

Initial Atlantic Ocean Carbon Synthesis Meeting

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Laugarvatn, Iceland

Co-sponsored by the EU Integrated Project CARBOOCEAN – Marine Carbon Sources and Sinks Assessment, and the International Ocean Carbon Coordination Project (IOCCP). This workshop was hosted by Jon Olafsson, Marine Research Institute of Iceland, and Chaired by Douglas Wallace, IfM-Geomar, Germany.

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1) Introduction to the Workshop

The WOCE / JGOFS hydrographic program of the 1990s provided a global survey of hydrographic properties in the global ocean and the first quasi-synoptic snapshot of the state of the global ocean. Based on this effort, it was possible to estimate the global ocean inventory of anthropogenic CO₂ for the mid-1990's to $\pm 20\%$. However uncertainties remain concerning possible bias in these estimates and additional key questions remain to be addressed, including: what processes control uptake, where does it occur, will uptake change in the future under possibly changed climate, circulation and ecosystem conditions, and what are the natural and anthropogenic changes in oceanic heat and freshwater inventories ?

An observing strategy suited to addressing these questions was the subject of the International Repeat Hydrography and Carbon Workshop, co-sponsored by JAMSTEC, the IOCCP and CLIVAR, in November 2005. At this workshop, it was emphasized that data syntheses addressing these questions require an integrated approach that brings together modeling and observations from multiple platforms carried out in each ocean basin.

Further, one of the five major objectives of the EU CARBOOCEAN integrated project is the quantification of decadal-to-centennial large-scale Atlantic and Southern Ocean carbon inventory changes. Operationally this implies a need to quantify: “the Atlantic and Southern Ocean carbon sink, and its decadal change, through highest accuracy measurement of the changing inventories of inorganic carbon and carbon-related tracers. Atlantic and Southern Ocean data would then be integrated into a coherent global data base. The ability of prognostic models to represent the observed changes for a reliable now-cast would be assessed against the data-based syntheses.” The science delivery associated with this objective is “a large scale assessment of the ocean carbon storage”.

With this CARBOOCEAN project objective and the larger international context in mind, CARBOOCEAN took the lead in initiating a workshop to identify key approaches, interested research groups and new data sets relevant to an international synthesis effort for the Atlantic Ocean. The IOCCP joined CARBOOCEAN to assist in making this an international effort, linking North American and EU scientists through partnerships for data exchange and joint scientific analyses.

Specific goals for this workshop were:

- To identify the ocean carbon and related data that have been collected in the Atlantic Ocean (including Arctic and Southern Ocean sectors) that will contribute to a synthesis of ocean carbon, heat and freshwater transport and storage;
- To document the plans and interests of individual research groups for conducting scientific analysis of ocean carbon and other hydrographic data;
- To establish collaborations between groups based around key science questions;
- To assess progress with compilations of Atlantic carbon and other hydrographic data (e.g., CARINA data) being carried out as part of CARBOOCEAN;
- To discuss comparisons of methods to estimate anthropogenic CO₂.
- To make plans for an Atlantic Ocean synthesis using new integrated and multi-disciplinary approaches, outlining as far as possible joint collaborations, data sharing, data management, quality-control and co-authorship issues.

- To address issues and needs for common methodologies and approaches to be used for syntheses that will be carried out in other basins to ensure a globally-consistent approach

Participants also recognized the need to document how far the community has come in answering key questions about issues such as ocean carbon, heat, and freshwater transport, uptake and storage, and ventilation using data obtained from ship-based hydrography, and to identify gaps in knowledge, concerns and challenges for future observational programs.

The meeting was hosted by Jon Olafsson of the Marine Research Institute of Iceland, and held at Laugarvatn, Iceland from 28-30 June 2006. The meeting brought together 23 participants from 9 countries with expertise ranging from ship-based carbon hydrography, physical oceanography, surface pCO₂ variability, CFC and tracer measurements, O₂ on profiling floats, modeling, and data synthesis and management (see Participants List, Section 7)

The basic structure of the Workshop was:

- 1) Science presentations: recent developments on the basis of individual synthesis/analysis efforts;
- 2) Status reports and sharing of relevant prior experience with large-scale synthesis efforts;
- 3) Establishment of working groups, including allocation of synthesis effort;
- 4) Discussion and planning of synthesis within working groups.

2) Science Highlights

Jon Olafsson and Thorarinn S. Arnarson (MRI, Reykjavik, Iceland) Overview of Icelandic CO₂ Research

The main features of work in the Irminger Sea west of Iceland and to the north in the Iceland Sea were described. This has included:

- Time series stations occupied 4 times a year since 1983.
- Studies of seasonal variations in the two regions and calculated air-sea fluxes.
- Underway pCO₂ measurements.

The data are sufficient to document the seasonal cycle of pCO₂ in the waters around Iceland and the long-term as well as interannual variability of surface water pCO₂ in the region.

Scott Doney (WHOI, Woods Hole, USA). The Changing Carbon Balance of the Atlantic from a Model Perspective.

The current ocean carbon sampling strategy for the ocean interior relies on infrequent reoccupations based on decadal-scale hydrographic surveys. Calculating long-term secular changes in anthropogenic carbon and related biogeochemical tracers using this approach is complicated by natural variability, which is large on these scales. Results of numerical experiments suggest that existing empirical techniques (C*, eMLR, etc) provide useful, but incomplete, corrections, especially in regions of mode water and intermediate mode water

formation, and when long-term secular trends are considered. Work is underway on historical model hindcasts and data assimilation with biogeochemistry that may help address the representativeness of observations and the design of improved sampling approaches.

Terry Joyce (WHOI, Woods Hole, USA). [The Changing Hydrographic Balance of the Atlantic Ocean.](#)

Changes in the North Atlantic since the end of WOCE are dominated by the cessation of strong convection in the Labrador Sea and the reduction in formation of mode waters in both the subtropical and subpolar gyres. This can be traced to changes in the NAO in the first case, while the second is surprising since the usual NAO sea-saw favors weak mode water production either in the subtropical gyre or western subpolar gyre, but not both at the same time. This has import for changes in both the potential vorticity and dissolved oxygen of ventilated parts of the N. Atlantic.

Ute Schuster (UEA, Norwich, UK) [Air-Sea Fluxes: Is the North Atlantic Air-Sea CO₂ Flux Decreasing?](#)

Based on a collection of measurements mainly from volunteer observing ships, the sea surface pCO₂ in the North Atlantic has been increasing faster than the atmospheric pCO₂ over the last 10 to 15 years, particularly in the eastern mid-latitudes and the sub-polar gyre. This implies a reduction in the uptake of atmospheric CO₂ by the North Atlantic. Reasons for this change are as yet unclear. A synthesis of temporal and spatial changes of sea surface pCO₂ is needed, as well as of the underlying biological (photosynthesis and respiration), chemical (e.g., Revelle Factor), and physical (circulation and ventilation) properties influencing sea-surface pCO₂ and air-sea flux of CO₂. The estimation of the air-sea flux is critical due to the question of wind-speed to be used and hence needs to be studied in detail.

Are Olsen (University of Bergen, Bergen, Norway). [Carbon Storage in the Greenland-Iceland-Norwegian Seas.](#)

Are Olsen synthesized some recent results on pCO₂ changes in the sub-polar gyre and the Nordic Seas over the last few decades. The results suggest that in the Atlantic waters, the pCO₂ is increasing at a greater rate than in the atmosphere due to anthropogenic carbon input. These observations are reconcilable with a large lateral supply of anthropogenic carbon from further south. This is supported by estimates of the ¹³C Suess effect, and so the Arctic Mediterranean Seas (“the Nordic Seas”) appear to be an important region for transfer of anthropogenic carbon from the surface to the deep ocean.

Alison Macdonald (WHOI, Woods Hole, USA). [Carbon Transports in the Atlantic.](#)

Combining long-line zonal hydrographic transects in an inverse box model which computes estimates of horizontal and vertical circulation, interior source / sink terms, and air-sea fluxes, it is found that:

- although the underlying estimate of the circulation can effect the estimates of contemporary and natural TIC transport, the form of the constraints, in particular, the inclusion of the tracer O* can strongly affect estimates of net transport across some sections.
- combining sections from both the north and south Atlantic produces a fairly strong net northward transport of C_{ant} throughout the Atlantic in qualitative agreement with individual estimates and model analyses.

- estimates of storage and air-sea fluxes would benefit from non-zero analyses.
- understanding the variance of the transports on a variety of space and time-scales is paramount to understanding the uncertainty in the transport estimates themselves.

Doug Wallace (IFM-GEOMAR, Kiel, Germany). Decadal Carbon Storage in the North Atlantic Sub-Tropical Gyre.

This presentation focused on analysis of the Meteor 60/5 cruise data. The cruise had deliberately re-sampled stations in the mid-latitude North Atlantic that had previously been occupied in 1981 during the US-led TTO expedition. The data quality of both cruises permitted an analysis of the multi-decadal change in carbon concentrations. In particular, the cruise permitted testing of the “extended multiple linear regression” technique of assessing carbon changes. In addition, CFC data collected on the cruise were used to estimate anthropogenic carbon using the “transit-time-distribution” approach. A method for extrapolating decadal changes in carbon to total inventory estimates of anthropogenic carbon was applied. Overall, the two completely different and independent approaches to anthropogenic carbon content gave very consistent quantitative results and the qualitative distributions matched the distribution of CFCs and CCl₄ very closely. Comparisons with the delta-C* technique gave similar inventories but some significant differences in the depth-distribution of the inventory, especially in the deepest waters.

Reiner Steinfeldt (University of Bremen, Bremen, Germany). Atlantic CFC Data and Synthesis.

In the framework of CARBOOCEAN, CFC data are used to infer the parameters of Transit Time Distributions (TTDs) and from the TTDs the inventory of anthropogenic CO₂. These estimates have been made for two time frames, the WOCE period (the 1990s) and the post-WOCE period (i.e. after the year 2000). The spatial coverage of the CFC WOCE data set is good, whereas later on large data gaps in the South Atlantic exist. The WOCE data and a great part of the post-WOCE data have been quality controlled. The determination of TTD parameters from CFC is a difficult task. Some constraints on the parameters may be obtained from the temporal CFC increase at repeated sections or by simultaneous measurements of different CFC components (CFC-11/CFC-12 in conjunction with CFC-113 and CCl₄). First estimates of the inventory of anthropogenic CO₂ for the Labrador Sea Water (LSW) in the Subpolar North Atlantic look encouraging. The hydrographic findings (ceasing of LSW ventilation after 1997 and large formation of the lighter Upper Labrador SeaWater (ULSW) later on) are reflected by a constant C_{ant} inventory of LSW and a large increase within the ULSW between 1997 and 2003.

Aida Rios (IIM, Vigo, Spain). CARBOOCEAN Work Package 9 Report

The work carried out in the CARBOOCEAN WP9 was presented here. One of the objectives of WP9 is to establish optimal methods to assess anthropogenic CO₂ inventories and temporal change. The presentation showed the results of an intercomparison exercise using 5 different approaches to C_{ant} estimation applied to a common data set from a long meridional section extending from Arctic to the Southern Ocean. Overall some considerable agreement among the approaches was found: however results from the different approaches diverged at high latitudes.

Marco Vazquez-Rodriguez (IIM, Vigo, Spain). On Anthropogenic Carbon Calculation Methods.

A revision of the delta-C* back-calculation method for determining oceanic anthropogenic carbon (C_{ant}) has been developed. The proposed improved method (ϕCT°) is later applied to Atlantic modern sections. The main progress has been the use of the 100 to 200 meter depth sub-surface layer data as the only reference in C_{ant} estimation. This layer is found to reliably represent the water column from the carbon system and water mass variability point of view. Preformed total alkalinity (TA°) and air-sea disequilibrium (ΔC_{dis}), defined as the difference between the preformed total inorganic carbon and the theoretical C_T in equilibrium with the atmosphere, are parameterized using conservative variables. Silicate is used as an Antarctic water mass tracer. For water masses under the 5 °C isotherm (86% of the Atlantic's volume) the TA° and ΔC_{dis} are calculated through an Optimum Multiparameter (OMP) mixing analysis combined with the obtained parameterizations. The temporal variability of TA° and ΔC_{dis} is considered: the increase of surface alkalinity can account for 3.5% of the C_{ant} signal in a given sample, while results in this study show a 4 $\mu\text{mol kg}^{-1}$ average decrease modulated by ΔC_{dis} . The obtained C_{ant} distribution for the Atlantic Ocean is in agreement with previous results. Compared to other authors, slightly higher C_{ant} values are estimated for the Northern Hemisphere while results for the Southern Ocean match very well those obtained through more local studies. Overall, the calculated Atlantic C_{ant} inventory of 59.2 ± 13.2 Pg-C is in accordance with outputs from Global Ocean Biogeochemical models.

Fiz Perez (IIM, Vigo, Spain) Carbon Storage in the North Atlantic Sub-Polar Gyre.

Results from historical OVIDE cruises (2002, 2004 and 2006) were presented and compared in terms of oxygen and anthropogenic carbon content to previous cruises (FOUREX, AR7E and TTO). Results highlighted the different ventilation regimes having large impacts on regional C_{ant} inventories (Irminger sea).

Mario Hoppema (AWI, Bremerhaven, Germany) Carbon Storage in the Southern Ocean.

Anthropogenic carbon calculations were presented using the back-calculating technique of Chen, which resulted in very low C_{ant} inventories for the Southern Ocean (Weddell Sea). This was confirmed by the delta-C* technique. Reasons for this are the CO_2 flux inhibition by the sea ice and dilution by water masses void of C_{ant} . In the Weddell Sea, there seems to be no good correlation between C_{ant} and CFCs, but in the synthesis by Sabine et al., they correlate strongly. Lo Monaco et al. introduced the oxygen disequilibrium in the water mass formation region and found much higher C_{ant} inventories. Constant air-sea CO_2 disequilibrium, constant Redfield ratios, and simple or no mixing are assumptions that are not necessarily valid in the Southern Ocean. We need a robust method for C_{ant} calculation specific for the Southern Ocean.

Claire Lo Monaco (L'OCEAN, Paris, France). Carbon Storage in the Southern Ocean I.

Most data-based and model estimates indicate low inventories of anthropogenic CO_2 south of 50°S, while relatively large amount of CFCs are observed in recently ventilated Antarctic Bottom Water. In order to investigate this paradox we estimated the distribution of anthropogenic CO_2 along WOCE line I06 using a back-calculation technique corrected for taking into account the oxygen disequilibrium in ice-covered waters. Our results show that

this oxygen correction leads to much higher inventories south of 50°S, therefore suggesting an important role for Antarctic Bottom Water formation as a sink for anthropogenic CO₂.

Niki Gruber (ETH, Zürich, Switzerland). Carbon Storage in the Southern Ocean II.

Quantitative estimates of the air-sea CO₂ flux in the Southern Ocean have remained uncertain owing primarily to the lack of surface pCO₂ observations. The inversion of ocean interior observations permits us to overcome this limitation as well as to separate the total air-sea CO₂ flux into a natural and anthropogenic CO₂ component. The inversion, as well as a greatly expanded pCO₂-data based estimate point toward a substantially smaller present CO₂ sink in the Southern Ocean than previous estimates (0.3 to 0.4 Pg C yr⁻¹). We attribute this small sink to a near cancellation between a substantial outgassing of natural CO₂ and a strong uptake of anthropogenic CO₂. Hindcast modeling studies show that this mean flux may vary by up to nearly 80% from year to year, with about 30% associated with the Southern Annular Mode. Most of the flux variations are driven by anomalies in surface ocean DIC, brought about by wind-induced changes in upwelling.

Arne Körtzinger (IFM-GEOMAR, Kiel, Germany). The Story from Carbon-13.

Average surface ocean δ¹³C decrease during last two decades: -0.018 ‰ yr⁻¹. Depth-integrated δ¹³C decrease during last two decades: -15.0±3.8 ‰ m yr⁻¹. Direct comparisons of decadal trends (1981-1993-2003) yielded similar results as the more robust MLR approach. Anthropogenic perturbation δ¹³C extends all the way to the bottom in subpolar latitudes, to ~1000 m in subtropics, and <400 m in tropics. Using the ratio of δ¹³C/CO₂ perturbation ratio of -0.024 ‰ (μmol/kg)⁻¹ by Körtzinger et al. (2003) the depth-integrated δ¹³C decrease yielded an anthropogenic CO₂ uptake of 0.44±0.11 Pg C yr⁻¹. The average air-sea δ¹³C disequilibrium of 0.7 ‰ explains only half of the depth-integrated δ¹³C change in the N. Atlantic, the other half must be due to near-surface meridional transport from the south.

3) Status Reports and Lessons Learned

3.1 Oxygen on Argo - Nicolas Gruber (ETH, Zürich, Switzerland).

The objective of the Friends of Oxygen on Argo group is to develop a technical white paper outlining scientific interests and technical feasibility issues of a pilot project of oxygen sensors on Argo profiling floats. The primary scientific objective is to determine seasonal to decadal-time changes in sub-surface oceanic oxygen storage and transport, in order to:

- Detect changes in ocean biogeochemistry (Miner's canary bird of climate change)
- Improve atmospheric O₂/N₂ constraint on ocean/land partitioning of C_{ant}
- Determine seasonal to interannual net remineralization rates as a proxy for export production;
- Help interpretation of variations in water mass ventilation rates;
- Provide data (initial conditions, evaluation) for ocean biogeochemical models;
- Help interpretation of sparse data from repeat hydrographic surveys.

There are a number of technical issues that need to be examined to determine the technical feasibility of this:

- Accuracy, long-term stability of sensors;

- Cost (sensor, calibration, etc);
- Impact on float life-time;
- Deployment;

Development of the project would be carried out as a 2-stage process: a pilot project phase followed by full-scale deployment. For the pilot project, the goal is to test instruments and concept, determine long-term precision and accuracy in situ over a large concentration gradient, determine impact on float-life:

- 20-50 floats in one area;
- Several floats with two sensors;
- Repeat shipboard visits with discrete Winkler profiles;
- Associated with a time-series study site? (eastern subtropical Atlantic (ESTOC) or subarctic Pacific Station P)?

3.2 Status Report on Carbon Research in the US. - Richard Feely (NOAA/PMEL, Seattle, USA).

The U.S Ocean Carbon and Climate Change (OCCC) Program consists of a carbon observing network composed of the CLIVAR/CO₂ Repeat Hydrography Survey, the VOS underway pCO₂ measurement program, the North American Carbon Program coastal carbon network, and the ocean sites time series of carbon measurements. The process studies that are still in the planning phase include the upper water column process studies, mesopelagic process studies, continental margin studies that link with the North American Carbon Program, and the air-sea gas exchange process study in the South Atlantic. The CLIVAR/CO₂ Repeat Hydrography Program is well underway with almost half the cruises completed. The preliminary results indicate that uptake of anthropogenic carbon in the Pacific is possibly higher than the Atlantic, which may be related to decadal changes in rate of carbon assimilation. We are observing basin-to-basin differences in the rate of anthropogenic carbon uptake and the resulting changes in aragonite and calcite saturation state. We are using shipboard underway pCO₂ measurements in concert with satellite-based SST, chlorophyll and wind data to provide seasonal changes of the air-sea exchange of CO₂ in the global oceans. The preliminary results provide an estimate of $\pm 0.2 \text{ Pg C yr}^{-1}$ (1 sigma) for the interannual variability of the air-sea exchange of carbon dioxide for the global oceans. Our OCCC Program has data management, and data synthesis and modeling components that are just under development.

3.3 Status of CARBOOCEAN Data Management - Benjamin Pfeil (University of Bergen, Bergen, Norway).

Most of the data gathered within the first year of the project has been delivered to CARBOOCEAN data management. Many PIs also released historical data that are being made available via the CARBOOCEAN data portal. In total, historic data from more than 180 cruises have been delivered to the data management. Public data are being transferred to the CDIAC in order to have all carbon related data in the appropriate World Data Center.

All data are available online from the CARBOOCEAN data portal (<http://dataportal.carboocean.org>) while intellectual property rights are being obeyed. The data portal includes data from the three data centers: CDIAC, IFREMER and WDC-MARE. It is the first global distributed networked database that has successfully been initiated.

3.4 Lessons from the GLODAP Project

Chris Sabine (NOAA PMEL, USA) and Bob Key (Princeton, USA) led a discussion session on their experience with the GLODAP synthesis (see Key et al., 2004). They outlined the lessons learned during this project, noting that the most difficult aspect was simply getting the data, and that this exercise was only made possible because someone (Bob Key) took the data sets in many different formats and pulled them together in one location and common format. Another critical aspect of the synthesis was a careful review of the data quality. Having the proper metadata to document analysis procedures and the use of certified reference materials was a great benefit for evaluating data quality.

One lesson learned was that it's much easier to do a final synthesis when you have consistency in the measurement approaches. For example, the data collected during the Indian Ocean survey were much easier to evaluate because the same parameters were measured on each leg with consistent quality assurance procedures. The Pacific data, on the other hand, were much more difficult to evaluate because each leg had different parameters measured at a range of sample densities with much less documentation of methods and reference material analyses. Groups won't always agree on what to measure, but need to aim for consistency. The use of CRMs was the single best way of assessing data quality and consistency between cruises. However, enough CRMs need to be analyzed throughout the cruise to get a robust assessment (ideally one CRM per station). Another important element is the cross-over analyses. This makes a big difference for assessing the quality of the data, and groups need to be aware of what other cruises have been done and where existing lines are being crossed. Every reasonable effort should be made to take samples when you cross over or close to those points, and this is something that needs to be considered while planning the cruise rather than blindly sticking to a straight line approach.

The GLODAP synthesis and evaluation methods evolved over time, but the participants met regularly to discuss findings, discussions of methods, etc., taking advantage of other meetings at every opportunity. Much of this work is simply not possible by email. Nutrients got brought in after-the-fact and were not done as well, but this new North Atlantic synthesis group needs to worry about nutrients early on. All assessments were done in close association with the original measurement PI. Multiple assessment approaches were developed in an attempt to determine the most robust assessments possible. There were a few cases in GLODAP where the PI did not agree with the adjustments made to the dataset, but the group had to make tough decisions when the different assessments indicated an adjustment was necessary to make the data set consistent. It is important to always keep the synthesized adjusted data separate from core data.

This synthesis approach requires a lot of time and effort, but by discussing ahead of time which science papers individuals would lead, we determined that those who would benefit the most from the synthesis would lead the quality control work. Different people led the actual evaluations of different parameters (e.g., DIC, Alkalinity, etc), but comparisons and discussions among the groups often highlighted common problems that were actually associated with the hydrography itself. For GLODAP we reviewed the list of papers people would write every time because interests and intentions to actually carry out the work changed with time and to ensure that all those interested in collaborating were properly involved in the whole process. While this worked well for GLODAP it will be more

complex for CARBOOCEAN because of the international nature and size of the groups. However, given the amount of data available and the complexity of interpreting changes in the Atlantic careful quality control and good communication will be even more important. One of the early agreements of the group was that the major science articles (Science, Nature, etc) would be co-authored by all participants in the synthesis effort. This should be a founding rule to maintain.

The GLODAP project focused on one basin at a time, without really thinking ahead to the global synthesis. The North Atlantic group should work to establish a good method to apply in Atlantic that will be applicable to other basins. Most EU groups won't be active in Pacific or Indian, so having non-EU scientists involved in the North Atlantic synthesis is important for consistency with the other basins. It is also equally important to get physical oceanographers involved, since many of the GLODAP discussions were based on physical oceanography.

Key, R.M., A. Kozyr, C.L. Sabine, K. Lee, R. Wanninkhof, J.L. Bullister, R.A. Feely, F.J. Millero, and T.-H. Peng, A global ocean carbon climatology: Results from GLODAP. *Global Biogeochem. Cycles*, 18, GB4031, doi:10.1029/2004GB002247, 2004.

3.5 Status and Lessons Learned from the CARINA Project

Bob Key (Princeton, USA) provided an update on the data synthesis efforts for the CARINA data set and merging the water column data of CARINA with the GLODAP collection. CARINA was an essentially informal, unfunded project (organized by Ludger Mintrop and Douglas Wallace of Kiel) whose aims were:

- to bring together research groups that measure CO₂ in the Atlantic Ocean;
- to create an inventory of CO₂ measurements that had been carried out in the Atlantic Ocean;
- to make available also yet unpublished data to the data contributors;
- to form working groups, that cooperate on various aspects of the CO₂ system in the Atlantic;
- to exchange actual information concerning CO₂ research in the Atlantic and assist in future cooperation;

It is fair to say that primarily for reasons of funding (i.e. a lack of), only the first three of the CARINA objectives were realized. The result was the assembly of a large collection of useful, previously unavailable data. However no funds were available to allow the data contributors to quality-control these data sets or to work on them.

Within CARBOOCEAN, progress continues on the CARINA data assembly and, importantly, the quality assessment and analysis. Currently the collection includes data from 80 cruises that took place between 1980 and 2004. Primary quality control (metadata and precision/flagging) is already about 80% complete, however secondary QC is still needed for all parameters on all cruises. **It was agreed at the workshop that data from all cruises that were completed before the end of December 2004 would be included in the public CARINA data set immediately.** Users of these public data should be aware that the data may contain questionable or incorrect data and may not be internally consistent with respect to calibrations. A revised, corrected data set is likely to emerge from the activities of the synthesis working groups (see below).

Bob Key's experience in working with this dataset for the North Atlantic and beginning to deal with secondary QC provides valuable advice for the North Atlantic synthesis working groups as they begin to think about their data synthesis methodologies. He provided the following guidelines being used with the CARINA data set that may be useful to consider:

Quality Control Issues

Primary QC includes verification that the data are "final" followed by flagging outliers or suspect values (using WOCE conventions). The flagging is based on precision of each parameter for each cruise. Primary QC also includes verification of cruise metadata including pertinent publications. Secondary QC involves application of objective procedures to determine systematic errors for each parameter of each cruise. This is an accuracy assessment. The procedure is subjective because data are evaluated relative to a subset which has been deemed "correct". The work division was broken down by parameter (Temperature and Salinity; Oxygen and Nutrients; Carbon data) and Geographic Area (North of Iceland; South of Iceland). Secondary QC Methods include:

1. Crossover analysis (assumes stationary conditions for deep water at a given location);
2. Multiple Linear Regression (assumes that the combined influence of chemistry, biology, physics is constant with time);
3. Basin-wide MLR;
4. Isopycnal (assumes properties change smoothly in space on a given surface);
5. Internal Consistency (carbon system over determined);
6. New methods which consider the inherent time variability of the region;

Data Reporting Issues

Agreeing on and adopting standard methodology and reporting will greatly facilitate any future data synthesis efforts. One of the most important issues, yet often most ignored, is the adoption of standard practices for water column sampling and reporting. While it is recognized that long-standing habits are sometimes difficult to overcome, the difference for data synthesis can mean months of saved time for each cruise if recorded using standard methods. Key offered the following guidelines to facilitate synthesis efforts:

1. Number stations sequentially (pure numeric)
2. At each station record:
 - Station Number
 - Location (3-4 decimal precision)
 - Day, Month, Year (Time)
 - Bottom Depth (uncorrected PDR reading)
 - Maximum sampling pressure
 - Height above bottom (if known)
3. Number casts sequentially, starting with 1 for each station
4. Number each Niskin bottle (Murphy's Law suggests 1:N is the best choice).
5. Record (and keep) station, cast, bottle as the unique identifier. Unique ID numbers are an alternative, but not as good.

Some further suggestions and guidelines for recording measurements:

- Pressure is a basic measured quantity(record to 1 decimal); Depth iscalculated (reported as integer).

- Report T,S to 4 decimals. Preliminary T,S are ok for carbon calculations, but are NOT “good enough” for synthesis activity.
- Report Nutrients (2 decimal) and oxygen (1 decimal) in micromoles per kilogram.
- WOCE standards for other parameter precision and units.
- Report all measurements and assign a flag value of 2, 4 or 6 to each of your measurements (2=nominal, 4=known bad, 6=result of replicate analysis).
- Correct DIC and Alk to CRM (suggested only).

As part of the CARINA project, Key has compiled an extensive bibliography of literature associated with the data and techniques used in the programs that contribute to the dataset. The group agreed that this was an extremely valuable resource that should be made available on the CARBOOCEAN portal and should be continued for all new cruises.

4) Introduction to the Working Groups

In order to prepare for the working groups, an overview of the potential syntheses to be conducted with the data was obtained. Each of the research groups represented at the workshop was asked to identify their main scientific interest for an Atlantic synthesis of carbon- and carbon-related data. This identified the following issues (listed in no particular order and with no names attached):

- Changes in saturation state of ocean with respect to aragonite and calcite
- Inventory of anthropogenic carbon and decadal changes in NADW based on TTDs
- Meridional transport of anthropogenic carbon in the North Atlantic
- Anthropogenic carbon inventory and uptake in the Southern Ocean, with specific interest in the Weddell Sea
- Carbon uptake and storage in the Nordic Seas; how anthropogenic carbon is brought into the region and how this may change with changes in circulation and climate; also ¹³C Suess effect in the North Atlantic.
- Changes in ventilated waters in the North Atlantic, including all varieties of mode water and LSW, and the associated circulation changes.
- Anthropogenic carbon in the Southern Ocean, longer term sampling issues and observing system design
- Understanding whether or not we can measure transport of carbon (natural and anthropogenic) for the whole Atlantic but with a particular focus on the Nordic Seas.
- Comparison of surface pCO₂ trends and air-sea fluxes to transport/storage issues in mid-latitude North Atlantic;
- Comparison of different anthropogenic carbon estimation techniques
- Long term trends in O₂ inventories in North Atlantic; timescales of variability and how variability is linked to ventilation and supply pathways of oxygen, including LSW formation.
- Variability in natural and anthropogenic carbon in the Nordic seas; source waters for NADW and anthropogenic C and rate of change; also pH changes and aragonite/calcite saturation changes

- Long term changes in O₂ content and relation to changes in carbon; starting with N.Atlantic water “South of Iceland”.
- Examine repeats of A16 lines to look at decadal changes in C, O₂, and nutrients and changes in physics; whole Atlantic (south of Iceland). Long term interest is to develop framework to evaluate models vs observations (variability, secular trends)
- Carbon changes in North Atlantic south of Iceland: storage term for comparison with transport estimates (sub-tropical; sub-polar gyre)
- Inventory of anthropogenic carbon and comparison with models over the whole Atlantic, including north of Iceland
- Anthropogenic carbon and O₂ ventilation in LSW; carbon in sub-polar gyres from the OVIDE lines.
- MLR approach to look at decadal inventories along specific lines; using Argo data as a way to extrapolate lines to basins

In the end it was clear that the scientific interests of many participants were quite similar but tended to break down along regional / geographical lines. These divisions of interest may also correspond well to the interests and expertise of potential partners in the physical oceanography community (e.g. the ASOF community that works primarily north of 60° N). It was also clear that the work associated with the proposed syntheses is considerable and may benefit from the geographical separation of effort already applied in the CARINA quality-control (see above). Based on this, and considerations arising from the GLODAP and CARINA experiences, the following Working Groups were developed:

1. “Southern”: The Atlantic, south of approximately 16° N, with a very clear emphasis on the Southern Ocean
2. Northern: The Atlantic North of 60° N (Nordic Seas and Arctic)
3. “Middle”: The North Atlantic Sub-polar and Sub-tropical gyres

Consideration was also given to establishing an “Overarching Analysis Group” but this did not meet during the workshop. Likely some level of overall coordination will be needed, but at a later date once the 2nd level QC has been completed. Bob Key is a member of each working group to provide guidance and consistency amongst the groups.

The South Atlantic Ocean region, including the tropical/equatorial Atlantic, was identified as a problem area. There are few if any available new data collected in this region since WOCE. Exceptions are Japanese data collected along 30°S (WOCE A10) in 2003; a limited number of stations collected during the FICARAM cruises (by the Vigo group). This is barely sufficient data to initiate a new group synthesis activity and there were relatively few people present at the Workshop who expressed an interest in tackling this issue. **Chris Sabine and Aida Rios will work together to try to examine this issue and raise interest amongst the community.** Some new data are likely to be available soon: for example the Kiel group has recently completed (July 2006) a combined carbon and CFC section along the equator.

The working groups subsequently met and were charged with answering the following questions for reporting in plenary:

1. Identify WG “leaders”. The following were identified: Northern: Are Olsen; Southern: Mario Hoppema; Middle: Toste Tanhua (who was at sea but has subsequently accepted this task).
2. Identify other key collaborators, including those with expertise related to physical oceanography, Argo, and time-series data sets; plan to get those people involved.
3. Identify / refine key questions for the regions
4. Identify data sets; discuss “exact” boundaries; and who is going to do what (e.g. who will address quality control for which parameters)
5. Identify collaborations on synthesis papers and topics; who will do what?

5) Working Group Reports

5.1 “Northern Group” (Arctic and GIN Seas)

1. Identify Working Group Leader(s): Are Olsen, University of Bergen

2. Identify other key collaborators, including those with expertise related to physical oceanography, Argo, and time-series data sets; plan to get those people involved.

The working group comprised a mixture of mainly chemical oceanographers and one physical oceanographer. It was noted that key data holders and several persons potentially interested in the carbon-synthesis were not present. A number of additional key persons were identified and will be contacted to join the working group.

Chemical Oceanographers Present

Thorarinn Arnason (thorarn@hafro.is)
 Jon Olafsson (jon@hafro.is)
 Are Olsen (are.olsen@gfi.uib.no)
 Truls Johannessen
 Bob Key

Physical Oceanographers Present

Alison Macdonald (amacdonald@whoi.edu)

3. Identify / refine key questions for the regions.

The group is to remember that “synthesis” is the keyword. Therefore the aim is to build and take advantage of a combined, synthesized dataset. Analysis of individual cruise results should continue as quasi-independent activities by PIs, but the working group activity should operate at a bigger scale (i.e. the basin scale).

Key questions:

1. The large available data allow for the contribution of the high-latitude Atlantic and Arctic to the global C_{ant} inventory to be determined systematically. A suitable method for C_{ant} estimation in the region must be developed. How much C_{ant} is there and what is its spatial distribution?

2. How does C_{ant} enter the region (e.g. by advection; uptake) and how is it transferred downwards? (e.g. open ocean convection, sinking, brine-rejection, plume entrainment), interior/boundary issues:
3. How much is transferred to adjacent basins and how (advection, mixing).
4. What is the rate of change (both present and future, in all the various aspects above) and how is this related to circulation /climate change vs. C_{ant} accumulation (e.g. buffer factor change).
5. What are the associated changes in saturation state of carbonate minerals?
6. What are the future measurements we need to answer the above questions?

Notes:

Many of these questions involve links to climate change questions (e.g. issues related to the “Blue Arctic” and the MOC slowdown). Many require comparison with models. Unclear for the Arctic is the potential role/importance of DOC changes associated with climate change and altered river input, water temperatures, etc.

4. Identify data sets; discuss “exact” boundaries; and who is going to do what (e.g. who will address quality control for which parameters)

Data collected through the end of 2005 should be included in the synthesis.

Region:

From the Bering Strait – across the Arctic- down to the Greenland-Iceland-Scotland ridge (nominally 60°N). Includes the Canadian Arctic Archipelago and Baffin Bay so that the southern boundary is Davis Strait. The logical transport boundaries for this group are therefore the Bering Strait and a shared boundary with the “middle” working group at the Davis Strait and the Greenland-Iceland-Scotland Ridge system. In terms of marginal sea coverage, the North Sea and Baltic belong most naturally to this system (although carbon budgets for the North Sea are being worked on in other parts of CARBOOCEAN). Hence a transport boundary across the English Channel may also link this working group to the “Middle” group.

Datasets:

In making a table of data, the approach should be: look for the carbon data first. Assemble the T/S/O₂ data as needed (here a connection to Hydrobase may be useful).

All data to be used in the synthesis should be delivered to Bob Key by December 2006. These data are to include:

Bergen CO₂ data from GIN Seas. Delivered

Icelandic data: GIN Seas & Irminger and Iceland Sea time series. These data are presently being delivered via Benjamin Pfeil (CARBOOCEAN data).

Arctic Ocean data from Leif Anderson.

Possibly Russian alkalinity data from the Barents Sea and other regions.

Norwegian data: Institute of Marine Research nutrient data.

2nd level QC of these data.

Questions to ask of the data-collecting PI:

Did you correct your data to CRM?

What calibration scale was used (in particular for pH.)?

Temperature

In order to approach 2nd level QC it was suggested to identify a “trial region” and work on that first. Including consideration of approaches, software, techniques, etc.. Approaches outlined in the GLODAP report can be used as a starting point.

Specific Responsibilities – the working group outlined the following variables and developed a list of possible leaders for each. The working group will contact the nominees and develop a final list shortly:

- Discrete pCO₂
- Total Alkalinity
- Total Carbon
- pH
- Nitrate/Phosphate/Silicate
- DOC
- Oxygen
- T&S
- δ¹³C
- δ¹⁸O
- CFCs – CCl₄
- Other tracers

5. Identify collaborations on synthesis papers and topics; who will do what?

It was suggested that a further meeting is needed in early 2007 to decide these issues. Start to write in 2007.

5.2 Middle Group (Sub-tropical and Sub-Polar Gyre N. Atlantic; name subsequently changed to the “Atlantic Group”.)

1. Identify Working Group Leader(s): Toste Tanhua (IFM-GEOMAR) (was at sea during workshop; therefore represented at workshop by Doug Wallace)

2. Identify other key collaborators, including those with expertise related to physical oceanography, Argo, and time-series data sets; plan to get those people involved.

The group identified chemical and physical oceanographers whose expertise and interests match those of this group. The group agreed to write letters to formally invite participation of those listed. Collaborating scientists will be requested to hand in relevant data to the working group if they want to join in the synthesis effort.

Chemical and physical oceanographers present in this group:

Doug Wallace
Niki Gruber
Terry Joyce
Arne Körtzinger
Ute Schuster
Pete Brown
Steven van Hooven
Reiner Steinfeldt
Dick Feely
Chris Sabine
Fiz Perez
Bob Key

3. Identify / refine key questions for the regions

The following topics were identified, each of which could be the subject of at least one scientific paper based on the data collection and would be co-written by members of the working group:

1. New data allow the Mediterranean contribution to the worldwide C_{ant} inventory to be estimated.
2. Depth-distribution of C_{ant} and C_{ant} accumulation over past several decades. Associated changes in lysoclines, saturation state, etc.
3. What is the variability of dissolved oxygen in the region? What factors drive the variability?
4. To what extent can the basin-scale anthropogenic carbon budget, including the regional C_{ant} uptake from the atmosphere, be “closed” based on transport and storage estimates over decadal timescales?
5. What are the shifts in LSW ventilation and what affect do they have on carbon content (anthropogenic / natural) of this water mass
6. What is the variability of other Mode waters (e.g. 18° water) and the effect on the carbon budget?
7. Related to 5 and 6: do the water mass ventilation pathways of both the sub-tropical and sub-polar gyres vary in concert? What are the prospects for further spin-down of the sub-polar gyre?
8. A preliminary comparison suggests that the C_{ant} inventory increase in the Atlantic appears to be smaller than in the Pacific. Is this difference real or an artefact?
9. Is organic carbon storage important for the carbon budget?
10. How do MOC variability and changes in heat content affect the carbon balance? What effect on the carbon budget and (ultimately) on the air-sea flux of CO_2 ?

4. Identify data sets; discuss “exact” boundaries; and who is going to do what (e.g. who will address quality control for which parameters)

The “fuzzy” domain for this working group was set as 16°N to 60°N and therefore includes the North Atlantic sub-tropical and sub-polar gyres, as well as the Labrador and Mediterranean Seas. In terms of “boxes” suited to transport and storage calculations, this allows the extensive water mass transport estimates made at c. 24.5°N, as well as transport estimates across Davis Strait and the Greenland-Iceland-Scotland ridge systems to be used to define inputs and outputs. A transport boundary with the “Northern” working group at the English Channel is also assumed.

In terms of data resources for this working group, the following key data resources were identified:

GLODAP data from the region (“done”)

“original” CARINA data (still needs secondary QC, some cruises still missing)

US CLIVAR-CO₂ Repeat Hydrography (A16, A20, A22; available)

Two UK Cruises (36°N and 24.5°N; essential to add to CARINA collection)

Meteor 60/5 (recently submitted to CARINA collection)

Meteor 54 data from the Mediterranean (recently submitted to CARINA collection)

OVIDE data from 2002 and 2004 (2006 occupation data are too recent)

AR7W (Canadian data; check availability)

AR7E (Pelagia 2005)(need to be added to CARINA collection)

The CARINA collection will accept all relevant cruise data collected up to December 2005.

Data MUST be delivered before 31-12-2006 .PLEASE fill in Bob's cruise table when delivering data. Bob/Benjamin will make maps to point out which cruises still need to be delivered.

In general it was noted that there is very good coverage from this region of the Atlantic, including many crossovers useful for QA/QC of the data. There may be fewer crossovers within the Labrador Sea although even here data collected by Canadian and German groups are available for comparison. Some difficulties in performing 2nd level QC of the data will arise due to the significant temporal variability in water mass characteristics in the region.

Specific responsibilities were outlined for the following variables. The working group will contact the leaders nominated for each:

- Oxygen data
- DIC data
- Alkalinity / pH data
- T,S data
- Nutrient data
- CFCs

These specific responsibilities for doing 2nd level QC of the data are associated with specific interest in tackling some of the relevant scientific issues listed above.

In order to start working on these data, it was agreed to start with the GLODAP report and assess to what extent the GLODAP approaches meet the needs of this working group. Time-series data were identified as being especially important: Terry Joyce and Scott Doney are to enquire concerning availability of BATS data up to the end of 2005. CARBOOCEAN partner Melchor Gonzales will be approached re: ESTOC data.

It was agreed that work would start as soon as possible. Most likely during the last quarter of 2006. A meeting in Spring 2007 was envisioned. However alternatives to meetings were discussed. In particular, possibilities of on-line collaboration and meetings are to be explored.

5. Identify collaborations on synthesis papers and topics; who will do what?

The implications of the assignment of 2nd level quality control tasks outlined above is that these people who invest the time and effort in the checking and documentation on the combined data set can take the lead in writing synthesis papers on these variables (in collaboration with other members of the working group).

5.3 Southern Group (Southern Ocean)

1. Identify Working Group Leader(s): Mario Hoppema (AWI, Bremerhaven)

2. Identify other key collaborators, including those with expertise related to physical oceanography, Argo, and time-series data sets; plan to get those people involved.

Members of the Southern Ocean group present at the meeting were:

Mario Hoppema (chair)

Aida Rios

Claire Lo Monaco

Andrew Lenton

Bob Key

Other possible collaborators which were discussed during the working group sessions; these people will be contacted soon about joining the working group.

Initially, in the working group, it was decided to limit the area of investigation to the Atlantic and Indian sectors of the Southern Ocean, to stick close to the emphasis of the CARBOOCEAN proposal. However, during the following plenary session it was suggested to include the entire Southern Ocean, because this would make more scientific sense, for example for making large-scale Cant inventories. In that case, more names are added to the list of potentially interested investigators.

It may be a compromise to first contact some very key people for these additional regions. If they are positive and are willing to contribute their data within a reasonable time (set by our working group, probably until the end of 2006), we may give the final “go” for this extension. However the priority for CARBOOCEAN investigators remains the focus on the Atlantic and Indian Ocean sectors.

3. Identify / refine key questions for the regions

- Which is the optimal method for determining Cant in the Southern Ocean?

It has become clear that the Southern Ocean with its ice cover in water mass formation regions must be treated differently. We will also rely on the work done during WP9 of CARBOOCEAN

- Determine a regional and whole Southern Ocean inventory of Cant using as many data as possible. This is the main goal, but first we must possess the right method for this.
- Compare Cant with CFCs, look at regional differences in relationships. Is there agreement between the inventories of CFC and Cant?
- Comparison of observed data to modelled data. Sensitivity of the region to physical changes?
- Separating Cant from natural DIC changes

More questions are to be formulated during the further development of the project.

4. Identify data sets; discuss “exact” boundaries; and who is going to do what (e.g. who will address quality control for which parameters)

As already mentioned above we will in principle consider the whole circumpolar Southern Ocean as our area of investigation. To the north the region is limited by the Subtropical Front (roughly about 35°S).

Data sets/cruises

G signifies included in GLODAP data set.

OISO 1998-now (Paris)

Indigo 1985-1987 (Paris) – G

Geosecs – G

AJAX 1984 – G

Several Polarstern cruises 1992-2005 – not all in G

Meteor 1990

A17 – Cither (French/Spanish cruises) – G

A14 - Cither (French/Spanish cruises) – G

A13 - Cither (French/Spanish cruises) – G

FICARAM

I06 30°E line 1996 (French), 2002 (Spanish)

Fruela data (from Bransfield Strait)

There are definitely more data sets. The working group will search for these. Chris Sabine will be asked for the U.S. data (which possibly most of them are in GLODAP). Andrew Lenton will try to find out more about the Australian and New Zealand data. Mario Hoppema will make a Table with all cruises and the parameters measured during it. Initially it was suggested to include only data from cruises that were completed prior to the end of 2004.

However following the other working groups formed during the workshop, the group will accept new cruises to the data base until the end of 2006. This to include data collected up until the end of 2005 if at all possible. Primary Quality Control (QC) must be finished until that date. Secondary QC may start either in 2007 or, if possible, earlier. During the second half of 2006 the members will do final processing of their data (if necessary) for incorporating it in the Southern Ocean data base.

Because the membership of working group is still relatively small, we adopted the strategy that all investigators will work on all parameters per cruise for secondary QC. We may change this approach if deemed necessary.

5. Identify collaborations on synthesis papers and topics; who will do what?

The group felt that it needed to first contact other scientists about participating in the working group before outlining collaborations. This should be accomplished by early 2007.

6) Action Items List

Many of the key action items are to take place within the working groups. These working groups should develop their own lists of specific action items that can be compared via a common net-based working area on the CarboOcean web-site. The following general list of action items was developed at the meeting:

1. The Middle Working Group needs to look at Bates & Gruber paper to see what carbon was doing during the 1997-2003 period with respect to changes in ventilation presented by Terry.

2. It was noted during the science presentations that there remains a need for a set of standard approaches to air-sea flux calculations, choice of wind products, etc, that everyone will use as a point of comparison, in addition to their own “favourite” parameterizations. This need is to be communicated to those working in the more appropriate Theme of CARBOOCEAN dealing with air-sea fluxes (leader: Andy Watson). **Ute Schuster and Dick Feely are the appropriate workshop attendees to communicate this need.**

3. Bob Key has collected a useful list of publications associated with the CARINA data set. This **bibliography to be made available via the CARBOOCEAN data portal (Benjamin Pfeil)**. The bibliography should be maintained, annotated and added to in order to support the working groups.

4. There needs to be some semi-formal communication with relevant CLIVAR groups and physical oceanographers concerning the carbon synthesis effort being undertaken. This can be done on an individual basis by the working groups. **Doug Wallace to write short description and send copy of workshop report to relevant CLIVAR group leaders.**

5. Nutrient standards – use of MLR approaches to examining carbon concentration changes rely heavily on accurate nutrient data collected at different time periods by different groups. The accuracy levels required for this application are at least the levels specified by WOCE and may be even more demanding. Quality problems have multiple sources including: the nature of the analytical methods used, the wide dynamic range of concentrations encountered, and the competing interests of potential users of the data (biologists’ need for sensitivity at ultra-low-levels compared to need of some chemical oceanographers for ultra-high accuracy at high concentrations). Experience suggests that there still remain major uncertainties with nutrient data calibration that need to be addressed urgently. This issue requires international effort and coordination. Two measures can be suggested to individual laboratories to improve the precision and accuracy of nutrient analyses:

1. Subscribe and work according to a laboratory performance program, e.g., QUASIMEME AQ-1 Nutrients in sea water (<http://www.quasimeme.org/>)
2. A laboratory reference material, LRM (Aminot and K erouel, 1998) can be regularly produced and compared to the QUASIMEME materials. The LRM should be run with each batch of samples.

Reference; Aminot, A. and K erouel, R., 1998. Pasteurization as an alternative method for preservation of nitrate and nitrite in sea water samples. Mar. Chem., 61: 203-208.

No specific workshop attendee was assigned this problem as it lies a little outside of the carbon synthesis task and the nature of the problem will become clearer as the working groups start the 2nd level QC. Suggestion: Wallace, Olafsson, Key and Feely (or Wanninkhof) develop a strategy off-line. This could, for example, become an issue that can be tackled by the EurOcean network of excellence in its next phase.

6. **Make a public release of the CARINA data set**, defined as all cruises up to end of December 2004 (see CARINA discussion above). **Key, Kozyr, Pfeil.**

7. Most of the subsequent synthesis work can take place in the working groups. These groups must: identify their extended membership; proceed with final assembly of their respective data sets; initiate 2nd level QC; finalize an initial list of scientific papers and potential contributors; etc.. **Responsible: working group leaders (Olsen, Tanhua, Hoppema).**

8. The GLODAP effort was associated with numerous face-to-face meetings to discuss individual data sets. Funding for this travel for the large number of geographically-groups involved in the Atlantic synthesis is not available. The workshop discussed possible enhanced use of internet working areas for this purpose. Specifically: **Benjamin Pfeil will establish working areas and discussion areas for the working groups via the CARBOOCEAN data portal. Consideration should be given to use of Wiki's or other groupware internet software solutions for use by the working groups.**

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