Arctic–Subarctic Ocean Fluxes

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Defining the Role of the Northern Seas in Climate

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Foreword

The Ocean-Atmosphere-Cryosphere system of the Arctic is of unique importance to the World, its climate and its peoples and is changing rapidly; it is no accident that the Arctic Climate Impact Assessment (ACIA) was the first comprehensive regional assessment of climate-impact to be conducted. Reporting in 2005, ACIA concluded that changes in climate and in ozone and UV radiation levels were likely to affect every aspect of life in the Arctic. In effect, the ACIA process was essentially one of prediction: projecting that large climatic changes are likely to occur over the 21st century and documenting what might be their projected impacts.

Although the ACIA Report was based on the most modern synthesis of observations, modelling and analysis by hundreds of Arctic scientists, it notes with clarity that its conclusions are only a first step in what must be a continuing process. Reporting in November 2007, the 2nd International Conference on Arctic Research Planning (ICARP II) has recently made much the same point. To make its projections with higher confidence, --- to take the crucial second step in other words, ---- both reports plainly state the need for a more complete and detailed understanding of the complex processes, interactions, and feedbacks that drive and underlie ‘change’ at high northern latitudes, including particularly the long-term processes of circulation and exchange in our northern seas where much of the decadal ‘memory’ for Arctic change must reside.

In this volume, assembled for the first time, we find a detailed description of much of what we believe is essential to take that crucial second step. Here, for example, are described the controls, ‘near and remote, short-term as well as long-term’ that have been involved in providing the polar basin in recent years with a steady supply of increasingly warmer water through subarctic seas. We find, more-over, a detailed description of the interplay between the storage and release of freshwater from the Central Arctic and its likely impact on the ‘workings’ of the Ocean’s thermohaline ‘conveyor’. And throughout the book, we are given a modern account of how well we can simulate the important elements of Arctic-subarctic exchange ---– in some cases very well indeed.

In the future there will, of course, be new stages of understanding and observations, better models and perhaps even a different set of ‘driving questions’ before society eventually learns to project, adapt and respond to Arctic change. This volume spells out what we now perceive are the driving questions to be addressed if we are to move our skills in prediction to a higher level.

The release of this publication coincides with the [4th] International Polar Year, a comprehensive, international effort in polar science and climate change. As the global scientific community conducts its latest polar study, the reader should be assured that the benchmarks this volume represents are a necessary and a considerable step towards understanding the critical role that the Arctic and subarctic seas play in the global climate system and hence, their importance to humanity everywhere.

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Arctic–Subarctic Ocean Fluxes: Defining the Role of the Northern Seas in Climate

A General Introduction

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1 Background

Almost 100 years ago, Helland-Hansen and Nansen (1909) produced the first complete description of the pattern of oceanic exchanges that connect the North Atlantic with the Arctic Ocean through subarctic seas. At a stroke, they placed the science of the Nordic seas on an astonishingly modern footing; as Blindheim and Østerhus (2005) put it, *'Their work described the sea in such detail and to such precision that investigations during succeeding years could add little to their findings'*. Nonetheless, in the century that followed, oceanographers have gradually persisted in the two tasks that were largely inaccessible to the early pioneers – quantifying the exchanges of heat, salt and mass through subarctic seas and, piecing-together evidence for the longer-term (decade to century) variability of the system.

Evidence of variability was not long in coming. As hydrographic time series lengthened into the middle decades of the 20th century, they began to capture evidence of one of the largest and most widespread regime shifts that has ever affected our waters. For these were the decades of "the warming in the north", when the salinity of North Atlantic Water passing through the Faroe–Shetland Channel reached a century-long high (Dooley et al. 1984), when salinities were so high off Cape Farewell that they were thrown out as erroneous (Harvey 1962), when a precipitous warming of more than 2 °C in the 5-year mean pervaded the West Greenland banks, and when the northward dislocations of biogeographical boundaries for a wide range of species from plankton to commercially important fish, terrestrial mammals and birds were at their most extreme in the 20th century (reviewed in Dickson 2002).

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Measuring the ocean fluxes through these waters proved harder, and indeed we are still not quite able to tackle all of them. Recording current meters were not available till the 1960s, and when Worthington (1969) first attempted to capture the violence of overflow through the sill of the Denmark Strait (1967), his moorings were almost all swept away; it was another decade (1975–1976) before year-long records of overflow were successfully recovered from the Greenland–Scotland Ridge by the ICES MONA Project (Monitoring the Overflow in the North Atlantic). The flows through the Canadian Arctic Archipelago (CAA) proved even harder to capture. Understandably so; it is one of the hardest observational tasks in oceanography to measure vigorous flows in a remote complex of narrow passageways with strong seasonal variability in ice-covered seas where the scales of motion are small, where moving ice and icebergs pose a hazard to moored gear and where even the direction of flow is obscured by the proximity of the Earth's magnetic pole. Yet moorings have been maintained in Lancaster Sound since 1998 and in the other five main channels of the CAA since then. Nowadays, making direct flow measurements on the ice-covered subarctic shelves in the presence of heavy fishing activity and grounding bergs remains the last and greatest challenge; though successes have been achieved, it will probably take the development of sub-ice Seagliders to make these shelves routinely accessible to measurement.

The perceived stimulus to making these measurements has also changed with time. Initially, the primary impetus to measuring change, in the European subarctic seas at any rate, was as an aid to understanding the ecosystem, including especially the fluctuations in the great commercial fish stocks. In 1909, Helland-Hansen and Nansen had been concerned with applying what they knew of environmental change to the fluctuating success of the Arcto-Norwegian cod stock. And even in wartime, under the Presidency of Johan Hjort (1938–1948), Martin Knudsen's ICES Sub-committee on Hydrographical and Biological Investigations continued to plan the data collection that would be needed to meet Hjort's aim of fish stock prediction. We retain that legacy today in the small scattering of ultra-long (100-year plus) hydrographic time-series that afford us a glimpse of decade-to-century variation in the hydrography of our northern seas.

Later in the 20th century, it would be fair to say that the primary stimulus for these investigations diversified from this focus on the success of fish stocks to include the ocean's role in climate. Two studies in particular took on the task. Between 1990 and 2002, the WCRP World Ocean Circulation Experiment (WOCE) – the most ambitious oceanographic experiment ever undertaken – circled the globe with the twin aims of establishing the role of the oceans in the Earth's climate and of obtaining a baseline dataset against which future change could be assessed. About 30 nations participated in the observational phase of the programme (from 1990 to 1998) and sophisticated numerical ocean models were developed both to provide a framework for the interpretation of the observations and for the prediction of the future ocean state. The key WOCE scientific goal was thus to develop models useful for predicting climate change and to collect the data necessary to test them.

Overlapping the period of the WOCE Experiment, a second WCRP initiative focused on the more regional study of the high Arctic and its role in global climate. Between 1993 and 2003, the Arctic Climate System Study (ACSYS) attempted to answer two questions in particular: What are the global consequences of natural or human-induced change in the Arctic climate system? Is the Arctic climate system as sensitive to increased greenhouse gas concentrations as climate models suggest? To address these, the twin aims of ACSYS were to understand the interactions between the Arctic Ocean circulation, ice cover, the atmosphere and the hydrological cycle, and to provide a scientific basis for an accurate representation of Arctic processes in global climate models.

2 The Role of the Subarctic Seas in Climate

Despite their global scope, the WOCE and ACSYS initiatives fell short of complete coverage in one important respect. In the Atlantic sector, the measurement programme of WOCE did not extend north of the Greenland–Scotland Ridge, while the ACSYS coverage of the high-latitude ocean was focused north of Fram Strait. The subarctic seas were largely excluded from consideration. Yet we would nowadays strongly assert that the two-way oceanic exchanges that connect the Arctic and Atlantic oceans through subarctic seas are of fundamental importance to climate (and thus to the aims of WOCE and ACSYS). Change may certainly be imposed on the Arctic Ocean from subarctic seas, including a changing poleward ocean heat flux that is central to determining the present state and future fate of the perennial sea-ice. And the signal of Arctic change is expected to have its major climatic impact by reaching south through subarctic seas, either side of Greenland, to modulate the Atlantic thermohaline ‘conveyor’.

The global thermohaline circulation (THC), driven by fluxes of heat and freshwater at the ocean surface, is an important mechanism for the global redistribution of heat and salt and is known to be intimately involved in the major changes in Earth climate; thus, a partial shutdown of this worldwide overturning cell appears to have accompanied each abrupt shift of the ocean–atmosphere system towards glaciation (e.g. Broecker and Denton 1989). In turn, the overflow and descent of cold, dense water from the sills of the Denmark Strait and the Faroe–Shetland Channel into the North Atlantic forms a key component of the THC, ventilating and renewing the deep oceans and driving the abyssal limb of this great ‘overturning cell’.

Most computer simulations of the ocean system in a climate with increased greenhouse-gas concentrations predict a weakening thermohaline circulation in the North Atlantic as the subpolar seas become fresher and warmer. A representative set of milestones for this prediction might run from the pioneering modelling work of Bryan (1986) and Manabe and Stouffer (1988) through the intermediate complexity of Rahmstorf and Ganopolski (1999), Delworth and Dixon (2000) and Rahmstorf (2003) to the full complexity of earth system modelling by Mikolajewicz et al. (2007). Despite such major advances in simulating the system, we remain undecided on many of the most basic issues that link change in our northern seas to climate, for both observational and modelling reasons. Put simply, uncertainties in our observations are bound to delay the development of our climate models and hinder their critical evaluation.

3 The Development of ASOF

Recognising the importance of Arctic–subarctic exchanges as the source or as the conduit of change in both the high Arctic and in the global ocean, two major collaborative studies in particular set out to meet the deficiencies in our observational coverage throughout the subarctic seas. A first *regional* programme covering all significant ocean fluxes through the Nordic Seas in the EC-VEINS Study (Variability of Exchanges in Northern Seas) of 1997–2000 quickly developed into the full multinational *pan-Arctic* ASOF study (Arctic–Subarctic Ocean Fluxes) from 2000 to the present. The primary scientific objective remained the same – *to measure and model the variability of fluxes between the Arctic Ocean and the Atlantic Ocean with a view to implementing a longer-term system of critical measurements needed to understand the high-latitude ocean's steering role in decadal climate variability*.

Thus, from the outset, it was seen that ASOF had necessarily to be a pan-Arctic exercise if it was to describe the balances of flow entering and leaving the Arctic Ocean through subarctic seas, and that it should involve continuing iteration between the technicalities of observations and the demands of climate models. Since it was already apparent that change was spreading through the subarctic–Arctic system on a timescale of decades (e.g. Morison et al. 2000), it was also clear that our observations of that system had to be of decadal 'stamina' and had if possible to be simultaneous, to the extent permitted by funding. To measure such a system *successively* by moving our focus and our resources from place to place would be to risk confusing spatial changes with temporal ones.

The full pan-Arctic ASOF programme was achieved by instituting task-based planning across the full ASOF domain according to 6 regional task-groups, supported by a 7th system-wide Numerical Experimentation Group (see Fig. 1).

In late June 2006, approximately 10 years after the start of VEINS, the ASOF community met in Thorshaven, Faroe Islands, with two main objectives: *first, to describe progress in quantifying, by both observations and modelling, the two-way exchanges of heat, salt and mass that take place between the Arctic and Atlantic Oceans through subarctic seas*. Within this primary objective were included all aspects of Arctic–subarctic ocean fluxes that seem of importance to the development of our global climate models – the forcing of these oceanic exchanges, their variability at all scales accessible to us, and the interconnected nature of both forcing and variability in space and time. Having assessed progress, our *second*

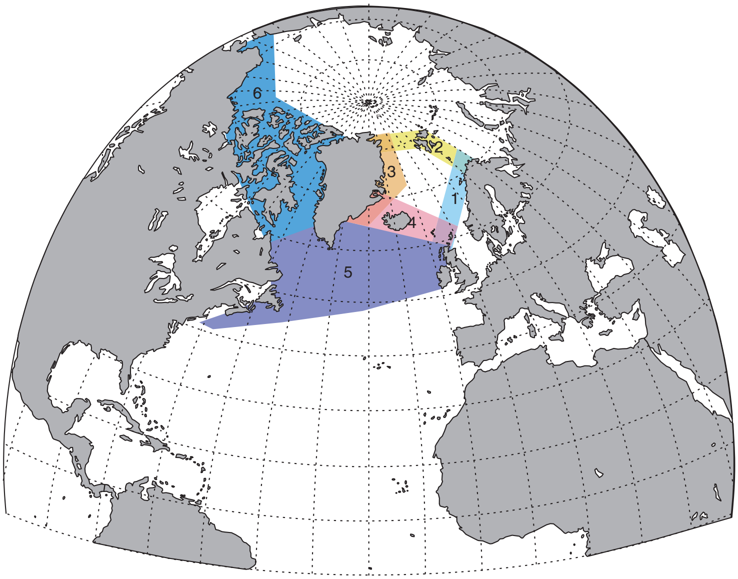

Fig. 1 The full domain of the international ASOF study, showing the distribution of its six regional task-related Working Groups. 1 = warm water inflow to Nordic Seas; 2 = exchanges with the Arctic Ocean; 3 = ice and freshwater outflow; 4 = Greenland–Scotland Ridge exchanges; 5 = Overflows to Deep Western Boundary Current; 6 = Canadian Arctic Archipelago throughflow. A 7th Numerical Experimentation Group covers the whole domain

objective was to redefine the remaining cutting-edge questions regarding the role of the northern seas in climate as the World embarked on its 4th International Polar Year (April 2007–April 2009).

These two objectives are also what have motivated the present volume though here, we have widened our authorship beyond the membership of the ASOF Task Teams in order to provide the fullest possible account of recent achievements in observing and modelling those aspects of our northern seas that seem to have an actual or potential importance to climate. The sub-title of the volume – *Defining the role of the Northern Seas in Climate* – is thus carefully chosen. The volume does not in itself aim to assess the full complexity of that role, and indeed it may well be some time before our observations and our models are capable of doing that, to the point of anticipating future changes in the system. Instead the volume intends to assemble the body of evidence that climate models will need if they are one day to make that assessment, quantifying the ocean exchanges through subarctic seas, describing their importance to climate as we currently understand it, explaining their variability, setting out our current ideas on the forcing of these fluxes and our improved capability in modelling the fluxes themselves and the processes at work. Much of that evidence is assembled here for the first time.

4 Contents, Structure and Rationale

So where are climate models deficient? What aspects of the physics of our northern seas can ocean scientists most usefully contribute to their development? In fact the list is quite long. Climate models are inherently weak in the important subtleties of deep convection, interior diapycnal mixing, boundary currents, shelf circulations (climate models have no continental shelves!), downslope flows that entrain new fluid during their descent, thin cascading overflows, delicate upper ocean stratification by both heat and salt with its strong influence on convective geography, ice dynamics – all of which contribute to a level of uncertainty that may crucially affect our assessment of thermohaline slowdown. And most underline the importance of direct, sustained observations in the regions that lie *between* the dominant polar and subtropical climate programs.

Altogether, in piecing together a modern statement that will define the role of the Northern Seas in climate, we find a need to describe 28 separate facets of the subject, with three main themes (chapters mentioned in this brief introduction are numbered #1–#28).

First we have quantified the fluxes themselves. It is now soundly established, for example that 8.5 million cubic metres per second of warm salty Atlantic Water pass north across the Greenland–Scotland Ridge carrying, on average, some 313 million megawatts of power (relative to 0 °C) and 303 million kilograms of salt per second (# 1; see also Østerhus et al. 2005). A little further north, from a decade of direct measurements off Svinøy (# 2), we find that the inshore (slope) branch of the Norwegian Atlantic Current carries 4.3 Sv and 126 TW poleward, with no sign yet of any trend in transport, while further north still, an Atlantic inflow of 1.8 Sv, increasing by 0.1 Sv per year, carries 48 TW (increasing by 2.5 TW per year) into the Barents Sea. Nine years of intense effort in the Fram Strait complete our accounting of the warm, saline northward flux at its point of entry to the Arctic Ocean (# 3). In fact, while we have resolved the debate about the importance of this poleward ocean heat flux to climate (# 4), the Fram Strait study opens up a new debate about how that flux should be measured. It suggests that the physical concept of oceanic heat transport is only meaningful in terms of its ability to add heat to or take away heat from a defined ocean volume. Thus, oceanic heat transport to the Arctic Ocean, calculated from velocity and temperature measurements at its boundary are only meaningful when the *entire* boundary – and all of the inflows and outflows that cross it – is taken into account, a strong vindication of the ASOF preference for simultaneity of observations; and this will also be true for the temporal variability of that transport. Chapters on our growing ability to simulate the Atlantic water inflow to and through the Northern Seas and its long-term variability (# 5), together with new insights into the strongly mesoscale structure of that Atlantic current west of Norway (# 6) round off this section of the volume.

As with the poleward flux of heat, a similarly broad range of chapters are devoted to describing our improved capability and our changing ideas on the variable and equally important outflows that pass from the Arctic in the opposite sense to modulate the Atlantic Meridional Overturning Circulation – the proximal end of the Ocean's 'Great Conveyor'. No less than 12 chapters describe aspects of the flux of ice and freshwater whose projected increase in recent simulations tends to slow down – and in at least one recent model to shut down – the Atlantic MOC. Here we provide a modern assessment of the freshwater storage in the northern seas (# 7), updating the seminal work by Aagaard and Carmack (1989) before going on to describe the full range of direct measurements of the freshwater flux into and through the six main passageways of the Canadian Arctic Archipelago to the Davis Strait (# 9), the sizeable outflow joining it through Hudson Strait (# 10), and our present (and still incomplete) measures of the equivalent flux passing south to the east of Greenland (# 11 and 28). Companion chapters describe our growing capability in measuring and modelling the terms in the Arctic hydrological budget (# 14 and 15) and in simulating its more important components, the sea-ice and freshwater exports through Fram Strait (# 8 and 17).

In support of the second ASOF goal, we discuss a selection of the cutting edge questions in observing and modelling the Arctic–subarctic system, as we currently perceive them. Real issues remain: for example, although estimates of the total freshwater flux reaching the North Atlantic have recently been published (~300 mSv according to Dickson et al. 2007), there remain real constraints, debated here, on our ability to make such estimates (#13); equally while there would be general agreement that an increasing freshwater flux to the North Atlantic is likely to be of climatic significance, we remain uncertain as to whether the impact on climate will result from *local* effects on overflow transport (e.g. from the changing density contrast across the Denmark Strait sill; Curry and Mauritzen 2005), from the *regional* effect of capping the water column of the NW Atlantic (leading to a reduction in vertical mixing, water mass transformation, and production of North Atlantic Deep Water), or from *global-scale* changes in the Ocean's thermohaline fields and circulation arising from an acceleration of the Global Water Cycle (Curry et al. 2003). Most fundamental of all, opinion remains divided both on whether thermohaline slowdown is threatened (# 16), is already underway or on whether any variability that we see is natural or anthropogenic (# 12).

Model results are also helping to reshape our thinking on the role of the northern seas in climate; we provide illustrations from two of our most advanced atmosphere–ocean general circulation models. First, the analysis of results from 200 decade-long segments of HadCM3 runs bears the clear implication that a given volume of freshwater, when spread to depth (as, for example, through the descent of the dense-water overflows from the sills of the Greenland–Scotland Ridge into the deep Atlantic) effects a much smaller slowdown of the MOC than when the same freshwater anomaly is spread across the surface – the normal practice and assumption in the 'hosing experiments' (# 12). This observation naturally begs the question as to whether any *future* increase in the freshwater outflow from the Arctic is likely to be incorporated into the overflow system, or (effectively the same thing) *whether any future increase of the freshwater efflux is likely to pass to the west or to the east of Greenland.* And one model study currently makes that prediction. Recent coupled experiments by the Hamburg M-P-I Group using ECHAM 5 and the M-P-I Ocean

Model suggest that although the freshwater flux is expected to increase both east and west of Greenland, the loss of the sea-ice component (which currently dominates the flux through Fram Strait) suggests we should expect a much greater total increase through the CAA by 2070–2099 than through Fram Strait (Haak et al. 2005; # 8 & 12). As a third, intriguing (and perhaps salutary) model result, we revert to HadCM3 which in a large ensemble of experiments has appeared to offer an encouragingly close fit between the density of northern seas and rate of the Atlantic overturning circulation at 45° N (# 12). However, when the density changes are decomposed into those due to changes in temperature and those due to changes in salinity, the three types of experiments (‘hosing runs’, ‘initial perturbation’ experiments and greenhouse gas experiments) each behave very differently, suggesting that each class of experiments might involve fundamentally different feedbacks (# 12). If so, how can we be sure that we have yet adequately employed the full range of models that spans the possible and likely behaviour of the real climate system?

Whatever may be the role of the freshwater flux from high latitudes in slowing down the AMOC, it is the overflow and descent of cold dense water from the sills of the Denmark Strait and Faroe–Shetland Channel that ventilate and renew the deep oceans and thus drive the abyssal limb of this overturning cell. Forty years on from Val Worthington’s first heroic but unsuccessful attempt to deploy current meters across the violent flow through Denmark Strait, direct measurements in both overflows are now relatively routine. From the longer of the two series (Denmark Strait) a decade of continuous observation shows variability in transport out to interannual timescales, but with no evidence (as yet) of any longer-term trend and no convincing evidence of covariance with the eastern dense overflow through Faroe Bank Channel (# 18 & 19). Observations over many decades have identified a complex of locally and remotely driven large-amplitude variations in the hydrographic character of both overflows and their sources, including a long-sustained trend in salinity of 3–4 decades duration. From the passage of conspicuous thermohaline anomalies (# 21), from the use of novel tracer techniques (# 20) and from a greatly improved modelling capability (# 22), we can now more confidently trace the changing sources and pathways of overflow upstream from the Fram Strait or track them downstream to the abyssal Labrador Sea. It will be downstream, along that track, that the major impact on the global thermohaline circulation will take effect. Through detailed hydrographic analysis of the principal water masses passing through the great storage and transformation basins south of the Greenland–Scotland Ridge, we can now much better describe the combination of local, regional and remote influences that have driven record hydrographic change through the water column of the Northwest Atlantic in recent decades (# 21 & 24). The Irminger Sea is seen to have features of unique global importance for the transfer of ocean climate signals between water masses and to great ocean depths (# 26 & 21). And at the southern boundary of the ASOF domain, the intractable but climatically vital problem of North Atlantic Deep Water formation in the Labrador Sea, its recirculation through the subpolar gyre and its discharge to the subtropics – once described by McCartney (1996) as *‘the greatest problem in Oceanography’* – is finally being resolved, through a combination of state-of-the-art observational and modelling techniques (# 27). [It is sobering to reflect, and thus important to acknowledge, that without John Lazier's singular achievement in following the processes of convection and climate change in the Labrador Sea from the first (and only!) three-dimensional hydrographic survey of 1965–1966 to the institution of annual Hudson sections between Hamilton Bank Labrador and Cape Desolation, Greenland, we might have missed the 'greatest change in Oceanography', as it passed through the basin].

The bulk of this brief overview has understandably concerned the task that formed the original primary goal of VEINS and ASOF – the idea of measuring and modelling a complete set of oceanic exchanges between the Atlantic and Arctic Oceans through subarctic seas, simultaneously and with decadal stamina. Our approach to this goal has not been unchanging. In fact, the complexity of our data sets and the need to extract and display its essence have both prompted and required a diversification of technique. Importantly, the strict definition of ocean circulation as integrated volume transport and zonally-averaged overturning streamfunction is now being augmented at many points in this volume by the hydrographer's approach of displaying change on the potential temperature/salinity plane. Transports of heat, freshwater and mass are thus unified on a single diagram, returning us toward articulate description of water masses, their transports across key sections and their transformation and air–sea interaction within boxes bounded by these sections.

Equally important, as our time-series have lengthened, other factors have developed to help sustain these series.

The first is a growing realisation that although the individual flux estimates and their local controls are important, the processes that 'drive' their variability may form part of a full-latitude *system* of change; and that it is the recognition of how that *system* works that will most rapidly advance our ablity to simulate change and predict its onset. One current illustration will make the point, and it concerns some of the largest changes we have ever observed in our waters. Very recently, the temperature and salinity of the waters flowing into the Norwegian Sea along the Scottish shelf and slope have been at their highest values for >100 years. At the 'other end' of the inflow path, the ICES Report on Ocean Climate for 2006 (ICES 2007) will show that temperatures along the Kola Section of the Barents Sea (33° 30′ E) have equally never been greater in >100 years. Shorter records en route and beyond, on the Norwegian arrays off Svinoy (# 2), on the moored array monitoring Fram Strait (# 3), and on Polyakov's NABOS moorings at the Slope of the Laptev Sea (Polyakov 2005, 2007) have all remarked the passage of this warmth; Holliday et al. (2007) have described its continuity along the boundary. It forms part of the rationale for Overpeck's (2005) statement that '*a summer ice-free Arctic Ocean within a century is a real possibility, a state not witnessed for at least a million years*.'

Why? What is driving extreme change through the system? Satellite-based observations seem to provide a plausible explanation: during the whole TOPEX-POSEIDON era (since 1992), as the Labrador Sea Water warmed (# 24), altimeter records reveal a slow rise in sea surface height at the centre of the Atlantic subpolar gyre, suggesting a steady weakening of the gyre circulation (Hakkinen and Rhines 2004; # 23). This weakening, together with a westward retraction of the gyre boundary, appears to have operated as a kind of 'switchgear' mechanism to control the temperature and salinity of inflow to the Nordic seas (Hatun et al. 2005); by that mechanism, when the gyre was strong and spread east (early 1990s), the inflows recruited colder, fresher water direct from the subpolar gyre but when the gyre weakened and shifted west (as in the 2000s), the inflows to Nordic Seas were able to tap-off warmer and saltier water from the subtropical gyre, explaining the recent warmth and saltiness of inflow of Atlantic waters into the Norwegian Sea (# 4). Thus, although the local and the short term have certainly played their part west of Norway – the speed of the Atlantic Current is locally storm-forced so that it tends to change coherently from Ireland to Spitsbergen (# 2) – the ultimate source of the observed changes in the Arctic Ocean lies in a whole system of interactions between polar and sub-polar basins. Near and remote, short-term as well as long-term controls have been involved in providing the Polar Basin with a steady supply of increasingly warmer water through subarctic seas.

We have only just begun to glimpse evidence of this 'system'. But model results too seem to vindicate the view that it is the whole full-latitude system of exchange between the Arctic and Atlantic Ocean – not just spot 'examples' of it – that has to be addressed simultaneously if we are to understand the full subtlety of the role of our Northern Seas in climate. As Jungclaus et al. (2005) conclude from their model experiments using ECHAM5 and the MPI-OM, while *'the strength of the (Atlantic) overturning circulation is related to the convective activity in the deep-water formation regions, most notably the Labrador Sea,.....the variability is sustained by an interplay between the storage and release of freshwater from the central Arctic and circulation changes in the Nordic Seas that are caused by variations in the Atlantic heat and salt transport.'* Likewise, Hakkinen and Proshutinsky (2004) find that *'changes in the Atlantic water inflow can explain almost all of the simulated freshwater anomalies in the main Arctic basin'.*

The final factor that has sustained our time-series has been technical advance. As our understanding of the role of the northern seas in climate has developed in complexity, so the necessary parallel advances have been made in terms of technique. For example, orbiting satellites now contribute an increasingly comprehensive view of ice and circulation. From showing, visually, the areal extent of sea-ice and its remarkable responses to the wind, satellite altimetry now routinely provides maps of the draft/thickness distribution of sea-ice, while retrievals of ocean dynamic topography at the centimetre level (hence measures of the Arctic Ocean circulation) are now possible even in the presence of ice; since 2002, the twin satellites of the Gravity Recovery and Climate Experiment (GRACE) have contributed their own new measure of the grounded-ice mass balance. Within the ocean, there is no better example of technical advance than the evolution of SeaGlider technology to its first uses on survey during ASOF, initially in waters west of Greenland, more recently adding its fine-scale space–time resolution to the classic ship-based hydrography across the Faroe–Shetland Channel and Iceland–Faroe Ridge (# 25).

It is a nice point that the oldest time-series that we have relied on in ASOF, the hydrographic transects of the Faroe–Shetland Channel begun by HN Dickson aboard HMS Jackal on 4 August 1893 and carried-on by the Scots ever since (with Faroese and Norwegian partners), are now supplemented in their coverage by repeat deep SeaGlider sections from the cutting-edge of technical advance (# 25). Its further development to a Deep Glider able to cruise the whole watercolumn of the subpolar gyre is called for (# 19) as a necessary aid to capturing the baroclinic adjustments that cause interannual changes in the transport of overflow from Nordic Seas.

The above rapid tour through the chapters of this volume will justify, or at least explain why ASOF and why this volume have the scope that they do. Why simultaneity and stamina in observation seem key. What the driving questions of the programme now are. And why defining and re-defining the role of the northern seas in climate has become, in itself, a continuing goal of the programme.

Acknowledgements What this introduction does not explain is the structural role played by the ASOF Science Officer, Roberta Boscolo, throughout the life of the ASOF programme from the discussion meetings in 2000 that shaped its goals, through the annual series of outputs and meetings that adjusted its focus, to the actual editing of this volume. Our 7 years and now our 101 authors and co-authors could not have proceeded to this conclusion without her, as we three who are designated editors are happy to acknowledge.

The concept of ASOF was brought to life by the Arctic Ocean Sciences Board under the leadership of Tom Pyle and Lou Brown of the US National Science Foundation and owes much to their enthusiasm. We also gratefully acknowledge the support received from a wide range of national and international funding agencies and individual laboratories whose funding has permitted both the ASOF Conference in the Faroes and the production of this volume. They are identified and thanked by the full list of their logos on the cover.

Finally, it goes without saying that the observations on which this volume is based, won from some of the most difficult waters on Earth, could not have been achieved without the help of the research vessel fleet and their crews over many years. We are most happy to acknowledge their contribution.

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Chapter 1
The Inflow of Atlantic Water, Heat, and Salt to the Nordic Seas Across the Greenland–Scotland Ridge

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1.1 Introduction

The flow of warm, saline water from the Atlantic Ocean (the *Atlantic inflow* or just *inflow*) across the Greenland–Scotland Ridge into the Nordic Seas and the Arctic Ocean (collectively termed the Arctic Mediterranean) is of major importance, both for the regional climate and for the global thermohaline circulation. Through its heat transport, it keeps large areas north of the Ridge much warmer, than they would otherwise have been, and free of ice (Seager et al. 2002). At the same time, the Atlantic inflow carries salt northwards, which helps maintaining high densities in the upper layers; a precondition for thermohaline ventilation.

The Atlantic inflow is carried by three separate branches, which here are termed: the *Iceland branch* (the North Icelandic Irminger Current), the *Faroe branch* (the Faroe Current), and the *Shetland branch* (Fig. 1.1). These are all characterized by being warmer and more saline than the waters that they meet after crossing the Ridge, although both temperature and salinity decrease as we go from the Shetland branch, through the Faroe branch, to the Iceland branch. All these branches therefore carry, not only water, but also heat and salt across the Ridge.

Systematic investigations on the Atlantic inflow started already at the start of the 20th century with the Shetland branch, which long was treated as by far the dominant inflow branch. These investigations were mainly carried out by Scottish researchers and included measurements of temperature and salinity on two standard sections in the Faroe–Shetland Channel (Turrell 1995). Later, similar investigations were

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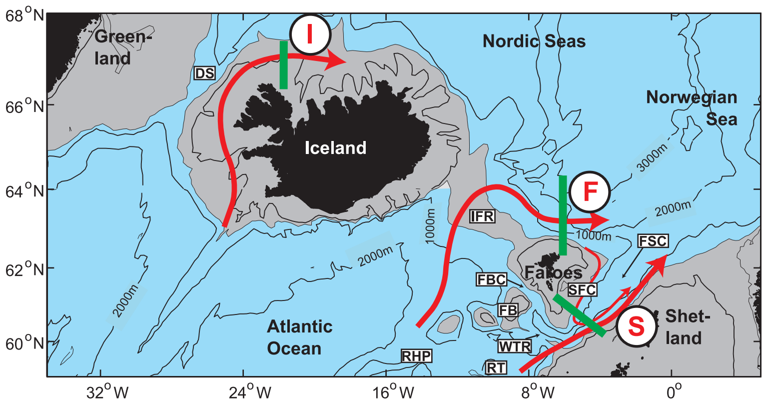

Fig. 1.1 Bottom topography between Greenland and Shetland. Shaded areas are shallower than 500 m. Thick red arrows indicate the three inflow branches: the Iceland branch (I), the Faroe branch (F), and the Shetland branch (S). A thinner red arrow indicates the "Southern Faroe Current (SFC)" and its re-circulation in the Faroe–Shetland Channel (FSC). Thick green lines show the locations of standard sections along which hydrographic and current data have been obtained. Indicated locations are: the Denmark Strait (DS), the Iceland–Faroe Ridge (IFR), the Faroe Bank Channel (FBC), the Faroe Bank (FB), the Faroe–Shetland Channel (FSC), the Wyville–Thomson Ridge (WTR), the Rockall Trough (RT), and the Rockall–Hatton Plateau (RHP)

initiated on the Iceland branch and on the Faroe branch. Sporadic attempts were made to measure currents from research vessels early in the 20th century, but systematic long-term measurements with moored current meters were only initiated in 1985 when Icelandic researchers started monitoring the currents in the Iceland branch (Kristmannsson 1998). For the other two branches, systematic current measurements were initiated with the Nordic WOCE project in the mid-1990s. Building on this, a system has been established, which monitors all the branches of the Atlantic inflow with regular CTD cruises and quasi-permanent current meter moorings. The system is maintained by research vessels from the marine research institutes in Iceland, the Faroes, and Scotland and has received support from the European research programmes through the projects VEINS (Variability of Exchanges In the Northern Seas) and MAIA (Monitoring the Atlantic Inflow toward the Arctic).

This system was further maintained and refined in the MOEN (Meridional Overturning Exchange with the Nordic Seas) project, which was supported by the European FP5, and was a component of ASOF. In the framework of this project, measurements of temperature, salinity, and currents were continued through the ASOF period. ASOF-MOEN also included a numerical modelling component, which studied the exchanges across the Greenland–Scotland Ridge, using an ocean model driven by atmospheric fluxes from reanalysis fields.

The aim of this chapter is to synthesize the information on the Atlantic inflow across the Greenland–Scotland Ridge, based mainly on the results gained by the ASOF-MOEN project and its predecessors, but including other relevant sources, as well. No attempt will be made to repeat the more detailed reviews that have included the Atlantic inflow (Johannesen 1986; Hopkins 1991; Hansen and Østerhus

2000) and neither will we attempt to make a systematic distinction between ASOF and non-ASOF produced results.

1.2 The General Setting

1.2.1 Topographic Constraints

The Greenland–Scotland Ridge separates the Arctic Mediterranean from the Atlantic Ocean and acts as a constraint on all the exchanges across it, the Atlantic inflow as well as the East Greenland Current, and the overflows. On a section (Wilkenskjeld and Quadfasel 2005) following the crest of the Ridge (Fig. 1.2), the warm and saline Atlantic water is seen to be most prominent in the south-eastern parts, where it dominates the section, above the cold and less saline overflow water flowing over the Ridge in many places. In the surface, the Atlantic water extends west of Iceland (Fig. 1.2). The Ridge reaches above the sea surface in Iceland and the Faroes, which split it into three gaps, and this determines the branching structure (Fig. 1.3).

The gap between Greenland and Iceland, the Denmark Strait, is wide and reaches a depth of 640 m. The Atlantic inflow through this gap has to share the cross-sectional area with both the East Greenland Current and the Denmark Strait overflow, and is confined to the easternmost part of the strait.

Between Iceland and the Faroes, the Atlantic water has to flow across the Iceland–Faroe Ridge, which has typical sill depths from 300–480 m along its crest. Atlantic water crosses this ridge over its whole width, in many places passing above the cold overflow water that intermittently crosses the Ridge in the opposite direction.

The Atlantic water that passes between the Faroes and Shetland, can do so along several different routes. The warmest and most saline component flows over the slope as the “Slope Current” (Swallow et al. 1977; Ellett et al. 1979), or “Shelf Edge Current” (New et al. 2001), which has its origin to the south of the Rockall Trough. In addition to this, water of more oceanic origin can pass through the

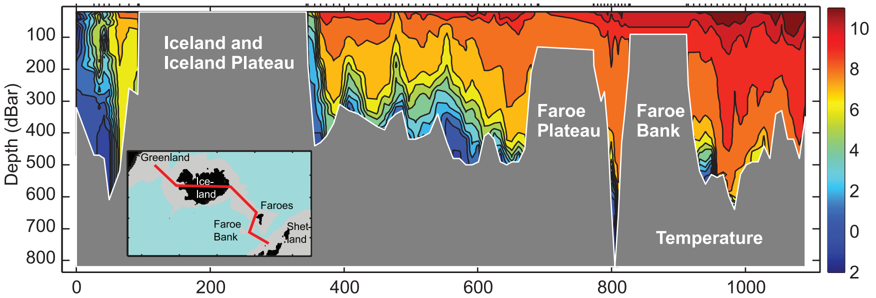

Fig. 1.2 A section following the crest of the Greenland–Scotland Ridge (red line on inset map) showing the temperature in degree Celsius during a cruise in summer 2001

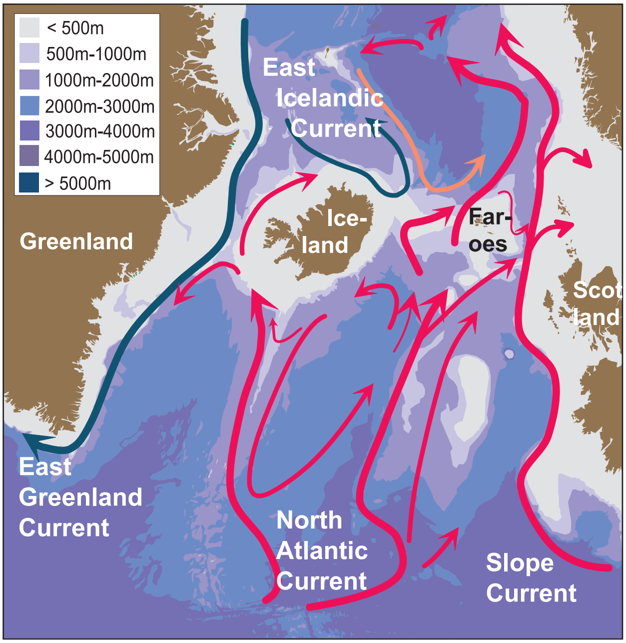

Fig. 1.3 Main flow patterns of warm (red arrows) and cold (blue arrows) currents in the upper layers of the Northeastern North Atlantic. Background colours indicate bottom depth

Rockall Trough, over the Rockall–Hatton Plateau, and even through the Faroe Bank Channel to reach the Faroe–Shetland Channel, although the persistence of some of these pathways is unknown. As these waters pass south of the Faroes, they meet a counter-flow of Atlantic water over the south-eastern Faroe slope. This flow, termed the "Southern Faroe Current" by (Hátún 2004), derives from the Faroe branch. Most of it recirculates in the Faroe–Shetland Channel and joins the other Atlantic water masses in the Shetland branch (Hansen and Østerhus 2000).

1.2.2 The Origin of the Atlantic Inflow Water

In much of the classical literature (see, e.g. review by Hansen and Østerhus 2000), the Atlantic water crossing the Ridge was seen to derive either from an oceanic or from a more continental source (Fig. 1.3). The oceanic source fed the Iceland branch, the Faroe branch, and part of the Shetland branch, whereas the continental source fed the Slope Current and thereby the Shetland branch of the Atlantic inflow. In the Faroe–Shetland Channel, especially, waters from these two sources were treated as different water masses: the "North Atlantic Water (NAW)", carried by the Continental Slope Current, and the "Modified North Atlantic Water (MNAW)", deriving from the oceanic source.

An extreme version of this view, was the proposal by Reid (1979), who suggested a direct import of Mediterranean Water to the Nordic Seas. This suggestion never gained much support and recent observational (McCartney and Mauritzen 2001) and modelling (New et al. 2001) studies have rejected it convincingly.

Distinguishing between an oceanic and a continental source does, however, ignore the continuous exchange between the waters of the Continental Slope Current and the adjacent off-shore waters and time-series show a high degree of coherence between the different Atlantic inflow branches (Section 1.4.2), whether over the continental slope or farther offshore. An alternative view, therefore, does not distinguish between oceanic and continental origin, but rather considers all the Atlantic inflow branches to be fed from two source water masses: the warm and saline ENAW and the colder and less saline WNAW.

The ENAW (Eastern North Atlantic Water) (Harvey 1982; Pollard et al. 1996) gains it properties in the region south of the Rockall Trough, called the “Inter-gyre region” (Ellett et al. 1986; Read 2001; Holliday 2003). This name might indicate a mixed contribution from the two gyres but, certainly, the ENAW has much less input from the Subpolar Gyre than the other source water mass, the WNAW (Western North Atlantic Water), which is carried towards the inflow areas by the North Atlantic Current. The North Atlantic Current is generally considered to originate in the Subtropical Gyre, but it is bounded by the Subpolar Gyre on its northern flank and water from that gyre is admixed into the flow. When it reaches the eastern North Atlantic, it has received sufficient amounts of Sub-Arctic Intermediate Water (SAIW), so that the WNAW is colder and fresher than the ENAW.

1.2.3 The Downstream Fate of the Atlantic Inflow Water

After passing the Greenland–Scotland Ridge, the different branches of Atlantic water progress into the Nordic Seas and from there, parts of the water continue into the Arctic Ocean. The details of the paths and associated water mass changes on route have been reviewed by various authors (Johannesen 1986; Hopkins 1991; Mauritzen 1996; Hansen and Østerhus 2000; Blindheim and Østerhus 2005). The main point to note is that the three different branches affect different regions in the Arctic Mediterranean. The Iceland branch has direct effects only on the southern parts of the Iceland Sea (Swift and Aagaard 1981; Jónsson 1992). The Faroe branch apparently feeds the recirculating water in the southern Norwegian Sea (Fig. 1.3) and thus probably delivers much of its heat and salt to these areas. A part of the Faroe branch also joins with the Shetland branch, which must be considered the main contributor to the North Sea and probably also the Barents Sea.

1.3 Monitoring System

Our knowledge of the Atlantic inflow has been accumulated from a long history of observations, mainly on the hydrography. Here, we focus on the observational system that has been established to monitor the three Atlantic inflow branches and was used in the ASOF-MOEN project.

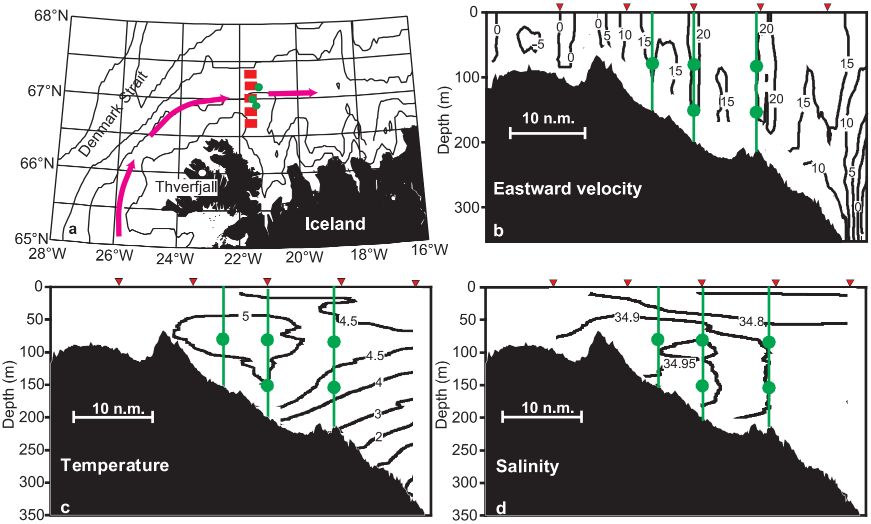

Fig. 1.4 Monitoring system and properties of the Iceland branch. (a) CTD standard stations are indicated by red rectangles. Current meter mooring sites are indicated by green circles. Magenta arrows indicate Atlantic water pathways towards and through the section. (b) Average eastward velocity (cm s^{-1}) based on a total of 20 sections of vessel mounted ADCP data from November 2001–2004, and August 2005 with four sections taken each time. CTD standard stations (red triangles) and current meter moorings (green lines with green circles indicating Aanderaa current meters) are shown. (c, d) Average distributions of temperature in degree Celsius (c) and salinity (d) on the section, based on CTD observations at standard stations (red triangles) in the period 1999–2001

The systematic observations of the Iceland branch have been focused on the Hornbanki section (green line labelled "I" on Fig. 1.1). On this section (Fig. 1.4), CTD profiles have been obtained by the Marine Research Institute in Iceland on several standard stations up to four times a year since 1994 and, during the same period, the inflow of Atlantic water has been monitored by moored current meters. From September 1999, the measurements were extended to three moorings carrying a total of five current meters (Fig. 1.4).

The Faroe branch has been monitored on a section extending northwards from the Faroes along the 6°05′ W meridian (green line labelled "F" on Fig. 1.1). On this section (Fig. 1.5), CTD profiles have been acquired by the Faroese Fisheries Laboratory on several standard stations, at least four times a year since 1988. From the mid-1990s, ADCPs have been moored on the section almost continuously. The number and locations of ADCP moorings have varied somewhat, but since summer 1997, there have always been at least three and sometimes five ADCPs on the section, except for annual servicing gaps.

The observations of the Shetland branch were carried out on a section crossing the channel south of the Faroes (green line labelled "S" on Fig. 1.1). At least four, and before summer 2000, five ADCP moorings have been maintained along the section since November 1994 (Fig. 1.6). These observations have been complemented with ADCP data acquired from oil platforms. Both the Faroese Fisheries Laboratory and the Marine Laboratory in Aberdeen do regular CTD cruises along

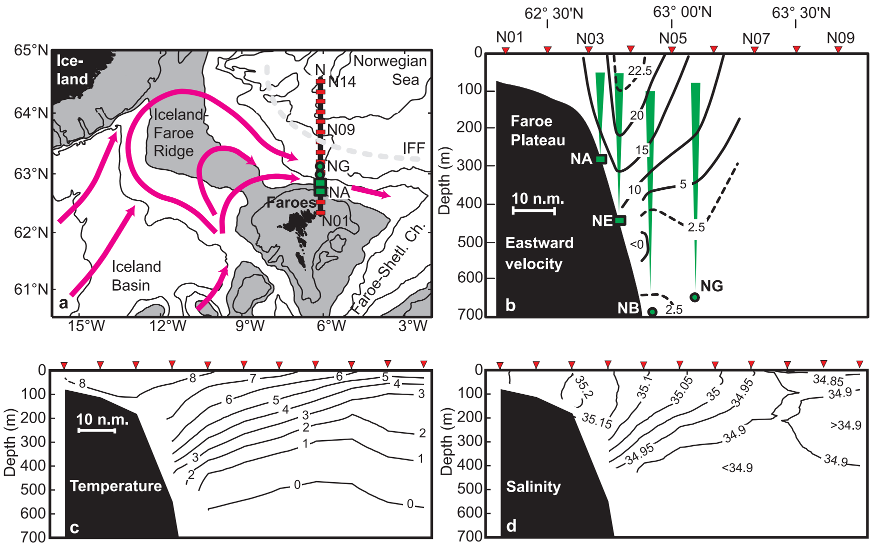

Fig. 1.5 Monitoring system and properties of the Faroe branch. (a) CTD standard stations are indicated by red rectangles, labeled N01–N14. ADCP mooring sites are indicated by green circles (traditional moorings) or rectangles (trawl-proof frames) labeled NA to NG. Shaded areas are shallower than 500 m. The dotted yellow curve indicates the general location of the Iceland–Faroes Front (IFF) and magenta arrows indicate Atlantic water pathways towards and through the section. (b) Average eastward velocity (cm s^{-1}) 1997–2001. The innermost CTD standard stations (red triangles) are indicated as well as the ADCP mooring sites (green circles or rectangles with green cones indicating sound beams). (c, d) Average distributions of temperature in degree Celsius (c) and salinity (d) on the inner part of the section, based on CTD observations at standard stations (red triangles) in the period 1987–2001

this section and altogether four to eight CTD sections have been obtained annually since the mid-1990s.

The region between Iceland and Shetland is heavily fished and traditional current meter moorings have a short survival time in this area. This was the reason for using upward-looking ADCPs instead of more traditional instrumentation. At deep sites, the ADCPs are moored in the top of traditional moorings with the ADCP sufficiently deep to escape trawls. On the slope north of the Faroes, two of the ADCPs are deployed directly on the bottom within frames that protect the ADCPs and other instrumentation from fishing gear (Fig. 1.7).

1.4 Observed Properties

1.4.1 Typical Structure and Properties of the Inflow Branches

The Iceland branch is highly variable but it is of great importance to the regional marine climate and hence the ecosystem in North Icelandic waters (Jónsson and Valdimarsson 2005). There is usually a core of Atlantic water identified by high

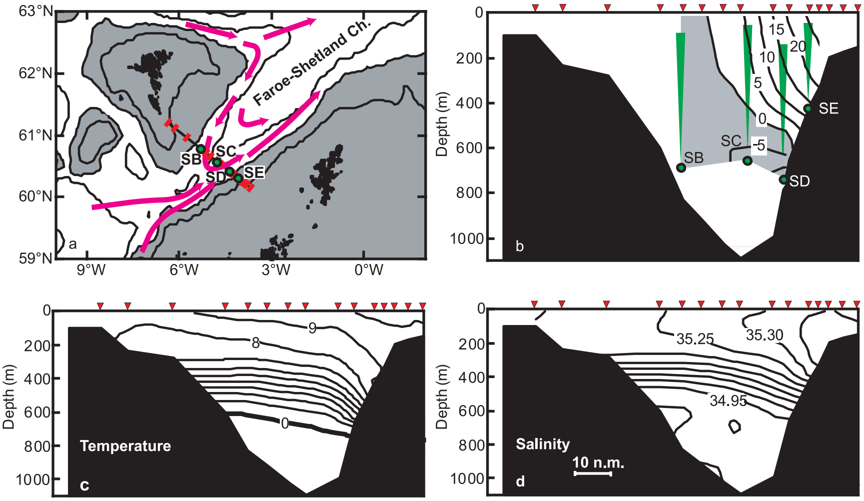

Fig. 1.6 Monitoring system and properties of the Shetland branch. (a) CTD standard stations are indicated by red rectangles. ADCP mooring sites are indicated by green circles labeled SB, SC, SD, and SE. Shaded areas are shallower than 500 m and magenta arrows indicate Atlantic water pathways towards and through the section. (b) Average along-channel velocity (cm s^{-1}) as measured by the ADCP moorings in the period 1994–2005. Shaded area indicates reverse (SW-going) flow. CTD standard stations (red triangles) and ADCP mooring sites (green circles with green cones indicating sound beams) are indicated. (c, d) Average distributions of temperature in degree Celsius (c) and salinity (d) on the section, based on CTD observations at standard stations (red triangles) in the period 1994–2005

Fig. 1.7 Trawl-proof frame containing ADCP, double acoustic releases, ARGOS beacon, and buoyancy, on top of concrete anchor, is being made ready for deployment onboard R/V Magnus Heinason