# Climate records from the Faroe-Shetland Channel using *Lophelia pertusa* (Linnaeus, 1758)

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**Abstract.** The longest available time series on ocean currents indicates that the southward flow of water from the Greenland Sea is weakening, and that correlative large-amplitude changes have occurred in the rate of formation of intermediate Labrador Sea water. These have been linked to changes in regional climate which, if trends continue, could within 30 years alter the flow of the North Atlantic Drift and possibly interrupt the formation of Labrador Sea water, profoundly affecting regional climates, marine ecosystems and fisheries. We are attempting to use the carbonate skeletons of cold-water corals to find out how rapidly and how often the thermohaline circulation of the NE *vs*. NW Atlantic has changed in the past, just as tree rings and ice cores are used to investigate climate change on land.

We have focussed on the NE Atlantic for our preliminary work, notably the Faroe-Shetland Channel: a major gateway between the Atlantic Ocean and the Norwegian Sea. Warm North Atlantic Drift water passes north through this channel on the surface, warming northern Europe. Cold Norwegian Sea Overflow Water returns at depth, contributing to the formation of North Atlantic Deep Water. Existing records are too short to allow conclusions regarding recent temporal changes in this inflow, so proxies are sought. We have analysed live-collected *Lophelia pertusa* skeletons collected in October 2001 using a ring dredge from RV Scotia along the worlds longest-running hydrographic transect (from 1893). Corals were sectioned using a slow-speed Isomet saw, and sampled for isotopic analysis using a Merchantek micromill. Observation of sectioned corals revealed dense-less dense couplets, as in every coral studied to date from tropical to deep cold-water environments worldwide. We sampled circumferentially, in the centres of individual bands, so as to produce temperature estimates using the "lines" technique of Smith et al. (2000). The results were simultaneously encouraging and confusing.

Each of the coral samples generated lines from which temperatures could be estimated. Dense skeletal bands had lower temperatures than the less-dense bands,

hence we conclude these were winter and summer bands, respectively. The mean annual temperature (MAT) range determined from one of the corals was 3.8°C. Pooling results from several corals yielded a lower estimate for MAT range: 2.3°C. The absolute temperatures from the corals, however, were somewhat lower than the instrumental record with "winter" records being more depleted than the "summer values". This was unexpected and shows that determining detailed climate records from *L. pertusa* may be more difficult than hoped.

## Introduction

Obtaining climate records from coral skeletons is proving to be an invaluable aid to climatology (Druffel et al. 2001; Tudhope et al. 2001) in a time of what could possibly be massive and fundamental climate change (Jones et al. 1999; Mann et al. 1999). Most of this research has focussed on tropical reef corals, which have been shown to be archives of past water temperature, large-scale climate events, and sediment stress. These corals produce annual dense/less dense skeletal banding couplets, allowing precise stratigraphic resolution. Massive tropical reef corals may live several centuries allowing long proxy records of ocean climate to be obtained. The major drawbacks to the use of reef corals are restrictions in their depth and geographic range: large colonies of massive corals suitable for climate work tend to be restricted to the eastern fringes of tropical coastlines.

In recent years, however, research in coral paleoclimatology has discovered the enormous potential of climate records in the skeletons of cold-water corals: the "New Archive" (pers. comm. W. Broecker 1995). Families of hexacorals, octocorals and hydrocorals are distributed in all oceans, at virtually all depths from sea level to at least 4 km.

Early use of cold-water corals in paleoclimate research was that of Smith et al. (1997) using *Desmophyllum cristagalli* (Milne-Edwards and Haime, 1848) from Orphan Knoll, located 500 km off the SE coast of Newfoundland. This was followed by work on the skeletal structure of deep-water corals (Lazier et al. 1999), how "vital effects" could be overcome (Smith et al. 2000), and on ocean ventilation (Goldstein et al. 2001). Deep-water scleractinians are proving to be more difficult to work with than the massive forms used in the sclerochronology of tropical coral heads such as *Porites* spp. Many are small in comparison with tropical reef corals, usually less than 10 cm, and slow-growing so although they may be faithful recorders with several decades' information on ocean temperatures the tight spacing of the growth bands makes stratigraphic control extremely difficult. For example, recent work on the gorgonian *Primnoa resedaeformis* (Gunnerus, 1763) has shown that it has beautifully-defined growth bands with climate records spanning almost a century, but the bands are extremely tightly spaced (Sherwood et al. 2003; Sherwood and Risk in press).

*Lophelia pertusa* may be the most widely-distributed scleractinian on the globe; in the north Atlantic it constructs deep reefs from the Gulf of Mexico to Nova Scotia in the west and from Mauritania to northern Norway in the east with scattered records from locations worldwide (Wilson 1979; Rogers 1999). There is great interest in *L. pertusa*, because of the importance of these reefs as fish habitat coupled with increasing threats from trawling (Hall-Spencer et al. 2002). In addition to the value of this coral in creating fish habitat, it is possible that it may also contain a priceless archive of climate data. We report herein preliminary attempts to read that record.

The Faroe-Shetland Channel is one of the key regions in the thermohaline circulation of the North Atlantic. This channel, only 25 km wide at its narrowest point, forms the main gateway between the Atlantic Ocean and the Norwegian Sea. Warm, saline water of the North Atlantic Drift (the northern extension of the Gulf Stream) flows from the Atlantic into the Norwegian Sea, delivering a significant amount of heat to the climate of northwestern Europe. This water then cools and sinks, and flows south through the Denmark Strait, across the Iceland-Scotland Ridge, and back through the Faroe-Shetland Channel at depth, contributing to North Atlantic Deep Water (NADW) (Crease 1964). This then completes the northern loop of the thermohaline conveyer-belt circulation in the Atlantic. In short, an oceanographic phenomenon which controls much of the distribution and history of civilization in western Europe may be monitored at one site. Another place where both the Gulf Stream and the Gulf Stream Return Flow has been investigated using cold-water corals is Orphan Knoll, some 500 km NE of Newfoundland (Smith et al. 1997).

Recent concerns about climate change due to an increase in greenhouse gases have emphasized the need for long-term proxies of climate change in the oceans. At present, we are unable accurately to predict weather far into the future as a complete understanding of global climate will require much better understanding of ocean circulation. Because long-term oceanographic records at depth in the oceans are so rare, we will have to depend on climate proxies. At the moment, cold-water corals show great promise of being able to provide long, accurate records of ocean conditions (Smith et al. 1997; Adkins et al. 2003; Frank et al. 2003; Sherwood et al. 2003).

Recently, there have been reports of decreases in the intensity and density of overflow through the Faroe-Shetland Channel (Hansen et al. 2001), resulting in a decrease in the water supply to the NADW. When NADW flow is strong, a strong northward flux of warm surface waters in the North Atlantic maintains mass balance, warming northern Europe. An interruption or decrease in NADW flow could plunge much of north-western Europe into frigid conditions (Keigwin and Boyle 2000). There have been recent suggestions that the circulation of this part of the Atlantic has indeed been changing over the past 30 years (Turrell et al. 1999). Increases in meltwater fluxes 12-14 ka BP caused extreme climatic cooling, and the exchange of waters between the Nordic Seas and the Atlantic was essentially reversed (Rasmussen et al. 2002). Increased meltwater flows from polar ice caps might result in similar conditions in the future, a change that could occur with shocking

rapidity (Smith et al. 1997). Proxy records are essential, especially ones that could span several centuries - *L. pertusa* reefs are known to be thousands of years old (Freiwald et al. 2002; Hall-Spencer et al. 2002), hence are excellent candidates for long climate records (Frank et al. 2003).

Because *L. pertusa* is so widespread in regions of critical interest with regard to oceanic change, climate records obtained from their skeletons could prove to be invaluable. In this paper, we report preliminary analyses of *L. pertusa* taken from the Faroe-Shetland Channel. Our hypothesis was that the internal banding observed in the skeletons *L. pertusa* represented annual couplets, similar to those observed in tropical reef corals (Knutson et al. 1972). These couplets might then record variations in annual temperature range.

## Methods and materials

Fisheries Research Services, Marine Laboratory Aberdeen run regular (usually triannual) surveys of the Faroe-Shetland Channel using RV Scotia to characterise the water masses below two historic hydrographic transects (Fig. 1). We joined one of these cruises (1501S) on 5-19 Oct 2001 to take ring dredge (1 m wide, 50 mm mesh) samples targeting the calcareous macrobenthos between sampling standard CTD stations. Nine ring dredge samples were taken from four stations on the Fair Isle - Munken transect, amended for the presence of Foinaven oil platform (Fig. 1). The stations were FIM-05 (995 m, 60°29.00' N, 04°26.00' W, two dredge samples taken), FIM-04 (655 m, 60°25.00' N, 04°19.00' W, one dredge sample), SEFOS (330 m, 60°18.00' N, 04°04.50' W, four dredge samples) and FIM-01 (150 m, 60°10.00' N, 03°44.00' W, two dredge samples). Living and dead *Lophelia pertusa* colonies were encountered in two of the dredge samples taken at 330 m, close to the Foinaven oil platform. These samples were washed in freshwater, air dried and transported to the laboratory. The British Oceanographic Data Centre (http://www.bodc.ac.uk) database was accessed for data relating to the site where our *L. pertusa* samples were taken (Table 1).

Coral samples were bleached for one week with sodium hypochlorite before sample preparation. Individual polyps were cut from the mass of coral with a small hand-held circular saw. These polyps were cleaned three times for 10 minutes each time in an ultrasonic bath and dried overnight in an oven at 40 degrees C. In order to ensure the utility of the "lines" technique of Smith et al. (2000), one of the polyps was intensively sampled that was alive when collected. Samples for isotopic analysis were carefully scraped from the outer edges of septa and from the uppermost edge of the septathecal wall. These samples should have been coeval, and hence should record the water temperature at the time of sampling.

In order to investigate isotopic values associated with banding within the coral skeletons, a slow-speed Isomet™ saw was used to cut transverse sections through individual coral polyps, which were then polished flat. Samples for isotopic analysis were milled from these sections using a Merchantek™ microsampler.
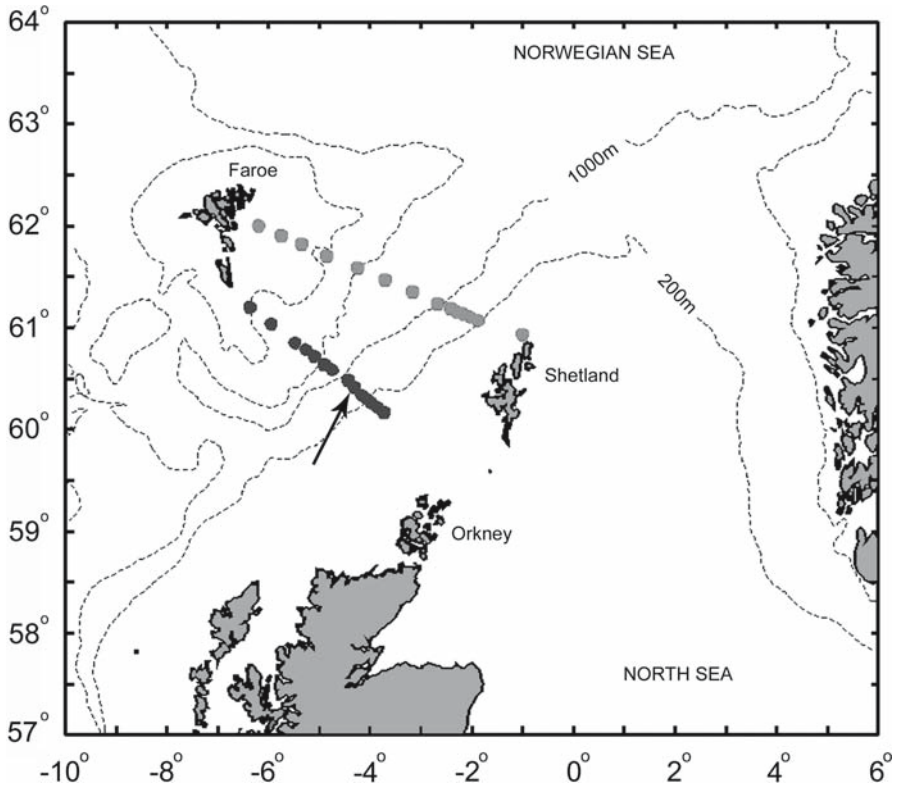
**Fig. 1** Two standard hydrographic transects started in 1893. Benthos was sampled in a ring dredge aboard RV Scotia (cruise 1501S) along the southern Fair Isle - Munken transect in October 2001, the arrow shows where *Lophelia pertusa* samples were obtained (source Fisheries Research Services, Aberdeen)

**Table 1** Recent hydrographic data for the Faroe-Shetland Channel site where *Lophelia pertusa* was sampled for isotopic analyses (source BODC)

| Date | Time | Position | Water depth | Sample depth | Salinity [‰] | Temp [°C] |
|---|---|---|---|---|---|---|
| 4.6.96 | 12.32 | 60°18.1'N 4°4.3'W | 328 m | 292 m | 35.3326 | 9.037 |
| 20.10.96 | 19.12 | 60°18.1'N 4°4.3'W | 325 m | 311 m | 35.2856 | 9.091 |
| 5.10.98 | 11.19 | 60°17.7'N 4°4.7'W | 324 m | 314 m | 35.4294 | 10.062 |
| 4.12.98 | 02.56 | 60°17.9'N 4°4.6'W | 322 m | 300 m | 35.3960 | 9.904 |
| 9.5.00 | 23.33 | 60°18.2'N 4°4.2'W | 330 m | 324 m | 35.3482 | 8.697 |

# Results

All isotopic data are presented in Table 2. Representative specimens of the corals used in this study are archived at McMaster University.

The results from the sampling of supposedly coeval skeleton are given in Figure 2. Plotted in C-O space, the data form a tight straight line. Using the formula in Smith et al. 2000, we calculate a temperature at time of collection (October) of 5.73°C. Figure 3 shows the measured temperature profile for the Fair Isle - Munken transect of the Faroe-Shetland Channel at the time of collection. The bottom temperature where the *L. pertusa* sample was taken was c. 10°C with other recent measured values ranging from 8.697°C (May 2000) to 10.062°C (Oct 1998) (Table 1).

**Table 2** Data from *Lophelia pertusa* collected in the Faroe-Shetland Channel

| | $\delta^{13}C$ | $\delta^{18}O$ | | $\delta^{13}C$ | $\delta^{18}O$ | | $\delta^{13}C$ | $\delta^{18}O$ |
|---|---|---|---|---|---|---|---|---|
| Inner | -4.390 | 0.867 | Dense | -6.812 | 0.197 | Less dense | -4.959 | 0.914 |
| Inner | -6.594 | -0.282 | Dense | -6.565 | 0.283 | Less dense | -4.085 | 1.421 |
| Inner | -7.743 | -1.118 | Dense | -7.858 | -0.260 | Less dense | -3.881 | 1.419 |
| Inner | -7.023 | -0.553 | Dense | -7.977 | -0.497 | Less dense | -2.228 | 2.058 |
| Inner | -6.321 | -0.063 | Dense | -7.564 | -0.370 | Less dense | -3.163 | 1.578 |
| Inner | -7.564 | -0.968 | Dense | -7.844 | -0.532 | Less dense | -4.884 | 0.977 |
| Inner | -7.171 | -0.831 | Dense | -7.383 | -0.583 | Less dense | -2.961 | 1.775 |
| Inner | -7.528 | -1.006 | Dense | -6.206 | 0.272 | Less dense | -2.901 | 1.830 |
| Inner | -7.132 | -0.676 | Dense | -6.769 | -0.180 | Less dense | -4.789 | 1.066 |
| Inner | -6.805 | -0.499 | Dense | -7.929 | -0.834 | Less dense | -3.908 | 1.463 |
| | | | Dense | -7.817 | -0.807 | Less dense | -4.468 | 1.206 |
| Septa | -3.699 | 0.908 | Dense | -7.914 | -0.730 | Less dense | -4.562 | 1.175 |
| Septa | -5.377 | 0.480 | Dense | -7.473 | -0.134 | Less dense | -4.129 | 1.368 |
| Septa | -3.134 | 1.512 | Dense | -7.135 | 0.096 | Less dense | -6.225 | 0.305 |
| Septa | -3.644 | 1.420 | Dense | -8.360 | -1.013 | Less dense | -5.376 | 0.793 |
| Septa | -3.559 | 1.392 | Dense | -8.121 | -0.607 | Less dense | -4.673 | 0.826 |
| Septa | -2.404 | 1.741 | Dense | -7.585 | -0.696 | Less dense | -5.622 | 0.353 |
| Septa | -3.026 | 1.665 | Dense | -4.761 | 1.001 | Less dense | -3.968 | 1.244 |
| Septa | -3.966 | 1.125 | Dense | -7.955 | -0.983 | Less dense | -3.595 | 1.340 |
| Septa | -3.084 | 1.611 | Dense | -8.126 | -1.105 | Less dense | -5.325 | 0.622 |
| Septa | -3.304 | 1.582 | Dense | -7.173 | -0.423 | Less dense | -4.190 | 1.052 |
| | | | Dense | -7.784 | -0.812 | Less dense | -5.583 | 0.343 |
| | | | Dense | -8.252 | -0.673 | Less dense | -5.004 | 0.722 |
| | | | Dense | -7.214 | -0.124 | Less dense | -5.987 | 0.151 |
| | | | Dense | -7.721 | -0.488 | Less dense | -6.130 | 0.037 |
| | | | Dense | -8.169 | -0.641 | Less dense | -5.760 | 0.470 |
| | | | Dense | -6.292 | 0.297 | Less dense | -5.188 | 0.651 |
| | | | Dense | -8.352 | -0.906 | Less dense | -6.657 | -0.018 |
| | | | Dense | -8.532 | -1.006 | Less dense | -3.914 | 1.624 |
| | | | Dense | -7.732 | -0.658 | Less dense | -5.353 | 0.908 |
| | | | Dense | -8.043 | -0.473 | | | |
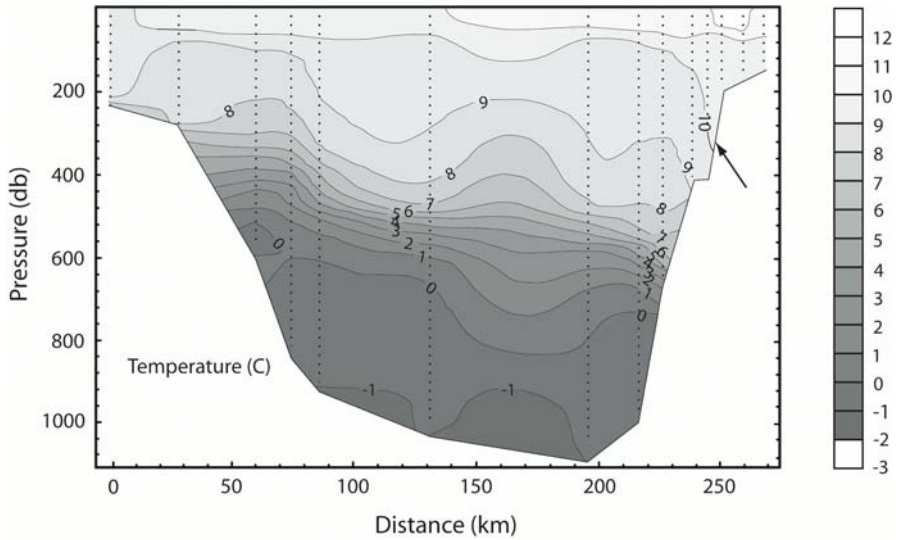
**Fig. 2** Temperature profile of the Fair Isle - Munken transect recorded on 12-13 October 2001, dotted vertical lines show positions of the standard hydrographic stations. Note the sub-zero bottom-water and the arrow showing where *Lophelia pertusa* colonies were sampled at 330 m on the eastern side of the Faroe-Shetland channel on 7 October 2001 in 10°C water (source FRS Aberdeen)
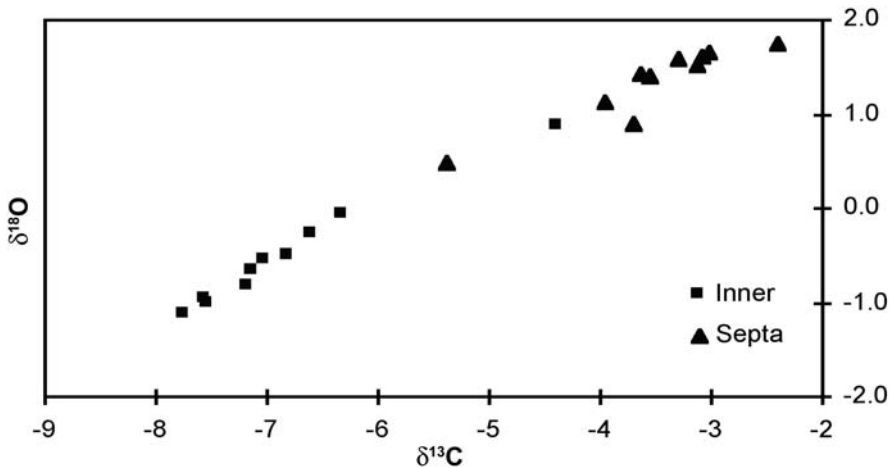


**Fig. 3** $\delta^{13}C/\delta^{18}O$ plot of coeval samples taken from one polyp. The line is highly significant, and the calculated temperature for Oct. 2001 is 5.73°C

Results from independently sampling dense and less-dense bands of the skeleton are presented in Figure 4. Results from four polyps are pooled. The calculated temperatures are 3.47°C (dense) and 5.82°C, yielding a mean annual temperature (MAT) range of 2.3°C. Results from one individual polyp returned a MAT range of 3.8°C. Less-dense bands were on the outside of the skeletons, and we assume these represent summer growth. This assumption is reinforced by the higher temperature calculated from isotopic values in these bands. Dense bands were consistently further from equilibrium than less-dense bands.
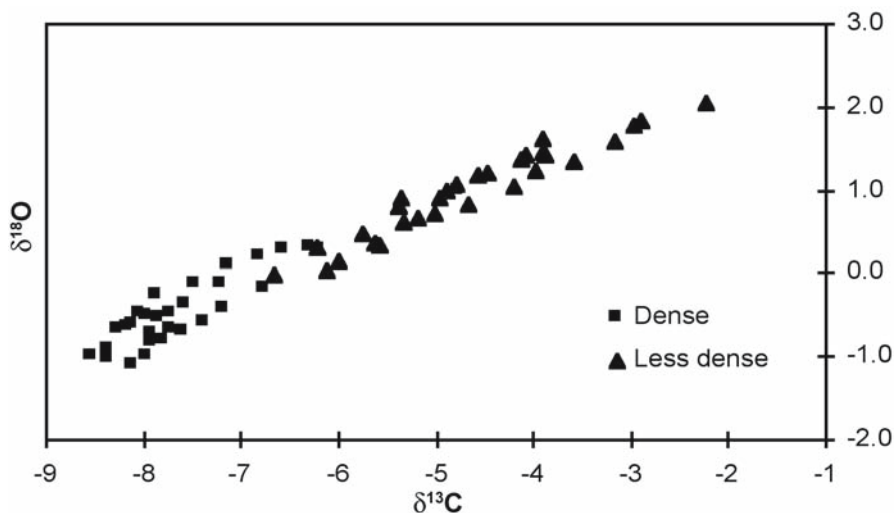


**Fig. 4** $\delta^{13}C/\delta^{18}O$ plot of samples from dense and less-dense areas micromilled out of four polyps

## Discussion

The lines in C-O space generated by the coral samples are consistent with the results of Smith et al. (2000). In general, isotopic records from deep-sea corals are dominated by scattered departures from equilibrium (so-called "vital effects", or kinetic isotopic equilibrium effects) to such an extent that paleoclimate determinations from these corals by traditional means are impossible (Smith et al. 2002).

From analogy with banding in tropical reef corals, and from the external location of the less-dense bands at time of collection, we assume that less-dense bands are laid down in summer months, and the dense bands in winter. The October temperature determination is very close to those determined from the less-dense "summer" bands, which follows - the warmest months of the year will be August - September. Even with the use of a microsampler, it was extremely difficult to sample precisely along coeval growth lines. Any errors in location will translate into smaller differences between summer and winter determinations: thus, while one polyp returned a temperature range of 3.8°C, the other sampled polyps gave lower

ranges. While these values seem low by comparison with those reported by Hansen and Osterhus (2000) this region of the ocean can experience extreme fluctuations in time and space. Temperatures around 330 m depth on the eastern flank of the Faroe-Shetland Channel typically have a mean annual range of around 4°C (George Slesser, Fisheries Research Services Aberdeen, pers. comm.). However, recent records of temperature from the site where the coral was sampled have a recorded range of just 1.365°C although these are point samples and unlikely to encompass the full range of temperature fluctuations in an area as dynamic as the Faroe-Shetland Channel (see Bett 2001).

Our lowest calculated temperature, 2.3°C, is considerably lower than the 4°C reported by Rogers (1999) from other sources as being a lower limit to the distribution of live *L. pertusa*. On the other hand, Bett (2001) reports on results from a moored CTD that recorded live *L. pertusa* in an area at 550 m on the eastern flank of the Faroe-Shetland Channel that regularly experienced lower temperatures than 4°C, and even reports their ability to survive brief periods of subzero temperatures.

The origin of the kinetic isotope effects in these corals continues to elude us. Adkins et al. (2003) suggest a mechanism to explain "vital effects" that involves pH gradients in the calcifying region. Much of their explanation hinges on data from *Desmophyllum cristagalli* that deviate from straight lines - for some points far from equilibrium, $\delta^{13}C$ remains constant while $\delta^{18}O$ continues to increase. The largest data set for *Desmophyllum cristagalli* may be found in Smith (1997), which includes bulk- and microsampled data points. She was unable to find the same deviations reported by Adkins et al. (2003). Pursuing this line of research may prove to be very fruitful, however, as French colleagues have also suggested involvement of pH in isotopic values in corals (Blamart et al. 2003). There are indeed large fluctuations in pH in coral skeletons: Risk and Kramer (1981) report elevated pH's (over 9, in some cases) from regions immediately under the calicoblastic epithelium, where water chemistry of these tiny compartments is dominated by the activities of boring algae. Further down in the skeleton, nutrient regeneration takes over, and metabolic $CO_2$ drives the pH down to values well below ambient (Risk and Muller 1983).

Variations in the amount of metabolic $CO_2$ incorporated into the skeleton may also profoundly impact isotopic values. Here, we suggest that a hard look at the biology of *L. pertusa* is in order. *Lophelia pertusa* is not a filter-feeder (cf. Adkins et al. 2003) and can feed voraciously on copepods in the laboratory and when observed by manned submersible, although submersible lights attract swarms of small Crustacea (Roberts pers. comm. 2002). Like many coelenterates, their nutrition probably is a combination of microcarnivory combined with dissolved organic matter (DOM) absorption. Values of $\delta^{15}N$ in coral tissue reported by Grehan et al. (2003), combined with very high values of free fatty acids in the bottom waters near *L. pertusa* reefs (Kiriakoulakis et al. 2003) support this assumption. Skeletal formation in *L. pertusa*, and indeed many cold-water corals, may therefore be an episodic process controlled fundamentally by feeding rate. Skeletal growth in these corals may be extremely slow for much of the time, as the coral survives on DOM, punctuated by rapid growth when food stocks become available. This would go a

long way to explaining the spread in isotopic values seen by us and others.

The distribution of values along the C/O lines remains one of the most intriguing aspects of our results. In the preliminary investigation, samples from the inner part of the polyps, although coeval with the septa, were consistently further from equilibrium than were the septa (Table 2). Similarly, dense bands were further from equilibrium than less-dense bands. Presumably, the dense bands result from slower growth, and hence might be expected to be closer to equilibrium. This aspect of our results deserves further investigation and may shed light aspects of coral skeletogenesis.

The largest mean annual temperature range of 3.8°C calculated from one of the corals closely agrees with the known temperature variation for this depth. Fluctuation in the annual temperature range can be valuable in providing records of past climate variability. For example, oscillation in the MAT recorded in tropical corals has been used by Tudhope et al. (2001) to show the existence of ENSO over the past 130,000 years by demonstrating interannual variation in temperature from fossil coral records. Climate proxies from the Faroe-Shetland Channel could similarly demonstrate long-term fluctuations over time, allowing us to put present changes in perspective and to help constrain predictions of future changes in thermohaline circulation

## Conclusions

1.  Temperature values extracted from *Lophelia pertusa* samples, using the "lines" technique of Smith et al. (2000), were consistently lower than instrumental records for the site.
2.  The range of temperature values obtained from the corals accurately reflected the mean annual temperature range at 330 m in the Faroe-Shetland Channel.
3.  Distribution of values along the lines in C/O space shows systematic fractionation, the nature of which is unexplained.

## Acknowledgements

## References

Adkins JF, Boyle EA, Curry WB, Lutringer A (2003) Stable isotopes in deep-sea corals and a new mechanisms for "vital effects". Geochim Cosmochim Acta 67: 1129-1143

Bett B (2001) Benthic ecology of the Faeroe-Shetland Channel. In: Atlantic margin environmental surveys of the seafloor 1996 and 1998. CD-ROM Geotek Ltd

Blamart D, Rollion-Bard TC, Cuif J-P, Juillet-Leclerc A, Lutringer A, van Weering T, Henriet J-P (2003) C and O isotopes in deep-sea corals (*Lophelia pertusa*) measured by ion microprobe. Erlanger Geol Abh Sonderbd 4: 22

Crease J (1964) The flow of Norwegian Sea water through the Faroe Bank Channel. Deep-Sea Res 12: 143-150

Druffel ERM, Griffin S, Guilderson T, Kashgarian M, Schrag D (2001) Changes of subtropical North Pacific radiocarbon and correlation with climate variability. Radiocarbon 43: 15-25

Frank N, Paterne M, Ayliffe L, Lutringer A, Blamart D, van Weering T (2003) Cold-water corals of the northeast Atlantic margin: archives of intermediate water circulation during the Holocene. Geophys Res Abstr, 5, Europ Geophys Soc

Freiwald A, Hühnerbach V, Lindberg B, Wilson J, Campbell J (2002) The Sula Reef Complex, Norwegian Shelf. Facies 47: 179-200

Goldstein SJ, Lea DW, Chakraborty S, Kashgarian M, Murrell MT (2001) Uranium-series and radiocarbon geochronology of deep-sea corals: implications for Southern Ocean ventilation rates and the ocean carbon cycle. Earth Planet Sci Lett 193: 167-182

Grehan AJ, Kiriakoulakis K, Mahaffey C, Wolff GA (2003) Food web relationships in deep-water corals from the Porcupine Sea Bight and Rockall Trough, west coast of Ireland. Erlanger Geol Abh Sonderbd 4: 40

Hall-Spencer J, Allain V, Fosså JH (2002) Trawling damage to Northeast Atlantic ancient coral reefs. Proc R Soc London B 269: 507-511

Hansen B, Osterhus S (2000) North Atlantic-Norwegian Sea exchanges. Progr Oceanogr 45: 109-208

Hansen B, Turrell WR, Osterhus S (2001) Decreasing overflow from the Nordic Seas in the Atlantic Ocean through the Faroe Bank channel in 1950. Nature 411: 927-930

Jones PD, New M, Parker DE, Martin S, Rigor IG (1999) Surface air temperature and its changes over the past 150 years. Rev Geophys 37: 173-199

Keigwin LD, Boyle EA (2000) Detecting Holocene changes in thermohaline circulation. Proc Nat Acad Sci 97: 1343-1346

Kiriakoulakis K, White M, Freiwald A, Wolff GA (2003) Biogeochemistry of deep-water coral systems at the NW European Continental Margin. Erlanger Geol Abh Sonderbd 4: 52

Knutson SW, Buddemeier RW, Smith S (1972) Coral chronometers: seasonal growth bands in reef corals. Science 177: 270-272

Lazier AV, Smith JE, Risk MJ, Schwarcz HP (1999) The skeletal structure of *Desmophyllum cristagalli*: the use of deep-water corals in sclerochronology. Lethaia 32: 119-130

Mann ME, Bradley RS, Hughes MK (1999) Northern hemisphere temperatures during the past millennium: interferences, uncertainties, and limitations. Geophys Res Lett 26: 759-762

Rasmussen TL, Bäckström D, Heinemeier J, Klitgaard-Kristensen D, Knutz PC, Kuijpers A, Lassen S, Thomsen E, Troelstra SR, van Weering TCE (2002) The Faroe-Shetland Gateway: Late Quaternary water mass exchange between the Nordic Seas and the northeastern Atlantic. Mar Geol 188: 165-192

Risk MJ, Kramer JR (1981) Water chemistry inside coral heads: determination of pH, Ca and Mg. 4th Int Coral Reef Symp, Manila, pp 54

Risk MJ, Muller HR (1983) Porewater in coral heads: evidence for nutrient regeneration. Limnol Oceanogr 28: 1004-1008

Rogers AD (1999) The biology of *Lophelia pertusa* (Linnaeus 1758) and other deep-water reef-forming corals and impacts from human activities. Int Rev Hydrobiol 84: 315-406

Sherwood OA, Sinclair DJ, Risk MJ, Scott DB (2003) Testing the fidelity of Mg/Ca as a temperature proxy in the deep-sea coral *Primnoa resedaeformis*: Records since 1950. Erlanger Geol Abh Sonderbd 4: 79

Sherwood OA, Risk MJ (in press) Climate significance of growth patterns in the deep-sea coral *Primnoa resedaeforms*. Mar Ecol Progr Ser

Smith JE (1997) The use of deep-sea corals as paleoceanographic monitors. PhD thesis, McMaster Univ, Hamilton, Ontario, Canada

Smith JE, Risk MJ, Schwarz HP, McConnaughey TA (1997) Rapid climate change in the North Atlantic during the younger Dryas recorded by deep-sea corals. Nature 386: 818-820

Smith JE, Risk MJ, Schwarcz HP, McConnaughey TA, Keller NB (2000) Deep-sea corals as paleotemperature indicators: overcoming "vital effects". Palaios 15: 25-32

Smith JE, Schwarcz HP, Risk MJ (2002) Patterns of isotopic equilibrium in azooxanthellate coral skeletons. Hydrobiologia 471: 111-115

Tudhope AW, Chilcott CP, McCulloch MT, Cook ER, Chappell J, Ellam RM, Lea DW, Lough JM, Shimmield GB (2001) Variability in the El Niño-Southern Oscillation through a glacial-interglacial cycle. Science 291: 1511-1517

Turrell WR, Slesser G, Adams RD, Payne R, Gillibrand PA (1999) Decadal variability in the composition of Faroe Shetland Channel bottom water. Deep-Sea Res I 46: 1-25

Wilson JB (1979) The distribution of the coral *Lophelia pertusa* (L.) [*L. prolifera* (Pallas)] in the north-east Atlantic. J Mar Biol Ass UK 59: 149-164