OCEAN Challenge

Volume 16, No. 3, 2006
(published Autumn 2009)

The views expressed in *Ocean Challenge* are those of the authors and do not necessarily reflect those of the Challenger Society or the Editor.

ISSN 0959-0161

SCOPE AND AIMS

Ocean Challenge aims to keep its readers up to date with what is happening in oceanography in the UK and the rest of Europe. By covering the whole range of marine-related sciences in an accessible style it should be valuable both to specialist oceanographers who wish to broaden their knowledge of marine sciences, and to informed lay persons who are concerned about the oceanic environment.

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Angela Hatton, Scottish Association for Marine Science, Dunstaffnage Marine Laboratory, Oban, Argyll, PA37 1QA

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Printed by Halstan Ideal, Amersham.

OCEAN Challenge

The Magazine of the Challenger Society for Marine Science

SOME INFORMATION ABOUT THE CHALLENGER SOCIETY

The Society's objectives are:

To advance the study of Marine Science through research and education.

To disseminate knowledge of Marine Science with a view to encouraging a wider interest in the study of the seas and an awareness of the need for their proper management.

To contribute to public debate on the development of Marine Science.

The Society aims to achieve these objectives through a range of activities:

Holding regular scientific meetings covering all aspects of Marine Science.

Supporting specialist groups to provide a forum for discussion.

Publication of a range of documents dealing with aspects of Marine Science and the programme of meetings of the Society.

Membership provides the following benefits:

An opportunity to attend, at reduced rates, the biennial five-day UK Marine Science Conference and a range of other scientific meetings supported by the Society.

An electronic newsletter (*Challenger Wave*) which carries topical marine science news, and information about jobs, conferences, meetings, courses and seminars.

The Challenger Society Website is
www.challenger-society.org.uk

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The subscription for 2010 costs £40 (£20.00 for students in the UK only). If you would like to join the Society or obtain further information, contact the Executive Secretary, Challenger Society for Marine Science, Room 251/20, National Oceanography Centre, Waterfront Campus, Empress Dock, Southampton SO14 3ZH, UK; Fax: +44(0)23-80-596149; Email: jxj@noc.soton.ac.uk

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Articles for *Ocean Challenge* can be on any aspect of oceanography. They should be written in an accessible style with a minimum of jargon and avoiding the use of references. If at all possible, they should be well illustrated. Copy may be sent electronically.

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The maps and diagrams were drawn by The ArtWorks.
The cover was designed by Ann Aldred Associates.
On the cover, the photograph at top-right was taken by Phil Williamson, and won the President's Photographic Prize ar the 2008 Challenger Society Conference in Bangor.

Message from the Editor

In the wake of the International Polar Year, and with the Copenhagen Climate Change Conference imminent as we go to press, it is appropriate that this issue of *Ocean Challenge* contains articles with relevance to both the polar oceans and climate change. Phil Williamson describes a multidisciplinary analysis of the glacial biogeography of Atlantic cod and speculates what its results might mean for the distribution of cod species in an ice-free Arctic, in the not-so-distant future. Geraint Tarling and Angus Atkinson consider the challenges facing Southern Ocean krill and those who study them, and Yueng-Djern Lenn describes recent investigations into the transformation of warm Atlantic Water as it circulates in the Arctic. We also have news of a unique research facility off the coast of Norway, and an article on the much neglected polar explorer, Frank Wild.

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News & Views

Unpicking contributions to sea-level rise ...

Everyone now knows that sea-level is rising, and (almost) everyone accepts that human activity is playing a part, but the debate about how fast sea-level is rising is hindered by uncertainty. Even the latest IPCC report avoids definitive statements about the contribution of human activity prior to 1950, because of lack of knowledge about the relative contributions to sea-level rise of melting glaciers and ice sheets on the one hand, and increasing heat content (and hence expansion) of the oceans, on the other.

Most research into climate change has tended to focus on the effect of one variable, such temperature. Now, researchers have used a statistical inverse model to evaluate the contribution to sea-level change of various natural factors and human activities over the past 1000 years.* The results were constrained by more than 1000 tide-gauge records, including ones from Liverpool, Amsterdam and Stockholm (going back to 1768, 1700 and 1774, respectively).

It was found that any change in sea-level before 1800 can be explained by natural variation, but that cooling resulting from reduction in solar radiation reaching the Earth's surface after volcanic eruptions may have masked a potential warming due to greenhouse gases (from land-use change) from as early as 1700.

The research indicates that human activity is to blame for 50–70% of the rise in sea-level since 1850, and that during the 20th century, 14 cm of the observed 18 cm sea-level rise was a direct result of human activities. What is more, if by chance there had been no volcanic eruptions since 1880, sea-level would be 7 cm higher than it is.

... and warming

A recent article in *Nature Geoscience*† tries to pick apart causes of warming observed from the 1910s to the 1940s, and concludes that, though global forcing factors play a part, the warming is best explained by climatic changes on a regional scale. In the 1930s, a climatic fluctuation involving 'dust bowl' droughts and heat waves in North America may have been caused by a cool tropical Pacific and a warm tropical Atlantic. Warming of the Arctic in the 1930s and '40s seems to have been caused by unusual atmospheric circulation over a warming North Atlantic, bringing warm air from lower latitudes. This phase of warming ended in the 1940s, with the strong El Niño of 1939–1942 possibly marking its peak.

*Jevrejeva *et al.* (2009) *Geophysical Research Letters*, **36** L20706; doi: 10.1029/2009GL040216.

†Brönnimann, S. (2009) *Nature Geoscience*, **2**, 735–6; doi: 10.1038/ngeo670

Algae leave clues to ice-extent

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A recent article in *Nature Geoscience* explains how the varying abundance of two biomarkers (biogeochemical fossils) in a sediment core from the northern part of the Fram Strait (between Greenland and Spitsbergen) have been used to generate a record of sea-ice conditions in the Nordic seas and the northernmost Atlantic for the past 30 000 years. As ice conditions here are largely controlled by the flow of warm water from the Atlantic, the position of the edge of the ice reflects circulation at lower latitudes.

The two biomarkers are IP_{25}(a C_{25} isoprenoid lipid) produced by diatoms that live in/under sea-ice, and brassicasterol, produced by open-water phytoplankton. By determining the relative contributions of these biomarkers at various depths in the core, it was possible to deduce presence at the site of perennial sea-ice (both zero/low abundance); a stationary ice-margin or polynya (both high abundance); predominantly ice-free (IP_{25} zero, brassicasterol high); or seasonal ice-cover (both intermediate).

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A warmer Arctic is windier

Over the last 30 years, and particularly in very recent times, the extent of sea-ice in the Arctic in September (end-summer) has been declining significantly. Dramatic changes have also been observed in Arctic weather, and researchers at the University of Melbourne* have confirmed that the two are related, and their analysis reveals that stronger cyclonic storms have been playing a central role in the changes observed in the Arctic basin, especially in the last few years.

In 2009, ice growth was brisk as polar darkness returned in October but the growth rate slowed for a time as strong warm winds from the south helped prevent ice from forming along the Siberian coast. At the end of the month, there were still extensive areas of open water to the north of Svalbard and north of Alaska.

*Simmonds, I., and K. Keay (2009) *Geophys. Res. Lett.*, **36**, L19715: doi:10.1029/2009GL039810.

Star-shaped satellite will observe ocean salinity

In November, the European Space Agency (ESA), the Spanish Centre for the Development of Industrial Technology and the French Space Agency (CNES) successfully launched the Soil Moisture and Ocean Salinity (SMOS) Earth observation satellite. The SMOS instrument is known as MIRAS, which stands for Microwave Imaging Radiometer with Aperture Synthesis. It has three antenna arms, that have now folded out, forming a three-pointed star, and it carries 69 receivers that measure radiation emitted from the Earth's surface within the 'L-band', around a frequency of 1.4 GHz which provides the highest sensitivity to variations in soil moisture, and changes in the salinity of surface ocean water.

Mission Moho

The aim of drilling a complete section of ocean crust, down to the Moho – the boundary between the crust and mantle – has been reaffirmed by the International Ocean Drilling Project. The first stage will be to revisit IODP Hole 1256D, in super-fast-spreading crust on the East Pacific Rise. The deepest hole drilled so far reaches 5 km beneath the sea floor, which is only about a quarter of the distance to the Moho.

The idea of drilling through the Moho was first proposed by Walter Munk in 1957, when the idea of continental drift was still controversial. Although it did not achieve its intended purpose, Project Mohole showed that deep ocean drilling was a viable means of obtaining geological samples.

Will Shiva upstage Chicxulub?

The Chicxulub crater off the Yucatan Peninsula, Mexico, is generally thought to have resulted from the meteorite impact that killed off the dinosaurs (and much else) at the end of the Cretaceous Period, around 65 million years ago. However, its claim to notoriety may be about to be upstaged by another sea-floor feature of similar age, in the Indian Ocean, west of Mumbai.

At 600 km long by 400 km wide, the Shiva Basin – named after the Hindu god of destruction and renewal – could be the largest impact crater on Earth (the Chicxulub crater is around 180 km across). Sankar Chatterjee of Texas Tech University and a team of researchers believe that the object that caused the Shiva crater could have been 40 km in diameter, and that the impact was so powerful that it fragmented, sheared, and deformed the lithosphere and mantle across the western Indian margin and contributed to major plate reorganization in the Indian Ocean, in the process of which the Seychelles were torn from the Indian tectonic plate and sent drifting towards Africa.

Shiva's outer rim is rough and faulted, and surrounds a central peak known as the Bombay High, which rises ~5 km above the surrounding ocean floor. It seems that the Earth's crust was vaporized at the point of collision, allowing hot mantle to well up from below.

Most of the crater lies under India's continental shelf, but where it comes ashore it is marked by cliffs, active faults and hot springs. It is likely that the impact increased the volcanic activity that was at that time producing the flood basalts, known as the Deccan Traps, that were covering much of western India.

Information by courtesy of the Geological Society of America.

Forams' flexible life-style key to surviving mass extinction

Foraminiferans – fondly known as 'forams' by those who work on them – are a group of unicellular shell-building marine organisms, whose small fossils provide palaeontologists with an extraordinary amount of information on ocean temperatures and climate change.

It had been thought that all modern planktonic foraminiferans were descended from the few lucky survivors of the meteorite impact that wiped out much of life on Earth 65 million years ago. However, living specimens of the planktonic species *Streptochilus globigerus*, collected in the Arabian Sea, have been shown to be genetically identical to the benthic species *Bolivina variabilis*, found off the coast of Kenya, indicating that at least some species of foraminiferans can switch between planktonic and bottom-dwelling life-styles. This in turn suggests that planktonic foraminiferans may have survived the end-Cretaceous mass extinction by abandoning the no-longer hospitable oceans for the relative safety of the sea-floor. When the oceans returned to normal, the survivors were able to colonise the surface waters once more.

Darling *et al.* (2009) *Proceedings of the National Academy of Sciences (PNAS)* doi: 10.1073/pnas.0902827106.

Flawed taxonomy hastens skate extinction

The European common skate, *Dipturus batis*, has been on the IUCN Red List of Threatened Species since 2006, and could become the first marine fish species to be driven to extinction by commercial fishing, due to an error of species classification 80 years ago.

From the mid-19th century the common skate was described as two distinct species, the flapper skate, *D. intermedia,* and the blue skate, *D. flossada*. However, in 1926, an influential work by R.S. Clark recognised only one species, '*D. batis*'; this opinion went largely unchallenged, and reported landings are therefore predominantly registered as *D. batis*. As a result, marked depletion of the flapper skate was not detectable in the catch record and the species may be in an irreversible decline towards extinction.

Recent confirmation that there were indeed two species is thanks to morphological studies, molecular data, life history investigations and fishery statistics.*

*Iglésias *et al.* (2009) *Aquatic Conservation: Marine and Freshwater Ecosystems*, doi: 10.1002/aqc.1083

Molluscs are safer in the sea

According to the 2007 IUCN Red List, molluscs are the group most affected by extinctions, with 302 species and 11 subspecies being listed as extinct. However, the quality of information relating to invertebrates is much poorer than that for vertebrates, and the Red List assessment was based on an evaluation carried out in 2000. Recent research* based on literature searches and consultation with experts indicates that the number of known mollusc extinctions is almost double that given in the IUCN Red List.

More than 70% of known mollusc extinctions took place on oceanic islands, but marine habitats seem to have experienced few extinctions.

*Régnier *et al.* (2009) *Conservation Biology,* 23, Issue 5, 1214–21.

An interview with the President of the Challenger Society

Carol Robinson began her term as President of the Challenger Society in September 2008. She is currently a Reader in Ocean/Atmospheric Biogeochemistry at the University of East Anglia. We are delighted that she has agreed to be *Ocean Challenge*'s first interviewee in what we hope will be a series of such features.

Q: Why did you decide to go into oceanography?

Carol: I did maths, physics and biology A-levels at school, originally wanting to be a Maths teacher. At some point during the lower sixth I realised I was much better at biology than maths and so applied to do Zoology at University. After the student open day at Newcastle University, with a visit to the Dove Marine Laboratory (which is literally on the beach), I was hooked on Marine Zoology. I enjoyed the fact that everything is interconnected in the marine environment, so that modules on physical and chemical oceanography helped in understanding modules on biological oceanography, unlike the 'pure' zoologists who had lectures on parasitology which (to me) didn't seem to connect to, or help explain, those on endocrinology or those on evolution. I was fascinated by marine microbiology, especially the fact that global nutrient cycles appeared to be dependent on processes known as 'decomposition' or 'regeneration' effected by microbes that no-one seemed to study.

The lecturers were incredibly supportive of my enthusiasm, allowing me to take modules for a joint bacteriology/zoology degree in the second year (which meant writing an exam paper just for me), letting me switching back to single honours Marine Zoology in the final year, and even thinking up a choice of three final-year projects for me on marine microbiology topics.

I remember wanting to do a marine microbiology Ph.D that was of benefit to society, which interestingly suggests that I thought not all of them at the time were! I ended up working in a civil engineering department isolating anaerobic methanogenic bacteria from marine sediments in the hope that they could be used in the breakdown of industrial waste-waters that have a high salt content, with the production of methane as a useful by-product. By then I was an avid scuba diver, spending as much time underwater as possible, seeing for myself haloclines, thermoclines, up- and downwelling currents, coccolithophore and jellyfish blooms, seals, dolphins, turtles, manta rays, cuttle fish, coral reefs, kelp forests, walls of jewel anemones and the rest of the amazing underwater world. I was attracted to the advert for my first postdoc position because it involved studying plankton, its relevance to climate and actually going to sea. Twenty-one years later I'm still studying plankton, its relevance to climate, and going to sea, and loving it.

Q: What aspect(s) of your job do you enjoy the most?

Carol: Learning new things and enthusing others about the marine environment. I particularly like the satisfaction of completing a paper where I've analysed my own results and interpreted them in light of other people's, and then defined the question to study next. Then I enjoy writing the proposal to study the next question. I enjoy doing science at sea, and it never fails to amaze me what opportunities I've had to see whales, dolphins, penguins, glaciers, icebergs and phenomenal sunrises and sunsets. I enjoy seeing the awe on people's faces (be they divers, schoolchildren, the general public or undergraduates) when they learn or understand something new about oceanography.

Q: What aspect of your job do you like least?

Carol: Over the past 10 years, cuts to funding have meant that I've been involved in discussions about cuts to science projects, including redundancies. No-one enjoys making these types of decisions.

Q: What was your most difficult career decision?

Carol: Moving jobs, first from Menai Bridge to Plymouth and recently from Plymouth to Norwich. In each case a tiny part of me knew that it was for the best work-wise – having the right proportion of new challenge, great terror and much excitement – but the other 99% of me took some time to be persuaded to leave friends, colleagues, diving clubs, running clubs, badminton clubs, houses and familiar, safe and comfortable surroundings.

Q: Do you think that being a woman has affected your career?

Carol: That's an interesting question! Presumably so. Much of the science I do involves working in a team, leading a team, negotiating, coercing, sometimes telling people things they don't want to hear. My ability to communicate is based on my experience of watching how others do this, and on my own personality– which is influenced by being a woman. Working with people also depends on the way they perceive me. I was recently welcomed on board RRS *Discovery* with comments from various officers and crew that they were looking forward to sailing with me as they had never worked with a female Principal Scientist before! Obviously, they were expecting me to undertake the role in a way that would be distinguishable from the wide spectrum of ways in which male Principal Scientists perform the role – but how?

I remember that my first interview for a lecturing position began with an apology from the Chair of the interview panel that he had been unable to find a female panel member. I wish now I'd had the confidence to say that he could easily solve his problem by employing me, but instead my mind wandered off to an image of four male oceanography professors touting the local high street for a female, any female, to interview me. Was I such a freak that only women could ask me questions? Was he trying to put me at my ease? Or trying to provoke a discussion of equality in the workplace? Did he open interviews of male candidates in a similar way, or did he think I would be especially disadvantaged by not being asked questions by a female interviewer? Was I supposed to apologise for being a woman? I told him not to worry, and thanked him for considering the issue. Luckily, the scientific questions then started and I could concentrate on much more straightforward issues.

If the question you're asking is 'has being a woman hindered your career?' then the answer is 'No, I don't think it has.' I have two examples of not having done something in a certain way because I'm a woman, but in each case I've achieved the objective I had in mind. As an undergraduate I was interested in doing a Ph.D on coral diseases. The person who seemed to me to be at the forefront of the field at the time worked in the Middle East. I was dissuaded from applying there (by a female Professor) as she thought it was no place for a Western woman to be. Instead, I led a student scientific diving expedition to a Caribbean coral reef, and successfully applied for research money to work on coral diseases.

During my Ph.D, while avidly reading the job adverts in *Nature* and *New Scientist* every week, I came across an advert for a job with British Antarctic Survey, with wording something along the lines that only males without dependents should apply. I remember being so incensed, that I threatened to apply as Carl Robinson to see how far I got in the application process. Fortunately I was just about mature enough to realise I was simply rebelling against being told I couldn't do something – I didn't actually want to spend two-and-a-half years of my life at a BAS base. Instead, I achieved my ambition of visiting Antarctica a few years later, when I spent four months at the Australian Antarctic base, Davis, where I wasn't just a woman – I was 'that Pommy bird'.

Being a woman has also given me opportunities that I may not have had as a man. I've often been invited onto committees (including Challenger Council in 1996), or to give presentations (including at AMBIO in 2006), where as part of the invitation conversation I've been told 'it would be great to have more women involved'.

Has being a member of the Challenger Society helped you in your career?

I don't know how to prove whether or not it has helped my career, but I'm proud to be able to put 'invited keynote speaker, Hon. Secretary, Council member, Challenger Fellow and President of the Challenger Society for Marine Science' on my *curriculum vitae*, all of which presumably help. The benefit I feel myself is through getting to know people I wouldn't otherwise have had the opportunity to get to know e.g. as Honorary Secretary I worked with the consecutive Presidents, Mike Whitfield, Harry Elderfield and John Shepherd; by organising and attending the biennial conferences I get to know who's doing what research where, which helps when I'm organising other conferences (e.g. UK IMBER January 2009) and need a 'good speaker on palaeo-oceanography', or someone to help me answer a question on physical oceanography. Of course, it also means that UK scientists in a wide range of subject areas see *me*, so when they're looking for a conference speaker or an external examiner or a scientific collaborator they might think of me, and when I phone up asking if they will give a presentation or would like to be part of a research project, they already know who I am. It seems a lot of what we do is enhanced through 'networking'.

Q: What advice would you give to someone starting off in marine sciences today?

Carol: Be open minded, ask questions, work hard, learn to think at both global and microscopic scales, remember how privileged you are, and try never to lose your sense of awe of, or wonderment in, the marine environment.

A closer look at Marine Conservation Zones and fisheries management

Joe Horwood

Marine Conservation Zones (MCZs) are a new tool for UK marine managers, which will be established through the *Marine and Coastal Access Bill* (see p.8). MCZs, along with EU designated sites of Special Areas of Conservation and Special Protected Areas, will form a network of Marine Protected Areas. MCZs will be established in four sea regions off England, Northern Ireland and Wales.

The Bill determines that MCZs will be used to conserve flora, fauna, habitats and geological structures. Draft Defra implementation guidance states that MCZs will conserve and aid the recovery of: the range of marine biodiversity in our waters; rare or threatened habitats and species; globally or regionally significant areas for geographically restricted habitats or species; important aggregations or communities of marine species; areas important for key life-cycle stages of mobile species, including habitats known to be important for their reproduction and nursery stages; areas contributing to the maintenance of marine biodiversity and ecosystem-functioning in our seas; and features of particular geological or geomorphological interest. The use of MCZs to aid commercial fisheries is not explicitly included. The reason for this is that other legal instruments can be used, and often such measures need to be implemented internationally.

Notwithstanding the above, fisheries scientists are often perceived as being neutral, at best, to the use of such marine protected areas to support fisheries, whilst others are impassioned advocates. There is some truth in this perception, and for good reason.

Fisheries science has a long tradition of quantitative argument. It uses mathematical models of life to explore options, and we can use such models to look at the benefits of a closed area.

A model fish stock and fishery

We are going to construct a 'model' of a fish stock and fishery based on North Sea cod. From this we will see how numbers of fish, and the catch, will change as we vary attributes of the fish and fishery. In particular we will use the model to see what happens to fish numbers if we introduce a closure of the spawning fishery.

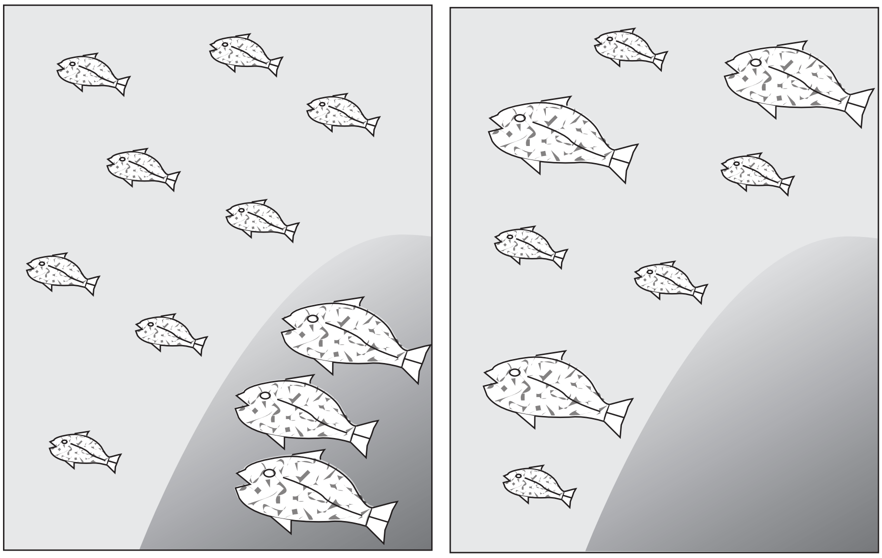

Figure 1 *Model representation of the effect of a spawning migration on the distribution of adult and juvenile fish:* ***(a)*** *at spawning time there is a segregation of adults onto the spawning grounds (darker grey area), where they are easier to catch;* ***(b)*** *outside of the spawning period, all ages of fish mix together.*

In our model fish stock, a constant number are born each year. The fish grow bigger at each age and natural mortality reduces with age. Juvenile and adult fish separate in spring, as adults mate on the spawning grounds, and they mix freely together for the rest of the year. Fish are caught in the fishery from age one. In spring, when the adults aggregate on the spawning grounds they are more accessible to fishing, so catch-rates are increased, by a factor ψ. A value of $\psi = 10$ means that the catch-rates of adults in the spawning fishery are 10 times higher than during the rest of the year, outside the spawning grounds. The effect of the spawning migration is caricatured in Figure 1.

In our model fishery, fleet-size does not change. Vessels fish at random on juveniles and adults for most of the year, but in spring a proportion of the fleet (θ), moves to the spawning grounds. If $\theta = 0.4$ then 40% of the fleet will fish on the spawning aggregations. As the fish have segregated, that part of the fleet will catch only adults, whilst the remaining 60% of the fleet will catch only juveniles.

The total fishing effort over the year is *E*.* We set *E* = 1.0 to generate a fishing mortality rate of unity, which is equivalent to catching 60% of the stock each year. The following results give the long-term steady-state size of the adult stock, and the total annual catch, for a range of the parameters described above. We can then examine the effect of a spawning closure by putting $\theta = 0$, i.e. the whole fleet stays away from the spawning ground, and remains fishing on the juveniles.

The effect of spawning closure

Table 1 shows the effect on adult spawning stock biomass (SSB), and the weight of the catch, of closing a

**E* is an 'instantaneous' fishing mortality rate.

Table 1 *Effect of closing the spawning ground to fishing (θ = 0) compared with the effect when 40% of the fleet moves to the spawning ground. Fishing effort E = 1, and there is a tenfold increase in adult catch rate on the spawning ground, so ψ = 10.*

		Proportion of fleet on fishing ground		
		40% (θ = 0.4)	**0% (θ = 0)**	change
ψ = 10	SSB	77.6	83	+ 7%
	Catch weight	803	790	– 2%

spawning fishery (θ = 0), compared with a scenario of 40% of the fleet fishing on the spawning adults (θ = 0.4), when in both cases it is assumed that spawning densities, and adult spawning catch-rates, are 10 times higher than for the rest of the year (ψ = 10).

The results show that an initial adult stock is increased by 7% by this closure whereas the annual catch falls by 2%. The closure would be beneficial for conservation but with a slight loss of catch.

The effect of different catch rates of spawning adults

Table 2 compares the above results (in italics) with calculations assuming that catch-rates of spawning adults are only twice as high as normal (ψ = 2). The spawning stock size is now higher than in the first scenario because the catch-rate on adults is lower and fewer adults are killed. The introduction of the spawning closure now results in a 19% decrease in the SSB. Total catch is relatively unchanged.

What we are seeing is that the saving of adult fish is more than offset by the additional killing of juveniles by the displaced effort. This additional mortality is not just inflicted once on a cohort, it occurs at ages one, two, three and four. In this case the spawning closure would be a disbenefit.

Effects of fleet aggregation

The above model, with catch-rates being twice as high at spawning (ψ = 2), can be used to examine the effect of different proportions of the fleet prosecuting the spawning fishery, from 10% to 90% (Table 3). The disadvantage of the spawning closure is steadily increased as more effort is displaced from the spawning fishery.

Total catches remain about the same and are not presented here. Essentially this stock, fished at rate of about 60% per year, has few adults left and annual recruitment from the juveniles to the mature stock is important.

Effects of a reduced fishing rate and of a closure

The effect of adult catch rate is examined in a case when the total annual effort is half of that used above (E = 0.5, Table 4). In this case we see a similar pattern to that of Table 2 but the relative benefits of a closure are enhanced, and the large disbenefit has virtually disappeared. Again changes in total catch are small. With lower total fishing pressure, there are more adults, and there are greater long-term benefits in their protection than when overall fishing effort was higher.

Table 2 *The effect of different catch-rates of spawning adults (assuming fishing effort = 1.0).*

		Proportion of fleet on spawning ground		
		θ = 0.4	**θ = 0**	change
ψ = 10	*SSB*	*77.6*	*83*	*+7%*
ψ = 2	SSB	103	83	–19%
ψ = 10	*Catch weight*	*803*	*790*	*–2%*
ψ = 2	Catch weight	799	790	–1%

Table 3 *The effect of varying degrees of fleet aggregation (assuming fishing effort = 1.0).*

	Proportion of fleet on spawning ground (θ)	**0**	**0.1**	**0.4**	**0.9**
ψ = 2	SSB	83	87	103	141
	Change in SSB	none	–5%	–19%	–41%

Table 4 *Comparison of the effect of reduced fishing rate on spawning grounds and of a closure (assuming fishing effort = 0.5).*

		θ = 0.4	**θ = 0**	change
ψ = 10	SSB	520	739	+42%
ψ = 2	SSB	758	739	–3%
ψ = 10	Catch weight	952	900	–5%
ψ = 2	Catch weight	924	900	–3%

Table 5 *Effect of reducing fishing rates, assuming catch rate on spawning ground, ψ, is 2.*

		θ = 0.4	**θ = 0**	change
E = 1	SSB	103	83	–19%
E = 0.5	SSB	758	739	–3%
	Change in SSB	+636%	+790%	
E = 1	Catch weight	799	790	–1%
E = 0.5	Catch weight	924	900	–3%
	Change in catch wt	+16%	+14%	

Table 6 *Effect of reducing fishing rates, assuming catch-rate on spawning ground, ψ, is 10.*

		θ = 0.4	**θ = 0**	change
E = 1	SSB	77.6	83	+7%
E = 0.5	SSB	520	739	+42%
	Change in SSB	+570%	+790%	
E = 1	Catch weight	803	790	–2%
E = 0.5	Catch weight	952	900	–5%
	Change in catch wt	+19%	+14%	

Effects of reduced fishing

Tables 5 and 6 (for $\psi = 2$ and $\psi = 10$, repectively) provide a direct comparison of the effect of reducing total effort (reducing *E* from 1 to 0.5) with the effect of a closure. The striking feature in each Table is that a reduction in total effort, or fishing mortality, gives a massive increase in the adult stock, dwarfing any positive effect of the closed spawning ground. Catches are also increased.

Conclusions

The above simple, but very realistic, model illustrates some important points. Table 1 shows that a closure of the spawning ground could benefit the fish. But Table 2 shows that it is dependent on the fish biology, in this case the shoaling density of the fish and hence its catch rates on the spawning ground. Table 3 shows that different results can be expected depending on how the fleet behaves. Table 4 shows that the benefits of a spawning closure are dependent upon the current fishing rates themselves. Table 5 shows that other measures can have much greater effects.

The conclusion that fisheries scientists draw from such work is that spawning (or other) closures may have a part to play in fisheries management, but that their application needs to be evaluated on a case by case basis that takes account of at least the biology of the fish, the intensity of fishing and the behaviour of the fishing fleet.

I have produced a 'rule of thumb' evaluation of the relative merits of proportional reductions in the fishing mortality on juveniles and adults (see Further reading) which stated that, if t_d is the number of years from recruitment to maturity, and *Z* is the adult fishing mortality rate, then if $t_d \times Z > 1.0$ the spawning stock is increased more by a proportional decrease in juvenile mortality rather than by a decrease in adult mortality. Application of this principle can be seen in the above results.

There are additional considerations. Small vessels may have limited ability to move and for safety reasons derogations may be needed to allow vessels to continue fishing locally. This tends to reduce the benefits of any closure.

There can be environmental concerns. Fishing patterns are generally conservative because new grounds often hold risk to gear. Consequently although fishing effort has been high in waters around the British Isles, areas of richer biodiversity remain. The 2001 closure of cod spawning grounds in the North Sea diverted effort onto new grounds and had a negative effect on biodiversity.

Finally, fisheries management is not shy of using closed or restricted areas. A recent review found that areas with spatial regulation of fisheries, such as the Mackerel Box to protect juvenile mackerel, regulated under EC rules, or Sea Fishery Committee regulations, in waters of England and Wales, extended to some 100 000 km^2 or about 35% of those waters.

Consequently, although fisheries scientists do support closed or protected areas for fisheries management, it must be remembered that it is easy to cause damage to the stock and to the environment by poor choices of closed areas. Each closure needs to be evaluated in its own right. And other measures might be more effective.

Joe Horwood
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Further reading

Horwood, J.W., J.H. Nichols and S. Milligan (1998) Evaluation of closed areas for fish stock conservation and the Trevose spawning ground. *J. Appl. Ecol.*, **35**, 893–903.

'A moment of quiet celebration' as the *Marine and Coastal Access Bill* becomes law

'The Bill has long been campaigned for by many people. This is a moment for quiet celebration ...' This is how Hilary Benn (Secretary of State for Environment, Food and Rural Affairs) welcomed the closing parliamentary debates on the *Marine & Coastal Access Bill*, and his feelings were no doubt shared by many.

The Bill received its final approval by the House of Lords on 11 November 2009 and is now an Act of Parliament and law in England and Wales. It sets up a new Marine Management Organization under which many diverse areas of marine regulation will be centralised, streamlines the existing marine licensing system, and provides powers to create a joined-up marine planning policy. It introduces new measures to reform fisheries management and provides a framework for establishing marine conservation zones (MCZs). Finally, it enables the creation of a walkable route around the English coast.

Some parts of the final Bill are not entirely to the liking of conservation groups. The Marine Conservation Society in particular had proposed three amendments. The first of these was that there should be a specific commitment in the Bill to designate 'Highly Protected Sites'. The proposal was not accepted, but MCS will receive written reassurance that there will indeed be highly protected sites, with the level of protection being decided on a site-by-site basis.

There was also concern that the Bill could allow socio-economic factors to over-ride conservation priorities: ideally MCZs should be identified using scientific criteria alone, like SSSIs on land. Again, there will be written reassurance that socio-econmic factors will be of secondary importance, only to be taken into consideration in choosing between sites of equal conservation value.

Clause 140 of the Bill makes it illegal to damage protected features of MCZs, but this clause is qualified by another providing a blanket defence for any activity done in the course of sea fishing. In recognition of objections, a new provision gives a power to the Secretary of State to restrict or remove the 'sea fisheries defence' in the future. Removing it now would be a breach of our European obligations under the Common Fisheries Policy (unless it were to apply only to UK boats) but the amendment means that it can be changed when the CFP is reformed.

The following reports may be downloaded from www.naturalengland.org.uk (along with many others).

Sea fisheries: steps to sustainability (NE 193) How sustainable fishing methods and improved management could contribute to conservation and secure a profitable fishing industry. The report calls for a radically reformed CFP, with ecological objectives at its core.

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The Challenger Society for Marine Science

Challenger 2010

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Dr Tim Kruger : Debator in Ocean Geoengineering
Dr David Santillo : Debator in Ocean Geoengineering
Dr Emily Shuckburgh : Probing the Polar Oceans
Dr Darius Campbell : Safe Seas for the Coming Century
Dr Vicky Pope : Dealing with Uncertainty in Models and Observations

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Explaining 'the other CO_2 problem'

Plymouth school students rise to the challenge of communicating the science of ocean acidification

Kelvin Boot

Ocean acidification is widely regarded as 'the little sister' of climate change, both born of the same carbon dioxide parent but each with its own personality. Ocean acidification science is relatively simple – CO_2 is absorbed at the ocean surface and combines with seawater to produce a weak acid – a lowering of ocean pH. Under natural circumstances the balance between absorbed CO_2 and overall ocean chemistry would remain more or less constant and the life-forms that inhabit the sea would stay in harmony with their environment. Now, that balance is under threat from the spectre of ocean acidification, as seawater pH drops and the ocean moves further towards acidity due to a growing concentration of CO_2 in the Earth's atmosphere resulting from human activities such as burning fossil fuels and cement manufacture.

Our understanding of the impacts of ocean acidification is still fairly basic: the chemistry may be clear but the longer term effects on marine environments are the focus of increasing research interest. Some experimental work shows that calcifying organisms, like corals and molluscs, and planktonic organisms such as coccolithophores, are likely to be restricted when it comes to shell or skeleton building. Other research appears to contradict these findings. So, as with all challenges there are potential winners and losers, we just don't know what they will be or how they, in turn, will affect the rest of the marine ecosystem. What is not in doubt is that the chemistry of the ocean is changing and that is bound to have an effect on the life within it. And whilst almost everyone has heard of climate change, very few are familiar with the concept of ocean acidification.

Carol Turley (Plymouth Marine Laboratory) spends part of her time engaging with policy-makers, politicians and other stakeholders through seminars, meetings and briefing documents highlighting what ocean acidification is likely to mean, but she wanted a more accessible method that could bring the message home to the public. Remembering a successful project with a local school that led to the production of a short, award-winning film about climate change, Carol approached Plymouth's Ridgeway School again, this time to tackle the subject of ocean acidification.

Ridgeway teacher Karen Findlay accepts that not everyone finds science fun and so she is always on the lookout for innovative ways of engaging pupils. Under her guidance, the project became a real team effort, with students across the school's entire age-range being advised by professional film makers, becoming inspired after a visit to the National Marine Aquarium to meet the 'cast', and helped out with the science by Carol Turley and Helen Findlay (also from PML). Stuart Moore from Sundog Media worked with the students on the previous film and so had no doubts that they could produce the goods: 'With a tight deadline of one week, a complex subject and an age-range from 11 to 15 they have to work as a team, and they did. We helped with technical backup and advice, but it is very much their film, with their ideas and their emphasis.'

The students used a low-tech approach of clay modelling to create the stars of the film, then followed up with sophisticated computer-based animation techniques to bring them to life. This method produces immediate results, allowing the students to make improvements as they went along. The resulting film stars King Poseidon and his team of advisors: Doctorpus, Britney Star and Squid Marley. Each agent reports back to the King about how acidification is affecting their ocean. The film ends with a plea from the under-sea world to us terrestrials to stop producing the CO_2 that is slowly but surely killing Planet Ocean.

Fifteen year-old Merryn Hunt summed up the students' feelings: 'We were shocked; we hadn't heard of this before and we felt we had to do something. We had heard of climate change, but now there are two threats and we have a chance to make a difference ... I've told friends and family, and everyone is as shocked as me. We can all make a difference by simple things like turning lights off, it all adds up.' Fellow student Ruth Blake-Lobb added: 'We know that this film will make a difference. It's important and it has a real message. Above all it's in our language for our age group. It makes me feel really proud to know that someone like a Prime Minister might see it and think a bit more. It would be great if Barrack Obama gets to see it – we've sent a copy to his kids in the US.'

There's no doubt that this film is short enough and hits the right level for the 'busy' generation of youngsters to take note, and within Ridgeway School it has already had an impact. What's more, it's equally effective in engaging adults. 'The Other CO_2 Problem' was premiered at the Copenhagen Climate Change Congress earlier this year, followed by an airing at the Royal Institution in March; it created quite

Creating the 'Doctorpus' character: the success of the film proved that simple techniques can have powerful results

a stir at the recent EPOCA (European Project on Ocean Acidification) science meeting in Plymouth and has won the Royal Society of Chemistry Bill Bryson Award for Science Communication. During and after its making it attracted wide media interest, featuring on BBC network news, Newsround and many local media outlets; it is even being shown on a specialist TV channel in Brazil. It has been translated into German and French, has been linked through many environmental websites and blogs, and is the subject of much newspaper and magazine coverage. Such is its impact that since the original DVD pressing, funded through EPOCA, it has received further support from the European Geological Union and the Oak Foundation.

The prize-winning animated film, 'The Other CO_2 Problem', can be accessed through:

PML website:
www.pml.ac.uk

EPOCA website:
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YouTube:
www.youtube.com
watch?v=55D8TGRs14k

Carol Turley is very pleased with the reception the film has enjoyed: 'We knew the film would be good and we hoped it would make an impact but even we were surprised. It obviously strikes a chord with everyone who watches it. It makes people – people who make decisions – realise that the upcoming generation is concerned. They have made it clear through this short film that they want something done. This year is going to be very important for new climate change negotiations and this little film is going to be crucial in bring the other CO_2 problem to the forefront of the minds of policy makers.'

Kelvin Boot
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Two new Oceanography Professorships

... at SAMS ...

Toby Sherwin of the Scottish Association for Marine Science (SAMS) has been awarded a personal chair by the UHI Millennium Institute (www.uhi.ac.uk), for his contributions to physical oceanography. This makes him the first Professor of Oceanography at SAMS.

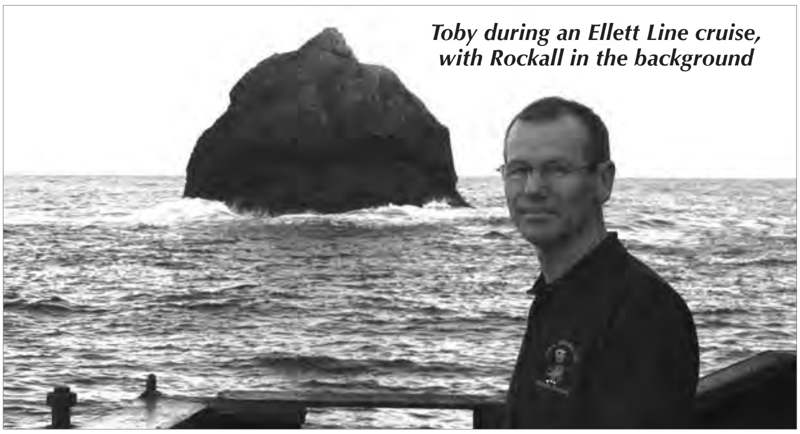
Toby is particularly well known for his expertise on the generation and properties of internal waves. More recently his research has focussed on ocean circulation, particularly the nature and causes of the variability in ocean currents in the North Atlantic and the oceanography of the Faeroe–Shetland Channel. In the last few years he has been investigating the properties of dense overflows across the Wyville–Thomson Ridge and into the Rockall Trough.

Whilst at SAMS, Toby inherited the Ellett Line, a hydrographic section across the Rockall Trough which was initiated in 1975 by Dave Ellett. This section has been maintained in collaboration with the National Oceanography Centre at Southampton and has been extended out to Iceland. Always looking towards the latest technology, Toby is pioneering the introduction of a marine 'glider' to supplement observations across the Ellett Line. In this regard, Toby is at the forefront of the development and application of marine gliders in the UK.

In his 30 years of research activity, Professor Sherwin has published over 45 peer reviewed papers and 64 reports. He is also making valuable contributions to teaching and providing students with opportunities to go on research cruises. He is highly committed to public understanding of science through raising awareness of the inherent environmental risks of continuing CO_2 emissions. Toby is well known within the Challenger Society community and is a regular attendee of the Challenger conferences.

... and in Liverpool

From January 2010 Jonathan Sharples – another strong supporter of the Challenger Society – will take up a Professorship with the University of Liverpool. His post, supported equally by the University and the Natural Environment Research Council, is in the Department of Earth and Ocean Science (soon to become part of a larger School of the Environment). It allows Jonathan to spend half of his time at the University and half at POL, where he will continue to lead the Shelf Sea Processes Programme and the Irish Sea Observatory.



Toby during an Ellett Line cruise, with Rockall in the background

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Toby Sherwin of the Scottish Association for Marine Science (SAMS) has been awarded a personal chair by the UHI Millennium Institute (www.uhi.ac.uk), for his contributions to physical oceanography. This makes him the first Professor of Oceanography at SAMS.

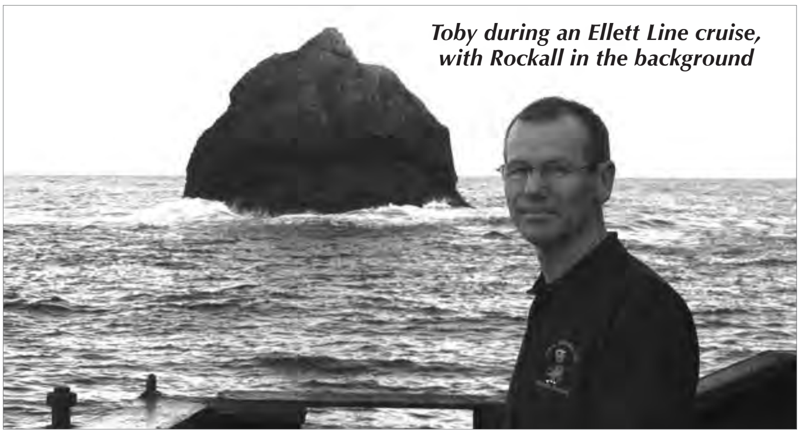
Toby is particularly well known for his expertise on the generation and properties of internal waves. More recently his research has focussed on ocean circulation, particularly the nature and causes of the variability in ocean currents in the North Atlantic and the oceanography of the Faeroe–Shetland Channel. In the last few years he has been investigating the properties of dense overflows across the Wyville–Thomson Ridge and into the Rockall Trough.

Whilst at SAMS, Toby inherited the Ellett Line, a hydrographic section across the Rockall Trough which was initiated in 1975 by Dave Ellett. This section has been maintained in collaboration with the National Oceanography Centre at Southampton and has been extended out to Iceland. Always looking towards the latest technology, Toby is pioneering the introduction of a marine 'glider' to supplement observations across the Ellett Line. In this regard, Toby is at the forefront of the development and application of marine gliders in the UK.

In his 30 years of research activity, Professor Sherwin has published over 45 peer reviewed papers and 64 reports. He is also making valuable contributions to teaching and providing students with opportunities to go on research cruises. He is highly committed to public understanding of science through raising awareness of the inherent environmental risks of continuing CO_2 emissions. Toby is well known within the Challenger Society community and is a regular attendee of the Challenger conferences.

... and in Liverpool

From January 2010 Jonathan Sharples – another strong supporter of the Challenger Society – will take up a Professorship with the University of Liverpool. His post, supported equally by the University and the Natural Environment Research Council, is in the Department of Earth and Ocean Science (soon to become part of a larger School of the Environment). It allows Jonathan to spend half of his time at the University and half at POL, where he will continue to lead the Shelf Sea Processes Programme and the Irish Sea Observatory.



Toby during an Ellett Line cruise, with Rockall in the background

Martin Angel and Bettina Schmitt

Each year in late autumn, RV *Polarstern* leaves Bremerhaven to steam south to service the German Antarctic station. During the long haul south, sea-time is made available to make observations along the transect down to the Southern Ocean – a German equivalent of the Atlantic Meridional Transect Programme (AMT) run by Plymouth Marine Laboratory. At the end of October 2007 *Polarstern* left Bremerhaven to make the long voyage south. This cruise – *Polarstern* ANT XXIV – was an important milestone for the ship, being its 25th anniversary, and on the following leg there were real-time interviews in the media between the principle scientists and the German Chancellor, Angela Merkel.

Onboard *Polarstern* there was a multinational (eleven nationalities) mix of scientists from a variety of disciplines, but predominantly biologists, who were to make observations while the vessel was underway. The main thrust of the first leg of the cruise was to collect a series of very deep net tows under the aegis of the Census of Marine Zooplankton (CMarZ) Programme (see Box below). The objectives were to discover new species, to plot the zoogeographical ranges of bathypelagic and abyssopelagic zooplankton species (those living in deep water, down to the sea-bed) and to sequence segments of the DNA of as many plankton species as possible. By 2010 CMarZ hopes to sequence the DNA of every known holoplanktonic species – i.e. every animal species that spends its entire life living in the plankton.

Overview of the Census of Marine Zooplankton (CMarZ)

The Census of Marine Zooplankton is working to produce a global assessment of the species diversity, biomass, biogeographic distribution and genetic diversity of holozooplankton, focussing on the ~7000 described species. CMarZ has carried out comprehensive biodiversity surveys, particularly in the deep sea, under-sampled regions, and biodiversity hotspots, using an integrated morphological and molecular (DNA barcodes) approach to analysis and assessment.

The growing DNA barcode database will serve as a Rosetta Stone for species identification of individual specimens and environmental sequencing of bulk samples. The CMarZ database contains species-level, specimen-based, geo-referenced entries; data and information are accessed via the CMarZ and CMarZ-Asia websites (http://www.cmarz.org and http://www.cmarz-asia.org/db/), as well as the Ocean Biogeographical Information System, OBIS (www.iobis.org/).

The scientific party therefore included an unusually large contingent of a dying breed – biologists capable of identifying live plankton. Many of these experts are now past retiring age, and almost past their sell-by date! They still, however, have much to offer – although one of us (Martin) is more than a little prejudiced in this matter, being, at 70, the most ancient of the scientific party! At sea, it was evident that the work-rate of the 'golden oldies' matched many of the younger personnel. However, the group that worked the longest hours were the young cadre, who under the guidance of Ann Bucklin (University of Connecticut), extracted DNA from the specimens we picked out and identified. All these extracts were deep-frozen and transported back to Connecticut, but in many cases the CO1 gene was sequenced at sea, a process known colloquially as DNA finger-printing.

The samplers of choice were MOCNESS nets. These nets were designed by Peter Wiebe (WHOI) who was onboard with his CMarZ team of Dickie Alison and Nancy Copley, and operated the MOC 10 system (Figure 1). Fred Bucholz operated the MOC 1, which belonged to the Alfred Wegener Institute for Polar and Marine Research. The MOCNESS system is towed on a conducting cable and is controlled from a console onboard the ship. Sequences of 10 samples are collected by the MOC 1 (mouth area 1 m^2) and 5 samples by the MOC 10 (mouth area 10 m^2); during each tow the nets can be opened and closed at will, and a whole range of physical parameters monitored. Since zooplankton living below 1000 m are extremely sparsely distributed, the MOC 10, which samples large volumes of water, was specially fitted with fine-mesh nets so as to catch as many zooplankton as possible (it is usually worked with large-mesh nets to sample large micronekton such as shrimps and small fish). The protocol was for Peter to fish long oblique tows with the MOC 10 from 5000 to

1000 m, while Fred sampled the more densely populated depths from 1000 m to the surface with the MOC 1. At each station, vertical net tows were also collected using the German Multinet sampler as part of a long-term series of a north–south transect of samples, a programme directed by Sigi Schiel, who was the Principal Scientist for this leg of the cruise. (See Figure 2(a) for details of sampling undertaken off West Africa.)

Other groups included Jonathan Barber and Clare Benskin (Lancaster University) who were collecting atmospheric POPs (persistent organic pollutants) being blown offshore, and were also avid bird-watchers. Another group led by one of the authors (Bettina) was sampling phytoplankton, while a third group, in one of the ship's small boats, was measuring irradiance both at the surface and, whenever possible, down through the water column. A meteorologist gave us daily briefings on what the weather was likely to be, and in the context of what follows below, provided some excellent background.

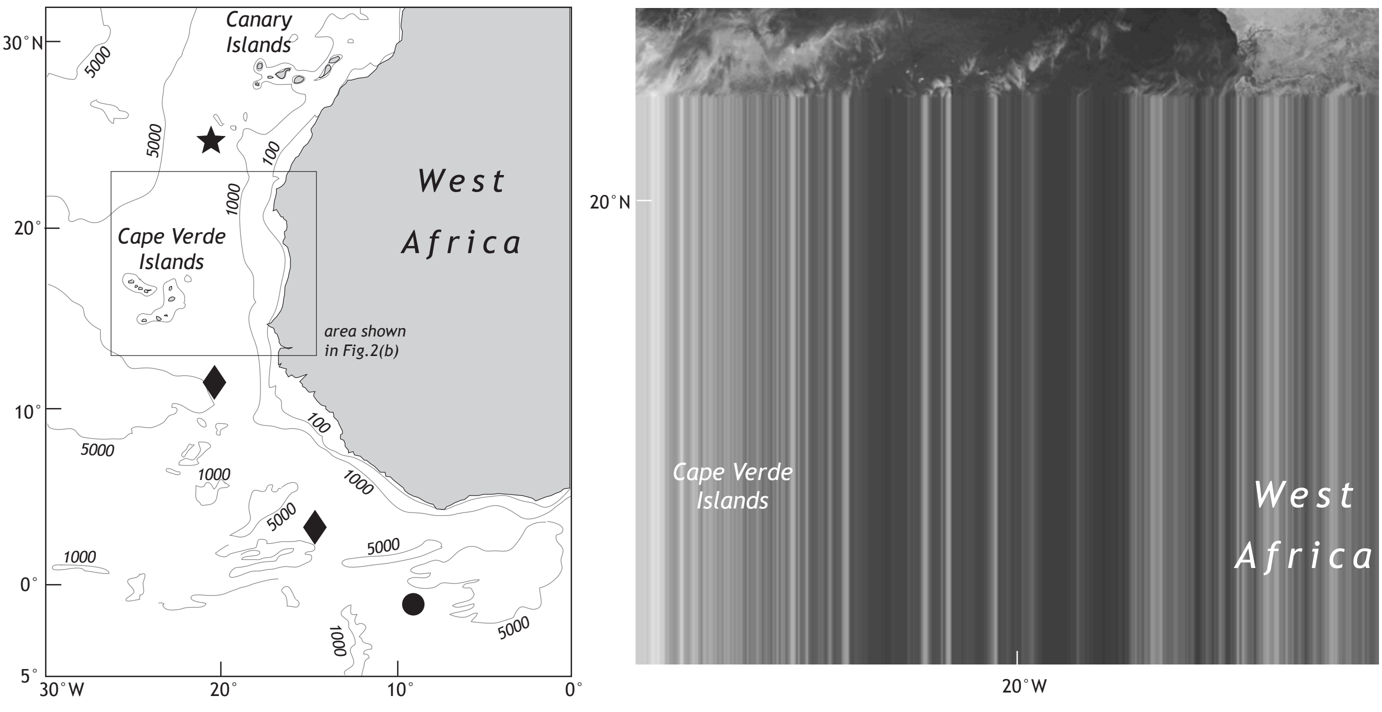
After a boat-exchange of scientists at Gran Canaria, dropping off some technicians who had tested the new Parasonde system, and picking up some biologists who had been unable to be on the ship during the five days it took us to get to the Canary Islands, we steamed on south towards the Equator. On the morning of 7 November, when the ship was near 17°15′ N, 21°W, at least 200 nautical miles from land and not far from the Cape Verde Islands, we woke to find the weather had turned very hot and muggy. The atmosphere was murky and there was a distinctly unpleasant smell of land on deck. Underfoot the decks were crunchy, thanks to a covering of fine dust.

Figure 1 *The MOCNESS 10 being hung up to allow the rigging to be checked. MOCNESS = Multiple Opening/Closing Net and Environmental Sensing System; the MOCNESS 10 carries five separate nets which are fished sequentially.*

The MOCNESS 10 system was used to sample waters > 1000 m, which are only sparsely populated with zooplankton

Figure 2 ***(a)*** *Locations of sampling stations off West Africa on the November 2007* Polarstern *cruise:* ★ *Gear-testing site.* ◆ *MOCNESS 1; MOCNESS 10.* ● *Multinet sampler; radiometer (100 m); fluorometer (100 m); use of small boat. Contour depths are in metres.* ***(b)*** *Satellite image of part of the area affected by the dust cloud, the effects of which were observed onboard* Polarstern *(by courtesy of NASA).*

Polarstern ***workers were able to observe the effect of dust-laden winds***



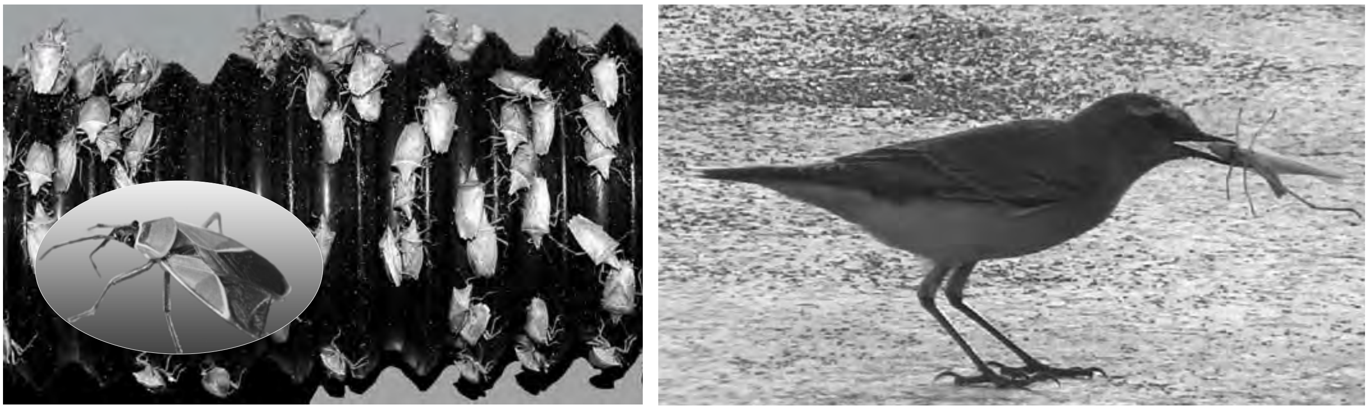
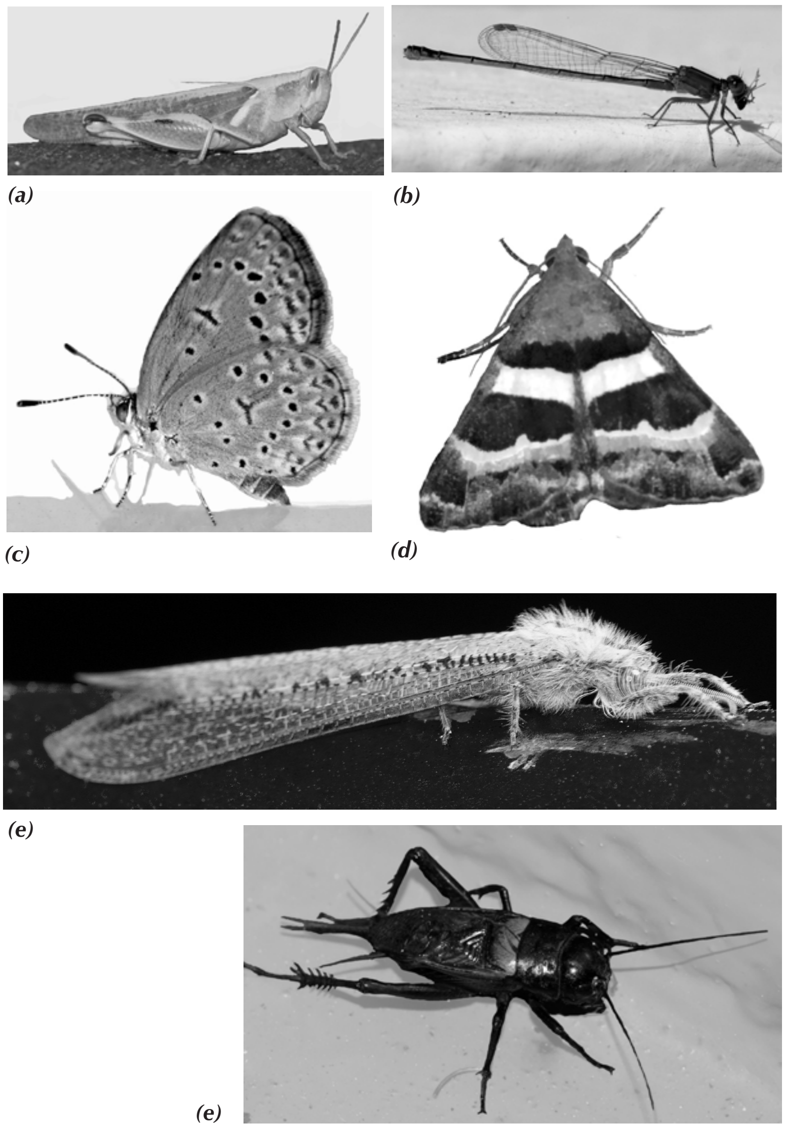

(a) (b)

Figure 3 ***(a)*** *Some of the numerous plant-eating bugs that landed on the ship;* ***(b)*** *a desert wheatear, also blown offshore, consuming a grasshopper.*
Photo (b) by courtesy of Jonathan Barber.

Figure 4 *Some of the insects that were collected from the deck of the* Polarstern: ***(a)*** *grasshopper,* ***(b)*** *damselfly,* ***(c)*** *blue butterfly,* ***(d)*** *moth,* ***(e)*** *neuropteran, and* ***(f)*** *cricket (*Gryllus bimaculatus*).*

Examples of the rich assortment of insects that landed on the deck


(a) (b) (c) (d) (e) (e)

Then we saw, hopping across the deck, a grasshopper – then another and another and another. During the next day, vast numbers of insects landed on the ship, providing useful snacks for several land birds, which had joined at much the same time (Figure 3). The variety of insects was quite amazing. We wandered round the decks of the *Polarstern* picking up as many different types of insect as we could find, and had soon collected over thirty species. In places on deck the accumulations of corpses of thousands of plant bugs had to be hosed away to get the decks clean (cf. Figure 3(a)).

The ship was continually buzzed by several varieties of hawker dragonflies, and there were several species of the less powerfully flying damselflies. There were at least three species of butterfly and about 10 species of moth, a host of different plant bugs and a large and spectacular neuropteran (a relative of the ant-lion) (Figure 4). There were several desert locusts, and many large black crickets, *Gryllus bimaculatus,* scuttled across the deck.

One of us (Martin) had encountered these crickets before in February 1968 when *Discovery* was working even further offshore, about 500 n.m. from the coast. On that occasion the nocturnal singing of the hoards of crickets that had come aboard produced such an ear-piercing cacophony that the watch-keepers were unable to sleep and there was nearly a mutiny. When, at night, neuston nets (nets that sample the upper 10 cm of the water) were deployed, they caught lantern fish (myctophids) that had migrated up from daytime depths of 500 m. They had gorged themselves with crickets and will have passed the remains at their daytime depths. Indeed, when these same fishes and other non-migrant fishes were sampled during the day at mesopelagic depths (250–750 m), their guts were all full of cricket remains. Peter Foxton recounts that when he was sampling off Woods Hole in the 1960s, he encountered a similar phenomenon with swarms of ladybirds.

As a consequence of the 1968 event, for several years one of us (Martin) was designated to run suction traps at sea to sample what Alister Hardy had termed 'aerial plankton', but all the pumps caught were soot particles from the ship's funnel! At the time, the entomologists at the Agricultural Research Station at Rothampstead were actively engaged in tracking insect migrations; each year, swarms of aphids were being blown into the UK from Europe, and were causing substantial damage to British agriculture. Movements of locusts have been of importance since biblical times, and still cause considerable damage to crops in sub-Saharan Africa. Maybe the recent increases in grain prices will rejuvenate interest in such migrations by insects.

So, are our current organic flux studies missing a trick? Maybe in most oceans such events either do not occur or have a negligible impact. But, in the North Atlantic oligotrophic (low-nutrient) gyre, could terrestrial exports of organic material be having a significant impact on the dynamics of the midwater ecosystem?

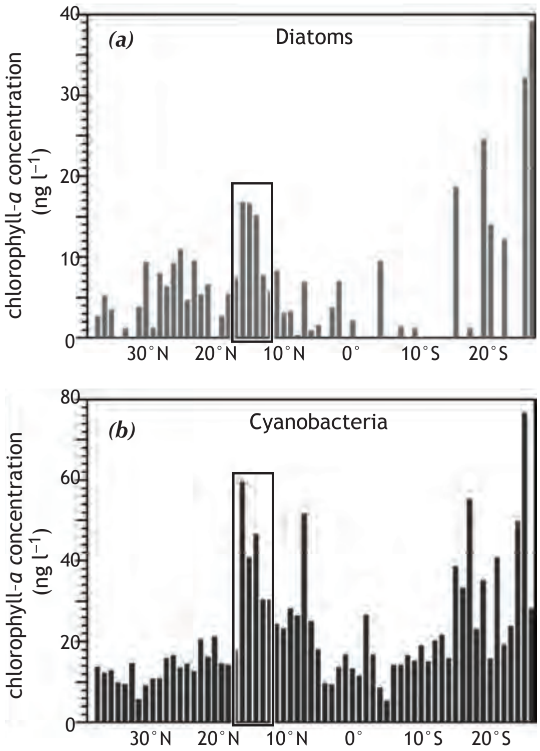
The importance of terrestrial exports from the African continent to the North Atlantic ecosystem has been well documented in the past, but more in the context of the impact of Saharan dust, rich in iron, and fuelling primary production.* The significance of iron as a limiting nutrient in marine systems has been the focus of several large-scale fertilization experiments around the globe, looking to enhance primary production in order to increase CO_2 uptake. Our phytoplanktonologists on board confirmed these experimental results by observing a peak in certain phytoplankton groups that coincided with the Saharan dust event. As shown in Figure 5, both diatom and cyanobacteria chlorophyll-*a* concentration increased considerably in the water samples taken between 17° and 10° N when our vessel was cruising through waters that had been hit by the Saharan dust storm.

An increase in particulate organic carbon (POC) – faecal pellets, bacteria, phytoplankton, marine snow, mucus etc. – is generally linked to growing phytoplankton populations. The data analysed by the phytoplankton group following the *Polarstern* expedition could also confirm this relationship for the dust-induced increase of some phytoplankton groups. The samples that showed higher chlorophyll-*a* concentrations for diatoms and cyanobacteria (Figure 5) also showed higher POC and total nitrogen concentrations (Figure 6).

Other implications

It is not only oceanographers who are actively interested in these events. The dust clouds cool the surface of the Atlantic, and hence reduce the frequency of Atlantic hurricanes. They are easily seen by Earth-observation satellites and our event was well mapped by the Total Ozone Mapping Spectrometer (TOMS). Images of the dust cloud over the Cape Verdes are available on the web on the Earth Observatory and Natural Hazards website (http://earthobservatory.nasa.gov/NaturalHazards). On the same website is an image taken on 7 November of extensive agricultural burning in Senegal and Mali, no doubt the source of the rather nauseating smell we experienced at sea, indicating that these fires were contributing to the export of all sorts of 'interesting' chemicals. The same sensor also mapped locust swarms moving across the Sudan; could our locusts have originated from much the same source? On

*Saharan dust is also believed to be an important source of nutrients for the Amazonian rainforests.



Standard underway measurements of surface water revealed the ocean's response to the dust event

Figure 5 *Chlorophyll-*a *concentrations of **(a)** diatoms and (**b**) cyanobacteria for the water samples taken on the* Polarstern *cruise in November 2007 (cruise XXIV-1 of the German ANT programme). The box indicates the days of the Saharan dust event.*

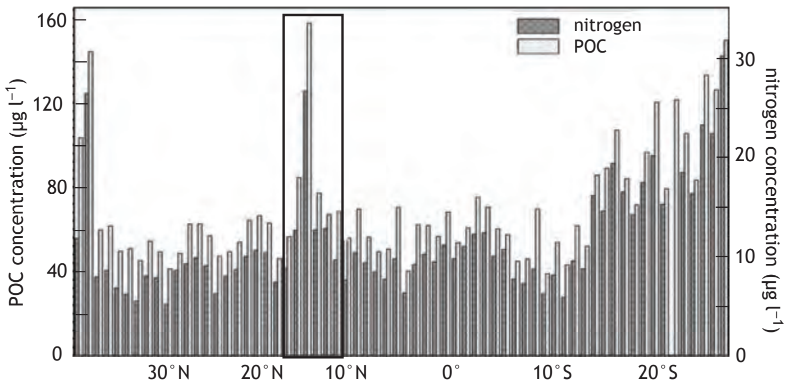


Figure 6 *Concentrations of particulate organic carbon (POC) and total nitrogen for the water samples taken on the November 2007* Polarstern *cruise. The box indicates the days of the Saharan dust event.*

11 November, the dust was reported arriving at the Caribbean island of Guadeloupe where it persisted for four days.

Estimates of the quantities of dust being transported annually range between 250 and 500 million tonnes, and over half is reported to come from a single location, the Bodélé Depression, close to Lake Chad. With erosion at such a rate, supplying so much dust, it is hardly surprising that there is now a depression at the main source of the dust. Since fine mineral particles are well known to cause respiratory and heart disease, these seasonal winds (known as the Harmattan in West Africa) are considered important contributors to the 'African Burden of Disease'.

Perhaps the peak in surface chlorophyll that coincided with our dust event suggests that those who are conducting iron fertilization experiments should pay greater attention to the seasonality (or periodic recurrence) of these natural events. They occur over far greater spatial scales than can be achieved in experimental fertilization experiments, and so offer a much greater opportunity for understanding the longer-term and larger-scale impacts of iron fertilization.

Such observations will be particularly relevant just now, in light of the commercial proposals to use iron fertilization of the open ocean as a way of off-setting carbon emissions. Considerable concern is being expressed at meetings of the International Maritime Organization not only as to the effectiveness of such fertilization in drawing down atmospheric carbon dioxide, but also about the long-term impact on ocean ecosystems. Should such 'fertilization' be regarded as an effective contribution to moderating increases in atmospheric carbon dioxide, or as unacceptable dumping of industrial waste?

Further reading

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Perry, S.M. and D.G. Fautin (2003) Beginning with the *Challenger* (about OBIS), *Ocean Challenge,* Vol.13, No.1, 4–6.

Ridgwell, A. (2002) The 'inconvenient ocean': undesirable consequences of terrestrial carbon sequestration, *Ocean Challenge,* Vol. 12, No.1, 28–32.

Martin Angel* Since he retired 12 years ago Martin has been keeping his hand in with the taxonomy of planktonic ostracods. As one of three people competent to identify these poorly known but important animals he continues to be in demand for his expertise at sea and has produced a comprehensive web-based atlas for the ostracods in the Atlantic at http://www.nhm.ac.uk/research-curation/research/projects/atlantic-ostracods/index.html.

*National Oceanography Centre, Southampton, SO14 3ZN, UK. Email: mva@noc.soton.ac.uk

CMarZ achievements to date

- Completion of more than 100 cruises since 2004; collection of plankton samples from more than 12 000 stations; analysis of an additional 6500 archived samples.
- Discovery of 85 new species; formal description and publication of 47 new species in 7 new genera and 2 new families (see http://www.cmarz.org/gallery new species.html).
- DNA barcoding of nearly 30% of described species of holozooplankton carried out at five CMarZ barcoding centres (University of Connecticut, USA; Ocean Research Institute, Japan; Institute of Oceanology, Chinese Academy of Sciences; AWI, Germany; National Institute of Oceanography, India);
- Training of new zooplankton taxonomists through 37 educational workshops and courses, numerous international student exchanges, and other capacity-building efforts that have reached more than 400 participants.

Acknowledgement

We would like to thank Nancy Copley and Peter Weibe for their assistance with the Boxes relating to CMarZ and the map in Figure 2.

Bettina Schmitt† is a post-doctoral researcher in the Helmholtz University Young Investigators Group, 'Phyto-optics', at the Alfred Wegener Institute for Polar and Marine Research in Bremerhaven, Germany. The group's aim is to improve estimates of marine primary production by retrieving new bio-optical information from the ESA satellite sensor SCIAMACHY. Bettina provides the ground-truth data for the group, performing field and laboratory measurements of bio-optical and biochemical parameters for characterizing different phytoplankton functional groups.

† Alfred-Wegener-Institute for Polar and Marine Research D-27570 Bremerhaven, Germany; Email: Bettina.Schmitt@awi.de; see also http://www.awi.de/en/go/phytooptics

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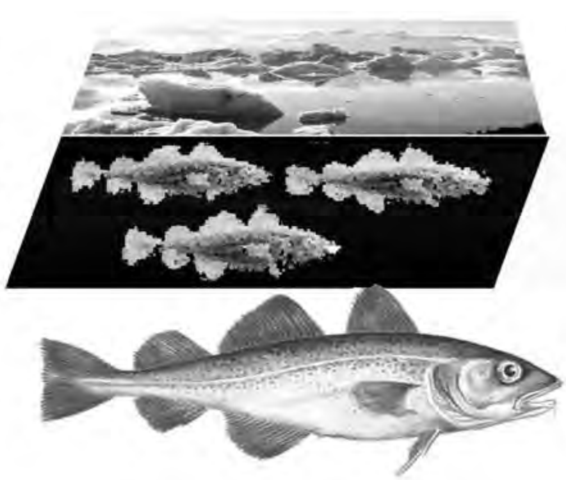
It's not too late to see what's been happening in the International Polar Year!

The International Polar Year (IPY 2007–8), organized through the International Council for Science (ICSU) and the World Meteorological Organization (WMO), officially ended in March 2009. The time-table allowed IPY 2007–8 to cover two full annual cycles from March 2007 to March 2009 giving full and equal coverage of both the Arctic and the Antarctic. IPY 2007–8 was the fourth 'polar year', the previous ones being in 1882–3, 1932–3, and 1957–8. Although IPY 2007–8 has ended, the IPY website – a source of a wide-ranging and fascinating information – has moved to a new site under the Arctic Portal where IPY.org will have a permanent home.

This December marks the 50th anniversary of the signing of the Antarctic Treaty. In celebration, the Antarctic Treaty Summit: Science – Policy Interactions in International Governance is being convened in Washington to highlight lessons learned about international governance 'with the interests of science and the progress of all mankind'.

See p.27 for the story of Frank Wild, who was awarded the Polar Medal for 'extreme human endeavour against the appalling weather and conditions that exist in the Arctic and Antarctic' (right: reverse of medal, showing the* Discovery *Expedition sledge party).

Cod in the deep freeze



Phil Williamson

From a human perspective, the climate of the past century or so is ‘normal’, providing the baseline either for future global warming or past glacial periods. But from a more objective, geological perspective, the present day can be regarded as either anomalously cool, in comparison with the average for the past 65 million years (the Cenozoic Era), or warm, in comparison with that for the past 2 million years (the Quaternary Period). Focussing on the latter, humans evolved – together with most other species around today – during a time when polar ice-sheets were mostly much thicker and more extensive than they are now and, since so much water was then ice, with global sea-level mostly considerably lower. Glacial conditions inevitably had major effects on marine organisms; indeed, distributional changes in foraminiferans have been used to reconstruct temperature regimes in the open ocean. However, much less is known about the implications of major natural climate change for shelf-sea species and communities. A recent multidisciplinary analysis of the glacial biogeography of Atlantic cod is summarized here, with speculative consideration of implications for an ice-free Arctic in the relatively near future.

Shelf seas currently cover around 7% of the Earth’s surface. Not that great, yet they have much more significance in terms of global marine primary and secondary productivity, and consequently as the source of harvested marine resources. In biomass terms, 8 out of the top 10 fish catches worldwide involve shelf-sea species (FAO State of world fisheries and aquaculture; www.faoorg/fisheries/sofia/en). But it has only been in the past ~10 000 years that the shelf seas that we are familiar with today – such as the Irish Sea, North Sea and Baltic – came into existence, having been either land or under ice for the previous 120 000 years. The last glacial/interglacial cycle was the most recent of more than 20 such events in the Quaternary Period, with global mean temperatures and sea-level yo-yoing together over ranges of around 5 °C and 100 m respectively. Since the extremes of cold generally became more intense, much of the direct geomorphological evidence of one glacial maximum was physically removed by the one that followed. Within a single cycle, the cold glacial conditions generally lasted an order of magnitude longer than the warm interglacial ones.

To investigate the biogeographical consequences of the last glacial maximum for the Atlantic cod *Gadus morhua*, six scientists recently pooled their very different skills. In the UK, Grant Bigg and Martin Wadley tailored their palaeoclimate models to provide the spatial and temporal framework for the study; in Norway, Geir Ottersen brought together relevant information on cod ecophysiology and population biology; whilst in the USA, Cliff Cunningham and Grant Pogson re-analyzed existing genetic data and carried out additional DNA sequencing to elucidate cod’s family history. My role was as instigator and cheer-leader for this ‘spare time’ research project; the team never met as a single group, and there were times when a publishable outcome seemed extremely unlikely.

The starting point was a synthesis of knowledge about where Atlantic cod live now, using extensive stock-specific ICES* data. This information was then used to define a ‘climate envelope’ of environmental factors that strongly correlate with, and hence are likely to constrain (directly or indirectly), the species’ distribution. Such methods, originally developed by terrestrial ecologists and crop scientists, typically define a free-living or cultivated species’ distribution in terms of temperature data (annual mean isotherms, extremes or length of growing season) which might be combined with other parameters, such as rainfall. Those two-dimensional boundaries can then be used to show potential for range extension, or to predict or hindcast likely future or past ranges under different climatic regimes. Interactions with other species (predators, prey or competitors) are generally excluded; however, they could potentially be included through consideration of their own climate envelopes and overlap effects.

For marine species, a three-dimensional approach is needed, taking account of water depth; furthermore, there is a strong rationale for focussing on conditions at and soon after spawning. That is not only because reproductive success is self-evidently critical to species’ survival, but also because there are physiological reasons why optimal environmental conditions are needed for successful reproduction by cod (and other aquatic animals). Thus

*ICES, the International Council for the Exploration of the Sea, coordinates and promotes marine research on oceanography, the marine environment, the marine ecosystem, and living marine resources in the North Atlantic. See http://www.ices.dk/indexfla.asp

At the present day, adult cod live in shelf waters < 500 m deep

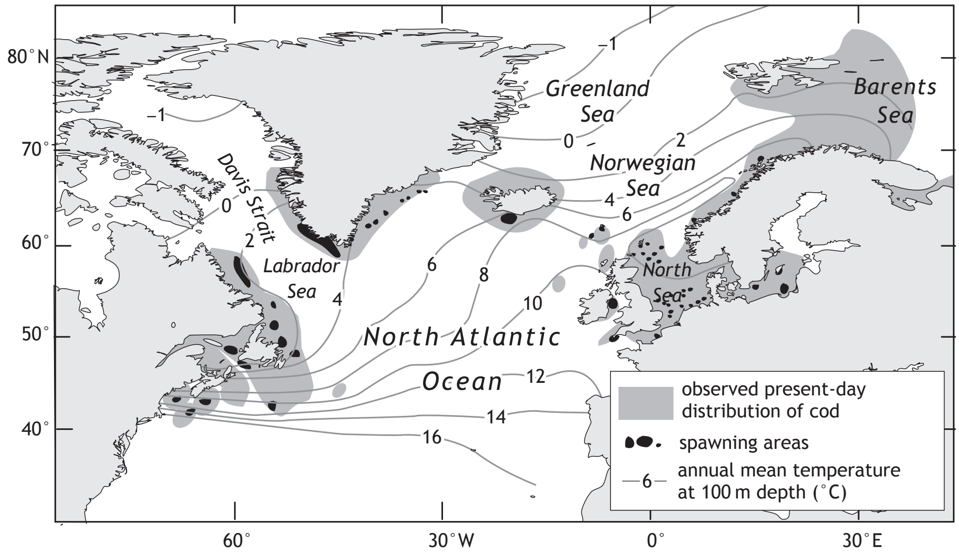


Figure 1 *Present-day distribution of adult Atlantic cod (*Gadus morhua*), and its spawning areas.**

breeding adults, eggs and young life stages of fish are inherently more sensitive to temperature stress, related to their increased oxygen demand during periods of high metabolic activity. A climate envelope for cod was therefore constructed using information on conditions where spawning occurs for 23 cod stocks covering the species' current North Atlantic range, from Cape Cod to northern Norway (Figure 1).

These empirical data show that cod predominantly spawn in water that is less than 500 m deep, between February and June at a time when surface waters are ice-free and at temperatures between 0 and 10 °C. A narrower temperature range of 3–7 °C can be considered to represent 'core' conditions, on the basis of multi-stock laboratory egg-survival studies and additional published analyses of field data, the latter showing that cod year-class success is more variable (and temperature-dependent) for populations at the species' northern and southern limits; i.e. although spawning may occur in water 0–3 °C and 7–10 °C, long-term population survival would not necessarily be ensured.

Present-day distributions could then be simulated by combining the environmental constraints either with measured climatologies (observed long-term averages of climatic variables) and bathymetry fields, or with a variable-resolution ocean circulation model providing a mathematical description of such conditions. The circulation model was originally developed to investigate the linkage between hydrodynamic and cryospheric processes in the North Atlantic; its spatial resolution was therefore greatest around Greenland, whilst its temporal resolution could also be adjusted in order to focus on palaeo-periods of particular interest. Both the climatological and model results gave a close match to the observed present-day distribution of cod stocks (Figure 1 and Figure 2(a),(b)), although both outcomes suggested that spawning could occur in a greater proportion of the adults' range than it currently does. Additional local factors (physical, chemical or biological) are therefore also important in cod's choice of specific spawning sites. Nevertheless, such factors do not substantively override the wider constraints determined by the climate envelope approach. The discrepancies that do occur between the observations, the climatologically derived maps and the model-based maps are partly due to limitations in the spatial resolution of the simulations; however, other complicating factors are that the models do not take account of climatic variability occurring on a 5–100-year time-scale, nor of any effects of recent human (over-)exploitation.

Whilst the effectiveness of model-based relationships in describing the existing situation is a good start, it is essentially a 'so what?' result; the interesting outcome arises when the climatic framework is changed to conditions at the last glacial maximum (LGM) around 20 000 years ago. In the LGM simulation (Figure 2(c)), the climate model included major changes in North Atlantic coastlines and bathymetry, reflecting sea-level changes and ice-loading; it also showed a decrease in sea-surface temperatures by as much as 12 °C, and a sharp temperature front at around 50 °N separating polar and temperate surface waters. Habitat considered suitable for cod spawning was reduced to ~20% of its present-day extent, mostly around Europe in the area of the present-day Bay of Biscay. Whilst some potentially suitable habitat was also identified around Iceland, Greenland and North America, this was fragmented and did not meet the core temperature criteria.

Can we believe the model hindcast? Did cod populations survive the LGM on both sides of the North Atlantic, or might the populations in the west (where suitable habitat was much reduced) have become extinct? At this point in the study, the genetic analyses proved decisive. Crucially, a time-scale could be included – based on the main opening of the Bering Strait, around 3.5 million years ago. This information could be used to calibrate the rate of genetic separation beteween Pacific cod *Gadus macrocephalus* and its Atlantic cousin *G. morhua*. Thus (with a few assumptions) it is possible to use DNA differences occurring within the *G. morhua* species group to estimate the likely dates of 'internal' population separations.

*For more details see Brander, K. (2005) Spawning and life history information for North Atlantic cod stocks, ICES *Cooperative Research Rep.* No. 274, downloadable from http://www.ices.dk/pubs/crr/crr274/crr274.pdf

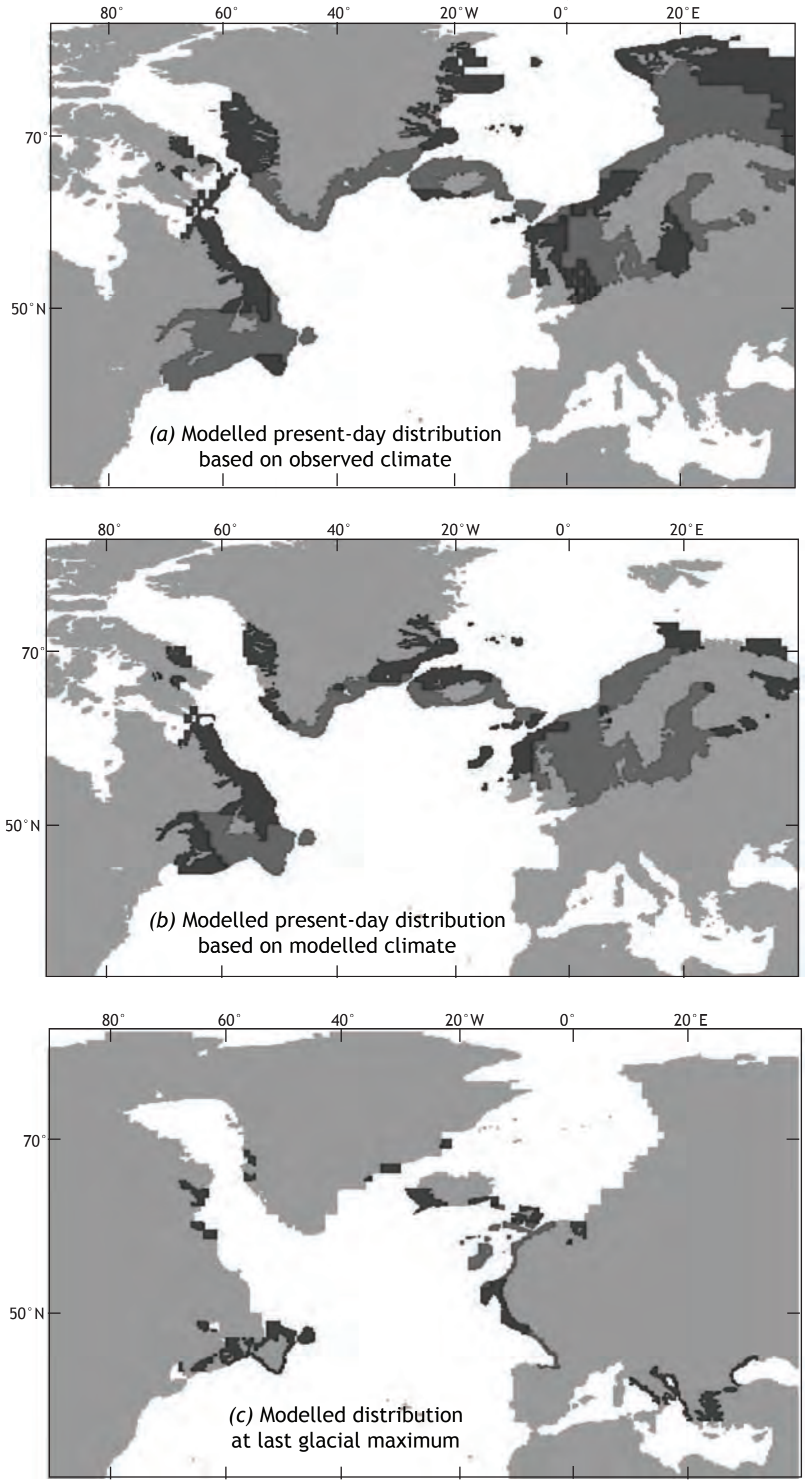


Figure 2 *Regions of the North Atlantic with depth <500 m that satisfy the 'climate envelope' criteria for cod-spawning and egg-development of Atlantic cod, based on:* ***(a)*** *present-day temperature climatology and bathymetry;* ***(b)*** *present-day model-derived environmental data; and* ***(c)*** *model-derived data for the last glacial maximum* 20 000 years ago. *Light grey: areas with core range temperature parameters (3–7 °C in February–June); dark grey: marginal ranges (0–3 °C and 7–10 °C).*

The present-day genetic comparisons were based on four regional groups of *G. morhua* (Atlantic Canada, Greenland, Iceland and Europe; Figure 1), using four genes (mitochondrial Cyt-B; nuclear S2, pantophysin-A and pantophysin-B). Differences between Canadian and European populations were sufficiently great to indicate a period of separation of between 80 and 200 thousand years, suggesting that they both separately survived the last glacial maximum 20 thousand years ago, but only one population – almost certainly the European one – had survived the penultimate glaciation, around 150 thousand years ago, and had spread to re-populate the area off western Canada. The occurrence of high and comparable levels of endemic alleles (genetic variations not found elsewhere) in Canadian and European populations provides supporting evidence for that interpretation, whereas the Greenland population appears to be newly founded, with low levels of endemic alleles.

The ability of cod populations to maintain genealogical continuity over extreme natural climate variability suggests considerable inherent resilience. Whilst the future location of cod's climate envelope has not yet been modelled using similar approaches, it can be expected to show dramatic northward shifts over the next 100 years – with increases of potentially suitable habitat in an ice-free Arctic potentially exceeding habitat losses in the North Atlantic. Yet not all parts of the envelope will necessarily be filled, and the time-scale of population movements may be slower than that of key climatic parameters. Whilst changes in the distribution of planktonic species can be expected to closely follow changes in their favoured temperature conditions, fish showing preferences for specific spawning sites (presumably determined either by benthic features and/or local hydrodynamic conditions) are inherently less adaptable. Furthermore, range expansion beyond a species' current distributional boundaries typically occurs when total population is expanding, producing a 'surplus' of young adults that can occupy and breed in new habitats.

For cod, the failure of the Grand Banks population to recover since the stock collapse of the early 1990s (despite the cessation of fishing) shows that occupation of potentially suitable habitat cannot be assumed, despite the species' high fecundity. Yet it is not out the question that Atlantic cod and Pacific cod will meet again, either off northern Canada or Siberia, with that reunion also including other family members, such as the Alaska pollack *Theragra chalcogramma* and the Greenland cod *Gadus ogac*. Whether they will all get on, and whether there will be enough food to go round, remains to be seen.

During the LGM, habitat suitable for cod spawning was much more limited than at present, and very fragmented

Further reading

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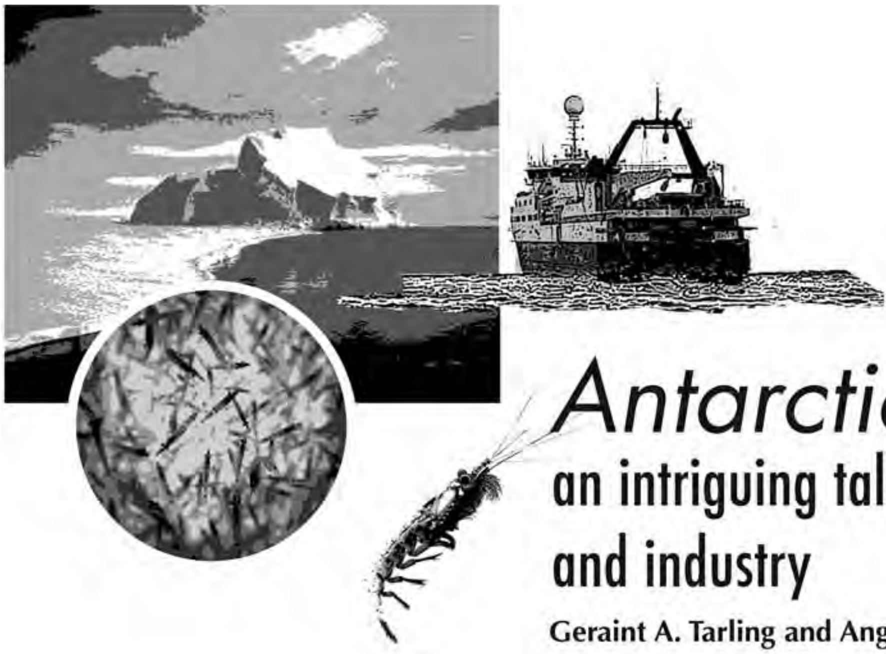
Phil Williamson is based at the University of East Anglia, where he works for NERC as a science coordinator. He has a long-standing interest in the factors determining the abundance and distribution of marine organisms.



Antarctic krill
an intriguing tale of ice and industry

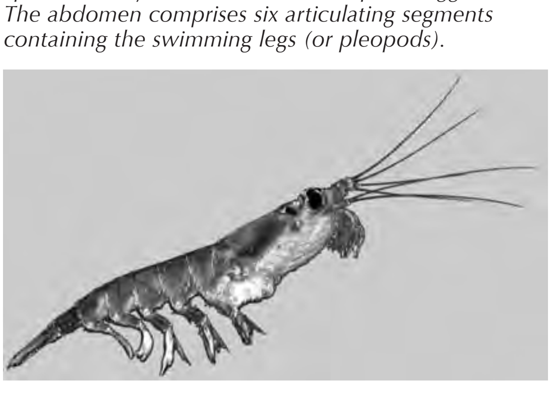
Geraint A. Tarling and Angus Atkinson

Antarctic krill are experiencing rapid changes in their habitat as a result of regional warming and decreasing areas of winter ice in the Southern Ocean. They are also receiving renewed attention as a source of high-value health products, which could lead to much higher levels of exploitation. The combination of these factors is increasing pressure on existing krill stocks – a situation that demands careful management. To make effective management policy, krill scientists must continue to overcome major logistical and theoretical challenges to assess stock size, distribution and behaviour with sufficient accuracy. Here, we examine the latest issues being tackled in this new age of krill science.

An introduction to krill

If asked to name a small marine organism that formed large swarms or schools, most people would automatically think of small pelagic fish such as anchovy or sprat. In the Southern Ocean, however, such swarms would not be made up of fish but of Antarctic krill (Figure 1). The name 'krill' derives from the old Norwegian word 'kril' or 'whale food', but is nowadays the common name for members of the Order Euphausiacea. This order comprises 86 species from 12 genera and two families. The distribution of these krill species is worldwide and spans shelf seas and open ocean, from the surface layers to considerable depths. Species range in size from a few millimetres to 15 cm, with the smallest being found mainly in warmer waters and closer to the surface and the largest in colder waters deeper down or towards the poles.

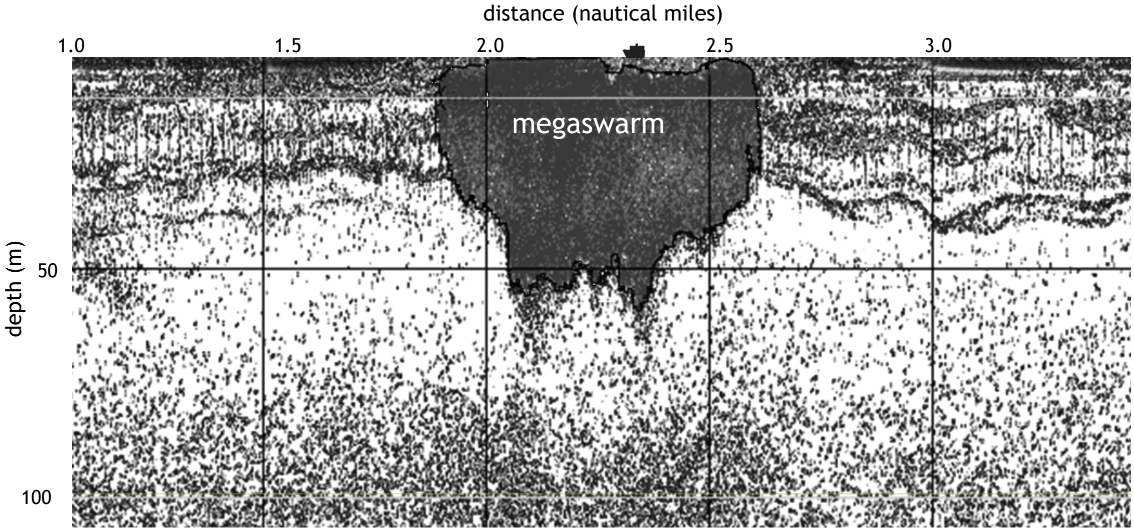
Figure 1 *Antarctic krill (*Euphausia superba*). Total length 6.5 cm. The body is divided into the cephalothorax (carapace, two pairs of antennae, the eyes, mouthparts and thoracic limbs) and abdomen. The gills are external, located amongst the thoracic limbs. The carapace may swell greatly in reproductive females due to the amassing of large numbers of lipid-rich oocytes, which will develop into eggs. The abdomen comprises six articulating segments containing the swimming legs (or pleopods).*



Antarctic krill are amongst the largest of euphausiids and are strong swimmers

Antarctic krill – *Euphausia superba* – is amongst the largest of all euphausiid species, reaching around 6.5 cm, from the front of the eye to tip of the tail. Krill are also by far the most prominent euphausiid species in terms of biomass, making them an important resource for large numbers of higher predators as well as for commercial fishing.

Antarctic krill are found exclusively in the Southern Ocean and their intricate life-cycle may be an adaptation to coping with the extreme seasonality of their environment. They spawn thousands of eggs in a series of batches throughout the summer months when plankton blooms are numerous (Figure 4(b)). The eggs sink hundreds of metres over a period of a week or so until they eventually hatch into small larval forms called nauplii. These swim back towards the surface over the next 7–10 days, using their body reserves to fuel the ascent and further larval development. Body reserves are depleted by the time they emerge in the surface layers and there is a pressing need to locate food sources such as patches of phytoplankton and microzooplankton. This may be a critical period in their life-cycle and the reason that only certain Southern Ocean environments, such as the ice-edge and regions of frequent phytoplankton blooms, are suitable for producing the next generation.



A single krill swarm may contain thousands of tonnes of krill and extend for considerable distances

Figure 2 *A krill 'megaswarm' detected acoustically from aboard RRS* James Clark Ross *in February 2003. The swarm was over remote, deep ocean in the eastern Scotia Sea in a region containing only moderate concentrations of phytoplankton. It was 1.3 km long and 50 m thick, with an estimated biomass of 8000 tonnes (the 100 m-long* James Clark Ross *is shown to scale above the swarm; the vertical scale is exaggerated). The darker the grey tone, the greater the density of krill, as determined by acoustic backscatter values; lightest grey represents 1 krill m^{-3}, darkest grey represents > 100 krill m^{-3} (the apparently high levels in near-surface waters are an artefact of the system. An RMT 8 net (cf. Figure 5) was used to sample the swarm (see text).*

Further development of *E. superba* is slow, passing through many moults and five main life-cycle stages before reaching adulthood. It may take three or four years before they reach their final adult size. Their total lifespan is difficult to estimate because adults are capable of both growth and shrinkage, making size a poor indicator of age. Other methods, such as examining eyeball size and fluorescent age pigments (lipofuscins), suggest a life-span longer than four years but have not been capable of providing further precision. In captivity, some specimens have been maintained for over 11 years, but such ages are unlikely in the wild, given the combined effects of the risk of predation and physiological senescence.

Antarctic krill are extremely active, which may be a necessary means of overcoming their negative buoyancy and remaining within the water column. Adults have a cruising speed of 15–20 cm s^{-1} and are fully capable of swimming against currents in some regions. Forward swimming is achieved through sequential motion of the pleopods. Rapid backward movement is also possible through flexion of the abdomen. This is mostly carried out as an avoidance behaviour.

Krill are an extremely social organism and can form some of the largest swarms on the planet, many kilometres across and containing up to a million tonnes of biomass (Figure 2). The ways in which individuals communicate to maintain the integrity of swarms is far from clear but could involve tracking each other's flow fields or responding to chemical cues. Krill have relatively large eyes and vision is also likely to be involved in communication, facilitated by light organs called photophores, mainly located on the underside of the abdomen. Swarming may benefit krill through decreasing the risk of predation and increasing the chances of finding patchily distributed food, such as blooms of phytoplankton.

Commercial exploitation of krill

We have known about the importance of Antarctic krill to the Southern Ocean food web since the earliest whaling expeditions more than a century ago. However, it was not until the 1960s that krill themselves became the target of a fishery. Krill fishing peaked in 1982 with an annual harvest of 528 000 tonnes but then subsequently declined for a number of reasons. Firstly, the main krill fishing fleet was run by the Soviet Union in the 1970s and early 1980s, but subsequently collapsed in the late 1980s. A further factor was that krill rapidly spoil because of powerful enzymes that are released when their digestive gland is damaged, which often occurs within nets. This means that the most commercially valuable components of krill, the proteins and lipids, are rapidly broken down between the time of capture and freezing. The lack of suitable processing facilities meant that the quality of the catch returning to market was compromised and its value reduced.

There are also difficulties in processing euphausiids because of high levels of fluoride in their exoskeletons (protective outer coverings made of chitin) which rapidly leach into the tissues when they die. Farm animals fed krill-meal were found to accumulate detrimental levels of fluoride in their bones and tissues, exceeding safe levels (as set by the European Community) by as much as four times. However, commercial fish were found not to accumulate fluoride in their tissues when fed krill, probably because euphausiids are part of their natural diet.

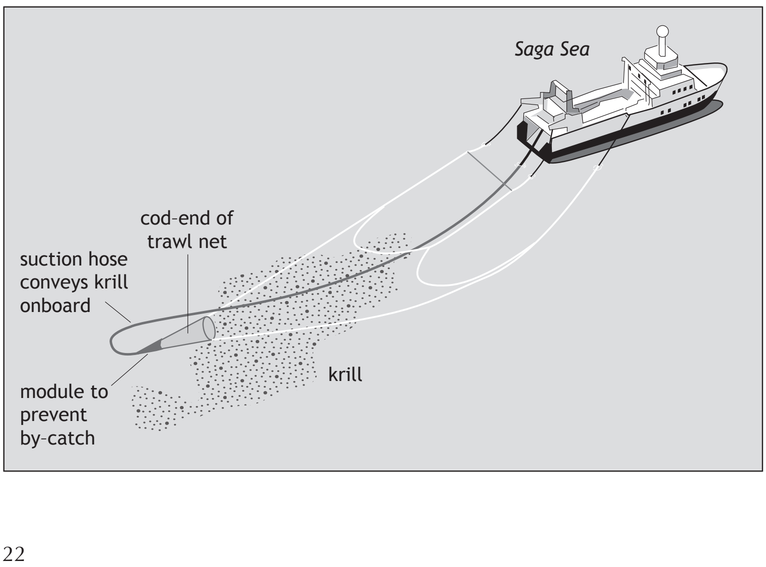
Nowadays, most harvested krill is used in aquaculture. Krill have a number of important features which make them a suitable fish-feed: they increase feed-palatability to fish, they are a source of caretenoid pigment to colour the tissues, they provide essential fatty acids and a broad range of amino acids, and they improve the rate of survival of larval fish. Krill are also used as chum for sport fishing and as freeze-dried feed for home aquaria.

Nevertheless, such uses give a low return per unit bulk and the profitability of travelling to the Southern Ocean to catch Antarctic krill becomes marginal during times when fuel costs are high.

Krill are also marketed for human consumption. 43% of the Japanese Antarctic krill catch is processed for human consumption as boiled then frozen krill, or peeled krill tail meat (both processes minimizing fluoride content). There have been efforts in other countries to produce low shell (low fluoride) products for human consumption (e.g. in Russia and Poland) but there is presently little demand for such products in the wider international market. There appears to be much greater potential for krill products as dietary supplements. It has been proposed that concentrated krill oil can assist health during pregnancy and during treatments for cancer and for immunodeficiency and nutritional disorders, and other benefits are continually being put forward. The main active components are polyunsaturated omega-3 fatty acids, which make up 19% of the total fatty acids in krill. These are relatively stable during processing and can be stored for long periods. Krill are also a source of chitin, which makes up just under 3% of their dry weight.

Figure 3 Upper *The FV* Saga Sea*, a 92 m stern trawler with the capacity to take 120 000 tonnes of krill per year using a suction harvesting method in which the net remains under water during the entire operation.*
Lower *The suction harvesting method whereby krill are pumped onboard the vessel still alive, and so remain fresh for much longer.*
By courtesy of Aker BioMarine

Today's krill-harvesting vessels can take many thousands of tonnes of krill annually



Chitin and chitosan, which is derived from chitin, have a range of potential uses in membrane production, hair products and cholesterol-lowering drugs. The pharmaceutical industry is further exploring krill enzymes in the treatment of inflammation and to assist in the healing of wounds.

The emergence of high-value products from Antarctic krill has renewed interest in harvesting this species. In 2008, there were at least four firms planning to expand krill-fishing operations. A major hurdle is to maintain caught krill in sufficiently good condition to extract the valuable biochemical components. When a full net is hauled out of the water, the organisms compress each other, resulting in great loss of the krill's liquids and a release of the degradation enzymes. One solution is to pump krill directly onboard through a tube connected to a net cod-end (the part of the net where the krill are retained). The krill arrive on board still alive and fresh, increasing the chances that subsequent extraction procedures for biochemical components will be successful. The FV *Saga Sea* (Figure 3(a)), owned by Aker BioMarine, employs such 'suction' harvesting methods and has the capacity to fish up to about 120 000 tonnes of krill annually. After a successful first season, Aker BioMarine have provisional plans to build more such ships.

The Southern Ocean krill fishery is monitored and managed by the Convention for the Conservation of Antarctic Marine Living Resources (CCAMLR), as part of the Antarctic Treaty System. Part of its remit is to minimize the risk of altering the Southern Ocean marine ecosystem, through the regulation of harvesting. It set an allowable catch of 4 million tonnes (Mt) of krill, of which only a fraction is presently being taken. However, figures submitted for future catch intentions are steadily rising. Can this rise in demand be accommodated?

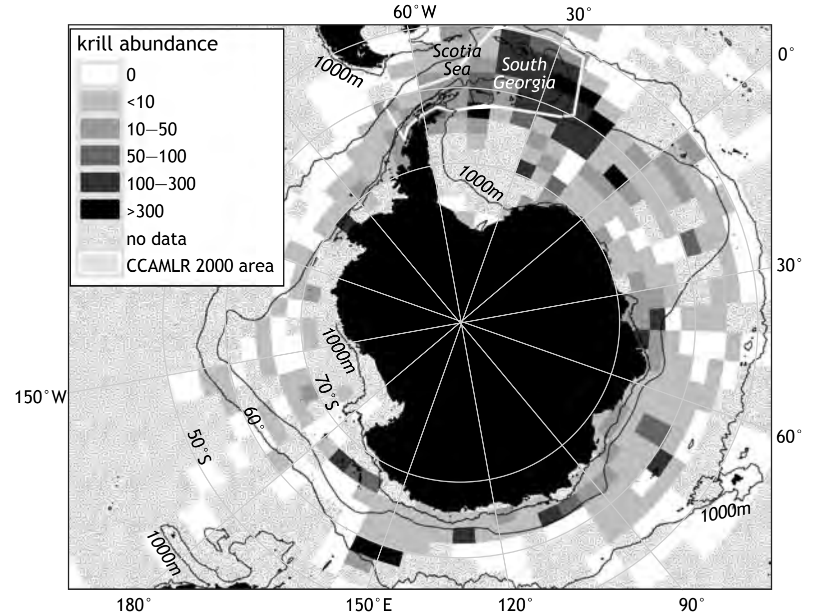
How many krill are there?

Effective management of a fishery depends on good estimates of standing stocks and overall production (i.e. how fast this biomass is turning over). However, Antarctic krill has a geographic range of between 10 and 20 million km^2, a patchy distribution, and regional stocks that can vary tenfold in biomass between successive years. In combination, these factors have led to orders of magnitude of uncertainty over the total biomass and secondary production of krill. As well as extrapolation upwards from regional surveys using echo-sounding or net-sampling (see below), a variety of other indirect approaches have been used. One example is to back-calculate the amount of krill that would be required to support the large stocks of whales before they were exploited. After some wildly over-optimistic estimates during the early days of the krill fishery, and then a rebound effect which went perhaps too far the other way, the general consensus nowadays is that total krill biomass is roughly 100–500 million tonnes (wet mass) with an annual production of a roughly similar amount.

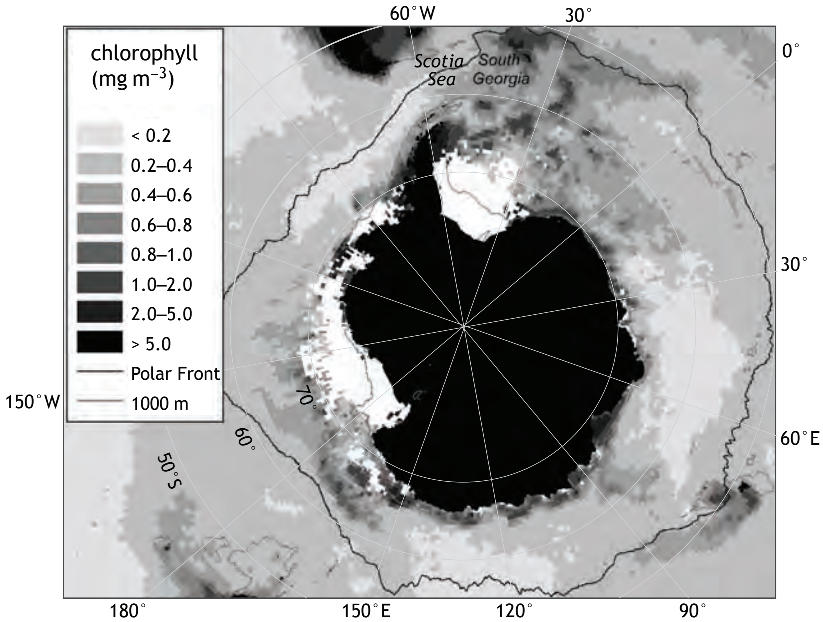
Because knowledge of total biomass is so central to fisheries management, CCAMLR coordinated a large-scale international survey in 2000, sampling 2 million km^2 of prime krill habitat (Figure 4(a)). Biomass within this region was estimated to

Figure 4 ***(a)*** *Circumpolar distribution of krill, showing the high concentration in the Atlantic sector at the top of the map. This was sampled by the CCAMLR Synoptic Survey, within the 2 million km² area outlined in white. Krill abundance is plotted as numbers of individuals under 1 m² of ocean. Black lines indicate positions of the Sub-Antarctic Front and the Polar Front.*

(b) *The distribution of enhanced summer phyto-plankton stocks in the upper water layers is broadly concordant with the circumpolar distribution of krill (cf. (a)). Data are average summer chlorophyll-*a *concentration, determined from SeaWiFS images. (By courtesy of NASA.)*



(a)



(b)

The distribution of krill around Antarctica broadly reflects that of phytoplankton, although large krill populations are found in areas with only moderate primary productivity

be 44 Mt. Parallel studies showed that the survey region contained around 30% of the Southern Ocean stock of krill, which would make total krill biomass around 150 Mt in that year. However, acoustic methods are still undergoing refinement. In particular, it is difficult to determine the exact amount of sound that is reflected back from an individual krill within a sonar beam (i.e. the target strength). Calibrations have shown target strength to be dependent on the orientation, size and tissue-density of krill, but these parameters vary between swarms and such variation can alter the acoustic estimate of swarm biomass by a significant amount.

The alternative to sampling krill acoustically is to catch them directly with nets. Typical krill nets are large (e.g. a mouth area of 8 m²; cf. Figure 5) to prevent large numbers of this strong swimmer

Figure 5 *The RMT 8 net system has a mouth size of 8 m² and nets with a 2 mm mesh; it is usually equipped with two opening and closing nets to allow two successive catches to be made. Acoustic or down-wire communication allows depth, haul rates and release mechanisms to be controlled during deployments, which are usually carried out at ~ 2–3 knots to maintain specimens in a healthy condition.*

When live specimens are required for experiments, hauls are usually quick (< 20 minutes) and are often aimed at acoustically detected layers or swarms of krill (cf. Figure 2). Such sampling is often carried out at night, when the krill are probably closer to the surface and less able to see and avoid the net. When the aim is to determine distribution and densities of krill, hauls are carried out at random fixed positions, sampling many hundreds of metres of water column.

An RMT 8 net is one of the main types of scientific nets used to sample euphausiids such as Antarctic krill

Krill population size can vary enormously from year to year

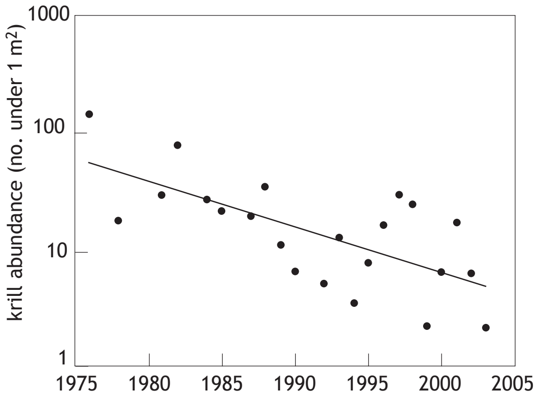


Figure 6 *Mean summer krill abundance (number under 1 m² of ocean) across the south-west Atlantic sector, with values on a log scale to encompass the great variability between years. The regression line shows a significant downward trend since 1976.*

escaping but, even so, the ability of krill to avoid nets leads to some underestimation of abundance. Also because nets only sample relatively small amounts of water, many hauls are needed to provide a realistic picture of the average abundance of this patchily distributed species. Despite these problems, nets are still the only way to catch krill for experiments and to determine the size of krill present in the population. This latter information is useful not only to learn of the status of the stock, but it also is needed to calibrate the acoustics. Net sampling comes into its own when many hauls are combined, and this idea was behind the KRILLBASE project – an international initiative to put all available net haul data into a central database. This database of over 8000 net hauls led to the recent finding that there had been a statistically significant decline in krill stocks in the Scotia Sea region over the last three decades (Figure 6).

The decline was only recorded in the Atlantic sector of the Southern Ocean – a region encompassing the Antarctic Peninsula, Weddell Sea, Scotia Sea and the South Shetland Islands. Krill scientists are still in vigorous debate over the causes of this decline. One candidate is the simultaneous decrease in winter ice-cover and increase in water temperature that were observed specifically in this Antarctic Peninsula/south-west Atlantic sector where the decline was found. An alternative explanation invokes 'top down' factors, in which the population size reflects control by a suite of higher predators still re-adjusting to the very rapid removal of probably their major predator a century ago – the great whales.

How do krill overwinter?

The winter period is often viewed as a time of hardship for pelagic grazers in high latitudes, since there are few algae in the water column during the dark season and around half of the Southern Ocean is under sea-ice. Some grazers just cut their losses and hibernate, but remarkably, a larval krill can actually double in size through the winter. In the late 1980s the first pictures of krill feeding upside-down on algae growing on the underneath of sea-ice marked a step-change in the way we think about krill. However, since then, progress has been frustratingly slow, due to the logistical problems of working under ice in the dark season.

Two basic types of overwintering have been described: non-feeding strategies and feeding strategies. The non-feeding strategy is a type of hibernation, which may be triggered by the light regime. If krill adopt this strategy, feeding ceases, metabolism slows right down and they live off their fat reserves. Krill even have the ability to use body resources and shrink in size. By contrast, some observers have noted a continuation of feeding in winter, on sea-ice algae, small copepods, or the benthos.

These so called 'switch food sources' have been the subject of much speculation, some controversy, yet few data. In winter, they certainly offer alternatives to feeding on the scarce phytoplankton. However nobody has yet managed to quantify the importance of these food sources in any consistent way, and the conclusion of most papers seems to be that krill have flexible overwintering strategies, with this flexibility being a key to their success. The challenge now facing krill researchers is to predict how krill will respond to a changing environment. Since phytoplankton biomass is low for two-thirds of the year, krill scientists are trying to go beyond the catch-all explanation that krill are simply 'a flexible species' and understand some of the actual mechanisms involved.

Whichever way krill manage to survive winter, there is no doubt that their life-cycle is intimately linked to sea-ice. Their abundance can vary up to tenfold from year to year (Figure 6), and this variation is a help to krill biologists because it provides insights into what drives population increases and decreases. In summers with many krill, which generally follow winters of extensive sea-ice, and occur maybe once or twice a decade, the population is swelled by many small juveniles. It is likely that good ice winters mean extensive and long-lasting shelter and food for the larvae. The larvae grow, yielding a strong cohort of juveniles the following summer, which boosts the population. The total population may then dwindle following a couple of years with less extensive sea-ice, until the next ice cycle replenishes the stock.

How are krill populations dispersed?

As krill develop into adulthood, they generally move further away from the seasonal sea-ice zone. However, there remains some mystery as to where they go next. Antarctic krill inhabit one of the largest currents in the world, the Antarctic Circumpolar Current (ACC), which flows clockwise (eastwards) around the Antarctic continent, transporting 140 million m^3 of water per second. Current speeds within the flow reach up to 50 cm s^{-1}, more than twice krill's cruising speed. Models predict that if krill were transported passively by this current, it would take them between one and two years to travel from the Antarctic Peninsula to South Georgia (cf. Figure 4). This fits with the widely held view that large stocks of larval krill depart the ice-fields around the Antarctic Peninsula, travel across the Scotia Sea and arrive at the krill-rich South Georgia region as two-year old adults.

Nevertheless, the circumpolar distribution of krill does not seem to reflect that of a free-drifting organism. Copepods and salps (gelatinous zooplankton), which have very limited swimming capabilities, are relatively evenly dispersed throughout the Southern Ocean. As shown in Figure 4(a), the distribution of krill is, by contrast, asymmetric, with over three-quarters of all krill being concentrated in one quarter of the circumpolar range (i.e. in the Atlantic sector). This suggests that krill have some degree of control over their distributional fate. For instance, krill may employ behavioural tactics to reduce displacement by currents, e.g. vertical migration, which allows them to move between layers of water flowing in different directions, and frequent turning when in favourable locations.

The issue of 'krill flux' – the degree of transport or migration of krill from one region to another – is currently a major topic taxing krill biologists. Since the fisheries are currently highly localized the issue has practical implications for fisheries management, as well as for a more basic level of understanding. At the Antarctic Peninsula there is a northward migration of adult krill in spring, to spawn offshore, followed by a southward migration in autumn back towards the shelf. However, whether krill in other regions complete migrations of this sort, and whether thay maintain geographically distinct sub-populations, is debated. Krill cannot be tagged externally because they moult every fortnight or so, and they are too small for even the latest in transmitter technology. Instead genetic approaches may give us some clues to the interchange of krill between geographical regions

Regardless of the degree of connectivity between populations, shelf habitats are undoubtedly important to krill. This association with shelves appears to vary according to sector – for example, at the Antarctic Peninsula, krill are often found in the highest concentrations in the inner shelf regions, whereas in the Indian sector they are often more concentrated at the shelf–slope transition and just offshore. The ultimate reason for high krill densities over shelves may be plentiful food. Much of the Southern Ocean has low concentrations of iron, a micronutrient essential for photosynthetic function. Regions near land and shelves are replenished with iron, allowing blooms of phytoplankton which attract the krill.

Productive shelves make up only a relatively small part of the Southern Ocean, with considerably greater areas covered by the open ocean, where concentrations of phytoplankton are mostly either moderate or low. Recent research has shown that even moderate food concentrations are adequate for krill. For example, the swarm shown in Figure 2 occurred in a region where phytoplankton biomass was only 0.8 mg chlorophyll-*a* m^{-3} (compared to typically >2 mg chlorophyll-*a* m^{-3} in shelf environments) yet the krill captured from this swarm had guts full of diatoms. Subsequent incubations found these krill to be growing at very high rates, increasing their dry mass by 5% per day.

A recent paper concluded that 87% of the Antarctic krill population is found in the open ocean. Far from land, krill are less likely to encounter land-based predators, and in the Southern Ocean, many krill predators, such as seals, penguins and flying seabirds, must remain within the vicinity of land during the summer months, to return and feed their young.

Krill and climate

The size of the krill population in some regions of the Southern Ocean has been shown to expand and contract in a cyclical fashion over a period of decades. This cyclical pattern has been linked to larger scale climatic signals, particularly the El Niño – Southern Oscillation (ENSO) cycle. The cycle has two major impacts on krill. First, it alters the amount of ice, so affecting how many new offspring survive beyond the larval stage, and secondly, it interferes with the spread of mature krill away from the ice into productive northerly regions, such as South Georgia. The increasing number of strong El Niño years over the past 30 years is a potential explanation for the decline in krill numbers. One study has predicted that an increase in El Niño events over the coming decades could wipe out krill in certain Southern Ocean localities.

The accuracy of any prediction depends on how well it captures important details. Models of krill populations are still in their infancy but they are becoming increasingly sophisticated. The latest models focus on the interaction between life-cycles and movement within circumpolar currents. It is hoped they will demonstrate how the asymmetric circumpolar distribution develops and is maintained, and identify whether or not separate krill stocks exist. This is particularly important for management purposes and could assist in dividing the fishery into small-scale units, where the demands of higher predators and industrial fishing can be balanced effectively. Models also rely on good data to set them up and to test their output. International efforts are moving apace to amass datasets sufficiently comprehensive to assist with modelling.

New frontiers of krill research

Many potential krill habitats remain to be mapped and new technology is being used to explore them. One relatively inaccessible environment is under the seasonal pack-ice, where it is believed much krill biomass is located, especially during the winter months. Major new insights were obtained through the use of an autonomous submersible (*Autosub*) which travelled 30 km under the ice and found high concentrations of Antarctic krill between 1 and 13 km beyond the ice-edge. Recent expeditions into the marginal ice-zone (that part of the pack ice which is significantly affected by ocean swell) also deployed a net sampling device capable of moving along the underside of the ice using specialized tracks. Under-ice krill samples provide valuable insights into how these animals cope in such environments.

Another under-sampled environment is the deep sea. Recent dives by the ISIS submersible found concentrations of krill feeding at the sea-bed at depths as great as 3500 m, suggesting that part of the population may be lying out of the range of nets and acoustics. This is an interesting development which changes our view of Antarctic krill as a species limited to the surface ocean layers. A new wave of autonomous vehicles, called 'gliders', which can cover thousands of kilometres with a trajectory that oscillates between different ocean layers, may provide further information on these understudied habitats if suitable biological sampling devices can be devised. The fresh momentum in exploring new krill habitats reflects the increasing recognition of the ecological and commercial importance of this species. There remain many frontiers for krill researchers to explore in the years to come.

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Angus Atkinson, also at BAS, is a lead scientist in the ecology and biogeochemistry of the Southern Ocean and is currently focussing on the contribution of krill to the flux of carbon and micronutrients through the ecosystem. Email: aat@bas.ac.uk

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Official opening of the Runde Environmental Centre & Coastal Observatory

On 1 October 2009, the new Environmental Centre on the Norwegian Island of Runde was officially opened with an inauguration ceremony that included not only scientific seminars but contributions in art and music.

The €6 million facility is offering its services and infrastructure to visting scientists. Typical users will be universities, research institutes and colleges, as well as public bodies and industry. Visitors will be accommodated in the appartment annexe (on the left in the photo).

It is intended that the Centre become a key site for the promotion of sustainable use of energy and resources, and pollution abatement. Its strategy is to become a regional and national focal point and an integral part of environmental monitoring in Norway. Staff are already undertaking R&D and environmental monitoring in the north-east Atlantic, and many projects (including EU-funded ones), mostly relating to the environment and renewable energy, are already underway.

The wave climate off Runde is extremely harsh, with a high energy intensity (averaging 50 kW m^{-1}), and the island has an approved test site for wave energy devices, which includes a cable connection to the local electricity grid. Testing of such devices began in summer 2009.

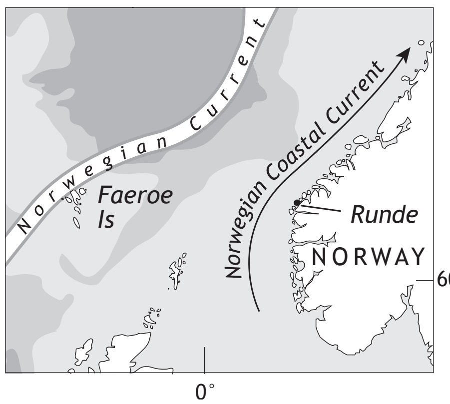
The seas around Runde have a very rich marine flora and fauna, and support the richest coastal fishery in Norway.

The new Centre near the harbour on Runde, facing the Norwegian Sea; the facilities incude offices for visitors, wet and dry labs, field equipment including a vessel suitable for making observations, and an Ocean Modules ROV. On the left is the appartment annexe for visitors, and the centre section has a cafeteria, and a display and public information area. There is an auditorium holding 120 people, and modern facilities for courses, training and recreation. The Centre, built largely through private funding, with some public and state sponsorship, has been constructed to the highest standards of energy and water conservation.

Photo: Knut W. Alsen.

For this reason, environmental monitoring will be a particularly important part of the work being done at Runde. Oil and gas production are inexorably approaching, and the risks associated with the steadily increasing traffic of large oil carriers from north-west Russia and elsewhere for the European market, represent a potential threat to the fauna around Runde. The Centre is therefore preparing to host expertise and equipment for washing contaminated seabirds and marine mammals.

For more information, see the Runde website: http://www.rundecentre.no. For specific requests, contact Lars G. Golmen, Email: lars.golmen@niva.no; Tel.: +47-4789-0957.



Location and oceanographic setting of the Island of Runde. A bridge connects Runde to the national road network, and the nearest airport is 1 hour away. Bathymetry: pale grey 0–1000 m; mid-grey 1000–2000 m; dark grey > 2000 m.

Another under-sampled environment is the deep sea. Recent dives by the ISIS submersible found concentrations of krill feeding at the sea-bed at depths as great as 3500 m, suggesting that part of the population may be lying out of the range of nets and acoustics. This is an interesting development which changes our view of Antarctic krill as a species limited to the surface ocean layers. A new wave of autonomous vehicles, called 'gliders', which can cover thousands of kilometres with a trajectory that oscillates between different ocean layers, may provide further information on these understudied habitats if suitable biological sampling devices can be devised. The fresh momentum in exploring new krill habitats reflects the increasing recognition of the ecological and commercial importance of this species. There remain many frontiers for krill researchers to explore in the years to come.

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Geraint Tarling heads the Ecosystem Analysis team at the British Antarctic Survey* and has special interests in the behaviour and life-cycles of polar pelagic species, particularly euphausiids, copepods and pteropods. Email: gant@bas.ac.uk

Angus Atkinson, also at BAS, is a lead scientist in the ecology and biogeochemistry of the Southern Ocean and is currently focussing on the contribution of krill to the flux of carbon and micronutrients through the ecosystem. Email: aat@bas.ac.uk

*British Antarctic Survey, High Cross, Madingley Road, Cambridge, CB3 0ET UK.

Official opening of the Runde Environmental Centre & Coastal Observatory

On 1 October 2009, the new Environmental Centre on the Norwegian Island of Runde was officially opened with an inauguration ceremony that included not only scientific seminars but contributions in art and music.

The €6 million facility is offering its services and infrastructure to visting scientists. Typical users will be universities, research institutes and colleges, as well as public bodies and industry. Visitors will be accommodated in the appartment annexe (on the left in the photo).

It is intended that the Centre become a key site for the promotion of sustainable use of energy and resources, and pollution abatement. Its strategy is to become a regional and national focal point and an integral part of environmental monitoring in Norway. Staff are already undertaking R&D and environmental monitoring in the north-east Atlantic, and many projects (including EU-funded ones), mostly relating to the environment and renewable energy, are already underway.

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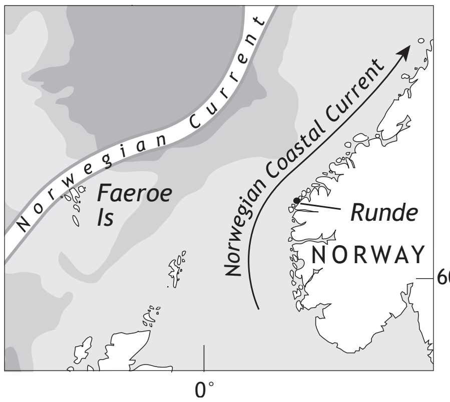


Location and oceanographic setting of the Island of Runde. A bridge connects Runde to the national road network, and the nearest airport is 1 hour away. Bathymetry: pale grey 0–1000 m; mid-grey 1000–2000 m; dark grey > 2000 m.

Frank Wild, veteran of five Antarctic Expeditions

Glenn M. Stein

John Robert Francis ('Frank') Wild, CBE, RNVR, FRGS (1873–1939) is one of only two people ever to receive a Polar Medal with clasps for four expeditions: Wild's medal has clasps for Antarctic 1902–04, Antarctic 1907–09, Antarctic 1912–14, and Antarctic 1914–16, and is engraved A.B. F. WILD "DISCOVERY".

Because of my strong interest in medals (and through the kindness of Robert Stephenson, Coordinator of the website 'The Antarctic Circle', and author Angie Butler), I have been corresponding and speaking with Frank Wild's family. The family wished to part with the medal and a number of others (including his CBE) and were seeking advice on how best to do this while preserving their provenance and Frank Wild's memory.

Frank Wild is not as well known as many polar explorers, yet he had more Antarctic experience than anyone else during the Heroic Age of Antarctic exploration (1895–1922), participating in five expeditions between 1901 and 1922. Wild's work and leadership were universally respected by his Antarctic comrades, who virtually never had a critical word to say or write about him.

Wild first went to Antarctica as an Able Seaman with Scott during the British National Antarctic Expedition of 1902–04, having had 12 years in the merchant navy before joining the Royal Navy in 1900. He took part in several sledge journeys, including the tragic first attempt to reach Cape Crozier. His spirited leadership brought several men back to the ship after the death of Able Seaman George Vince, who drowned after slipping down a steep ice slope during a blizzard. Scott thought highly of Wild's service and specially mentioned him in despatches, and Wild was duly promoted to petty officer. During the expedition, Wild struck up a friendship with the third lieutenant, Ernest Shackleton.

As a member of Shackleton's *Nimrod* Expedition (1907–09), Wild was placed in charge of provisions, and was one of the four-man sledge party to come within only 97 miles of the South Pole. Fellow Yorkshireman and expedition geologist Douglas Mawson afterwards wrote that his experiences during this time, 'acquainted me with Wild's high merits as an explorer and leader'. Upon his return, Frank Wild left the Royal Navy by purchase.

Though Scott asked Wild to join his second Antarctic venture, Wild declined, as he felt Scott was 'too much the navy man.' Instead, he joined Mawson's 1912–14 Australian Antarctic Expedition as a sledging expert and was appointed leader of the Western Base. Under him were seven untried men – none had previously served in the polar regions. In spite of terrible sledging conditions, Wild led successful sledge parties to open up a new region, Queen Mary Land.

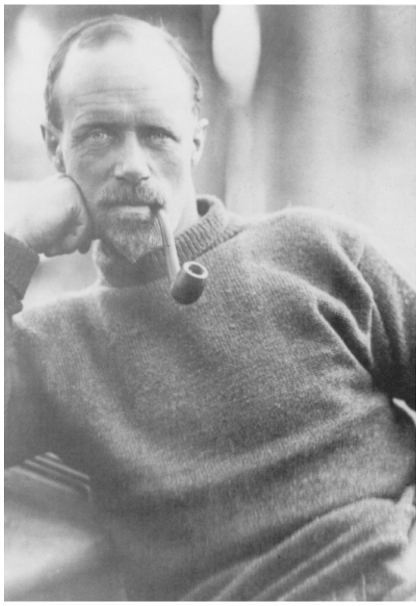
Wild then played a vital role as second-in-command of the *Endurance* during the Imperial Trans-Antarctic Expedition of 1914–17. After the ship sank, the men made their way by sledge and boat to land on the desolate Elephant Island. Here, Wild's leadership abilities were tested to the full, as he was left in charge while Shackleton went on his epic boat journey to get help on South Georgia. Wild never gave up hope that Shackleton would return to rescue them, and whenever the sea-ice cleared, he would say, 'Roll up your sleeping-bags, boys: the boss may be coming today.'

Wild's Polar Medal. The only other recipient of a Polar Medal with four clasps is Ernest Joyce

Courtesy of Dix Noonan Webb Auctioneers, London

Frank's younger brother, Harry, also took part in the Imperial Trans-Antarctic Expedition during which he looked after the stores and dogs of the Ross Sea Party. Harry Wild died of typhoid in 1918, and in 1923 was posthumously awarded the Albert Medal (Second Class/Land) for the expedition.

On returning home, Frank Wild volunteered for duty and was made a Temporary Lieutenant, Royal Naval Volunteer Reserve. After a Russian language course, he became the RN transport officer at Archangel, supervising arriving war materials during the Allied Intervention in Russia.



Frank Wild, photographed by F. Hurley

After the war, Wild went to South Africa where he farmed with two former Antarctic comrades. They worked the soil in British Nyasaland, clearing the then virgin forest and planting cotton. Despite intermittent bouts of malaria they loved the life, until 1921 – when Wild's final Antarctic adventure began.

Wild was second-in-command of the 1921–22 Shackleton–Rowett Expedition, a poorly-equipped venture, with no clear plan, and a small ship – the *Quest*. Shackleton died of a heart attack on South Georgia, and Wild took over and completed the journey, combating unfavourable weather to Elephant Island and along the Antarctic coast.

Frank Wild died on 19 August 1939, in Klerksdorp, South Africa, where he was a storeman at the Babrosco Mine. His name lives on in the Antarctic, in two Mount Wilds (one in the Queen Alexandra Range, one at the tip of the Antarctic Peninsula) and Point Wild, the Wild Icefalls (the glacier at the head of the Beardmore Glacier), and Cape Wild on Elephant Island.

Glenn 'Marty' Stein FRGS is a polar historian with a passion for medals. He is the designer of the Antarctic Treaty Summit Medal 2009, commemorating the 50th anniversary of the signing of the Antarctic Treaty.

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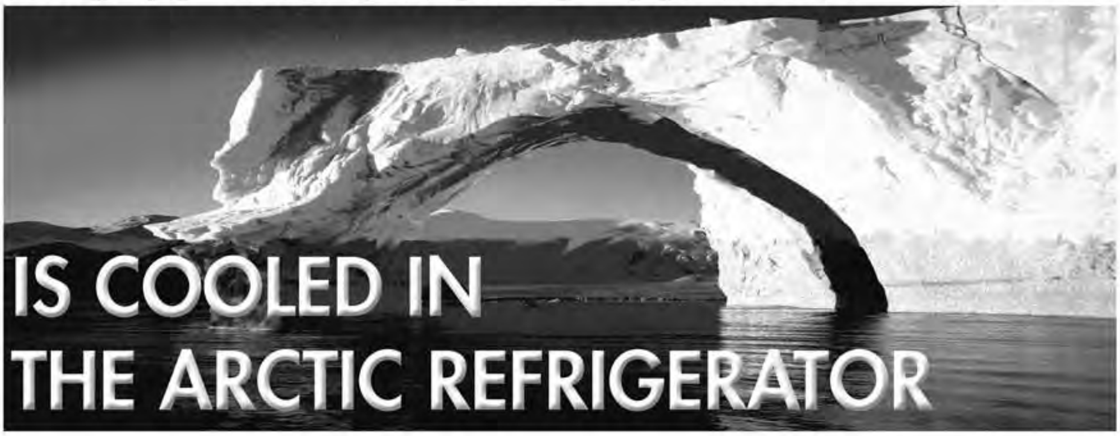
HOW ATLANTIC WATER IS COOLED IN THE ARCTIC REFRIGERATOR



Yueng-Djern Lenn

The term 'Arctic Ocean' evokes images of a harsh, perpetually ice-covered region at the remote northern pole of our planet. Recent headlines about dramatic Arctic sea-ice loss were prompted by the record low summer ice-extent observed in 2007, and highlight the region's enhanced sensitivity to climate change. Unlike the region itself, Arctic climate change should not be considered remote from us because processes occurring in the Arctic Ocean play a major role in determining the characteristics of the global overturning circulation which regulates global climate.

The Arctic Ocean is connected to the global ocean by warm salty water from the North Atlantic entering via the eastern side of Fram Strait, a Pacific inflow through the Bering Strait, and a much colder, fresher and very dense overflow exiting the Arctic via the western side of the Fram Strait, the Canadian Archipelago, and the Nordic Seas (Figure 1).

While flowing around the Arctic basin, Atlantic Water is transformed, becoming much colder, fresher and denser

Figure 1 *Map of the Arctic Ocean showing the path of Atlantic Water in relation to bottom topography. Black arrows: Alantic inflow; grey arrows: the Arctic boundary current and Bering Strait inflow. Decreasing dash-length indicates the transformation of warm salty Atlantic Water to denser, colder and fresher water which overflows into the Nordic Seas, and through the Canadian archipelago. Depth contours are for 500 m, 1500 m, 2500 m and 3500 m.*

Over recent decades scientific studies by Bogi Hansen, Bob Dickson and others have documented a freshening and slowing of these dense Arctic overflows that ultimately feed into the global overturning circulation. Possible future impacts of changes to pathways and properties of the Gulf Stream and other limbs of the global overturning thermohaline circulation have been explored in the popular science media. Extreme scenarios will be familiar to viewers of the influential BBC Horizon programme 'The Big Chill', or sensational Hollywood films such as 'The Day after Tomorrow'.

To better anticipate future changes, considerable effort has been expended in monitoring the variability of the inflow of Atlantic Water and its pathway within the Arctic Ocean. Pioneering observations by Fridtjof Nansen in the 1890s confirmed his theory that the polar basin was occupied by a frozen sea surrounding the North Pole, and revealed for the first time that relatively warm and salty Atlantic Water enters the Arctic Ocean from the North Atlantic through Fram Strait (Figure 1) beneath a colder fresher shallow outflow originating within the Arctic. Since then, modern observations have shown that the inflowing Atlantic Water flows eastwards in a boundary current along the periphery of the Arctic basin, following the continental slope north of the

Barents Sea. However, instead of flowing through Fram Strait, some of the Atlantic Water is diverted through the Barents and Kara shelf seas. Here, during its year-long passage north to rejoin the boundary current, is it subject to intense winter cooling and mixing with fresher shelf-sea waters. As they converge, the two branches of Atlantic Water interleave at intermediate depths (~180–500 m), and the resulting intrusive layers are carried along by the boundary current (Figure 2). The lateral spreading of these intrusions of warm Atlantic Water is thought to be the major source of heat for the interior Arctic Ocean. Divergence of the boundary current at it encounters topographic highs such as the Lomonosov Ridge further facilitates the lateral spreading of the Atlantic Water into the Arctic interior.

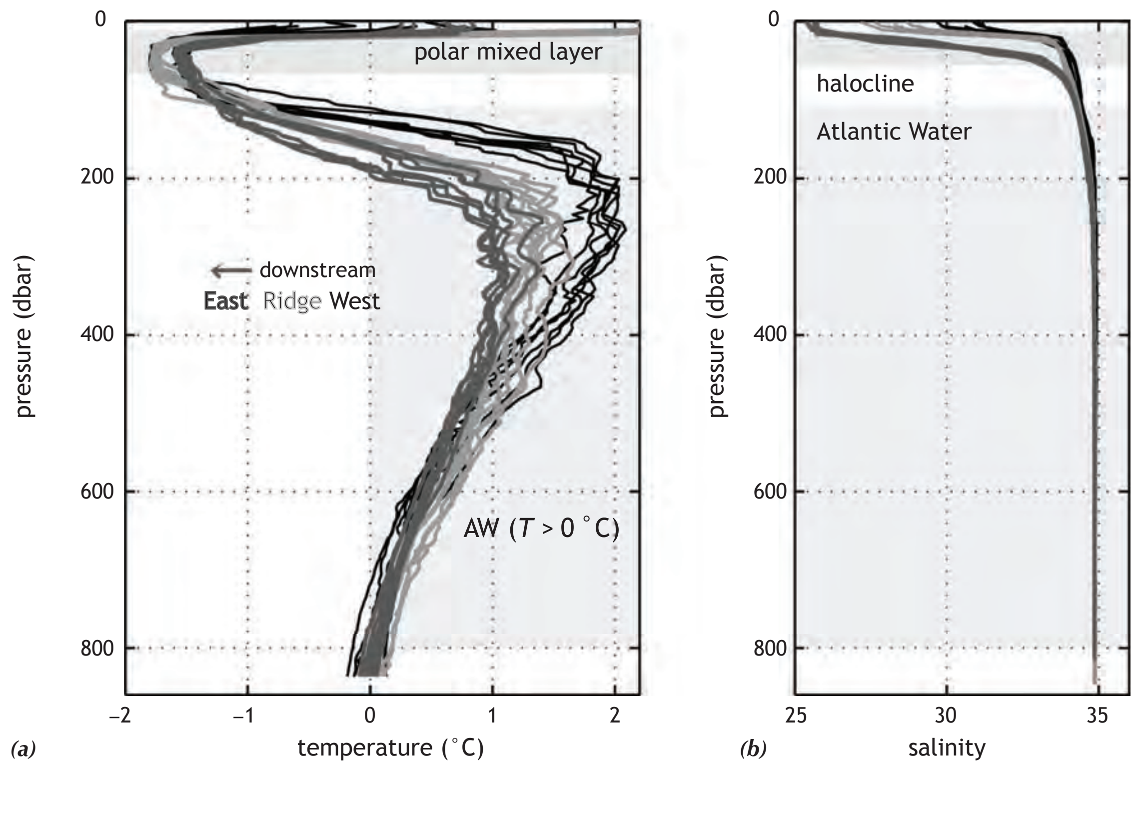
At first sight, it may be surprising that the Arctic sea-ice is not melted by heat lost directly from the Atlantic Water intrusions. This does not occur because the Atlantic Water intrusions do not extend to the surface. Instead, below the ice, in the uppermost 30–50 m of water, there is a low-density layer of cold and very fresh water known as the 'polar mixed layer' (Figure 2). This lies above a strongly stratified layer known as the Arctic halocline in which salinities (and temperatures) gradually increase with depth to values associated with the Atlantic Water intrusions directly below. Together, the polar mixed layer and Arctic halocline essentially 'insulate' the sea-ice from the warmth of the Atlantic Water because they form a stable, strongly stratified system which cannot be mixed up without an input of energy.

In addition to the transformations known to be occurring in the Barents and Kara seas, the Atlantic Water in the Arctic boundary current is also exposed to influences from the other Arctic continental shelf seas along its path, notably the the Laptev, East Siberian and Chukchi Seas. These Arctic shelf seas contain sites of dense bottom-water production in coastal and lee polynyas.* The Arctic shelf seas are freshened by the large input from rivers, which in the Eurasian sector alone combines to equal about thirty River Rhines. Hence, the Arctic shelf seas are not only important sources of dense bottom water for the deep Arctic, but are also sources of less dense, fresher water which replenishes the Arctic halocline. The exact nature of the processes responsible for the modification of Atlantic Water along the Arctic boundary, and how shelf seas buffer oceanic and terrestrial climate change, are therefore important questions for our time.

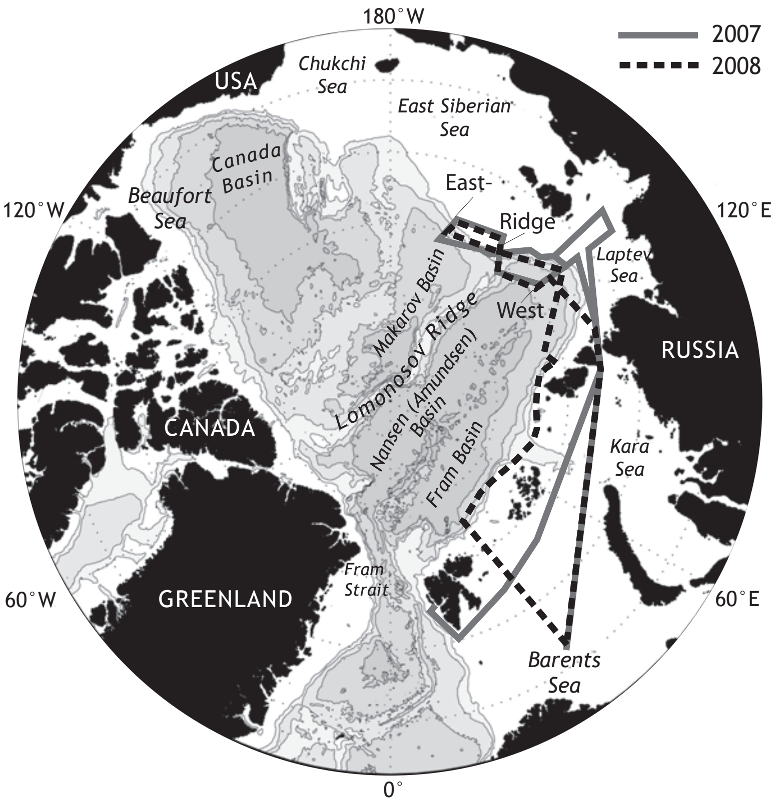
Bangor University recently participated in the Arctic Synoptic Basin-wide Oceanography project (ASBO) which was funded by a NERC International Polar Year consortium grant. We were responsible for making observations of turbulence and temperature/salinity microstructure along the Eurasian Arctic Ocean boundary during two field seasons in 2007 and 2008 (Figure 3, overleaf) organized by collaborators at the University of Alaska, Fairbanks. Our observations were taken in the region covered by the long-term moorings deployed and maintained by our Alaskan and other international colleagues as part of the Nansen–Amundsen Basin Observational System

*Polynyas are areas of open water where newly-formed ice is constantly blown away from coasts or from the lee-side of islands. This results in the accumulation of brine rejected during ice-formation, and hence in the formation of dense, high-salinity bottom waters.

Figure 2 *Profiles of **(a)** temperature and **(b)** salinity from three 2007 sections across the Arctic boundary current, to the west of the Lomonosov Ridge ('West'), above the ridge ('Ridge'), and to the east of the ridge ('East') (see Figure 3 overleaf). Moving eastwards (downstream in the boundary current), there is a marked cooling and freshening in the Atlantic Water layer (AW). The salinity changes, though marked, do not show at this scale. The alternating layers of the two branches of Atlantic Water can be clearly seen in (a). (On the vertical scale, pressure in decibars is equivalent to depth in metres.)*



Atlantic Water transported in the Arctic boundary current becomes progressively cooler and fresher



During NASBOS and ASBO cruises, observations were made of the Arctic boundary current and adjacent shelf-sea waters

Figure 3 *Bathymetric map of the Arctic Ocean overlain with the cruise tracks from the September 2007 and October 2008 NABOS/ASBO expeditions. (See text.)*

project (NABOS; cf. Figure 3). Our main objectives were to investigate and quantify the processes responsible for vertical mixing in the Arctic boundary current, and to assess the extent to which the characteristics of Atlantic Water in the current are altered by vertical mixing.

Three cross-sections of the boundary current (referred to as West, Ridge and East; cf. Figure 3) from the ice-free September 2007 field season revealed that there was a clear cooling and freshening trend as we progressed downstream north of the Laptev and East Siberian Seas (Figure 2). This was best quantified by differences in the heat and salt content observed in the transition layer at depths of 100–250 m; these changes corresponded to 0.76 °C cooling between the West and Ridge sections, and 0.30 °C cooling between the Ridge and East sections. Mean halocline salinities fell 0.13 between the West and Ridge sections, and by a further 0.04 between the Ridge and East sections.

To asses the vertical mixing, we used microstructure shear observations to evaluate the dissipation of turbulent kinetic energy in the Arctic boundary current. The dissipation occurs as a result of the energy being transferred to ever smaller and increasingly less energetic eddies, and can bring about irreversible changes of water properties when there is mixing between denser and less dense water masses. We found that the turbulent kinetic energy along the Arctic boundary was insufficient to mix the existing stratification. Instead, the observations resolved fine 'thermohaline staircases' indicative of double diffusive convection (Figure 4, in Box opposite). We showed conclusively that double diffusive convection, not turbulent mixing, was the dominant process driving vertical mixing through the Arctic halocline along the Arctic boundary. However, heat fluxes due to double diffusive convection accounted for only a tenth of the observed along-stream cooling and freshening of the Atlantic Water core (i.e. the least-mixed Atlantic Water, at about 250 m depth; Figure 2). This strongly implies that lateral mixing, most likely with waters originating from the shelf seas, must be responsible for much of the along-stream modification of Atlantic Water.

Our research therefore highlights the importance of the extensive Arctic continental shelf seas in the global climate system. These shelf seas act as a critical interface between the terrestrial Arctic environment and the branch of the thermohaline circulation that passes through the Arctic Ocean. The acceleration of the hydrological cycle associated with global warming, and the resulting increases in the outflow of Eurasian rivers to the Arctic, mean that changes in the terrestrial ecosystem are rapidly being communicated to the Arctic shelf seas. Increasing the freshwater storage of the shelf seas may inhibit lateral mixing with the oceanic waters on the boundaries of the shelf seas because of greater salinity and density differences, or increase the amount of freshwater exported into the Arctic interior. Alternatively, less-dense fresh shelf water may be exported from the shelves only at the surface, further suppressing vertical mixing processes in the Arctic interior. In each scenario, the modification of Atlantic Water along its path will probably be affected and the properties of the dense cold overflows to the Nordic seas changed. The consequences for the shelf seas and their influence on the stratification and ventilation of the Arctic Ocean, and hence global circulation, are now therefore a high priority for Earth System science.

Further Reading

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Double diffusion and mixing

The global ocean is stably stratified, with less dense water masses overlying denser water masses; the density of a water mass depends on both its temperature and its salinity. Mixing and the exchange of properties between different water masses usually takes the form of energetic turbulent mixing. This fast and efficient process is driven by an input of kinetic energy from currents, which cascades to smaller scales, resulting in overturning eddies several metres in diameter, that erode the existing stratification. These overturning eddies displace and stretch water parcels with temperature and salinity characteristics of the underlying water mass across the interface with the overlying water mass, and vice versa.

However, in certain stably stratified low-energy environments, mixing can be dominated by slow molecular diffusion which occurs at very small scales. Oceanic double diffusion arises from the differing molecular diffusion rates for heat and salt (heat diffuses 100 times faster than salt), and occurs in locations where temperature and salinity either both increase with depth or both decrease with depth.

When warmer, more saline water lies below cooler fresher water (as commonly occurs at high latitudes) the faster upwards diffusion of heat drives convective cells both above and below the interface (Figure 4), reinforcing the differences across it. This phenomenon acting over some depth of water results in numerous homogeneous layers, which appear in profiles of temperature and salinity as groups of steps, known as thermohaline staircases.

Perhaps the best known phenomenon associated with the double diffusion of heat and salt is salt-fingering (not shown), in which closely packed blobs of sinking high-salinity water, are interspersed with rising fingers of fresh water. The increased area of the interface resulting from the formation of the 'fingers' means that the rate of diffusion is greatly amplified. Salt fingering has been more commonly observed at lower latitudes, where high levels of solar energy result in evaporation from a warm sea-surface, and warm higher salinity surface water overlies cooler fresher water.

Both kinds of double diffusive instability have been shown to be widespread in the Arctic. In the upper part of the Arctic boundary current, where both temperature and salinity increase with depth, double diffusive convection staircases are observed (Figure 5). Below the Atlantic Water (>600–800 m), temperature and salinity both decrease with depth, and there are salt-finger staircases.

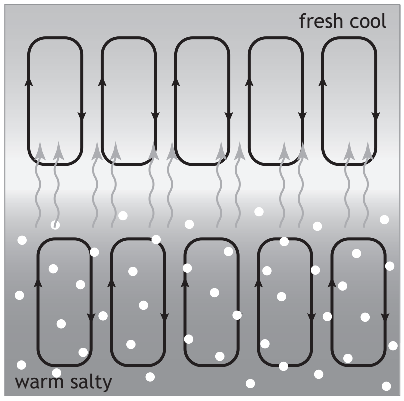
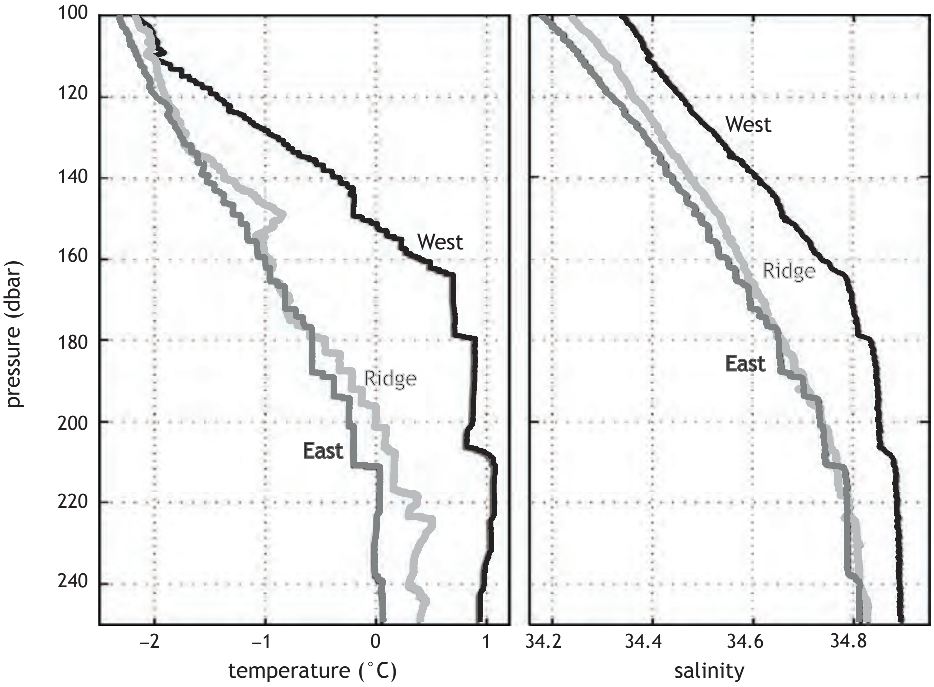


Figure 4 *Double diffusive convection: lighter tone = cooler water; darker tone = warmer water; dots = salt content. The wavey arrows indicate the faster diffusion of heat across the interface, which drives the convecting cells.*

Figure 5 *Thermohaline staircases observed in the upper part of the Arctic boundary current. The well-mixed layers (vertical sections) range in thickness from 5 cm to 60 m.*



Thermohaline staircases have been observed elsewhere in the Arctic, but seldom with the resolution obtained during the 2007 ASBO cruises

Yueng-Djern Lenn is currently a Postdoctoral Researcher at the School of Ocean Sciences, Bangor University in Wales. She is an observational oceanographer with an interest in the dynamics of the polar oceans and their role in global climate. Recently, she has been investigating mixing processes in the Arctic Ocean and shelf seas, while maintaining an ongoing interest in Southern Ocean dynamics.

Book reviews

To Follow the Water: exploring the ocean to discover climate, from the Gulf Stream to the blue beyond by Dallas Murphy (2008) Basic Books (Perseus Books), 296pp. £9.99 (paperback, ISBN-13: 978-0-465-00150-9).

Dallas Murphy presents a compelling tale which criss-crosses the Atlantic and has such unlikely heros as Chaucer, Otis Reading and a container full of Nike training shoes! Murphy describes how early Atlantic navigators as far back as Columbus learned to take advantage of the wind curl and the Gulf Stream to speed their trans-Atlantic voyages. He then goes on to chronicle the early development of physical oceanography in Scandinavia, together with growth of the Woods Hole Oceanographic Laboratory and the Scripps Institution in the US, bringing the story up to date with RAPID and Hollywood blockbuster 'The Day After Tomorrow'.

From the great Arctic explorer and polymath Fridjof Nansen speculating about the influence of the Earth's rotation on wind-induced currents in the Arctic Ocean, and his Norwegian colleague Vagn Ekman developing a theory to explain the motion, the story moves across the Atlantic to fellow Norwegian Harald Sverdrup, and his extension of the theory of wind-driven circulation to explain basin-scale gyres. Murphy then clearly presents Henry Stommel's explanation of the intensification of western boundary currents, adding Walter Munk's friction, thus enabling the Gulf Stream to be explained in terms of a balance of fundamental forces.

The story then meanders around 'ocean weather' before diving down to look at deep circulation and bottom-water formation, and then speculating on the potential disruption of the thermohaline balance, responsible for ocean circulation, by our changing climate.

The book then moves back through time to look at past disruptions of North Atlantic circulation such as the Younger Dryas event around 12 000 years ago, and examining more recent adaptations of civilisation to changing climate. Murphy then draws a rather chilling analogy between the threat posed to our society by global warming and the rapid extinction of the Greenland Vikings at the onset of the Little Ice Age in mediaeval times.

Despite the breath of the topics covered by the book I was slight disappointed that it barely touches on two key areas of the science. Firstly, there is little of the observations of Bob Dickson, Bill Turrell, Bogi Hansen and others which showed changes in the flow of deep water leaving the Arctic Ocean, leading to speculation that they will result in disruption of the overturning circulation. It would seem likely that these observations triggered the media interest which saw the production of the BBC Horizon programme 'The Big Chill' and the film 'The Day After Tomorrow'.

Also missing is the hunt for 'dark mixing' – the source of the kinetic energy required to drive the vertical mixing which sustains the overturning circulation of which the Gulf Stream is a part – despite this topic recently being identified by climate scientists as one of the great unknowns of the Earth System. It is also a topic hotly debated within the physical oceanography community, not least since the publication of Sjöborg and Stigebrandt's seminal paper in *Deep Sea Research* back in 1992!

Further reading

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Tom Rippeth
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Charles Darwin's *On the Origin of Species*: the Illustrated Edition edited by David Quammen (2008) Stirling Publishing Co. Inc, 544pp, £25 (hard cover, ISBN 13: 978-1-4027-5639-9).

This sumptuously illustrated book combines the many facets of Darwin's life and career in one volume. The main text of *On the Origin of Species* is superbly enhanced with over 350 illustrations and photographs, in full colour, and also includes extracts from *The Voyage of the Beagle* and from Darwin's letters, diaries and correspondence. Although the book devotes most attention to his five years aboard HMS *Beagle*, with images of the places visited, the people encountered and the many plant and animal species observed and recorded, it also includes many illustrations and extracts relating to the rest of Darwin's life, giving a fascinating insight into his upbringing, family life and the events that influenced and transformed his thinking.

Unlike many previous books on Darwin's life, this volume combines the scientific thoughts and ideas he recorded in *On the Origin of Species* with more personal thoughts from his autobiography and letters to friends, colleagues and opponents. It also includes reflective extracts from *The Life and Letters of Charles Darwin*, edited by his son Francis and published six years after Darwin's death. By bringing these components together, the book transforms Darwin's great original work – which, though fascinating, can sometimes appear rather dry to anyone other than the most dedicated scholar – into an extremely readable edition.

Illustrations and extracts are incorporated where most relevant, providing a window into Darwin's world and the events that influenced his thoughts, ideas and actions. Perhaps the most poignant is the highly critical letter from Adam Sedgwick, in which he describes having 'read your book with more pain than pleasure' – to Darwin this must have felt like a knife through the heart. However, it is clear in supportive letters from other correspondents such as Charles Lyell, Thomas Huxley and Joseph Hooker, that he also had many champions. This book reveals Darwin as great man of science who painstakingly gathered evidence to support his theory of evolution, ever sensitive to the impact that this might have. His letters to friends and adversaries alike reveal him as a true English gentleman, polite even in the face of intense criticism.

Perhaps somewhat surprisingly, the book contains fewer references to his personal life than might have been expected, particularly the much documented impact of the death of his beloved daughter Annie. However, in all other respects it is an excellent scientific and historic digest of his life. It is easily readable and visually attractive. The rich collection of photographs, sketches, portraits, woodcuts and other reproductions, including many beautifully coloured lithographs, also make it perfect for browsing. In the words of the editor: 'We have taken the liberty, for your pleasure and information, of adding some literary side dishes and visual condiments to the main course'.

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