DS³F
WP6:
Climate Change & response of deep-sea biota
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SEVENTH FRAMEWORK PROGRAMME

Deep-Sea and Sub-Seafloor Frontiers (DS3F): WP6 Workshop protocol, Climate change & response of deep-sea biota

1. General information

Urbino, Italy, 23-26 July 2010
Local Host: Simone Galeotti

2. Logistics

2.1. List of participants:

C. Agnini, J. Backman, H. Brinkhuis, I. Hall, J. Henderiks, D. Kroon, U. Ninneman, H. Pälike, I. Raffi, U. Röhl, R. Schneider, L. Skinner

2.2. Agenda and overall aim:

The aim of this workshop is to demonstrate the importance of palaeo data and to set the agenda for potential future EU FP calls, building on the outcome of existing projects, reports and efforts. Ths outcome is designed to feed into a larger report and conference of DS^{3}F activities.

3. Scientific Case

3.1. Introduction

Ocean floor sediment cores provide an archive that enables us to reconstruct past environmental conditions including climate that are needed to understand Earth System processes on a wide range of scales in space and time. The oceans are a major influence on Earth's climate, and provide the unique time-continuous sedimentary archive that records Earth processes on a wide range of temporal and spatial scales. The knowledge this contains is critical to our understanding of how the planet works. Obtaining sub-seafloor samples and the pioneering paleoclimate research it spawned have been central to our present understanding of fundamental earth science as well as providing societally relevant discoveries such as the role of atmospheric CO_2 in moderating global climate, and past changes in ocean acidification, palaeoceanography, polar processes and rapid climatic and ocean change. Reading this sediment archive enables us to reconstruct and understand key biogeochemical cycles, fluxes, and interactions between the biosphere, the oceans, the atmosphere, the terrestrial system and the solid Earth. Sub-seafloor samples contain key information on crucial parameters including global and regional temperatures, ocean currents and overturning circulation, sea-water *pH* and alkalinity, the hydrological cycle, sea-level, ice-volume, and the feedback mechanisms between elements of the climatic system. Paleoclimatic research has illuminated the nature of climate variability on all time scales, including orbital and glacial-interglacial cycles, and confirmed the global nature of high-amplitude yet short-lived oscillations such as Dansgaard-Oeschger cycles, Heinrich events, monsoons, ENSO, and millenial scale variability. Records from climate archives are the only way to extend historical and instrumental records of climate and to obtain environmental reconstructions from time periods with larger amplitude perturbations under different boundary conditions. Marine sediment cores allow the spatial correlation of records with ice-cores, lake records and terrestrial archives on time scales ranging from annual through geological. Sediment cores and samples are the only means by which we are able to extend and thus rewind Earth's environmental history to times and resolutions not accessible through other methods, that more closely resemble conditions predicted for the next few centuries and beyond, and to those that allow us to test and improve climate and Earth System models. The understanding obtained from ocean drilling is essential if society is to succeed in meeting the challenges of recent and projected changes in Earth's surface environment. These arise from human activity and complex natural feedbacks, and as a consequence that atmospheric greenhouse gas levels will soon exceed any experienced during the past 20 million years. Key responses that are accessible through coring include climate sensitivity and polar amplification in response to large scale perturbations or extreme events, latitudinal heat transport, ice sheet stability and sea-level change, ocean acidification and its ecological impacts, and changes in ocean circulation and biogeochemistry in the context of climate variability on different time scales. The relevance of palaeoclimate data have recently been reviewed by Henderson et al., (2009).

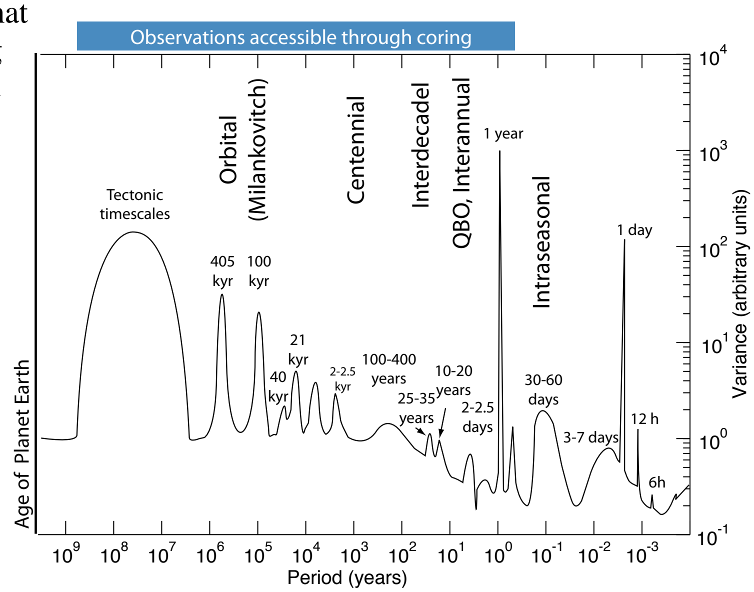

Figure 1: Ocean drilling allows reconstruction of climatic processes in a time-continuous way across a wide spectrum of time scales ranging from annual through tectonic time scales (blue bar). redrawn from J Murray Mitchell, Jnr., (1976) *Quaternary Research* 6, 481-493

3.2. Overall Challenge and identified Themes for future research

The key challenge of the scientific theme covered by WP6 is illustrated in Fig. 2. The aim is to use palaeodata to reconstruct past conditions and climate behaviour to inform future predictions. The key research approaches identified to enable palaeoclimate data to improve future prediction were given by Henderson et al. (2009) as

i. Quantifying proxy uncertainty and interpretation
ii. Synthesis of palaeoclimate data
iii. Testing model predictions against palaeodata

Interpreting the past relies on the application of palaeo-proxies, which in turn require knowledge of associated uncertainties. As the range of climate conditions observed in the instrumental record is small compared to predicted future change, and does not capture long-term processes and feedbacks, it is necessary to explore those scenarios from past conditions with climate proxy records.

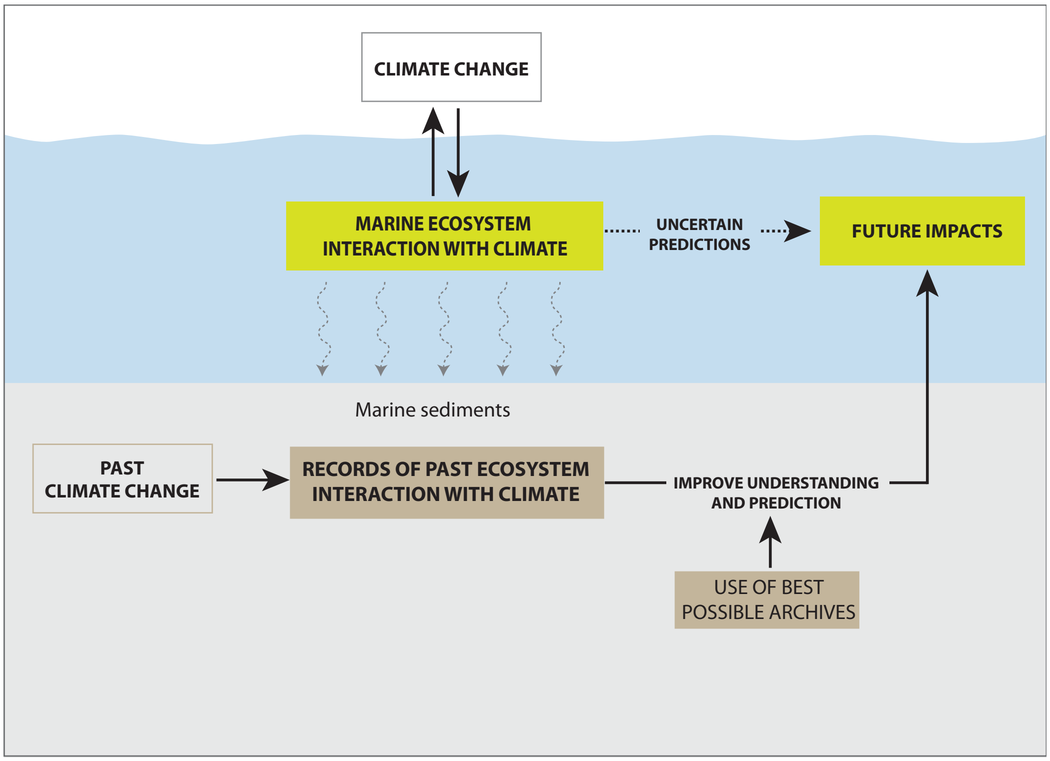

Figure 2: Schematic illustration showing how reconstruction of past climatic records from climate archives improves and guides the interpretation and prediction of future climatic impacts.

3.3. Results and Discussion

The WP6 workshop identified a number of Science problems of high importance with a Focus on climatic change and its impact on biota. For each problem, the workshop participants mapped out the overall problem, key questions and unsolved challenges, recommendations for required coring or sampling, required platforms, tools or infrastructure, and linkages and cross references.

3.3.1. Biotic response to perturbations on different time-scales and for different rates of change, including extinctions and evolution (threshold behaviour of both biota and the climate system)

3.3.1.1. Set out of the overall problem

Marine sediment-forming plankton are important for three major reasons:

1. They constitute the base of the food chain in the oceans;
2. They influence global climate;
3. They respond to changes in global climate climate, and therefore their fossil remains are the backbone of reconstructions of past conditions in the oceans and the history of global climate.

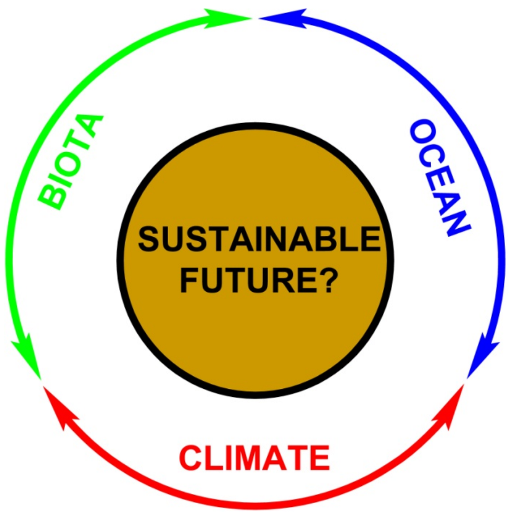

Figure 3: Interaction of the oceans, the global climate and the marine plankton communities. A change in one part of this three-component system influences the other two, like a domino effect. For example, climate change will influence biogeographic distributions of the plankton communities and, in turn, plankton influences biogeochemical cycles such as the carbon cycle, which is a crucial component of the global climate system.

The co-evolution of our planet and life is of fundamental interest. Yet, we currently have little appreciation for how our environments, and the species we depend upon, will respond to future global change. Gaining an improved understanding of marine ecosystems has direct societal relevance because these systems provide a vital part of human welfare, such as food availability. An improved understanding of these systems is also key to the understanding of the dynamics of the global biosphere.

The Earth's fossil record preserves a high fidelity archive of the vitality of life on our planet. Ocean sediments are central to understanding the role of the biosphere in Earth evolution because they contain the continuous temporal records of how ocean biological communities both respond to and force climate change (Figure 4).

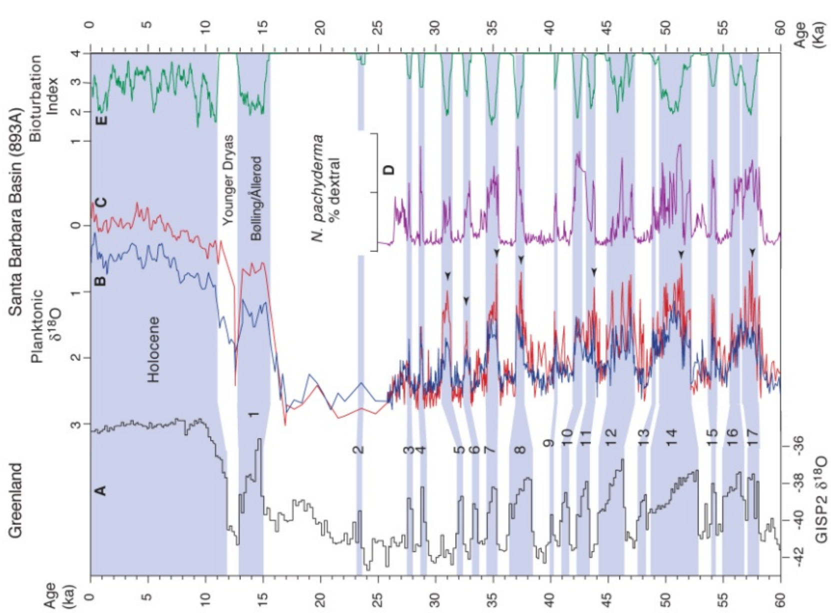

Figure 4: Link between plankton and benthic communi-ties, and climate change. The fauna of both realms show a direct and rapid (decadal-scale) response to climate forcing, highlighting biological feedbacks to climate. An example of how sensitive life is to climate driven change. (Hendy & Kennett, Geology 1999).

The unrivaled time resolution available for deep sea sediments place discoveries in modern ecology into a detailed historical record showing not only a history of events, but also refining our understanding of the interplay between global change and life's diversity. This fossil record can be sampled through presently available coring techniques.

3.3.1.2. Key questions and unsolved challenges

1. Productivity of marine plankton and the long term storage of their fossil remains in deep sea sediments is a major component in the carbon cycle. Establishing the detailed workings between productivity, the carbon cycle and global climate are crucial for construction of global biogeochemical models. This information is needed in order to reduce uncertainties in models of global climate change**. A key goal is to determine the link between productivity variations and climate through time (the past 100 million years).**
2. Exploiting the richness of the marine fossil record can address key issues in the evolution of life, the rate of evolutionary change, building on appearances and extinctions of taxa. Knowledge about the dynamics of speciation and extinction is relevant not only to modern evolutionary theory, but also to evaluating the sensitivity of life to global change. Such information is of great value to stratigraphers worldwide, far beyond academic circles and there are widespread industrial applications. All studies of past climate and environmental change relies heavily on the resolution and accuracy of the chronological models used. Biostratigraphy is a major component in the development of such models. **A key goal is to further develop and refine the history of evolutionary change among marine plankton communities, and hence the biostratigraphic information contained in this evolution.**
3. The fact that marine microfossils contain within them diverse chemical clues to their life environment makes a powerful combination for reconstruction of ocean paleoecology and paleoclimate. **A key goal is to obtain highly resolved temporal records of paleoecology and paleoclimate from various geographical and environmental settings in order to reconstruct rates and amplitudes of climate change through time.**

The diversity of life in marine ecosystems includes also the deep realms of the oceans, which can be studied through analysis of bottom living biota, amongst them the benthic foraminifers and deep cold-water coral reefs. Another crucial part in the marine ecosystem is the shallow, warm water thriving, coral reefs. A key goal is to employ information contained in these biotic archives for reconstructions of deep sea environments, sea-level fluctuations and seasonal shallow water temperature fluctuations in tropical and equatorial regions.

Many of our most pressing questions concern how ecosystems that we depend upon are likely to change over the next several centuries, which will influence our ability to achieve a sustainable future (Fig. 3). Yet, ecosystem dynamics are notoriously complex and hard to model, and individual species may react very differently to the same environmental changes. The fossil record in the oceans holds the actual record of how ecosystems responded to events like abrupt climate warming, ocean acidification, and mass extinction. These past examples of ecological response to change are not, of course, exact analogs to our near future. Nonetheless such examples show how ecological dynamics play out as integrated systems of tipping points, resilience and resistance to change. Therefore, the marine fossil record can teach us how ecosystems and their species function as dynamical systems. Such studies must range across all the timescales that ocean drilling can deliver, from decadal change to the multi-million year evolution of the Earth and its climate.

3.3.1.3. Recommendations for required coring/sampling

- latitudinal and meriodinal transects
- transects accounting for depth dependent environmental conditions and variability in the oceans
- shelf to deep ocean transects
- specific locations representing unique environmental settings

3.3.1.4. Requirements in terms of platforms/tools/infrastructure

- Access to ocean drilling vessel with capabilities like the IODP vessel *Joides Resolution*
- Access to high-quality sediment piston cores
- Access to sufficient core material
- Construction of high-resolution and continuous time series (triple coring)

3.3.2. Climate Sensitivity and biotic impact

3.3.2.1. Set out of the overall problem

The term '*equilibrium climate sensitivity*' originates from the climate modelling community, and is described in (Core Writing Team For the AR4 Synthesis Report, 2007) as a measure of the climate system response to sustained radiative forcing. It is defined as the equilibrium global average surface warming following a doubling of CO_2 and greenhouse gas equivalent concentrations. The AR4 provides an assessment that "*climate sensitivity is likely to be in the range of 2 to 4.5°C with a best estimate of about 3°C, and is very unlikely to be less than 1.5°C. Values substantially higher than 4.5°C cannot be excluded, but agreement of models with observations is not as good for those values*". In the current context, climate sensitivity is more extensive than the narrow definition, and crucially includes feedback processes that may operate on a wide range of time scales including phenomena such as carbon cycle feedbacks, cloud cover, albedo, glacial processes, weathering, and acidification. Climate Sensitivity may also be non-linear (feedbacks affected by feedbacks) and most likely depends on the state of the

> *"Recent modelling studies show that uncertainty in carbon cycle feedbacks are as significant as physical uncertainties in controlling the future increase of atmospheric CO_2."* Huntingford *et al.* , 2009

climate system (cold versus warm mean state). Climate Sensitivity may also affect the characteristics of climate variability, for example the response to orbital forcing in a warm climate compared to a cold climate state.

AR4 states that, "*Models differ considerably in their estimates of the strength of the different feedbacks in the climate system*" and that "*The magnitude of future carbon cycle feedbacks is still poorly determined*". The main uncertainties highlighted in AR4 include: (1) incomplete understanding of the impacts of changes in ocean circulation on ocean CO_2 uptake; (2) the response of marine biota to ocean acidification; (3) the role and response time of terrestrial vegetation feedbacks; and (4) our knowledge of the global methane cycle. Recent modelling studies show that uncertainty in carbon cycle feedbacks are as significant as physical uncertainties in controlling the future increase of atmospheric CO_2 (Huntingford *et al.,* 2009), thus allowing a major contribution to this debate to be made by Ocean Drilling.

Increasing atmospheric CO_2 is the main driving force for future projected climatic change. The rate of this increase is dependent on the addition of carbon to the atmosphere, but also on a range of feedbacks within the carbon cycle. Such feedbacks play a significant role in regional climate change through their influence on ecosystems, albedo and water budgets. Understanding these biogeochemical feedbacks in the carbon cycle is thus fundamental to the prediction of future climate change. Important aspects of this cycle operate on time scales that make paleoclimate a powerful tool for better quantification (Henderson *et al.,* 2009).

It is one of the major strengths of sub-seafloor sampling and coring to provide unique data that bear on the quantification of climate sensitivity in the past, as well as understanding the feedback processes that need to be included for a successful modelling of this topic of great societal relevance. This is so because paleo proxy data can deliver estimates of both temperature and ocean chemistry, including pCO_2, from a wide range of different past boundary conditions, and over a whole range of time scales inaccessible by modern, historical, or ice-core records.

> *"The PETM either resulted from an enormous input of CO_2 that currently defies a mechanistic explanation, or climate sensitivity to CO_2 was extremely high."* Mark Pagani, 2006

3.3.2.2. Key questions and unsolved challenges

The major hypothesis to be addressed by sub-seafloor sampling is : *"Sediment records can provide otherwise unaccessible high-resolution paleoclimate records on a multitude of time scales that provide information on the coupling between global temperatures and greenhouse gas concentrations, and provide insights into the feedback processes that will allow a reduction in uncertainty of Climate Sensitivity and climate feedbacks for future climate predictions*".

- How have atmospheric CO_2 levels and temperatures varied through time, what is the relationship between atmospheric CO_2 levels, ocean chemistry, for example surface ocean *pH*, depth of the carbonate compensation depth (CCD) and temperatures in various oceans and overturning and circulation, and climate?
- What has been the biotic impact of changes in greenhouse gases and temperature?
- For past changes in the carbon cycle, what were the rates of pCO_2 increase, temperature increase and earth system recovery, as compared to present and future rates?
- During past warming and cooling events, what was the partitioning between direct radiative forcing and feedback components to global temperature change (Zeebe *et al*., 2009; Pagani, 2006)?
- How has Climate Sensitivity changed in the past?
- Are there pCO_2 thresholds in the climate system (cryosphere, ocean physical/chemical state)? What are the thresholds for different past time periods (deConto *et al*., 2008)?
- How does the meridional temperature gradient depend on pCO_2? What are the implications for poleward heat transport?
- What are the properties of the hydrologic cycle during warmer climate regimes? To what extent does it feedback on the climate state?
- How are transient climate states affected by climate sensitivity?
- Has Earth's system become more sensitive in the Neogene?
- What is the temporal evolution of pCO_2 (with higher accuracy)?
- How can we use orbital forcing to better understand climate feedbacks and variability? Why is there a change in response after 1 Ma?
- What were past methane levels?
- What role do boundary conditions play in determining Earth's climate (e.g. paleogeography, topography)?
- To narrow the uncertainty and improve temporal resolution of paleo–pCO_2 and paleotemperatures.
- To address how climate sensitivity and variability depend on the mean state of the climate system (Greenhouse *vs.* Warmhouse *vs*. Icehouse worlds), temporal variation of Climate Sensitivity.
- To establish the spatial response of the climate system, especially temperature and changes to the hydrologic cycle, requiring latitudinal and land-ocean transects.

3.3.2.3. Recommendations for required coring/sampling

Previous sampling has demonstrated the need for a more complete and global coverage to fully understand the coupled global carbon cycle, allowing us to exploit data from drill sites (Panchuk *et al.,* 2008). One important requirement for additional drilling is to constrain the Pacific CCD prior to the PETM (Zeebe *et al.,* 2009).

Existing cores provide only partial information for climate sensitivity reconstructions, for example during the Pliocene. There is a need for latitudinal transects for other warm climate intervals, and continued funding is required to process existing cores with new proxies. In addition, there is an expressed need to obtain sediment cores from thermally immature, expanded sections that are stratigraphically complete. Ideally, these would be from clay rich horizons with good carbonate, silica and organic matter preservation.

For the Miocene time interval, a much higher temporal resolution is required to address this problem includes new drill sites located along latitudinal and depth gradients, as well as continent-ocean transects. Such improved geographic and depth coverage is, for instance, necessary to constrain the location and latitudinal variation of the CCD, and of deep circulation and overturning in various oceans in detail so these data can be used in carbon cycle models.

New drilling is needed specifically in shelf and marginal sea regions where there is a requirement for clay-rich sediments which contain better preserved carbonates as well as organic fossils and biomarkers. These records will be complimentary to deep-ocean transects, as they are likely to be less complete, but will allow geochemical analyses that necessitate better preserved material, such as recently obtained by Pearson et al. (2009) from Tanzania

3.3.2.4. Requirements in terms of platforms/tools/infrastructure

Scientific strategies required in order to determine and understand Climate Sensitivity require three main steps. As a first priority, the time scales of interest needs to be identified, and then continuous records need to be obtained across these time scales of interest. Possible target intervals include times of rapid and large amplitude climate state reorganisations such as the Early Eocene Climatic Optimum (Zachos *et al.,* 2001), the MECO (Bohaty *et al.,* 2009), the Eocene/Oligocene boundary (Coxall *et al.,* 2005; Liu *et al.,* 2009; Pearson *et al.,* 2009); the Oligocene/Miocene boundary (Pälike *et al.,* 2006), and Neogene time intervals (Pagani *et al.,* 2009).

Identified target time slices should then determine the drill site selection, with the requirement that the material to be cored allows the application of multiple proxies (carbonate and organic carbon based). This will probably require drilling near margins, and in areas of with high sedimentation rates. Over a ten year period, it could be possible to conduct a latitudinal transect, following the paleo-geosecs approach identified in the CHART report (2009).

Platform needs are dictated by the desirability to determine long-term pole-to-equator thermal gradients for specific time slices. One important missing piece, for example, is to recover the missing time intervals from the ACEX Arctic Ocean Drilling Expedition (IODP 302, Moran *et al.,* 2006).

A new approach will also be required to fully exploit the opportunities offered by collaborating with international partner organizations. Interaction with ICDP is requested to connect continental processes with the oceans. Closer and more frequent interaction with the modelling community is required to develop synergies and expand observations globally. Interaction with the ice modelling community is needed to fully appreciate glacial stream flows. More collaboration with physical oceanographers is required to comprehend the potential impact of ocean circulation pattern changes on Climate Sensitivity, and ANDRILL and SHALDRILL expertise and data will form a natural link to fully exploit the breadth of data required to tackle this problem of extreme societal relevance.

3.3.3. Ocean acidification

3.3.3.1. Set out of the overall problem

The ocean is the largest sink for anthropogenic CO_2 and has absorbed nearly 35% of the carbon released to the atmosphere by fossil fuel combustion. Since the beginning of the Industrial Revolution, ocean acidity has increased by 30%, at a rate 100 times faster than any change in acidity experienced by marine organisms for at least the last 20 million years (Orr et al. 2005). Model simulations of the ocean/atmosphere response to the eventual complete utilization of fossil fuels indicate that atmospheric CO_2 will rise to levels that Earth likely has not experienced for at least 40 million years. The planet will continue to warm, and the surface ocean may undergo acidification which will make large parts of the water column undersaturated for $CaCO_3$ and reduce or even inhibit shell formation of many organisms, including molluscs, foraminifers, phytoplankton and corals (including the deep sea dwelling cold-water corals) (Fig. 5).

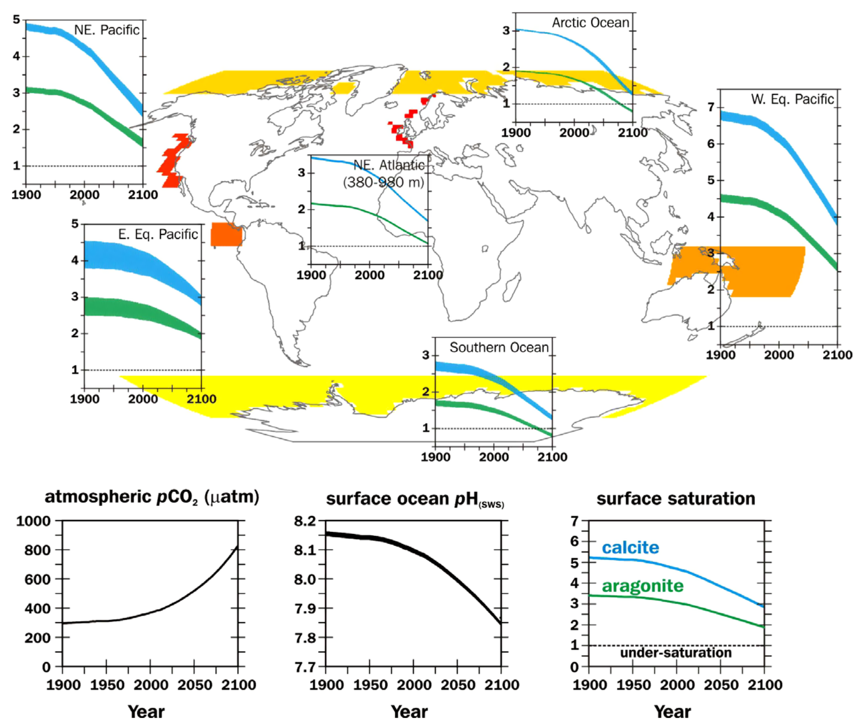

Figure 5: Projected future changes in seawater saturation state for aragonite (green) and calcite (blue). Values above 1 indicate super-saturation, below 1 undersaturation. From C. Turley et al., 2010.

3.3.3.2. Key questions and unsolved challenges

1. What is the sensitivity of biological calcification to the saturation state of seawater?

The most complete approach would compare laboratory, sediment trap, and sedimentary evidence across diverse organisms, including corals, foraminifers, coccolithophores, pteropods, and other marine calcifiers. Different time scales to consider…

2. What is the natural variability of seawater carbonate saturation state, the long-term trend, and the recent detectable response by marine biota?

Premier variables to reconstruct are the saturation state and the rates of calcification, dissolution, and other parameters.

3. What are the feedbacks between marine biota and the ocean carbon cycle?

The mechanisms of ocean carbon cycling, and specific uptake and storage areas, are still under debate. Proxy estimates of surface, intermediate and deep-water carbonate chemistry, organic carbon production and deposition, temperature distribution, ocean circulation changes, and many more, are either missing or too sparse to unambiguously identify the controlling factors.

4. What are the impacts of sequestration within the ocean or under the seafloor?

Decisions to purposefully sequester carbon require improved understanding of the processes described above (eventually leading to a predictive capability for carbon in the ocean). The size and location of potential reservoirs, chemical reactions beneath the seafloor, and fluid flow in permeable rocks are all questions that need to be addressed. Progress in this area would benefit from collaborations **between industry and academia**.

The impact of lowered pH and carbonate saturation state of the oceans on marine biota remains largely unknown, in part because modern organisms show highly variable, non-predictable responses.

The absorption of fossil fuel CO_2 by the ocean is not instantaneous, but we do not know how much CO_2 can be absorbed by the oceans, where and how it spreads, how fast it is neutralized, or how acidification will affect organic carbon production and oceanic biota.

3.3.3.3. Recommendations for required coring/sampling

The cycling of carbon in the ocean varies dramatically among different regions. A pragmatic, stepped approach should target key environments including low latitude open-ocean environments, high-latitude open ocean environments, shallow water carbonates (including coral reefs), and coastal upwelling areas. Past global warming events, termed hyperthermals, provide a unique opportunity to gain insight into the long-term impacts of rapidly rising CO_2 levels on modern climate, ocean carbonate chemistry, and biotas. They also provide an opportunity to identify potential non-linear feedbacks, and test climate and biogeochemical model sensitivity. Target projects in order of geological age include the Paleocene-Eocene Thermal Maximum (PETM) and other hyperthermals of the early Paleogene, Cretaceous Oceanic Anoxic Events (OAEs) as acidification events in an extreme greenhouse world. The effects of

pCO_2 fluctuations on coral reef environments and carbonate platforms can be examined within the Cenozoic trend of declining pCO_2-levels and cooling, Plio-Pleistocene Glacial/ Interglacial dissolution cycles. Once long-term proxy records are obtained it will be possible to determine the feedbacks within the carbon-climate system, and the timescales and processes that restore the system back to base conditions after a change in ocean *pH*.

3.3.3.4. Requirements in terms of platforms/tools/infrastructure or linkages

Ocean drilling is required to obtain past records of ocean acidification, complemented by geological outcrop sampling. Transect strategies (shallow shelf to deep, palatolatitudinal) will be required to fully assess the impact of ocean acidifcation in the past. Long-term proxy records of past ocean chemistry and marine biota variability will be able to draw on significant interactions with dedicated research efforts, including the European Project on Ocean Acidification (EPOCA), the Ocean Acidification Network, the International Ocean Carbon Coordination Project (IOCCP), the Integrated Marine Biogeochemistry and Ecosystem Research (IMBER), the US Ocean Carbon and Biogeochemistry Program (OCB) ocean acidification subcommittee, the International Geosphere-Biosphere Programme (IGBP), as well as directed national ocean acidification research efforts in the EU, USA and Japan.

3.3.4. Magnitude and Rate of sea-level change

3.3.4.1. Set out of the overall problem

One of the most societally-relevant objectives within the earth sciences is to understand the history and impact of global sea-level (eustatic) fluctuations at different timescales. Paleo-observations may be the only way to constrain ice sheet models to improve projections of the ice-sheet component of future sea-level rise.

In the last few decades most sea-level rise has been from the thermal expansion of the oceans but **ice sheets provide the greatest potential risk for future sea-level rise** because of their huge volume (64 m sea level equivalent). Satellite-based mass balance estimates show that ice sheets have recently begun to lose ice, with projections to 2100 suggesting an increase in the order of 20 times the 1993-2003 average. However, **uncertainties in sea-level projections are large** because ice sheet dynamics as climate warms are still poorly understood. Because **the instrumental record of sea level extends back only to about 150 years**, the refinement of the predictions of sea-level rise and of its impact on shoreline stability and habitability for the coming decades and centuries **requires the acquisition of sea-level records on a wide range of timescales.**

Over the past 100 My, changes in sea level reflect the evolution of global climate from a time characterized by small- to medium-sized and ephemeral Antarctic ice sheets (100 to 33 Ma), through a time when large ice sheets existed only in Antarctica (34 to 2.5 Ma), to a world with large Antarctic ice sheet and variable Northern Hemisphere ice sheets (2.5 Ma to the present), when Earth has been colder than any time in the last 65 My. Over the past ~800 kyr, the cyclic growth and decay of ice sheets induced rapid sea-level change every ~100 kyr with maximum amplitudes of 120–140 m. However, the timing, rates, and contributions of various ice sheets to these changes remain poorly constrained, making possible future scenarios difficult to predict. (Fig. 6).

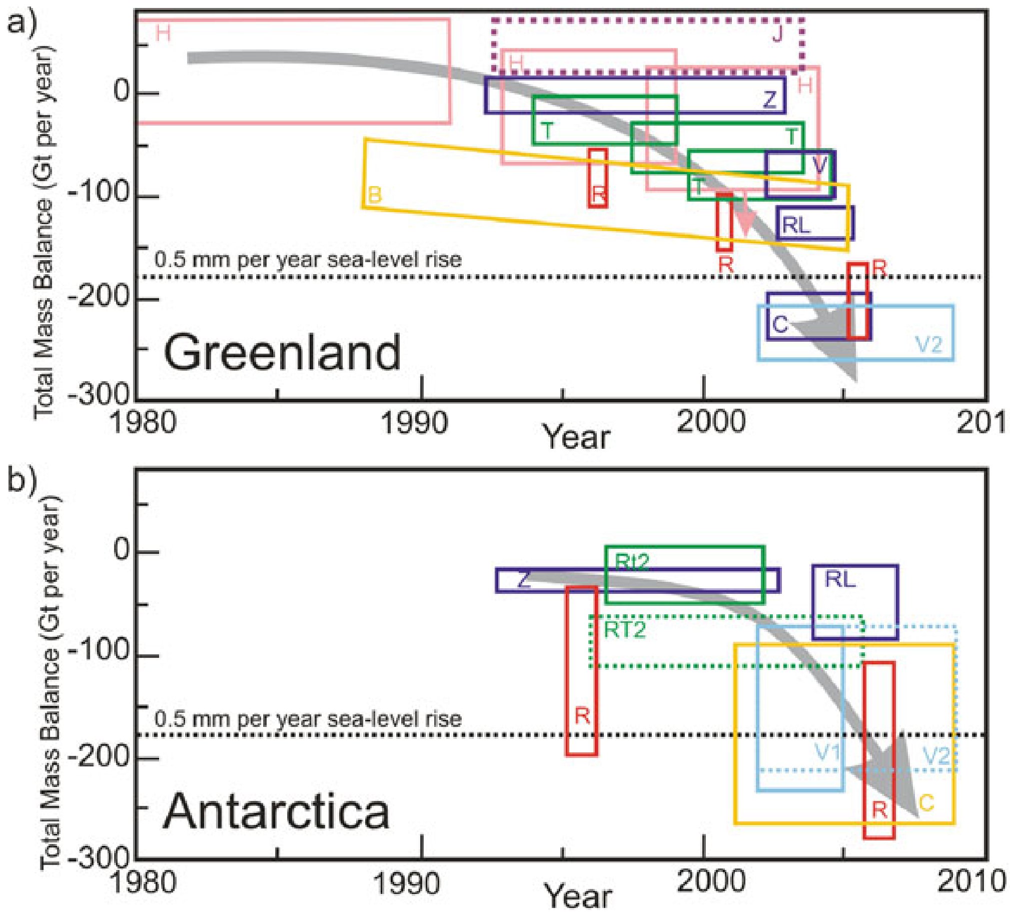

Figure 6: produced by Peter Barrett for IODP New Science Plan. Estimates of polar ice loss over the last 30 years. Each box represents a range in equivalent sea level rise from an individual paper. Noticeable is the general trend towards ice-volume loss and therefore sea-level change towards the future. Estimates converge on a rate of 0.5 mm sea-level rise per year for a) Greenland and b) Antarctica. Sources are listed in Bertler, N.A.N and Barrett, P.J. 2010 (in press). Polar Ice Sheets. In Changing Climates, Earth Systems and Society, Ed J. Dodson. Springer, New York.

3.3.4.2. Key questions and unsolved challenges

The reconstruction of evolving global ice sheet volumes will primarily rely on the timing and magnitude of sea-level change during interglacial and glacial periods, typified by relative sea-level highstands and lowstands. **Variations in sea level can be estimated from shoreline markers, oxygen isotopes ($\delta^{18}O$), and the flooding history of continental margins and cratons.** Records from **tropical coral reefs provides exceptional records of sea-level change**, but the existing ones are too limited to accurately constrain the timing and magnitude of Pleistocene sea-level fluctuations and to understand past ice sheet behaviour. Key questions include how fast sea-level has changed in the past (rate of sea-level change), how is sea-level change related to the relative stabilities of the northern hemisphere, west and east Antarctic ice sheets, and how has sea-level varied spatially in response to the non-isostatic adjustment of sea-level in response to the gravitational attraction exerted by large ice sheets.

3.3.4.3. Recommendations for required coring/sampling and infrastructure

Continuous high resolution reef and sedimentary records that will yield physical constraints on past ice sheet behaviour in space and time as a guide to the future are needed from a variety of key locations.

Some estimates of Pleistocene and Pliocene interglacial sea level range from +20-40 m and imply a significant retreat of the East Antarctic Ice Sheet (EAIS) in addition to Greenland and the West Antarctic Ice Sheet (WAIS), thus raising the question of the vulnerability of the EAIS (~52m of sea level) to future warming. **Determining the behaviour of individual ice sheets and how sea level varied during the Quaternary interglacials and past intervals of global warming and elevated CO_2 levels** (e.g. 'mid' Pliocene warmth, the middle Miocene climate optimum, the early Eocene, and the Late Cretaceous) **will provide a baseline for evaluating the relative contributions of Northern and Southern Hemisphere ice sheets to past and future sea-level change**, with each ice sheet responding in different ways and on different time scales.

During glacial « terminations », ice volume decreased and sea level rose, as temperatures and greenhouse gas concentrations increased rapidly. These periods therefore offer potential analogues for future scenarios involving a rapid sea-level rise and coeval climatic and environmental changes. **The reconstruction of rates and magnitudes of sea-level rise during several «terminations»** characterized by distinctive ice sheet conditions will provide **constraints for modelling ice-sheet behaviour and dynamics**, and will help in clarifying the mechanisms of catastrophic ice sheet collapses, in understanding suborbital climate variability, and in determining the timing and the volume of meltwater released during deglaciations under varying thermal regimes.

Current discrepancies between models and sea-level reconstructions are largely due to the lack of accurate reconstructions of past sea-level change. These records must be obtained from a wide latitudinal range, in different tectonic and sedimentary settings, and at variable distances from former glaciated regions to decipher the eustatic signal from interacting processes (e.g. tectonic movements, sediment supply, mantle response to ice sheet unloading and the redistribution of mass between ice sheets and the global ocean).

Core data from beneath the McMurdo Ice Shelf suggest that the marine-based WAIS collapsed many times in the period extending from 2 to 5 Ma, when CO_2 levels were < 400 ppm though with global temperature ~3°C higher than present. New ice sheet modelling integrated with geological data on climate and ice extent was used for estimating contributions from past ice sheet changes to sea level, and indicates that much of that loss might have been achieved in centuries. High quality cores were recently recovered off East Antarctic margin during the IODP Expedition 318 for similar studies, emphasizing the **need for records from other sectors of the Antarctic margin and from the Arctic** (linkages with Cryosphere section).

Strategies and data needs were identified to quantify conditions contributory to abrupt climate change in the late Quaternary including evaluating the sensitivity of ice sheets and sea level to past climate change to answer such questions as whether the West Antarctic Ice Sheet collapsed during previous interglacials. How sensitive were ice sheets (and sea level) to past climate change, especially during periods warmer than today (e.g., Marine Isotope Stages 5e, 11, 31)? What were the rates of change?

3.3.5. Modes of Ocean and Ecosystem Variability

3.3.5.1. Set out of the overall problem

Modern climate oscillates in a few preferred patterns or modes (North Atlantic/Arctic Oscillation, El Niño Southern Oscillation/ENSO, Pacific Decadal Oscillation, Southern Annular Mode). These natural oscillations impact regional climate and ocean ecosystems over a range of timescales, from annual to multidecadal or even longer. One way to narrow uncertainty in future projections is to constrain how these climate modes have varied in response to a range of external forcings and past climate states. On shorter timescales solar and volcanic forcings largely control the Earth's energy balance, while on longer timescales orbital and greenhouse gas changes are more important. Consequently, paleo-environments offer critical case studies, spanning the full range of potential future climate states, for evaluating climate modes under increased anthropogenic greenhouse forcing. Only recently have the proxy techniques and deep sea archives allowed modes of climate variability to be examined beyond the instrumental period. Together with modeling, these reconstructions provide the basis for substantial improvements in regional climate predictability in the future.

For example, there has been significant progress in theoretical understanding of ENSO, which is the largest mode of interannual variability in the global climate system. The wide impacts of ENSO on regional climate, ecosystems and societies make it a key focus for both adaptation of society to short-term variability and as a dynamical component of longer-term change Despite progress in the prediction of short-term seasonal variations in

ENSO, there is no consensus on how tropical Pacific mean-climate and ENSO variability might change as a function of increasing greenhouse gases.
The large inherent variability of ENSO makes it difficult to assess changes from the observed historical record (Stott and Kettleborough, 2002). The number of interacting physical and biological processes (e.g. ocean upwelling, clouds and radiation, intraseasonal atmospheric dynamics, attenuation of sunlight by plankton) involved in the ENSO cycle present a continuing challenge to climate modelling. The lack of any model consensus means that we must persist with approaches that combine paleo-observational data and complex climate models in order to refine our best estimate of the impact of global warming on ENSO and its associated impacts.

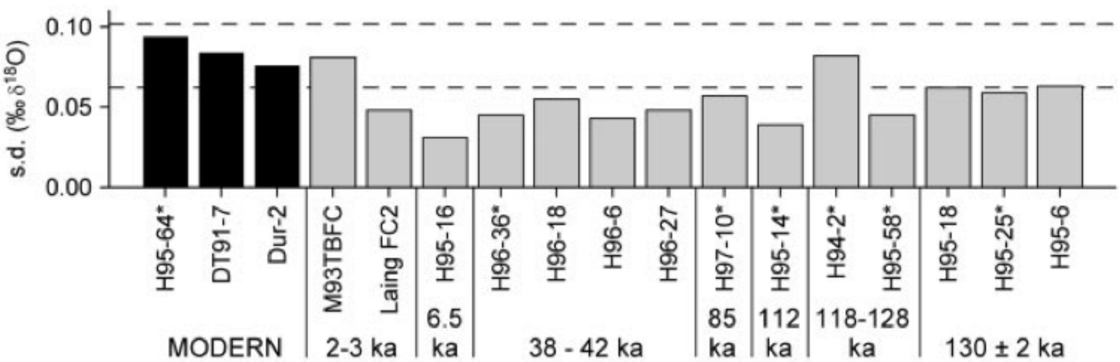

Figure 7: From Tudhope (2001): Standard deviation of the 2.5- to 7-year (ENSO) bandpass-filtered time series of all modern and fossil corals discussed in this study. *:time series is <30 years long. The horizontal dashed lines indicate maximum and minimum values of standard deviation for sliding 30-year increments in the modern coral records. Black bars, modern corals; gray bars, fossil corals.

Indeed, the weak ENSO variability of the early-to-mid Holocene (6-9kyr ago) recorded in tropical corals (Tudhope et al., 2001) (Fig. 7) and other palaeoclimate records (Rodbell et al., 1999) suggest that ENSO is sensitive to modest variations in seasonality caused by changes in Earth's orbit. Efforts to understand the ability of ENSO to weaken in this way have examined a number of different hypotheses and models (Brown et al., 2008; Liu et al., 2000) and helped to understand the behaviour of ENSO in altered boundary conditions.
The mid-Pliocene "permanent" ENSO state (Bonham et al., 2009; Haywood et al., 2009; Molnar and Cane, 2007), perhaps more accurately described as a mean warming of the east Pacific relative to the west, has motivated theoretical and modelling studies (Fedorov et al., 2006). This time period has been identified as a model-intercomparison case in the PMIP project because of elevated levels of CO_2 that make it highly relevant for future warming.

3.3.5.2. Key questions and unsolved challenges

- Does the observational period capture the full extent of variability in leading climate modes?
- What is the dependency of climate modes on climate boundary conditions? How will they change as the Earth warms?
- What are the imprints of climate mode shifts recorded in ocean archives and what does this tell us about how ecosystem and biota changes affect, and are affected by, changes in climate modes.

3.3.5.3. Recommendations for required coring/sampling

3.3.5.4. Requirements in terms of platforms/tools/infrastructure

3.3.6. Ocean ventilation

3.3.6.1. Set out of the overall problem

Ocean ventilation and circulation play significant roles in regional and global environments via their influence on the physical, chemical, and biological processes determining carbon storage, ocean oxygenation, and regional temperatures. Particularly relevant for Europe is the role of Atlantic meridional overturning circulation (AMOC) in transporting heat into the North Atlantic region and anthropogenic CO_2 into the deep ocean. Deep sea sediment archives demonstrate that the AMOC has varied considerably during the last 2 million years (the Pleistocene) to cause global climate changes of magnitude and rapidity far beyond that recorded over the last hundred years of direct instrumental observations (e.g. Charles et al., 1996; McManus et al., 2004). These past changes in the AMOC have had major regional and global impacts, extending from Europe to the mid-latitude monsoon systems, to the Antarctic and atmospheric methane (CH4) and CO_2 (Ahn & Brook, 2008). Similar ocean changes are possible in the future, though by their nature they remain extremely difficult to predict, with the most recent IPCC model projections suggesting a wide range of possible scenarios (0-50% slower AMOC than the present) by the end of the 21st century (e.g. Schmittner et al., 2005; Schneider et al., 2007).
A particularly relevant example for future climate is the 8.2ka climate event, the largest and most abrupt climate shift of the last ten thousand years. This event provides a past example of surface freshening and the associated weakening of the AMOC in climate conditions much like those of today (Ellison et al., 2006; Kleiven et al., 2008). An array of climate simulations has been used to assess the sensitivity of the ocean and atmospheric circulation to freshwater release during the 8.2ka event (e.g. Alley and Agustsdottir, 2005; LeGrande and Schmidt, 2008; Renssen et al., 2002). Exploring the AMOC's thresholds and tipping points—where an incremental change can provoke a significant and rapid shift—during warm climate states, similar to what we will face in the future, could help to narrow predictions of future ocean behavior.

Understanding AMOC behavior is also crucial for predicting decadal and regional climate change (Knight et al., 2008). However, observational information on the natural variability of the AMOC on these societally relevant timescales is lacking. Very high-resolution palaeoceanographic records can be used to extend modern observations of ocean ventilation change further into the past. Such records are beginning to reveal evidence for multidecadal AMOC instability related to large scale climate changes that have occurred over the last 1000 years. To fully understand how AMOC variability on these 'human timescales' can impact on European climate and ocean ecosystems, new 'high resolution' records that extend the modern observational database further are crucial.

The impacts of ocean ventilation changes on the marine biosphere can be wide ranging and potentially profound. Ventilation controls the distribution of physical and chemical properties (e.g. temperature, oxygen concentration, *pH* and nutrients) that pelagic and benthic ecosystems rely on. Changes in the ocean ventilation will therefore strongly influence the biodiversity of ecosystems and the efficiency with which they are able to process nutrients and organic carbon. A pressing concern for the future is the spreading of 'dead' anoxic zones and the acidification of deep waters. Deep sea archives of past ocean variability allow the sensitivity of these systems to be assessed, revealing tipping points and thresholds, beyond which induced changes are difficult to reverse. For example, recent changes in the oxygenation of the low latitude thermocline appear to be coupled to changes in high latitude climate and ocean ventilation. Similarly, the cycling of nutrients and their distribution in the ocean are affected by the coupling between high latitude ocean dynamics and biology. Modelling studies highlight the important role of ventilation-controlled nutrient transfer from high to low latitudes in controlling the ability of marine ecosystems to sequester CO_2 within the ocean (Matsumoto et al., 2002). The links and feedbacks between changes in marine biota and ocean ventilation/oxygenation during previous periods of global warming can only be fully understood through the analysis of deep sea sediment archives. Such records provide vital constraints on how our marine ecosystems could evolve as the oceans warm.

3.3.6.2. Key questions and unsolved challenges

- Which processes exert direct control on natural deep-ocean variability in terms of temperature, water mass structure, chemical properties and nutrient inventories on timescales ranging from sub-decadal to multi-millennial?
- How do these ocean changes impact and control the biodiversity and functioning of deep ocean ecosystems?
- Do the shifts observed over the past decade in deep ocean climatology and carbon/carbonate systems fall within the range of their natural variability, or do they exceed that range; what are the implications for future climate and ocean habitats?
- Can we identify early warning signs from the sedimentary record that herald changes in the deep-sea environment associated with tipping points and periods of accelerated climate change?
- What is the interaction between deep-ocean circulation and the polar cryosphere during different modes of climate variability?
- Can we quantify the feedback mechanisms between deep-ocean biosphere, biogeochemistry and climate?

3.3.6.3. Recommendations for required coring/sampling

- Identify an optimum array of global locations, transects, and palaeo-data streams that help to minimise uncertainties in constraining changes in the deep-ocean environment and its link to major climate changes.

- Optimise identification and retrieval of high quality and large volume sediment cores by means of state-of-the-art deep-sea drilling and large diameter piston/box coring from locations that will allow reconstruction of past variations of the deep-ocean environment at a temporal scale relevant to the pace of both natural and anthropogenic climate change.
- Advance installation of centralized sediment core repositories in Europe with state-of-the art sampling facilities and innovative core logging/scanning devices.
- Optimise calibration of palaeoenvironmental proxies from benthic organisms to deep-sea parameters, and allow retrieval of quantitative information on past deep-ocean dynamics and biogeochemical cycles.
- Develop techniques for assimilating palaeoenvironmental datasets into climate models to better guide and optimise deep sea sampling strategies.
- Provide advanced synoptic presentation tools to visualise the continuous change of the deep-ocean environment as documented in palaeo-data streams.

3.3.6.4. Requirements in terms of platforms/tools/infrastructure or linkages

External linkages are provided by IODP, IMAGES, and PAGES.

3.3.7. Ocean-bio-geochemistry, eutrophication, primary productivity

3.3.7.1. Set out of the overall problem

The main food resource for deep-sea organisms is the organic matter produced in the sun-lit surface waters of the global oceans. Marine planktonic algae, including diatoms, coccolithophores and dinoflagellates, provide about 45% of the global annual net primary productivity [Field et al. 1998; Morel & Antoine 2002]. These organisms constitute the base of the marine food chain and are a fundamental component in biogeochemical cycles, through photosynthetic fixation of carbon, release of oxygen and biomineralisation of silicate- and carbonate minerals. The overall ecological success of marine phytoplankton, but also their taxonomic diversity and size distribution, determines the efficiency by which fixed carbon is transferred to higher trophic levels and into the deep ocean- and sedimentary carbon reservoirs.
Perturbations to plankton succession impact food chain and biogeochemical cycling of carbon, nitrogen, phosphate etc. For example, eutrophication of coastal waters leads to excessive blooms of phytoplankton that in turn results in severe oxygen depletion (hypoxia) of the deeper waters (Oxygen Minimum Zone, or “Dead Zone”).

3.3.7.2. Key questions and unsolved challenges

1. How do shifts in deep-ocean circulation modes affect deep-sea ecosystems and biogeochemical cycles?

2. Can we quantify the feedback mechanisms between deep-ocean biosphere, biogeochemistry and climate?

3. Eutrophication / Dead zones /oxygen minimum zone (OMZ): We need to constrain the natural spatial extent and temporal variability of the OMZ. (e.g., upwelling areas)

4. What is the relationship with primary productivity and ocean ventilation?

Dead zones or coastal areas that experience a severe lack of oxygen (hypoxia) have expanded across the ocean at alarming rates. Dead zones are caused by agricultural runoff, especially nitrogen-rich fertilizers, and the burning of fossil fuels. The pollutants cause marine eutrophication, whereby the ecosystem receives too many nutrients, triggering massive algae blooms, which eventually die and are broken down bacteria. By breaking down the algae the bacteria consume excessive amounts of oxygen, essentially starving the marine system.

5. To gain better knowledge of the varying magnitudes and response times (phasing) of deep-ocean biogeochemical cycles.

For instance, it has not yet been possible to quantify, using palaeoceanographic data, the significance of contributions from the different marine 'carbon' reservoirs to changes in Earth climate on long timescales. Even more challenging is the fact that, despite decades of research on past changes in ocean plankton productivity and nutrient cycling, no firm conclusions prevail on the role of the deep ocean as the largest carbon reservoir in the ocean-atmosphere carbon cycle – a cycle that ultimately modulates climate at a global scale. Finally, an 'internal' variability exists within the deep-ocean environment that operates without a clear external forcing. The magnitude of such variability on different timescales needs to be documented through time.

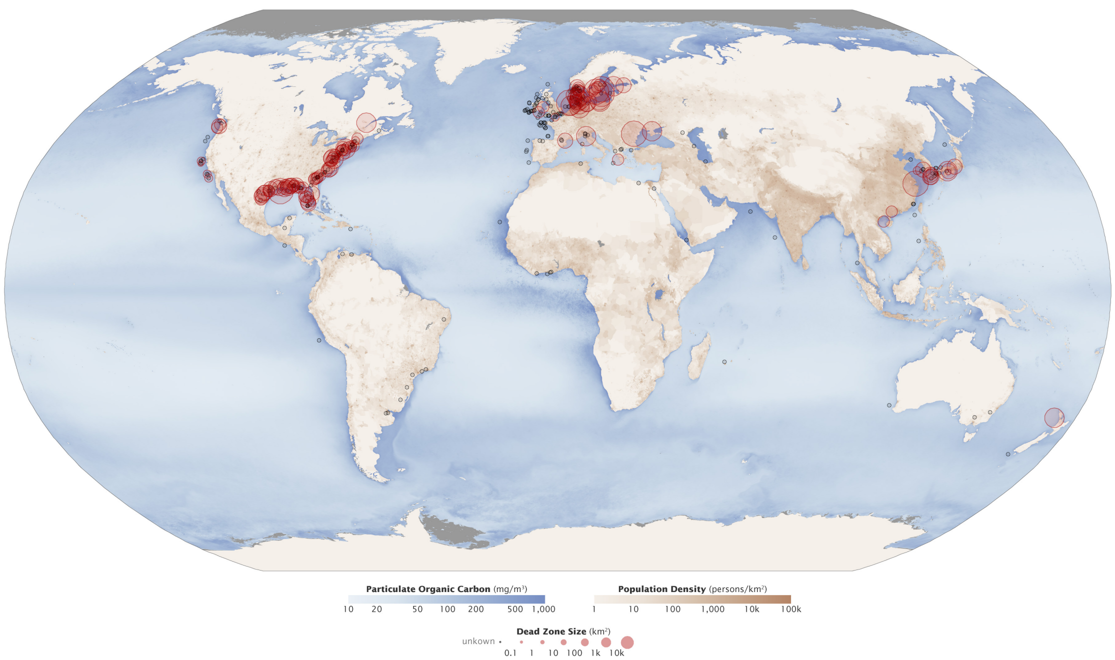

Figure 8: From NASA: Global occurrence of "dead zones".

3.3.7.3. Recommendations for required coring/sampling

There is a requirement for coastal surveys and transects across shelf across the oxygen minimum zone, into deep-sea. The $\delta^{15}N$ proxy needs further development and interpretation.

3.3.7.4. Requirements in terms of platforms/tools/infrastructure

3.3.8. Evolution of the hydrological cycle

3.3.8.1. Set out of the overall problem

It is necessary to address hydrological cycle variability as a general problem in reconstruction past changes and forecasting future trends. Bach, Ravelo et al., (INVEST report, 2010), state that:

"Understanding the processes that control changes in the hydrologic cycle is one of the most pressing issues in climate-change research because changes in precipitation and evaporation impact the salinity/density distribution in the surface ocean, ecosystems on land, floods, aridification, water resources, and climate-vegetation feedbacks. A comprehensive examination of climatic controls on the hydrologic cycle requires the study of long-term trends and variability over a range of climatic states. In fact, even small global temperature changes impact the energy balance in tropical regions, resulting in changes in evaporation and storm and hurricane activity. In the mid-latitudes, changes in atmospheric thermal gradients can impact atmospheric circulation, the location of storm tracks, and the intensity of storms. There is an urgent need to understand controls on the Intertropical Convergence Zone (ITCZ), climate oscillation modes (ENSO, NAO, IOD) and their behavior during different mean climate states, wind-driven upper ocean circulation and its coupling to atmospheric forcing, monsoon dynamics, and the relationship between precipitation patterns, density stratification, and biogeochemical processes, to name a few. Deep-sea coring is absolutely necessary to obtain the records needed to constrain past changes in surface ocean conditions associated with major changes in large-scale atmospheric circulation. This must be complemented by continental climate reconstructions obtained from drilling sediments on continental margins and on land. Finally, ocean drilling studies focused on the hydrologic cycle should be used to validate regional climate models used to predict climate change and its associated impact on water resources. Because of the strong impact of precipitation on the environment and its habitability (e.g., water resources, floods, etc.), and thus the urgent need to develop a deeper understanding of the factors that control regional precipitation, many of the climate-related INVEST working groups emphasized the need to study the hydrological cycle. Specifically, discussion in many working groups emphasized the need to understand controls on the Intertropical Convergence Zone (ITCZ), to study climate oscillation modes and their behavior during different mean climate states, to focus on wind-driven upper ocean circulation and its coupling to atmospheric forcing, to understand the relationship between precipitation patterns, density stratification, and biogeochemical processes, to examine past changes in monsoons, among other topics."

Rapid or long-term changes in the hydrological cycle can cause single or multiple extreme flood and drought events on the one hand and preset more arid or humid climate conditions at a regional scale on the other. The latter determines the balance in the amount of precipitation, prospering vegetation and river runoff compared to the extent of desertification and eolian transport as well as between physical and chemical weathering. Thus the hydrological cycle controls eolian and fluvial supply of a huge detrital sediment load into the ocean and, more important for the marine biota, the supply of anorganic dissolved and particulate biochemical relevant elements. Response of marine biota to the rates of nutrient and freshwater supply is fairly unknown (diatoms vs. coccoliths, foraminifera vs. radiolaria), as is the adaptation to the evolution of sedimentary systems, slope failures and hydrocarbon seeping in the deep-sea fan systems beyond the shelves.
Particularly, for marginal seas, surrounded by continents and facing limited deep-water mass exchange with the open ocean, the supply of freshwater, micro- and macronutrients, and sediment load is pivotal in pre-conditioning biochemical processes in the surface waters, e.g., oxygen minimum conditions, rates of primary plankton production and ecosystem development. For the deeper waters and the benthic boundary layer profound changes in the hydrological cycle can lead to highly variable benthic habitats with respect to sediment deposition and down-slope mass transport and with respect to biochemical conditions (hypoxia and anoxia, salt brines). In case of the tropical hydrological cycle mainly expressed as monsoonal systems, ENSO and ITCZ, such processes are even valid in open seas in the vicinity of large rivers or deserts. Thus the Mediterranean, Baltic and Black Seas can be considered as extremely sensitive to climate driven switches in the hydrological cycle. However, the response of biological, chemical and sedimentary interactions to varying supplies of large quantities of freshwater and dust remains is not well understood, even for the eastern Mediterranean Sea where the influence of the hydrological cycle for the generation of sapropels is still questionable.

3.3.8.2. Key questions and unsolved challenges

Pressing questions that can only be answered by studying geological archives of past climate change are focused on three large-scale climatic features that influence continental patterns of precipitation.These relate to variations of the Intertropical Convergence Zone (ITCZ), Monsoons and mid-latitude storm tracks

3.3.8.3. Recommendations for required coring/sampling

- What was and will be the extent of precipitation changes and run off over Europe under the influence of rapid climate change and long-term warming ?
- What was and will be the response of marine biota and ecosystems to heavily varying runoff conditions and Saharan dust supply ?
- To what extent did and will biochemical conditions in the water column and sediment water interface mediate the biogeochemical cycling in marginal and open seas and thus life in the ocean as a response to varying continental supply of nutrients ?
- climate modeling of the hydrological cycle mainly in the mid-altitude and ITCZ regions

- Disentangle hydrological cycle effects on ocean biogeochemistry from those due to ocean dynamics
- Multiple coring in fan systems to retrieve a continuous record of changes in the hydrological cycle?
- Extinction, dilution of marine climate signal carriers under extreme salinity, chemical changes in the water column and at the water-sediment interface

3.3.8.4. Requirements in terms of platforms/tools/infrastructure

Riser drilling shallow and deep-sea fan systems as well as estuaries, drilling through massive salt sequences (Hübscher et al. "Salt Giant?"), of large quantities of sediment volume to compensate for strong dilution of marine climate proxy carriers, depth transects through the chemoclines evolving in marginal seas. Giant piston and box coring as CALYPSO and CASQ is required, as is riser drilling in deep sea fans.

3.3.8.5. Linkages

- biological production in response of eolian and fluvial nutrient supply (SOLAS, LOICZ)
- eutrophication and oxygenation
- evolution of sedimentary systems and geohazards as function of ocean dynamics and sediment supply;
- preconditioning for slope failures and other types of sediment movement; slope stability and mass movements
- risks to deep-sea biota through deep-sea hydrocarbon exploration in fan systems (e.g., GoM oil spill)

3.3.9. Cryosphere, Arctic and Antarctic research

3.3.9.1. Set out of the overall problem

The high-latitude regions of the Arctic Ocean and Antarctica are undergoing some of the fastest temperature and ice-volume changes on the planet. To understand high latitude climate and ice-cover change, it is necessary to sample the history stored in the sediments of the Arctic Ocean, and deciphering the climate history and sensitivity of Antarctica.

Arctic Ocean sediments, except for the piston-cored superficial record, have been sampled only on the Lomonosov Ridge in 2004 (IODP ACEX) and in 1993 in the ice-free waters in the Fram Strait/Yermak Plateau area (ODP Leg 151). Antarctica has been drilled most recently around Wilkes Land in 2010, but a large number of proposals are targeting ice-sheet stability, history, and behavior during extreme warmth, which is crucial to provide boundary conditions for past, present and future changes of sea-level, and climate feedback systems.

High-latitude scientific coring is required to determine the recently postulated threshold behavior of ice-growth and decay in both hemispheres, the evolution of sea-ice and its impact on climate feedback processes, as well as the determination of potential rates of sea-level change in the past and in the future. Two recent workshops plotted out future requirements of Arctic and Antarctic coring (INVEST white papers by Stein and Coakley, 2009, for the Arctic and DeSantis et al., 2009, for Antarctica).

Figs. 9 and 10 show currently proposed areas for coring, site surveys and site characterisation to enable drilling in the high latitudes over the forthcoming decade. For both, the Arctic and Antarctica, the coring areas target climatically important regions, but also include targets of interest for the understanding of tectonics and climatically sensitive storage and release of gas hydrates. One of the key areas of investigation will include the determination of existing "climate commitment". Ocean Drilling in the high latitudes will benefit from synergies with other international programs, such as ANDRILL.

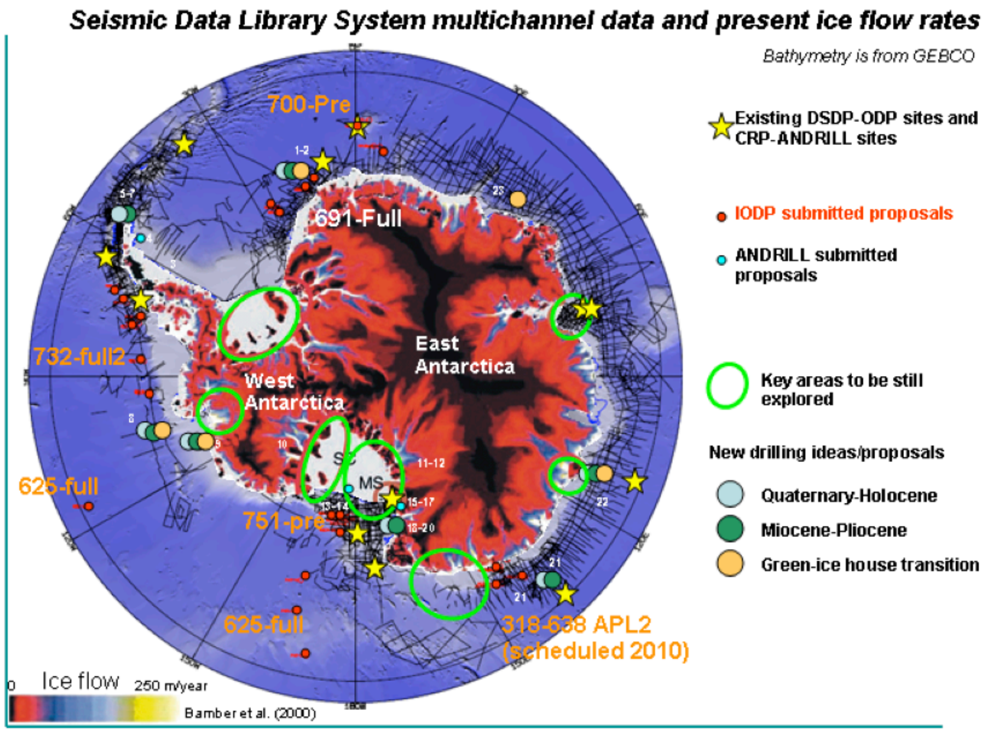

Figure 9: Key areas around the Antarctic continent with existing and potential future coring targets (DeSantis et al. INVEST White Paper)

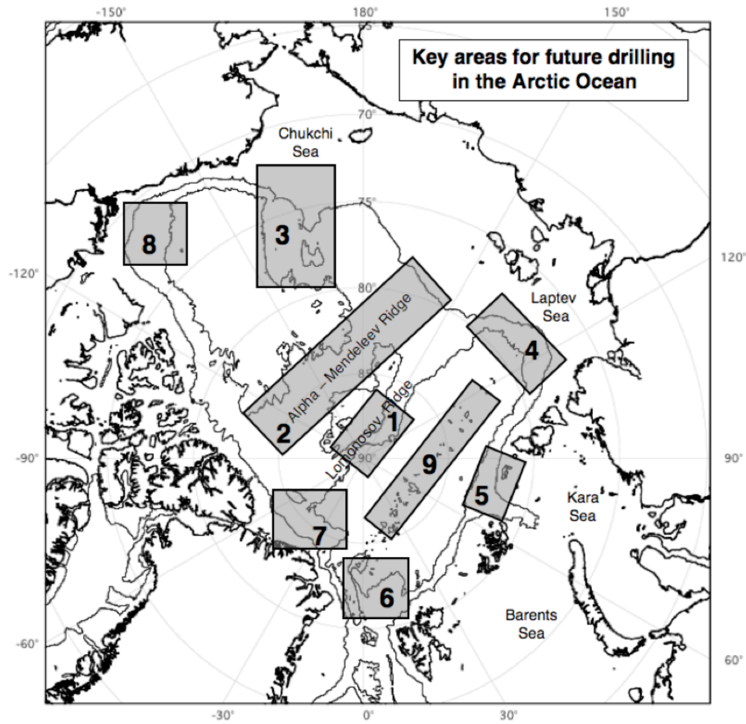

Figure 10: from Stein & Coakley INVEST Paper, 2009): Key areas for future drilling areas in the Arctic Ocean. 1 = Lomonosov Ridge; 2 = AlphaMendeleev Ridge; 3 = Chukchi Plateau/Northwind Ridge; 4 = Latev Sea continental margin; 5= Kara Sea continental margin; 6 = Fram Strait/Yermak Plateau; 7 = Morris Jessup Rise; 8 = Mackenzie shelf/slope; 9 = Gakkel Ridge.

3.3.9.2. Key questions and unsolved challenges

The following key questions were identified by deSantis et al (2009) as part of a workshop:

- What is the contribution of continental ice to the rate and magnitude of sea-level changes both in the past and projected into the future? Will sectors of marine-based ice sheets experience □runaway collapse‘ as climate warms? Can ocean drilling provide constraints on past rates of this process?
- How did paleo ice sheets respond when Earth‘s atmosphere had 400 ppm CO2?
- How did ice sheets respond the last time Earth‘s atmosphere contained 600-1000 ppm CO2?
- What did a □Greenhouse Earth‘ look like in the polar regions? Can Antarctica sustain any ice sheets when the atmospheric CO2 concentration is above 1000 ppm?
- Can ice-volume and sea-level records be reconciled with far-field deep ocean oxygen- isotope and temperature proxy records? How much of EAIS is vulnerable to marine melting?
- Southern Ocean drilling will enable us to delineate behavior of several major climate cycles and climate shifts such as YD/Antarctic Cold Reversal (ACR), D-O cycles, the mid-Brunhes climate shift, late Miocene cooling, major Antarctic glaciation around the Oligocene/Miocene boundary and first ice sheet inception around the Eocene/Oligocene boundary.

- Did the dramatic millennial-scale D-O climate cycles of the Northern Hemisphere manifest themselves in the Southern Hemisphere? If so, what was the amplitude of the response, and was the Southern Hemisphere in-phase or out-of-phase with the D-O cycles?

3.3.9.3. Recommendations for required coring/sampling

The highest research priorities for the next decade were identified by Stein and Coakley (2009), and DeSantis *et al*. (2009). In the Arctic Ocean, despite the success of IODP Expedition 302 – Arctic Coring Expedition (ACEX), major questions related to the climate history of the Arctic Ocean and its long- and short-term variability during Mesozoic-Cenozoic times cannot be answered from the ACEX record due to the poor core recovery and, especially, a major mid-Cenozoic hiatus. This hiatus spans the critical interval when prominent changes in global climate took place during the transition from the early Cenozoic Greenhouse world to the late Cenozoic Icehouse world. Nevertheless, the success of ACEX has certainly opened the door for further scientific drilling in the Arctic Ocean during the next decade, and the 2008 Bremerhaven workshop report provides details of specific Arctic targets that have already fed into the current proposal system. The ACEX results will frame the next round of questions to be answered from new drill holes to be taken by a series of drilling legs during the next decade and beyond. In the Antarctic, DeSantis *et al*. (2009) and INVEST identified a list of priorities that include urgent drilling in the Indian sector of the Southern Ocean and proximal to Antarctica, as well as integration with ANDRILL, SHALDRIL and other efforts.

3.3.9.4. Requirements in terms of platforms/tools/infrastructure

Re-newed coring in the Arctic ocean will require efforts similar in scale to the previously successful ACEX expedition, i.e. a fleet of dedicated ice-breakers working around an ice-hardened drill ship. In the Antarctic, icebergs provide additional challenges. Appropriate drilling strategies have been successfully exemplified by ANDRILL, and IODP Expedition 318.

4. Linkages to WP7 and WP8

Technological requirements for sub-seafloor sampling and measurements and emerging infrastructure needs identified

- Optimise identification and retrieval of high quality and large volume sediment cores by means of state-of-the-art deep-sea drilling (*Joides Resolution* type) and large diameter piston/box coring from locations that will allow reconstruction of past variations of the deep-ocean environment at a temporal scale relevant to the pace of both natural and anthropogenic climate change.
- Provide better and coordinated access to site-survey capabilities to advance future drilling
- To complete important pole-equator-pole and other transect strategies, more drilling in high-latitude areas is required, specifically the Arctic and Antarctic. This will require MSP style expeditions with ice-breakers similar to the ACEX

IODP project (Expedition 302), or approaches as those implemented during IODP Expedition 318 (Wilkes Land).

- Advance installation of centralized sediment core repositories in Europe with state-of-the art sampling facilities and innovative core logging/scanning devices as a higher level/common requirement
- Optimise calibration of palaeoenvironmental proxies from benthic organisms to deep-sea parameters, and allow retrieval of quantitative information on past deep-ocean dynamics and biogeochemical cycles.
- Develop techniques for assimilating palaeoenvironmental datasets into climate models to better guide and optimise deep sea sampling strategies.
- Provide advanced synoptic presentation tools to visualise the continuous change of the deep-ocean environment as documented in palaeo-data streams
- Riser drilling in deep sea fans to study linkages between tectonics and climate
- MSP approach for Common European long piston coring system
- Provide funding and access to Calypso type coring system, portable long coring systems, high volume coring systems
- Mobile DOSECC type coring system, particularly for lake drilling activities (e.g., ICDP)
- Access to MeBo type system (~50–100m coring depth), 2-5 km water depth
- Large volume coring systems (CASQ coring)

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