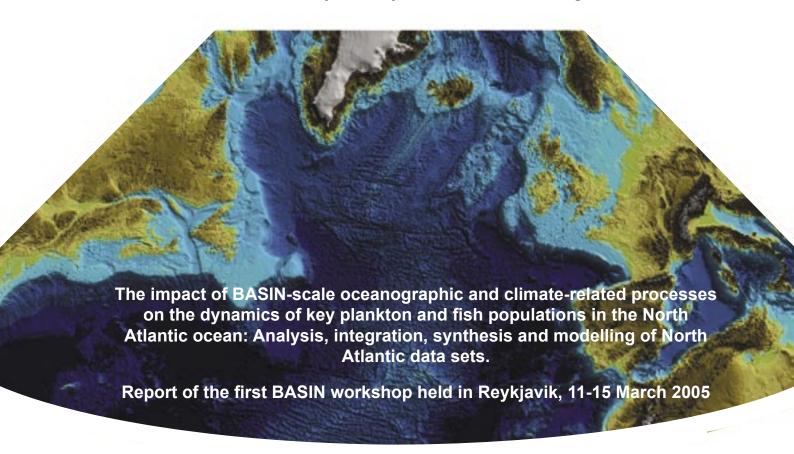**GLOBAL OCEAN ECOSYSTEM DYNAMICS**

GLOBEC Report No.23
and
U.S. GLOBEC Report No.20

BASIN

Basin-scale Analysis, Synthesis, and INtegration

The impact of BASIN-scale oceanographic and climate-related processes on the dynamics of key plankton and fish populations in the North Atlantic ocean: Analysis, integration, synthesis and modelling of North Atlantic data sets.

Report of the first BASIN workshop held in Reykjavik, 11-15 March 2005

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No. 7a. Report of the meeting of the Southern Ocean Planning Group, San Diego, California, 1-3 August 1997.

No. 8.   Report of the first planning meeting on Small Pelagic Fishes and Climate Change Program. La Paz, Mexico, June 20-24, 1994.

No. 9.   IGBP Report No. 40. Global Ocean Ecosystem Dynamics Science Plan.

No. 11. Small Pelagic Fishes and Climate Change Programme Implementation Plan.

No. 12. Report of the first SPACC Modelling workshop. Ispra, Italy, 14-16 October 1996.

No. 13. IGBP Report No. 47. Global Ocean Ecosystem Dynamics Implementation Plan.

No. 14. Report of a Workshop on the Use of the Continuous Underway Fish Egg Sampler (CUFES) for Mapping Spawning Habitats of Pelagic Fish.

No. 15. Report of a GLOBEC-SPACC/APN Workshop on the Causes and Consequences of Climate-induced Changes in Pelagic Fish Productivity in East Asia, 25-27 October 2001, Kobe, Japan.

No. 16. Report of a GLOBEC-SPACC/IDYLE/ENVIFISH Workshop on Spatial Approaches to the Dynamics of Coastal Pelagic Resources and their Environment in Upwelling Areas, 6-8 September 2001, Cape Town, South Africa.

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No. 19   Ecosystem Studies of Sub-Arctic Seas (ESSAS) Science Plan, 2005. Hunt, G.L., Jr and Drinkwater, K.F. (Eds).

No. 20   Background on the Climatology, Physical Oceanography and Ecosystems of the Sub-Arctic Seas. Appendix to the ESSAS Science Plan, 2005. Hunt, G.L., Jr and Drinkwater, K.F. (Eds).

No. 21   Report of a GLOBEC/SPACC Workshop on Characterizing and Comparing the Spawning Habitats of Small Pelagic Fish, 12-13 January 2004, Concepción, Chile. van der Lingen, C.D., L. Castro, L., Drapeau and D. Checkley.

No. 22   Report of a GLOBEC/SPACC Meeting on Characterizing and Comparing the Spawning Habitats of Small Pelagic Fish, 14-16 January, Concepción, Chile. Castro L.R., P. Fréon, C.D. van der Lingen and A. Uriarte.

No. 23   Report of the first BASIN workshop held in Reykjavik, March 2005

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No. 6.   Report of the second meeting of the SPACC/IOC Study Group on 'Use of environmental indices in the management of pelagic fish populations', 9-11 November 2002, Paris, France.

No. 7.   Update of the GLOBEC National, Multinational and Regional Programme Activities, 2004. D.M. Ashby (Ed.)

PREFACE

The BASIN Workshop in Reykjavik was organised under the auspices of GLOBEC. Funding support for the meeting was provided by the US National Science Foundation, through U.S. GLOBEC (NSF OCE-0431054), and the European Union through the EUR-OCEANS Network of Excellence. A workshop steering committee consisted of Olafur S. Astthorsson (Iceland), François Carlotti (France), Dale Haidvogel, Cisco Werner, Peter Wiebe (USA), Roger Harris (UK), Mike St. John (Germany) and Brad deYoung (Canada).

The planning logistics of the meeting were organised by Peter Wiebe and Chip Clancy, Woods Hole Oceanographic Institution. Local facilities and hospitality were provided by the Marine Research Institute, Reykjavik. The support of the Director, MRI, and in particular Olafur Astthorsson and Astthor Gislason was crucial for the success of the meeting.

Discussion groups during the meeting were led by Gregory Beaugrand, Ken Drinkwater, Mike Fogarty, Dale Haidvogel, Erica Head, Mike Heath, Pierre Pepin, Benjamin Planque, Kurt Tande, Svein Sundby and Alain Vezina. Reports from these groups provided the initial draft material on which this Report is based.

Further editorial work, subsequent to the Reykjavik meeting, was carried out by Brad de Young, Mike St. John, Cisco Werner, Peter Wiebe and Roger Harris.

Final layout was provided by Jessica Heard of the EUR-OCEANS office at Plymouth Marine Laboratory.

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LIST OF ACRONYMS

BASIN	BASIN: Basin-scale Analysis, Synthesis, and INtegration
CLIVAR	Climate Variability and Predictability
COPEPOD	Coastal and Oceanic Ecology, Production & Observation Database
CPR	Continuous Plankton Recorder
ECOMIP	Ecological Model Intercomparison Project
ENSO	El Niño/Southern Oscillation
ESD	Equivalent Spherical Diameter
FAO	Food and Agriculture Organization of the United Nations
GCMD	Global Change Master Directory
GEOSS	Global Earth Observation System of Systems
GLOBEC	Global Ocean Ecosystem Dynamics
GODAR	Global Oceanographic Data Archaeology and Rescue
GOTM	General Ocean Turbulence Model
HYCOM	HYbrid Coordinate Ocean Model
IBM	Individual-based modeling
ICES	International Council for Exploration of the Sea
ICOS	Investigation of *Calanus finmarchicus* migrations between oceanic and shelf seas off north-west Europe
IGBP	International Geosphere-Biosphere Programme
IOC	Intergovernmental Oceanographic Commission
JGOFS	Joint Global Ocean Flux Study
MARMAP	Marine Resources Monitoring Assessment and Prediction Program
MERSEA	Marine Environment and Securites for the European Area
NAO	North Atlantic Oscillation
NCAR	National Centre of Atmospheric Research
NPZD	Nutrient Phytoplankton Zooplankton Detritus
OGCM	Ocean General Circulation Models
OPC	Optical Plankton Counter
PLATO	Plankton Time Series Observations
POM	Princeton Ocean Model
ROMS	Regional Ocean Modeling System
SBM	Stage-based models
SCOR	Scientific Committee on Oceanic Research
SPACC	Small Pelagic Fish and Climate Change
TASC	Trans-Atlantic Study of *Calanus finmarchicus*
WBM	Weight-based models
WGZE	Working Group on Zooplankton Ecology
WOCE	World Ocean Circulation Experiment
WODC	World Ocean Database Centre

EXECUTIVE SUMMARY

Major nationally-funded programmes in the European Union, the United States, and Canada have sought to understand the effects of climate variability on ocean ecosystems, and thereby to better predict the impacts of global change in regions of national interest around the North Atlantic basin. Over the past decade, many of these programmes focused upon understanding the dynamics of key zooplankton and fish species at local to regional scales, with special emphasis on their coupling to the physical environment and other components of the ecosystem. The overall goal of a number of these programmes was to contribute to the elucidation of the basic functioning of these key components of marine ecosystems in order to enable an understanding and prediction of the possible responses to climate variations.

In March 2005, an international workshop was held in Reykjavik, Iceland to bring together researchers and ecosystem managers to consider and plan the next steps in North Atlantic ocean-basin scale analysis, integration, synthesis, and modelling of biological, chemical, and physical oceanographic data sets. A principal goal was to build upon the previous and ongoing research in the North Atlantic, integrating and synthesizing the results of these programmes, thus elucidating the mechanisms that link biogeochemistry, zooplankton, fish, and the environment at ocean basin scales. This workshop report is intended to provide a framework for the integration and synthesis of data resulting from major oceanographic research programmes, including GLOBEC programs in the USA, Canada, UK, and EU-funded programmes, including TASC, ICOS, and others. The Reykjavik workshop provided a forum for discussion of an action plan for new research on the processes controlling dynamics of ocean-basin populations of zooplankton and fish and the input needed to improve management of fisheries resources.

A crucial element of the BASIN plan is the development of conceptual and quantitative models capable of elucidating ecosystem dynamics and responses on a broad range of space and time scales. There is currently no fully integrated ecosystem model that can address BASIN's goals. Basin scale models intended to represent complex food webs must concentrate the biological resolution at the level of the species or trophic level of interest, and decrease the resolution, with distance both up and down the trophic scale from the target species. Following this approach, the focus of the BASIN modelling programme will be on selected key species and functional groups. We envisage a variety of models with differing focus on species and trophic levels. We foresee significant efforts in modelling the lower and higher levels, identified here as the phytoplankton/microbial food web (lower) and the planktivorous (higher) level, including vertebrate and invertebrate predation.

Within BASIN, data will be required for several purposes. First, long-term time series are necessary for retrospective analyses. BASIN activities will identify available historical data sets for integration and synthesis. These datasets will include climatological, oceanographic, chemical, and biological data. Second, new data will be required in order to understand and better parameterize the physical and biological processes in the models and to address gaps in process knowledge. Such data will be critical for model improvements and the models will be used to help prioritize the data collections required both in the field and laboratory, as well as to identify the geographical locations where such measurements should be carried out and the frequency of sampling needed. Third, data are required for model validation. We will rely heavily on historical data but new measurements will also be required where existing information is limited or non-existent, either in type, space, or season.

There is growing recognition of the need to explicitly account for the human impacts in the marine environment. BASIN will provide an important foundation for the development of options and tools for ecosystem-based management in the North Atlantic. Potential changes in fundamental production characteristics of regional subsystems driven by basin-scale climate events will require understanding leading to adaptation strategies in integrated ocean management.

The following recommendations must be implemented to move forward on this ambitious plan.

(i) Assess the status of climate related marine ecosystem research in the North Atlantic basin and associated shelf seas,

(ii) Identify gaps in systematic observations and process understanding of atmospheric and oceanic parameters,

(iii) Resolve the potential for consolidation of long-term observations from international databases for oceanic modelling and prediction, and

(iv) Implement knowledge and understanding developed during BASIN into marine resource management strategies including Ecosystem Based Management.

The BASIN research programme will focus on: resolving the natural variability, potential impacts, and feedbacks of global change on the structure, function, and dynamics of North Atlantic marine ecosystems; improving the understanding of marine ecosystem functioning; and developing ecosystem based management strategies for the North Atlantic. BASIN will contribute significantly to the development of comprehensive, coordinated and sustained observations of the Earth System, improved monitoring of the state of the Earth, increased understanding of Earth processes and enhancing our capabilities to provide quantitative projections of future scenarios of the state of marine ecosystems.

INTRODUCTION

The overarching aim of the BASIN initiative is to understand and simulate the population structure and dynamics of broadly distributed and trophically and biogeochemically important plankton and fish species in the North Atlantic ocean to resolve the impacts of climate variability on marine ecosystems, and thereby contribute to ocean management.

The scale of influence of global change and the added value of co-ordinating the scientific activities of the EU, the US, and Canada to assess, predict, and mitigate the effects on marine ecosystems of the North Atlantic and their services is the justification for the development of BASIN. An important step towards such a co-ordinated approach is the development of an Implementation Plan whereby jointly funded international research projects can be supported. The development of such a plan is the first goal of BASIN. The second goal of BASIN is to develop an integrated basin-scale North Atlantic research programme that will seek joint support from EU, US, and Canadian agencies. Programmatic goals will be achieved in working groups including experts from both the EU and North America as well as delegates from funding organisations. An initial meeting of scientists from European countries, Iceland, the USA and Canada, took place in Reykjavik in March 2005. This report presents a synthesis of the discussions at the Reykjavik BASIN meeting. The recommendations of that meeting include:

(i) Assess the status of climate related marine ecosystem research in the North Atlantic basin and associated shelf seas,

(ii) Identify gaps in systematic observations and process understanding of atmospheric and oceanic parameters,

(iii) Resolve the potential for consolidation of long-term observations from international databases for modelling and prediction, and

(iv) Implement knowledge and understanding developed during BASIN into resource management strategies including Ecosystem Based Management.

In order to fulfil these recommendations, a BASIN research programme will focus on: resolving the natural variability, potential impacts, and feedbacks of global change on the structure, function, and dynamics of North Atlantic ecosystems; improving the understanding of marine ecosystem functioning; and developing ecosystem based management strategies for the North Atlantic. Hence, BASIN will contribute significantly to the Global Earth Observation System of Systems (GEOSS) 10-Year Implementation Plan via the development of comprehensive, coordinated and sustained observations of the Earth System, improved monitoring of the state of the Earth, increased understanding of Earth processes and enhanced prediction of future scenarios.

1.1 Research elements of BASIN

The BASIN programme will seek to achieve a number of specific goals:

- Integration and synthesis of the existing basin-wide data sets from previous programmes in Europe and North America,

- Improvement of the current state of the art in bio-physical modelling,

- Development of hindcast modelling studies and thereby an understanding of the observed historical variability of the North Atlantic ecosystem,

- Construction of scenarios of possible ecosystem changes in response to future climate variability,

- Identification of data gaps that limit process understanding – and contribute to uncertainty in model results,

- Specification of new data needed to assess the performance of forecasts, and

- Provision of information relevant to resource managers and decision makers.

The Basin Programme will have two phases. In its first phase BASIN will focus on organising and developing existing data for use with basin-scale marine ecosystem models. Based on these activities, data and knowledge gaps will be identified necessitating the collection of new data in order to resolve crucial basin-scale problems. Thus, the second phase of BASIN will involve a substantial field effort whose detailed design will be guided by the modelling and synthesis activities accomplished during the first phase, as well as directed laboratory studies.

1.2 Background

1.2.1 Regional Studies

Beginning in the 1990's and continuing to the present day, major nationally-funded programmes in the EU, US and Canada have sought to understand the effects of climate variability on ocean ecosystems, and thereby to better predict the impacts of global change in regions of national interest around the North Atlantic basin. An earlier meeting was convened in 2001 (Head *et al*., 2001) to review a basin-scale approach to the northwest Atlantic ecosystem. In the North Atlantic, many of these programmes focused upon understanding the dynamics of key zooplankton and fish species at local to regional scales, with special emphasis on their coupling to the physical environment and other components of the ecosystem. This research has been carried out particularly under the auspices of national GLOBEC (Global Ocean Ecosystem Dynamics) programmes (US, Canada, UK, Germany, Spain, Portugal, etc.), GLOBEC-related projects (ICES Cod and Climate Change programme, Norwegian Mare Cognitum), and EU projects, particularly ICOS and TASC, which both focussed on *Calanus finmarchicus*. ICOS was an EU funded project designed to investigate the oceanographic connection between aggregations of overwintering *Calanus finmarchicus* at depth >600m in the Faroe-Shetland Channel, and the spring abundance of *Calanus* in the northern North Sea. The hypothesis was that the North Sea is seeded each spring by advection of overwintered copepodites from the Faroe-Shetland Channel. The results of this programme provided a possible explanation for the correlation between *Calanus* abundance in the North Sea and the NAO revealed by earlier analyses of Continuous Plankton Recorder (CPR) data. TASC (Trans-Atlantic Study of *Calanus finmarchicus*) was a funded by the European Commission for four years (1996-1999). The project focussed on the population dynamics of this important zooplankton species in the North Atlantic, in order to elucidate the mechanisms responsible for the variability in the generation pattern of the species. Emphasis was on determination of the scales of interaction between the oceanic deep-water habitat and the shelf regions, as the basis for understanding the seasonal and long-term changes in population size.

The overall goal of a number of these programmes was to contribute to the elucidation of the basic functioning of this key component of marine ecosystems in order to enable an understanding and prediction of the possible responses to climate variations. A selection of key findings are described below:

1.2.2 Climatic forcing and ecosystem response

Changes in natural patterns or "modes" of the atmosphere and ocean, such as the North Atlantic Oscillation (NAO), the Arctic Oscillation (AO), the El Niño/Southern Oscillation (ENSO), and the longer term multi-decadal climate variations (MDC) result in large variations in weather and climate over much of the globe on interannual and longer time scales. For instance, much of the global warming signal observed in recent decades has been attributed to decadal changes in the phase and amplitude of these dominant patterns of variability. Moreover, it has been argued that the

spatial pattern of response to anthropogenic forcing may be amplified by coherence with modes of natural climate variability (e.g., Corti *et al*. 1999). The interaction of climatic forcing (NAO), ocean circulation and changes in greenhouse-gas concentrations affect the dynamics of the thermohaline circulation of the North Atlantic, a factor that has been identified as exerting fundamental influence on global climate (e.g., Broecker, 1997; Clark *et al*., 2002). Similarly, these changes in the physical environment in the North Atlantic Basin have been linked to fluctuations in for example, the population dynamics of key plankton species and exploited fish stocks in the oceanic basin as well as associated shelves (e.g., Reid *et al*., 2001; Greene *et al*, 2003; Beaugrand *et al*., 2003; Richardson and Schoeman, 2004). The mechanisms for these changes are a result of abiotic climatically-driven changes in circulation and mixing patterns as well as in changes in physiological rates of organisms influencing for example the timing of the spring bloom (e.g., Edwards and Richardson, 2004).

Particular research interest focused on the distributions of cod stocks and *Calanus finmarchicus* in the North Atlantic because they tend to co-occur (see figures in Sundby, 2000). Additionally, strong relationships have been found between temperature and cod recruitment (particularly when cod inhabiting the colder extremes are exposed to warming of oceanic waters. In contrast, recruitment of cod stocks inhabiting warmer waters is found to decrease with increasing temperatures. While temperature will affect cod vital rates directly, Sundby (2000) proposes a basin-scale generation mechanism for Atlantic cod recruitment where temperature change is linked to advection of *C. finmarchicus* from core production regions (including cross-shelf exchanges with open ocean *Calanus* populations, e.g., Backhaus *et al*. 1994; Heath, 1999; and Heath *et al*. 1999). This provides favourable feeding for young stages and strong recruitment of cod stocks that are distributed around the fringes of the core regions of *C. finmarchicus*.
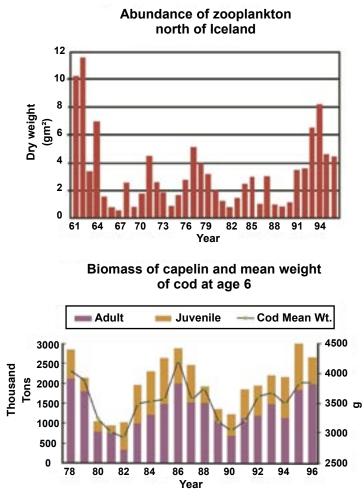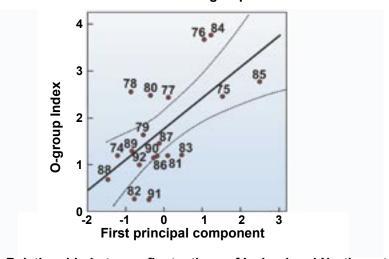

Figure 1. Inferred zooplankton, capelin, and cod relationships in Icelandic waters (re-drawn from Jakobsson and Stefánsson,1998).

C. finmarchicus is also an important component in the diet of a number of other fish species, including many commercial species. Among them are capelin, haddock, salmon, redfish, herring and mackerel. For capelin surveyed in the waters to the north of Iceland, dramatic decadal variations in stock size covaried with changes in zooplankton biomass (Jakobsson and Stefánsson, 1998), see Fig. 1 (from Wiebe, 2001). Enhanced recruitment of many of these fish species appears to be linked to the abundance of *Calanus*. For example, a relationship exists between the abundance of Icelandic O-group cod and zooplankton abundance (Astthorsson and Gíslason, 1995) see Fig 2 (from Wiebe, 2001). A similar relationship has been found on Georges Bank between plankton volume and a cod recruitment index (Mountain and Wiebe, U.S. GLOBEC newsletter), although the role of *Calanus* in this relationship remains to be determined. This is emphasized by cases where there seems to be a negative relationship between *Calanus* abundance and cod recruitment and survival (Gaard, 1998; Drinkwater and Frank, 2001). *Calanus* has been studied in sufficient detail for a long enough time that linkages to climate change indices are now apparent. Strong correlations between the abundance of *Calanus* and the NAO index (an indicator of climate variation and change) have been observed or implied in both the Northeast Atlantic (Planque, 1996; Astthorsson and Gíslason, 1995) and the Northwest Atlantic (Conversi, Piontkovski, and Hameed, 2001; Greene and Pershing, 2000). Since the early 1990s, however, freshening over the NW Atlantic continental shelf, due to an increased contribution of Arctic water, which may be linked to circulation changes in the Arctic, may have had a more important impact than the NAO on the ecosystems, including the abundance of *Calanus* (Head and Sameoto, in press; Greene and Pershing, submitted; Pershing *et al*., submitted).

Relationship between fluctuations of zooplankton biomass and abundance of O-group cod

Relationship between fluctuations of Iceland and North-east Atlantic/British Isles zooplankton biomass/abundance
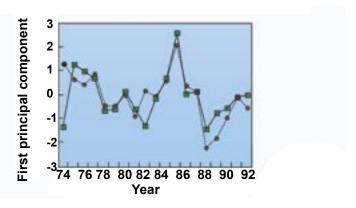

Figure 2. Zooplankton and O-group cod relationship in Icelandic waters and a comparison of Icelandic zooplankton variations with those in Northeast Atlantic regions (re-drawn from Astthorsson and Gislason, 1995). Bottom plot: ● = Icelandic data; ■ = Northeast Atlantic and British Isles data.

A major outcome of these studies has been the recognition that the dominant physical forcing across the North Atlantic basin is the large-scale atmospheric circulation, i.e. the spatial scale of biological events is often larger than national or regional waters. Linking regional-scale studies to provide a new level of understanding at ocean basin-scales will require higher order integration of data sets and modelling efforts. Such a new approach to integration will provide the basis for understanding the mechanisms responsible for the observed changes in physical and biological ocean properties and to predict the consequences of global change, one of the goals of a potential international BASIN research programme. An important point is that the correlative relationships identified cannot be used to imply causality. We lack the basic insights about the critical ecological mechanisms that may give rise to these relationships.

1.2.3 Interactions and exchanges between open ocean and shelf systems

Our understanding of the interactions between continental shelves and ocean basins remains unresolved. It will be necessary to quantify the transport and exchanges of heat, mass, nutrients and populations between these domains if we are to determine the relative role of shelves in the sequestration of carbon, the role of oceanic species (as prey or predators) in determining the variability of shelf species, and changes in the connectivity between shelf and oceanic populations across the North Atlantic. Shelf areas are particularly susceptible to the impacts of global change due to increases in stratification, freshwater input, and perhaps increases is variability of neighbouring deep currents and associated frontal regions. Despite their small areas, shelf seas are important in global commercial fisheries, diversity, habitat and trophic dynamics.

North Sea shelf pump

The North Sea shelf system is one of these regions that has been suggested to be important in the production and transport of organic carbon to the deep ocean via the "shelf pump" (Thomas *et al*. 2004). This system also supports a number of important exploited fish stocks. It is estimated that about 8 million tonnes of carbon are exported each year from the North Sea to the North Atlantic Ocean – representing about 93% of the CO_2 that the North Sea takes up from the atmosphere. Thomas *et al*. (2004) suggested that the world's coastal and marginal seas (just 7% of the world's oceans) may account for around 20% of the global oceanic annual uptake of anthropogenic CO_2 – much higher than previously thought.

Furthermore, transport of nutrients such as nitrogen into the North Sea is assumed to be one of the principal mechanisms influencing the group dominance and biomass production of phytoplankton in the North Sea. Changes in production, as well as phytoplankton group composition, may result in changes in the efficiency of the biological carbon pump thereby influencing the sequestering of organic carbon as well as altering the base of the pelagic food web and influencing bottom up controls on this system (e.g., Ware and Thompson, 2005). Productivity and species composition are affected by the transport of nutrients and organisms between the North Atlantic and the North Sea. Variability in the rate of this transport is a result of changes in climate and hence this region has the potential to be heavily affected by climate change. Similar examples exist for other shelves in the North Atlantic, such as the Scotian Shelf, and the Middle and South Atlantic Bight regions (Loder *et al*., 2001; Drinkwater *et al*., 2003; Pershing *et al*., 2004, 2005).

Global change influences on the North Atlantic Basin (shelves and deep ocean) have the potential to impact upon:

a)   The spatial and temporal dynamics of plankton composition and biomass,

b)   The sequestering of carbon via plankton composition and biomass,

c)   Changes in production of higher trophic levels due to availability of optimal prey species and groups,

d)   Ecosystem structure through fisheries exploitation patterns.

Thus the ecosystems of the North Atlantic basin and associated shelves, together with understanding the implications of changes in the structure and function of these ecosystems and their services, are important both for the development of Global Change research and Earth System Science.

1.2.4 Summary

With this as the background, it is clear that coordination of basin-scale North Atlantic studies is needed for several reasons.

•   First, the dominant physical forcing across the entire basin is the large-scale atmospheric circulation as reflected in the North Atlantic Oscillation (NAO) index.

•   Second, the spatial scale of biological events is often larger than national or regional waters, either North American or European. Studies at larger scales are important for elucidating the mechanisms responsible for the observed changes on local/shelf scales, which are needed if one is to predict ecosystem response to possible climate change.

•   Third, comparative trans-Atlantic studies allow us to address research questions that can not be answered from national studies alone by examining species under different ranges of their environmental conditions.

1.3 Relevance to Global Change

In its broadest sense, global change is the result of natural variability and anthropogenic activities such as the release of greenhouse gases, the response of the biosphere, and the exploitation of natural resources including modification of habitats. The responses of ecosystems to Global Change include changes that alter the composition of marine food webs and affect their ability to provide ecosystem services such as fisheries and alter their ability to sequester carbon associated with greenhouse gas emissions. Such sequestration, which plays an important role in the rate of global climate change, depends on physical, chemical, and food web processes which both modify and are modified by marine food webs. Hence, changes in the dynamics of key trophic interactions and biogeochemical processes influence the transport of greenhouse gases, thereby providing a feedback loop to climate. One of the key issues facing the scientific community is to further our predictive understanding of the complex linkages between physics, chemistry, and biology, and their importance for the functioning of marine ecosystems in order to predict and potentially to mitigate the effects of global change.

Based on the importance of the North Atlantic basin for global climate and for exploited fisheries resources, it is timely and appropriate to conduct a review focused both on the open ocean and associated shelves examining: the effects of climatic processes on ecosystems, available observatories and time-series stations, and existing infrastructure and data management, in order to explore opportunities and potential benefit of developing a major jointly coordinated international research programme between the European and North American marine research communities. BASIN will generate such a research programme the context of which will be supported by:

- The importance of the North Atlantic system for global climate;

- The geographic scope and complexity of the system;

- The fragmented nature of existing databases;

- The need for a multinational multidisciplinary approach to the assembly of existing data sets, and the development of predictive capacities and mitigation approaches;

- The necessity for the continuation and implementation and integration of appropriate of Pan North Atlantic (EU, CA,US) monitoring programmes;

- The increasing level of existing multidisciplinary expertise in climatology, physical oceanography, marine biogeochemistry, biological oceanography, fisheries science, and ecosystem and biogeochemical modelling.

1.4 BASIN in relation to existing Global Change Programmes

BASIN is intended to contribute significantly to the success of the Global Earth Observation System of Systems (GEOSS). The purpose of GEOSS is to achieve comprehensive, coordinated, and sustained observations of the Earth System, in order to improve monitoring of the state of the Earth, increase understanding of Earth processes, and enhance prediction of the behaviour of the Earth System. Hence, as a contribution to GEOSS, the BASIN research programme would answer the need for timely, quality, long-term global information as a basis for sound decision-making, and the need to enhance delivery of benefits to society. BASIN would also provide a step toward addressing the challenges articulated by United Nations Millennium Declaration and the 2002 World Summit on Sustainable Development, including the achievement of the Millennium Development Goals.

Finally, BASIN would contribute to the Synthesis and Integration (S&I) phase of the IGBP/SCOR/ IOC GLOBEC (Global Ocean Ecosystem Dynamics) programme, which will focus in the coming years on regional and global ecosystem comparisons enabling an improved understanding of the functioning of marine ecosystems and their responses to physical forcing. It will also contribute to the overall goals of the new IMBER programme (Integrated Marine Biogeochemistry and Ecosystem Research, IMBER, 2005).

2. DATA: AVAILABILITY AND ANTICIPATED NEEDS

Within BASIN, data will be required for several purposes. First, long-term time series are necessary for retrospective analyses and to this end BASIN activities will identify what historical data sets are available and where they can be accessed for integration and synthesis. These datasets will include climatological, oceanographic, chemical, and biological data. The programme will also identify, locate, and attempt to rescue historical data sets that are not presently accessible or are in danger of being lost. This will include the processing of data collections that are considered critical (in type, time, or space) that have not yet been processed, such as preserved, but as yet unanalyzed, biological samples. This activity will build on the EUR-OCEANS programme of data rescue.

Second, new data will be required in order to understand and better parameterize the physical and biological processes in the models as well as to address gaps in process knowledge. These data will be critical for model improvements and the models will be used to help prioritize the data collections required both in the field and laboratory, as well as to identify the geographical locations where such measurements should be carried out and the frequency of sampling needed.

Third, data are required for model validation. While most of these will be in the form of presently available data sets, new measurements will also be required where existing information is limited or non-existent, either in type, space, or season.

2.1 Existing Data

Historical data and recently collected measurements will form the basis of the retrospective analysis, synthesis, and integration within BASIN. As a first step, key data sets required to carry out these activities will be identified as well as strategies for assembly for example via meta-database development. Climate and hydrographic data have already been assembled by many groups and organizations. Links to these databases at such locations as the World Climate Data Center, ICES, CLIVAR, etc., will be made to facilitate ready access to the data. This will not only include station measurements, but also gridded data such as those provided by the climate re-analyses. See Appendix A for further data considerations.

Do the data resolve climate time-scales?

Most available physical and biological oceanographic data have been collected only over the past 50 years. This allows us to examine interannual and decadal scale variability with some degree of certainty. However, to examine multi-decadal climate scale variation, longer data sets of the order of 100 years or more are required. For example in the North Atlantic, the late 1800s and early 1900s were years of relatively cold conditions. Rapid and intense warming occurred in the 1920s and 1930s and conditions remained warm, albeit with high interannual variability, through to about the 1960s when strong cooling occurred. After the cold period of the 1960s and 1970s, conditions improved through to the 1990s when again there was a rapid warming. Large ecological changes occurred during the warming and the cooling periods. These low-frequency changes are generally not captured by most of the available data sets because of the relatively short record lengths. One dataset that does exist over longer time scales than 50 years and at the geographical scale of the basins is the Continuous Plankton Recorder (CPR) data (Reid *et al*., 2003). Without such data we would not have been in a position to begin to detect certain relationships between plankton and climate.

It is also recognized that the ecosystem response to climate forcing is most likely a function of the frequency of the forcing. Although few long-term datasets are available, other local and shorter data sets can provide insights into responses to climate variability. These datasets can be used together with models to help us understand and hindcast past observations as well as predict potential

impacts of anthropogenically-induced climate changes. Similarly, the existing (shorter) time series help set the present ecological baseline, although it is recognized that this baseline may have been established under a specific ecosystem regime that was heavily affected by human activity such as fishing and pollution.

2.2 Key Data Features to Model

Several features in the observations that need to be modeled include:

1. Changes in stratification and nutrient fluxes

2. Seasonal and interannual variability in the spatial and temporal distribution and abundance of key species under different climate conditions, i.e., changes in biogeographical boundaries and phenology.

3. Trophic linkages, including (a) changes in phytoplankton group composition and their effects on higher trophic levels as well as flux of carbon to depth (b) the effects of zooplankton abundance on growth, condition, and survival of fish larvae and (c) the predation of adult planktivorous fish on zooplankton populations.

4. Changes in the size spectra observed in the CPR dataset.

5. The spatial scales of coherent variability for zooplankton (approximately 1000 km) and fish (approximately 500 km) abundance.

6. The advection of zooplankton, in particular cross-shelf transport and whether the process is continuous or episodic.

7. The observed exchanges and fluxes at the shelf break and their relative importance to the overall primary and secondary production and sequestration of green house gas materials.

8. The estimated retention times of zooplankton and fish on continental shelves and banks, as well as zooplankton in the deep basins in the open ocean.

9. Regional differences in productivity and stock size of cod, e.g., the largest populations occur in cold waters whereas maximum individual productivity occurs in the warmest waters they inhabit.

2.3 New Data Collections

New data collected within BASIN will be essential for the improvement of model parameterization and validation. In turn, models will be crucial for helping to design sampling strategies. However, there is still a general need for better seasonal (especially winter where logistical difficulties in conducting field work have rendered the observations sparse) and spatial coverage of most of the biological and certain of the physical variables, especially in some of the poorly studied deep basins. For example, there are fewer biological observations in the Labrador Sea-Irminger Basin or the Northwest Atlantic Slope Water than in, for example, the Norwegian Basin. See Appendix A for additional considerations.

2.4 Database Management

BASIN will collect and organise large amounts of data including selected model output. While it is not considered a requirement to centrally manage these data sets, a person or group will undertake responsibility for (1) coordinating assembly of the historical data bases and linking to data collected during relevant recently completed and ongoing programmes such as GLOBEC regional and national studies, (2) ensuring data collected during BASIN are made available and shared as quickly as possible, (3) fostering the establishment of data portals to help BASIN scientists access the data, and (4) undertaking local archiving of new data and model results. It is anticipated that the data will be in the form of distributed databases with a BASIN website supplying seamless access to the data links.

Several programmes and projects have already dealt with many of the data management issues anticipated within BASIN, e.g., GLOBEC, JGOFS, CLIVAR. We will adopt the best tools and solutions available.

There will be a policy of open access to all data. It is recognized, however, that some of the historical or recently collected data sets, particularly fisheries related ones, may require some restricted access for a limited time period. BASIN will examine and adopt policies that other large programmes (e.g., CLIVAR, GLOBEC) have already established and comply with the laws of the EU and US. Regarding data obtained during BASIN, steps will be taken to ensure quick access to such data while still maintaining high quality calibration and processing standards.

While local archiving of the new data will be carried out, steps will be taken to discuss with centralized database managers such as WODC permanent archiving of the data. This is essential to ensure that the data are available long after BASIN is completed.

There are several ways in which interactions between observationalists and modelers are anticipated. A funded BASIN programme would facilitate information exchange between modelers and observationalists and develop tools to allow observationalists to easily query model results, help identify critical field measurements (including processes, season or location), and identify model limitations or unexpected predictions. A step towards this end, subsequent to the Reykjavik meeting, has included a GLOBEC meeting on "Mathematical modeling of zooplankton dynamics", held at CIRM, Marseille, 2-5 May 2006. Additionally a EUR-OCEANS/GLOBEC meeting on "Parameterization of trophic interactions in ecosystem modelling" will be held in Cadiz, 20-23 March, 2007.

3. MODELLING

3.1 Goals

- *Hindcast modelling studies to understand the observed variability of the North Atlantic ecosystem over (at least) the last 50 years,*

- *Construction of scenarios of possible ecosystem changes in response to future climate variability.*

3.2 General Approach

There is currently no fully integrated ecosystem model that can address BASIN's goals. The key steps in representing complex food webs in basin scale models are to concentrate the biological resolution at the level of the species or trophic level of interest, and to decrease the resolution, with distance both up and down the trophic scale from the target species (De Young *et al.*, 2004). The target species can for example be represented by developmental stage structured representations in which the key life-history stages and their links to the environment are explicitly formulated. Competitors, prey, and predators can be represented by less detailed structures, perhaps based on species-aggregated, bulk biomass properties, or even external forcing data, leading to a rhomboid shaped representation of detail (Figure 3). The coupling between levels of differing biological resolution or representation is a necessary focus for research. The physical models, in which the biological representations are embedded, should have resolution, characteristics, and complexity matched to the species and process of interest, although they should also consider the requirements of the lower and higher levels. Complexity should be matched to the species and process of interest, although the models should also consider the requirements of the lower and higher levels.
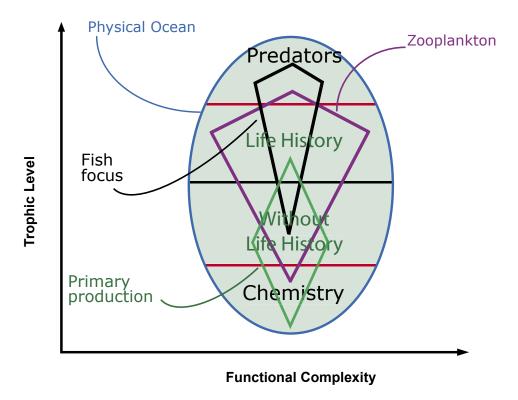

Figure 3. Schematic representing complex food webs in basin scale models as rhomboids.

Following this approach, the focus of the BASIN modelling programme will be on a few key species and functional groups for which the most detailed spatially-explicit models would be developed. However, we also propose significant efforts in modelling the lower and higher levels (Figures 4, 5), identified here as the phytoplankton/microbial food web (lower) and the planktivorous (higher) level, including vertebrate and invertebrate predation. A major research element of the programme will be to identify the required level of detail for the models at these levels and the best approaches to couple the biological models with the circulation models. This would entail a sustained effort in inter-comparing models against common data sets (a proposed ECOMIP effort – see Section 3.4.4 herein) and dedicated efforts to focus specifically on the required two-way flows of information across the interfaces between the ecological levels.

Figure 4. Schematic highlighting the structural components required for a basin-scale study focused on primary production. The arrow at the side indicates that, to first order, the primary scale of importance is the vertical structure.

BASIN will support continuing improvements in hindcasting the past 50-year record of climate and ecological conditions (longer if information is available) and in projecting change over the coming decades. The ultimate goal should be a common modelling environment for basin-scale operation of diverse ecological models. One possible avenue for this common environment is the development of a coupler that exchanges information among heterogeneous models, similar to that which is already being developed for Earth System models. Much of what is proposed here would place ecological modelling studies on the path already taken by climate and physical oceanographic models (e.g., model inter-comparison, nesting/interfacing between different models, hindcasting/forecasting scenarios). However, there remain fundamental differences between physical and ecological models. In contrast to physical models, increasing the complexity of ecological models does not necessarily lead to improved simulations or predictions of ecological phenomena. (e.g., Raick *et al*. 2006). It bears repeating that this effort cannot be viewed as leading to coupling of increasingly complex and comprehensive ecological models, but rather as leading to the identification of the simplifications and performance indicators that are robust for the modelling of basin-scale ecological dynamics over the recent past and for the future.

Open Ocean   Shelf

Planktivorous
Fish Focus

Fishing, Piscivorous
fish, birds, mammals

Planktivorous Fish-Structured
population with closed life
cycle, broadly distributed
species-sandlance, capelin,
mackerel, Norway pout, blue
whiting, redfish

Unstructured
competitors
for structured
fish

Fish food: aggregates
of zooplankton taxa

Fish food: aggregates
of zooplankton taxa

Physics and chemistry - highly resolved shelf
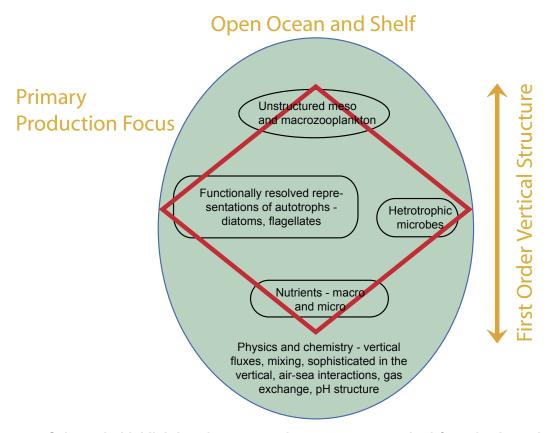circulation, ocean-shelf exchange

First Order Horizontal Structure

Figure 5. Schematic highlighting the structural components required for a basin-scale study focused on planktivorous fish. The arrow at the bottom indicates that, to first order, the primary scale of importance is the horizontal circulation, which advects populations around the basin. Note that fishing, a human impact, would be required to represent one important component of predation.

3.3 Elements of the modelling programme

State of the art physical and ecological models will be used in developing BASIN's goals. Reviews for Physical Models, Ecological Models, Coupled Models, Modelling Challenges and Data Assimilative Models are provided in Appendices B-F respectively. Perhaps more importantly at this stage for BASIN are the challenges we face in extending these approaches and integrating them to obtain new insights at the larger spatial and temporal scales implied by the basin-scale questions.

Integration across trophic levels

In order to develop the understanding and tools necessary to simulate population structure and dynamics of key species and biogeochemical processes that span the basin of the North Atlantic, BASIN will develop a suite of models needed to capture the relevant ecosystem and biogeochemical dynamics on the continental shelves as well as at the North Atlantic basin scale. BASIN will approach the problem of understanding basin-scale ecology by selecting key targeted species and functional groups and then building an ecosystem approach focused on these targeted components.

The selection of the targeted components will require extensive analysis and review as it is important that they are both ecologically and biogeochemically significant and scientifically tractable. The approach for the identification of targeted species will include a review based upon a suite containing the following criteria

- Functionally important (e.g., biogeochemical or trophic)
- Extensive data sets (spatial and temporal)
- Concurrence with other relevant data sets
- Understanding of life history and physiology
- Well resolved taxonomy
- Widely distributed/across the basin
- Economic and societal importance

The targeted species in BASIN will span the trophic levels from microbial loop and phytoplankton through to fish and build on recent work on zooplankton in the North Atlantic, from GLOBEC, TASC and the UK Marine Productivity programme many of which have focussed on *Calanus finmarchicus* as a key species. The BASIN approach will explicitly include an integrated strategy spanning the range between lower trophic level biogeochemical processes and top predators following the rhomboidal modelling approach presented in a recent review on modelling basin scale ocean ecosystems by deYoung *et al*. (2004). Four major components are envisaged focusing on differing trophic levels (described in Appendix C):

- Primary production and biogeochemical cycles
- Zooplankton
- Planktivorous fish
- Demersal fish

Of the four components, those of zooplankton and planktivorous fish are viewed as central to BASIN in particular as our existing databases are contain most information on these two components. However BASIN recognizes that expansion in the areas of primary production and the microbial loop is necessary for advancing our understanding the importance of top down and bottom up controls on ecosystem structure and function (e.g. Frank *et al*., 2006) in particular with respect to the sequestering of green house gases and the carbon cycle. The demersal fish component (e.g., cod and haddock) is significant because of the importance of these fishery resources to society as well as the predatory controls these species exert on marine ecosystems (e.g., Frank *et al*., 2005).

Following the rhomboidal strategy (Fig 6) (See Appendix C for more detail), each component would include some aspect of data or modelling from neighboring trophic levels, either above or below the component of emphasis. Thus, for example, the zooplankton component would include some elements of primary production, but at a greatly simplified level relative to the effort describing primary production. Likewise the zooplankton component would include data or perhaps simplified models to represent the predation impact from other fish and other predators. Although each of the four components has differing primary areas of interest, there is substantial overlap between them.

3.4 Modelling Activities

3.4.1 Interfacing the models

The last few decades have seen important advances in coupling physical models, from 1D to 3D, to trophic-level specific ecological models. Although there are still many outstanding and difficult

issues in coupling circulation models to NPZD or to population dynamic models, the expertise in these areas is advancing rapidly. In contrast, there has been comparably little experience in interfacing models for different trophic levels other than at the primary producer and herbivore levels. To progress, the challenges are substantial. For example, models for the population dynamics at different trophic levels operate at fundamentally different time and space scales (phytoplankton days; zooplankton weeks to months; small pelagic fish annual to multi annual; demersal fish annual to decadal) and within very different ecological realities as a result of different habitats or different modes of life history closure. At this stage, it is difficult to envisage a concentration-based approach or an individual-based approach that would work across all trophic levels. Even if we can express biological dynamics across all trophic levels in the same currency (e.g., carbon), fundamental differences in the way the chosen currency flows within each level (e.g., continuous versus discrete transfers) prevents a single unified approach. Also, limitations to ecological knowledge and computational power force a focus on a key trophic level with lower resolution for the levels above and below (the rhomboidal approach) leading to a proposed focus on developing the interfaces between NZPD-Zooplankton and Zooplankton-Planktivores components.

Figure 6. The emphasis of the programme will be determined by the ecological requirements to achieve the understanding required to simulate the population dynamics of the selected targeted organisms. Thus for example, a focus on zooplankton will require some attention to phytoplankton and perhaps microzooplankton as food for zooplankton and consideration of planktivorous fish, and possibly other zooplankton as predators of the selected targeted organisms. Likewise for other targeted organisms such as planktivorous fish or for a focus on primary production, in which case the species focus may be replaced by a focus on functional groups, or for demersal fish on the shelf for which there may be a necessary inclusion of planktivorous fish as prey or possibly zooplankton if larval stages of fish development are considered.

3.4.2 Research nodes

BASIN will consider the mechanisms needed to coordinate and implement research on interfacing the NPZD-Zooplankton and Zooplankton-Planktivore levels in basin scale models (Figure 7). The charge would be to identify the required information flows and controlling processes and feedback processes from one level to the next and the time and space scales (horizontal and vertical) at which these flows must be transferred. The research might proceed by examining first bottom-up flows (in isolation from top-down feedbacks), then top-down flows (isolated from bottom-up feedbacks), and then reconciling these research strands into a coherent view of required bottom-up and top-down feedbacks. Investigations should be fostered with a diversity of modelling approaches within and between levels (e.g., empirical algorithms, functional groups, size-spectra, and dynamic energy budgets) and with development of specific research activities driven by advances and gaps identified during progress in model development and identification. This will require coordination during model development activities.

φ=physics

NPZD: concentration-based models
FT: funtional type approach
Size: size spectra approach
WBM/SBM: weight- and stage-based models
IBM: individual-based models
PD: population dynamics

Planktivores
(Fish, jellies)

PD/IBM/Size

Zoo-Plankt. interface

φ

Zooplankton

WBM/SBM/IBM/Size

NPZD-Zoop interface

φ

NPZD/FT/Size

Primare producers
and μ-bial foodweb

φ

Figure 7. Schematic emphasizing the need to interface the NPZD-Zooplankton and Zooplankton-Planktivore levels in basin scale models.

3.4.3 Common modelling environment

BASIN will by necessity deal with multiple trophic level models interacting with multiscale circulation models operating over a range of environments and institutions around the North Atlantic basin and associated shelves. This will strain existing arrangements for collaborations and exchange of information that usually deal with coupling two models (physics and NPZD or single species modules) for regional issues. In order to make the BASIN goals a reality, a modelling environment that can be accessed transparently from a range of institutions using diverse models will need to be developed.

Collaborative environments for multidisciplinary modelling are beginning to appear. An example is the open source General Ocean Turbulence Model (GOTM http://www.gotm.net) which packages a range of turbulence closure models in a 1D physical model, distributes it through a web site, and receives, evaluates and incorporates changes to the code provided by the community. A similar approach has been used for 3D modelling, e.g. ROMS, POM, HYCOM, and others. These modelling environments include NPZD models, but nothing at or above the zooplankton level as yet. An expanded open-source environment for BASIN would be an excellent tool for the rapid improvement of models and their dissemination through the community. It would be an important first step towards improved collaboration among researchers around the North Atlantic basin.

However, this may not by itself bring the ambitious BASIN vision to reality. This may require a more structured environment that deals explicitly with multidisciplinary hindcast and forecast modelling at basin scales. One possibility for such an environment is outlined in Figure 8. In this approach, heterogeneous models exchange information through a coupler. The coupler allows models running at different time steps on different resolution grids to exchange information. This gridded information can also be used to assimilate data that have been appropriately scaled and interpolated. The idea behind these couplers is that they can easily deal with replacing one model with another. Such a concept is already used at NCAR to couple atmospheric, oceanic, sea-ice, and land-surface models for climate scale simulations (http://www.ucar.edu/communications/staffnotes/9510/CSM.html). It is also being implemented for a combined model-observation system for short-term forecasting in the coastal zone (http://cmep.ca/index.php?id=201). BASIN can benefit from the experience from these programs and others.
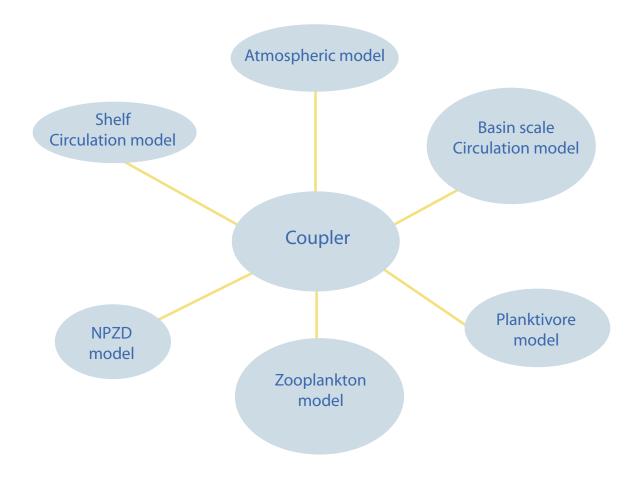

Figure 8. Schematic of how heterogeneous models can exchange information through a coupler.

3.4.4 Ecological Model Intercomparison (ECOMIP)

Ecological models have been employed in oceanography since the late 1940s. Advances in understanding and the greater availability of computing power have led to rapid developments in ecological modelling in the past few decades. A number of approaches are available to BASIN to model the different trophic levels, from concentration-based models of bulk properties to individual-based and structured population simulations. These diverse models provide different views of ecosystem dynamics and have different relationships to observations. Currently, there is no structured programme in oceanography to assess the predictions of various ecological models and their relationships to data. It is arguable that the absence of such an activity is a major impediment to further advances in ecological modelling and that it makes it difficult to quantify the uncertainty in ecological simulations.

Intercomparison exercises have become increasingly common in the physical and earth sciences. Examples are the CLIVAR Pilot Ocean Model Intercomparison Project (http://hycom.rsmas.miami. edu/bleck/omip/body.html), the Arctic Ocean Model Intercomparison Project (http://fish.cims.nyu. edu/project_aomip/overview.html) and the Ocean Carbon-Cycle Model Intercomparison Project (http://www.ipsl.jussieu.fr/OCMIP/). When data are available to test the models, intercomparison exercises accelerate the repetitive loop of model development, evaluation, and reformulation. Model intercomparison also allows research to focus on important regions where data are sparse or on mechanisms that are poorly understood. Through model intercomparison important differences between models can be identified and their causes investigated. Regarding predictions, model intercomparisons provide more information concerning uncertainties than would a single model simulation.

A programme such as BASIN depends critically on accelerating the development of ecological modelling approaches for hindcasting at basin scales. Also, projections of ecosystem changes will require better estimates of the uncertainties associated with ecological models. Therefore, BASIN will take the lead in initiating an ecological version of the physical intercomparison model exercises, an ECOMIP initiative. This initiative would identify a limited suite of ecological models that cover all three trophic levels and the major modelling approaches. It would implement these models in a common physical framework. It would also identify data sets (see section 2.0 above) against which all the models can be compared. The ECOMIP also needs to develop common metrics to assess the model simulations and their degree of agreement (quality measures) with data. It is also crucial given the aims of BASIN that this intercomparison exercise includes both hindcasts and forecasts as targets in comparing models.

Given the diversity of ecological modelling approaches available, this is a much more complex task than is the case with physical or biogeochemical models. This is why ECOMIP would have to start early in the programme with a pilot test project with initially very limited aims (e.g. test a subset of models at one trophic level) and then expand gradually as better understanding is gained of how such an intercomparison exercise would work with ecological models. Eventually, the ECOMIP should address the coupled models that are developed through the activity on interfacing models.

3.4.5 Fifty-year hindcast and analysis

In recent years, re-analyzed meteorological products that go back 50 years or more, improvements in oceanic circulation models, and increases in computing power have made hindcasting ocean conditions over the climatic scale feasible. Such hindcasting exercises with NPZD models are now possible. This may also be the case for simulations that directly couple circulation models with stage-structured zooplankton models. Climate-scale hindcast simulations with interacting trophic levels are still far off, but must be a central longer-term goal of BASIN.

3.4.6 Scenario production (links to Intergovernmental Panel for Climate Change, IPCC)

IPCC has begun the production of climate change scenarios in response to the possible levels of greenhouse gas emissions. These scenarios include responses of the ocean with respect to temperature, salinity, currents, etc. that can be used to drive models of ocean biology and biogeochemistry (Sarmiento *et al*., 2004; Hashioka and Yamanaka, 2006; Vikebo *et al*., 2006). As the resolution of the resolution and detail of the projections improves, the coupling to ocean models that capture ecologically relevant scales will be possible and will be part of BASIN.

4. ECOSYSTEM-BASED MANAGEMENT

4.1 Goals

The need to explicitly account for the human impacts in the marine environment is increasingly recognized. Calls for ecosystem-based approaches to integrated ocean management have recently been voiced in a number of national and international settings (Pikitch *et al*. 2004). Ecosystem-based management recognizes the complexity of interactions in these systems and the role of humans as part of the ecosystem(s), and attempts to formulate strategies for sustainable use of natural resources .

BASIN will provide an important foundation for the development of options for ecosystem-based management in the North Atlantic. Potential changes in fundamental production characteristics of regional subsystems driven by basin-scale climate events would require adaptation strategies in integrated ocean management. Management considerations include those for highly migratory species (which in some instances span the entire North Atlantic) and those for regional population or metapopulation structures for individual species which exhibit some level of basin-scale synchrony. The need for a basin-scale perspective is particularly clear for transboundary stocks. For regional populations and metapopulations exhibiting coherence in population fluctuations related to large-scale forcing, substantial improvements in predictive capability may be obtained by considering basin-wide effects.

Ecosystem Based Management Goals

We have adopted the following overall goal for BASIN in the context of management needs:

Understand and quantify pathways of production through the food web, coherence among regional systems around the northern North Atlantic basin, and the role of climate fluctuations in order to develop and evaluate options for ecosystem-based management.

The following subgoals have been identified:

- Develop, evaluate and apply conceptual and analytical models of ecosystem processes under climatic variability and change relevant to management on regional to basin scales

- Identify knowledge gaps and provide new data and information on ecosystem structure and functioning utilizing new and existing sampling and observation technology

- Undertake population dynamic studies of geographically widespread trophically important plankton and fish species to improve understanding of the effects of the natural and anthropogenic forcing through meta population analysis and regional comparisons

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4.2 Institutional Framework

Management of living marine resources is set within a complex institutional framework at the national and international levels. International assessment and management needs on a global basis are addressed by the Food and Agriculture Organization of the United Nations. The principal vehicle for international fisheries agreements is the United Nations Convention on Law of the Sea. The subsequent ratification of the United Nations Fisheries Agreement for Straddling Stocks and Highly Migratory species in 1995 explicitly recognized the importance of large-scale spatial perspective and the need for a precautionary approach in resource management. The FAO Code of Conduct for Responsible Fisheries, adopted in 1995, highlighted the importance of elements of an ecosystem approach to marine resource management.

The Convention on Biological Diversity, established in 1992 under the auspices of the United Nations Environment Programme affirmed the central role of the ecosystem approach in management.

The subsequent Conference of the Parties in Jakarta in 1995 called for approaches to:

Augment present mono-species approach to modelling and assessment by an ecosystem process-oriented approach with emphasis on ecologically critical processes that consider spatial dimension

and further noted that:

Models of ecosystem processes should be developed through transdisciplinary scientific groups and applied on coast resource use management

The need for broad scale scientific coordination in the North Atlantic has been recognized since the early 20th century with the establishment of the International Council for Exploration of the Sea. The complementary need for coordination of management actions at various scales of spatial resolution is reflected in the establishment of the International Commission for Northwest Atlantic Fisheries in the mid 20th century (and its successor, the North Atlantic Fisheries Organization), the development of the Common Fisheries Policy of the European Union, and bilateral or multilateral international fishing agreements

BASIN can materially contribute to the needs for ecosystem-based approaches to management of living marine resources in the North Atlantic. The research programme to be established under BASIN is entirely in accord with the development of an ecosystem approach to management accomplished through the promotion of transdisciplinary ocean science.

4.3 Basin-Scale Effects and Resource Management

Total reported yield from marine capture fisheries has leveled off at approximated 85 million t after a period of rapid development over the last half century (FAO 2004). Forty-seven percent of the world's fisheries for which assessments are possible are considered to be fully exploited with no capacity for further development, 18% are considered to be overexploited, 9% depleted and not currently capable of supporting fisheries, 21% are moderately exploited, and 4% are considered underexploited. It has been estimated that yield could increase by 20 million tons with improved management. Consideration of observed yields and estimated production potentials suggests that we are close to the limits to production and yield from capture fisheries in coastal/continental shelf regions and that the potential for changes in production under global change must be carefully considered.

Estimates of the production potential of the seas in coastal and continental shelf systems is on the order of 100 million t based on estimates of primary production and transfer efficiencies in marine food webs (see Pauly 1996 for a review). Basin-scale changes in primary production under different climate change scenarios can be expected to have direct effects on expected fish yields. Further, there is strong evidence that changes in temperature regimes could result in shifts in distribution of exploited species.

Understanding the potential for synergistic interactions between basin-scale climate forcing, ecosystem productivity and exploitation regimes is critical in devising appropriate management approaches. Populations of exploited marine species are strongly shaped by environmental variability on a broad range of space and time scales. High frequency variation in environmental forcing plays an important role in variability in the growth and survival of young fish and shellfish while lower frequency forcing on broad spatial scales affects overall levels of productivity on multidecadal time scales. Fishery management strategies must contend with the uncertainties introduced by large-scale variation in the number of young surviving the critical early months of life and must consider the implications of climate-induced changes on broader time horizons.

BASIN will focus two of its four principal research themes on economically important species partitioned between pelagic and demersal fishes. Commercially important pelagic fish species are planktivorous and can be expected to exert important grazing effects on zooplankton species also selected as target species under BASIN. Further, they play an important role as a forage base for higher trophic levels and therefore occupy the nexus of many marine food webs. Many of these pelagic fish species undergo extensive seasonal migrations, emphasizing the need for a broad (and often transboundary) perspective in management

Striking examples of coherence of yields of pelagic fish species (sardines and anchovies) on basin- and trans-basin scales are evident in upwelling systems (e.g. Alheit & Hagen, 1997; Alheit & Niquen, 2004; Chavez *et al*. 2003; Schwartzlose *et al* 1999). For the pelagic fish species to be studied under BASIN, including herring, mackerel, capelin, and sandlance, similar studies have not yet been undertaken although evidence for large-scale forcing on population levels has been reported, suggesting the potential importance of basin-scale processes in their dynamics.

For demersal fish to be studied in BASIN, cod has been identified as a key species. Evidence of climate forcing on cod populations mediated through the North Atlantic Oscillation has been reported by Brander and Mohn (2004). Brander and Mohn note regionally specific effects on cod recruitment throughout the North Atlantic Basin (Figure 9). The direction of the NAO effect on cod recruitment exhibits patterns consistent with the regional manifestation of the NAO, with a coherence in the NAO effect in northern Canada and Iceland and between southern Canada-United States and Western Europe (Figure 9).
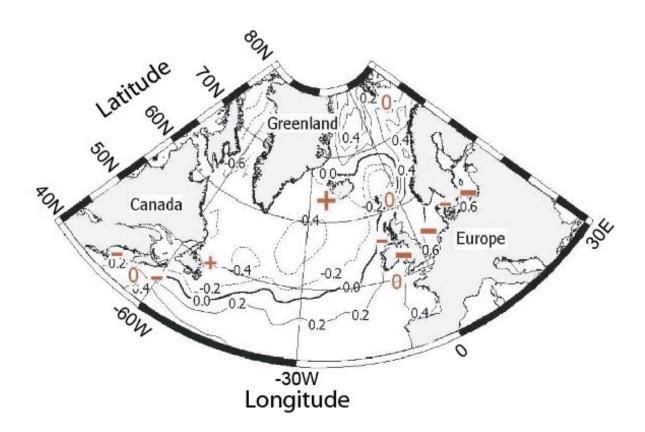

Figure 9. Contours of the seasonal correlation between winter NAO and SST in March to May 1948-2000. The symbols (+, +, 0, -,) indicate the sign and strength of the relationship between NAO and cod recruitment (from Brander and Mohn, 2004).

4.4 Resource Management Modelling

The development of conceptual and mathematical models has played a central role in marine biology and ecology as a tool for synthesis, prediction, and understanding. This activity has encompassed the development of models for single species, multispecies communities, and for whole ecosystems (e.g. Hofmann and Lascara, 1998, Hofmann and Friedrichs, 2002). The use of models has proven especially important because marine systems are typically not amenable to controlled experimental manipulation and alternate strategies involving the interplay of observation and modelling are critical. For applied problems such as fishery management and environmental protection, models are essential for predicting outcomes of proposed management actions. Models applied to problems in fishery management have typically focused on single species dynamics although there is an extensive literature on multispecies and ecosystem models for exploited marine systems (Hollowed *et al*. 2000; Whipple *et al*. 2000).

The development of hindcasts, nowcasts, and forecasts of the status of living marine resources is an integral component of fishery research and management. These models depend on an extensive existing observing system designed to monitor catches, fishing effort, and demographic characteristics of the catch (size and/or age structure). In many areas, fishery-independent scientific surveys have also been conducted to monitor ecosystem status. The most common type of model used for hindcasts and nowcasts is sequential population analysis in which the abundance and survival rates for each age or size class of a population are determined (Quinn and Deriso 1999). Other models of production processes at the population level are routinely used to set management targets and limits to exploitation and to evaluate the effects of alternative management actions (Quinn and Deriso 1999).

Considerable attention has recently been directed to the development of models and management strategies to meet broader ecosystem-based management strategies (including protection of vulnerable habitats, preservation of ecosystem structure and function; see Jennings *et al*. 2001; Walters and Martell 2004). BASIN can make an important contribution to the development of model and management strategies directed at these higher levels of organization (multispecies and ecosystem levels) by providing detailed information on the dynamics of lower trophic levels and system-wide production levels that could then be used as 'drivers' in management-oriented models or in fully integrated models linking the dynamics of the upper trophic levels under exploitation to the lower trophic levels.

Multispecies Models

Explicit representation of species groups or assemblages in multi-species models has been undertaken in a number of marine systems (Hollowed *et al*. 2000). Most often, these models consider interactions among members of identified communities of organisms and typically span a limited number of trophic levels. Predator-prey and competitive interactions have been most extensively modeled. In contrast to individual species models, these models provide explicit representations of interacting species and can be used, therefore, to examine the implications of changes in the relative abundance of species within biological communities. In the context of BASIN, the pelagic and demersal fish components are clearly linked through predator-prey dynamics and multispecies models can be refined through the anticipated benefits of BASIN research.

Multi-species sequential population analysis is an extension of sequential population analysis that can be used to account for the effects of predator-prey interactions in an exploited community. The features of the models follow the single species structure outlined above with the addition of information on the diet of the species in the model. These models allow a partitioning of natural mortality into a predation component and a component due to other sources of mortality such as disease. Estimates of total consumption of a prey item are treated as a removal term just as

harvesting represents a loss term. Multi-species sequential population analyses are data intensive and have been employed in fewer settings than their single species counterparts. Examples of regional applications include the Baltic and North Seas and the Georges Bank region of the Northwest Atlantic (ICES 2003; Tsou and Collie 2001). Again, the interaction between demersal and pelagic fish components provides the most direct link to BASIN research. The fundamental structural models used in multispecies virtual population analysis can also be used in a forward projection mode. In this context, the extent to which BASIN can contribute to a mechanistic understanding and forecasting of recruitment dynamics of the target pelagic and demersal species will determine its potential utility in prediction of multispecies assemblages.

Extension of single species production models to assemblages of interacting species have been applied in both non-structured (bulk biomass) and demographically structured forms (Whipple *et al*. 2001). These models typically include explicit terms for various forms of biological interactions, particularly competition and predation with the objective of determining the community-wide effects of exploitation. This approach recognizes that, in a community of interacting species, the yield of all species cannot be simultaneously maximized since changes in the abundance of each species affect the abundance of interacting species. These models can be cast in terms of system carrying capacity and productivity. BASIN research can, in principle, help determine potential changes in carrying capacity and could be used to adjust estimates of overall production potential.

Non-structured multi-species models have included forms in which individual species are not explicitly modeled and only the total yield from an assemblage of interacting species is considered and biological interactions are implicit (Mueter and Megrey 2006). These models have been employed particularly where separation by species is not possible (e.g., high diversity tropical fisheries. Other forms include specific consideration of competition and predation in an extension of the classical Lotka-Volterra equations incorporating harvesting mortality. The yield of individual species as well as the total yield from all species is modeled.

Multi-species analogues of age- or stage-structured production models have been less commonly employed (but see Stefansson and Palsson 1998). These models do permit consideration of age. or size, specific processes that can be critical in devising management strategies. For example, predation mortality is often highest on pre-recruits and models that explicitly consider the biological interactions in the stock-recruitment relationship are more realistic.

Ecosystem Dynamics

Models of whole ecosystems have been developed for a number of marine systems with direct consideration of nutrient inputs and representation of each trophic level from primary producers through top predators (Whipple *et al*. 2000; Jennings *et al* 2003; Walters and Martell 2004). This class of models is entirely consistent with the general approach advocated in BASIN; most often, the highest level of resolution is centered on key components of the system with lower resolution at higher and lower trophic levels (as in the rhomboidal structure in BASIN). Due to the complexity of these ecosystems, aggregate species groups are often used to represent at least some trophic levels, thus reducing the overall number of compartments in the model to a more manageable size, e.g. phytoplankton in two or three size classes, microzooplankton, gelatinous macrozooplankton, copepods, filter feeding fish, and predatory fish. The recognized importance of the development of ecosystem-based management approaches highlights the need to develop operational ecosystem models for the purposes of fisheries management. Ecosystem-based management recognizes the importance of essential fish habitats, multi-species interactions, and nutrient cycling as parameters of the growth, abundance and distribution of exploitable fish stocks. Accordingly, it is critical to understand and predict both direct and indirect effects of human activities on marine ecosystems including the following:

(1) alterations in food web structure and changes in biodiversity that may result from fish harvests or nutrient over enrichment (thereby altering food supplies or predation rates);

(2) habitat loss or modification due to human activities or natural hazards (thereby decreasing rates of recruitment and increasing exposure to predators); and

(3) introductions of non-native species that may reproduce and grow (and outcompete native fish stocks, produce biotoxins that cause mass mortalities of fish or make fish toxic to humans, or modify essential fish habitat).

Ecosystem network models provide static snapshots of ecosystem processes under certain mass balance assumptions. Dynamic ecosystem simulation models have also been developed and applied to these fisheries (e.g. Christensen and Walters 2004). Typically these models provide high resolution on the upper trophic levels (particularly exploited species) with more aggregated system representations at lower trophic levels.

5. RECOMMENDATIONS AND NEXT STEPS

It is recommended that the following further steps be taken towards achieving the BASIN goal:

Specific actions:

1. Convene alternating European and North American meetings including a balanced selection of scientists from climatology, field and experimental ecology, physical and biological oceanography, ecosystem modelling, and biogeochemistry, which would consider the following topics:

   • Assess the current status of climate-related ecosystem research in the Atlantic research area (Atlantic Ocean and associates shelf seas) with an emphasis on common research initiatives.

   • Identify and document gaps in systematic observations and the process understanding of atmospheric and oceanic parameters. This objective will form the basis for the development of a meta-database.

   • Evaluate the potential for consolidation of long-term observations from EU, North American, and other international databases for the modelling and prediction of the dynamics of the North Atlantic and associated shelf ecosystems.

2. Convene a smaller group of scientists already participating in one or both of the previous workshops together with delegates of the key international funding agencies with the goal of developing appropriate and effective implementation mechanisms whereby a joint BASIN research initiative involving the EU and other nations (e.g. USA, Canada) can be developed.

3. Based on the results of the first two meetings, develop an implementation plan with the key points being agreed by a joint group from European and North American countries and focusing in a balanced way on the key BASIN objectives being to:

   • Resolve the effects of natural and anthropogenically driven climate variability, on the structure, function and dynamics of the Atlantic Basin and regional seas;

   • Improve the understanding and predictive capacities necessary to mitigate the effects of climate variability on the marine ecosystems of the North Atlantic Basin and its regional seas;

   • Develop ecosystem based management strategies incorporating the influence of global change and hence contribute to the sustainable management the North Atlantic Basin and regional seas.

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7. APPENDICES

APPENDIX A: Data Considerations

A.1 Existing Data

Plankton databases have also been or are being assembled (including those gathered by the ICES Working Group on Zooplankton Ecology (WGZE) and proposed for the Plankton Time Series Observations (PLATO) program (Figure 10). Although the CPR transects dominate, other data sets are also identified, particularly coastal time-series stations. Additional plankton data sets will also be identified within BASIN.

Several GLOBEC programmes have been, or are presently, involved in field programmes. Their different areas of operation are identified, along with the area of the CPR transects (Figure 11). These programmes have assembled or collected relevant physical and biological data and relevant metadata are being deposited with Global Change Master Directory (GCMD) which is a comprehensive directory of descriptions of data sets of relevance to global change research. Additional relevant data sets will be sought and the scientists familiar with the data will be solicited to help to carry out the integration and synthesis of the data.

Extensive fish and fisheries data are available through ICES and NAFO working groups, national assessment committees, and within specific programmes such as the ICES/GLOBEC Working Group on Cod and Climate Change. These data, which include some egg and larval data but mostly juvenile and adult data, will also form an integral part of the BASIN dataset for the integration and synthesis.
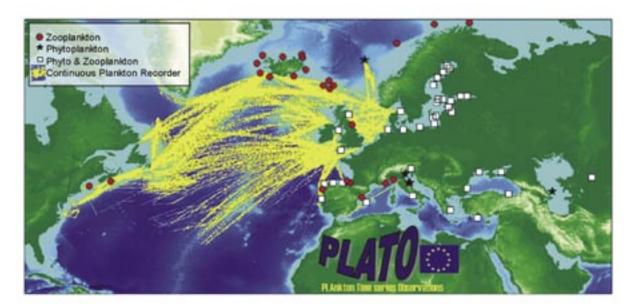

Figure 10. Transects and fixed stations for both phytoplankton and zooplankton collections identified by the proposed PLATO project.

A - Georges Bank GLOBEC
B - Canada GLOBEC
C - UK GLOBEC
D - TASC
E - ICOS
F - PNDR France
G - Baltic Sea GLOBEC
H - Station L4
I - Iceland Time-Series
J - CPR Time- Series
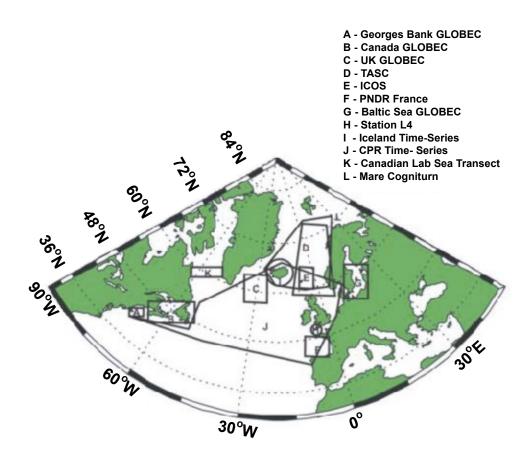K - Canadian Lab Sea Transect
L - Mare Cogniturn

Figure 11. GLOBEC study sites in the North Atlantic.

A.2 Data Archaeology and Recovery

In addition to the readily available historical data, there are data sets that are not in electronic format or have not yet been processed. This is especially true of zooplankton data although other types of data also need to be recovered. Several zooplankton data sets have been identified that are not readily available or in electronic format, e.g., off West Greenland extending back to the 1920s; Swedish collections from the North Atlantic extending from the 1800s to 1920; from Weather Station M in the Norwegian Sea; French cruises to the Newfoundland area in the 1920s and 1930s; oil company data from Davis Strait, the Labrador Shelf, and Newfoundland region; early collections from the Gulf of Maine as well as some MARMAP data; data from around Iceland, Russia, Ukraine, Canada, and Norway. More recent video data on zooplankton also need to be recovered and made accessible. Additional data sets will be added, as they become known.

Data quality is often an issue with recovered data as the data may be uncalibrated or not directly comparable with other available data sets. This is especially true for very early collections. In some such cases old instruments can be reconstructed for calibration against more up-to-date instrumentation.

Several programmes or projects are already involved in data archaeology and recovery. GODAR has been working primarily with physical oceanographic data. The number of large scale efforts for biological data are few. One exception is the Census of Marine Life History of Marine Animal Populations (HMAP), which has focused on the recovery of fish data. Another is the Coastal and Oceanic Ecology, Production & Observation Database (COPEPOD), http://www.st.nmfs.gov/ plankton/, a global plankton database that is presently residing on a server at the U.S. National Marine Fisheries Service. It contains abundance, biomass and species composition data. This programme is presently putting into electronic format all of the NORWESTLANT data from the

Labrador and Irminger Sea regions collected in the 1960s. Within the EUR-OCEANS Network of Excellence an active programme of data rescue has been launched. The objectives of the programme are (1) to rescue historical data by funding research institutes directly to help them transform and/or create digital datasets and to give networked access to these datasets through EUR-OCEANS data portal; and (2) to encourage institutions to develop long-term capacity for preparing/archiving data and metadata, thus increasing their level of integration in the Network and fostering their collaboration with European and international research scientists (http://www.eur-oceans.org/dataportal).

Information on the key predators on zooplankton is needed, in particular the small pelagic fish. While historical time series on fisheries catches and surveys are generally easy to access, hydroacoustic surveys have been conducted in a number of countries that could supply valuable spatial information for modelling. Many of these data are archived and could be accessed for analysis. Myctophid data from the open ocean are more rare but some are available, e.g., the Woods Hole collections of Backus and the more recent information available through the Census of Marine Life program (Backus *et al*., 1977).

Metadata associated with the measurements are very important and will also have to be recovered or generated from existing information. For zooplankton and fisheries data for example this will include such things as mesh size, tow speeds, any known biases in the gear, time of day, etc.

A.3 Collection of new data

A multidimensional approach will be used for new data collections, during the proposed Phase II of BASIN, that will include fixed stations, transects, and process-oriented field programmes. Moorings may be placed in the gyres containing the major populations of *Calanus finmarchicus*, which includes the Norwegian Sea, the Labrador/Irminger Sea, and the slope water (1000-2000m); exact placement would depend upon model considerations. The moorings should contain instrumentation to measure the physics (CTD), chemistry (O2, nutrients), phytoplankton (fluorometers), and zooplankton (acoustic methods, optical plankton counters (OPCs), and video imaging). The instrumentation will be designed to vertically profile the water column. The data would provide information on the spring bloom, overwintering of zooplankton populations, time of diapause, vertical ascent speed of the plankton when they emerge from diapause as well as whether they move continuously or rest at times during their ascent to the surface layers.

Transect data in the gyres should also be obtained at least twice per year during phase II (ideally the spring and autumn) from which it can be determined how representative the fixed station data are spatially. Measurements should include those on the moorings plus other additional data, such as pH. Process studies will be undertaken either along transects or separately during the oceanographic cruises. In addition to research ship-based transects, it is anticipated that instrumented ships-of-opportunity will be utilized including equipping CPRs with more sensors, and in the future, by using gliders.

Process studies at much smaller regional scales will also be required. Examples include: research focussed on microzooplankton, particularly their role as prey for mesozooplankton and how microzooplankton affect the fecundity and growth of their predators; the triggers into and out of diapause; estimations of mortality of zooplankton and its causes; the role of euphausiids in the basin-scale ecosystems; the importance of gelatinous zooplankton in these ecosystems; and trophic interactions, such as *Calanus*-fish and cod-capelin. Biological measurements associated with cross-shelf and frontal exchange processes will also be undertaken.

The physical measurements related to the biological processes will be obtained within other programmes in which the physical system is a major focus. BASIN will take advantage of existing measurement programmes and piggyback on these as much as possible in the collection of new data.

For example, studies as part of CARBOCEAN and MERSEA already have moorings in the Irminger Sea (www.soc.soton.ac.uk), hydrographic transects are routinely taken within CLIVAR, existing CPR sampling may be expanded into new areas, sampling during annual fisheries surveys, as well as monitoring programmes. Examples are the Atlantic Zone Monitoring Programme , which includes hydrographic and biological sampling along transects on the Scotian and Newfoundland Shelves and in the Gulf of St. Lawrence 1-3 times a year together with time series stations with at least monthly sampling (HL2, Stn 27, Rimouski) (http://www.meds-sdmm.dfo-mpo.gc.ca/zmp/main_zmp_e.html). There is also annual occupation of the AR7W section across the Labrador Sea between Hamilton Bank and Cape Desolation. Again there is hydrographic and biological sampling and in most years there is usually a current meter mooring at stn BRAVO.

Emphasis will be placed on climate-scale observations. Although the programme may not generate sustained, long-term time series, sampling can be designed to address selected climate issues. Long time scales are usually associated with large spatial scales, thus observations will need to be undertaken at the basin scale. Also, areas or regions previously sampled should be re-sampled using similar technology to allow temporal comparisons.

BASIN will use new technologies and future instrumentation and methods as they become available. One example of the latter is the emerging use of gliders. Satellite data will be used to obtain sea surface temperatures, current estimates from altimetry data, chlorophyll-*a*, and primary production estimates.

Finally, BASIN will make recommendations at the end of the programme on a monitoring strategy for sustained long-term data collections.

APPENDIX B: Physical Models

B.1 Multi-scale circulation models

Within the field of ocean general circulation modelling there are presently four classes of numerical models that have achieved a significant level of community management and involvement, including shared community development, regular user interaction, and ready availability of software and documentation via the World Wide Web. These four classes are loosely characterized by their respective approaches to spatial discretization (finite difference, finite element, and finite volume) and vertical coordinate treatment (geopotential, isopycnic, sigma, and hybrid). Technical background on these various model classes – including representative examples and web links – may be found on the gateway Ocean Modelling web site at http://www.Ocean-Modelling.org.

Many, if not all, of today's community modelling systems were first devised for a particular class of problem – e.g., z-coordinate and isopycnal models for basin-to-global-scale applications, terrain-following ("sigma") coordinate systems for coastal modelling, etc. This distinction is rapidly losing significance as these modelling systems are generalized to apply increasingly across multiple geographical and temporal scales, and physical phenomena of interest. Algorithmic "solutions" (really, more accurate approximations) to common issues such as intersection of isopycnals with sloping topography have been developed in all model classes, leading to an array of robust, reliable, and routinely applicable numerical circulation models.

As a result of this evolution, physical circulation modelling systems have achieved an impressive level of sophistication. Among the important new capabilities are: generalized vertical coordinate systems allowing more effective transition across the deep/coastal ocean boundary; well developed sub-models for the evolution of coupled biological and geochemical tracers; robust procedures for one-way nesting of models with differing spatial windows and resolution; efficient algorithms for multi-variate data assimilation of physical variables; and pre-operational prediction systems for global, regional, and local areas. Over the next five years, further progress is anticipated, including the refinement of operational forecast and analysis systems for the North Atlantic and other regions, the emergence of powerful new alternatives for multi-scale ocean modelling based upon unstructured grid techniques, and the availability of novel approaches and techniques for interdisciplinary modelling and data assimilation.

An important goal of these activities is the development and demonstration of end-to-end modelling systems such as the one shown in Figure 12. Such a system will entail four principal components:

(1)   Multi-scale circulation models for the ocean and atmosphere;

(2)   Coupled sub-models for example ecosystem dynamics, etc,;

(3)   Observational networks to provide data for initial and boundary conditions, forcing functions, etc.; and

(4)   Advanced methods of data assimilation to optimally merge the models and data.

The last of the four components is particularly essential because of inherent limitations on model accuracy on the one hand, and on how much data that can be routinely collected in the ocean on the other. Data assimilation is therefore needed to make the best combined estimate of the oceanic state taking into account uncertainties in the models and available data sets.

Although much progress has been made towards assembling such multi-scale systems in both the North Atlantic and North Pacific, several challenges and developmental issues remain. The most important of these include the following:

B.2 Multi-scale spatial treatment

Two avenues are presently being explored to extend the spatial coverage of oceanic circulation models to simultaneously encompass basin, regional, and local (coastal and estuarine) scales. The first is the use of nesting techniques to embed successively finer grids within sub-regions of particular interest and/or dynamical/ecological significance (Figure 13). These nesting techniques have been traditionally used with structured-grid models of the atmosphere and ocean. Such nested sequences of grids may be linked via one-way nesting (in which data from the larger-scale models provide boundary conditions for the inner regional grids, and there is no feedback to the larger-scale model) or two-way (in which data are shared in both directions). The former approach has some advantages – e.g., it allows the various grids to be run asynchronously, with the outer grid being computed first, the inner ones next, etc. However, the specification of suitable boundary conditions on the open edges of the inner grids continues to be a taxing technical problem. A second multi-scale approach, rapidly gaining in interest, is the use of unstructured (triangular or quadrilateral) grids. In principle, such unstructured grids may be devised to cover combined basin/regional/local scales on a single heterogeneous grid (see, e.g., Figure 14). Ocean models utilizing unstructured grids are rapidly evolving, and should soon offer an alternative to the nesting of multiple overlapping grids (see http://wessex.eas.ualberta.ca/~myers/FE/fe-page.html).
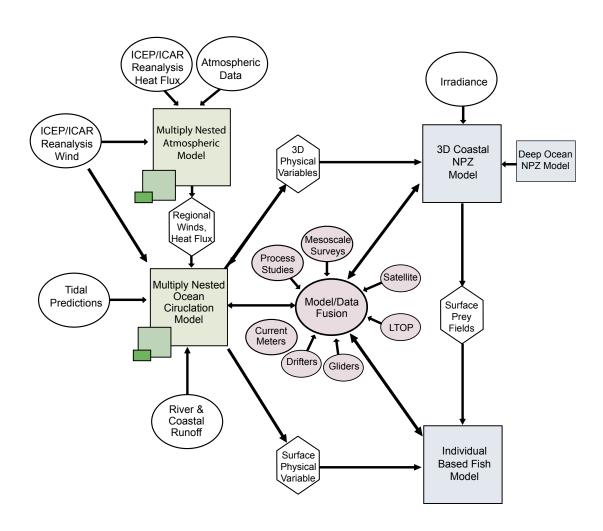
Figure 12. An example of an end-to-end modelling system.

B.3 Hybrid vertical coordinates

Until recently, ocean models could be conveniently categorized by their choice of vertical coordinate system – i.e., geopotential (z-based), isopycnal (layered), or terrain-following (sigma). Each of these traditional choices has its own strengths and weaknesses, now well known, and various corrective measures have been devised for some of the biggest sources of approximation error. Despite continued improvements in each of these individual vertical coordinate systems, another promising possibility is the development of hybrid coordinate systems that generalize the properties of z-based, isopycnal, and terrain-following, and thereby share their respective desirable properties. Such systems are being actively explored.

B.4 Accuracy, minimization of spurious damping, and non-oscillatory tracer advection

These three desirable model attributes are mutually related but, to some extent, also mutually exclusive. Typically, monotonic tracer advection near sharp features such as fronts requires the local addition of smoothing and (possibly) the loss of formal accuracy. Development of advection schemes that are increasingly targeted in their use of local dissipation is of high priority.
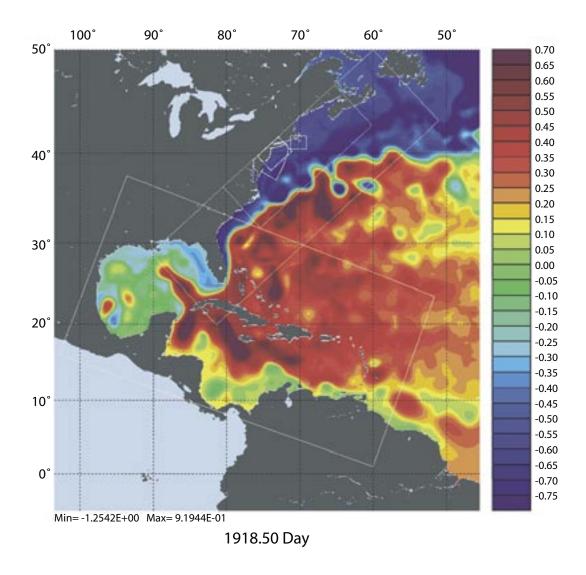

Figure 13. An example of such a nested hierarchy for the Northwest Atlantic.

B.5 Local conservation of tracers

It is usually desirable to ensure that tracers are advected (and diffused) in a conservative manner locally at each grid point or element. This is typically not an issue with ocean models based upon finite difference or finite volume techniques, both of which lend themselves readily to locally conservative approximations. In contrast, finite element formulations of the equations of motion require careful treatment to ensure local conservation. One approach, the use of the Discontinuous Galerkin Method is being widely explored.

B.6 Adaptive spatial resolution

A further improvement in spatial representation may be achieved by adaptively refining or coarsening the model grid in order to follow the evolution of specific features. Grid adaptivity has been in use in computational fluid dynamics for some time, and prototype ocean models with adaptivity are being developed (see, e.g., http://amcg.ese.ic.ac.uk/ngogcmprop).
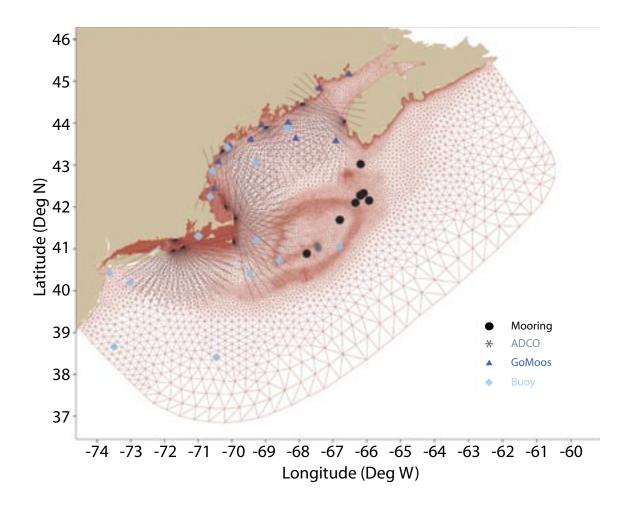

Figure 14. The Finite Volume Coastal Ocean Model, an example of the use of an unstructured grid.

APPENDIX C: Ecological Models

Primary production. The focus on primary production (Figure 4) will include both open ocean and shelf regions, but the structure of the modules will be common over the two domains. These models will be driven by stoichiometry in comparison to complex structured life history models, which are important for fish and zooplankton. Critical for the prediction of fluxes both of biomass and green house gas materials is the development of models based on functional groups (e.g. Le Quere *et al.*, 2005). The development of key species models will also be necessary in order to capture transfer efficiencies and vertical flux rates.

Zooplankton. The focus of zooplankton modelling (Figure 15) will be built upon advances achieved over the past decade on *Calanus* spp. and euphausiids. Although the bulk of their biomass is in the open ocean, they are also ecologically important in a number of the BASIN shelf regions. As the red rhomboid indicates, predation will be more simply represented than the zooplankton that require both structured population and biomass based (for zooplankton competitors) models. Likewise the food supply for zooplankton, including microzooplankton, diatoms, and non-diatoms will include models of intermediate complexity, such as functional groups based NPZD or mass balance models, or data (e.g., remote sensing) to represent the food supply.
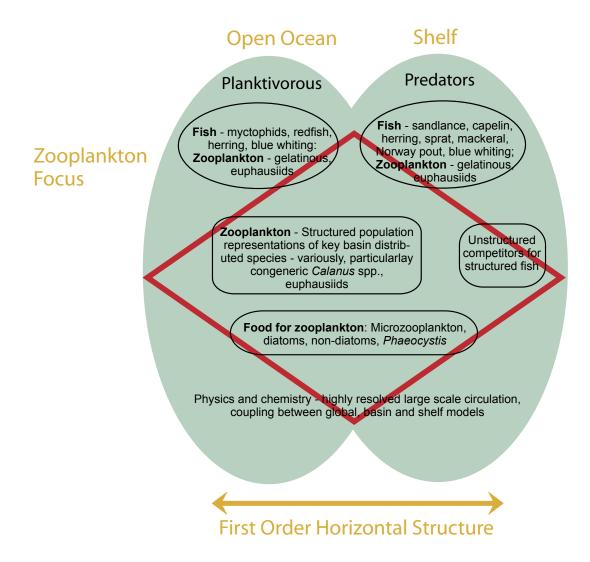

Figure 15. Schematic highlighting the structural components required for a basin-scale study focused on zooplankton. The arrow at the bottom indicates that, to first order, the primary scale of importance is the horizontal circulation, which advects populations around the basin.

Planktivorous fish. The focus on planktivorous fish (Figure 5) is a logical development to follow the work on zooplankton given the widespread geographic distribution and economic importance of these fish in the region, e.g., herring, capelin, sand lance, and others. As with zooplankton, the distributions of these fish span the associated shelves and open ocean however in most cases life cycle closure is heavily dependent upon shelf processes. To represent removal by fishing and predation, which is important for the dynamics of populations of these planktivorous fish, data rather than models will be used to represent the predation/consumption/ removal terms. Representation of the food supply will benefit from information on distribution and production of prey from the zooplankton component, but this will involve greatly simplified models as the rhomboidal overlay makes it clear that the goal is to limit the overall complexity of the required models. Here, coupling with the primary production, and zooplankton modelling rhomboid components has the potential to allow life cycle closure of targeted small pelagic species. (SPACC)

Demersal fish. The focus on demersal fish (Figure 16) will require life history models that range from egg and larval representations to simulations of the complex behaviours of adult fish. These fish are primarily centered on the continental shelves and with the work completed in the first two themes it should be possible to limit the model representations and simulations to the shelves. Because the targeted species, cod and haddock, occur on both the western and eastern sides of the Atlantic, there will be significant opportunities for collaborative work that spans the Atlantic. As with the focus in planktivorous fish, fishing will be an important component in the predation module.
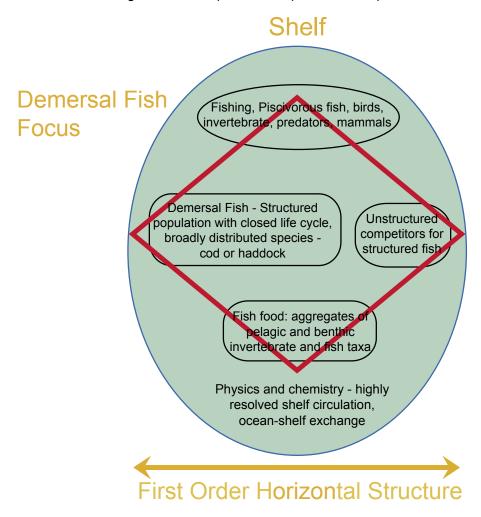

Figure 16. Schematic highlighting the structural components required for a basin-scale study focused on demersal fish. The arrow at the bottom indicates that, to first order, the primary scale of importance is the horizontal circulation, which advects populations around the basin. Note that fishing, a human impact, would be required to represent one important component of predation.

Existing capabilities

C.1 Phytoplankton/microbial food web (NPZD)

The vast majority of marine ecological models used in physical-biological modelling are concentration-based, where the flows of materials (usually carbon or nitrogen) among a network of compartments are simulated. There is a large diversity of model structures (number of compartments, patterns of interconnections, parameterizations of flows). Most of the models use the NPZD structure (for nutrient, phytoplankton, zooplankton and detritus), where the compartments P and Z at least represent bulk averages of diverse assemblages. These models are popular due to their relative simplicity and low computational burden in coupled physical-biological calculations. They are generally able to accurately simulate seasonal cycles of plankton variables in specific ocean areas. However, their generality across ocean basins and their ability to represent spatial and temporal variability are limited. In general, 3D simulations with NPZD models tend to produce much smoother fields of quantities like phytoplankton biomass than is observed from ocean colour for example.

This has lead to exploration of more complex structures where the P and Z compartments are split into separate boxes intended to represent more accurately the structure of the real ecosystem. A popular criterion for splitting boxes is organism size. Size is a reasonable predictor of many functional attributes of living organisms (e.g., metabolic activity) and of trophic interactions (generally size-dependent). Also size is considered a good indicator of the biogeochemical fate of plankton production, with small plankton production being largely recycled in the surface layer and larger plankton production being largely exported to depth. A size-boundary between recycled and exported production is difficult to establish, but phytoplankton less than 5 μm are generally lumped into a small phytoplankton (recycled) box and the phytoplankton larger than 5 μm are generally lumped into a large (exported) phytoplankton box. The 5 μm threshold is often considered the lower limit of phytoplankton food available to copepods so it is a useful threshold to keep in mind in the context of BASIN. Size-dependent models with multiple size classes have also been developed.

An alternative way to increase complexity in NPZD models is to identify functional groups that become separate boxes (e.g., Green Ocean Model - Dynamic Green Ocean Project, 2004). This functional division will vary depending on the goals of the model. For biogeochemical models, the emphasis is on phytoplankton groups that have contrasting roles in carbon and nutrient cycling (e.g. silica- vs. carbonate-shelled phytoplankton). The identification of functional groups might be different for trophic applications such as those envisaged here. This identification of functional groups is more advanced for the phytoplankton than the zooplankton (especially the microzooplankton) where functional roles are less well understood.

Although bulk NPZD-like approaches dominate modelling at the lowest trophic levels, Lagrangian and individual-based approaches comparable to the ones more widely applied for zooplankton and planktivores (see below) have also been developed. The general argument for their use is similar to that used to justify individual-based (IBM) approaches for the higher trophic levels, namely that modelling the interaction between a population average and the environment does not account for the nonlinear interactions between individual trajectories and their environment. These approaches have been used mainly to explore the interactions between vertical motions of phytoplankton cells and the vertical gradients in light, temperature and nutrients. However, they can be extended to include biogeochemical and trophic interactions in the plankton. Although the computational demands of these plankton IBMs do impose limitations in their applicability to regional and basin scales, they should be seriously considered because at the very least they can be used to parameterize bulk models, and the coupling with zooplankton and planktivore models.

C.2 Zooplankton

In contrast to phytoplankton, bacteria, and protozooplankton, unicellular organisms with short life-cycles (one to ten days), planktonic metazoans such as copepods or gelatinous zooplankton have longer (weeks to years), more complex life cycles, and diverse, species-specific physiological rates (e.g., ingestion, respiration, and excretion) and behaviors (e.g., ontogenetic and vertical migration, feeding). Therefore, a first-order task in quantitative description of metazoan zooplankton population dynamics is the description of stage or size structure at the species level, allowing more accurate portrayal of their life history and consequently of their seasonal dynamics and availability to higher trophic levels.

Copepod life history models have traditionally considered the demographic structure of the population using variables to describe the biomass in different weight categories (i.e., weight-based or WBMs) or the abundance in different life-stages (i.e. stage-based models, or SBM). In WBMs, the transfer between the different weight classes depends on the growth rates, which are usually modeled as bioenergetic formulations of ingestion, respiration, and egestion that can be complicated. Weights are usually related to stages through a prescribed classification based on observations. The variables in SBMs quantify stage abundances directly. The rate of change of the population size within a stage is typically based on empirical relations for development, using the reciprocal of stage durations for given temperature and food conditions.

There is an increasing trend towards modelling individual copepods as discrete entities, using a large number of individuals to represent the population. This approach is known as i-state configuration or more commonly in marine literature as individual-based modelling or IBM. IBMs keep track of a number of variables related to each individual (e.g., age, weight, stage, lipid content). Changes to these variables arise from the physiological responses to the environment (e.g. growth, development, reproduction), often described by formulations that are analogous with the WBMs and SBMs. However, since IBMs can keep track of an individual's history, these formulations can be adapted to account for individual variation in vital rates, such as that due to the length of time it has been starving While IBMs provide for representation of individual variability, they can be computationally taxing and may not be the approach of choice for representing linkage to higher trophic levels.

C.3 Planktivores

Larval fish and small pelagics are in many instances the main predators on mesozooplankton. However, there is increasing recognition of the important role of invertebrate predation. Large gelatinous plankton can play a critical role. There are indications that the main predators of zooplankton in the NE Pacific have sporadically switched from vertebrate predators to gelatinous zooplankton. There is also geographic variability in the relative roles of vertebrate and invertebrate predation (e.g. among Norwegian fjords). However, invertebrate predation, especially by gelatinous zooplankton, is poorly understood. Therefore, this remains a problem mostly for field and experimental observations. In what follows, we briefly look at modelling approaches for small pelagic and larval fish.

Because the spatial distributions of temperature, zooplankton, and other factors important to larval fish growth and survival are greatly influenced by the physics of water movement (i.e., hydrodynamic transport), coupling individual-based fish larvae to spatially-explicit NPZ and zooplankton life history models is a logical approach for simulating larval fish growth and survival. Fisheries scientists have often developed models of larval fish growth and survival that go into great detail on larval feeding behavior, while the zooplankton prey are treated as a forcing variable or that side-step the issues of fine-scale spatial variability by using implicit approaches such as statistical distributions that mimic encounter rates in patchy environments.

While not a necessity, the larval fish component of many coupled physical-biological models uses a Lagrangian approach that tracks individual larvae through space and time. A Lagrangian individual-based approach is useful in coupled bio-physical models because few larvae survive, and it is the history of experiences of the larvae and local interactions (between larvae and its prey and larvae and its predators) that can be important to determining the rare survivors. Accurately simulating individual experiences that vary among individuals and representing the effects of local interactions is difficult with other, more aggregated modelling approaches (e.g., matrix projection modelling), but is, at least conceptually, relatively straightforward to implement with an individual-based approach.

C.4 Generalized size spectra approaches

Organism size is used in models for each of the three ecosystem levels above to parameterize the variability in biological rates and to determine trophic interactions. We can also consider size spectra approaches that cross lines between the phytoplankton/microbial food web, zooplankton and planktivorous fish. Much of what follows is adapted from: http://silvert.home.sapo.pt/output/iclarm/

The role of size in determining how organisms are constructed and how they function has long been appreciated. The use of size-structured models to describe aquatic ecosystems originated with the empirical observation that the biomass spectrum, which is a plot of the biomass concentration of particles in logarithmically equal size ranges, is close to constant. Subsequent research has established a theoretical foundation for the use of size to model marine ecosystems.

One of the advantages of using size-structured models is that trophic interactions are largely determined by particle size. Pelagic predators generally eat particles that are one or two orders of magnitude smaller than themselves. Since the size classes used in the size-structured models cover a ten-fold range in Equivalent Spherical Diameter (ESD), predation is modeled by assuming that organisms in one size class eat those in the next two smaller size classes. For example, organisms in the 10-100 mm size range (identified as mostly small fish), feed on organisms in the range 0.1-10 mm ESD, corresponding to fish larvae and two size classes of zooplankton (Sheldon *et al*, 1972).

In a strictly size-structured model, each size class is connected to the two classes below it (as a predator) and to the two above it (as prey). In the more general extended size structure approach, a single size class may include more than one functional group, such as the 10-100 um range which covers both microzooplankton and algae. The result is a food web structure which in many ways resembles a food chain. Energy flows through this web from smaller to larger organisms.

There has been a renewal of interest recently in these approaches in the context of macroecology. (Lopez-Urrutia *et al*, 2006). The statistical patterns between biomass and size structure are being re-visited with new data from flow cytometry for example that extend the size range and depth of the analyses (San Martin *et al*, 2006). These patterns can then be used to parameterize some of the complexity within bulk-aggregated compartments in ecological models, analogous to parameterizations of subgrid scale processes used in physical models. Size-structured models and size-based parameterizations cannot explain all the diversity and variability inherent to marine ecosystem. Furthermore, they cannot be used to predict population dynamics of individual species with complex life histories. They should however be considered an essential tool in the BASIN programme to develop workable simplified representations of complex ecological dynamics.

Challenges

Within each ecosystem level discussed above, the challenge is to identify the minimum level of complexity that produces reasonable seasonal to interannual dynamics. The complexity of

ecological models has tended to follow the the expansion of our empirical understanding of marine eco-systems. One example is the realization of the importance of microbial components in pelagic ecosystems that has led to a tendency to expand plankton models from linear food chains to food webs with feedback loops. Although there is no doubt about the importance of microbial processes in sustaining productivity in the ocean, the level at which they need to be represented in plankton models is still a matter of debate. Resolution of these questions about appropriate model structure must depend on the questions asked and on the scales at which they are asked. Knowledge gained from one-dimensional seasonal studies at specific sites for example cannot necessarily be transferred to basin and decadal scales. Therefore, a BASIN modelling programme must include dedicated efforts at model identification at each of the three levels.

With respect to the species of interest to BASIN, modelling the life-history for all zooplankton species in a given ecosystem remains a challenge. One approach to the study of mesozooplankton population dynamics involves as a first step the identification of key species or functional groups. In temperate, subarctic, and polar pelagic environments, the major zooplankton contributors to the pelagic ecosystem and recruitment dynamics can be narrowed down to a relatively small list. A feature of a relatively small number of key species is that it is possible, through field and laboratory study, to acquire quantitative knowledge of the physiology and behavior of the targeted species. This understanding can be applied to the formulation of a biological model that is, in a sense, custom fit for that species in a given geographic region. The key species targeted in these systems belong mainly to the Copepoda and Euphausiacea, which are prominent in the zooplankton, both by their presence in plankton net tows and their ecological roles. The challenge for modelling zooplankton life cycles is therefore to quantitatively describe the change of population size and structure while accounting for environmental variability and transport.

APPENDIX D: Coupled Physical-Biological Models

D.1 Physics-NPZD

An NPZD model is usually coupled to a physical model as though it were a set of tracers being moved by the advection-diffusion equation. Each state variable of the NPZD model will have a separate equation describing its motion in space and time. Typically the physical motion terms are obtained from a physical model run simultaneously with the biological dynamics. These models range from simple one-dimensional (1D) models with biological dynamics averaged over the mixed layer, to full 3D models with high-order turbulence-closure submodels.

D.2 Physics-Zooplankton

There are two basic approaches to coupling copepod life history models with circulation models. The first uses an Eulerian framework, akin to spatially-explicit NPZ models, which consider copepod population densities as concentrations. The biology and circulation are thus coupled using an advection-diffusion-reaction equation, which describes the local rate of change of population abundance affected by biological rates, currents, and turbulence. Vital rates may be dependent on local food conditions and temperature derived from the circulation models, and behavioral movement can be included through a behavioral advection and/or diffusion term.

While the coupling with circulation models is straightforward, the advection-diffusion-reaction equation that solves for copepod abundance is subject to the same kinds of numerical issues as can arise in circulation models (e.g. negative concentrations in advection-dominated flows). The transport/mixing routine in these models is presently costly computationally, so that the number of stage, age, or weight classes may be a strong limitation. A promising approach to speed up the calculations is to use an age-structured matrix model of population dynamics in an Eulerian framework. This approach permits the use of a complex weight or age structured matrix for the biological part of the model, which have been shown to clearly resolve the copepod demography and dynamics, but requires specific preprocessing of the physics, i.e., defining the mixing and transport matrix operator. In this approach, the mixing or transport matrix operator is defined from multiple particle trackings with surface velocity fields from a 3D circulation model. Currently, this approach is limited to 2D (horizontal) grids.

The second approach uses a Lagrangian framework (i.e. particle tracking) wherein particular particles are followed as they move to different locations. Each particle can represent a cohort with the same history (e.g. ensemble approach or population sub-sampling), or it can represent an individual copepod. Trajectories for a number of particles are simulated by considering the displacement due to local currents and turbulence, the physiological history of the individual or cohort is computed as the particle moves through the environment. With an IBM, the particle can also be given behavior specific to its unique state.

The simulation of numerous trajectories, usually 10^3-10^5 particles, needed to gain insight into the population dynamics is computationally demanding. Hence, while the Lagrangian approach may perform well for qualitative study, its applicability to quantitative estimation of transport, exchange between sub-population and simulations over long time periods may be limited by the cost of analysis, although this situation continues to improve with advances in technology. Lagrangian water column models use a derived approach that follows the development of a cohort in a water mass that is assumed to be isolated. In these models, time series of physical conditions (turbulent mixing, temperature) prevailing in the water column are extracted from a drift scenario and are used to drive the copepod life history model. This approach allows the use of complex physiological models of copepods life history (as age or weight structured models) and trophic coupling with primary producers. However, the assumption of an isolated water column transported as a whole

is only valid perhaps for the upper layer of the ocean (0-100 m). Vertically sheared circulation that prevails for example in the North Atlantic or on coastal shelves, in conjunction with the range of possible diel and ontogenetic vertical distributions of copepods like *C. finmarchicus*, restricts their applicability.

Since each approach has its own advantages and disadvantages, it is better to consider them as complementary. Local process studies may need good resolution of individual growth and population demography for which the IBM approach can be applied. For larger scale studies, seasonal evolution of stage abundance described with a simpler stage-based model coupled with realistic circulation patterns can capture within the right order of magnitude the effect of advection on regional population dynamics of a target species. A computationally efficient matrix-operator approach may be preferred at basin scales. Basin scale modelling studies may require a nesting approach between different local, regional, and basin scale approaches.

D.3 Physics-planktivores

In its simplest form, the coupling is achieved through the advection of passive and/or behaviorally active larvae to determine retention, transport pathways, etc., through the use of spatially-explicit IBMs. Taking advantage of the advent of sophisticated and robust circulation models that capture realism on relevant spatial and temporal scales, perhaps the best established use of IBMs focuses on determining Lagrangian trajectories of planktonic stages of marine organisms in realistic flow fields. The simplest of these studies ignore biotic factors such as feeding and predation; but include imposed swimming behaviors, spawning locations, etc. (e.g. Grimm and Railsback 2005).

APPENDIX E: Challenges in Coupling Physical-Biological Models

There are three general issues that arise when coupling different trophic level models with physics and with each other: reconciling temporal and spatial scales between these heterogeneous models, determining how to include the effects of the lower trophic levels on the higher and vice-versa (i.e., feedbacks), and determining how to represent behavior-related movement of the zooplankton and planktivores and top predators in a spatially explicit setting. These issues are explored in the context of the different interfaces between physics and the trophic level models and between the trophic levels that are relevant to BASIN.

E.1 Physics-NPZD

Coupling continuous variables like those in a NPZD model to a circulation model is relatively straightforward and is now widely done. There are numerical issues that arise because biological variables typically develop stronger horizontal and vertical gradients than physical variables, which cause problems with artificial diffusion. Significant progress has been made on this problem with the development of advanced transport schemes. The major challenge is actually matching the priorities of the circulation modelers with those of the ecological modelers. For example, circulation modelers often focus on meso- to large scale horizontal advective features. Tuning the circulation models to represent those features accurately can lead to distortions in the representation of vertical structure. The latter is critical for the proper operation of NPZD models that rely on a correct representation of vertical gradients of forcing terms such as nutrients. A programme such as BASIN will need to ensure coordination in the design, tuning (e.g., data assimilation), and operation of circulation and NPZD models.

E.2 Physics-Zooplankton

Many zooplankton, including copepods are not just drifters, but active vertical migrators as well. These migrations operate on diel and seasonal time scales, can be stage-specific, and can range from several meters to several hundred meters in vertical extent. Such vertical movements are one order of magnitude higher than typical vertical velocity fluctuations in the ocean, but one order of magnitude less than typical horizontal velocities. Hence, copepods may be free of vertical advection or turbulent mixing, but are always subject to transport by horizontal currents prevailing at their resident depth. This poses major challenges in representing their dynamics in 3D circulation models. Only in special cases of shallow vertically homogeneous water such as the littoral zone, can the interactions between swimming behavior and circulation be (sometimes) neglected.

In temperate and polar regions, the life-cycle of some planktonic copepods includes a diapause phase: a quiescent period, generally in winter, during which the animals wait (at depth) for favorable conditions for reproduction and growth, which usually follow the development of the spring phytoplankton bloom or the suppression of winter convective mixing (Backhaus *et al* 2003). The match between the timing of arousal from diapause and the seasonal variation of environmental conditions for these species, mainly temperature light and food abundance, may crucially influence interannual variation in their population dynamics. The coupling of the diapause response with seasonal variations in circulation can be another important factor controlling interannual variability of population abundance over large areas (Speirs *et al.*, 2004, 2005).

While the physiological responses to diapause are reasonably well known, there is much less understanding of the environmental or physiological cues that induce entry into diapause or the processes that control emergence from diapause. In existing models, diapause is generally ignored or parameterized simply. Diapause can be neglected in seasonal models that address processes during the active period. In other cases, diapause is generally prescribed through imposed probabilities of ascent and descent based on empirical observations of life cycle timing. Others have used prescribed temperature and food conditions or lipid allocation criteria. Recently, more

sophisticated, empirically based models or genetic algorithms for timing of entry into and exit from diapause are promising for application in the coupled models. Results presented at the BASIN workshop indicated that only cueing diapause cycles to photoperiod allowed simulations of copepod distribution at basin scales that resembled observations. However, the biological mechanisms behind many of these cues used in models remain unclear. Both field observations of the timing of entry and emergence from diapause and new experimental studies are needed in order to deterministically formulate diapause in models of population dynamics.

The challenge therefore is to build both the observational data base and the fundamental biological understanding of control of stage-specific diel vertical migration and seasonal migrations of target species in order to adequately represent vertical distribution in spatially explicit models. Coupled 3D modelling can be used to identify areas in which the interaction between circulation and vertical distribution are especially critical, which can then contribute to the design of field studies.

E.3 Physics-planktivores

Fish larvae and of course small pelagics exhibit active movement not related to advection. Active movement can be critical because such movement can greatly affect the transport, environmental conditions, and prey experienced by the individual larvae. Modelling active movement by fish remains a difficult area. For example, we do not really know why larval fish move, especially on the scale of minutes to hours and over relatively short distances (e.g., meters). Externally imposed (and/or passive) behaviors may not make sense as the coupled biophysical models move more and more towards simulating the growth and survival of the larvae. Such static approaches to movement will be likely replaced by model-derived behaviors that include components maximizing some biological characteristic, such as reproductive value, survival to maturity, or short-term tradeoffs between growth and mortality. Dynamic programming methods allow organisms to "find" optimal habitats by balancing risks of predation, growth, and advective loss. The issue of how to represent active movement on fine scales is important, but remains unresolved at this time. The realism of predicted growth and mortality from coupled bio-physical models that must include active movement of larvae and small pelagics may very well rely on how well we can model fish movement and the behavior of their predators.

E.4 NPZD-Zooplankton

Most work in this area has focused on the bottom-up flows from the NPZD to the zooplankton model. It is tempting to conclude that NPZD models are sufficiently advanced to the point of providing spatial and temporal distributions of food supply for application in higher trophic-level models. However, while relationships of growth and reproduction to bulk estimates of food concentration seem to work for some species in some regions, there are also many examples where such relationships do not hold There is need for more work determining the relationships between phytoplankton and zooplankton growth and reproduction in key zooplankton taxa. For species and regions where relatively simple functional relationships do not work or are insufficient to capture variability in growth and reproduction, continuing investigations of the relationship between food and zooplankton vital rates are required. In some cases phytoplankton is not a proxy for food for key zooplankton species – for example, the carnivorous euphausiid, Meganyctiphanes norvegica – in which case a relationship is not expected In other cases, food type, chemical composition (food quality), and size distribution, and the spatial/temporal distribution of food are important sources of variability in functional relationships with food concentration. These are fundamental issues for modelling studies of inter-annual or inter-decadal variability at basin scale.

Spatial and temporal scaling issues must also be considered in coupling NPZD models to higher trophic levels. All models of plankton dynamics produce results that are averaged both spatially

and temporally. The degree of averaging usually depends on the questions being asked and the computer power available. Typically, models average temporally over a day, and/or spatially over the mixed layer. A vertical spatial averaging reduces out-of-phase oscillations in vertically adjacent layers that could generate unrealistically strong (and evanescent) gradients of properties in the euphotic zone. However, such averaging removes any ability of the model to reproduce vertical variations of food for higher trophic levels, including the deep chlorophyll maximum. Just as in coupling physics to NPZD, the issue of the vertical scales that need to be resolved for accurate simulations needs attention.

Equally important is the problem of defining the flows from the zooplankton to the NPZD level. NPZD models are typically closed by simplified schemes, such as applying linear or quadratic mortality terms to the P and Z boxes. These schemes are generally selected on the basis of their impact on the stability of the NPZD model simulations, not their ecological realism. A common view is that the bulk of the grazing on phytoplankton is done by the microzooplankton so that the potential feedback of larger zooplankton on phytoplankton would be small. However, it is not clear that this is applicable in all marine systems, especially temperate to subarctic ecosystems where phytoplankton are at times dominated by large cells and where the mesozooplankton biomass can be substantially higher than that of the microzooplankton. Also, this does not address the issue of the zooplankton impact on microzooplankton. The trophic feedbacks from zooplankton to the NPZD level will be a strong focus of investigation in BASIN.

E.5 Zooplankton-planktivores

Environmental effects on planktivores are generally approached implicitly through relationships with temperature. Population size distribution can be modeled as a function of trajectories through variable temperature fields, where growth is based on a Q10 relationship. Temperature (resulting from a circulation model) can also be used as a proxy for the feeding environment. For haddock for example, it was found that the model-derived spawning locations resulting in the highest larval growth rates (as the larvae are advected in the model domain) coincided with the observed preferred spawning locations. This "fish eat temperature" approach is convenient, but may have only local applicability because of geographical and species-specific differences in the linkages between temperature and food availability or the individuals' ability to modify vital rates via changes in enzyme concentration.

The next level of complexity is to impose spatially-dependent (but temporally fixed) prey distribution based on field observations. The linkage of prey abundance to growth is achieved through bioenergetic modelling that relates the new weight of a larva to its previous weight plus gains and minus losses. Such studies are a first step to introducing realistic representations of the spatial distribution of key variables such as temperature, oxygen, light levels, prey availability, etc. Similar approaches, but based on model-derived spatial structure of prey and habitat have been applied recently. A natural extension is the computation of individual Lagrangian trajectories within the prey field. This requires models to capture not just the spatial distribution of biotic components, but also their modulation by certain abiotic environmental factors. Some form of dynamic bottom-up coupling would be required for successful hindcasts and forecasts of ecosystem conditions, but much more research in that area is required.

The time step and spatial resolution of the physical model are dictated (or limited) by numerical considerations, which may not coincide with the ideal time step and spatial resolution for simulating growth and survival of fish larvae. Simulating purely advective and dispersive transport of passive particles is in a relatively advanced state of development. Scaling issues arise when the particles have behaviors, especially when simulated growth and mortality are dependent on dynamic prey and predators. The generally fine-scale of the physical models would involve simulating fish larval behavior on the scale of minutes at the spatial resolution of the hydrodynamics. Larval fish

ecologists are often more comfortable simulating larval dynamics on scale of hours to days, and therefore also at a coarser spatial resolution that matches the longer time step. Output from the hydrodynamics and lower trophic models are often aggregated to some extent to permit coarser simulation of the larval dynamics. How to aggregate the output without losing dynamically-relevant variability is an important consideration.

Including the effects of the larval fish on the lower trophic levels (consumption of zooplankton and addition of nutrients via excretion and egestion) can additionally complicate the modelling. Most coupled biophysical models use the hydrodynamics and lower trophic level predictions as input to the larval fish component. This enables the lower trophic level models to be solved independently of the larval fish dynamics. However, a separate solution of the lower trophic and larval fish models prevents any density-dependent effects from operating. Perhaps under most average conditions, the effects of larval fish on their prey and on nutrients are small enough to be ignored. But it may very well be that the rare set of conditions when such feedback effects are important is of most use to those interested in fish recruitment. Density-dependent effects may be elusive as they may operate only under certain conditions (e.g., years of high egg production and low food production), but such effects are not possible to predict (or dismiss) if the coupled biophysical model does not include the capability to include these feedbacks. Yet, including these feedbacks would require that the lower trophic level component and the larval fish component models be solved simultaneously. For some situations, this can create computational limitations on the analyses and heartache for the programmer. Linking larval fish models where full hydrodynamics and fully evolving population dynamics co-occur will likely be attempted in the next five years and would be an important focus for research within a BASIN programme.

APPENDIX F: Data Assimilative Models

(Taken from "Strategies for Synthesis in U.S. GLOBEC", U.S. GLOBEC Report, in preparation).

Coupled physical-biological models offer a framework for dissection of the manifold contributions to structure in population distributions. However, their utility is predicated on an ability to construct a simulation that is representative of the natural system. One technique for doing so (the "forward" problem) is to initialize a coupled model with a set of observations, integrate forward in time, and then compare with the next set of observations. A successful outcome results in minor discrepancies between observations and predictions, and the model solutions thus can be used as a basis for diagnosis of the processes controlling the observed patterns. Unfortunately, satisfactory completion of the forward problem is not always achievable, owing to limitations in the models, in the observations, or in both. Inverse methods provide an alternative approach that is particularly useful in such cases. These techniques can be used to determine the model inputs (e.g. parameters, forcing functions) that minimize the misfit between observations and predictions, thereby producing an optimal solution from which the underlying dynamics can be gleaned. At the heart of this problem lies the topic of data assimilation, which is the systematic use of data to constrain a mathematical model (Hofmann and Friedrichs, 2001).

Data assimilation was first used in the 1960s in numerical weather forecast models, with the goal of providing short-term predictions of meteorological conditions. The use of data assimilation techniques was made feasible by the development of a world-wide atmospheric data network that could provide the needed measurements. Data assimilation provided a methodology to use these observations to improve the forecast skill of operational models, which has led to important societal benefits. Such systems have also proven to be useful for scientific purposes, insofar as their hindcast products (so-called "re-analysis") provide realistic four-dimensional fields on which process studies can be based.

In the 1970s numerical ocean general circulation models (OGCMs) became an important tool for understanding ocean circulation processes (Hofmann and Friedrichs, 2001). Initial applications of these models focused on simulation of the large-scale structure of ocean currents. From these simulations, the limitations of the OGCMs were clear. Data assimilation was looked to as an approach for constraining these dynamical models with available data (Bennett, 1992; Wunsch, 1996). For example, data assimilation could be used to quantitatively and systematically test and improve poorly known sub-grid scale parameterizations and boundary conditions. With recent advances in data availability it is also now feasible to use data assimilative OGCMs for global ocean state estimation, as is being done for the WOCE era (Stammer *et al*. 2002). Rapid improvements in coastal ocean models and observational infrastructure have led to realistic data assimilative models in the coastal ocean as well (Brink and Robinson, 1998; Robinson and Brink, 1998).

Implementing data assimilation in coupled physical-biological models has been problematic because of the paucity of adequate data (Hofmann and Friedrichs, 2001). Historically, biological and chemical data were obtained almost exclusively by ship surveys, and thus were extremely limited in both space and time. However, recent advances in satellite and mooring instrumentation, as well as in the understanding of the structure and function of marine ecosystems, now makes it feasible to begin the development of data assimilative coupled physical-biological models. As a result, the last fifteen years has seen a dramatic increase in the types of data that are input into such models, and the development of robust and varied approaches for assimilating these data (e.g. Ishizaka, 1990; Matear and Holloway, 1995; McGillicuddy and Bucklin, 2002; Natvik and Evensen, 2003).

Initial results are encouraging and data assimilation approaches, such as adjoint methods, show promise for improving the capability of these models (Hofmann and Friedrichs, 2001). For instance, assimilation of biogeochemical data can reduce model-data misfit by recovering optimal parameter sets using multiple types of data (Lawson *et al*. 1996; Friedrichs, 2002). Perhaps even more

importantly, these data assimilation analyses can demonstrate whether or not a given model structure is consistent with a specific set of observations. When model and data are shown to be consistent, the specific mechanisms underlying observed patterns in simulated distributions can be identified. A recent example of such an approach applied to the population dynamics of *C. finmarchicus* using GLOBEC data from Georges Bank is described in Li *et al*. 2006. On the other hand, if a model is determined to be inconsistent with observations, it may be possible to isolate the specific model assumption that has been violated, and to reformulate the model in a more realistic fashion. Thus, although the assimilation of data into a model cannot necessarily overcome inappropriate model dynamics and structure, it can serve to guide model reformulation.

In the past decade, large interdisciplinary oceanographic programmes (including GLOBEC) have included model prediction and forecast as specific research objectives (Hofmann and Friedrichs, 2001). However, it is clear that much more work needs to be performed before this becomes a realistic and achievable goal. Until high resolution biological and chemical data are available over large regions of the ocean, and until a better understanding of the dynamics of marine systems is attained, data assimilation in coupled physical-biological models will be likely to be used more for model improvement and parameter estimation than for operational prediction. A necessary precursor to the latter is the quantitative demonstration of forecast skill in specific applications, which is the subject of the following section.

APPENDIX G: Participants at the Reykjavik BASIN workshop

List of Attendees

Name	Affiliation	Email
Allen, Icarus	Plymouth Marine Laboratory	jia@pml.ac.uk
Allison, Dicky	WHOI	dallison@whoi.edu
Astthorsson, Olafur	Marine Research Institute, Iceland	osa@hafro.is
Beardsley, Bob	WHOI	rbeardsley@whoi.edu
Béaugrand, Gregory	Univ. des Sciences et Technologies de Lille	Gregory.Beaugrand@univ-lille1.fr
Buckley, Larry	Univ. RI NOAA CMER	lbuckley@gsosun1.gso.uri.edu
Bucklin, Ann	Univ. New Hampshire	ann.bucklin@unh.edu
Davis, Cabell	WHOI	cdavis@whoi.edu
Drinkwater, Ken	Institute of Marine Research, Bergen	kendrink@imr.no
Fogarty, Mike	NMFS	fogarty@usglobec.org
Gernez, Caroline	EUR-OCEANS, France	Caroline.Gernez@univ-brest.fr
Gislason, Astthor	Marine Research Institute, Iceland	astthor@hafro.is
Haidvogel, Dale	Rutgers Univ.	dale@imcs.rutgers.edu
Harris, Roger	Plymouth Marine Laboratory	rph@pml.ac.uk
Head, Erica	Bedford Institute of Oceanography	heade@mar.dfo-mpo.gc.ca
Heath, Michael	Marine Laboratory, Aberdeen	heathmr@marlab.ac.uk
Hurrell, James	NCAR/Climate & Global Dynamics Div.	jhurrell@ucar.edu
Irigoien, Xabier	AZTI	xirigoien@pas.azti.es
Jonsson, Steingrimur	University of Akureyri, Iceland	steing@unak.is
Köster, Fritz	Danish Inst. for Fisheries Research	fwk@dfu.min.dk
Lopez-Urrutia, Angel	Centro Oceanografico de Gijon	alop@gi.ieo.es
Lough, Greg	NMFS	Gregory.Lough@noaa.gov
McGillicuddy, Dennis	WHOI	dmcgillicuddy@whoi.edu
Misund, Ole	Inst. of Marine Research, Bergen	ole.arve.misund@imr.no
Mountain, David	NMFS	David.Mountain@noaa.gov
O'Brien, Todd	NOAA-NMFS	todd.obrien@noaa.gov
Pepin, Pierre	Department of Fisheries & Oceans, Canada	PepinP@dfo-mpo.gc.ca
Planque, Benjamin	IFREMER	Benjamin.Planque@ifremer.fr
Reverdin, Gilles	LEGOS	Gilles.Reverdin@lodyc.jussieu.fr
Runge, Jeff	Gulf of Maine Research Institute	jrunge@gmri.org
Speirs, Dougie	Strathclyde University	dougie@stams.strath.ac.uk
St. John, Michael	Univ. of Hamburg	michael.st.john@uni-hamburg.de
Sundby, Svein	Institute of Marine Research, Bergen	svein.sundby@imr.no
Tande, Kurt	University of Tromso	kurtt@nfh.uit.no
Thingstad, Frede	University of Bergen	Frede.Thingstad@im.uib.no
Treguer, Paul	EURO-CEANS, France	Paul.Treguer@univ-brest.fr
Valdimarrson, Hedinn	Marine Research Institute, Iceland	hv@hafro.is
Vézina, Alain	Bedford Institute of Oceanography	vezinaa@dfo-mpo.gc.ca
Werner, Cisco	University of North Carolina	cisco@marine.unc.edu
Wiebe, Peter	WHOI	pwiebe@whoi.edu
deYoung, Brad	Memorial Univ. of Newfoundland	bdeyoung@physics.mun.ca

Abbreviations:
AZTI = AZTI technalia
IFREMER = Institut francais de recherche pour l'exploitation de la mer
LEGOS = Laboratoire d'Etudes en Geophysique et Oceanographie Spatiales
NCAR = National Center for Atmospheric Research, U.S.A
NMFS = National Marine Fisheries Service, U.S.A.
NOAA = National Oceanic and Atmospheric Association, U.S.A.
WHOI = Woods Hole Oceanographic Institution