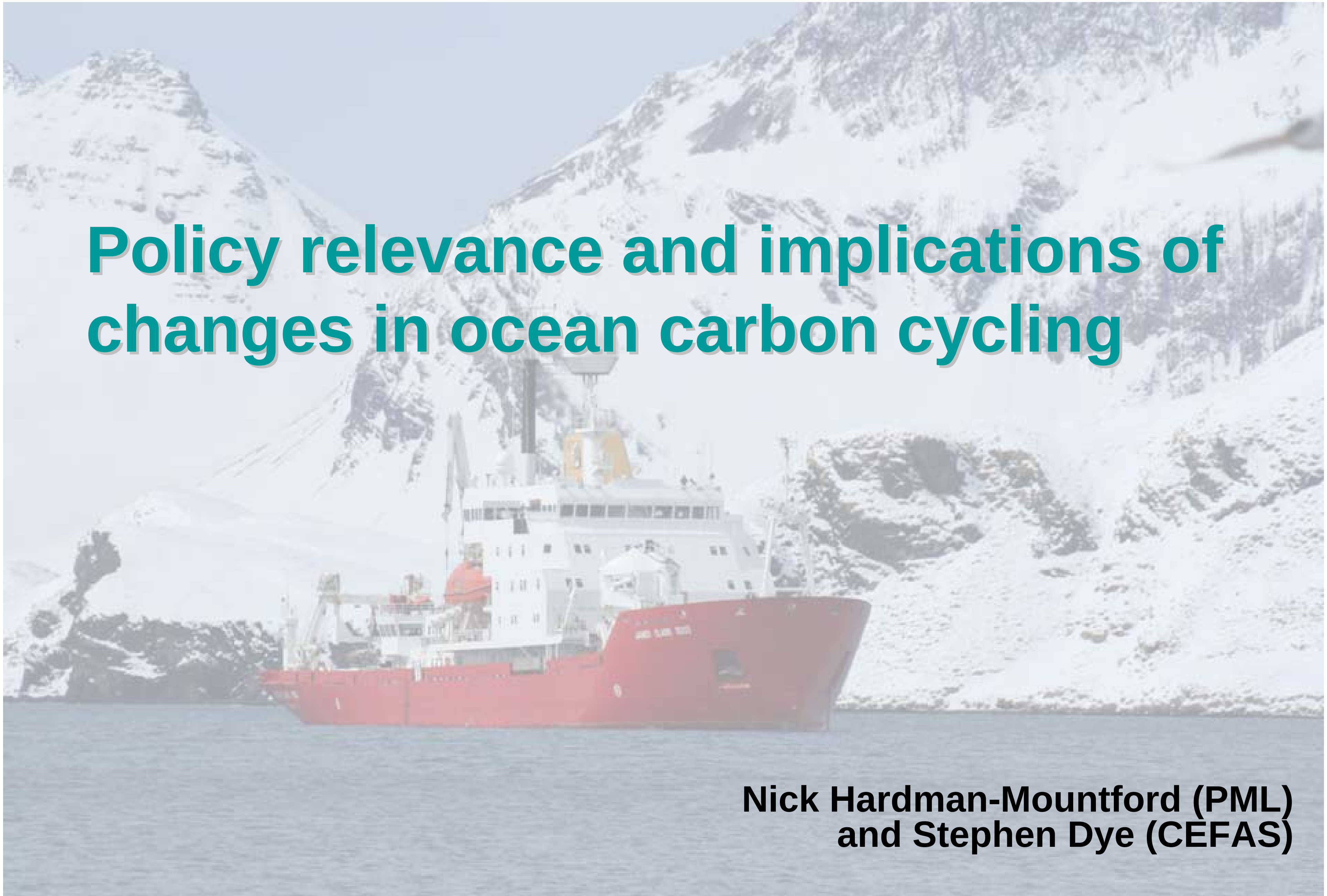


Policy relevance and implications of changes in ocean carbon cycling

Nick Hardman-Mountford (PML)
and Stephen Dye (CEFAS)

Overview

- Ocean regulation of atmospheric CO_2
  - Benefits
  - Uncertainties
  - Costs
- Policy relevance of ocean CO_2
- What science is needed?
- Summary

❖ Ocean regulation of atmospheric CO_2: Benefits

- Ocean is net sink of atmospheric CO_2
  - Ocean has absorbed ~half of all CO_2 released by human activities since 1800 (Sabine et al., 2004)
  - Currently absorbing ~1/3
  - Global ocean net sink of CO_2 ~1.22 Pg C y^{-1} for climatological year 2000 (Takahashi 2008, in press)
  - North Atlantic net sink of CO_2 ~0.33-0.36 Pg C y^{-1} (Schuster, in IOCCP 2007), i.e. ~30% of total net sink
  - Continental margins net sink of CO_2 ~0.34 Pg C y^{-1} (Chen, in IOCCP 2007), i.e. similar contribution to whole North Atlantic!

- Surface ocean pCO_2 expected to rise to double pre-industrial values by ~2050 (IPCC, 2001, 2007)
- Forced by increasing atmospheric pCO_2

Q: Can the ocean continue to buffer atmospheric CO_2 rises at this rate?

❖ Efficiency of the ocean sink: Uncertainties

A: No (high certainty)

- Rising temperatures decrease CO_2 solubility
- Revelle factor (chemical buffering capacity)

- Other feedbacks (+ve/-ve?) impact not yet quantified:
  - melting sea ice
  - changes in primary production
  - changes in precipitation
  - changes in ocean circulation

Big uncertainties

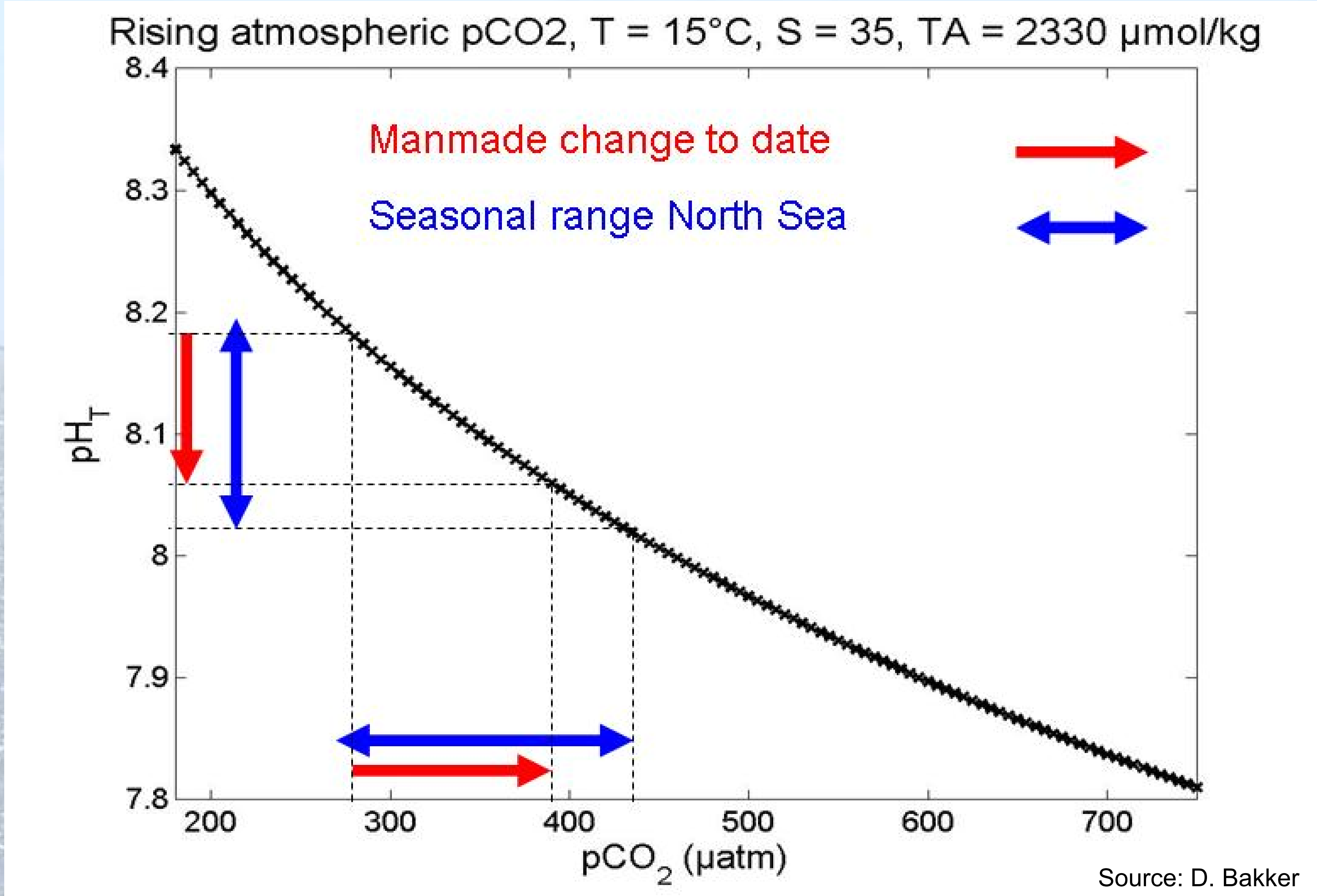
- Evidence suggests efficiency/capacity of ocean sink is already decreasing (Le Quéré et al. 2007, Schuster & Watson, 2007, Canadell et al. 2007)

❖ The other CO_2 problem: acidification

- pCO_2 changes **influence whole ocean carbonate system**:
  - Partial pressure CO_2 (pCO_2)
  - Total CO_2 (TCO_2)/Dissolved Inorganic Carbon (DIC)
  - Total Alkalinity (TA)
  - pH
- **Increasing CO_2 will decrease pH**
  - i.e. oceans → more acidic
- **0.1 pH units decrease so far** (~ 30% increase in H^+ ions)
- **Expected to decrease by 0.5 pH units by 2100**
- Probable **adverse impacts** on ocean organisms & ecosystems, possibly globally

(For overview see Royal Society report, 2005)

❖ Manmade pCO_2 & pH change on large natural variation



❖ What is the policy relevance?

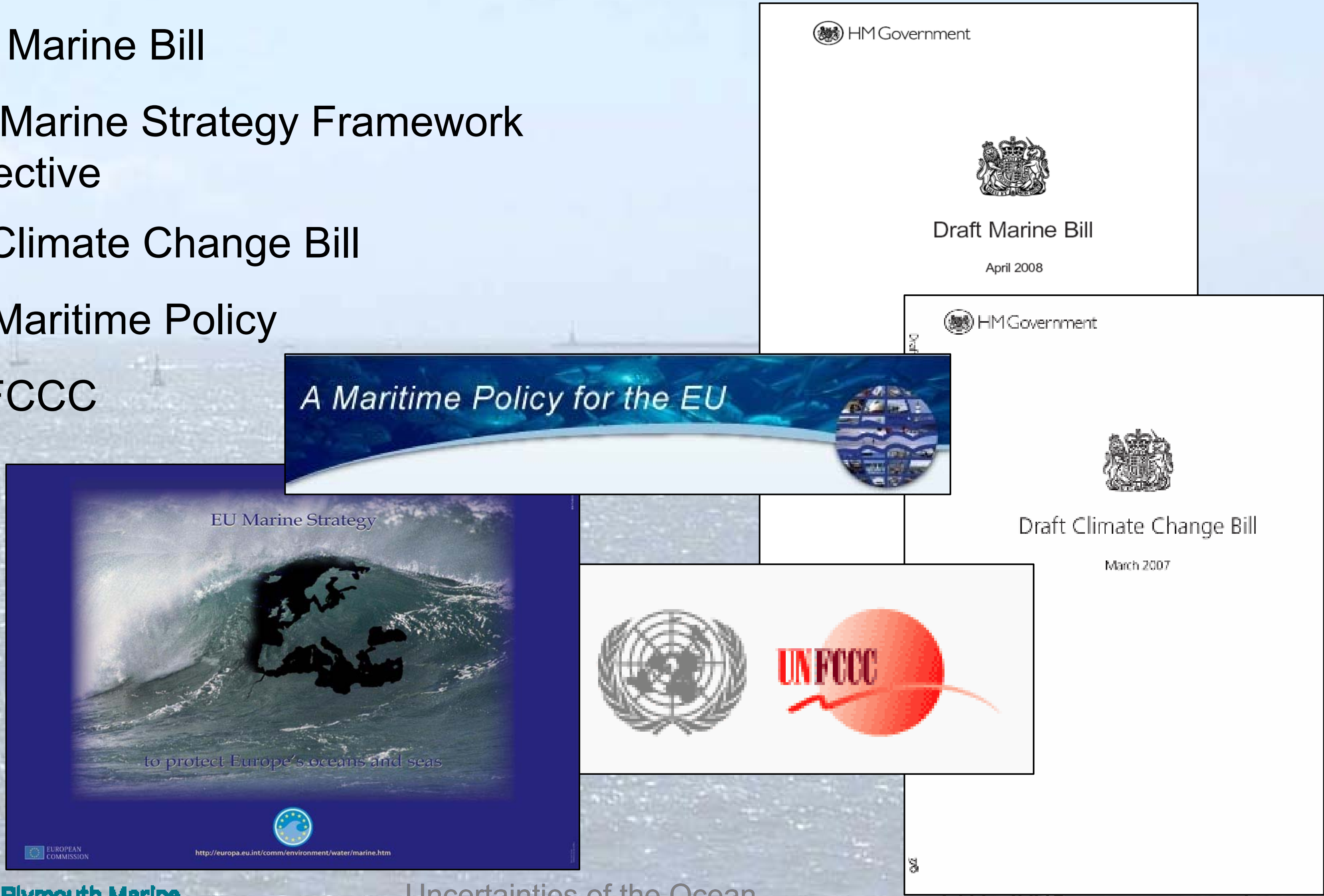
a) UK Marine Bill

b) EU Marine Strategy Framework Directive

c) UK Climate Change Bill

d) EU Maritime Policy

e) UNFCCC



❖ Marine Bill


Draft Marine Bill

April 2008

Importance of **ocean's role in CO_2 'system'** is clearly recognised in *impact assessment* component of the draft Bill, and in references to **acidification** and **climate**.

Annex 1:***Carbon Assessment***

44. … In general, the Marine Bill's objective of managing the marine area in a more sustainable manner will help maintain the sea's crucial role in CO_2 absorption….

And using the PML work of Beaumont et al. (2006) Smyth et al. (2005) in Annex 3

Annex 3:***Gas and climate regulation***

63. Gas and climate regulation has an aggregate annual UK value estimate of £8.2bn, this is significantly higher than the estimates for other ecosystem goods and services …

Reference to direct monitoring of CO_2 in the ocean:

- Probably the commitment to OSPAR?
- Leading into the European Marine Strategy Framework Directive…

❖ EU Marine Strategy Framework Directive

http://europa.eu.int/comm/environment/water/marine.htm

In next 10 to15 years MSFD will become central with key stages in 2012, 2016 and 2020, all requiring marine observations and understanding

Member States have to take the necessary measures to achieve or maintain good environmental status in the marine environment by the year 2020.

- Qualitative descriptors:

  (7) Permanent alteration of hydrographical conditions does not adversely affect marine ecosystems.

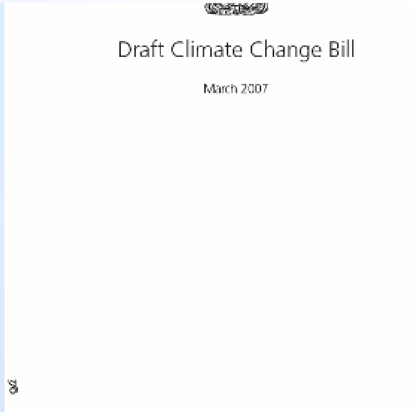
  (8) Concentrations of contaminants are at levels not giving rise to pollution effects.

Marine strategies to be developed in order to protect and preserve the marine environment, prevent its deterioration, restore marine ecosystems and prevent and reduce inputs in the marine environment.

Establish and implement coordinated monitoring programmes for the ongoing assessment of the environmental status of their marine waters.

- Annexes III and V give more details on ideas for monitoring programmes
- Identify pH, pCO_2 profiles or equivalent information as ‘characteristics’ to be monitored to measure marine acidification

❖ Climate Change Bill


Draft Climate Change Bill

March 2007

Role of ocean CO_2 monitoring and research is less clear but

- 'removals' are likely to impact the marine environment
- carbon budgets include the UK marine area.

The amount of UK emissions and UK removals of a greenhouse gas for a period must be determined consistently with international carbon reporting practice.

Territorial scope of provisions relating to greenhouse gas emissions

(1) The provisions of this Act relating to emissions of greenhouse gases apply to emissions from sources or other matters occurring in, above or below—

(a) UK coastal waters, or

(b) the UK sector of the continental shelf,

- Shelf-sea carbon budget currently one of largest areas of uncertainty!
- Important to improve estimates for reporting of natural sinks/sources and changes in these

❖ EU Integrated Maritime Policy

An integrated maritime policy will change the way policy is formulated and decisions taken in the maritime sectors.

Actions cover a wide spectrum of issues ranging from maritime transport to the competitiveness of maritime businesses, employment, scientific research, fisheries and the protection of the marine environment. They include initiatives to develop:

- National integrated maritime policies
- European network of maritime clusters
- A European Marine Observation and Data Network
- A Strategy to mitigate the effects of Climate Change on coastal regions.

How can ocean CO_2 monitoring and research inform and contribute to these initiatives?

❖ UNFCCC (Kyoto, Montreal, Bali)

- Adaptation: consequences of staying within 2° target
  - reduction in ocean sink
- Tracking carbon sinks and sources
  - e.g. REDD
  - extend to oceans?
- Integrated Carbon Observing System (ICOS)
  - EU contribution to IGCO
  - new research infrastructure to decipher the greenhouse gas balance of Europe and adjacent regions
  - Provide independent check on UK emissions?

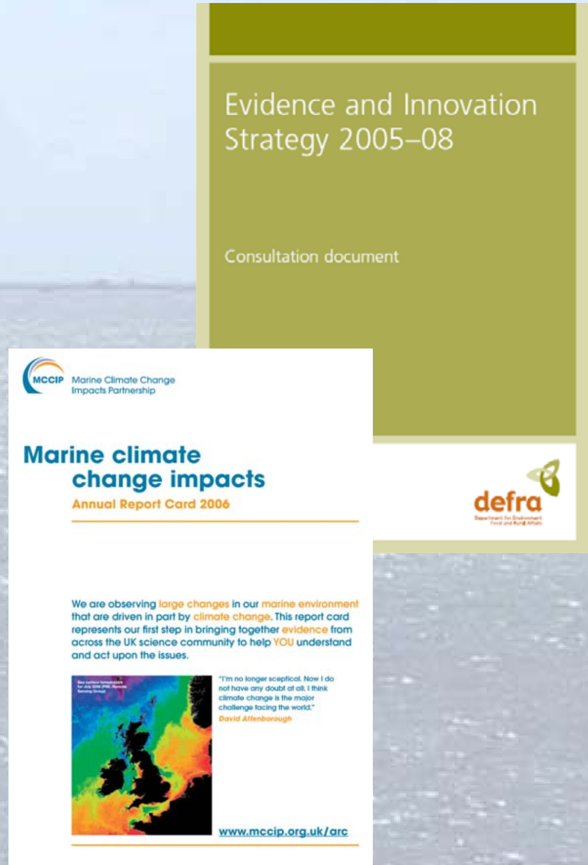
http://icos-infrastructure.ipsl.jussieu.fr/

❖ What science is needed?

- Three main areas in policy:
  1. Quantification of sinks and sources
  2. Monitoring for change in ocean CO_2 and key processes
  3. Assessment of vulnerability of key processes, i.e. risk of decline to ‘goods & services’
- Region of interest is mainly UK EEZ but also contribution to international commitments

What science is needed?

- **Defra: Evidence & Innovation strategy (2005)**
  - climate change & energy:
    - operational CO_2 data collection,
    - improved CO_2 sensors
    - Improved CO_2 modelling capability
  - marine ecosystems:
    - CO_2 data for monitoring pH changes

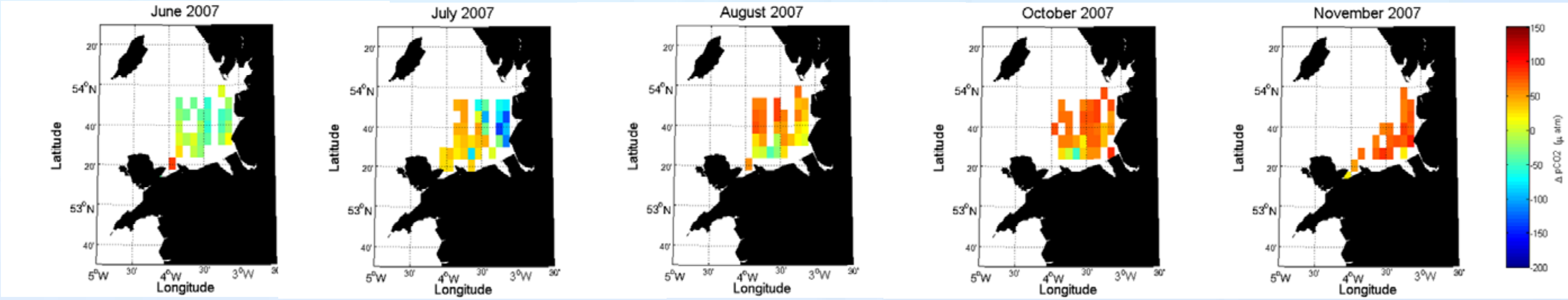


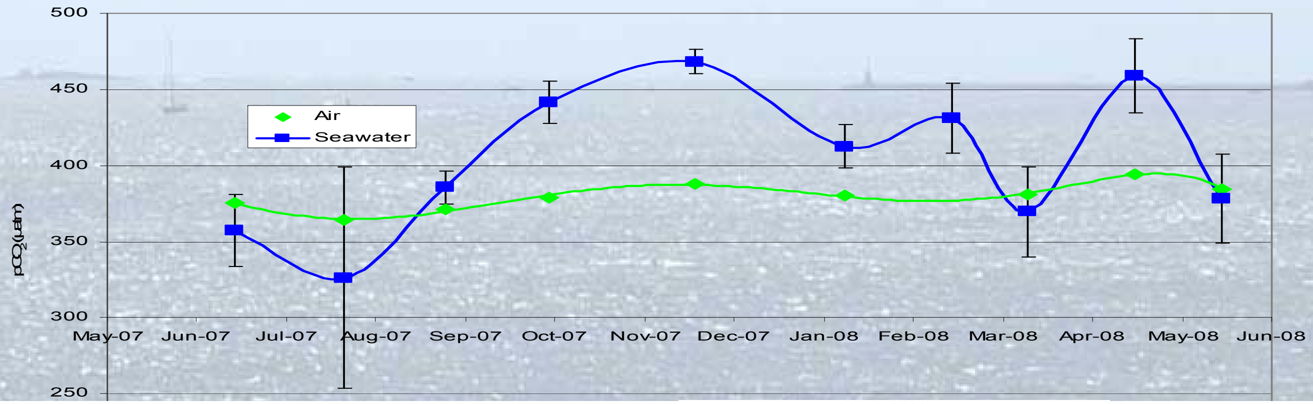
- **Current state of knowledge needs to be reviewed for MCCIP in a CO_2 Annual Report Card (in progress)**

❖ Current knowledge & needs: Quantification

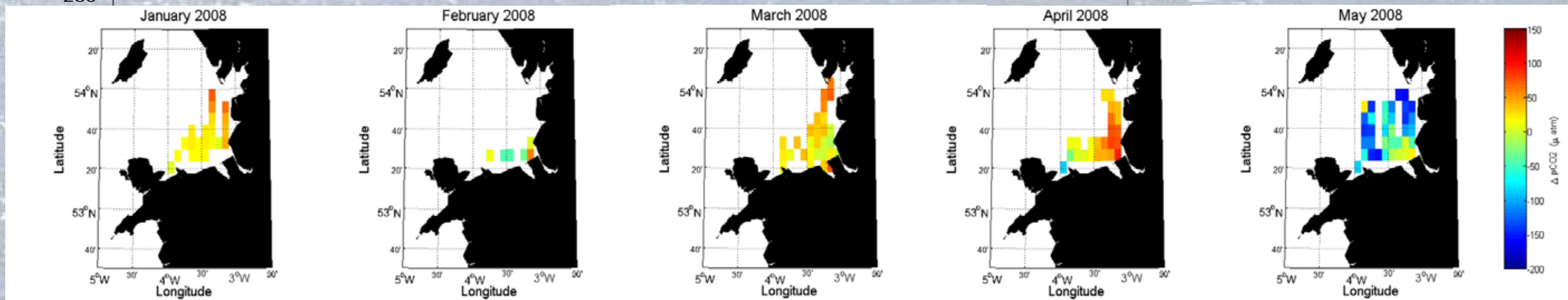
- Current:
  - Models suggest NW European Shelf is net sink
    but shelf includes both source and sink regions (Holt talk)
  - Direct measurements being made for each regional sea (Irish Sea, English Channel, North Sea by other EU countries) to better quantify seasonal cycle
- Needs
  - Increased space-time coverage to better quantify full range of environments over full seasonal cycle
  - Improvements in satellite retrievals over the ocean
  - Improvements in forecast models

❖ Seasonal cycle of pCO_2 in Liverpool Bay





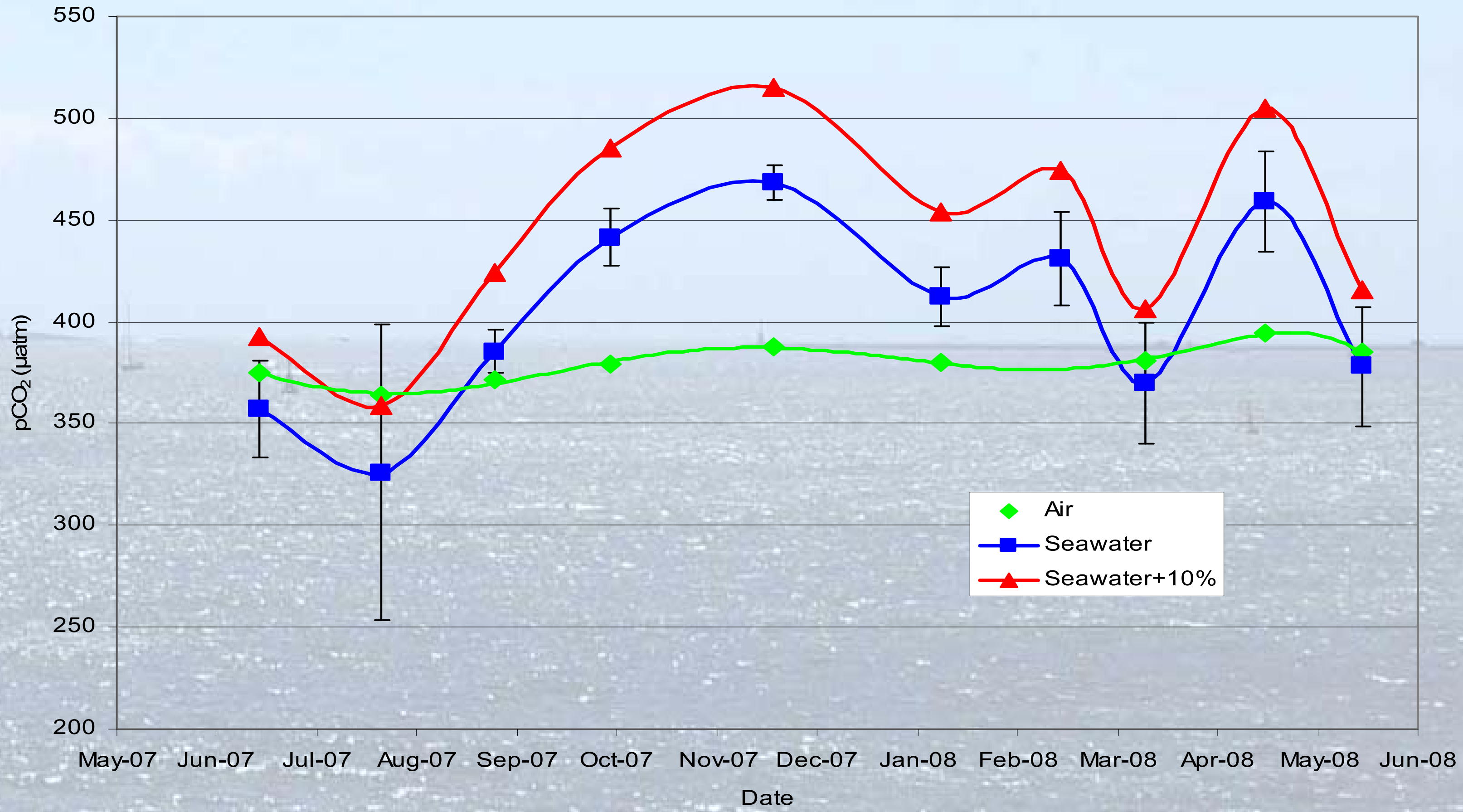
Data and plots by
Emmer Litt (UWB/PML)



❖ Current knowledge & needs: Vulnerabilities

- Current:
  - Warming: could shift weak sinks to sources?
    - 2°C rise = ~10% decline in pCO_2
  - Revelle factor: changes in rainfall and DIC input from rivers
    - 1% change in DIC =~10% change in pCO_2
  - Circulation changes: changes in strength of slope current influence off-shelf carbon export to deep ocean
  - Primary production: could be affected by changes in various processes (run-off, stratification, storminess)
- Needs:
  - Improved knowledge of changes in primary production and phytoplankton community
  - Improved knowledge of slope current forcing
  - Measurements of ice-edge and sub-ice regions
  - Combined assessment of feedbacks

❖ Liverpool Bay: seasonal cycle of pCO2 + 10%



→ Lose seasonal CO_2 sink

Data processed by
Emmer Litt (UWB/PML)

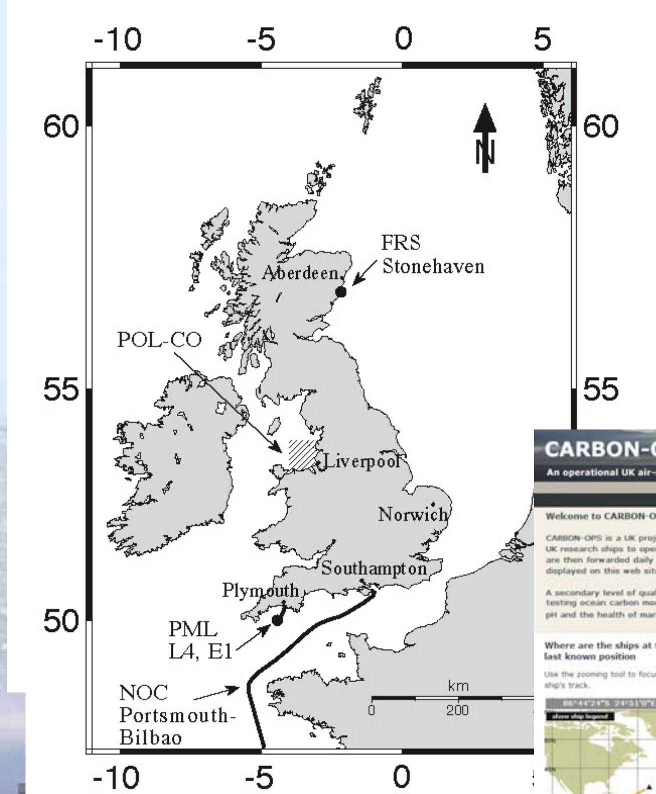
❖ Current knowledge & needs: Monitoring

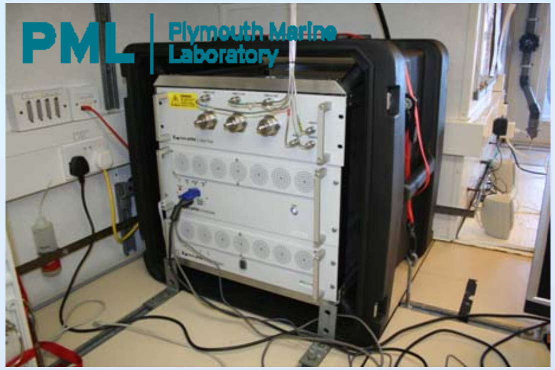
- Current:
  - CO_2 system monitoring (pCO_2, pH, DIC, TA) being implemented for selected UK shelf areas (DEFRApH)
  - Builds on existing UK pCO_2 measurements from research vessels & VOS for UK shelf, N. Atlantic & other regions (NERC CARBON-OPS, EU CARBO-OCEAN)
  - Already linking to Met Office to improve models
  - Long-term time series locations give measurements of some key processes (MECN, NERC O2025)

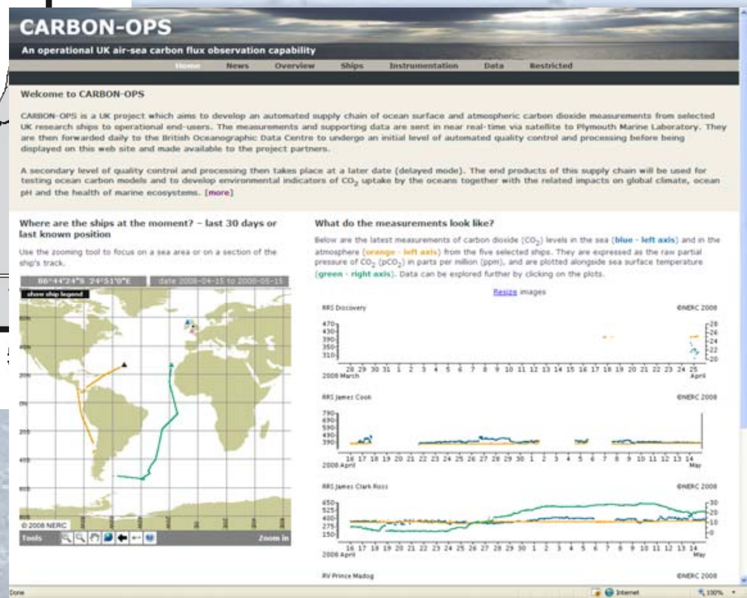
- Needs:
  - Sustained long-term monitoring of CO_2 system & key processes (beyond 2010 for CO_2)
  - Development of CO_2 indicators

❖ DEFRApH & Carbon-Ops monitoring

Photo courtesy of Ute Schuster







❖ Conclusions

- Last five years have led to big increases in our knowledge of ocean-atmosphere CO_2 exchange
- Feeding these findings into policy and using them to support policy is now key
- Three main areas identified:
  - Quantification of sinks and sources
  - Monitoring for change in ocean CO_2 and key processes
  - Assessment of vulnerability of key processes, i.e. risk of decline to 'goods & services'
- [To policymakers] What do you need?

❖ Acknowledgements

- Centre for observation of Air-Sea Interactions and fluXes (CASIX), a NERC Centre of Excellence in Earth Observation.
- CARBON-OPS NERC Knowledge Transfer project (NE/E002021/1).
- Development of pCO_2 systems NERC (NE/C513277/1).
- DefraPH (Defra project ME4133)
- Collaborators at BAS, UWB, NMF-SS
- Crews of RRS James Clark Ross, James Cook, Discovery, RV Prince Madog, Plymouth Quest

❖ Additional slides

❖ Monitoring ocean CO_2 : the challenges

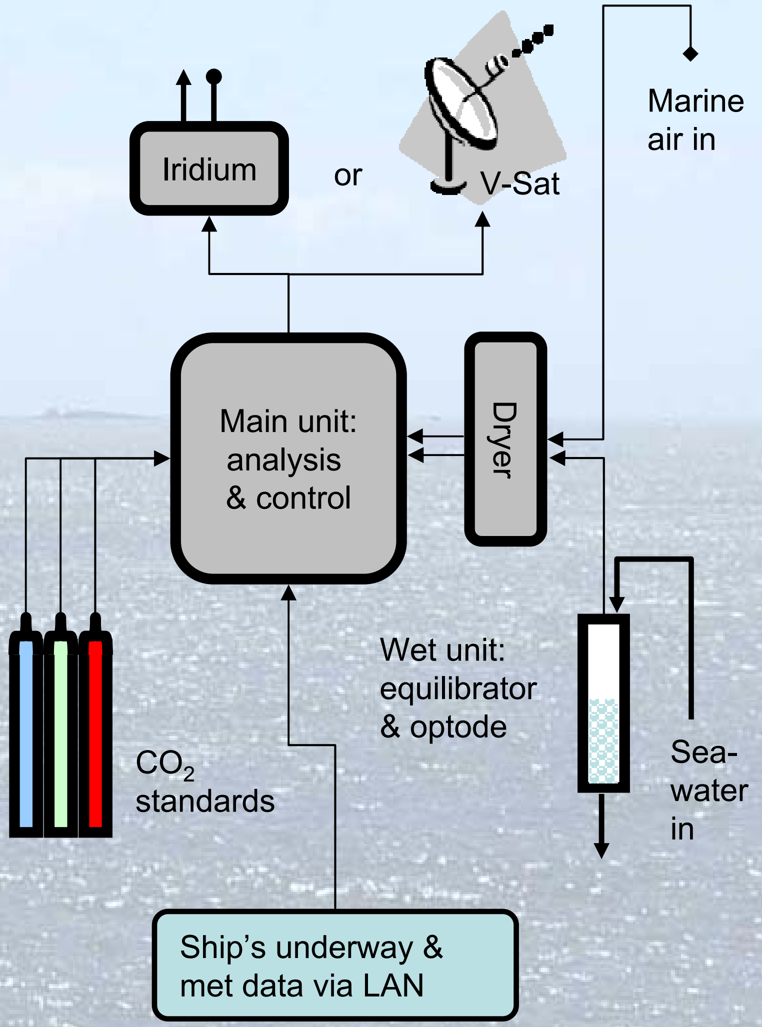
- **Need for more measurements globally:**
  - **So few** that global estimates project all observations to a single year (Takahashi et al., 1998, 2002, 2007)
  - Especially poor in shelf seas, Southern Ocean, Southern Hemisphere gyres
- **Need for robust instruments**
  - Automated pCO_2 is OK (see next slide)
  - Automated DIC, TA, pH systems still in development
- **Need for operational use**
  - Automated processing
  - Feed to prediction & analysis systems (modelling)
  - Development of operational products/indicators

→ Activities described address these 3 needs

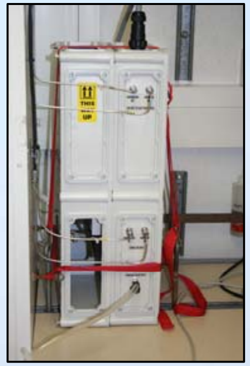
❖ Technology: PML pCO_2 systems (2004-2007)

- Re-designed underway pCO_2 measurement systems to make more reliable and low-maintenance
- Autonomous *Live pCO_2* systems manufactured for PML by Dartcom
- 5 installed on UK research vessels (as VOS):
  - RRS James Clark Ross
  - RRS Discovery
  - RRS James Cook
  - RV Prince Madog
  - RV Plymouth Quest

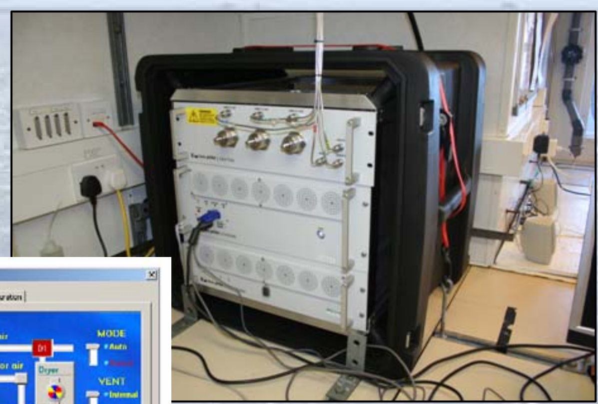
Live pCO_2 underway measurement system



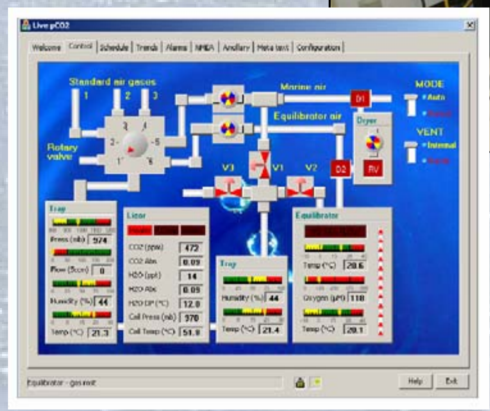
Seawater 'wet unit'



Dryer

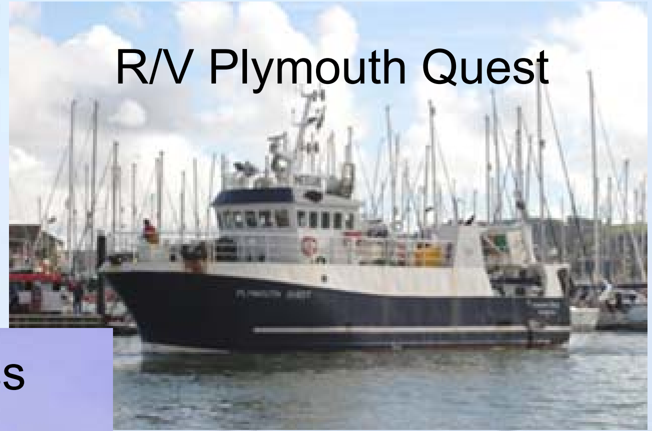


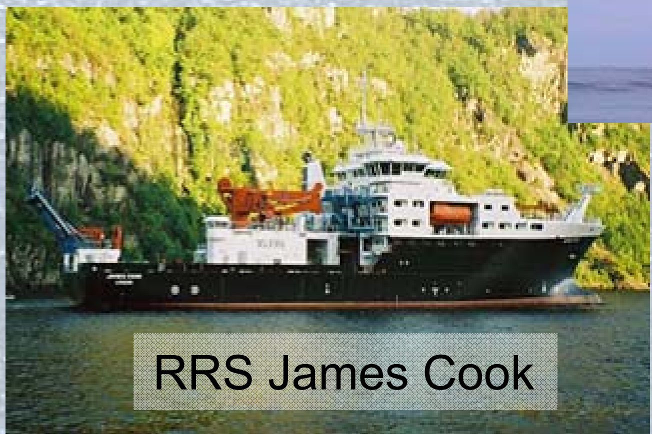
Main unit



Control software

The Research Vessels

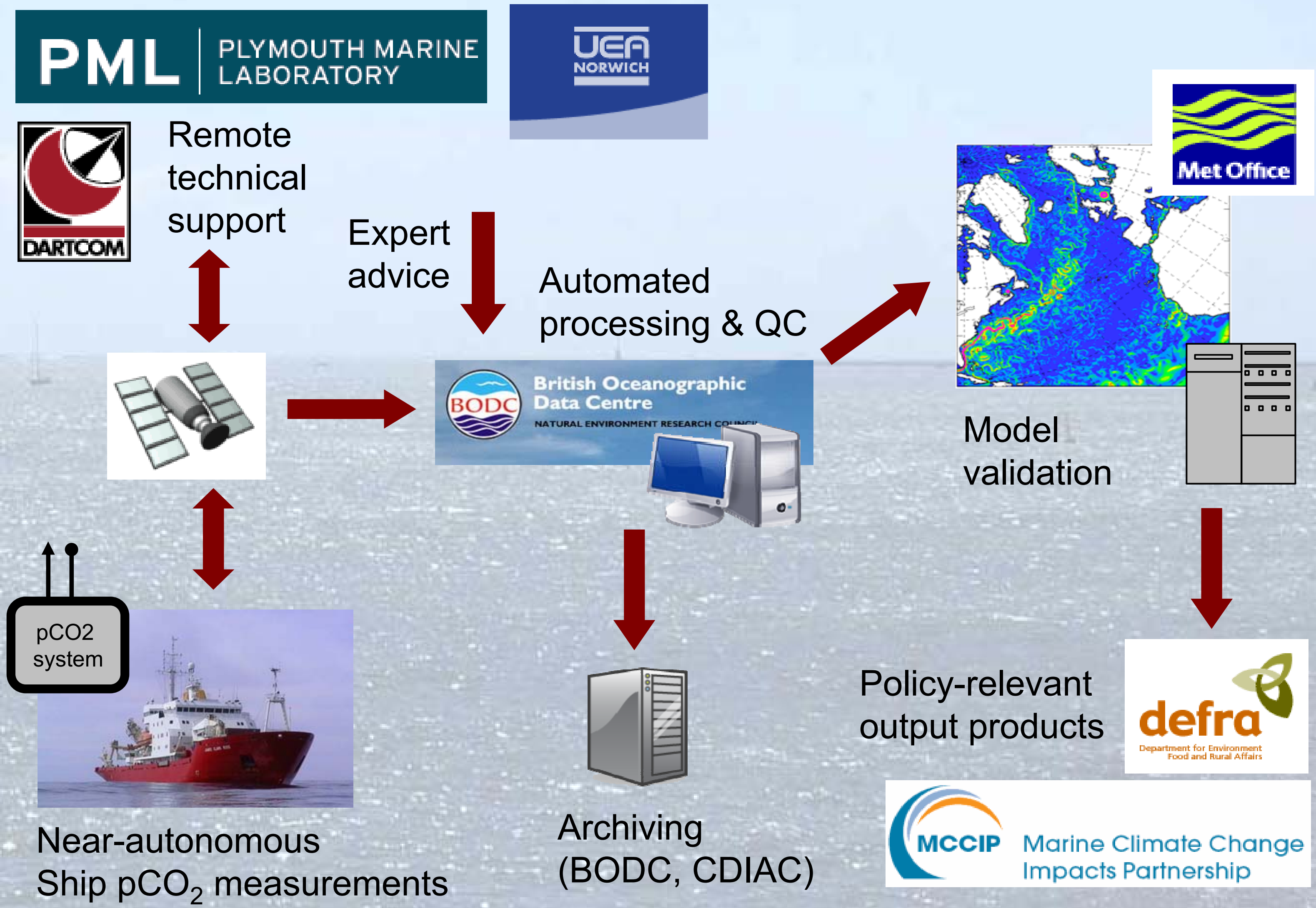




CARBON-OPS: 2007-2009

- NERC Knowledge Transfer (KT) project
- Partners: PML, BODC, UEA, Met Office, MCCIP, NMF-SS, BAS, UWB
- Uses 5 new, autonomous PML/Dartcom *Live* pCO_2 instruments on UK research vessels
- (Other VOS may be added later)
- Goal: Establish and demonstrate operational pCO_2 monitoring 'supply chain' infrastructure (2 years)

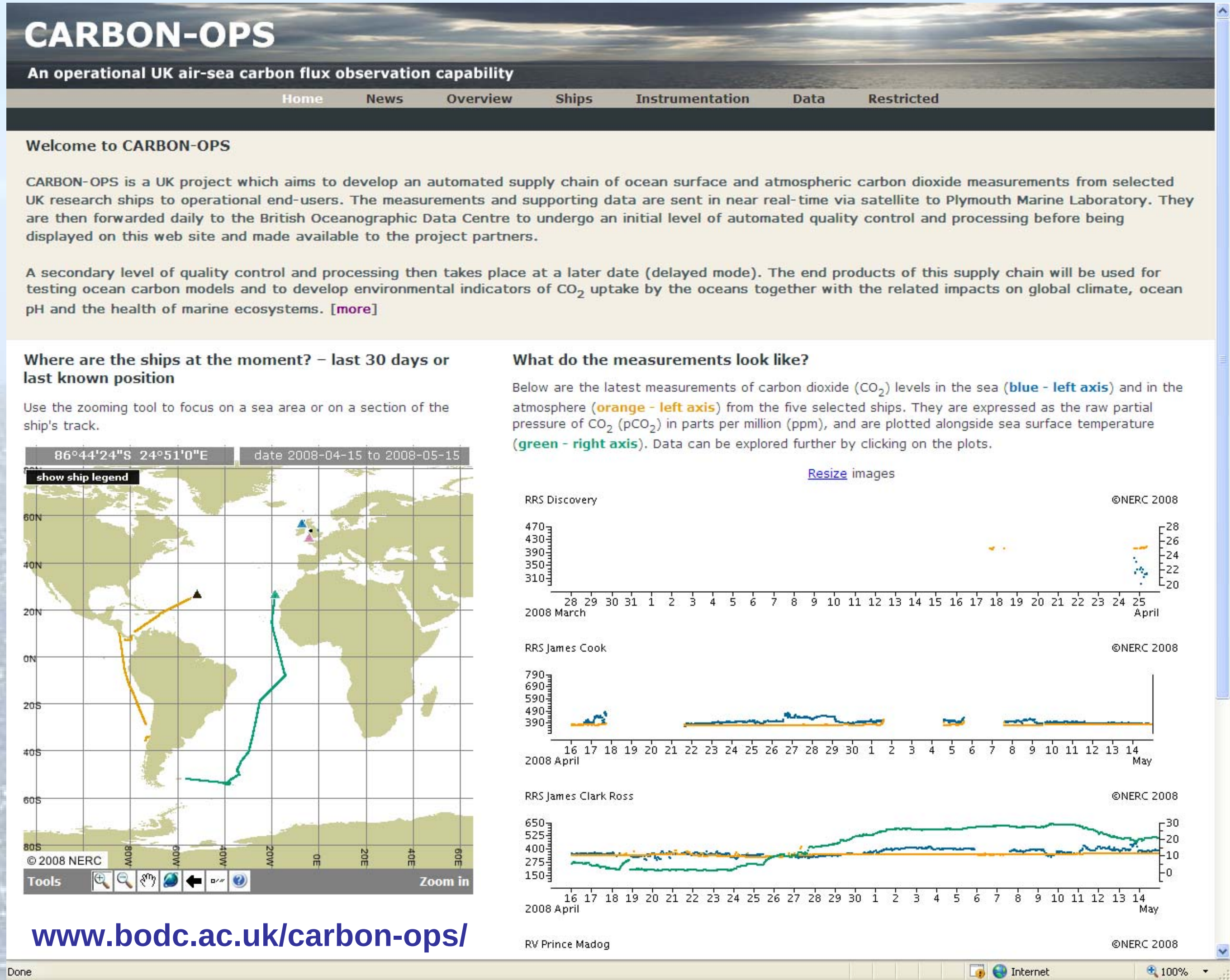
❖ KT ‘supply chain’



Automated processing & QC

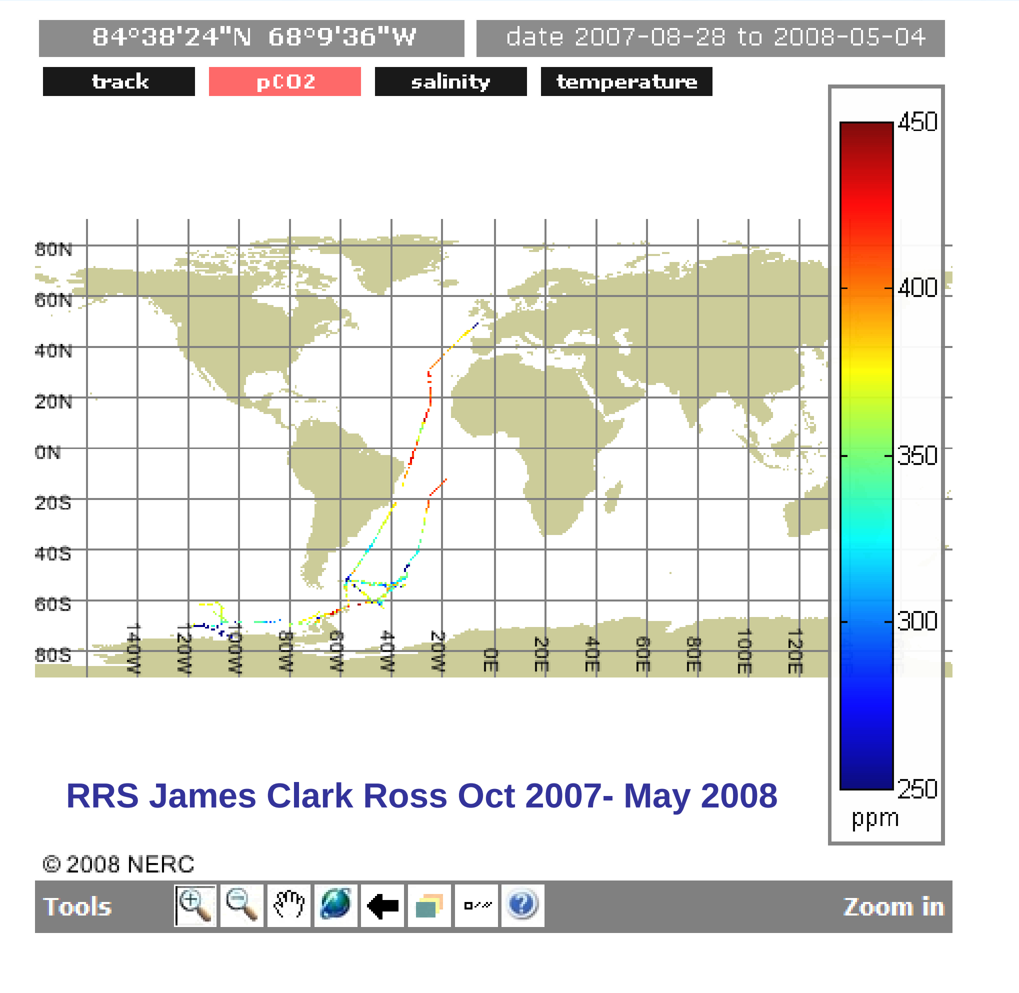
- **NRT** & **delayed mode** processing of data from ships
- **NRT automated activities** (calibration, processing, QC)
  - quick access to results
  - diagnostic checking (e.g. flow rates, humidity levels)
  - automated flagging procedures
  - tracking of CO_2 trends (e.g. through blooms)
  - model nowcast validation
- **Delayed mode activities** (advanced calibration & QC)
  - takes account of additional data if available
  - manual QC flagging (BODC bespoke software)
  - improves usable data volume

Interactive website for live data



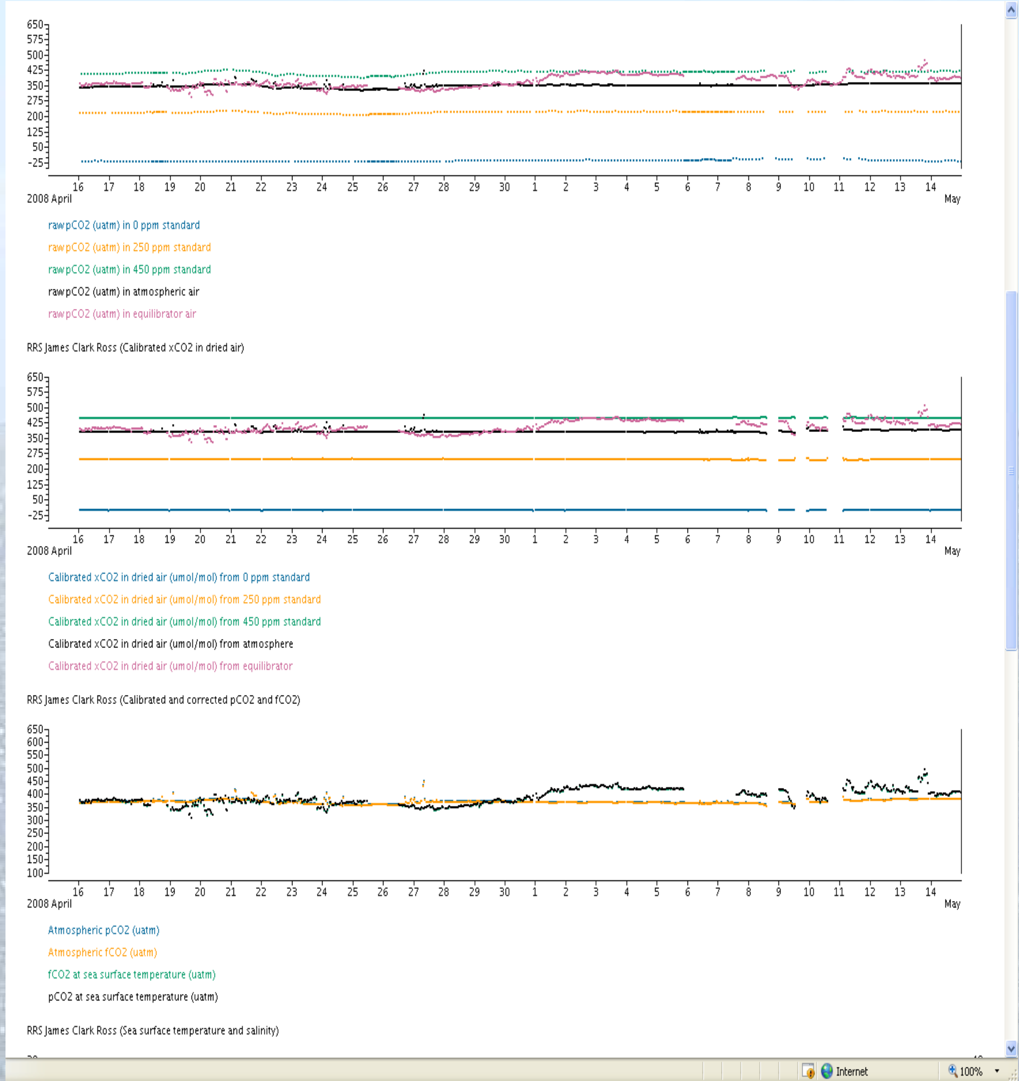
www.bodc.ac.uk/carbon-ops/

Map display



- Interactive plotting
- Zoom in/out
- Select ship/time period
- GIS layers (bathymetry, place names)

Real-time processing

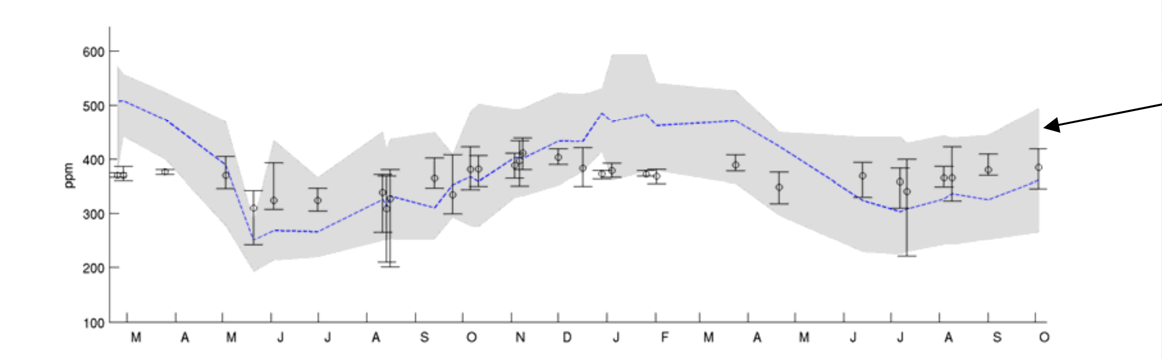


- raw measurements,
- calibrated xCO_2
- fully processed pCO_2

Other web features

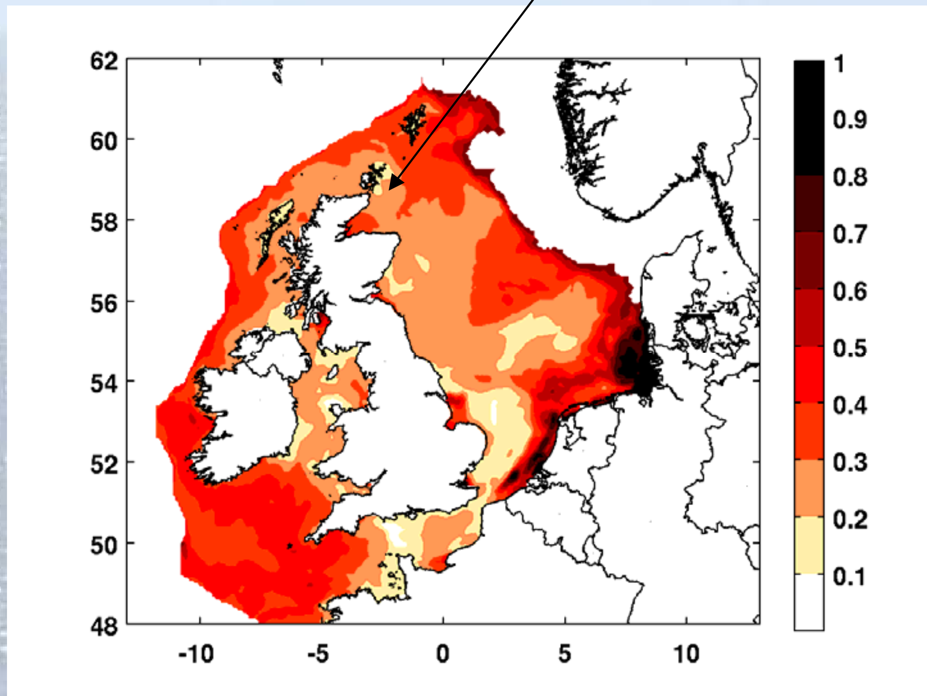
- Diagnostic variables for checking performance
- Choice of flags
- Details of processing & QC methodology, instruments & cruise reports
- Downloadable data files (registered users)
- Model output (to be added)

Model validation & products



Validation of POLCOMS- ERSEM model output for English Channel using pCO_2 data measured by VOS from the CAVASSOO project

POLCOMS-ERSEM modelled in situ pH range across the annual cycle for the NW European Shelf



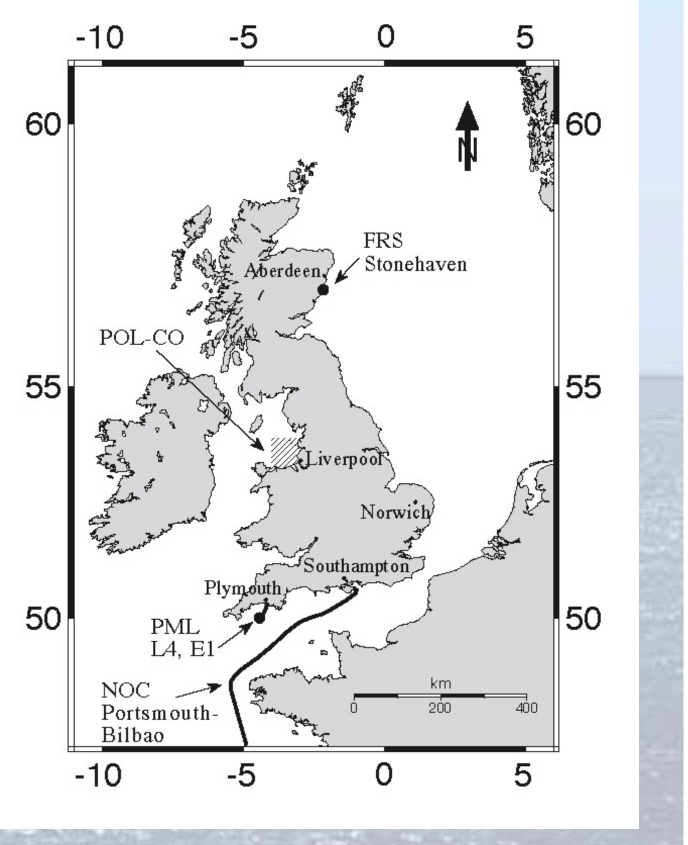
- Use of in situ observations for validation improves confidence in model outputs
- Models can provide integrated (space, time) measures of useful indices (e.g. pH range)

Areas for future development

- **Expand range of variables measured**
  - Proposal to Defra submitted to add DIC, TA bottle samples to existing pCO_2 observations (NOCS, PML, UEA collaboration)
- **Autonomous sensor development** (underway & moored)
  - pH, DIC, TA still need development – some promising prototypes
- **Automated data handling**
  - pCO_2 live from Feb 08
  - Provides basis for expanding to more variables
- **Policy-based forecast capability**
  - Range of CO_2 issues need addressing by policy evidence groups (currently only pH covered in ARC)
  - Development of policy-based indicators from combined *in situ* and modelled output (link with UKMMAS)
- **Sustainability of funding for monitoring**
  - The (coupled) CO_2 problem (climate change, acidification) is not going away!

Defra pH baseline proposal (2008-2010)

- Measure pCO_2, TA, DIC
  → calculate pH
- Trial some pH measurement systems
- Characterise UK shelf waters – sampling different regimes (e.g. estuarine influence, seasonally stratified)
- Compare with modelled pH
- Determine impacts of oceanographic drivers (e.g. T, S, N) on variability using historical time series
- Recommendations for a future pH monitoring programme



Summary

- pCO_2 is a key variable for climate and ocean acidification monitoring
- Operational autonomous underway measurements of pCO_2 are achievable in NRT
- Carbon-Ops is demonstrating operational monitoring, data processing, QC and dissemination system
- Possibility to expand system for other variables
- Use to improve model assessments & forecasts
- **Sustained funding is needed**

Acknowledgements

- CARBON-OPS project funded by NERC through its Knowledge Transfer programme (NE/E002021/1).
- Development of pCO_2 systems was funded by NERC through capital equipment grant (NE/C513277/1).
- Collaboration with British Antarctic Survey through Antarctic Funding Initiative CGS funding (CGS8/28).
- NHM funded through the Centre for observation of Air-Sea Interactions and fluXes (CASIX), a Centre of Excellence in Earth Observation.
- CAVASSOO funded by EC 2000-2003, grant EVK2-CT-2000-00088
- FerryBox grants FP5 EVK2-CT-2002-00144 & NERC Capital NE/C513418/1

Others involved with project:

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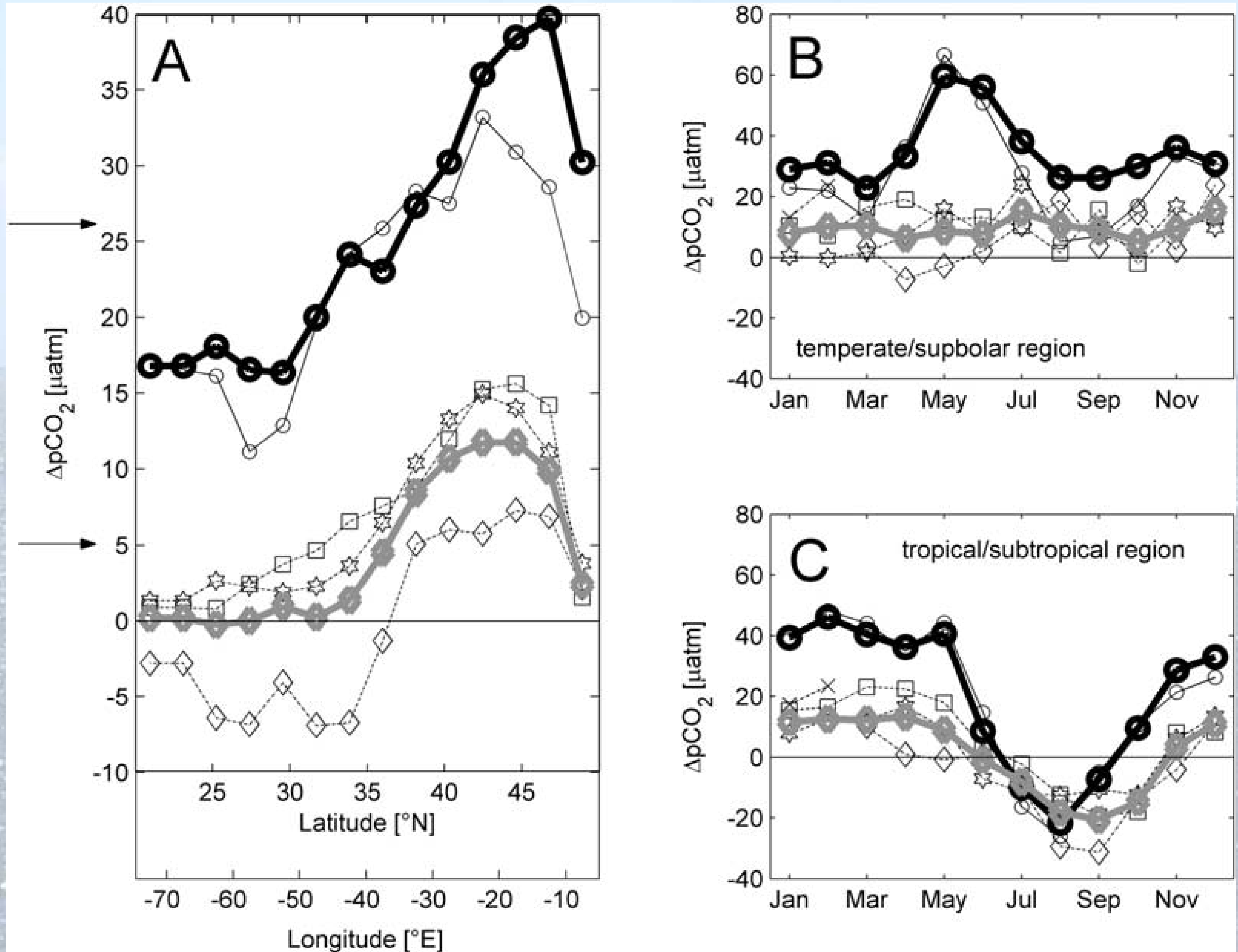
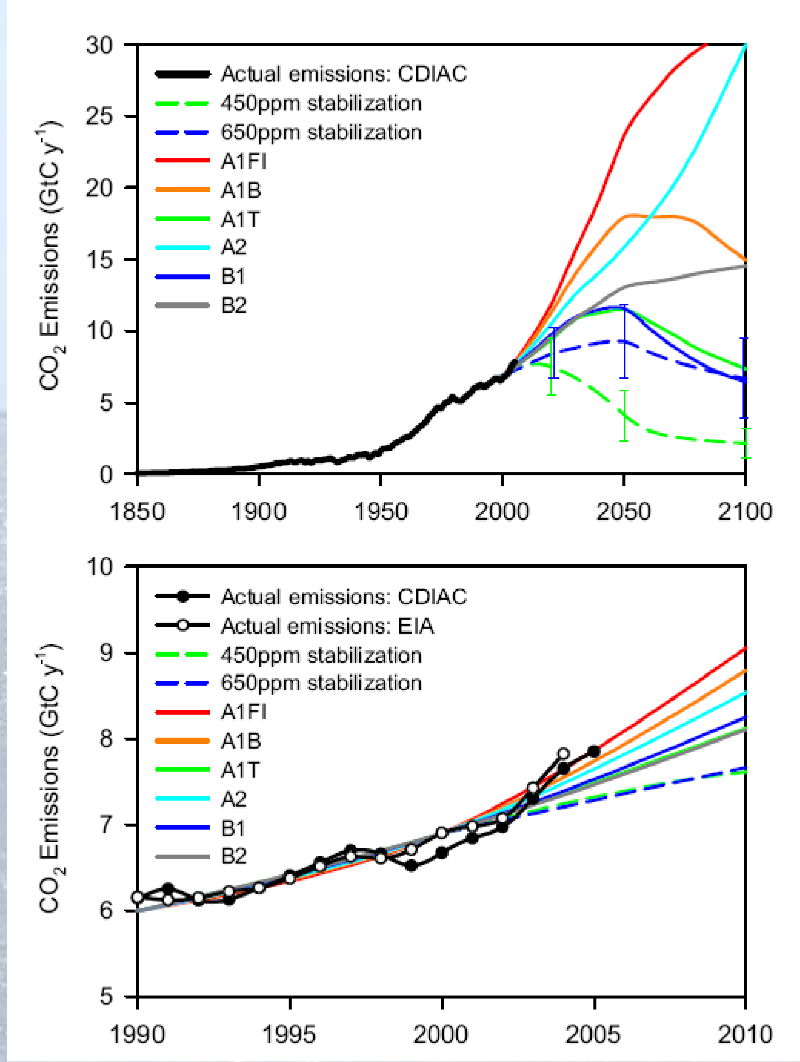
- Colin Opie, Dave Wright (Dartcom)
- Angus Atkinson, AME and RRS JCR crew (BAS)
- Gay Mitchelson-Jacob, Ray Wilton & team (UWB)
- Gareth Knight & team (NMF Sea Systems)
- Libby Jones (UEA)

Schuster & Watson (2007) JGR



❖ Raupach et al. (2007) PNAS

CO_2 emissions from fossil-fuel burning and industrial processes have been accelerating at a global scale, with their growth rate increasing from 1.1% y^{-1} for 1990–1999 to >3% y^{-1} for 2000–2004. The emissions growth rate since 2000 was greater than for the most fossil-fuel intensive of the Intergovernmental Panel on Climate Change emissions scenarios developed in the late 1990s. Global emissions growth since 2000 was driven by a cessation or reversal of earlier declining trends in the energy intensity of gross domestic product (GDP) (energy/GDP) and the carbon intensity of energy (emissions/energy), coupled with continuing increases in population and per-capita GDP. Nearly constant or slightly increasing trends in the carbon intensity of energy have been recently observed in both developed and developing regions. No region is decarbonizing its energy supply. The growth rate in emissions is strongest in rapidly developing economies, particularly China. Together, the developing and least-developed economies (forming 80% of the world's population) accounted for 73% of global emissions growth in 2004 but only 41% of global emissions and only 23% of global cumulative emissions since the mid-18th century. The results have implications for global equity.



❖ Canadell et al. 2007 PNAS

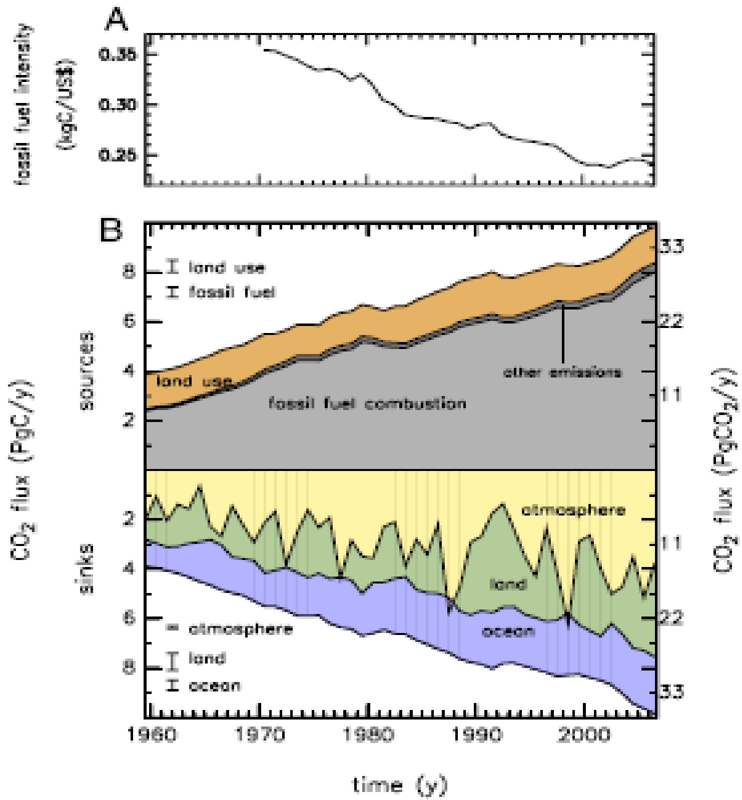


Fig. 1. Fossil-fuel intensity of the GWP from 1970 to 2006 (*A*) and the CO_2 budget from 1959 to 2006 (*B*). Fossil-fuel intensity uses GWP data based on market exchange rates, expressed in U.S. dollars (referenced to 1990, with inflation removed). (*B Upper*) CO_2 emissions to the atmosphere (sources) as the sum of fossil fuel combustion, land-use change, and other emissions, which are primarily from cement production. (*Lower*) The fate of the emitted CO_2, including the increase in atmospheric CO_2 plus the sinks of CO_2 on land and in the ocean. Flux is in Pg y^{-1} carbon (left axis) and Pg y^{-1} CO_2 (right axis).

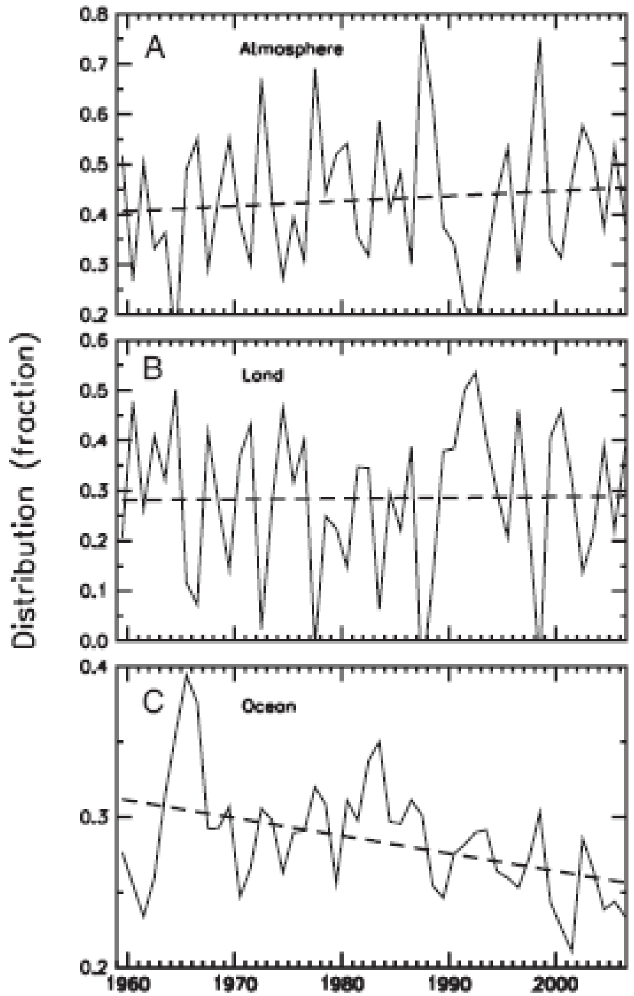


Fig. 2. Fraction of the total emissions (F_{Foss} + F_{LUC}) that remains in the atmosphere (*A*), the land biosphere (*B*), and the ocean (*C*).