the previous events in the Marmara Sea suggests that another major earthquake in the area is likely within the coming decades (Parsons et al. 2000, Parsons 2004). The Gulf of Corinth is another area of high seismic activity (Lykousis et al. 2007). Other European areas with major earthquake history include Italy, and even areas of France, the United Kingdom, Norway, and the Azores, Portugal have had contemporary activity greater than magnitude 5. The Aegean Sea has especially complex fault stress and resulting motions (Fig. 4B, Kreemer et al. 2003). Discerning plate subdivisions and fine scale motions can help to clarify kinetic links in seismic variations (Mantovani et al. 2007, Burrato et al. 2008). Although convergent, collision, and divergent spreading plate processes dominate the European area, transform sheer, and rotation also have importance. Seafloor spreading and associated submarine volcanoes, seismic activity, plate fracturing, hydrothermal venting, and diffuse fluid flow are all found in European seas.

2.1.2 Gas hydrate stability

Gas hydrates hold vast quantities of solid methane in marine sediments (Judd et al. 2002) and often outcrop in sloped areas (Paull et al. 2005). Seismic activity and warming can make gas hydrates unstable, which can increase slope instability and result in large releases of greenhouse gases that add positive feedback to global warming (Kennett et al. 2000, Mienert et al. 2000, Schmale et al. 2005, Greinert et al. 2006, Kessler et al. 2006, Archer 2007, Archer et al. 2009) and contribute to hypoxia in small semi-enclosed marine basins, such as the Iznit Gulf in the Sea of Marmara (Çağatay et al., 2008) and Gulf of Corinth (Marinaro et al. 2006). Active hydrate release is known to be occurring in the Black Sea, Mediterranean, Gulf of Cadiz, Nordic, and Arctic sites (Bohrmann et al. 2003, Woodside et al. 2006, Lykousis et al. 2009, Westbrook et al. 2009, Hustoft et al., 2009).

Ocean warming could have destabilising impacts on gas hydrate stability in areas where hydrates outcrop at the seabed, but few *in situ* data exist on hydrate disassociation dynamics. Gas emissions in the Arctic, an area projected to have relatively intense climate warming impacts, have already been documented (Fig. 5, IPCC 2007, Westbrook et al. 2009, Shakhova et al. 2009). Mechanisms for positive feedback between warming and release of methane have been described, but the lack of detailed observation limits budgeting (Judd et al. 2002, McGinnis et al. 2006).

Monitoring methane fluxes can aid in studying fluid-fault processes related to earthquakes (Görür and Çağatay, 2009), as can variation in sediment pore water pressure. Gas emissions related to active faults have successfully been mapped with acoustic methods in the Gulf of Corinth (Soter 1999) and Sea of Marmara (Géli et al. 2008). However, links between gas emissions, the seismic cycle and oceanic warming have to be understood more clearly (Etiope and Favali 2004). Preliminary results suggest it will be possible to test hypotheses related to systematic physical and chemical changes that occur throughout an earthquake cycle (e.g. Géli et al. 2008).

2.1.3 Seabed fluid flow

Fluid flow within and through the seabed transfers substantial amounts of mass, heat, and chemical energy and links to geophysical, biogeochemical, and ecological processes

(Tryon et al. 2001). Determining long-term variations in heat and chemical fluxes of hydrothermal vents will be valuable for balancing geothermal and oceanic heat and chemical budgets from carbon to trace elements (Fouquet et al. 1995, Cannat et al. 1999). The throughput of hydrothermal venting systems has been estimated to be comparable with other deep-ocean circulation turnovers with the entire volume of the ocean potentially being circulated through such systems every few thousand years (German and Von Damm, 2006). These vents act as a sink for magnesium and sulphate whereas Fe and reduced species of H_2, CH_4 and H_2S can be released in expelled vent fluids. This dissolved iron is believed to be an important source of iron for primary production in surface waters (Bennett et al. 2008, Tagliabue et al. 2010). The reduced species can provide important energy sources for chemosynthetic species often found at hydrothermal vents. Recent modelling results suggest that mid-ocean ridge vents may expel fluids for an average of around three years, but this remains to be validated (Coumou et al. 2008).

Abiotic synthesis of hydrogen occurs in vent systems suggesting potential for research on the production of natural hydrogen as a source of energy for fuel cells. Elevated concentrations of methane at Mid-Atlantic Ridge vents have been linked to the presence of mantle rocks exposed on the seafloor that are undergoing serpentinisation reactions. These discoveries show that the abiotic synthesis of hydrogen and hydrocarbons may occur in deep-sea environments in the presence of ultramafic rocks, water, and heat (e.g. Proskurowski et al. 2008).

Understanding fluid flow in deep-ocean sediments is important to the oil and gas industry for estimating production efficiency and averting unexpected dynamics in the behaviour of such fluids. Major uncertainty about behaviour of multiphase hydrocarbons in the deep sea remains including switches between solid, liquid, and gaseous states. The influence of dispersants used in accidents such as the Deepwater Horizon blowout in the Gulf of Mexico is also unknown. These uncertainties have hampered efforts to quantify the fate of oil and gas that leaked as a result of the accident (Camilli et al. 2010, Mezić et al. 2010). The efficacy of carbon capture and storage and implications for seabed fluid dynamics is also still in question (Shepherd et al. 2009, Blackford et al. 2009, Shaffer 2010).

2.1.4 Seafloor-water column interactions and Submarine landslides

Submarine landslides result in mass movements of material reshaping the seafloor, and can cause large tsunamis. Such slides can be caused by gas hydrate and seabed fluid stability and may be triggered by seismic events. Slides such as Nyk, Traenadjupet, and Storegga on the Norwegian margin are among the largest described (Mienert 2004, Mienert et al. 2004, Solheim et al. 2005, Micallef et al. 2008). The Storegga slide, for example, occurred off the central west coast of Norway about 8000 years ago and resulted in tsunami waves several metres high with devastating impacts as far south as the United Kingdom (Bondevik et al. 1997, Locat et al. 2003, Huhnerbach and Masson 2004).

Ridge crests, fjords, and submarine canyons are complex areas of sedimentary and fluid flow processes that influence the distribution and abundance of biogeochemical quantities and marine life (van Weering et al. 2002, Canals et al. 2006, St Laurent and Thurnherr 2007, Arzola et al. 2008, Bianchelli et al. 2008, Canals et al. 2009, Lastras et al. 2009). Changes in climate conditions, sea level, flooding, and seismic activity can transport large fluxes of fluids, sediment, and organic matter down slope (Christensen and Christensen 2003, Arzola et al. 2008, Leynaud et al. 2008). Measuring the evolution of seabed stability and sediment and organic matter transport processes offeres opportunities to improve geo-hazard understanding and constrains gaps in carbon budgets at the seafloor.

2.1.5 Geo-hazard Early Warning

Studies of geologically hazardous events ultimately aim to alleviate their impacts. Earthquake warnings of only minutes can make a major difference in the impact of hazardous events. Ocean and solid earth wave physics have achieved sufficient ability to locate emerging areas of fault activity and determine if the energy and characteristics of seismic events are hazardous. Semi-automated systems are basic components for the development of early warning systems providing policy makers with operational tools to reduce the impact on citizens living some distance away from the epicentre (Beranzoli et al. 2002, Blandin and Rolin 2005, Kanamori 2005, Frugoni et al. 2006, Lomax et al. 2007, Olivieri and Scognamiglio 2007).

New discoveries based on long-term, continuous monitoring should lead to improved probabilistic estimates of earthquake occurrence. As stress and instability accumulates detectable shifts in pressure, temperature, or chemistry of the porewater within sediments may be indicative of pending hazards such as earthquakes and slope failures (Berndt 2005, Micallef et al. 2008). High-resolution measurements should substantially aid in deciphering the factors that lead to earth motions and control geologic processes.

Currently less that 1% of the International Registry of Seismograph Stations operate below sea level even though the majority of Earth is covered by water several thousand meters deep. Furthermore only about 0.2% of these sensors are below 1000 m depth, none of which are located in European Seas (USGS, 2010). The integration of the European ocean observatory network with the European Plate Observing System (EPOS) infrastructure should prove transformational.

Tsunami warning systems have already been developed in the Pacific (Meinig et al. 2005) and Indian Oceans (GITEWS 2007). While such systems proved useful after the Chilean tsunami in 2010, wave height and arrival time models could not resolve if waves were hazardous after crossing the Pacific. This due in part to the fact that wave measurements used to build forecasts come almost exclusively from nearshore locations where waveforms differ from the open ocean. The Intergovernmental Oceanographic Commission programme Northeast Atlantic, Mediterranean and connected seas Tsunami Warning System (NEAMTWS) and the European Commission project Integrated Observations from Near Shore Sources of Tsunamis (NEAREST) are now planning for systems that will include open ocean nodes. The value of early warning systems is significant with tsunami wave heights that can reach well over 10 m in the Mediterranean Sea. As an example, the 1693 Catania earthquake caused the largest tsunami that flooded the coasts of Southern Italy with waves up to 13 m (Piatanesi and Tinti 1998; Tinti et al. 2004, Lorito et al. 2008).

Key questions in understanding and monitoring of geophysics:

Questions addressable with observatory systems:

- How can monitoring factors such as seismic activity, pore fluid chemistry and pressure, and gas-hydrate stability improve seismic, slope failure, and tsunami warning?
- What is the importance of oversteepening, storm and tide wave loading, sedimentation loading, gas charging, gas-hydrate dissociation, and fluid seepage in slope instability and failures?
- How rapidly can gas hydrate or other hydrocarbon reservoirs release large amounts of carbon into the atmosphere to potentially influence global climate or regional safety?
- Are there unidentified offshore areas of important seismic activity, active faults, plate separations, and plate subunits?
- What are the feedbacks between deformation, volcanism, seismic, and hydrothermal activity?

- What are the physical and chemical fluxes at hydrothermal vents and other regions of seabed fluid and chemical energy flow?
- What are the rates of abiogenic hydrogen and light hydrocarbon production from ultramafic outcrops found at mid-ocean ridges?
- What are the dynamics of mineral resource formation related to hydrothermal venting at mid-ocean ridges?

Questions addressable with additional data and contextual information:

- To what extent do seabed processes influence ocean circulation, seawater chemical composition, biogeochemistry, and marine ecology?
- How does the presence of fluid within submarine faults change their dynamics relative to terrestrial fault zones?
- How might any changes in terrestrial hydrology lead to changes in marine sediment transport and deposition?

2.2 Physical Oceanography

2.2.1 Ocean Warming

One of the most pressing issues in ocean science today is assessing the impacts of global change on the marine environment, which will likely be long lasting (IPCC 2007a, Doney and Schimel 2007). Significant shifts in ocean heat (Levitus et al. 2000, Barnett et al. 2005, Palmer et al. 2007) and freshwater (Curry and Mauritzen 2005, Boyer et al. 2007) content are already apparent. Mediterranean Intermediate Water (MIW) entering the North Atlantic is warming and becoming more saline (Millot et al. 2006). Continued warming is anticipated to increase stratification in large areas of the ocean including the North Atlantic (Bopp et al. 2005, Marzeion et al. 2010). Related changes to heat content, wind stress, and circulation across European seas are also likely with cascading impacts into biogeochemistry and ecology.

Reduction of ice cover in the Arctic Ocean is occurring and expected to continue with high certainty (IPCC 2007a). Major associated changes in the hydrographic structure of the Arctic waters are expected. Melting sea ice and glaciers can lead to freshwater anomalies, changes in surface-ocean currents, positive feedback between changes in albedo and warming, and destabilisation of gas-hydrates in marine sediments. Changes in physical and biogeochemical conditions are already evident (Soltwedel et al. 2005, Hoste et al. 2007, Westbrook et al. 2009), but current estimates on the ultimate impacts have relatively low certainty (IPCC 2007a, MCCIP 2010).

2.2.2 Wind-Driven Circulation

Upper ocean momentum, heat and freshwater fluxes drive ocean transport and stratification (mixed layer dynamics) which in turn controls the interior ocean supply of substances as carbon dioxide, methane, oxygen, and nutrients. These processes are crucial for marine ecosystems functioning (Woods 1985, Joyce et al. 2000, Fasham 2003, Sarmiento and Gruber 2006, Våge, et al. 2009). Observing upper ocean transport and properties underpin assessing the role of the ocean in the climate system and understanding the oceans ecosystem function with relevance from sub-millimetre to basin scale. Winds in the North Atlantic affect circulation to depths of 1000 meters or more with substantial seasonal and interannual variability (Siegel et al. 2002, Palter et al. 2005). Oceanic flow is turbulent and as such the “mean flow” is masked by, sometimes long life, mesoscale and submesoscale (<10km) eddies with local dynamics that generate a significant feedback on marine ecosystems (Puillat et al. 2002, Taupier-Letage et al. 2003).

Wind-driven circulation is sensitive to climate variation. The North Atlantic Oscillation (NAO) dominates interannual climate variation around Europe and tends to bring changes in position and intensity of the North Atlantic atmospheric jet stream which in turn is associated with changes in winds, cloudiness, storms, precipitation, and heat flux (Hurrell 1995, Rodwell et al. 1999, Visbeck et al. 2001, Hurrell et al. 2003) and the functioning of the marine ecosystem (Greene et al. 2003, Sarmiento et al. 2004, Smith et al. 2006, Henson et al. 2009). Decadal scale shifts in North Atlantic surface currents suggest that warmer subtropical waters are increasingly moving northward (Hakkinen and Rhines 2009). The degree to which interannual to decadal climate variability and NAO affects seasonal cycles is not yet clear.

2.2.3 Deep-Ocean Circulation

The North Atlantic hosts the major deep convection regions of the northern hemisphere. In particular the formation and spreading of North Atlantic Deep Water (NADW) is of crucial importance for the stability of the meridional overturning circulation (MOC) and global climate. Variations in convection depth and water mass characteristics in the deep water formation regions have been observed (Pickart et al. 2003, Karstensen et al. 2005, Avsic et al. 2007, Sarafanov et al. 2008). Evidence for deep propagation of warming has been reported to at least 2000 m depth in the Atlantic Ocean (Fig. 6 and 7, Østerhus and Gammelsrød 1999, Dickson and Østerhus 2007, Johnson and Doney 2006, Zenk and Morozov 2007) and worldwide (Johnson and Doney 2006, Fukasawa et al. 2004, Kawano et al. 2006, Johnson et al. 2007, 2008). Deep-ocean ventilation is influenced by surface momentum and heat flux variability and linked to the North Atlantic Oscillation (NAO) variability (Dickson et al., 2002; Sarafanov, 2009). Also more local phenomena, such as ice extent (Våge, et al. 2009), and local heat and momentum fluxes (Pickart et al. 2003) control deep-water formation and circulation (Cunningham et al. 2007).

Clarifying what controls MOC variability is fundamental to assessing climate change impacts. A rapid decrease in the poleward transport of warm surface water in the North Atlantic could have devastating impacts on European climate with substantial regional cooling (Hansen et al. 2001, Vellinga and Wood 2002, Hansen et al. 2004, Hátun et al. 2005, IPCC 2007a), as well as changes in sea level (Yin et al. 2009). Large seasonal variability requires long-term and basin wide monitoring of MOC to detect any possible trend, as for example with the 26°N RAPID array (Cunningham et al. 2007, Kanzow et al. 2007, 2008). The confidence with which future projections on this important heat transport mechanism can be made, though, remains relatively low (IPCC 2007a, Kuhlbrodt et al. 2007, MCCIP 2010, Rhines et al. 2008, Stott et al. 2008) and observational evidence is required.

The complex interplay of wind and buoyancy-driven circulation and the MOC makes quantifying the importance of changes in water density, wind, and mixing challenging (Toggweiler and Samuels 1995, Jayne and Marotzke 2001, Talley 2003, Sarmiento et al. 2004, Boccaletti et al. 2005, Rhines 2006, Sarmiento and Gruber 2006, Killworth 2008, Rhines et al. 2008, Grist et al. 2009, Josey et al. 2009). Positive phases of the NAO, for instance, have been shown to be related to greater MOC over interannual to decadal timescales (Eden and Greatbatch 2003). A study forced by IPPC climate scenario A2 suggests that Mediterranean thermohaline circulation (MTHC) is also susceptible to long-term shifts in climate (Somot et al. 2006). Transient climate forcing, wind-driven and deep-water circulation can relate to planetary wave motions, manifested as slow moving surface and internal waves. These waves have lengths of hundreds to thousands of kilometres, can take months or years to cross an ocean basin, and have been related to NAO and MOC variation (Cromwell 2006, Hirschi et al. 2007).

2.2.4 Benthic-Water Column Interactions

Direct current measurements are rare and very few include seabed boundary conditions. The seafloor acts as a boundary and how water adjacent to the seafloor interacts with the rest of the ocean is poorly known. Near-bottom flow often driven by tides and density gradients can be complex. Interaction with topography as seamounts, ridges, and sills (Vergnaudgrazzini et al. 1989, Polzin et al. 1997, Munk and Wunsch 1998, Bashmachniko et al. 2004, Lauderdale et al. 2008, Dickson et al. 2008, Fer et al. 2010) create complex flow patterns that can be an important supply pathway for deep sea ecosystems (Davies et al. 2009)

Sediment laden runoff, dense shelf water, and entrained organic matter can cascade down slopes and become focused in canyons (Canals et al. 2006, Arzola et al. 2008, Canals et al. 2009, Lastras et al. 2009). This process has been observed in several areas around European seas, such as the Gulf of Lion, where changes in the North Atlantic Oscillation have had documented influences on organic carbon transport and a deep-sea fishery (Canals et al. 2006, Company et al., 2008, Maynou, 2008, Canals et al. 2009). Combined bathymetry and measurement of time-variant water flow and character has begun to describe this sequence of processes in substantially greater detail (e.g. Borenäs and Lundberg 2004, St. Laurent and Thurnherr 2007). The way in which the slow moving planetary waves interact with the bottom is not well described and long-term observations of wave oscillation are needed (Lecointre et al. 2008). The potential for long-term monitoring of such interactions is great with current observatory systems able to discriminate between various water masses by their various chemical and physical properties (Etiope et al. 2006).

2.2.5 Marine Forecasting

The socioeconomic interest in maritime safety in relation to transportation, pollution, search and rescue, and minimising consequences of natural hazards all require observations of ocean physics. At the OceanObs’09 conference there was extraordinary consensus that data from the deep ocean including from fixed points and moorings are among the greatest observational needs remaining (Dushaw et al. 2010, Garzoli et al. 2010, Hurrell et al. 2010, Lampitt et al. 2010, Rintoul et al. 2010, Trenberth et al. 2010). Forecast quality relies on the observations used to constrain models. Satellite retrievals provide as suite of important ocean and atmosphere input data to initialise the ocean surface. About 3000 Argo profiling floats provides *in situ* temperature and salinity observations to estimate the heat and freshwater variability in the upper 2000 m of the oceans every 10 days (Roemmich and Owens 2000). Upper ocean moored arrays in the tropical oceans, such as the Tropical Atmosphere Ocean (TAO) array in the equatorial Pacific Ocean (McPhaden and Picaut 1990) or the “Prediction and Research Moored Array in the Atlantic” (PIRATA, Boulres et a. 2008) have been found crucial for ocean forecasting Recent observing system evaluation has shown that both drifting floats and moorings contribute important forecast skill (e.g. Balmaseda and Anderson 2009).

Observatory systems that can simultaneously collect temperature and salinity for the full ocean depth, as well as collect related data such as currents, biogeochemical and ecological quantities, and physical samples are an important tool alongside others such as drifting floats. Long time series of data are of tremendous use when it comes to the validation of model results. Timely ocean physics data is important for monitoring and predicting of pollution in areas of maritime traffic (e.g., the Sea of Marmara, Alboran Sea, Bay of Biscay, or Strait of Gibraltar) where accidents and resulting pollution of oil and hazardous substances occur, such as the sinking of the oil tanker Prestige.

Key questions in physical dynamics and impacts from anthropogenic change:

Questions addressable with observatory systems:

- How does ocean heat and freshwater content change over time and how might it impact sea level?
- How rapidly do natural and anthropogenic changes in surface ocean conditions influence deep-sea water masses?
- What are the possible impacts of shifts in deep-water mass character?
- How will projected changes in the extent of Arctic sea ice, or ocean circulation influence regional and global climate, European or global ocean circulation, and biogeochemistry?
- What is the influence of climate variability on upper-ocean circulation and nutrient supply and how might anthropogenic change alter that circulation?
- How do waters within and above the benthic boundary layer interact?
- How do bathymetric features like canyons, valleys, and seamounts influence current directions and speeds and mixing from tidal scales to planetary wave motions?

Questions addressable with additional data and contextual information:

- How stable is deep-ocean circulation and mixing and what controls its variability?
- How can better understanding of slow moving planetary waves be used to clarify the often time-lagged connections between climate and oceanographic processes?
- How can eddies, fronts, and other smaller-scale features be better resolved and included in larger scale assessments?
- What is the importance of precipitation, river run-off, storms, tides and internal waves and other circulation features in resuspension and transport of sediment and its biogeochemical constituents?
- How do regional and local circulation processes interact with global climate variation?
- How does the sparseness of data below 2000 m depth influence current ocean modelling estimates?

2.3 Biogeochemistry

2.3.1 Solubility Pump and Ocean Acidification

About one third of anthropogenic carbon dioxide emitted into the atmosphere is thought to be taken up by the oceans through chemical and biological pathways (Sabine et al. 2004, Canadell et al. 2007) with major uptake in the North Atlantic. The process is driven by the combined effect of solubility differences between the atmosphere and ocean and the movement of dissolved carbon in ocean circulation. Present day increases in atmospheric carbon dioxide are partly being absorbed into the relatively lower partial pressure carbon dioxide surface ocean (Takahashi et al. 2002, 2009). Declining uptake of anthropogenic carbon dioxide by the ocean could increase the proportion that accumulates in the atmosphere. Research has suggested that natural sinks of carbon dioxide are already decreasing their uptake rates (Shuster and Watson 2007).

The solubility pump influences carbonate and pH dynamics, and absorbed carbon dioxide is then available to phytoplankton and the biological pump. Anthropogenic emissions of carbon dioxide appear to be increasing in rate relative to its oceanic uptake (Bindoff et al. 2007). Current techniques measuring carbon uptake in the ocean and related quantities, though, have an inadequate sensitivity to temporal variations (Gruber et al. 2009).

Increased carbon dioxide flux into the ocean is already leading to global secular acidification (Fig.8, Feely et al. 2004, Orr et al. 2005, Raven et al. 2005, Fabry et al. 2008, Feely et al. 2008). Ocean acidification is expected to continue for centuries and is a well constrained process in a variety of model scenarios, but the impacts from lowering pH are much less clear (IPCC 2007a, Zachos et al. 2008, Zeebe et al. 2008). Many marine organisms including calcifying primary producers, molluscs, and corals could be impacted (Orr et al. 2005, Hoegh-Guldberg et al. 2007, Tyrrell 2008). The depths at which calcium carbonate (calcite and aragonite) dissolve may change, as might the burial rates for calcium carbonate (Tyrrell 2008). The ability of organisms to calcify and the bioavailability of trace metals may deminish (Tyrrell 2008, Raven et al. 2005). Acidification is also increasing sound propagation (Hester et al. 2008) with unknown consequences for mammals.

The potential for unforeseen feedbacks in biological responses to acidification is considerable. Several experimental studies have found detrimental effects of increased acidity on calcification in coccolithophores (Riebesell et al. 2000, Zondervan et al. 2001, 2002, Herfort et al. 2004, Delille et al. 2005, Engel et al. 2005, Trimborn et al. 2007), but conflicting outcomes have also been found (Langer et al. 2006, Iglesias-Rodriguez et al. 2008). Deep-ocean pH may change at depth specific rates (Dore et al. 2003). Modelling work has found that it was not yet possible to forecast calcification-related trends conclusively because of the range in suggested possibilities (e.g. Ilyina et al. 2009).

Laboratory based experiments to discern potential impacts of changing pH conditions typically need *in situ* verification because pH influences many reactions. Time-series data on changes in acidification dynamics are rare and fewer still directly examine pH from decadal to seasonal scales. Results from the European Project on OCean Acidification (EPOCA) programme already suggest that comparable results in a broad spatiotemporal context are needed to foster more conclusive forecasts.

2.3.2 Biological Pump

Surface phytoplankton take up inorganic nitrogen, phosphate, silicate, and carbon dioxide during photosynthesis and a fraction of the resulting particulate matter sinks into the ocean depths as phytoplankton, fecal pellets, and other detritus forming the biological pump (Fig. 2, Volk and Hoffert 1985, Ducklow et al. 2001, Buessler et al. 2007). Ocean currents and nutrient supply are often tightly coupled to phytoplankton primary production (Fig. 9). Winds drive coastal and open-ocean upwelling which tend to bring nutrient rich water to the surface and enhances productivity with documented variations through decadal scales (e.g. Rykaczewski and Checkley 2008). Interannual variations in production have been associated with the depth of winter mixing (e.g. Somavilla et al. 2009). Seasonal drawdown of carbon dioxide in the North Atlantic has been linked to the biological pump (Körtzinger et al 2008).

Increasingly complex ocean movements further complicate estimation of pump dynamics. Eddies like those that spin off of the Gulf Stream in the North Atlantic are important in influencing plankton blooms as these eddies change local-regional circulation and nutrient availability (Taupier-Letage et al. 2003, McGillicuddy et al. 2007, Bashmachnikov et al. 2009, Smythe-Wright et al. 2010). The effects of large planetary wave motions and NAO variation are linked to chlorophyll concentrations (Mete Uz et al. 2001, Henson et al. 2009). A slowing of the MOC may slow nutrient replenishment resulting in reduced carbon dioxide uptake with a positive feedback to raising carbon dioxide accumulation rates in the atmosphere (Zickfeld et al. 2008).

Nitrogen is the most limiting nutrient in European seas with silicon, phosphorus, and iron also being important. Current methods cannot balance nutrient sources and losses and the spatiotemporal importance of specific nutrients continues to be redefined. Over the past few thousand years it has been suggested that nitrogen budgets have oscillated between net surpluses and deficits forced by climate (Altabet 2007). The supply of nutrient rich water from deeper waters can influence carbon dioxide uptake, even when surface nutrient concentrations show no synoptic variation (e.g. Marinov et al. 2008). Approximately 10% of the oceans ability to absorb anthropogenic carbon dioxide may be facilitated by atmospheric nitrogen deposition (Duce et al. 2008). Nitrogen fixation by diazotrophic phytoplankton, like cyanobacteria, facilitates production in areas of low nitrogen (Capone et al. 1997, Falkowski et al. 1998), and may account for about half of nitrate use (Yool et al. 2007). Model simulations suggest, though, that such biological fixation may not be as dominant in the North Atlantic as in the Equatorial Pacific (Deutsch et al. 2007).

Diatoms depend on silicate to form their frustules and are often an important part of carbon export to deeper depths (e.g. Allen et al. 2005, Henson et al. 2006a). Seasonal blooms of diatoms may account for 65% of exported production in the Irminger Basin, but typically consume silica during spring blooms and subsequently decline in abundance relative to other phytoplankton (Henson et al. 2006a). Fronts and eddies that continue to provide new silicate through mesoscale circulation can, however, prolong diatom blooms and export (Allen et al. 2005, Benitez-Nelson et al. 2007).

Phosphorous can limit primary productivity and microbial production in the eastern Mediterranean Sea (Krom et al. 1991, 2010). Coccolithophores, Trichodesmium, and Synechococcus appear to be sensitive to phosphorus (Vaulot et al. 1996, Lessard et al. 2005, Dyhruman et al. 2006). Nitrogen and phosphorus could be important for heterotrophic bacteria, even when carbon substrates are available and thus may have competitive interactions with phytoplankton (Mills et al. 2008), and phosphorus and iron could also be important co-limiters of nitrogen fixing phytoplankton (Mills et al. 2004, Arrigo 2005, Moore et al. 2008, Bucciarelli et al. 2010).

Variation in dust inputs primarily from the Saharan and Sahel desert regions (Duce and Tindale 1991, Stuut et al. 2005) add iron and other limiting nutrients (Martin and Fitzwater 1988, Boyd et al. 2007) and influence iron binding ligands in surface waters within about one week (Jickells et al. 2005, Rijkenberg et al. 2008). Up to one third of global dust inputs may occur through this route (Jickells and Spokes 2001). Transient iron limiting conditions have been found in the North Atlantic (Nielsdóttir et al. 2009). More aerosols, though, may not equate to greater productivity because of taxon-specific impacts of aerosol inputs including dust (Payton et al. 2009). Variation in the NAO has been linked to deposition of iron and aluminium in the North Atlantic, but these links remain to be characterised in detail (Tain et al. 2008). The source of aerosol iron can affect its solubility in seawater and thus influence nutrient limitation (Sedwick et al. 2007). Hydrothermal vents may supply 12-22% of the global dissolved iron in deep waters (Bennett et al. 2008, Tagliabue et al. 2010). Proposals to augment the ability of the ocean to store carbon through ocean iron enrichment or other fertilizers rely on an inadequate understanding of the effectiveness, impacts, and potential feedbacks from such enrichments (Boyd et al. 2007, Buesseler et al. 2008, Lampitt et al. 2008, Shepherd 2009, Yool et al. 2009).

Production and export flux from the surface have important variations which are often not well accounted for in models (Buesseler et al. 2007). The portion of surface production that is transferred to the deep sea has been hypothesised to be related to surface temperature, mineral and polymer content, and zooplankton. Greater recycling of material may occur at higher temperatures in the euphotic zone resulting in proportionally less export (Laws 2004). The mineral content and overall character of sinking phytoplankton is further thought to be important because denser and more protected material is more efficiently transported to deeper depths (Armstrong et al. 2002, Burd and Jackson 2002). The presence of transparent exopolymeric particles (TEP) has been shown to be related to aggregation and sinking rates (Alldredge et al. 1993). Increasing carbon dioxide and ocean acidity could have important implications on sinking rates modulated by TEP (Mari 2008) and mineral content. Zooplankton can consume and modify even smaller pico-phytoplankton into fecal pellets with faster sinking rates (e.g. Richardson and Jackson 2007).

2.3.3 Continental Shelf Pump

Continental shelves are highly productive environments and some portion of the carbon taken up by solubility and biological pumps on the shelf ultimately is exported laterally into deeper waters where it can become sequestered for decades or more (e.g. Bauer and Druffel 1998). The mechanisms and magnitudes of these transfers are still under debate, but could represent about 25% of the total carbon uptake of the ocean (Chen and Borges 2009). It is believed that much of the fixed carbon is ultimately remineralised to carbon dioxide on the shelf and is then carried to the shelf break in sub surface currents where it cascades into deeper waters (Fennel and Wilkin 2009, Holt et al. 2009, Huthnance et al. 2009). Because these mechanisms relate to such a large part of the oceanic carbon cycle, conclusively determining continental shelf pump processes and the long-term fate of carbon moving through these mechanisms should improve carbon cycle estimates. Open-ocean observatory systems that integrate with those developing for coastal and shelf research are expected to be able to further characterise the timing, intensity, and fate of pumping that is transporting carbon and nutrients across these ocean regions.

2.3.4 Deep-Ocean Biogeochemical Fluxes

Evaluating surface and deep-sea variations in fluxes synoptically connects the short-term and long-term capability of the ocean to take up and store carbon. Sinking organic carbon and other elements provide the primary food supply for deeper dwelling organisms. Organisms respire or otherwise transform the sinking material resulting in the gradual breakdown of most organic matter into its constituent compounds, a process known as remineralisation (Deuser and Ross 1980, Pace et al. 1987, Pfannkuche et al. 1999, Smith and Kaufmann 1999, Lutz et al. 2002, Ståhl et al. 2004). When oxygen utilisation rates exceed the long-term replenishment of oxygen from surface waters oxygen minimum zones (OMZs) can develop between 100 and 900 m depth (Karstensen et al. 2008, Stramma et al. 2008). The combined effects of increasing carbon dioxide and decreasing oxygen could lead to greater negative impacts on organism respiration than from oxygen decline alone (Brewer and Peltzer 2009), especially in OMZ areas such as east of Cape Verde in the North Atlantic.

Long-term Time-series data from abyssal depths comes from only a few locations, so addressing various areas of uncertainty simultaneously has been difficult (Lutz et al. 2002, Honjo et al. 2008, Glover et al. 2010), but some surprising results have been found. Variations like the NAO and ENSO have far reaching affects that include changes in gas and heat flux, ocean circulation, primary productivity, and the efficiency with which surface production is transferred to support deep-sea life (e.g. Cayan 1992, Wade et al. 1997, Ruhl and Smith 2004, Behrenfeld et al. 2006, Smith et al. 2006, Thomas et al. 2008, Henson et al. 2009, Billett et al. 2010, Lampitt et al. 2010). Year to year variability in the quantity and quality of particulate organic carbon (POC) fluxes to the abyssal seafloor can be as much as an order of magnitude in the Northeast Atlantic (Hartman et al. 2010, Lampitt et al. 2010). The efficiency of the transfer of carbon from surface waters to the deep sea is known to vary in space and time (Lampitt and Antia, 1997, Lutz et al. 2002, Laws 2004, Dore et al. 2003, Hartman et al. 2010, Lampitt et al. 2010).

There are major unexplained imbalances between the estimates of downward flux of organic matter and the rates of organic matter remineralisation at the seafloor (Smith and Kaufmann 1999, Smith et al. 2001, Smith et al. 2008a). These imbalances could be a result of unobserved lateral transport of organic matter or insufficient spatial or temporal resolution of measurements. Lateral transport can result, in part, from organic matter transported off continental shelves down slopes or through bights and canyons (Canals et al. 2006, Test et al. 2008). Some model scenarios show that shelves may be the source for up to almost half of the organic carbon that accumulates in deep-sea sediments (Dunne et al. 2007). Water near the seabed often forms a benthic boundary layer containing resuspended material tens of meters or more above the seafloor at abyssal depths (Baldwin et al. 1998).

Because circulation between the boundary layer and adjacent and overlying water is so poorly known the degree to which the entrained material can be transported is unknown further confounding the above mentioned lack of knowledge in organic matter transport in the deep sea. Current sedimentation traps may under sample sinking POC, especially aggregates that contain important quantities of sinking carbon (Baldwin et al. 1998, Robison et al. 2005, Smith et al. 2008a). A 17-year study in the Northeast Pacific found that even when accounting for presumed under sampling, perceived deficits in carbon inputs often remained (Smith et al. 2008a).

Assessing connections between the upper ocean and deep seafloor need improved estimates of when and where particles reaching deep-sea habitats originated, as well as what controls seafloor settling. Organic material reaching any particular point in the deep sea is generally believed to come from a funnel volume overlying the destination (Siegal and Deuser 1997). Long-term sedimentation trap records in conjunction with contemporary water velocity meters and satellite estimated surface conditions can be used to back track the potential origins of particles (Smith et al. 2006, Siegel et al. 2008, Hartment et al. 2010), but these techniques have yet to be widely applied.

Key questions in biogeochemical dynamics and impacts from anthropogenic change:

Questions addressable with observatory systems:

- What are oceanic carbon and greenhouse gas uptake and storage dynamics and how might anthropogenic change alter the efficiency of the biological pump?
- What aspects of marine biogeochemical cycling will be most sensitive to climate change?
- What are the biogeochemical implications of oxygen minimum zone intensification including changes in oxidation potential and hypoxia?
- Are observed deficits in organic carbon input vs. respiration linked to timescales of observation, basin selectivity, or to lateral transports of organic particles?
- What will the important feedbacks of potential ecological change be on biogeochemical cycles and how rapidly might they occur?

Questions addressable with additional data and contextual information:

- How will changes in atmospheric dust deposition rates influence ocean biogeochemistry?
- What quantities of sediment, nutrients, and/or organic material are transported in deep currents and turbidity flows and how does this transport vary?
- To what degree are terrestrial, coastal and slope regions influencing open-ocean biogeochemical quantities including potentially harmful contaminants?
- What will the intensity and distribution of ocean acidification be, and how will changes in acidity affect the bioavailability of trace metals important to primary production, marine life, and biogeochemical cycling?

2.*4 Marine Ecology*

2.4.1 Climate Forcing of Ecosystems

Evaluating the sensitivity of ecosystem function to anthropogenic change is a major marine science challenge of the coming decades (Sutherland et al. 2006). Life exists within environmental and resource constraints, most of which are hardly known. Marine organisms are influenced by their environment, and can exert strong feedbacks to their physical and chemical surroundings. Ecological change due to global warming and carbon dioxide accumulation in the ocean could have numerous repercussions when compared to terrestrial systems (Richardson 2008). Yet datasets capable of observing climatically-driven changes in marine biology are rare with very few capable of discerning between interannual and decadal variations and secular change (Rosenweig et al. 2008). The need to quantitatively assess the role of ecosystems as anthropogenic change progresses is driving ecosystem function to gain importance in ecology.

Manifestations of climate influence include synchronised variations between neighbouring local areas, temporal correlations between climate and ecological quantities, time lagged correlations, phenological shifts, and match-mismatches between co-dependent phenomena (Moran 1953, Stenseth et al. 2002, Royama, 2005). Temporal phenomena have spatial analogues where match-mismatchs could be a result of shifting distributions. When key elements of food webs are destabilised, effects can cascade to other food web elements, trophic levels, and ecosystem functions.

Climate can influence primary production from daily to decadal scales and longer (Kahru and Mitchell 2002, Behrenfeld et al. 2006, Heath and Beare 2008). Contemporary warming has been implicated in pelagic community change (e.g. Field et al. 2006) and an overall decline in the abundance of primary producers, including the north Atlantic (Boyce et al. 2010). Climate-driven changes in the nature of primary production can have cascading impacts (McGowan et al. 1998, Parsons and Lear 2001, Chavez et al. 2003, Attrill and Power 2004, Green and Pershing 2007, Rykaczewski and Checkley 2007). North Atlantic storm frequency may delay stratification leading to match-mismatches between light and nutrients thus diminishing production (Henson et al. 2006b). Mis-matches can then cascade to zooplankton and fisheries (Edwards and Richardson 2004, Richardson and Schoeman 2004, Piontkovski et al. 2006, Koeller et al. 2009). Connections between climate and ecological systems can be subtle and complex, but result in pervasive responses to abyssal depths (e.g. Billett et al. 2001, Ruhl et al. 2008).

2.4.2 Molecules to Microbes

Research in microbial oceanography regularly reveals fundamental knowledge. Marine viruses have been found to be very abundant with cell lyses influencing biogeochemistry (Azam et al. 1983, Fuhrman 1999, Azam and Long 2001) potentially limiting prokaryotic production in the deep sea (Danovaro et al. 2008a). Extracellular DNA in marine sediments, believed to be remnants of surface production, may account for 14-21% of phosphorus cycling in the deep ocean (Dell'Anno and Danovaro 2005) and harbour gene pools (Rohwer and Thurber 2009). The extent to which viruses influence the deep sea, though, remains to be confirmed (Williamson et al. 2008). The balance of production and respiration in the sea has also been questioned when microbial rates are accounted (del Giorgio et al. 1997). Evidence from Argo floats suggests that deficits were perceived because oxygen production is more episodic in space and time than previously thought (Riser and Johnson 2008).

Consensus on net respiration has, however, yet to be achieved. Dissolved organic carbon (DOC) is abundant in the ocean and likely accounts for some of the observed discrepancies between observed sinking POC fluxes and carbon demand (Burd et al. 2010). DOC, which is not accounted for in sinking POC flux estimates, is modified by microbes throughout the water column into relatively refractory forms through processes including respiration. New findings about the prevalence of chromophoric dissolved organic matter (CDOM) in surface waters require further attention partly because its presence is important in determining productivity from satellite ocean colour data (Nelson et al. 2007).

New natural products and drug discovery efforts frequently utilise specimens collected from a variety of unusual habitats (Fenical 1982). Specimens collected during observatory operation in extreme environments have potential for cancer, antibacterial, and enzymes. A common challenge in natural product exploitation is that once key compounds are identified, they may be difficult to produce (Baran et al. 2007). Linking sample collecting to comprehensive ecological observations should improve capability for producing valuable natural products commercially.

In situ metagenomics, or the links between genes and their environment and function, will likely reveal important metabolic aspects not otherwise discernable because many microbial fauna are not yet cultured in laboratory settings. It is now possible to collect molecular probe data that is processed *in situ*, in real time (Paul et al. 2007). *In situ* microbial community data will increase ability to discern if microbes have similar tendencies of community assembly and structuring found elsewhere in ecology (Hewson et al. 2006, Ruan et al. 2006, Horner-Devine et al. 2007, Fuhrman and Steele 2008, Fuhrman et al. 2008). Metagenomic sequencing and community fingerprinting are poised to improve understanding of microbial oceanography (Sogin et al. 2006, Karl 2007, Bowler et al. 2009, DeLong 2009, Fuhrman 2009). Within Europe coordination between Marine Genomics Europe, and LIFEWATCH, the European infrastructure for biodiversity data and observatories, are preparing microbial observatory users to make needed advances.

2.4.3 Fisheries

Sustainable fisheries management depends on informative estimations of nutrients and production conveyance to higher trophic levels of fished stocks. Partitioning climatic drivers from fishing pressure has major implications for managing sustainable fisheries into the future because of the growing potential for errors in asserting the causes of variations. Evidence of climate influence on fisheries is extensive in the North Atlantic (Beaugrand et al. 2003, Erzini 2005, Santos et al. 2005, Stige et al. 2006), Mediterranian (Company et al. 2008, Maynou 2008) and Pacific (Catchpole and Auliciens 1999, Hare and Mantua 2000, Chavez et al. 2003, Rykaczewski and Checkley 2007). The effects of fisheries in surface waters could extend thousands of meters below the surface (Drazen et al. 2008, Bailey et al. 2009). Fished populations are thought to be especially susceptible to climate related change because of cascading match-mismatch impacts (e.g. Edwards and Richardson 2004) and selective pressure on age and size within the populations and major climate-fishery links have already been observed (Hsieh and Ohman 2006, Brander 2007, Anderson et al. 2008, Hsieh et al. 2008, Hsieh et al. 2009). Fish have also been suggested to play an important role in controlling ocean alkalinity (Wilson et al. 2009), a process not fully considered in ocean models. In most cases, though, further investigation into the underlying mechanisms of fish stock dynamics is needed for direct use in resource management (Erzini 2005).

2.4.4 Bioacoustics

The oceans are filled with natural and biological sounds, although many artificial sources have contributed increasingly to its overall noise budget (Fig. 10). The influence of anthropogenic noise on marine life constitutes an issue of considerable interest both to the scientific community and public. Artificial sources can interfere with the natural use of sounds by marine organisms and may constitute a physical threat for the species exposed (Richardson et al. 1995, Engås et al. 1996, Gordon et al. 1998, McCauley et al. 2000, Guerra 2004). The quantity of anthropogenic noise in the ocean is increasing along with greater human marine activity (Hildebrand 2009). A key question is whether the human-generated sounds affect the ability of marine animals to pursue their normal activities, reproduce, and maintain healthy populations. The sources of human-related noise include intentionally produced noise from navigation and surveying to unintentionally generated noise, such as commercial shipping, offshore construction, and recreational boating (Hildebrand 2009).

Sound in the ocean is diverse and its detection appears to have evolutionary and ecological roles in the lives of many marine mammals, fish, and invertebrates (André and Nachtigall 2007). Unintentional sounds include, for example, those produced by schools of fish swimming through the ocean or release of air by large groups of fish as they adjust their buoyancy. Intentional sounds, including whale songs, dolphin clicks, and fish vocalisations, are believed to be produced in various species for communication, echolocation, and perhaps even acoustic imaging of the environment (Tyack and Clark 2000, Würsig and Richardson 2002). Current data on the impact of anthropogenic sounds on marine mammals and the marine ecosystem is sufficiently great to warrant further consideration by both the scientific community and the public (Hildebrand 2009, Jensen et al. 2009, Di Iorio and Clark 2010).

Long-term quantification of sounds is needed to establish a database for classification of sounds, monitoring of marine organisms and population dynamics, and ultimately assessments of anthropogenic effects on marine organisms. Passive hydrophones are a simple and powerful tool for biological sensing in ocean observatories and can evaluate the human and natural contributions to marine noise and describe the long-term trends in ambient noise levels. As gaps in marine acoustic research are filled, they will be used in the development of a model of ocean noise that incorporates temporal, spatial, and frequency-dependent variables to better understand recorded signals (e.g. Clark et al. 2009).

2.4.5 Export Flux Dependent Ecosystems

Changes in primary production and the quantity and quality of sinking organic matter have clear influences on the animals that depend on this food supply, but evidence for these connections and the processes leading to any observed changes in the deep ocean comes from only a few locations. If projected increases in stratification due to global warming occur, then smaller and more nutrient efficient phytoplankton species will likely be favoured (Bopp et al. 2005). Change in phytoplankton community structure could alter the quantity and quality of flux material to abyssal depths (Buesseler et al. 2007).

In addition to the makeup of surface water communities, the inhabitants of the deep sea, the world’s largest biome, have an important role in determining the depths to which carbon is exported (Robinson et al. 2010). Pelagic zooplankton, like filter feeding salps and appendicularians, can change in abundance in relative synchrony with production at the surface (Robison et al. 2005, Smith et al. 2008a). These zooplankton consume substantial amounts of organic matter and reform it into dense faecal pellets and organism fragments that are transferred relatively quickly to deeper depths as sinking POC (Pfannkuche and Lochte 1993, Robison et al. 2005, Richardson and Jackson 2007, Smith et al. 2008a, Sutherland et al. 2010, Wilson and Steinberg 2010). The lack of data from midwater depths severely limits the ability of researchers to quantify the importance of microbes and zooplankton in determining the efficiency of the biological pump (Robinson et al. 2010).

Deep-sea communities are food limited and respond to changes in their food supply, sinking POC, over timescales that are not very different from those of shallow water or terrestrial systems. Spatial studies have repeatedly found that higher abundances of benthic organisms from bacteria to megafauna are typically found beneath areas of higher productivity (Rowe et al. 1982, Cosson et al. 1997, Smith et al. 1997, Levin et al. 2001, Gambi and Danovaro 2006, Rex et al. 2006, Johnson et al. 2007, Smith et al. 2008b). Time-series data have confirmed that changes in the flux of POC relate to changes in meiofaunal (Pfannkuche et al. 1999, Galéron et al. 2001, Witte et al. 2003, Danovaro et al. 2004, Danovaro et al. 2008b), macrofaunal (Drazen et al. 1998, Galéron et al. 2001, Smith et al. 2002, Hoste et al. 2007, Ruhl et al. 2008), and megafauna community structure and function (Fig. 11, Billett et al. 2001, Ruhl and Smith 2004, Colaço et al. 2006, Dixon et al. 2006, Ruhl et al. 2008, Colaço et al. 2009, Billett et al. 2010), as well as deep-sea fisheries (Company et al. 2008, Maynou 2008, Bailey et al. 2009). Bacterial and meiofauna responses to food inputs were on the order of hours (e.g. Pfannkuche et al. 1999) and megafauna densities and community structure showed significant correlation to food inputs after several months (e.g. Ruhl 2008).

Particulate carbon that sinks to the seabed eventually becomes ingested and remineralised back into the water column, or buried geologically in sediments. Benthic fauna thus influence how much of the organic carbon reaching this system boundary remains in the contemporary marine environment as carbon dioxide, modified organic matter, or is buried. The notions that deep-sea communities respond readily to climate change and that diversity in deep-sea has been related exponentially to ecosystem functions like carbon cycling (Danovaro et al. 2008b) suggest that if large scale changes in food availability occur as predicted (Pierce 2004, Bopp et al. 2005), they could lead to major changes in the benthos and its function. Proposed ocean iron fertilisation efforts, which aim to increase POC fluxes (Boyd et al. 2007, Buesseler et al. 2008, Lampitt et al. 2008), will also likely have a major impact on the deep-sea benthos.

Corals in the deep ocean have higher diversity and levels of respiration and thus ecosystem function when compared to surrounding areas (Lavaleye et al. 2009, van Oevelen et al. 2009). They can be important habitat areas for some deep-sea fisheries (Costello et al. 2005, D’Onghia et al. 2010, Althaus et al. 2009). These coral fauna, though, have life-history traits that require longer-term sustained observation in order to evaluate their ecology. Current evidence suggests, though, that cold-water corals may have a relatively narrow range of POC flux tolerance below which they starve and above which they become smothered. There may be sensitivities to temperature and ocean acidification like those found for their shallow water congeners (Grottoli et al. 2006, Roberts et al. 2006, Fine and Tchernov 2007, Hoegh-Guldberg et al. 2007, Roberts et al. 2009).

Benthic processes influence the waters above and create a benthic boundary layer of water tens of meters or more above the seabed. Seabed modifications of organic matter can result in upward fluxes of buoyant particles that could be as high as two thirds of the downward flux over periods of one to two weeks (Smith et al. 1989). Because this process is not accounted for in current global carbon models, evaluating the degree to which processes occurring within the benthic boundary layer connect to the overlying water should add needed certainty to forecasts of ecological and biogeochemical change. Surface waters may not be well mixed with water at abyssal depths, but variations in surface conditions can influence life in the deep sea within weeks. The current estimate of ocean age below 1500 m depth for both the Atlantic and Southern Ocean is approximately 300 years (Fig. 14, Matsumoto 2007), which overlaps with the longer-term estimates of climate warming (IPCC 2007a). So even subtle changes in deep-sea ecological function could have a considerable impact on global biogeochemistry, especially if they persist over the centennial scales of climate change predicted.

2.4.6 Deep Biosphere and Chemosynthetic Ecology

The persistent discovery of life in environments that were previously thought to be relatively devoid of life continues to redefine the fundamental abundance, distribution, and function of life on Earth. The study of these extreme systems has importance for considering where life might be possible on other worlds. The discovery of chemosynthesis-based communities at the seafloor (e.g. Paull et al. 1985, Van Dover et al. 2002) and microbes in sediments several hundred meters below the seafloor (D’Hondt et al. 2004, Blair et al. 2007, Smith and D’Hondt 2006, Biddle et al. 2008) continue to redefine understanding of life (Fig. 12). Quantifying the diversity of form and metabolic function in these communities continues to be a major research focus with links to geosciences. The breakdown of water from background radiation, which releases the electron donor hydrogen, is a recent example of a novel source of energy to maintain microbial life (Blair et al. 2007, Chivian et al. 2008).

Synoptically monitoring these communities along with changes in biogeochemistry, fluid flux rates, and geophysical motions should increase understanding of how chemosynthetically-driven systems utilise reducing compounds like sulphur or methane to provide energy for carbon fixation instead of using light energy. Methanotrophic microbes, for instance, act as an important sink for methane released at the seafloor (Boetius et al. 2000, Boetius and Suess 2004, Niemann et al. 2006a, 2006b, Nuzzo et al. 2008, Lichtschlag et al. 2010). Chemosynthetic habitats can range from superheated waters with chemical concentrations lethal to most life (Van Dover et al. 2002) to more benign areas where methane seeps from sediments and supports life (Paull et al. 1985) often with important dependences on symbiotic relationships (e.g. Robidart et al. 2008). Their isolation allows for highly targeted studies of biogeographic processes (e.g. Gebruk et al. 2000, Bachraty et al. 2009). The presence of certain chemosynthetic dependant fauna can be indicative of the sometimes difficult to observe methane, sulphur, or gas hydrate reserves (Olu-Le Roy et al. 2004, Zitter et al. 2008). The degree to which chemosynthetic systems on the whole also have a dependence on the downflow of oxygen and nutrients from the upper layers of the ocean (Riou et al. 2010, Dixon et al. 2006) also needs clarification. These systems not only create localised communities, but also have poorly defined influences on surrounding habitats including upward fluxes of organic matter (Cowen et al. 2001).

Key questions in marine ecology dynamics and impacts from anthropogenic change:

Questions addressable with observatory systems:

- What marine life is influential in biogeochemical cycling and how sensitive are they to climatic and anthropogenic change?
- What are the ecological functions of the recently described diversity and abundance in microbial systems including viruses, archea, bacteria, and protozoa?
- How do community and ecosystem function changes throughout the water column influence biogeochemical fluxes and feedbacks across trophic levels?
- How do variations in environmental conditions and resources interact with resource partitioning, competition, and other factors to drive community change?
- To what extent are changes in productivity, diversity, community structure, and ecosystem function related, and what processes alter or maintain them?
- What is the influence of diversity and habitat structure from deep-sea coral communities and what factors control their growth and abundance?
- What are the distributions and migration patterns for marine mammals and what is the influence of anthropogenic noise and climate change on their ecology?
- How do seismic and other solid earth processes influence benthic and water column ecosystems?
- What are the fluxes of organic matter through chemosynthetic communities?
- What are the impacts of hydrocarbon, mineral and marine natural products exploration and exploitation, and how can they be minimised in future efforts?

Questions addressable with additional data and contextual information:

- How does the abundance and distribution of marine life vary over time and what will the influence of anthropogenic change be?
- What factors control deep-biosphere habitat and community dynamics and how does such life fix carbon and interact with other ocean systems?

- What is the importance of lateral transport and spatiotemporally aggregated biogeochemical fluxes in meeting observed metabolic demands of communities?
- What are the most influential taxa within various functional groups and which might be used as indicators of community wide change?
- What types of marine life are most sensitive to anthropogenic noise and in what areas could marine noise be particularly harmful?
- How are microbial dynamics, CDOM, and ocean colour related?

2.5 Transformative Ocean and Earth Science

Greater focus on socially relevant issues demands a more integrated approach than has been achieved. As more processes are identified and evaluated, the need to compare and understand potential connections and feedbacks between such processes increases. A clear way to bring greater continuity to discerning connections across disciplines, space, and time, is to more fully augment typical research projects with standardised and integrated *in situ* observations from a network of ocean reference stations. Socioeconomically important topics which cross-cut the above outlined science areas include themes spanning numerous spatial and temporal scales such as:

- Natural and anthropogenic change
- Interactions between ecosystem services, biodiversity, biogeochemistry, physics and climate
- Impacts of habitat destruction and pollution on ecosystems and their services
- Impacts of exploration and extraction of energy, minerals, and living resources
- Geo-hazard early warning capability for earthquakes, tsunamis, and gas hydrate release
- Connecting scientific outcomes to stakeholders and policy makers

There is now growing awareness of connections between climate and open-ocean environments and their importance for society. Developing frameworks for more formalised discussions of how to document and value ecosystem goods and services are making the societal relevance of surface and deep-sea processes clearer (e.g. Nellemann et al. 2008, Grehan et al. 2009). Bioeconomic modelling, for example, has been shown to be a powerful tool, but needs a stronger science basis (Armstrong et al. 2009). Ocean observatories and the consortiums that utilise them are now working to incorporate economic and legal perspectives in conjunction with natural science because together those perspectives inform policy on deep-sea resource use, geo-hazard warning, fisheries, and law of the sea legislation (Grehan et al. 2009). The United Nations Environment Programme (UNEP), HERMES, and the Center for Ocean Solutions have highlighted oceanic and deep-sea ecosystem functions, goods and services, and socioeconomic benefits they provide (Table 1, Nellemann et al. 2008, Center for Ocean Solutions 2009, Grehan et al. 2009).

Great socioeconomic gains are possible through increased understanding of ocean science. Links between research breakthroughs and socioeconomic gain are often complex, but relate to important portions of gross domestic product (GDP). Marine research and development influence extends well beyond marine GDP, especially considering climatic and geo-hazard aspects (Flemming 2007). The GDP attributed to marine research and development is about 1%, or more, of total marine GDP (Pugh 2008). Further investment in research that can enhance sustainability of marine economic sectors should stabilise or enhance overall GDP. Because most economic cost-benefit models do not capture the potential for environmental information in policy making, cost-benefit models need new science input to accommodate the pervasive influences of ocean processes on GDP.

It is the societal need to understand connections between ocean processes and society that drive ocean observatory science today. Socioeconomic services can be broken down into supporting (i.e. upstream services), and provisioning, regulating and cultural services that rely on supporting services. In the ocean these range from biogeochemical cycling and habitat structure upstream to natural resources, climate regulation, health and safety and quality of life. The connections between these forcing factors, supporting services, and services are often undefined.

The European Marine Strategy Framework Directive calls for sustainable use of the seas, ecosystem-based management, establishment of environmental status indicators and targets, and a means to evaluate if they are being achieved. The directive stipulates that the related monitoring should examine causes of change, ensure comparability of assessments, and address natural variability. Policies with similar attributes have been developed in many nations worldwide and typically include sustainable use and awareness of change as core principles. The European Commission has funded several programmes with integrating activities for open-ocean research. HERMES, MarBEF NoE, HERMIONE, and CoralFISH are examples of European projects integrating researchers studying ecosystem hotspots and highlighting connections between forcing factors like climate change, ecosystem services, and socioeconomic impacts. Active research using observatories in EuroSITES is providing standardised data capable of bridging various measurement scales across a dispersed network. Future observatory science and technical planning are progressing in ESONET NoE. EMSO is working to create a formal organisation to build and operate a distributed European research infrastructure of fixed point observatories in the open ocean. Ocean observatories can then combine with other infrastructures like satellites, EuroARGO, and the Integrated Carbon Observing System (ICOS) in the European Marine Observation and Data Network (EMODNET).

The greater potential of these systems will be realised when they can be utilised in a global setting. European observatory projects contribute to GEOSS, GMES, and geo-hazard networks and inform work in the IPCC (Intergovernmental Panel on Climate Change), UNEP (United Nations Environment Programme), and OSPAR (the Convention for the Protection of the Marine Environment of the North-East Atlantic). Other ocean observatory developments include NEPTUNE Canada, the US Ocean Observatories Initiative (OOI), the Monterey Accelerated Research System (MARS), the Japanese Dense Ocean Network for Earthquake and Tsunami detection (DONET), the Marine Cable Hosted Observatory (MACHO) offshore Taiwan, and the Deep-ocean Environmental Long-term Observatory System (DELOS) (Table 1; Favali et al. 2010b). Ultimately these programmes can all relate to GEOSS at a global scale. GEOSS may even develop long-term working groups to harmonise best practices, standards and organise global scale analyses from ocean observatory data.

3. Observatory Design

3.1 Observatory Fundamentals

The most transformative aspect of the observatory design will be its ability to address interdisciplinary objectives simultaneously across scales and relate that information to researchers and hazard managers in a timely manner. Various designs have been under consideration for more than a decade (Thiel et al. 1994, Berta et al. 1995, Rigaud et al. 1998, Beranzoli et al. 2002, Priede et al., 2003, 2005, Blandin and Rolin, 2005, Favali and Beranzoli 2006, Favali et al. 2006a, Frugoni et al. 2006). These tools can be brought to bear in the water-column, on the seafloor, and sub-seafloor depending on the application Ocean observatories can be attached to a cable providing power and data transfer or operate as independent benthic and moored instruments. Furthermore systems may include autonomous vehicles that can transfer data or recharge power supplies. Data can also be transmitted through acoustic networks that are connected to a satellite-linked buoy. Mobile systems can be used to expand the spatial extent of a node. Integration of science instrumentation into developing hydrocarbon extraction areas, as done in the DELOS project, is another promising infrastructure development. Observatories are being implemented in a staged manner to first deploy proven technology and incrementally include new technology to meet science objectives. Operation and maintenance is being done primarily by oceanographic marine research facilities.

Requirements for data transmission represent an important factor in observatory design and range from real-time, near real-time, delayed or truncated transmission, to systems where data is only recovered during observatory servicing. The most critical need for real-time data transmission is for time-sensitive geophysical measurements and geo-hazard early-warning systems. All other applications can rely on near real-time or less frequent feedback, albeit with relatively low data transmission rates. For observatories that are sufficiently close to shore, cables delivering power and communication can be an optimum solution, hence providing energy and real-time data transfer. Two-way communication may also be required to adapt sampling protocol to new conditions, but not necessarily via cable.

The infrastructure designs are being derived from an iterative process that considers the broad science objectives, establishes related requirements, and integrates technical and logistical input. The science objectives that drive ocean observatory development dictate ability to collect data without the presence of a research vessel over a range of timescales up to decades. The modular design must incorporate standardisation and interoperability concepts to improve system functionality, reliability, and comparability of results (Waldmann et al. 2010). It must transmit time-sensitive data sufficiently, and where feasible deliver power, two-way communication and instrument management, and ultimately make data products openly available. Data provenance should be maintained for quality control and crediting to the originator.

3.2 Principal Observatory Nodes

The proposed locations capture many facets of geology, biogeochemistry, and ecology of ocean regions around Europe, but they do so across an unprecedented spectrum of variation (Priede et al. 2003, 2005). Previously biogeochemical and other studies have been very limited in the extent to which the observed process rates and relationships could be applied. If variation is only observed over a limited range particular to a single biogeochemical province, those rates and relationships may not be applicable in environmental or resource variations that exceed the site-specific observed variation. The sites span the eight major biogeochemical provinces around Europe including the Boreal Polar (BPLR), Atlantic Arctic (ARCT), Atlantic Subarctic (SARC), the North Atlantic Drift (NADR), Northeast Atlantic Continental Shelf (NECS), North Atlantic Subtropical Gyre East (NASW), and Mediterranean (MEDI) described by Longhurst (2006) (Fig. 3). The sites capitalise on existing programmes which add substantial contextual data, and logistical value. It is envisioned that observatory sites in HERMIONE, EuroSITES, and ESONET will be able to join the formal ocean observatory organisation when basic readiness criteria are met.

The Arctic node is active across the Fram Strait (79°N) at the southern extent of the BPLR. Work there is focused on activities like evaluating heat and mass transport through the Fram Strait, links between climate and surface ocean processes and deep-sea ecosystems, and methane hydrate dynamics. The HAUSGARTEN observatory has operated at the site since 1999 (Soltwedel et al. 2005) and more recent activity includes the ESONET demonstration mission Arctic Ocean ESONET Mission (AOEM), as well as HERMIONE and HYPOX research. Because the Arctic is believed to be one of the most sensitive areas to anthropogenic change, research in this region is very likely to document substantial shifts in physical, biogeochemical, and ecological processes.

The Hakon Mosby Mud Volcano (72°N, 14°44' E) is a geologically active area situated roughly at the confluence of the SARC and NECS regions at the entrance to the Barents Sea at about 1250 m depth. Research at the site has found that mud and methane emitted from the seafloor create a complex caldera bathymetry and ecology. Methane has been found to be consumed by the microbial life around the area, but this process is limited by the presence of oxygen and sulphate (Niemann, 2006a). This site has been an area of intermittently active work and ESONET is running a demonstration mission at the site called Long-term Observations On Mud-volcano Eruptions (LOOME).

Meridional overturning and thermohaline circulation are measured at Weather Station Mike (66°N, 2°E) near the convergence of the ARCT and SARC biogeochemical regions in the southern Norwegian Sea. This site benefits from the use of an existing sub-sea cable and an existing decadal scale data record of currents at the site. Ship-based hydrography surveys to several thousand meters depth have been conducted in this vicinity since the 1950’s and produced detailed evidence of secular warming to depths greater than 2000 m (Fig. 6).

Time series observatories in the centres of deep convection in the Labrador (K1, 56.5°N, 52.6°W; Avisc et al. 2006) and Central Irminger Sea (CIS; 59.4°N, 39.4°W) have been operating for more than a decade. These observations are of globalimportance as they provide year-round crucial information on hydrographic properties during active convection (Figure 7) that are not accessible from ship expeditions. CIS is also in EuroSITES network and in the vicinity of one of the US OOI Global Scale Nodes. The co-location of international research effort in this region is expected to bring needed breath to observing capability and collaboration in this globally important area.

The Porcupine Seabight and Porcupine Abyssal Plain (PAP) have been areas of active physical oceanography, biogeochemical, and deep-sea ecological research since the 1980’s under programmes such as the international Joint Global Ocean Flux Study (JGOFS) and BENthic biology and Geochemistry of a north-eastern Atlantic abyssal Locality (BENGAL). More recently work at PAP has integrated into the EuroSITES project and is the site of the PAP – Sustained Observatory and the ESONET demonstration mission examining MOdular Deep Ocean Observatory (MODOO) design. The study area is located in the NADR in an area of 4850 m depth. The Porcupine Seabight and Gollum Channel can have significant movements of flocculent organic material along the seabed (Tudhope and Scoffin 1995). Integration of observing nodes from the upper seabight through Gollum Channel out to PAP could bring needed balance in carbon budgets.

The Mid-Atlantic Ridge near the Azores in the NASW biogeochemical province has been an active site for more than a decade in association with the international InterRidge programme (Fouquet et al. 1995). Work there is centred on the Lucky Strike hydrothermal vent field at 1700 meters depth and includes research on geophysical motion (seismicity and deformation) and the water, heat, and elemental quantities through the vent systems, behaviour of the physical and chemical properties of the fluids, as well as the variations in biogeochemistry, and on the ecological hotspots that occur in the vicinity of the vents (Miranda et al. 2005). Condor seamount offshore of the Azores area has been closed to the fisheries, and observatory studies are being conducted in order to promote a sustainable use of these ecosystems (Giacomello and Menezes, 2009; Morato et al, 2010). The Mid-Atlantic Ridge work has been part of the MarBEF – DEEPSETS, HERMIONE, and Coralfish programmes among others. The area is also the site of another ESONET demonstration mission, Monitoring the Mid-Atlantic Ridge (MoMAR).

Northeast of the Cape Verde islands is the Tropical Eastern North Atlantic Time Series Observatory (TENATSO; 17.4°N, 24.5°W) that consists of a water column observatory since 2006 and augmented with regular ship-based biogeochemistry observations. In combination with an atmospheric observatory in the lee of the ocean observatory comprehensive observations of the atmosphere/ocean system are accessible. Scientific motivation of the site includes the impact of iron enrichment through Sarahan dust outbreaks on ocean biogeochemistry and biology as well as observations in the origin region of hurricanes (Rijkenberg et al. 2008, Ye et al. 2009). Data collected at the site contributes to programmes such as the Surface Ocean Lower Atmosphere Study (SOLAS) and EuroSITES.

The European Station for Time-series in the Ocean, Canary Islands (ESTOC; 29.04°N, 15.5°W) has been operating since 1994 and focuses on ocean physics and biogeochemistry (Neuer et al. 2007, Troupin et al. 2010). A decadal record of ocean acidification is also available from this site (Santana-Casiano et al. 2007). The site is part of the EuroSITES network and contributes to research on the dynamics of the north Atlantic subtropical gyre in collaboration with researchers working at the Bermuda Atlantic Time-Series site (BATS; Helmke et al. 2010).

The Iberian margin is an area of geophysical activity near the Eurasian and African plate boundary off the Portuguese coast. The study site from 700 to over 4000 m depth is within the NASW near where Mediterranean Intermediate Water enters the Atlantic and influences meridional overturning circulation. The site has mud volcanoes, pockmarks, mud diapers, carbonate chimneys, hydrocarbon venting, and faulting. This is another area of active research by HERMIONE, as well as NEAREST and NEAMTWS geo-hazard early warning systems. A prototype tsunami meter was installed there on GEOSTAR (Geophysical and Oceanographic STation for Abyssal Research) with near-real-time data transmission through an acoustic link from the seafloor observatory to the surface buoy and through a satellite link from the buoy to the shore. (Favali et al. 2006a). The ESONET demonstration mission, LIstening to the Deep Ocean environment (LIDO), is also researching passive acoustics related to marine mammals and anthropogenic noise, and geo-hazard research.

The Ligurian Sea near the south coast of France in the Mediterranean has active research in sub-sea geophysics, slope stability, biogeochemical fluxes and marine ecology. The study area has sites extending to 2500 m depth in the MEDI biogeochemical region with wind driven coastal upwelling, particle plumes, nutrient benthic exchange, bottom boundary layer processes, and mesoscale research. Previous and existing programmes operating in the area included EuroSITES, JGOFS - Dynamics of Atmospheric Fluxes in the MEDiterranean sea (DYFAMED; 43.25°N, 7.52°E), International Ocean Drilling Program (IODP), and ANTARES (Astronomy with a Neutrino Telescope and Abyss environmental RESearch), one of the candidate sites for the KM3NeT infrastructure, which provides seafloor cable infrastructure.

The study area offshore of East Sicily is located in one of the most seismically active areas of Mediterranean in the vicinity of Mount Etna and MEDI biogeochemical region at a depth of 2100 m. On-going research at the site includes work related to LIDO and the NEMO-SN1 multidisciplinary observatory, which has been cabled since 2005 (Favali et al. 2006b, Favali et al. 2010a). The site benefits from seafloor cabled infrastructure support of the NEMO (NEutrino Mediterranean Observatory) neutrino telescope, another candidate for the KM3NeT (Migneco et al. 2006, 2008). Seismic, tsunami, and Mediterranean Intermediate Water formation are particularly important topics at this site, which also has used GEOSTAR technology.

The E2-M3A in the Adriatic Sea (41.84°N, 17.76°E) has been the location of ocean biogeochemical research in association with EuroSITES. Research at the site focuses on heat flux and convection (e.g. Cardin and Gacic 2003). Further to the southeast in the Mediterranean is the Hellenic study area over a series of four networks including a cabled system (NESTOR, another KM3NeT candidate site), EuroSITES Poseidon E1-M3A

(35.66°N, 24.99°E), the IODP site BUTT-1 (34° 18.6N, 24° 54.3E), and the Cretan and Rhodes basins. Research in the area examines benthic-pelagic interactions, benthic respiration, biogeochemical fluxes, and photography based ecology, as well as monitoring seismic processes, seabed methane fluxes, and oil and gas industry activities.

The Sea of Marmara, which lies between the Mediterranean and Black Sea, experiences regular tectonic activity because of its location on the North Anatolian Fault which is a major continental transform plate boundary. The fault cuts across a natural gas field beneath the Sea of Marmara and hydrocarbons seep from the seafloor. An ESONET demonstration mission is testing for possible relationships between fluid activity and seismicity at the site. After the 1999 Izmit and Düzce earthquakes, the next large earthquake (M_w>7) is expected in the Sea of Marmara close to Istanbul, a city with 15 million inhabitants (Parsons, 2004). Hence, the high tectonic activity and oceanographic setting makes the area a natural laboratory for multidisciplinary seafloor observations for geo-hazards, oceanography, and the relationship between fluids and seismicity. Improved geo-hazard warning is needed here where earthquake and tsunami hazards could have devastating effect in Istanbul and heavily populated coastal areas (e.g. Yalçıner et al., 2002; Görür and Çağatay, 2010).

The Black Sea is an area of research on extreme habitats, as well as geo-hazards like methane hydrate release (Blinova et al. 2005, Schmale, 2005, Greinert et al. 2006). Methane seeps have been mapped extensively in the Black Sea providing an excellent setting for long-term research of links between methane gas flux, seismicity, and ecology. The co-occurrence of these processes presents a good opportunity to understand the biogeochemical implications of methanotrophy.

3.3 Generic Sensor Module

The concepts of generic and specific aspects of observatory design are helping to guide observatory development in Europe. In practice the ability to address most questions has limits because one given site is not optimum for all applications. For instance, certain geo-hazard monitoring is best implemented in geologically active areas. Similarly marine communities, such as those linked to hydrothermal vents and cold seeps can be highly localised. There are, however, several variables that are sensible at all sites and depths, including temperature, conductivity [salinity], pressure [depth], turbidity, dissolved oxygen, carbon dioxide, ocean currents, and passive acoustics. Variants that include pelagic and benthic specialisation are also being developed with, for example, chlorophyll fluorescence, or time-lapse cameras respectively.

These generic module concepts can then be adopted and serve as the primary means for comparisons of processes between sites and core service of the system. The variables measured with the generic sensor module cover a subset of variables that are important in the context of climate system monitoring known as Essential Climate Variables (ECV) supporting the work of the UN Framework Convention on Climate Change (UNFCCC) and the IPCC.

These generic sensor variables have been operational for long time periods and are commercially available. Hence, they can be used and maintained with relative ease. Multi-probe, CTD-type (conductivity, temperature, and depth) systems often come with a basic set of sensors (Table 3) and possibilities to add a wide variety of others. Another advantage of such systems is that data capture and power supply units already have some integration and interoperability standardisation. As sensor development continues other variables can be added, such as the remaining ECV. Sensors for pH, CH_4, H_2S, Eh, and hydrocarbons are likely to become part of the generic scheme as sensors for them become adapted for observatories.

3.4 Science-Specific Modules

The science-specific sensor modules are designed to complement the generic sensors in addressing the above objectives. Specific modules can be set up in varying combinations according to site-specific objectives. For example, measuring synchronously seismic motion, gravity, magnetism, seafloor deformation, sedimentation, pore-water properties, gas hydrates, and fluid dynamics will provide a great opportunity to make advancements in geosciences and geo-hazard early-warning capability. Specific observatory applications in physical and biogeochemical oceanography require full water depth moorings that allow recording of long-term, high resolution time-series of hydrography, currents and biogeochemical state variables (oxygen, fluorescence, nutrients) throughout the water column. A suite of biogeochemical and physical sensors mounted on moored profilers can allow for high-resolution vertical profiling in the upper part of the water column. Hydrothermal vent systems need instrumentation for extreme conditions. Systems for more specialised biogeochemical research include sedimentation trap systems, pigment and hydrocarbon fluorescence sensors, and *in situ* mass spectrometry. Observatory systems addressing aspects of marine ecology include deep-biosphere monitoring systems, time-lapse and video imaging, active acoustics, plankton sampling, *in situ* respiration, and *in situ* molecular and genetic analysis. Acoustic systems, which use advanced signal processing, are capable of not only acoustic tomography and source localisation, but also recognition of shapes in water.

3.5 Data Infrastructure

The data infrastructure for European observatories is being designed as a distributed system. Both observatory data and archiving services are already provided by several data centres. Therefore, the main challenge is to provide architecture based on international standards to implement data management policies and work flows. ESONET has a developing online knowledge base for general information about observatory systems and how project-specific data management fits into larger contexts. Core standards include the Open Geospatial Consortium (OGC) Sensor Web Enablement (SWE) suite of standards, namely the OGC standards SensorML, Sensor Registry, Catalogue Service for Web (CS-W), Sensor Observation Service (SOS) and Observations and Measurements (O&M) (Fig. 13). OGC SensorML is an eXtensible Markup Language (XML) for describing sensor systems and processes. A core SensorML profile is being developed in cooperation with EuroSITES and OceanSITES to assure international compatibility of sensor descriptions. SensorML files can be stored in the Sensor Registry, the main catalogue of European ocean observatory sensors. The Sensor Registry consists of a web-based entry module which stores the SensorML files in a native XML database. On top of this database, an OGC CS-W interface provides the standardised methodology to publish and access the Sensor Registry. Access to real-time observatory data is then provided by the SOS. Delayed mode data can also be entered into the system through the SOS.

The SOS service harvests data for automated data flow from observatory nodes to a selected data archive. OGC standards are used to generate International Standardisation Organization (ISO) 19139 compliant metadata descriptions for the harvested data. O&M and ISO data is then uploaded to an appropriate data centre and ingested. Currently, the World Data Center for Marine Environmental Sciences (WDC-MARE) as well as Systèmes d'Informations Scientifiques pour la Mer (SISMER) are implementing routines to acquire data from observatories and are capable of long-term data archiving services. In addition, both data archives provide data curatorial procedures including quality control for manual or semi-automatic upload of data to the archive. Each data archive further provides XML metadata files on each data set in either ISO 19139 or Global Change Master Directory - Directory Interchange Format (GCMD DIF) format and offers metadata exchange via Open Archives Initiative Protocol for Metadata Harvesting (OAI-PMH) interface. As quality control and other post-acquisition processing are applied to data, these data can be catalogued alongside their raw counterparts.

The knowledge base uses the above standards to data from observatories via the internet. For example, it uses OAI-PMH to harvest metadata from contributing archives and uses SOS to retrieve the latest data from observatories. The technical platform managing the metadata catalogue of contributing data archives is panFMP (PANGAEA Framework for Metadata Portals, Schindler and Diepenbroek 2008). The knowledge base provides access to sensor metadata via the Sensor Registry and offers access to real-time and archived data delivered by the SOS servers, as well as access to third party data centres which support the standards described above.

4. Conclusions

The scientific questions posed above derive from elemental societal needs to understand the marine environment and its influences. While many basic aspects of ocean systems have been described, major uncertainties in understanding the factors controlling variations in the ocean remain, let alone the variation that might occur as a result of climate change. Important episodic variations are often missed resulting in major quantitative imbalances. Uncertainty about deep-water industrial impact is also still high. Deficiency in understanding results, in part, from the fact that geophysical, chemical, ecological and biological quantities can be simultaneously influenced by a complex set of factors over a wide range of spatial and temporal scales.

Multidisciplinary standardised reference data will facilitate interdisciplinary analysis required to improve geo-hazard warning, and effectively evaluate the influences of climate change and anthropogenic impacts. By including a variety of tools investigators will be able to make connections between processes that are usually observed in disparate ways using meta-analysis (Zwiers and Hegerl 2008). The resulting variation can importantly be influenced by linear, as well as non-linear dynamics where seemingly similar conditions may result in different outcomes (Scheffer et al. 2001). Therefore attentive monitoring of multivariate environmental and resource conditions over adequate spatial and temporal scales is necessary. This notion includes a need to verify outcomes of studies examining spatial gradients as a proxy for understanding temporal change.

Complementary to the observational and experimental research is the clear need to place the complex results into rigorous theoretical frameworks and models where the complexity can be addressed such as the Nucleus for European Modelling of the Ocean (NEMO) and more specific tools like diagenetic and food web models (Soetaert and van Oevelen 2009). Forecasts now cover physical state variables such as temperature, salinity, currents, and waves, but forecast extensions to include marine ecosystem variables are under development. Addressing the major gaps with data from fixed point systems extending below 2000 m depth should improve longer-term forecasting.

Continued harmonisation of links among developing European large-scale infrastructures like, Euro-Argo, EMSO, KM3NeT, EPOS, SIOS, ICOS, and LIFEWATCH is needed (ESFRI, 2008). More direct engagement with maritime industries could continue to improve access to observatory infrastructure and enhance scientific outputs and industrial best practices. Many questions outlined will require information from other sources such as climate analysis and measurements from satellites or drifting floats such as Argo. Further development of ocean observatories will ultimately allow for increased data and infrastructure to those that may not otherwise have access, a benefit that was found during the HERMES project (Weaver and Gunn, 2009).

Economic stability, health and well being rely now more than ever on sound information on climate, weather, water, ecosystems, biodiversity, living resources, energy resources, and geo-hazards. Investing in ocean observatories will be a key development in realising an effective global observation system that aims to address these many needs. The results of these observatory efforts will contribute to EMODNET, GEOSS, GMES, geo-hazard networks, and will inform work in UNEP, OSPAR, and the interannual IPCC Assessment Reports.

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Figure 1. Illustration of the overlapping scales of major ocean and earth processes. Figure adapted from work of D. Chelton, (Oregon State University), L. Beranzoli (Istituto Nazionale di Geofisica e Vulcanologia), and Dickey and Chang (2001). *In colour*

Figure 2. Illustration of major processes in the marine environment indicating the interconnectedness of atmospheric, surface ocean, biological pump, deep-sea, and solid-Earth dynamics. This figure is based on other similar figures prepared by P. Cochonat, C. Berndt, ESONET NoE, and the US Ocean Observatories Initiative.

Figure 3. Illustration showing general locations of proposed ESONET observatory nodes and the biogeochemical provinces of Longhurst (2006). Provinces shown include Boreal Polar (BPLR), Atlantic Arctic (ARCT), Atlantic Subarctic (SARC), the North Atlantic Drift (NADR), Northeast Atlantic Continental Shelf (NECS), North Atlantic Subtropical Gyre East (NASW), and Mediterranean (MEDI). Map projection from Google Earth. *In colour*

Figure 4. Illustrations of (upper panel) regional plate stress where warmer colours indicate greater stress, and (lower panel) relative plate motion for the European region with motion represented as vector arrows (*sensu* Kreemer et al. 2003, illustrations created at http://jules.unavco.org/Voyager/Earth). *In colour*

Figure 5. a) Location of survey area west of Svalbard; IBCAO bathymetry (Jakobsson et al., 2008). b) Positions of plumes of bubbles acoustically imaged with the EK60 sonar, depicted by “pins”, superimposed on perspective view of the bathymetry of part of the area of plume occurrence. Bathymetry is from EM120 multibeam survey of cruise JR211 gridded at 20-m resolution, combined with high-resolution survey data from the Norwegian Hydrographic Service for the shallower-than-200-m part of the map. The 396-m isobath is the expected landward limit of the GHSZ. c) Part of record from an EK60 acoustic survey from JR211, showing examples of observed plumes. Amplitude of acoustic response is given by the colour of the "bubbles". All plumes show a deflection towards the north caused by the West Svalbard Current. The seabed, at around 240-m depth, is shown by the strong (red) response. The position of CTD cast 10 is indicated by vertical red arrow. Figure and legend from Westbrook et al. (2009). *In colour*

Figure 6. Time-series data from Station M (a.k.a. Mike) in Nordic Sea showing a) salinity, b) temperature anomalies with depth. Figure courtesy of S. Østerhus, Bjerknes Centre for Climate Research. *In colour*

Figure 7. Potential temperature time series (colour shading) in the upper 1800m of the central Labrador Sea (after Avsic et al. 2006). The black dots in colour contour indicate the 30 days average instruments depth. After a period of deep convection with an associated cooling of the water column at the beginning of the 1990's a distinct warming since 1997 can be seen. Stick plot of currents at approximately 250m depth is indicated at top panels, while gray shading indicate periods with current speed larger 20 cm/sec often associated with the passage of transient eddies. *In colour*

Figure 8. Estimated change in sea surface pH from the pre-industrial period (1700s) to the present day (1990s). Δ pH here is in standard pH units. This change is caused by

the invasion of anthropogenic CO_2. Calculated using Richard Zeebe's csys package with data from the Global Ocean Data Analysis Project and World Ocean Atlas climatologies. Δ pH is plotted here using a Mollweide projection (using MATLAB and the M_Map package). Note that the GLODAP climatology is missing data in certain oceanic provinces including the Arctic Ocean, the Caribbean Sea, the Mediterranean Sea and the Malay Archipelago. Legend and image courtesy of Andrew Yool. *In colour*

Figure 9. A) Sea-surface temperature and B) near surface Chl-*a* concentrations in the Tropical Northeast Atlantic from MODIS satellite retrievals. The 8-day averaged data (16. May 2004 to 23. May 2004) is interpolated to a 4000 m horizontal grid. The figures illustrate how complex relations between the physical and biological parameters can be. *In colour*

Figure 10. This double unit figure (both acoustic spectral density and actual levels) relates ocean noise, hearing thresholds and the audibility of some specific sources. The two heavy-lined curves show (in black) a typical ocean ambient noise power spectral density and (in blue) the corresponding audibility threshold for odontocetes, mostly taken from dolphin data, as no large whale audiogram is yet known. Some estimates of received sound pressure levels from specific anthropogenic sources at example ranges are shown as large blue dots or horizontal bars towards the top of the figure. The transmission loss calculations for these are based on spherical and/or cylindrical spreading (as appropriate for the waveguide) and absorption; source levels range between 190 and 210dB re 1µPa @ 1 m for instruments and 210-240dB for long range low-frequency military sonar. The light blue boxes (whose vertical size and position is arbitrary) display the frequency range of some natural sources in the horizontal. Figure is from E. Delory’s PhD thesis and builds upon an original version published in (Potter and Delory, 1998). *In colour*

Figure 11. Climatic and abyssal time-series data for Station M in the NE Pacific and PAP in the NE Atlantic with A) the ENSO indicator the Northern Oscillation Index (NOI) with monthly (light dashed line) and 13-month running mean (compound line), and POC flux to 4050 m depth at Sta. M; B) mobile epibenthic megafauna variation at Sta. M including *Elpidia minutissima* abundance (crosses), *Echinocrepis rostrata* abundance (open circles), and an index of species composition similarity of the top ten most abundant epibenthic megafauna (solid circles); C) the North Atlantic Oscillation (NAO) index with monthly (light dashed line) and 13-month running mean (compound line), and POC flux to 3000 m depth at the PAP; and D) total megafauna variation at Sta. M including *Oneirophanta mutabilis* abundance (crosses), *Amperima rosea* abundance (open circles), and an index of species composition similarity of the benthic megafauna (solid circles). Figure and legend from Glover et al. 2010).

Figure 12. A) Corals above fresh pillow lava in a hydrothermal vent field (Menez Gwen), B) Flange structure at Lucky Strike hydrothermal vent field colonized by the mussel *Bathymodiolus azoricus* with some vent shrimps, C) Sulphide structure colonized by the mussel (adults and juveniles) *Bathymodiolus azoricus*, with the fish *Gaidropsaurus mauli* on the fissure. All images © Missão Seahma. 2002 (FCT/PCDTM 1999MAR/15281) *In colour*

Figure 13. Developing data management structure for European open-ocean observatories. The lowermost area shows the standards and interfaces, which are sensor related and the line represents the internet. Network connected and delayed mode data enter the scheme through the internet and SOS using O&M to encode the data itself. This data is archived in the data centres, represented to the right. SOS uses SensorML to identify and describe the observatory capacities. Capacities are also stored in the Sensor Registry and can be queried there via C-SW. SensorML is used to generate metadata for data archiving. The uppermost part of the figure shows the user perspective, the data portal and knowledge base.

Figure 14. A map of circulation 14C age below 1500 m. This is equivalent to conventional 14C age, but accounts for surface ocean 14C reservoir age and the different sources of deep water. Unit is years. Legend and figure courtesy of K. Matsumoto (© American Geophysical Union, 2007). *In colour*

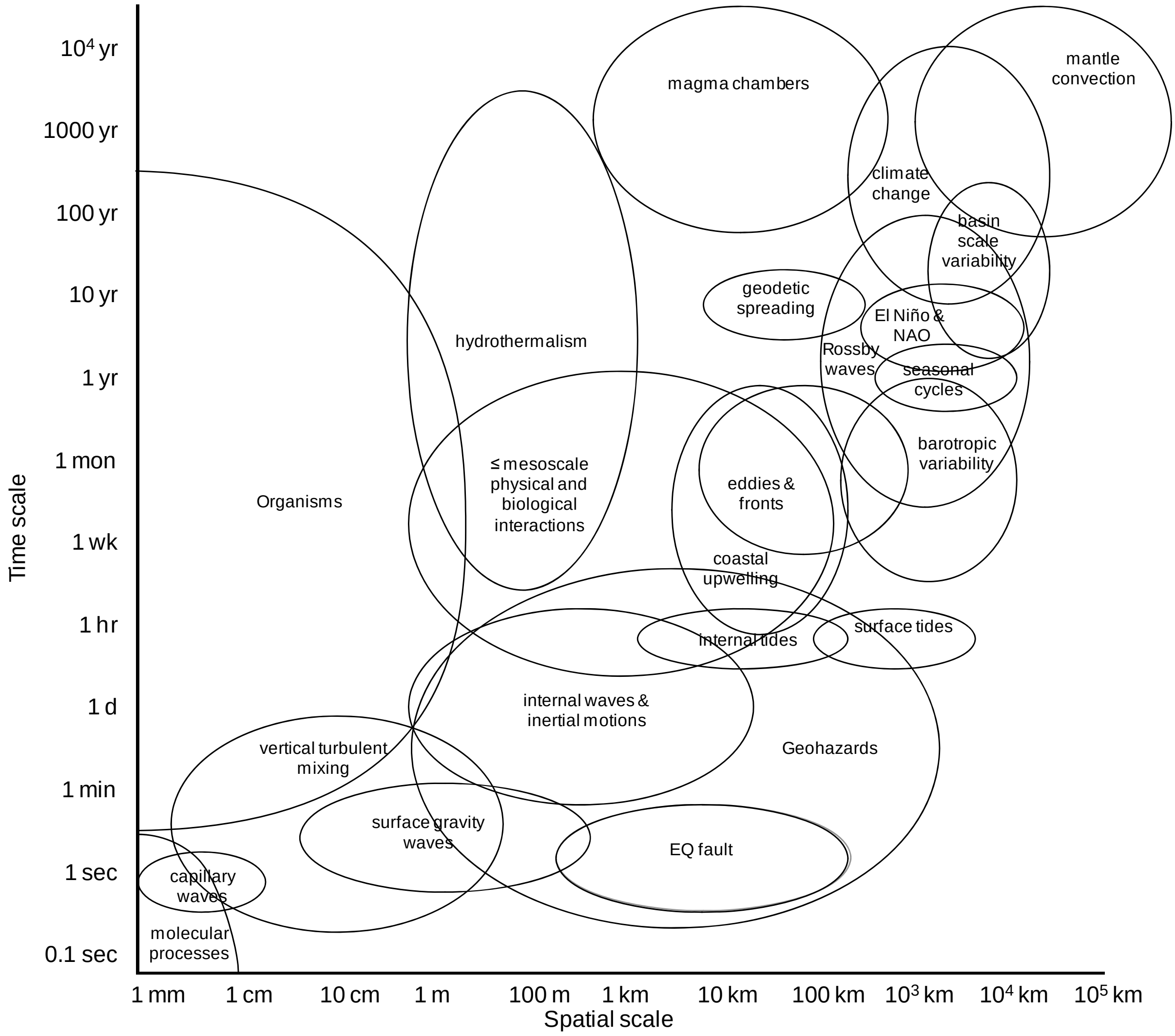

Time scale
10^4 yr
1000 yr
100 yr
10 yr
1 yr
1 mon
1 wk
1 hr
1 d
1 min
1 sec
0.1 sec
1 mm
1 cm
10 cm
1 m
100 m
1 km
10 km
100 km
10^3 km
10^4 km
10^5 km
Spatial scale
magma chambers
mantle convection
climate change
basin scale variability
geodetic spreading
El Niño & NAO
Rossby waves
seasonal cycles
hydrothermalism
barotropic variability
≤ mesoscale physical and biological interactions
eddies & fronts
Organisms
coastal upwelling
internal tides
surface tides
internal waves & inertial motions
Geohazards
vertical turbulent mixing
surface gravity waves
EQ fault
capillary waves
molecular processes

Figure 1.

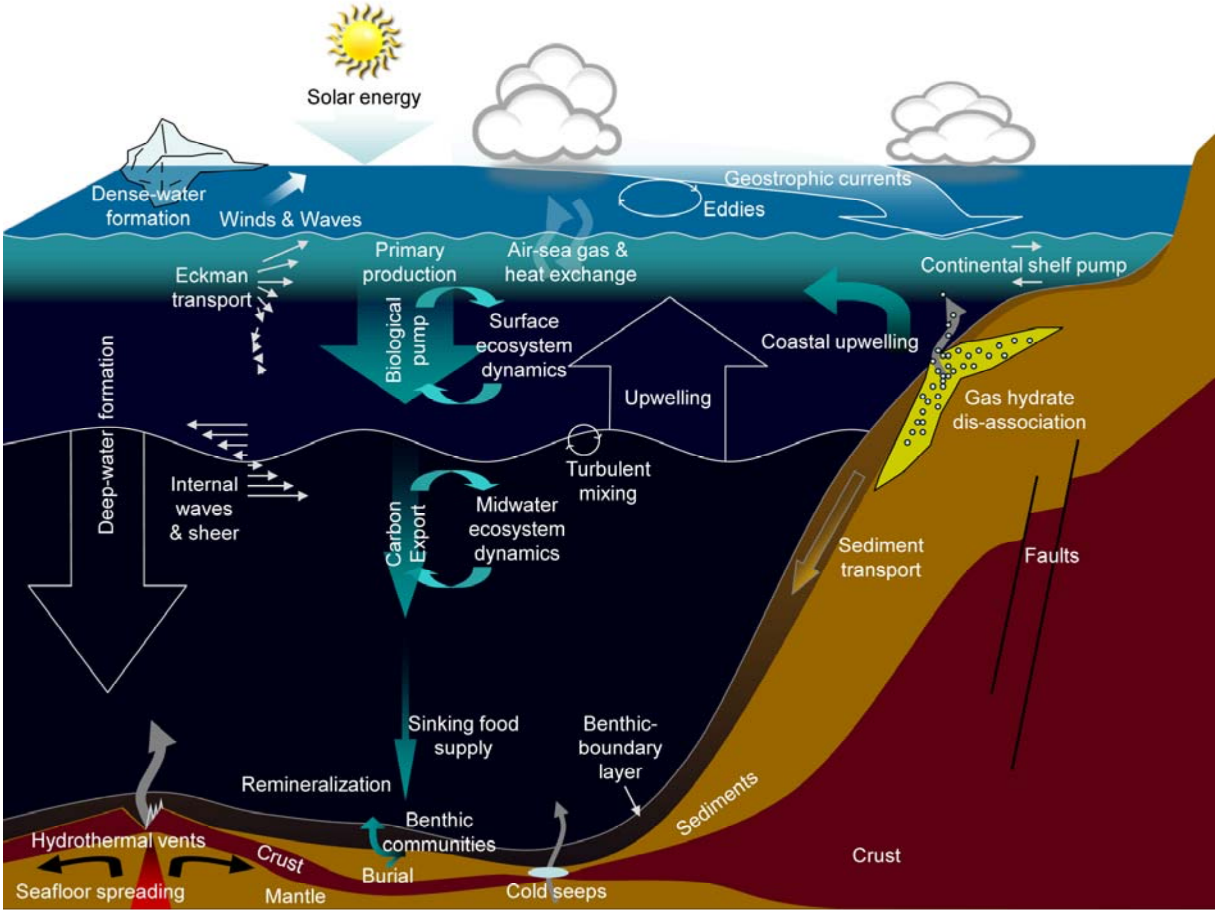

Solar energy
Dense-water formation
Winds & Waves
Geostrophic currents
Eddies
Air-sea gas & heat exchange
Primary production
Eckman transport
Continental shelf pump
Coastal upwelling
Biological pump
Surface ecosystem dynamics
Upwelling
Gas hydrate dis-association
Deep-water formation
Internal waves & sheer
Turbulent mixing
Carbon Export
Midwater ecosystem dynamics
Sediment transport
Faults
Sinking food supply
Benthic-boundary layer
Remineralization
Sediments
Benthic communities
Hydrothermal vents
Crust
Burial
Crust
Seafloor spreading
Mantle
Cold seeps

Figure 2

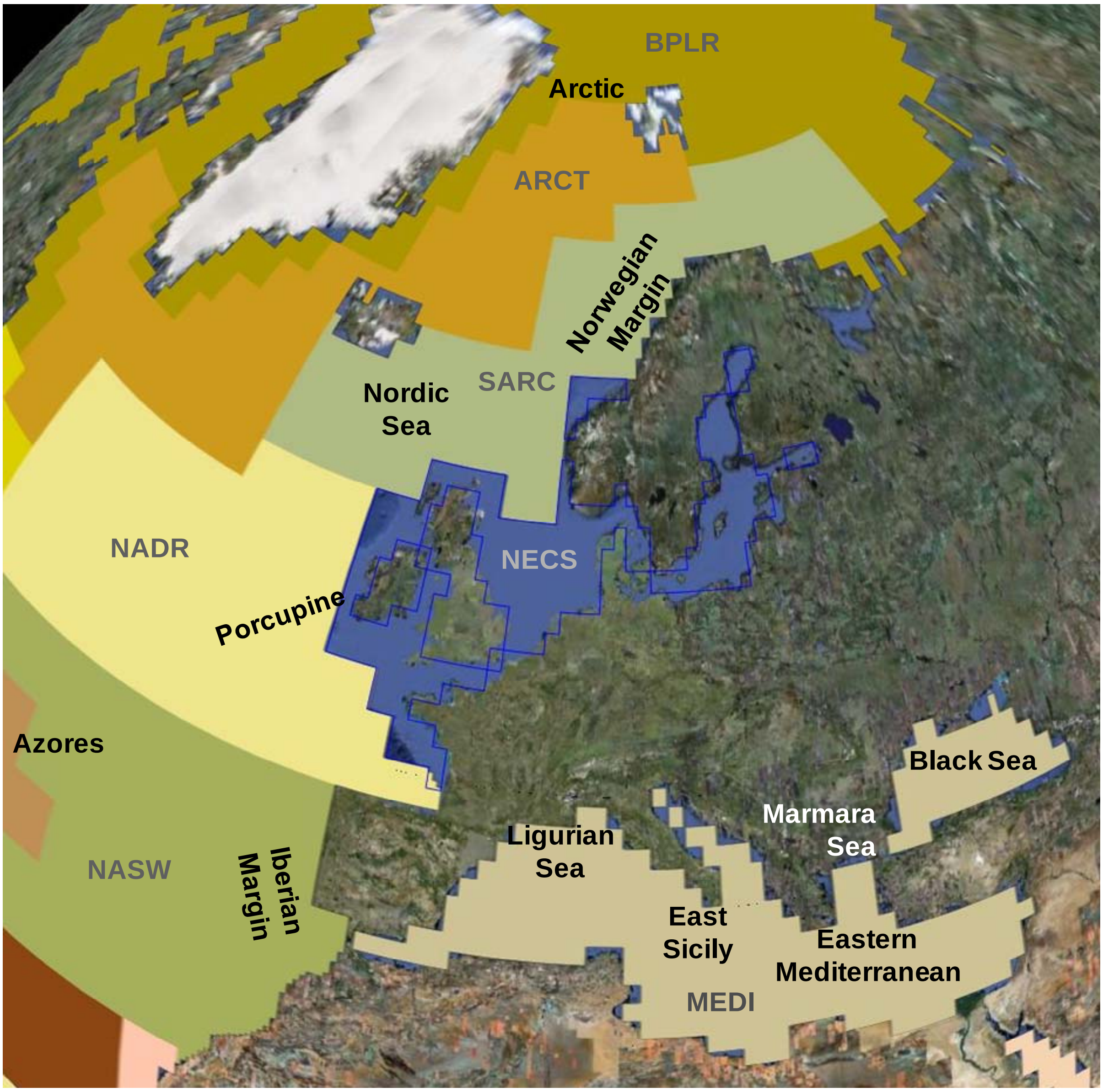

BPLR
Arctic
ARCT
Norwegian Margin
SARC
Nordic Sea
NADR
NECS
Porcupine
Azores
Black Sea
Marmara Sea
Ligurian Sea
NASW
Iberian Margin
East Sicily
Eastern Mediterranean
MEDI

Figure 3

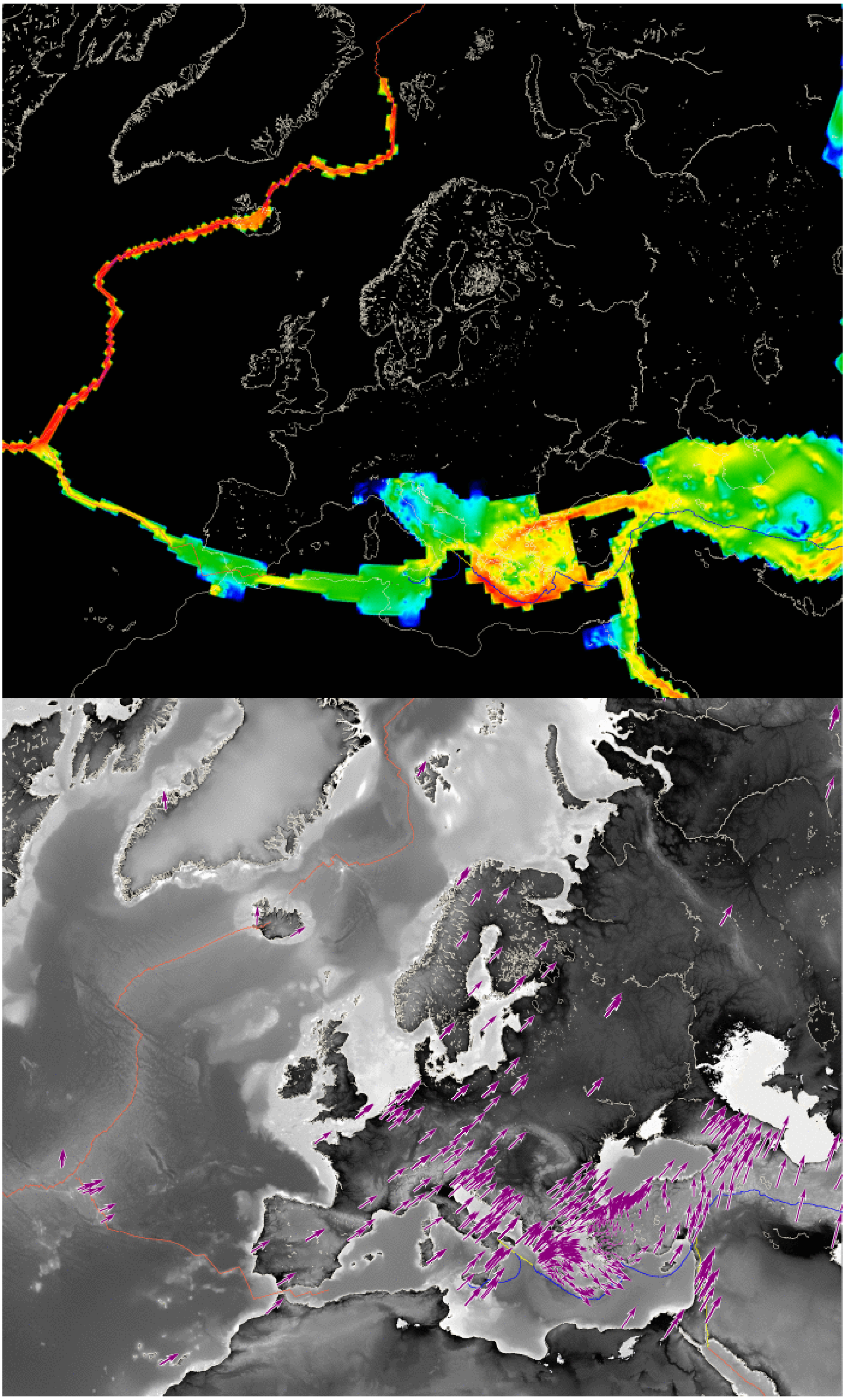


Figure 4

.

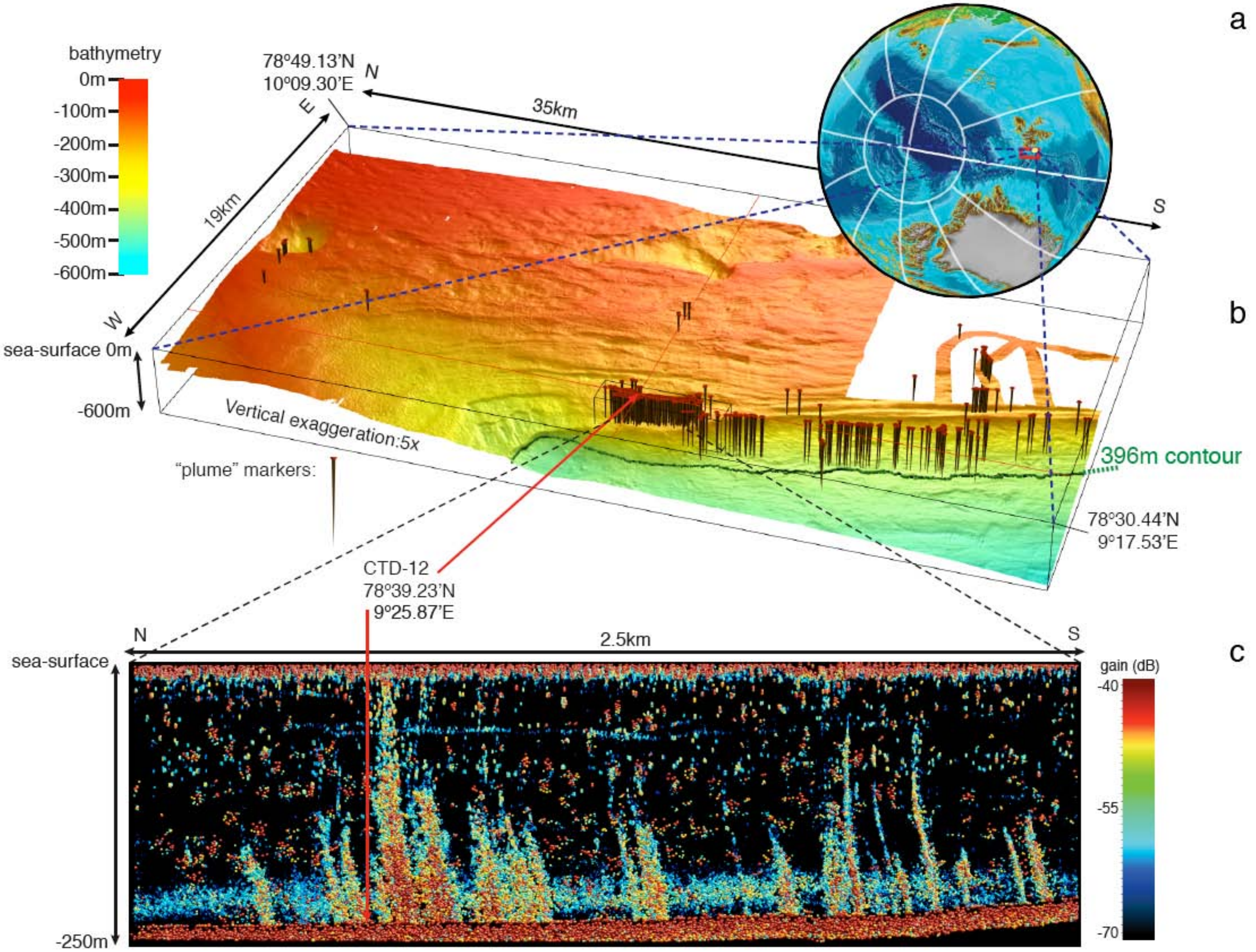

a
b
c
bathymetry
0m
-100m
-200m
-300m
-400m
-500m
-600m
78°49.13'N
10°09.30'E
N
E
35km
19km
W
S
sea-surface 0m
-600m
Vertical exaggeration:5x
"plume" markers:
396m contour
78°30.44'N
9°17.53'E
CTD-12
78°39.23'N
9°25.87'E
N
2.5km
S
sea-surface
-250m
gain (dB)
-40
-55
-70

Figure 5

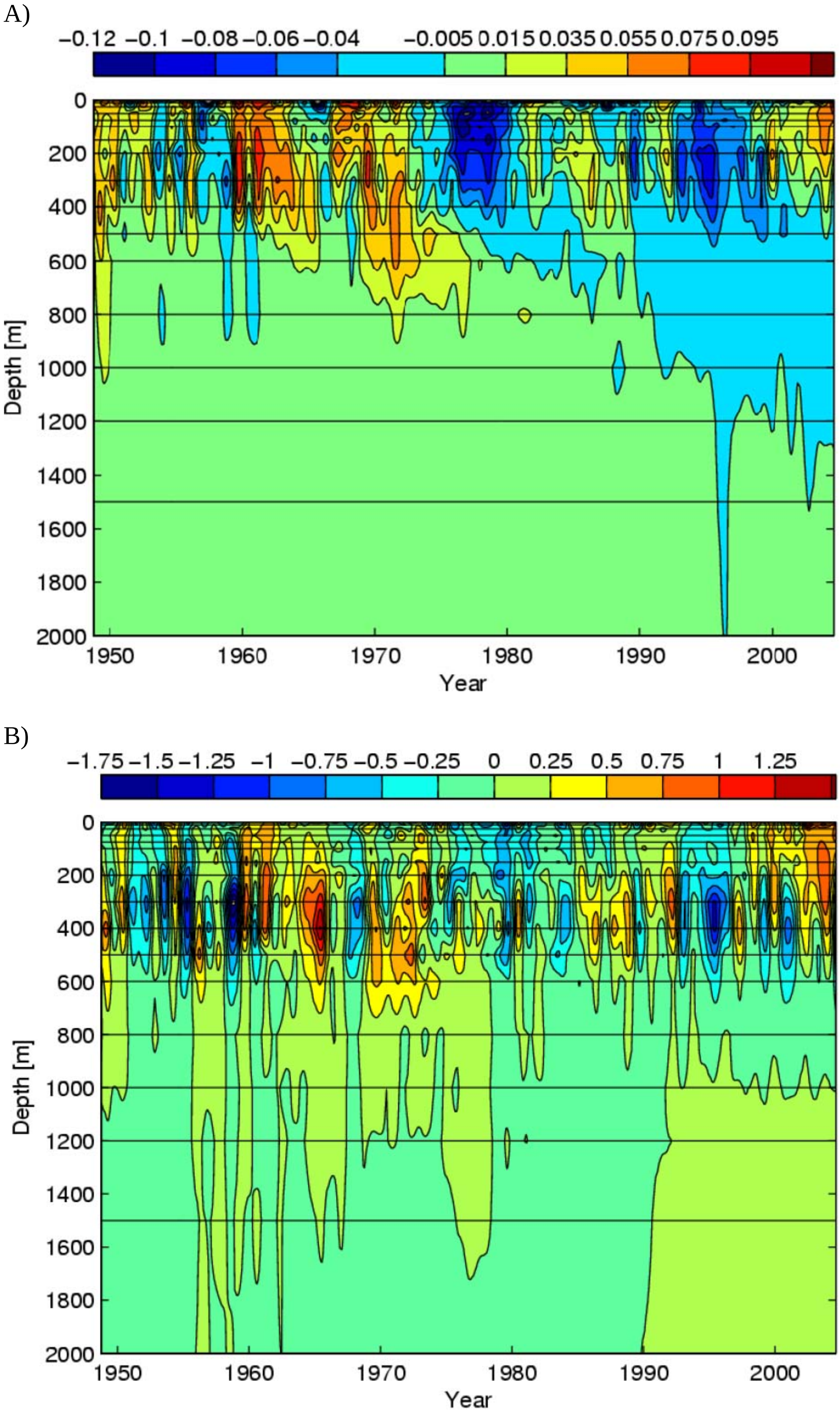

A)
−0.12 −0.1 −0.08 −0.06 −0.04 −0.005 0.015 0.035 0.055 0.075 0.095
Depth [m]
0
200
400
600
800
1000
1200
1400
1600
1800
2000
1950
1960
1970
1980
1990
2000
Year
B)
−1.75 −1.5 −1.25 −1 −0.75 −0.5 −0.25 0 0.25 0.5 0.75 1 1.25
Depth [m]
0
200
400
600
800
1000
1200
1400
1600
1800
2000
1950
1960
1970
1980
1990
2000
Year

Figure 6

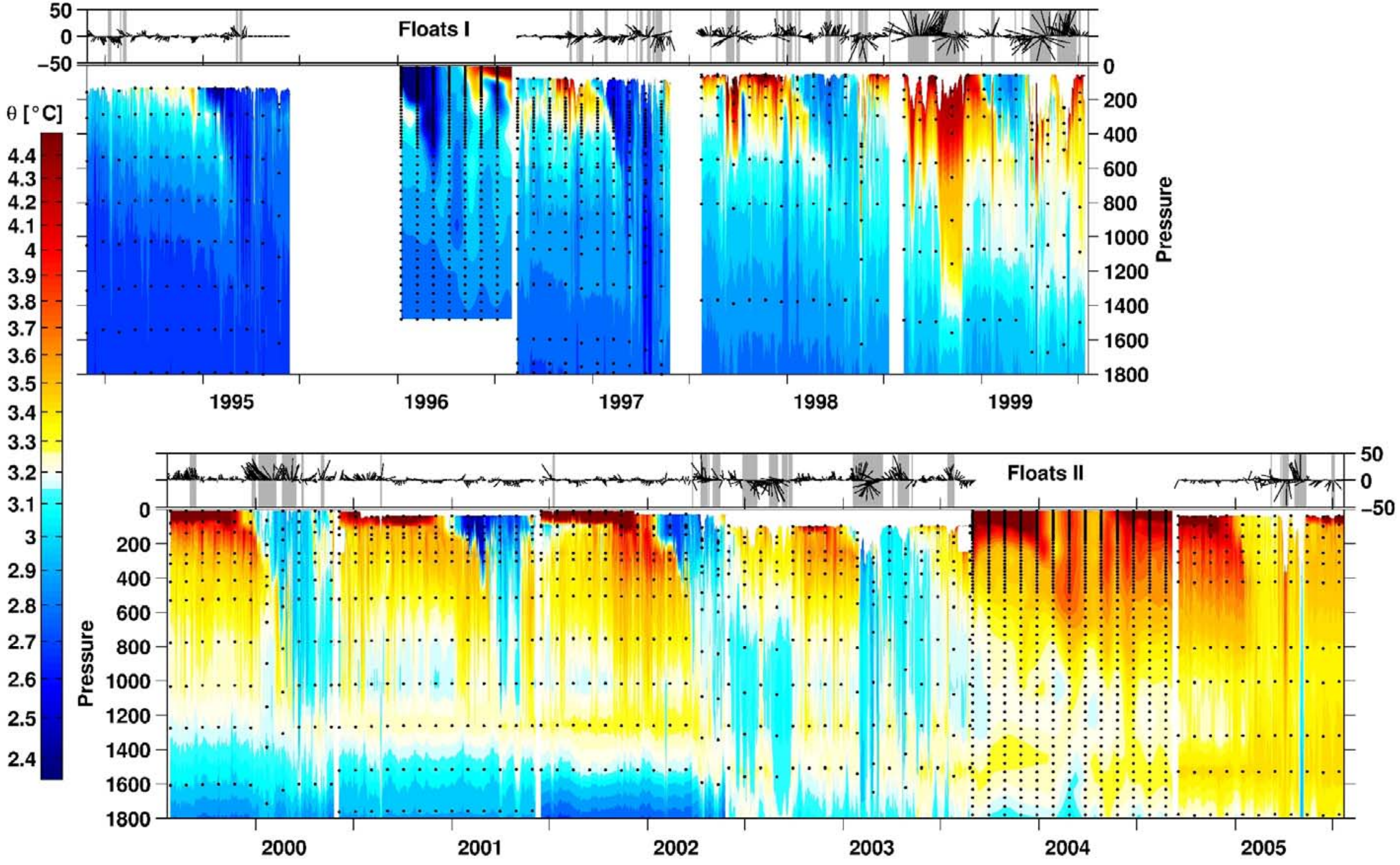

Floats I
Floats II
θ [°C]
4.4
4.3
4.2
4.1
4
3.9
3.8
3.7
3.6
3.5
3.4
3.3
3.2
3.1
3
2.9
2.8
2.7
2.6
2.5
2.4
50
0
−50
Pressure
0
200
400
600
800
1000
1200
1400
1600
1800
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005

Figure 7.

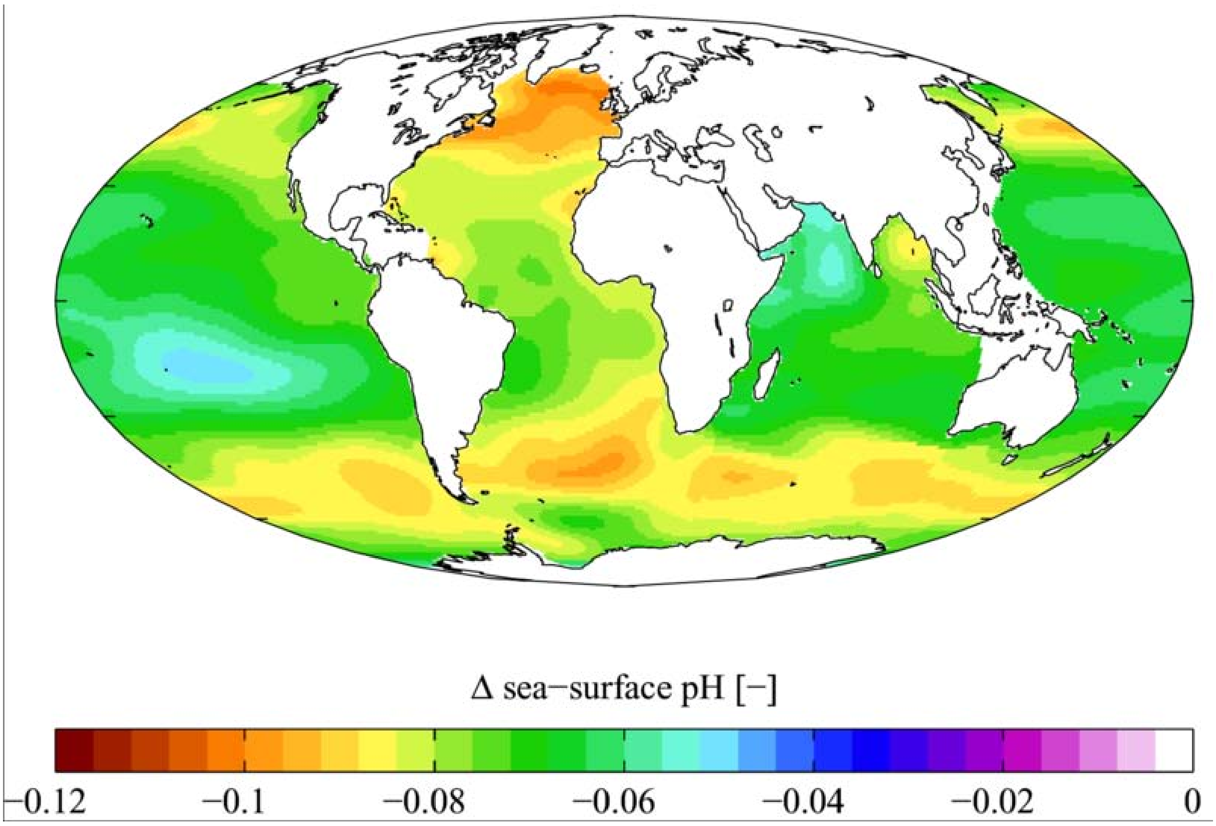


Figure 8

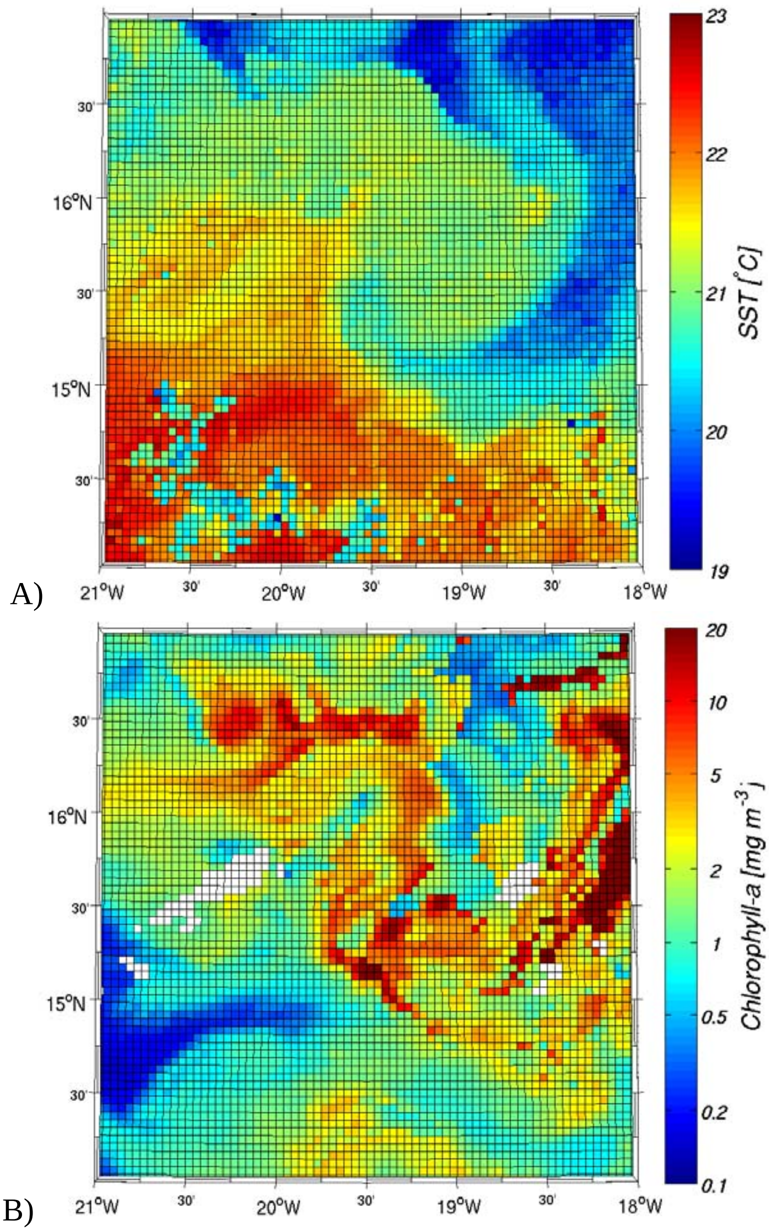


Figure 9.

Figure 8

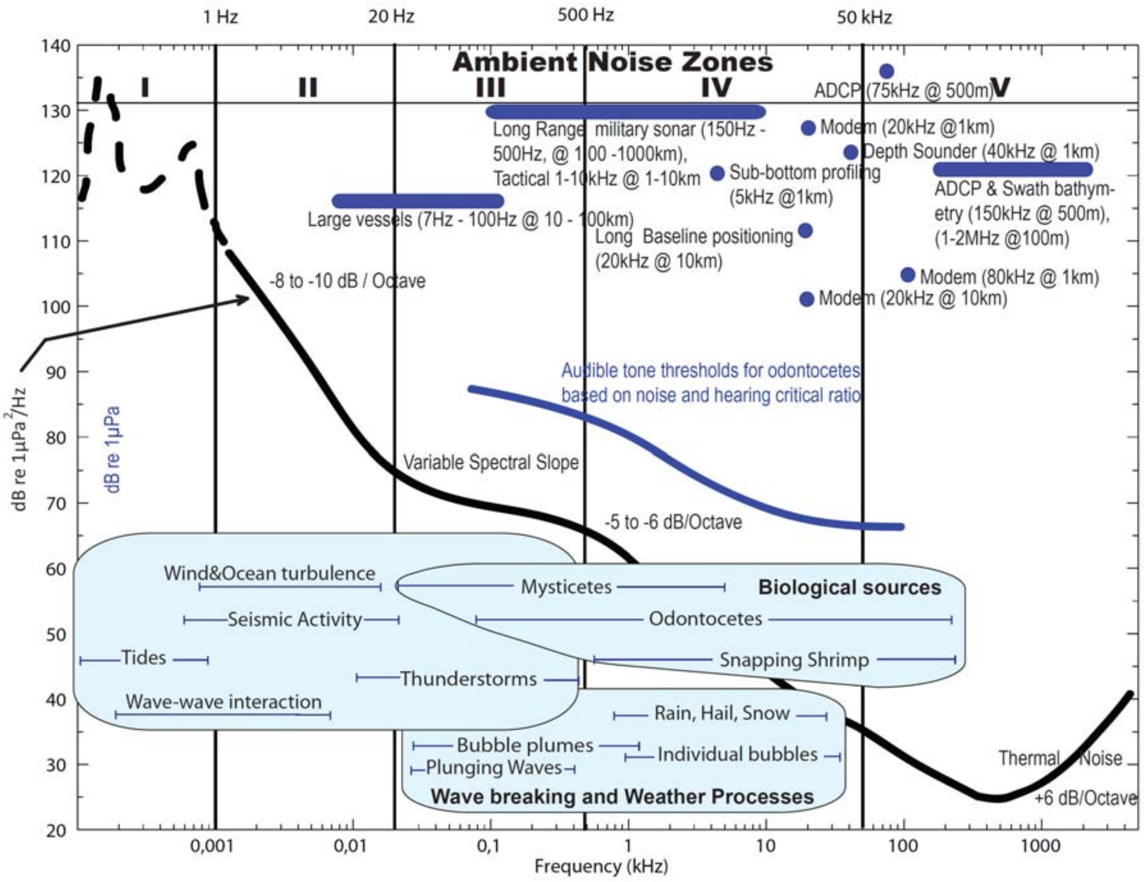

Ambient Noise Zones
I
II
III
IV
V
1 Hz
20 Hz
500 Hz
50 kHz
140
130
120
110
100
90
80
70
60
50
40
30
20
dB re 1µPa²/Hz
dB re 1µPa
0,001
0,01
0,1
1
10
100
1000
Frequency (kHz)
ADCP (75kHz @ 500m)
Long Range military sonar (150Hz - 500Hz, @ 100 -1000km), Tactical 1-10kHz @ 1-10km
Modem (20kHz @1km)
Depth Sounder (40kHz @ 1km)
Sub-bottom profiling (5kHz @1km)
ADCP & Swath bathymetry (150kHz @ 500m), (1-2MHz @100m)
Large vessels (7Hz - 100Hz @ 10 - 100km)
Long Baseline positioning (20kHz @ 10km)
Modem (80kHz @ 1km)
Modem (20kHz @ 10km)
-8 to -10 dB / Octave
Audible tone thresholds for odontocetes based on noise and hearing critical ratio
Variable Spectral Slope
-5 to -6 dB/Octave
Wind&Ocean turbulence
Seismic Activity
Tides
Thunderstorms
Wave-wave interaction
Mysticetes
Biological sources
Odontocetes
Snapping Shrimp
Rain, Hail, Snow
Bubble plumes
Individual bubbles
Plunging Waves
Wave breaking and Weather Processes
Thermal Noise
+6 dB/Octave

Figure 10

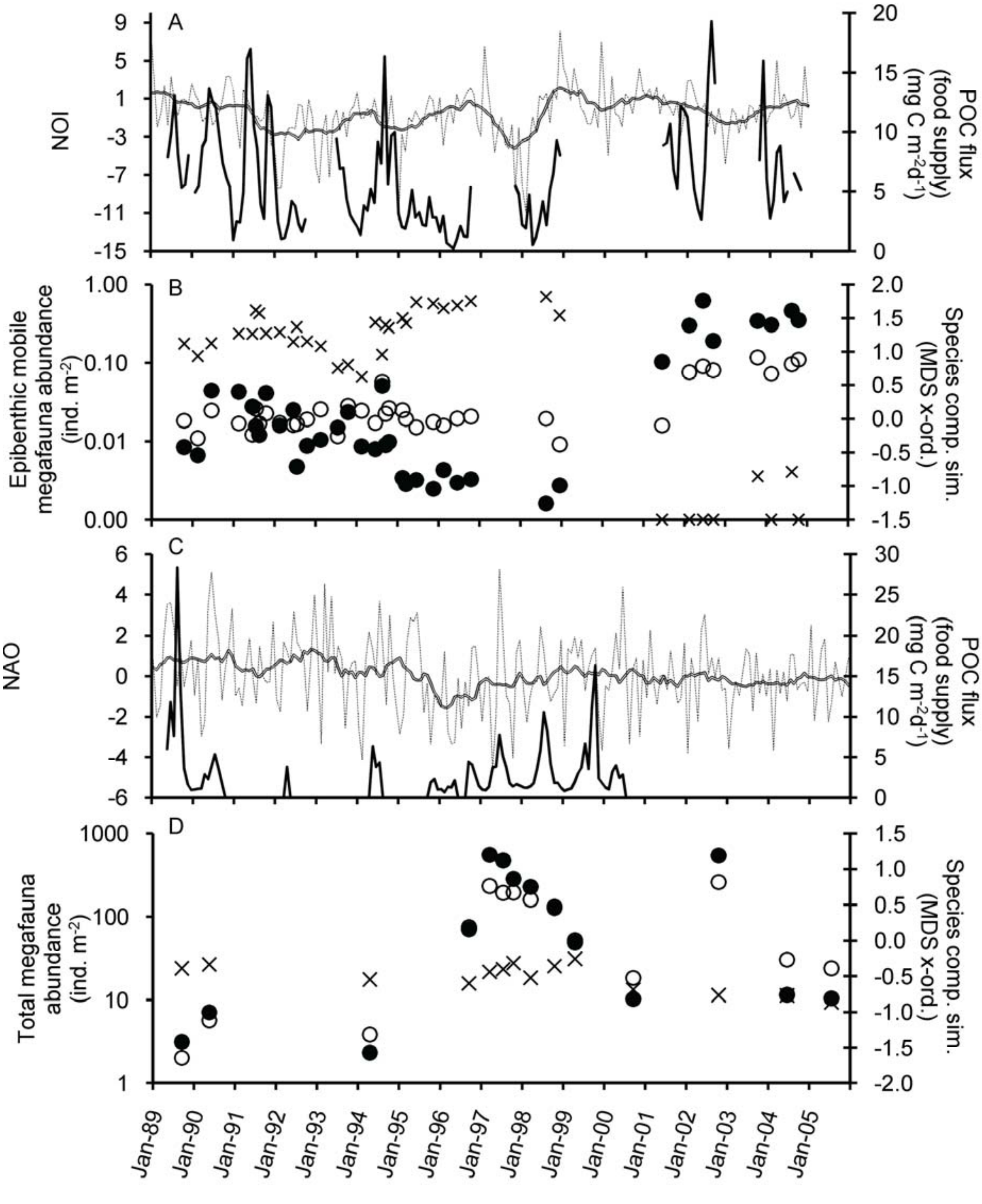

A
NOI
9
5
1
-3
-7
-11
-15
POC flux (food supply) (mg C m-2d-1)
20
15
10
5
0
B
Epibenthic mobile megafauna abundance (ind. m-2)
1.00
0.10
0.01
0.00
Species comp. sim. (MDS x-ord.)
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
C
NAO
6
4
2
0
-2
-4
-6
POC flux (food supply) (mg C m-2d-1)
30
25
20
15
10
5
0
D
Total megafauna abundance (ind. m-2)
1000
100
10
1
Species comp. sim. (MDS x-ord.)
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
-2.0
Jan-89
Jan-90
Jan-91
Jan-92
Jan-93
Jan-94
Jan-95
Jan-96
Jan-97
Jan-98
Jan-99
Jan-00
Jan-01
Jan-02
Jan-03
Jan-04
Jan-05

Figure 11

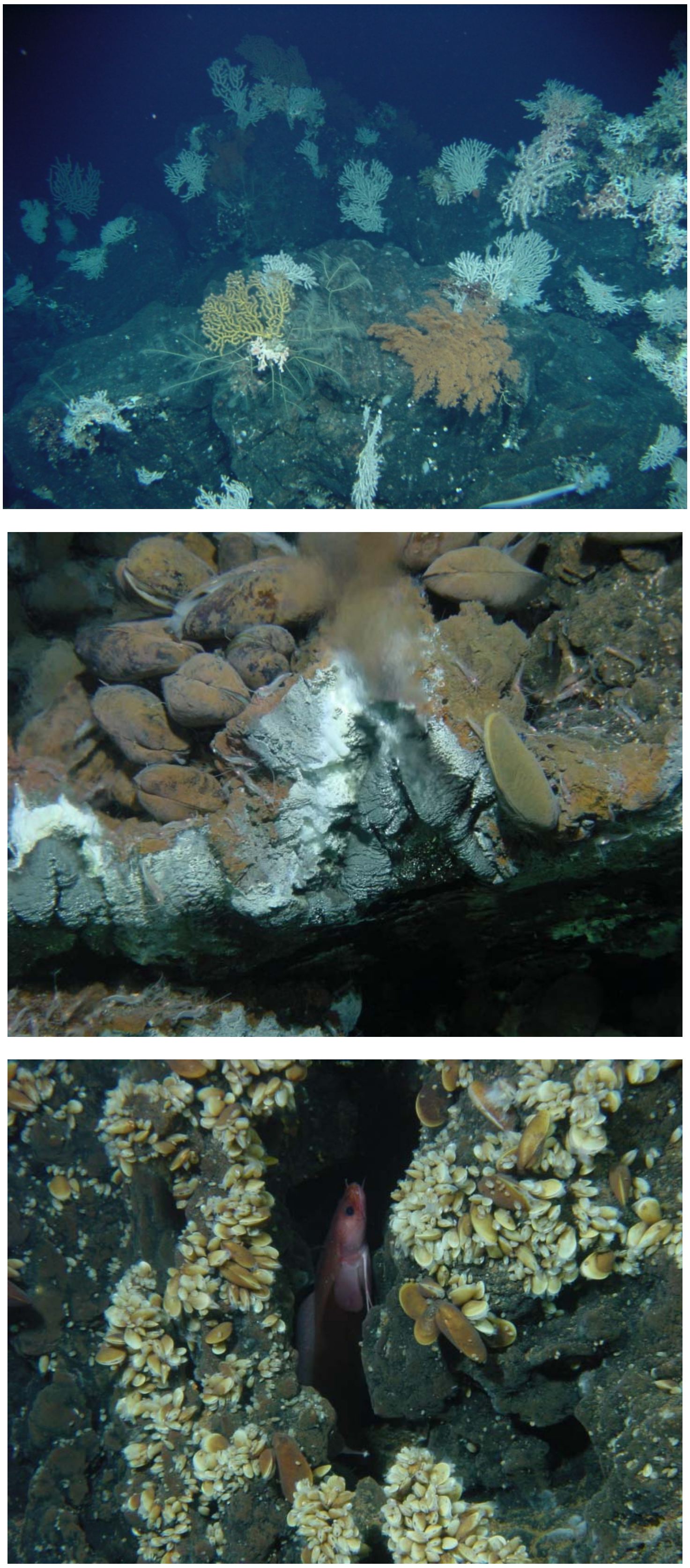


Figure 12

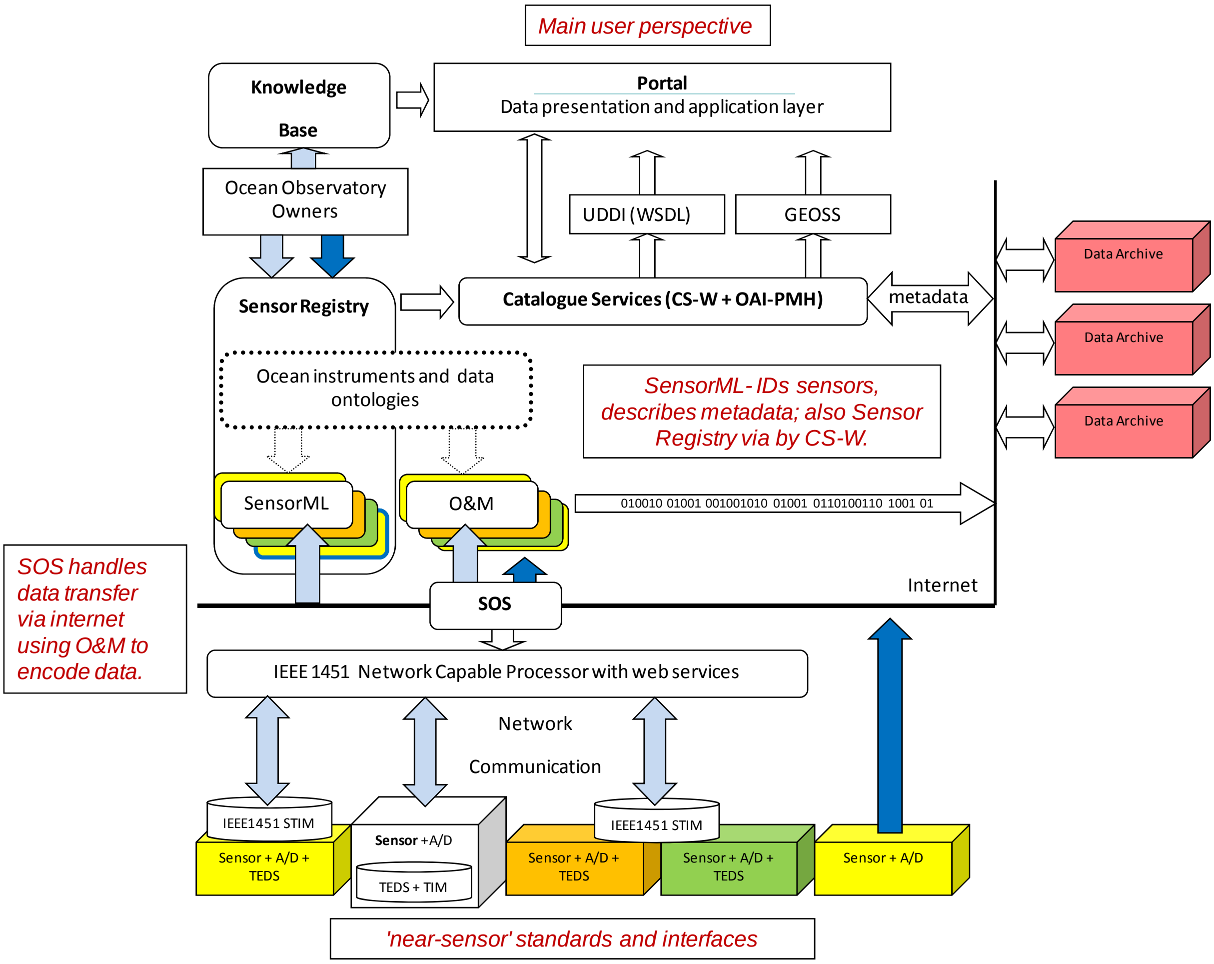

Main user perspective
Knowledge Base
Portal
Data presentation and application layer
Ocean Observatory Owners
UDDI (WSDL)
GEOSS
Sensor Registry
Catalogue Services (CS-W + OAI-PMH)
metadata
Data Archive
Data Archive
Data Archive
Ocean instruments and data ontologies
SensorML - IDs sensors, describes metadata; also Sensor Registry via by CS-W.
SensorML
O&M
010010 01001 001001010 01001 0110100110 1001 01
SOS handles data transfer via internet using O&M to encode data.
SOS
Internet
IEEE 1451 Network Capable Processor with web services
Network
Communication
IEEE1451 STIM
Sensor + A/D + TEDS
Sensor + A/D
TEDS + TIM
Sensor + A/D + TEDS
IEEE1451 STIM
Sensor + A/D + TEDS
Sensor + A/D
'near-sensor' standards and interfaces

Figure 13.

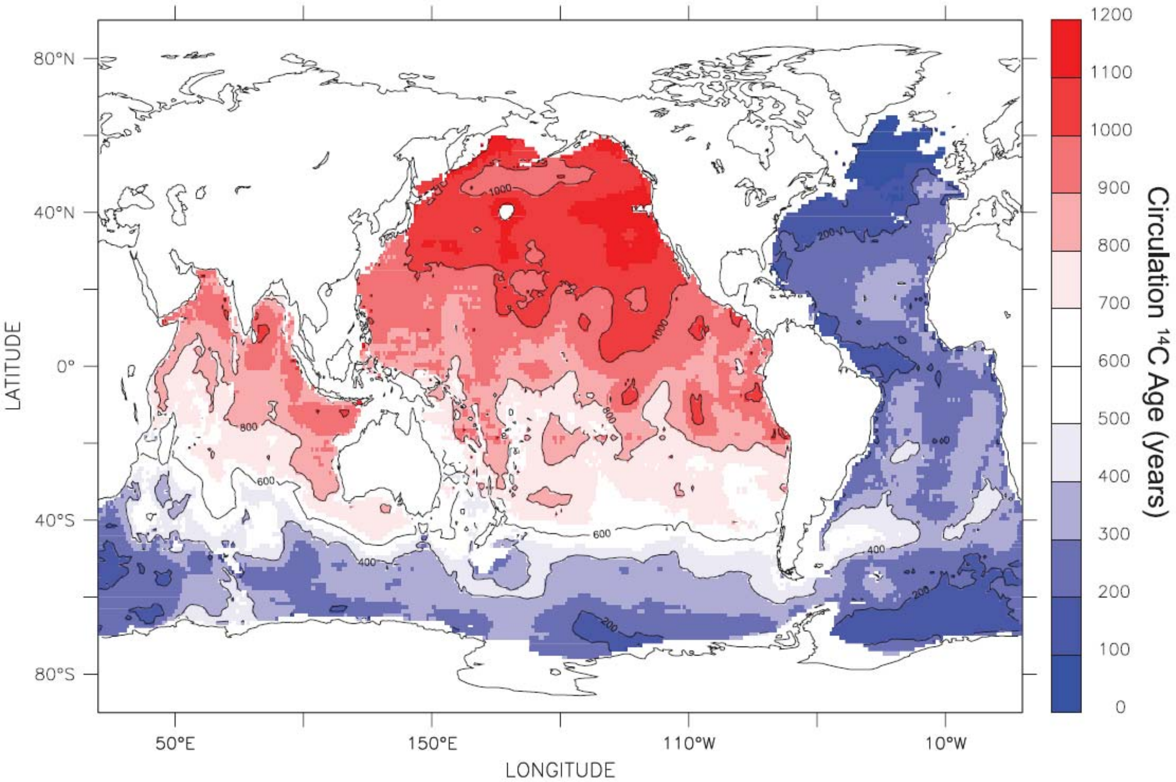

80°N
40°N
0°
40°S
80°S
LATITUDE
50°E
150°E
110°W
10°W
LONGITUDE
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
Circulation ^{14}C Age (years)
1000
800
600
400
200

Figure 14

Table 1. National and international projects and programmes with topics that relate to ocean observatory efforts.

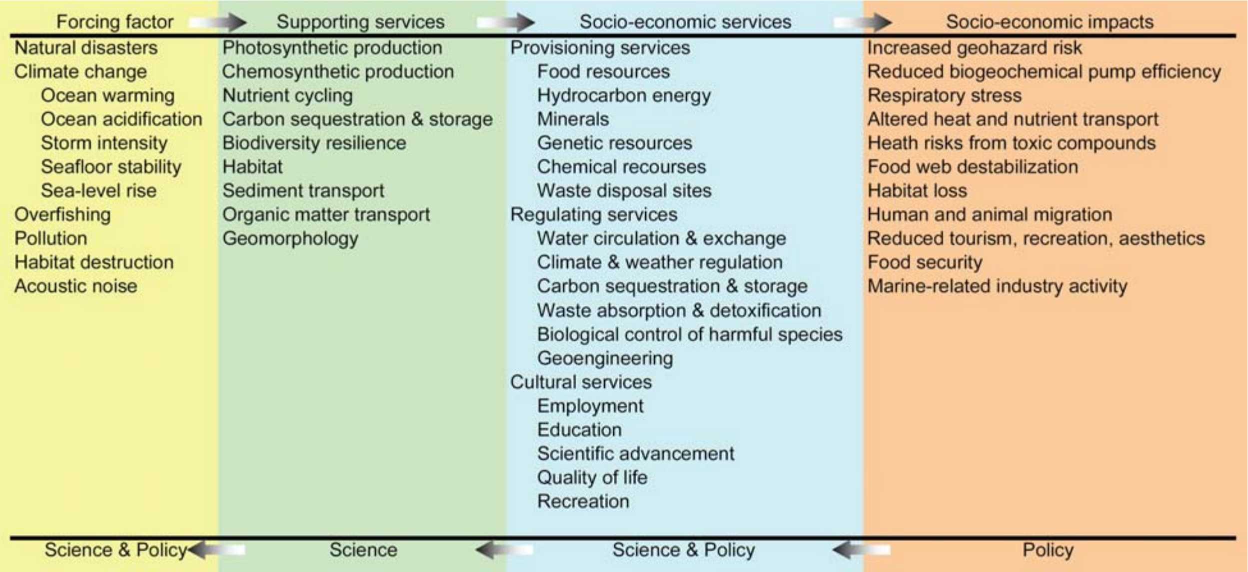
Table 2. Connections between forcing factors, supporting and utilized services, and socioeconomic impacts, as well as how these relate to policy and ocean observatory science which describes links between forcing and services and thereby informs societal policy. This table was adapted from the similar relationships outlined by the United Nations Environment Programme, HERMES, and the Center for Ocean Solutions (UNEP 2007, Center for Ocean Solutions 2009, Grehan et al. 2009). *In Colour*

Table 3. Overview of minimum specifications under consideration for in generic sensor modules that may be used across European ocean observatory sites

Table 1

Short name	Name or description
ANTARES	Astronomy with a Neutrino Telescope and Abyss environmental RESearch
Argo	Broad-scale global array of temperature and salinity profiling floats
BATS	Bermuda Atlantic Time Series
CarboOcean	Marine carbon sources and sinks assessment
DAMOCLES	Developing Arctic Modeling and Observing Capabilities for Long-term Environmental Studies
DELOS	Deep-ocean Environmental Long-term Observatory System
DONET	Dense Oceanfloor Network System for Earthquakes and Tsunamis
EMODNET	European Marine Observation and Data Network
EMSO	European Multidisciplinary Seafloor Observatory
EPOCA	European Project on OCean Acidification
EPOS	European Plate Observing System
ESFRI	European Strategy Forum on Research Infrastructures
ESONET CA	European Seafloor Observatory NETwork Concerted Action
ESONET NoE	European Seas Observatory NETwork Network of Excellence
ESONIM	ESONET Network Implementation Model
Eur-OCEANS	EURopean network of excellence for OCean Ecosystems ANalysis
EuroSITES	European Ocean Observatory Network, The European contribution to OceanSITES
EXOCET-D	EXtreme ecosystem studies in the deep OCEan: Technological Developments
GEOSS	Global Earth Observation System of Systems
GEOSTAR	Geophysical and Oceanographic Station for Abyssal Research
GMES	Global Monitoring for Environment and Security
GITEWS	German Indonesian Tsunami Early-Warning System (GITEWS)
HERMES	Hotspot Ecosystem Research on the Margins of European Seas
HERMIONE	Hotspot Ecosystem Research and Man's Impact on European Seas
HYPOX	*In situ* monitoring of oxygen depletion in hypoxic ecosystems of coastal and open sea, & land locked water bodies
IMBER	Integrated Marine Biogeochemistry and Ecosystem Research
IOC	Intergovernmental Oceanographic Commission
KM3NeT	Kilometre-cube Underwater Neutrino Telescope
MACHO	Marine Cable Hosted Observatory
MarBEF	Marine Biodiversity and Ecosystem Functioning
MERSEA	Marine Environment and Security for the European Area
MGE	Marine Genomics in Europe
MoMARNET	Monitoring deep sea floor hydrothermal environments on the Mid-Atlantic Ridge :A Marie Curie Research Training NETwork
MyOcean	The implementation project of the GMES Marine Core Service
NEAMTWS	North East Atlantic, Mediterranean and connected seas Tsunami Warning System
NEAREST	Integrated observations from NEAR shorE Sources of Tsunamis
NEMO	NEutrino Mediterranean Observatory
NEPTUNE Canada	The NorthEast Pacific Time-Series Undersea Networked Experiments
OceanSITES	A worldwide system of deepwater reference stations
OOI	US National Science foundation Ocean Observatories Initiative
RAPID-WATCH	Monitoring the Atlantic Meridional Overturning Circulation
OCB	US Ocean Carbon and Biogeochemistry programme
SeaDataNet	Pan-European infrastructure for ocean and marine data management
SIOS	Svalbard Integrated Arctic Earth Observing System
SOLAS	Surface Ocean Lower Atmosphere Study
WSO	Western Shelf Observatory (Ireland and United Kingdom)
THOR	Thermohaline Overturning – at Risk?

Table 2



Forcing factor →	Supporting services →	Socio-economic services →	Socio-economic impacts
Natural disasters	Photosynthetic production	Provisioning services	Increased geohazard risk
Climate change	Chemosynthetic production	Food resources	Reduced biogeochemical pump efficiency
Ocean warming	Nutrient cycling	Hydrocarbon energy	Respiratory stress
Ocean acidification	Carbon sequestration & storage	Minerals	Altered heat and nutrient transport
Storm intensity	Biodiversity resilience	Genetic resources	Heath risks from toxic compounds
Seafloor stability	Habitat	Chemical recourses	Food web destabilization
Sea-level rise	Sediment transport	Waste disposal sites	Habitat loss
Overfishing	Organic matter transport	Regulating services	Human and animal migration
Pollution	Geomorphology	Water circulation & exchange	Reduced tourism, recreation, aesthetics
Habitat destruction		Climate & weather regulation	Food security
Acoustic noise		Carbon sequestration & storage	Marine-related industry activity
		Waste absorption & detoxification	
		Biological control of harmful species	
		Geoengineering	
		Cultural services	
		Employment	
		Education	
		Scientific advancement	
		Quality of life	
		Recreation	
Science & Policy ←	Science ←	Science & Policy ←	Policy

Table 3

Type of sensor	Range†	Accuracy†	Sampling frequency
Conductivity	0 to 9 S/m	0.001 S/m	4 Hz*
Temperature	-5 to +35°C	0.01 K	4 Hz*
Pressure	0 to 600 bar	0.1 % FSR	4 Hz*
Dissolved oxygen	0 to 500µM	5%	0.01 Hz*
Carbon dioxide	0 to ≥600 ppm	1 ppm	1 min
Turbidity	0 to 150 NTU	10%	1 Hz*
Chl-a fluorescence‡	0 to ≥100 µg/l	5%	1 min
Currents	0 to 2 m/s	2%	1 Hz*
Passive acoustics	50 - 180 dB re 1 µPa	+/-3dB	96 KHz
Time-lapse camera$^{\sharp}$	Colour	5 Megapixels	hourly

†*Range and accuracy are given are often adjustable through calibration and given here as suggestions.*

**High-frequency only needed for a few applications (i.e. those related to turbulence)*

‡*Suggested for near surface stations*

$^{\sharp}$*Suggested for benthic stations*