MCCIP Briefing Note
Ocean uptake of carbon dioxide (CO_2)

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EXECUTIVE SUMMARY

The oceans exchange large amounts of carbon dioxide (CO_2) with the atmosphere.

- The net ocean-atmosphere exchange of CO_2 is currently estimated as an ocean uptake of 2.2 ± 0.5 gigatonnes of carbon per year.
- The oceans remove about a quarter of atmospheric CO_2 emissions from human activities.
- The partial pressure of CO_2 (pCO_2) in the surface ocean is expected to increase to double its pre-industrial value by the middle of this century, driven by increasing concentrations of atmospheric CO_2.

The role of the ocean in removing carbon dioxide from the atmosphere and the physical, chemical and biological processes responsible for this, are vulnerable to the effects of climate change.

- Rising sea surface temperatures will decrease the solubility of CO_2 in sea water. Consequently, the oceans will draw down CO_2 from the atmosphere less efficiently.
- Increases in the sea water CO_2 levels will themselves change the chemical buffering capacity of sea water, reducing its capacity for CO_2 uptake.
- The likely consequence of these two effects is that the fraction of CO_2 emissions taken up by the oceans will decrease in future, accelerating the rate of atmospheric CO_2 increase.
- The impacts of changes in other processes that influence the air-sea exchange of CO_2, such as stratification, upwelling, ocean circulation and primary production, are less well known.
- Recent studies suggest that the efficiency of CO_2 uptake by the oceans may be decreasing in some oceanic regions (e.g. Southern Ocean), but not in others.

Continental shelf seas play a key role in the global carbon cycle, linking the terrestrial, oceanic and atmospheric carbon pools.

- Evidence from measurements and modelling suggests that the North West European Shelf acts primarily as a sink for atmospheric CO_2.

Monitoring changes in surface-ocean CO_2 and the exchange of CO_2 between ocean & atmosphere can provide an early warning of changes in the ability of the ocean to absorb CO_2, and consequent feedbacks to the global climate system.

- The UK research community runs pCO_2 monitoring systems on five national research vessels and two Voluntary Observing Ships.
- Funding for the open ocean vessels is currently due to end in 2009 and for the shelf-sea vessels in 2010.

1. OCEAN UPTAKE OF CARBON DIOXIDE (CO_2)

The ocean exchanges large amounts of CO_2 with the atmosphere. This includes the natural cycling of CO_2 as well as the uptake of CO_2 from fossil fuel burning and other human activities. The ocean exchanges this CO_2 by a complex combination of physical, chemical, and biological processes. The processes driving this exchange are vulnerable to the effects of climate change and contribute to important climate feedbacks.

Key issues:

1. How is carbon dioxide cycled between the ocean and the atmosphere?

The ocean is the largest non-geological reservoir of carbon. It exchanges CO_2 with the atmosphere, with some regions acting as net sinks and others as net sources. The global net exchange of CO_2 between the ocean and the atmosphere is currently estimated to be an ocean uptake of 2.2 ± 0.5 billion tonnes of carbon per year (Denman *et al.*, 2007), which is approximately 2% of the gross flux. Therefore, the oceans are overall a net sink of CO_2.

The primary driver for ocean uptake of CO_2 is the gradient in CO_2 levels (difference in partial pressure, ΔpCO_2) between the ocean surface waters and the atmosphere. Key factors controlling this gradient are the solubility of CO_2, which is at its highest for cooler waters, and biological activity (phytoplankton taking up CO_2 through photosynthesis and organisms releasing CO_2 through respiration).

Ultimately the rate of net oceanic uptake of CO_2 is governed by the transfer of CO_2 from the surface ocean to the deep ocean. Downward transport mainly occurs via deep mixing and sinking of cold CO_2 rich water (solubility pump) at high latitudes (Volk and Hoffert, 1985). The biological pump, i.e. the downward transport of carbon in the dead remains of marine plants and animals, also contributes to the export, modulating the rate but not dominating it (Denman *et al.*, 2007). Calcifying organisms may influence biological carbon cycling in two ways: firstly they release CO_2 from sea water into the atmosphere in proportion to the CO_2 they fix in the creation of calcium carbonate ($CaCO_3$) structures. Secondly, because the $CaCO_3$ shell material produced by marine calcifiers is much denser than the soft body parts of plankton, its presence in aggregates with organic matter may play an important role in accelerating the rate of sinking, hence carbon sequestration (Armstrong *et al.*, 2002). Further details are provided in the MCCIP Ecosystem Linkages Report Card Review of Ocean Acidification (Turley *et al.*, 2009). Most of this carbon eventually returns to the surface layer by upwelling and diffusion. Carbon exported to deeper water remains out of contact with the atmosphere for decades to centuries (intermediate water) to millennia (deep water) (Denman *et al.*, 2007).

2. How much anthropogenic carbon dioxide do the oceans remove from the atmosphere?

Atmospheric concentrations of CO_2 are at their highest level for at least the past 650,000 years, possibly the past 15 to 20 million years (Pearson and Palmer, 2000; Cicerone et al., 2004; Siegenthaler et al., 2005). The oceans currently remove about a quarter of current CO_2 emissions from human activities taking into account changes in land use (or 'anthropogenic CO_2') (Canadell *et al.*, 2007). Over the period 1800 to present the oceans have mitigated the changes in atmospheric CO_2 by absorbing about half of the CO_2 released by fossil fuel burning and cement production (Sabine *et al.*, 2004). Anthropogenic CO_2 is taken up by the ocean because the increasing atmospheric concentrations of this anthropogenic CO_2 increase the gradient in CO_2

levels between the ocean surface waters and the atmosphere. This is then exported to the deep ocean, mainly via mixing and the solubility pump.

3. Can the ocean maintain this rate of atmospheric CO_2 *removal?*

As atmospheric CO_2 concentrations continue to rise, the Intergovernmental Panel on Climate Change (Prentice *et al.*, 2001) predicts that pCO_2 in the surface ocean is expected to increase to double its pre-industrial value by around 2050.

Rising sea surface temperatures will decrease the solubility of CO_2 in sea water. Consequently, the oceans will draw down proportionately less CO_2 from the atmosphere. Increases in sea water CO_2 levels will also change the chemical buffering capacity of sea water, which results from the equilibrium between different dissolved states of CO_2 (carbonate and bicarbonate ions). These two effects means that the ocean can take up CO_2 from the atmosphere less efficiently in future and this is likely to lead to a decrease in the fraction of CO_2 emissions taken up by the oceans, accelerating the rate of the atmospheric CO_2 increase (Denman *et al.*, 2007). Changes in the stratification of the surface ocean may either decrease or increase the rate of oceanic CO_2 uptake (Denman *et al.*, 2007; Le Quéré *et al.*, 2007).

The impact of changes in other processes that influence the air-sea exchange of CO_2 are less well known. Changes in primary production vary between years and regions with no current consensus on a global trend. Generally, an increase in primary production will increase the amount of CO_2 removed from the atmosphere, and vice versa, although the interaction of these effects with other processes needs to be taken into account. A reduction in winter sea ice could expose areas with high surface CO_2 levels to contact with the atmosphere, causing release of CO_2 from the ocean to the atmosphere in winter (Stephens and Keeling, 2000; Bakker *et al.*, 2008).

The rate at which CO_2 exchanges between the ocean and atmosphere is related to wind speed, sea state and temperature. Changes in sea state (significant wave height) linked to climate related processes have been detected (see storms and waves review in the Annual Report Card, Woolf & Coll, 2008). The impact of changes in these and other factors, such as ocean circulation, stratification and precipitation are not yet quantified.

Recent studies from the Southern Ocean (Le Quéré *et al.*, 2007) and North Atlantic (Corbière *et al.*, 2007; Schuster and Watson, 2007; Schuster *et al.*, 2009) suggest that the efficiency of CO_2 uptake by the ocean may be decreasing in some oceanic regions, but not in others. For example, atmospheric CO_2 levels suggest that the Southern Ocean CO_2 sink (south of 45°S) did not increase from 1981 to 2004, despite increasing atmospheric CO_2 levels (Le Quéré *et al.*, 2007), while surface ocean CO_2 increased at a rate greater than that of the atmosphere in the north-eastern subpolar North Atlantic Ocean (Schuster *et al.*, 2009). Globally, however, no significant change has been detected in the fraction of anthropogenic CO_2 emissions taken up by the oceans (Canadell *et al.*, 2007).

4. What are the impacts likely to be on marine ecosystems?

A major consequence of the increasing CO_2 concentration in the ocean is a significant change to the oceanic carbonate system: a decrease of surface pH and in the saturation state for calcium carbonates. The pH decrease is predicted to be three times greater and occur about 100 times faster than pH changes experienced during the transition from glacial to interglacial periods (Raven *et al.*, 2005). Such CO_2 -related changes in the oceanic carbonate system are already underway (Bates *et al.*, 2002; Gruber *et al.*, 2002; Dore *et al.*, 2003; González-Dávila *et al.*, 2003) and these could have profound impacts on marine organisms and ecosystems (Riebesell *et al*., 2000; Cicerone *et al*., 2004; Orr *et al*., 2005). Further details on this complex subject are contained in the MCCIP Annual Report Card review of ocean acidification (Turley, 2008) and 'Ocean Acidification - The Facts' (Ocean Acidification Reference User Group, 2009).

5. What are the implications for UK shelf waters?

Continental shelf seas, including coastal and marginal seas, are thought to play a key role in the global carbon cycle, linking the terrestrial, oceanic and atmospheric carbon pools (Omar *et al*., 2007). The role of shelf sea regions as sinks or sources of atmospheric CO_2 varies with latitude (Cai and Dai, 2004; Thomas *et al*., 2004a,b); globally shelf seas are thought to be net sinks for CO_2 with inner estuaries acting as net sources for CO_2 (Chen and Borges, 2009). Evidence from measurements and modelling suggests that the North-west European Shelf acts primarily as a sink for atmospheric CO_2 (Thomas *et al*., 2004; Borges 2005; Borges *et al*., 2005). Thomas *et al*. (2004) calculated the North Sea to be a highly efficient continental shelf pump exporting approximately 93% of atmospheric CO_2 taken up in the coastal waters off the North-west European Shelf into the deep waters of the North Atlantic. Extrapolating the North Sea to the global scale, Thomas *et al*. (2004) speculated that 20% of anthropogenic CO_2 taken up in the global ocean occurs in coastal areas. Measurements are ongoing that will help to understand the complex nature of coastal CO_2 uptake, as part of the CARBON-OPS, Defra-pH and CarboOcean monitoring programmes in the UK and north-western European sectors. Funding of these measurements is uncertain after 2009/ 2010.

6. How well can we observe changes in the uptake of CO_2 *by the ocean?*

Monitoring changes in surface-ocean pCO_2 and ocean-atmosphere CO_2 exchange can provide an early warning of changes in the ability of the ocean to absorb CO_2, and consequent feedbacks to the global climate system, yet ocean CO_2 is still under-sampled. This is especially the case for the shelf seas, the Southern Ocean and southern-hemisphere subtropical gyres (IOCCP, 2007).

The UK research community runs pCO_2 monitoring systems on five national research vessels (Hardman-Mountford *et al*., 2008) and two Voluntary Observing Ships (VOS) (Schuster and Watson, 2007; Schuster *et al*., 2009). The measurements from the research vessels are processed in near real time and made available over the internet, updated every day (see www.bodc.ac.uk/carbon-ops). Current funding for both open ocean research vessels and VOS ends in 2009 and for shelf-sea vessels in July 2010.

An EU and US-funded North Atlantic Observing Network has for the first time measured seasonal and intra-annual variation in the CO_2 sink across the North Atlantic for 2005, 2006, 2007 and 2008, with observations for 2009 underway (Schuster and Watson, 2007; Schuster et al., 2009; Olsen et al., 2008; Watson et al., 2009), but it is at risk without sustained funding.

pCO_2 observations are also important for acidification monitoring. pH and the saturation state of calcium carbonates can be calculated from simultaneous measurements of pCO_2 and one other parameter of the carbonate system, i.e. Total Alkalinity or Dissolved Inorganic Carbon.

7. Is there an international policy framework for these observations?

An ocean-carbon monitoring system has been identified as an essential part of the Global Ocean Observing System (GOOS) and the Global Climate Observing System (GCOS), established to support the United Nations Framework Convention on Climate Change (UNFCCC). The Integrated Global Observing Strategy (IGOS) proposed an integrated strategy for monitoring the global carbon cycle that combines *in situ* and remote sensing data with numerical models (Doney and Hood, 2002). A key part of this strategy, within its 'Integrated Global Carbon Observation Theme', is the requirement for the development of a global-scale operational ocean-carbon observation network using a coordinated combination of research vessels, ships of opportunity and autonomous drifters (Ciais *et al*., 2004). An EU-wide component of this is being developed as the Integrated Carbon Observing System (ICOS), linking national activities funded by member states together. International activities are currently being coordinated by the International Ocean Carbon Coordination Project (IOCCP), based at UNESCO.

8. Can we value the role of the oceans CO_2 storage capacity?

Only a preliminary valuation of the oceans' storage capacity for CO_2 has been undertaken. The 'goods and services' approach being used is common to socio-economic analysis of the environment. Ocean CO_2 uptake is considered as part of the service 'gas and climate regulation'. Its economic value is estimated using marginal damage costs avoided, based on current carbon market values. The approach is popular in the environmental economics literature which gives it a high confidence but arguments regarding the discount rate to use, reduce confidence, resulting in a medium-to-high confidence for the method. The application of these methods to carbon cycling in the oceans is still in its infancy, so current estimates should be treated cautiously.

An assessment by Beaumont *et al*. (2008) of the 'goods and services' provided by marine biodiversity in UK waters gave a figure for 'gas and climate regulation' of between about £0.5 billion and £9 billion per annum. However, this is considered an underestimate because primary production by marine phytoplankton was the only process considered and confidence in the cost estimate should be considered low. Furthermore, the current role of the biological carbon pump in shelf seas for cycling anthropogenic CO_2 is not determined, so this estimate only relates to natural cycling of CO_2.

2. HOW CONFIDENT IS THE SCIENCE?

what is happening now?

Atmospheric CO_2 levels are increasing (high confidence)
Global surface ocean temperatures are increasing (high confidence)
Ocean surface CO_2 response (overall low-moderate confidence):

- solubility response to temperature is well known (high confidence)
- carbonate chemistry response to a shift in pCO_2 is well known (high confidence)
- primary production responses are not well understood (low confidence)
- the influence of other processes (e.g. mixing, upwelling, stratification, circulation) are not well understood (low confidence)

Estimates of current global CO_2 uptake by the oceans is based on both direct and indirect measurements (moderate confidence)

Rates of change in surface pCO_2 and oceanic CO_2 uptake are documented for a few regions for relatively short time intervals, but are not well known globally and for longer periods (low confidence).

what could happen in the future?

Assessment of future changes in CO_2 uptake is based on modelling studies. Most of these studies take little or no account of feedback processes. Confidence in these assessments is low.

3. KNOWLEDGE GAPS

- relative importance of, and understanding of interactions between, processes which cause change in the oceanic uptake of atmospheric CO_2.

- mechanisms and magnitude of associated feedback processes on the climate system

- long-term monitoring of oceanic CO_2 uptake and ocean acidification by measurements of oceanic CO_2 parameters and of the atmospheric CO_2 and oxygen contents.

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