SEA7 Technical Report - Hydrography

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Executive Summary

SEA7 is the largest of the SEA regions with an overall area of 3.6×10^5 km^2, a volume of 4.6×10^5 km^3 and a mean depth of 1270 m. It covers the Scottish west coast shelf, Rockall Trough and Rockall Plateau and at its furthermost point, 900 miles from the Scottish mainland at 23º 52'.26 W, extends well into the Iceland Basin.

The oceanic part is a remote and, in winter, hostile region. The Iceland Basin is deepest part (3220 m) but in general is not well charted; the Rockall Plateau contains a large isolated shelf sea region (the Rockall Bank), while the Rockall Trough has a number of isolated seamounts.

SEA7 lies across the northern end of the Atlantic Meriodional Overturning Circulation and contains a number of major oceanic currents carrying surface water northward across the whole region and returning cold Artic water around the foot of some of its slopes.

In general both ocean current and depth averaged tidal velocities are small, of order 5 cm s^{-1}. Maximum speeds are about 15 to 20 cm s^{-1} in some local regions such as the Rockall Bank and parts of the European shelf edge.

Mesoscale eddies, internal tides and internal waves can enhance these background current velocities quite significantly, particularly in the Rockall Trough where large non-linear internal waves have been observed.

The mean wind speed over the region is about 7.7 m s^{-1} in summer rising to about 11.2 m s^{-1} in winter. The most frequent surface wave has, on average, a height of 2.4 m and a period of 8.5 s, although in winter this height increases to about 3 m and in summer it decreases to about 1.5 m.

The continental slope represents a transition between the oceanic and shelf systems, and a persistent northward slope current with speeds in the range of 15 to 30 cm s^{-1}, centred approximately over the 500 m isobath, is the physical manifestation of this transition.

To the east of the slope current in water shallower than 200 m we enter the Malin and Hebrides Shelf Seas. Here, though the net flow is still wind driven and northward (with a typical speed of 5 cm s^{-1}), the tides dominate the flow fields with current velocities up to 4.3 m s^{-1} in some of the channels.

The principal tidal components are the semi-diurnal (twice daily) tides although in some limited regions the diurnal (daily) tides are significant.

The physical structure of the shelf seas is largely determined by a balance between the stratifying influences of solar radiation and fresh water run-off from the land, and the mixing influences of the strong tidally and wind driven flows, themselves shaped by the intricate and irregular bathymetry and coastline of the SEA7 region.

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1 Introduction

SEA7 is the largest and most extensive of the SEA regions, extending some 900 km west to east at its widest point, and some 550 km from its most southerly to northerly points. Its approximate dimensions are given in Table 1.1. The range of marine environments to be found within the SEA7 region are probably the most diverse of all the SEA regions; from the abyssal ocean depths and isolated sea-mounts, to narrow coastal sounds and fjords. From a hydrographic point of view, the edge of the continental shelf at 200 m forms a natural break within the SEA7 region separating the deep ocean, where large-scale, slowly-evolving flows dominate, from the shelf and coastal seas, where tidal and seasonal changes dominate the variability.

This report is therefore presented to two sections: Chapter 2 covers the SEA7 region from its most westerly point in the Icelandic Basin up to, and including, the UK continental shelf break (defined here as the 200 m isobath); Chapter 3 covers the shallow shelf seas and coastal waters lying between the shelf break and the Scottish mainland.

	Shelf Sea region	**Open ocean**	**Whole region**
Area (km^2)	7.06×10^4	2.91×10^5	3.62×10^5
Volume (km^3)	6.95×10^3	4.51×10^5	4.58×10^5
Mean depth (m)	98	1550	1270

Table 1.1. The dimensions of the SEA7 region. The shelf and ocean parts are separated by the 200 m isobath. Depths for the open ocean were taken from the Gebco Centenary edition dataset provided by the British Oceanographic Data Centre and digitised at intervals of 0.2 º longitude and 0.12º latitude before summing. The derivation of the shelf sea region dimensions is given in Section 3.2.1

2 The SEA7 Oceanic Region

2.1 Bathymetry

The oceanic part of SEA7 stretches from the edge of the Scottish shelf to 23° 52'.26 W, about 900 km from the Scottish coast (Fig. 2.1). It occupies a sizable and remote part of the northern North Atlantic that is not well mapped, and the further west one goes the less there is known about its bathymetry. The region is composed of three parts, the Iceland Basin in the west, the Rockall Plateau and Rockall Bank, occupying the central part, and the Rockall Trough in the east.

2.1.1 The Iceland Basin

The Iceland Basin is a deep trough running approximately south-west to north-east, which is bounded in the north by Iceland and the Iceland-Färoe ridge, in the west by the Reykjanes Ridge (part of the Atlantic mid-ocean ridge) and to the east by the Hatton Bank. The maximum depth of the basin within SEA7 is 3220 m, which is also the maximum depth of SEA7 as a whole. The floor of the basin is relatively flat, so that the maximum depth at the northern end of SEA7 (about 270 km from the southern edge) is about 2800 m.

2.1.2 The Rockall Plateau

The eastern side of the Iceland Basin slopes up to the Hatton Bank, part of the Rockall Plateau. At its steepest the slope bordering the Iceland Basin has an angle of about 0.0075 as the depth decreases from about 2600 m to 800 m in about 270 km at a latitude of about 59° N. Towards the south of the region the slope is about half this steepness, whilst in the north there is a steep rise to the highest and narrowest part of the bank (< 500 m at 59° 9' N, 17° W). The Hatton Bank itself forms a narrow arc that stretches from about 57° N, 19° 48' W (just south of SEA7) to about 59° 30' N, 13° 24' W near the northern side of the region. The bank is effectively a long ridge with depths generally less then 1000 m and a significant area less than 800 m deep. It eastern side slopes gently down to the central part of the Rockall Plateau, an extensive fairly flat area with a depth of order 1100 m. The north-eastern end of the plateau is guarded by George Bligh Bank, a roughly circular seamount at 59° N, 14° W with a diameter of about 75 km and a minimum depth of about 450 m. On the northern side of the George Bligh and Hatton banks is a wide channel with a minimum depth of 1200 m that separates the Rockall Plateau from Lousy Bank to the north and just outside the SEA7 area. This channel provides a possible conduit linking water between the Iceland Basin and the Rockall Trough.

2.1.3 The Rockall Bank

To the south of George Bligh Bank is a small channel with a depth of about 1150 m. Across this channel lies the Rockall Bank which, centred on 14° W, occupies the southern half of the central part of the SEA7 oceanic region. The bank is a remarkable isolated shelf sea of order 300 km long and 100 km wide with typical depths ranging from about 400 m along most of its shelf edge but having a central area of about 100 by 50 km with depths < 200 m which is entirely within SEA7. In the centre of this shallower shelf area is the tiny rock pinnacle that lends its name to the bank. The western side of the Rockall Bank has a gentle slope that leads down to the central part of the Rockall Plateau. By contrast its eastern side, leading into the Rockall Trough, is very steep. Towards the southern end of SEA7 this slope is typically 0.04 as it descends from about 300 m down to 2200 m. Further north, at its steepest part, the slope between the 1000 and 1500 m contours is much more severe (about 0.08).

2.1.4 The Rockall Trough

The Rockall Trough is a fairly shallow part of the north-east Atlantic, which is blocked to the north by Lousy and Färoe Banks and the Wyville Thomson Ridge (all of which are outside, or on the border of, the SEA7 region). The Wyville Thomson Ridge, in particular, is a significant barrier to deep water flow with a maximum ridge depth of about 650 m. South of the ridge the floor of the trough increases fairly uniformly from a depth of about 1200 m in the north to about 2400 m at the southern end of the SEA7 region. Despite the steepness of the Rockall slope, deeper waters are located on the eastern side of the trough.

There are three seamounts in the SEA7 sector of the Rockall Trough. These are Rosemary Bank, at about 58º 10’ N, 10º 10’ W, the Anton Dohrn Seamount, at about 57º 30’ N, 11º W, and the Hebrides Terrace Seamount, at 56º 25’ N, 10º 20’ W in the very south of SEA7. Rosemary Bank is roughly circular, with a diameter of about 65 km and gently sloping side rising to a peak at a depth of about 500 m. Part of its southern flank is delineated by a narrow moat. The Anton Dohrn is a circular seamount has very steep sides leading to a fairly flat summit about 35 km wide and with a minimum depth of 600 m. By contrast the Hebrides Terrace Seamount is rather elongated (about 35 km east -west by 20 km north - south) and deep (minimum depth 1000 m), and unlike the other two seamounts it is tied to the continental slope by two fans, Barra to the north and Donegal to the south.

The eastern boundary of the Rockall Trough is a fairly steep slope (typically 0.04 to 0.06) that rises from a depth of about 1400 m to about 200 m where there is a well defined shelf edge, eastward of which the bathymetry gently shallows. The slope itself is fairly uniform and straight in the southern part of SEA7, running slightly east of north, but above 56º 40’ N it turns slightly westward with the slope increasing to about 0.1 after which it curves through north to approximately north-east with a gradually decreasing slope angle. The northern part of the slope region becomes irregular as it approaches the Wyville Thomson Ridge.

2.2 The tides

Despite its size the SEA7 oceanic region has been poorly served for tide gauges *[Andersen, 1994; Proctor and Davies, 1996]*, with about 6 having been located near the Scottish shelf edge, and one offshore at Rockall. Tidal data are often better derived from tidal models, which can be constrained over long distances and have been shown by comparison with altimeter data (e.g. Andersen *[1994]*) to give satisfactory predictions.

2.2.1 Tidal elevation

Name	**Period (h)**
Diurnals	
O1	25.82
K1	23.93
Semi-diurnals	
M2	12.42
S2	12.00

Table 2.1 Periods of the main tidal constituents in the SEA7 oceanic region

The problem of predicting the barotropic (or depth average) tidal elevation and current velocity in the open ocean was resolved by the Flather *[1981]*, ocean tide model which is used here for discussion of the tides. The diurnal (once a day, Table 2.1) and semi-diurnal (twice a day) tides propagate northward through SEA7 with a Kelvin wave like form, having the maximum amplitudes near the eastern, continental, edge (Figs 2.2, 2.3). High water at the southern end of the region is about 1 hour 20 min earlier than at the northern end on the eastern side, but on the western side it tends everywhere to coincide with the HW time in the SE corner. The amplitude of the major constituent (M2) is typically 1 m (range 2 m) in the SE corner, decreasing northwards to 0.85 m at the eastern end of the Wyville Thomson

Ridge and north-westwards to about 0.7 m in the Iceland Basin. The next largest constituent (S2), which is not shown as it has a very similar distribution to M2, is about 40% of the amplitude of M2 so a typical spring tide range is about 1.4 m in the SE corner. The amplitude of the diurnal tidal elevation is much smaller than S2 (K1 ~ 0.1 m and O1 ~ 0.05 m), and can normally be discounted.

2.2.2 Barotropic tidal currents

In regions of large bathymetric variation and oceanic stratification, such as the Rockall Trough and to a lesser extent in the Iceland Basin, tidal currents are never uniform with depth. The mixture of topography and stratification leads to the phenomenon of internal tides which will be discussed in Section 2.4.1. Here we discuss the barotropic tidal currents (Figs 2.4 to 2.6) which in general should be viewed as a theoretical concept, rather than an observable reality, in the oceanic part of SEA7.

In the Iceland Basin and throughout the western part of the Rockall Plateau and Hatton Bank tidal currents are very small (the M2 maximum is < 4 cm s^{-1}, and the other constituents are < 1 cm s^{-1}). Their impact on the physical dynamics of the regime can thus be assumed to be minimal.

Further east some of the strongest semi-diurnal tidal currents of the SEA7 Oceanic region are found on the Rockall Bank. In the shallowest part model predictions of a rotating M2 with a maximum speed of order 16 cm s^{-1}, and minimum of order 12 cm s^{-1} (Fig. 2.4), have been generally confirmed from observations by Huthnance *[1974]*. Strong diurnal currents (order 11 cm s^{-1}) are found on the deeper southern part of the bank (Figs 2.5 and 2.6), mainly outside the SEA7 area. Huthnance demonstrated that these currents are due to a trapped diurnal wave on the bank.

Tidal currents in the Rockall Trough are generally rectilinear, flowing parallel to the shelf edge, and M2 increases in speed from about 5 cm s^{-1} at the southern end of SEA7 to over 18 cm s^{-1} at the northern end over the Wyville Thomson Ridge. Diurnal currents are also generally very weak. However, in the deep water opposite the Western Isles, peaks in both semi-diurnal and diurnal currents are found and the diurnals in particular have a strong rotating component (see Figs 2.5 and Proctor and Davies *[1996]*). These currents are discussed further in Section 3.5.3.

2.3 Circulation and water masses

The SEA7 oceanic region occupies a substantial part of the northern North Atlantic, and UK waters intersect a significant part of the Atlantic Meridional Overturning Circulation

(AMOC), which is an important global oceanic circulation cell that draws heat and salt northward past Europe's shores towards the Arctic. The AMOC is generally believed to play a major role in moderating the UK's climate, and ensuring that northern Europe is anomalously warm. Therefore before considering circulation within the SEA7 oceanic region in detail, we briefly review transport throughout the northern North Atlantic (the area bounded by lines joining southern England and Labrador in the south and Greenland, Iceland, Färoe and Shetland in the north). In the past such a review would have been based on CTD stations and hydrographic sections, but in recent years there have been a number of drifter studies that can be used to illustrate the circulation patterns more effectively.

2.3.1 Patterns of water movement from drifter tracks

Surface drifters *[Flatau, et al., 2003; Fratantoni, 2001; Jakobsen, et al., 2003; Reverdin, et al., 2003]* show that strong currents are associated with regions of steep topographic change, and that almost without exception the strongest surface currents can be found along the western edge of the Atlantic. The surface waters of the northern North Atlantic can be separated into two parts (Fig. 2.7). Immediately to the west of the SEA7 is the cyclonic Sub-Polar Gyre, in which water rotates southward along the coast of Greenland and north-east Canada and northwards towards Iceland. In the central part of this gyre water sinks and spreads out across the North Atlantic (e.g. McCartney and Talley *[1982]*; Sy *et al. [1992]* , whilst surface waters on its eastern edge sweep through the Iceland Basin and are drawn northward across the Iceland-Färoe Ridge (e.g. Heywood *et al. [1994]*). The water on the eastern side of the northern North Atlantic tends to have been spun off the anti-cyclonic Sub-Tropical Gyre (which contains the Gulf Stream) and is warmer and saltier than that of the Sub-Polar Gyre. This water finds its way north-eastward across the Rockall Plateau *[Otto and van Aken, 1996]* and through the Rockall Trough towards Färoe and the Färoe-Shetland Channel. Further east, along the edge of the UK shelf, there is a persistent northward flowing slope current that connects Iberia with the Färoe-Shetland Channel *[Reverdin, et al., 2003]*.

Beneath the generally northward flowing surface waters, sub-surface drifters set at a nominal 700 m exhibit a more complicated flow pattern. Deep currents in the northern and western parts of the Iceland Basin, are derived from the outflow from the Arctic and this water flows towards the south west along the Iceland Shelf edge and Reykjanes Ridge *[Lavender, 2005]*. On the western flank of the Rockall Plateau there is a complementary north-eastward flow of 2-3 cm s^{-1}, which appears to cross the gap between Lousy and Hatton

Banks and enter the northern part of SEA7 in the Rockall Trough. Within the Rockall Trough, at 700 m, there is a fairly strong anti-clockwise rotating current (speed *c* 5 cm s^{-1}) at the southern end of the SEA7 area. Circulation patterns below 1500 m in the Iceland Basin and Rockall Trough appear to be similar to those higher up in the water column(*[Bower, et al., 2002; Lankhorst and Zenk, 2006]*.

2.3.2 Water mass types

There is no one definitive description of water mass types in the North Atlantic, and the definitions and names that are used depend on author and location. In part this reflects a limitation in the concept of water mass, which is not particularly useful in a complex region such as the North Atlantic, and which does not fully account for the fact that properties can change from year to year. The definitions given below are an amalgam from different sources and are approximate.

Water mass	S	θ	O_2	Si	NO_3	PO_4	Comments
LSW*	< 34.9	3.2 – 3.9	270-280	11-12	16.1-17.0	~1.2	
ISOW*	>34.98	< 3.0	275-280	12-13	15.9-16.0	~1.2	does not spread out
MEDW*	35.4 – 35.*	8.7 – 9.5					
SAIW†	34.8 ± 0.2	5 ± 1					
NADW	34.95 – 35.0	2 – 3	270-280	13-17	15.0-16.0	1.1-1.2	in Iceland Basin
NEAW	c 35.3	8 – 10	265-270	3-6	12.5-13.5	0.9-1.0	around Färoe
ENAW*	34.96 - 35.66 (±0.05)	4 -12					see below
WNAW*	34.99 - 35.56	4 -12					see below

θ	**ENAW** (± 0.05)	**WNAW** (*[Iselin, 1936]*)
12	35.66	35.56
10	35.405	35.30
8	35.225	35.13
6	35.09	35.03
4	34.96	34.99

Table 2.2 Definitions of water masses by potential temperature (θ in ºC) and salinity. Also shown (in μmol kg^{-1}) are dissolved oxygen (O_2), silicon (Si), nitrate (NO_3) and phosphate (PO_4). Source: *[Fogelqvist, et al., 2003]*, except * denotes definitions of θ and S by Harvey *[1982]*; and (†) SAIW is defined by $27.30 \leq \sigma_\theta \leq 27.65$ and $35.45 \leq S + 0.16\,\theta \leq 35.82$ *[Wade, et al., 1997]*.

2.3.3 The hydrography of the Iceland Basin

The Iceland Basin is a remote part of the North Atlantic and as the number of scientific cruises to the region, and hence the number of datasets, is relatively small we shall restrict ourselves by ignoring seasonal variations and discussing annual averages only. The original data were derived from the National Virtual Ocean Data System at http://ferret.pmel.noaa.gov/NVODS/servlets/dataset. In the centre of the Iceland Basin, at the farthest extent of SEA7, the mean temperature drops fairly rapidly from about 10° C at the surface to about 4° C at 1400 m, after which there is a more gradual fall to about 2.8° C at 3000 m (Fig. 2.8). This is the coldest water in the SEA7 region. By contrast salinity levels are a maximum at about 150 m below the surface (~ 35.23) but decrease steadily to a minimum of about 34.90 at 1500 m before increasing again to about 34.97 at 3000 m. Dissolved oxygen levels of about 6 ml l^{-1} in the surface 500 m drop to about 5.5 ml l^{-1} at 1000 m (the level of the classical DO minimum) before rising again to about 6.4 ml l^{-1} at 1750 m followed by a slight decline again to 2500 m (Fig. 2.9).

A typical TS plot from the basin is shown in Fig 2.10. Wade et al. *[1997]* identified three major water masses from long term observations taken at Ocean Weather Ship India (50° N 19° W) at the edge of the Hatton Bank. The upper 150 m, with $\sigma_t < 27.2$ kg m^{-3} and lying above the salinity maximum of 35.22, comprises a body of water that appears to be a modified form of North Atlantic Central Water, which enters SEA7 from the south with a flow of order 16 Sverdrups (1 Sv = 10^6 m^3 s^{-1}, Bacon *[1997]*). In the stratified intermediate depths, and lying between the salinity maximum and the deep salinity minimum at 1500 m, is a mix of two water masses: Eastern North Atlantic Water (ENAW), effectively warmer water from the east of the Atlantic *[Harvey, 1982]*, and subducted Sub Arctic Intermediate Water (SAIW) which is believed to originate in the Sub-Polar Gyre *[Wade, et al., 1997]* and enter the basin mainly from the south at a rate of about 2 Sv *[Bacon, 1997]*. The relative proportions of ENAW and SAIW in the Iceland Basin have been observed to vary on timescales of several years. Further south they are separated by the Sub-Polar Front, but at the latitude of SEA7 this front is very diffuse. Below them low salinity Labrador Sea Water overlies North Atlantic Deep Water (NADW) flowing cyclonically (anti-clockwise) around the bottom of the basin at a rate of 2-3 Sv *[Bacon, 1997]*. This flow is suggested by the uplift of the 27.8 kg m^{-3} isobar over the Hatton Bank to the east, and over the lower slopes of the mid-Atlantic Ridge to the west (Fig. 2.9).

The Iceland Basin has moderately high levels of eddy kinetic energy (EKE) with values of 100 cm^2 s^{-2}, which are typically 4 times higher than those in the centre of the Sub-Polar Gyre (*[Heywood, et al., 1994; Volkov, 2005]*) but nevertheless are an order of magnitude less than those in the Gulf Stream. The eddies are probably due to enhanced shear along the western side of the Hatton Bank where currents in the weak front at the edge of the gyre are enhanced by topographic steering.

2.3.4 The Rockall Plateau

Despite early interest by *[Nansen, 1913]*, and the regular Ellett line cruises to Rockall, the Rockall Bank and Plateau have remained rather neglected by physical oceanographers even though the bank has the unusual status, from a research point of view, of being an isolated shelf sea region. Archive data (Fig. 2.11) indicate that water at 57.5° N, 16.5° W (down to 1200 m) has similar properties to that in the Rockall Trough (Fig. 2.12) and is much closer to ENAW than water at the same depths in the Iceland Basin. The mean density section also shows that both the Rockall and Hatton Banks are areas of anomalously high density (Fig. 2.9). The water on the bank is generally fresher and cooler than that to the east in the Rockall Trough. The cause of this anomaly may be due to upwelling around the bank *[Steele, et al., 1971]*, although it is just as likely to be caused by differential winter cooling in the shallow waters of the bank *[Ellett, 1968]*. Current meter observations *[Ellett, et al., 1986]* suggest that there is a cyclonic circulation around the Rockall Bank, which may be driven by the density gradient across the edge. However, a detailed investigation of drifter data *[Otto and van Aken, 1996]* did not pick up this circulation, and instead it was found that whilst in general mean currents on the plateau were weak the north-eastward drift of surface water tended to diverge around it (see also Orvik and Niiler *[2002]*). This divergence appears to be supported by altimeter observations *[Heywood, et al., 1994; Volkov, 2005]* which indicate that EKE levels on the plateau are low. To date the story of the seasonal variation of water on the Rockall Plateau remains untold.

2.3.5 The hydrography of the Rockall Trough

The Rockall Trough is by far the most observed part of the SEA7 oceanic region, and has been host to some major research projects (e.g. JASIN, LOIS/SES) as well as being regularly surveyed by the Ellett Line. A typical annual mean CTD profile in the trough from 11.5° W (Fig. 2.13) reveals that beneath a shallow seasonal thermocline there is a fairly gradual drop in temperature to about 5° C at 800 m, below which temperature falls rather more slowly to 3.8° C at 1750 m and then a little more rapidly to about 2.6° C at 2000 m. Below the seasonal thermocline salinity descends monotonically with depth, largely imitating the temperature distribution, although there is only a very small change in salinity in the deepest 250 m. As in the Iceland Basin a dissolved oxygen minimum (<5.5 ml l^{-1}) can be found at about 1000 m, with a lower maximum of about 6.2 ml l^{-1} at 1750 m. The upper layers of the water column (σ_t > 27.3) appear to be seasonally warmed ENAW, whereas water in the range 9° C to 4° C conform to the general definition of ENAW of Harvey *[1982]*,. Below 1750 m the trough is influenced by Labrador Sea Water.

One of the main objectives of oceanographers working in the region has been to determine the mean transport of North Atlantic Water and its associated properties (particularly heat and salt). Geostrophic calculations based on CTD data collected between 1963 and 1968, which used a level of no motion set at 1800 m (the depth of Labrador Sea Water in the Trough), indicated that above 500 m north-easterly flows on either side of the Trough comprised 6.7 Sv. However, these currents were largely offset by a south-westerly flow of about 4 Sv in the vicinity of the Hebrides Terrace Seamount, giving a net residual NW flow of 2.7 Sv *[Ellett and Martin, 1973]*. More recent data (1975-1998), using a level of no motion of 1200 m, suggest that the net transport of ENAW is about 3.7 Sv *[Holliday, et al., 2000]*. This latter transport is made up of 3 Sv flowing northward in the slope current, with an additional 3.9 Sv to the west of the Anton Dohrn; and 3.1 Sv flowing southward, mainly to the east of the Anton Dohrn, but with 0.6 Sv along the Rockall slope. Holliday *et al. [2000]* also found that there can be a very significant interannual variation in the northward transport of between 0 and 8 Sv. None of this variability correlated with the NAO, but Hatun *et al. [2005]*, have shown that the size of the total influx of ENAW in the Rockall Trough correlates with a weakening of the Sub-Polar Gyre in the Iceland Basin. Below 1200 m LSW, which is unable to escape to the north, recirculates within the Trough. The sense of this recirculation is ambiguous, with some authors suggesting that it is cyclonic and others implying that it anti-cyclonic. A small part of the water mass of the Rockall Trough must also have its source north of the Wyville Thomson Ridge over which Norwegian Sea Deep Water occasionally cascades *[Sherwin and Turrell, 2005]* with a mean transport of about 0.3 Sv. This overflow water is thought to flow along the eastern flank of the Rockall Bank *[Lee and Ellett, 1965]*. Model predictions are able to reproduce the main features of this circulation pattern quite successfully *[New, et al., 2001]*.

The surface waters of the Rockall Trough (and Rockall Plateau) are notable for the fact that they experience very deep winter convection, to greater than 600 m (Fig. 2.14), which means that they are a major region for ventilation of the North Atlantic and facilitate the ocean-atmosphere heat exchange *[Meincke, 1986]*. It is possible that this deep convection is due to the low net velocity experienced in the Trough (estimated here to be about 0.6 km day^{-1} across the Anton Dohrn section). Surface salinities also exhibit annual, and longer term, variability. Regular observations between 1951 and 1990 show seasonal oscillations with a range of 0.08 between the maximum in March and minimum in September. Long term changes, which are due to variations in the formation and transport of low salinity water in the Sub-Polar Gyre, have resulted in lower than normal salinities in the trough during the decade centred on 1976 *[Ellett, 1994]*.

2.3.6 Mesoscale activity in the Rockall Trough

A schematic representation of the circulation pattern of the surface waters of the Rockall Trough drawn by Ellett *et al. [1986]* (not shown here) gives an indication of the complexity of the water movement, and generally agrees with the recent description based on hydrographic data by *[Holliday, et al., 2000]*. Current observations at 57° 30’ N, 12° 15’ W and 57° 14’ N, 10° 35’ W (near the Anton Dohrn) reveal very variable directions with speeds generally of order 10-20 cm s^{-1} in the upper layers and, about 5 cm s^{-1} near the sea-bed *[Ellett, et al., 1986]*. Wind stress levels in the Rockall Trough tend to peak in winter, whilst EKE levels (in the 3 to 28 day band) from a range of current meters in the SEA7 area appear to be at a maximum in spring *[Dickson, et al., 1986]*. Altimeter observations indicate that there is a very high seasonal EKE signal in the Rockall Trough which Heywood et al. (1995) suggest is due to direct forcing by the wind. Drifter observations in January 1984 *[Booth, 1988; Booth and Meldrum, 1984]* have demonstrated that the region around the Anton Dohrn seamount is rich in small eddies with periods of between 1 to 3 days. Other drifter observations *[Burrows and Thorpe, 1999]* have shown much larger eddies, with periods of order 10 days and speeds up to 25 cm s^{-1}.

A cold core mesoscale eddy has been observed drifting westward at about 1.4 km day^{-1} in the northern part of the trough to the west of Rosemary Bank *[Ellett, et al., 1983]*. The eddy had associated currents of up 30 cm s^{-1} at 200m depths and appeared to contain Norwegian Sea Deep Water that had overflowed the Wyville Thomson Ridge from the Färoe-Shetland Channel.

2.3.7 The European Slope Current

The general northward drift of surface waters through the Rockall Trough transforms into a more organised northward current against the continental slope on the eastern side of the Trough. The current itself occupies the upper part of the slope typically above 700 m *[Hill and Mitchelson-Jacob, 1993]*, spreading onto the shelf as far as the 100 m contour in places and extending westward at least as far as the foot of the slope, if not further *[Souza, et al., 2001]*. Its western extent and depth appear to vary considerably (Holliday *et al.*, 2000), as does the associated mass transport. It can be traced to the south of the Rockall Trough and it flows across the Wyville Thomson Ridge and into the Faroe-Shetland Channel *[Huthnance,* *1986]*. However, near the southern boundary of SEA7 the current makes an excursion across the slope and onto the shelf *[Ellett, et al., 1986; Souza, et al., 2001]* before continuing its path along the slope at the southern end of the Hebrides.

Maximum sustained velocities in the current within the SEA7 region range from 0.14 m s^{-1} in winter to > 0.28 m s^{-1} in summer in the south (Souza *et al. [2001]*, using moored ADCP observations), to about 0.5 m s^{-1} near the Wyville Thomson Ridge (Burrows and Thorpe *[1999]*, from drifter observations).

Transport (Sv)	Source	Comment
0.5	Booth and Ellett *[1983]*	Current meters
1.5	Huthnance *[1986]*	Current meters. Includes regions outside SEA7§
1.2 – 2.2	Huthnance and Gould *[1989]*	Current meters. Includes regions outside SEA7§
0.1 – 2.2	Hill and Mitchelson-Jacob *[1993]*	Geostrophic calculation
1 – 1.5	Burrows and Thorpe *[1999]*	Drifter study of top 50 m
3 ± 2.1	Holliday *et al. [2000]*	Geostrophic calculation (range 0 - 8 Sv)
2	Souza *et al. [2001]*	Ship borne ADCP section

§ The Huthnance *[1986]* and Huthnance and Gould *[1989]* papers contain some observations that are common to both.

Table 2.3. The northward transport of water in the Scottish slope current through the SEA7 area.

Estimates of the transport in the slope current are given in Table 2.3. Part of this variability can be explained by the assumed width of current (Holliday *et al. [2000]* took it to stretch to the Anton Dohrn seamount, whereas Booth and Ellett *[1983]* had it confined to a 10 km width). In addition the transport, velocity and structure of the current all vary considerably on 10 day *[Booth and Ellett, 1983]* to seasonal and annual *[Holliday, et al., 2000]* time scales.

The slope current comprises ENAW, which enters the Rockall Trough from the south. However, in summer a higher salinity core is often found at a depth of 2-300 m *[Hill and Mitchelson-Jacob, 1993]*. When this core is present (it is masked by mixing in winter) maximum current velocities occur offshore close to its outer edge *[Souza, et al., 2001]*. At one time it was thought that the current contained Mediterranean water, but analysis of the CTD data described above, as well as model predictions *[New and Smythe-Wright, 2001]* have demonstrated that this is not the case. The precise nature of the forcing of the slope current is uncertain: one possibility is that it is driven by an interaction between the north-south temperature gradient and the slope *[Booth and Ellett, 1983; Huthnance, 1986]*, but its intensity also appears to correlate with wind forcing in winter, when a 10 m s^{-1} southerly wind can force a 0.14 m s^{-1} current at 50 m depth *[Burrows and Thorpe, 1999]*. Rectification of internal tides may contribute up 0.05 m s^{-1} to the poleward current at the top of the slope *[Xing and Davies, 2001]*.

2.4 Topographically related non-linear processes

The steep slopes that border the Rockall and European shelves have a particular role to play in the dynamics of the North Atlantic. It has already been pointed out, implicitly and explicitly, that many of the major currents in the region flow along slope regions, but in addition these slopes, combined with its neighbouring shelf sea, give rise to potentially important baroclinic (stratified) phenomena that are much less prevalent either in the deep ocean or on the shelf. The Rockall Trough, with its relatively narrow width, steep sides and extensive neighbouring shelves is particularly prone to excitations from the slopes.

2.4.1 Internal tides and non-linear internal waves

Internal waves are waves that propagate within the body of a stratified fluid. The most important form of these waves in the ocean are internal tides, which are generated by the interaction between tidal currents and topography in the presence of stratification. Unlike the processes discussed elsewhere in this section, internal waves tend to be localised, intermittent and generally unpredictable. The prerequisite for large internal tide generation is that strong tidal currents should cross a steep topographic slope and they tend to be most prevalent in summer when the water column is stratified. There have been no reported observations of internal tides in the Iceland Basin and, in view of the fact that tidal currents are weak and topographic slopes are relatively gentle (at least in the SEA7 region), it seems reasonable to assume that they not particularly important there. In the Rockall Trough, however, it is a different matter. Internal tides, with isotherm elevation amplitudes of order 20 m, were observed in the deep water of the north-eastern part of the Rockall Trough (roughly the northern half of the SEA7 area between 10 and 14 °W) during the JASIN experiment *[Levine, et al., 1983]*. It was suggested that they had emanated from the Rockall Bank. A moderately large semi-diurnal internal tide has been observed on the Malin Shelf, on the southern border of the SEA7 region, with maximum surface current speeds about 0.25 m s^{-1} *[Sherwin, 1988]*. The equivalent seabed currents are of order 0.1 m s^{-1} and the wave propagates a distance of order 85 km onto the shelf. Three dimensional model predictions

[Xing and Davies, 1998] suggest that internal tides of this magnitude could exist along most of the shelf edge in the southern part of SEA7, at least as far as 58.5 °N.

Non-linear internal waves are a manifestation of an evolving internal tide and contain high bursts of energy. They have been observed on the Malin Shelf *[Inall, et al., 2000; Inall, et al., 2001]*, where they can displace the seasonal thermocline by up to 25 m and have associated surface currents of order 0.4 m s^{-1}. These particular non-linear waves are not correlated with the spring-neap cycle and *[Small, et al., 1999]*, have shown that they emanate from deep water in the Rockall Trough. More recently *[Stashchuk and Vlasenko, 2005]*, demonstrated that they probably originate 150 km away on the steep eastern side of Rockall Bank at times when large diurnal and semi-diurnal tidal currents coincide.

The Wyville Thomson Ridge is also known to generate large internal tides *[Sherwin, 1991]*, which can propagate into the Rockall Trough. It is thus inevitable that much of the northern part of the trough is disturbed repeatedly, and irregularly, by internal tides and non-linear internal waves.

2.4.2 Cascades

When water on a shelf is more dense than that in the surface layers of a neighbouring ocean, it can become unstable and can thus descend along the seabed towards the deep ocean. This process is called cascading. Cascades generally occur intermittently from late winter to spring, when at temperate latitudes water on a shelf can be colder than in the ocean. The possibility of the dense water cascading from the Rockall Bank was first suggested from observations by Nansen, 1913. Ellett *[1968]*, found evidence of cascading on the western side of the bank (on the eastern side it was restrained by a cyclonic geostrophic current) and estimated that the associated speed was about 0.02 m s^{-1}.

A cascade has been observed at 55 º N (about 150 km south of the SEA7 region) descending to 500 m *[Hill, et al., 1998]* with an estimated across slope speed of 0.035 m s^{-1}. It appeared to be forced by an excess of salinity on the shelf possibly due to a deflection of the slope current. Although conditions that are sufficient for cascading have been observed within the SEA7 region, there are no other reports of cascades from this part of the European shelf.

2.5 Wind and waves

In winter the North Atlantic can be one of the roughest regions in the world *[Woolf, et al., 2002]* although, by contrast with the Southern Ocean, it is much calmer in summer. Wind and wave data have been extracted from the online global wave statistics database operated by BMT Fluid Mechanics Ltd (www.globalwavestatisticsonline.com). These data originate primarily from visual observations made by voluntary observing ships and are banked at the Met Office.

2.5.1 Wind speeds

	all directions	from SW	from NW
Summer	7.7	8.2	6.9
Winter	11.2	11.6	9.3

Table 2.4. Mean wind speeds (m s^{-1}) in the SEA7 area (away from the coasts).

The predominant wind quadrant in the SEA7 region lies between south and west (157.5º to 292.5º) and accounts for between 45% of all winds in spring (Mar to May) and 61% in winter (Dec to Feb, see Figs 2.14 and 2.15).

The mean wind speed is typically 8 m s^{-1} in summer (Beaufort Force 4) rising to 11 m s^{-1} (Beaufort Force 5-6) in winter (Table 2.4), with winds tending to be 2 m s^{-1} stronger from the most prevalent south-westerly quadrant. Gales (> Beaufort Force 8) are 6 times more common in winter (when they occur 15% of the time) than they are in summer.

2.5.2 Wave climate

The most frequent surface wave (occurring about 8% of the time, Fig. 2.16) has a height of about 2.4 m and a period of 8.5 s. In winter its height increases to about 3 m (with little change in period or frequency of occurrence), whilst in summer for 10% of the time the most frequent waves have a height of about 1.5 m and period of about 6.5 s. An analysis of altimeter data has suggested the mean significant wave height - the mean of the highest 1/3rd of waves, equivalent to 4 times the standard deviation wave height - in the oceanic region of SEA7 is about 5 m in winter reducing to 3 to 3.5 m in summer *[Woolf, et al., 2002]*.

It has been long known that the mean wave height in the North Atlantic has been steadily increasing - according to Woolf *et al. [2003]* wave heights to the west of Scotland may have increased by 0.6 m between 1967 and 1991. In addition winter peak wave sizes in the SEA7 area can vary by a factor of 2 between one year and the next. Woolf *et al. [2003]* used satellite altimeter data to show that these short- and long-term variations correlate well with the North Atlantic Oscillation (NAO). This oscillation is the periodic fluctuation of the north-south atmospheric pressure gradient through the North Atlantic in winter, which has been demonstrated to correlate with a number of environmental parameters and which, in particular, is a surrogate for wind strength. At present, however, it is not possible to predict how the NAO changes, and so we cannot give an indication of the near future wave climate in SEA7.

The largest wave recorded in the Rockall Trough to date was measured on a research ship to have a height of 29.1 m *[Holliday, et al., 2006]*. It occurred at 57.5º N, 12.7º W, in the southern part of SEA7, on 8-9th Feb 2000 during an 18 h period when the WSW wind speed exceeded 20 m s^{-1} (Beaufort Force 9 to 10) and the significant wave height exceeded 18 m. Thus although the waves were extreme the winds, although severe, were not exceptional.

3 The SEA7 Shelf Region

3.1 Introduction: in from the ocean and onto the shelf

It has long been known that the upper layers of the Northeast Atlantic exhibit variability in temperature and salinity that can be distinguished from seasonal atmospheric influence *[Ellett, et al., 1986]*. It has recently been shown that these changes result from variations in the quantities of North Atlantic Current water and Eastern North Atlantic Water entering the Rockall Trough from the south, and that these changes may be linked to changes in the North Atlantic wind stress field, and ultimately the North Atlantic Oscillation (NAO) pattern *[Holliday, 2003]*. It is also known that the predominant influence upon the waters off the western coastline of the UK is the relatively warm and saline waters of the Northeast Atlantic *[Ellett, 1979]*.

Much has been written about the continental slope as an effective barrier to horizontal exchange between coastal seas and the deep ocean (see, for example, *[Huthnance, 1992; , 1995]*). There is also a growing body of literature detailing processes that can transport material across steep bathymetric contours, as reviewed by Huthnance *[1995]*; for example changes in slope gradient *[Hill, 1995]*, non-linear internal waves *[Inall, et al., 2000; Inall, et al., 2001]*, winter cascades *[Shapiro and Hill, 1997]*, enhanced shelf friction *[Burrows, et al., 1999]*, and slope current instability *[Dooley, et al., 1976]*. Of all the UK shelf seas, the SEA7 shelf area exhibits the greatest influence from the NE Atlantic.

3.2 Bathymetry

3.2.1 Background

From the Mull of Kintyre in the south to Cape Wrath in the north, the coastline of the west coast of Scotland is characterised by an intricate fjordic outline, with irregular sounds and passages between a myriad of islands (Fig. 3.1). Whilst this coastline forms an obvious feature, the continued bathymetric irregularity beneath sea level is often less appreciated (Fig. 3.2). The origin of the intricate coastline and irregular bathymetry is glacial. Glacially over-deepened valleys appear as classic coastal fjords (the sea lochs), drowned fjords, deep sounds between islands, or isolated deeps: the deepest of these being Muck Deep (320 m) west of Muck and the deeps north-east of Raasay (316 m). Basic bathymetric (and tidal) characteristics of all the sea lochs have been described *[Edwards and Sharples, 1986]*; 76 sea lochs lie within the SEA7 area, and can be seen clearly in Figs 3.1 and 3.2.

The major topographic break in the SEA7 area is the continental shelf edge, defined here as the 200m isobath (Fig. 3.2), and used to delimit the two major sections of this report. From the coastline to the 200 m contour at the shelf edge, the SEA7 region has an approximate 2D planar surface area at mean sea level of 70645 km^2, and an approximate volume of 6951.97 km^3. These values are based on 250 m resolution digibath bathymetry[1], and exclude the sea lochs. Based on manual digitisation of Admiralty charts *[Edwards and Sharples, 1986]*, the approximate total high water planar area and volume of all the sea lochs within the SEA7 area (76 in total) are 908 km^2 and 24.24km^3, respectively. Since they are outside the scope of this report, no further consideration of the sea lochs will be given.

Between the shelf edge and the major island chain of the Outer Hebrides, a distance of approximately 110 km, lie a scattering of smaller islands: principal amongst these being the St Kilda archipelago and the Flannan Isles. The Outer Hebrides island chain extends for approximately 220 km in a SSW NNE orientation, from Barra Head in the south to the Butt of Lewis in the north. The Minches lie eastward of the Outer Hebrides; with the North Minch lying between Lewis and the Scottish mainland, the Little Minch occupying the area between Harris, North Uist, Benbecula and the Isle of Skye, and the South Minch sitting with South Uist and Barra to the west, the Small Isles (Eigg, Muck, Rhum, and Canna) to the east, and Tiree and Coll to the south east. The Tiree Passage is a channel between the islands of Coll to the west, and Mull and the Ardnamurchan Peninsula to the east. The isle of Colonsay lies in the approaches to the Firth of Lorne, between the southern coast of Mull and north western coast of Islay and Jura.

Residual circulation is strongly influenced by topography (Section 3.3), and many areas of extreme tidal currents are experienced in the narrow passages and around headlands (Section 3.5). The SEA7 coastline is relatively insensitive to changes in mean sea level, and direct exposure to the wind and wave climate of the North Atlantic is a more significant issue *[Dawson, et al., 2001]* (Section 3.6)

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[1] Derived from DigBath250 under DIGBATH250 Licence 2004/134DB British Geological Survey. © NERC

3.3 Circulation

3.3.1 Background

Whilst tidal modelling of the northwest European shelf (Section 3.5) is reasonably well described (Holt *et al. [2005];* Sinha and Pingree *[1997]* and references therein), numerical modelling of the mean flows on the shelf and at ocean boundaries is a complex business *[Huthnance, 1992]* and although progress is being made, three dimensional hydrodynamic models are still not able to resolve the important physical processes *[Holt, et al., 2005; Holt and James, 2001; Holt, et al., 2001]*. The principle difficulties seem to be not with the models *per se* but with knowledge of the lateral boundary conditions, be they specified or taken from coarser scale, larger domain models. The discussion that follows, therefore, is predominantly based on observations.

The slope current transports oceanic water northward along the outer reaches of the UK continental shelf, with a characteristic salinity of 35.35. Some or all the current intermittently meanders onto the shelf north of Ireland where it dilutes the relatively polluted mixture of Irish and Clyde Sea waters flowing north through the North Channel. This mixture forms the Scottish Coastal Current (SCC) which continues northward, modified continually by mixing with the less saline, terrestrially influenced coastal waters and more saline shelf and slope water. Ultimately this blended water flows into the North Sea between Orkney and Shetland as the Dooley Current. Thus the input of Irish and Clyde Sea waters and their transported contaminants into the North Sea depends on the interaction with the Slope Current and coastal waters to the west of Northern UK, and on the retention or utilization of contaminants on route (Fig. 3.3).

Mean water movements which exist in addition to tidal flows, referred to commonly as residual circulation, are generally weak around in U.K. shelf seas (~ < 1 cm s^{-1}). In this respect the SEA7 region is exceptional, with a relatively strong northward flowing coastal current, the Scottish Coastal Current (SCC, U ~ 5 cm s^{-1}) which, although a persistent feature *[Simpson and Hill, 1986]*, exhibits spatial variation and is modified by both winds and atmospheric pressure gradients. The most comprehensive view of the residual flow pattern remains that from a series of current meter deployments in 1982 *[Simpson and Hill, 1986]*.

It would appear that the SCC is probably not a classic coastal current, driven by the action of the Coriolis force on a fresh water input, but rather a current driven northward by the atmospheric pressure field: both directly by the prevalent south-westerly wind stress, and also indirectly by the north-south gradient in atmospheric sea level pressure *[Hill and Simpson, 1988; Inall and Griffiths, 2003]*.

The effects of tidal rectification on residual circulation, although likely to be of local significance around headlands and over shallows, does not account for a significant driving mechanism of the SCC *[Xing and Davies, 1996]*. One potentially significant forcing mechanism of the SCC which remains to be assessed is that of the barotropic response to mean sea level set-up by the prevailing westerly component of the wind, driving water against the coast. Under the influence of the Coriolis force, the response to the pressure gradient established by the water driven against the coast would be to steer a flow northwards. In model simulations *[Pingree and Griffiths, 1980]* with a constant south-westerly windstress a mean sea level difference of ~7.5cm was established over the width of the Hebridean shelf.

Models demonstrate the importance of topography in steering the residual flow beneath the surface layer, something not demonstrable from *in situ* observation given the paucity of synoptic flow measurements in the area. Models are beginning to unravel the interactions between tidal flows and wind driven residual flows on the shelf *[Davies, et al., 2001]*.

A persistent feature in the residual flow in the SEA7 area is a recirculation at the south west entrance to the Minch *[Hill, et al., 1997]*. Often visible in thermal satellite imagery, a tongue of warmer (in early summer) and higher salinity water penetrates into the southern entrance to the Minch, between Barra and Tiree, and forces a portion of the SCC to recirculate cyclonically around this tongue and then flow northward to the west of the outer Hebrides.

A similar tongue of Atlantic origin water is often visible in thermal and ocean colour imagery at the southern entrance to the Tiree Passage, however no observations supporting cyclonic recirculation of SCC waters around this feature have been reported.

The volume flux through the Tiree Passage, monitored by SAMS since 1981 *[Inall and Griffiths, 2003]*, is northward and equal to that out of the Irish Sea through the North Channel. The time averaged ratio of Irish Sea/Clyde Sea origin to Atlantic origin water flowing through the Tiree Passage is approximately 3:1 (Fig. 3.4), but time variability of this ratio remains unknown, though it is clearly considerable (see Figs 3.5 and 3.6 and discussion thereof in Section 3.4)

Two schematic diagrams of the residual circulation with approximate volume fluxes complied from all available sources are shown (Figs 3.3 and 3.4, courtesy of A. Edwards). These figures are not drawn from numerical model simulations of the area: as noted above, whilst tides are relatively well modelled (Section 3.5), serious discrepancies still exist in modelled residual circulation *[Holt, et al., 2005]*.

3.4 Water masses: physical and chemical characteristics

3.4.1 Temperature and salinity

The water mass structure of Scottish coastal waters has been described in a number of publications *[Dooley, et al., 1976; Ellett, 1979; Ellett and Edwards, 1983; Hill, et al., 1997; Hill and Simpson, 1988; McKay, et al., 1986; McKinley, et al., 1981; Simpson and Hill, 1986]*. An overview drawn from these publications is given here.

During the winter months on the open shelf (December to April) the water column is vertically well mixed, and isotherms and isohalines are almost vertical. Temperature and salinity increase offshore and in deeper waters (greater than approximately 100 m), and on the outer parts of the shelf the water is of Atlantic origin (S > 35.2) and the boundary between coastal and oceanic water is sharp, typically 0.5º C per 10 km. This boundary lies approximately two thirds of the distance from Barra to the shelf break, running parallel to the Hebrides and passing close to St Kilda. All year round a tongue of warm saline water is found at the southern entrance to the Minch, although it does not penetrate far beyond Barra Head, and the Minch is almost full of coastal water. For example, Simpson and Hill *[1986]* show a near synoptic surface salinity distribution in May 1982 with the S = 35.2 contour penetrating as a tongue from the south between Tiree and Bara, whilst Ellett and Edwards *[1983]* show the S = 34.5 contour occupying a similar position a year earlier (July 1981).

The freshest coastal waters (surface values < 33.6) are found in the vicinity of the Firth of Lorne, which drains a large part of the western highlands *[Ellett and Edwards, 1983]*. Elsewhere the fresh run-off is more diffuse and its direct influence less evident. At the south west approaches to the Firth of Lorne is a persistent shelf sea front, the Islay Front, which exhibits strong salinity influence, extends approximately along the path of the 50 m isobath typically from Malin Head on the Irish north coast to Dubh Artach (one of the tallest of the Stevenson lighthouses, off the southwest tip of the Isle of Mull), a distance of approximately 65 km *[Simpson, et al., 1979]*.

Clearly there is considerable variability in the shoreward extent of waters of Atlantic origin, a point made clear in the surface salinity hodogram at 56.5ºN *[Ellett and Edwards, 1983]*, extended here to 1996 (Figs 3.5 and 3.6): note the prolonged episode of freshening from the coast to as far west 7.6º in 1986/87.

Closer to shore the SCC flows northward carrying a mixture of Irish and Clyde Sea waters from the North Channel *[Knight and Howarth, 1999; McKay, et al., 1986]*. The SCC, on average (based on dissolved radiocaesium tracer distributions), is subject to slight further dilution (<1.5% by volume) from fresh water input from the fjordic coast line of western Scotland *[McKay, et al., 1986]*.

The Atlantic origin water alluded to above comprises ENAW in the northward flowing European Slope Current (ESC, see also Section 2.3.7), a feature flowing along the continental slope, apparently continuous at least from the Goban spur to north of Shetland, a distance of approximately 1600 km *[Booth and Ellett, 1983; Burrows and Thorpe, 1999; Pingree, et al., 1999; Souza, et al., 2001]*. At the latitude of the Malin Shelf (~56°N) the ESC is a persistent, predominantly barotropic flow of ~20 cms^{-1} with greater flow variability in winter and a characteristic salinity of 35.35 *[Souza, et al., 2001]*. The ESC is constrained to the continental slope, with its velocity core centred approximately above the 800 m isobath and the high salinity core consistently displaced closer to the slope, and above the 200-300 m isobaths. An explanation of this phenomenon has been given is terms of the differing slope boundary conditions for salinity and momentum *[Souza, et al., 2001]*. Despite the high steadiness, intrusions of the ESC onto the shelf at ~56°N have been observed in the winter months *[Souza, et al., 2001]*, and there is a suggestion that in winter both mass flux and poleward momentum are directed upslope *[Burrows and Thorpe, 1999]*.

3.4.2 Dissolved metals and nutrients

Radioactive effluent from the nuclear facilities at Sellafield in Cumbria (formerly Windscale) and Cap de la Hague in northern France has been detected as far afield as Spitzbergen in the Arctic *[Livingston and Bowen, 1977]*. In the context of the SEA7 area radiocaesium isotopes have proved to be particularly revealing as water mass tracers *[McKay, et al., 1986; McKinley, et al., 1981]*. In 1977 concentrations of dissolved ^{137}Cs (half-life 30.23 years) varied from 1.3 Bq/l in the North Channel to 0.4 at Cape Wrath and to 0.01 at the vicinity of the shelf break. The distribution of dissolved ^{137}Cs forms the primary observational basis for quantification of the volume transports east and west of the outer Hebrides, and of the Atlantic water input to the coastal system (Fig. 3.4). Evidence from a suite of dissolved trace metal measurements (Al, Cd, Co, Cu, Mn and Ni) in 1984 *[Kremling and Hydes, 1988]*, though not as quantitatively powerful as the radiocaesium studies, indicated qualitatively the dilution of trace-metal rich Irish Sea waters by trace-metal poor Atlantic origin waters

Dissolved nutrient distributions are primarily delineated by the main salinity boundary between Atlantic and coastal waters *[Savidge and Lennon, 1987]*. Additional surface variability can be caused by intrusions of Atlantic waters onto the shelf at depth during the summer months and enhanced localised vertical mixing associated with topographic features, for example around Barra Head *[Savidge and Lennon, 1987]*, resulting in locally raised dissolved nutrient levels and, consequentially, also primary production.

3.5 Tides

The discussion on the distribution of the tidal characteristics in the SEA7 area which follows is based on the POL (Proudman Oceanographic Laboratory) High Resolution CS20 numerical model, run at 1.8 km horizontal resolution.

The semi-diurnal species, principally M2 and S2, dominate the surface tidal elevations of the SEA7 area, with the diurnal species (principally K1 and O1) typically an order of magnitude smaller. An exception to this is in the vicinity of the M2 amphidrome, located south of Islay (Figs 3.7 to 3.10). The position of the M2 amphidrome has been variously modelled to lie anywhere between the Islands of Jura and Rathlin Island, sometimes degenerate (on land), and sometimes over sea. The precise position of the M2 amphidromic point is still the matter of some observational uncertainty, and indeed it almost certainly moves in response to variations in flow speed and the resultant friction (in a similar manner to the well documented movement of the Irish Sea M2 amphidrome *[Pugh, 1987]*). With the exception of this amphidromic point and its influence in the vicinity of the North Channel, the M2 tide propagates as a Kelvin-type wave of surface elevation from south to north, with a phase change of approximately 60º (~2 hours) south-to-north (Fig. 3.8). Elevations are amplified towards the coast, and in particular around the Isle of Skye. There is a strong spring-neap modulation in the coastal surface tide, with a maximum range near Skye of approximately 4.5m at springs and 1.6m at neaps. Near Kintyre, in the sound of Jura, the corresponding springs and neaps ranges are approximately only 1 m and 0.5 m, respectively.

Although the tidal model shown here has not been directly compared with observations, other models, which show the same patterns, have been compared *[Proctor and Davies, 1996]*. They report that, with the exception of comparisons close to the amphidrome and one particular observation at Barra Head, the modelled and observed M2 tidal elevations generally agree to within 0.05 m.

3.5.1 Tidal currents

There is a wide range in tidal current strength across the SEA7 area. In general, the magnitude of tidal currents over the open shelf region can be estimated with reasonable accuracy by frictionless shallow water wave theory, which explains the near-uniform maximum current amplitudes for a mean spring tide over much of the uniform depth shelf west of 7.5° W (Figs 3.11 and 3.12). Over these parts of the shelf bed friction plays a minor role in determining the tidal currents, and the force balance is primarily between the tidal slope of the surface, inertia and the Coriolis force. Tidal currents are highly elliptical (between -0.25 and 0.25) over most of the region (Fig. 3.12). Tidal currents around the Stanton Banks area are more circular (rotating clockwise), and patchy areas to the west and north of the northern Outer Hebrides have more circular M2 tides (rotating anticlockwise). Regions such as these, where tidal ellipses are not rectilinear, experience little or no slack water. Spring-neap modulation of the semi-diurnal tidal currents is strong throughout the region with the S2 tidal currents exhibiting essentially the same pattern as the M2 currents (Figs 3.12 and 3.14), with approximately one half of the amplitude. Therefore the maximum amplitude of the depth-averaged currents for a mean spring tide again exhibits essentially the same patterns (Fig. 3.11), with the extended areas of strongest flows in, and northwest of, the North Channel, around the headlands of Barra Head and the Butt of Lewis, and in the constriction between northern Skye and Lewis.

3.5.2 Extreme tidal currents

Extreme tidal currents noted in any number of sounds and around headlands generally arise from large phase differences in tidal elevation along the sound, or across the headland because of the different route travelled by the tide wave in reaching either side or end of the headland or channel. As a result, large sea level slopes can drive fast tidal currents, and in these cases the predominant balance is surface slope and bed friction. For example, strong tidal flows through the North Channel (~ 1 m s^{-1}), the Sound of Islay and the Gulf of Corryvreckan (up to 4.3 m s^{-1}, between Jura and Scarba) are essentially determined by the different speed of the surface tide wave travelling through the Irish Sea on one hand, and the shelf to the west of Ireland on the other. Strong tidal currents directly north of the Isle of Skye (around the Shiant Isles, Figs 3.11, 3.12 and 3.14), and west of Islay are attributable less to an enhanced tidal elevation phase difference, but more to local shoaling of the sea bed.

3.5.3 Extraordinary diurnal currents: shelf waves

Extraordinary diurnal currents around the outer Hebrides were first noted in 1665 *[Moray, 1665]*. Detailed examination of this phenomenon *[Cartwright, 1969; Cartwright, et al., 1980; Huthnance, 1983]* has revealed the existence of a class of sub-inertial barotropic shelf wave, centred around St. Kilda, which accounts for the observed larger diurnal inequality in the tidal flows than can be explained by the local rise and fall of the sea surface. In addition to the northward propagating M2 and K1 barotropic Kelvin waves, outlined above, a shelf wave is identified, resonant with the K1 tide (see also Section 2.2). This wave has an alongshore (north-south) wavelength of ~680km (compared with ~6000km for the M2 and ~12000km for K1), a period of ~24 hours, and maximum zonal and meridional currents of 0.7 and 1.1 ms^{-1}, respectively, centred about 100km from the coast and 10-15km shoreward of the shelf break, matching closely the longitude of the St Kilda archipelago (Fig. 3.15). Strong diurnal currents are also predicted around the Flannan Isles and Barra Head. Shelf waves are also expected to exist at sub-tidal periods.

3.5.4 Distribution with depth: mixing and shear stresses

Tidal currents diminish in amplitude towards the sea bed. The decrease is traditionally modelled with a logarithmic profile, with rate of fall-off with depth dependent on the bed shear stress, τ_0, (the 'friction' or 'shear' velocity is defined as $U^* = \sqrt{\tau_0/\rho}$). The height above the bed to which the influence of the bed stress extends (termed the bottom-boundary-layer, or BBL) depends on the speed of the flow, the roughness of the bed (expressed through the non-dimensional drag coefficient C_D) and the degree of stratification of the water column, and may vary from a metre or less (in regions of low flow over a smooth bed) to the full depth of the water column, for example around Barra Head *[Savidge and Lennon, 1987]*, and the North Channel *[Knight and Howarth, 1999]*. In vertically well-mixed regions of the shelf, the thickness of the BBL is typically a few metres, and the amplitude of the current at 1 m above the bed is approximately half the mid-depth value. Traditionally the depth-averaged value is taken to occur at 0.4 times the water depth above the bed *[Howarth, 2005]*. Competition between the bed shear stress in extending the BBL upwards into the water column above the bed, and the stratifying influence of solar warming of the upper layers determines the position of the shelf sea fronts *[Simpson, 1981]* (Section 3.4).

The movement of sediment on the sea bed occurs when the bed shear stress (τ_0) exceeds the critical shear stress value, which depends on sediment type (grain size and cohesiveness). Assuming a the canonical constant value for the drag coefficient ($C_D = 0.0025$), and that the

BBL is fully turbulent, then the maximum tidal bed stress (Fig. 3.18) may be written $\tau_{0\_max} = \rho C_D u^2$, where u is the maximum amplitude of the depth-averaged currents for a mean spring tide (Fig. 3.11). Extensive areas of elevated bed stress are found to the south-west of Islay and the Mull of Kintyre, and, over a more limited area, between north Skye and Lewis (Fig. 3.18).

3.6 Wind and surface waves

3.6.1 Background

Of all the UK shelf waters, those of the SEA7 area are most strongly influenced by the wind and wave climate of the NE Atlantic. Wind and waves are strongly seasonal, and peak in the winter season (December to March). In contrast to the quantity and quality of standard meteorological observations around the SEA7 coastline, there is a dearth of long time-series of *in situ* wave climate observations within the SEA7 area *[Holliday, et al., 2002]*. The longest record, from the 1970s, comes from a seven-year deployment of a wave-buoy west of South Uist. Currently the Met Office K5 buoy (61° 18' N 6° 54' W) is the only wave measurement in service in the SEA7 area. On the open shelf and adjacent ocean basin, therefore, satellite altimetry provides the only observational method for estimating a wave height climatology; with an ability to estimate monthly mean significant wave heights on a 110km grid (1º latitude) *[Woolf, et al., 2003]*. Finer resolution spatial and seasonal (but not yet climatological) distributions of significant wave height are available from model simulation on a 12km grid *[ABPmer, et al., 2004]*, reproduced here as Fig. 3.19. No systematic observations or modelling of the wave climate of inshore waters have been reported in the literature.

3.7 Storm surges

In addition to their integrated effect of driving the mean northward flow of the SCC (Section 3.3), storms have associated with them sea level and current surges *[Flather, 1987]*. Surges occur both through the local action of the wind, in creating a set-up of the sea level against the coastline, and also through the inverse barometer effect; increases (decreases) in sea level atmospheric pressure lower (raise) the sea level by approximately 1 cm. Operational storm-surge models are run for the UK shelf region, and are particularly important for the shallow southern North Sea. Storm surge elevations with a return period of 50 years in the SEA7 area (Fig. 3.20, reproduced from Howarth *[2005]*, and taken originally from Flather *[1987]* show maximum values between 1 and 1.25 m east of 7.5ºW (the outer

Hebrides), with associated currents generally between 40 and 60 cms^{-1}, and exceeding 80 cms^{-1} in the Minch and west and north of Lewis (Fig. 3.21, reproduced from Howarth *[2005]*, and taken originally from Flather *[1987]*).

4 Conclusion

SEA7 is the largest of the SEA regions with an overall area of 3.6×10^5 km^2, a volume of 4.6×10^5 km^3 and a mean depth of 1270 m. It covers the Scottish west coast shelf, Rockall Trough and Rockall Plateau and at its furthermost point, 900 miles from the Scottish mainland at 23º 52'.26 W, extends well into the Iceland Basin.

The oceanic part is a remote and, in winter, hostile region. The Iceland Basin is deepest part (3220 m) but in general is not well charted; the Rockall Plateau contains a large isolated shelf sea region (the Rockall Bank), while the Rockall Trough has a number of isolated seamounts. SEA7 lies across the northern end of the Atlantic Meriodional Overturning Circulation and contains a number of major oceanic currents carrying surface water northward across the whole region and returning cold Artic water around the foot of some of its slopes. In general both ocean current and depth averaged tidal velocities are small, of order 5 cm s^{-1}. Maximum speeds are about 15 to 20 cm s^{-1} in some local regions such as the Rockall Bank and parts of the European shelf edge. Mesoscale eddies, internal tides and internal waves can enhance these current velocities quite significantly, particularly in the Rockall Trough where large non-linear internal waves have been observed.

The mean wind speed over the region is about 7.7 m s^{-1} in summer rising to about 11.2 m s^{-1} in winter. The most frequent surface wave has an average height of 2.4 m and a period of 8.5 s, although in winter the height increases to about 3 m and in summer it decreases to about 1.5 m.

The continental slope in the SEA7 region represents a transition between the oceanic and shelf systems, and a persistent northward slope current with speeds in the range of 15 to 30 cm s^{-1}, centred approximately over the 500 m isobath, is its physical manifestation.

To the east of the slope current we enter the Malin and Hebrides Shelf Seas. Here, though the net flow is still wind driven and northward (with a typical speed of 5 cm s^{-1}), the tides now dominate the flow fields. The principal tidal components are the semi-diurnal (twice daily) tides although in some limited regions the diurnal (daily) tides are significant with current velocities up to 4.3 m s^{-1} in some of the channels. The physical structure of the shelf seas is largely determined by a balance between the stratifying influences of solar radiation and fresh water run-off from the land, and the mixing influences of the strong tidally and wind driven flows, themselves shaped by the intricate and irregular bathymetry and coastline of the SEA7 region.

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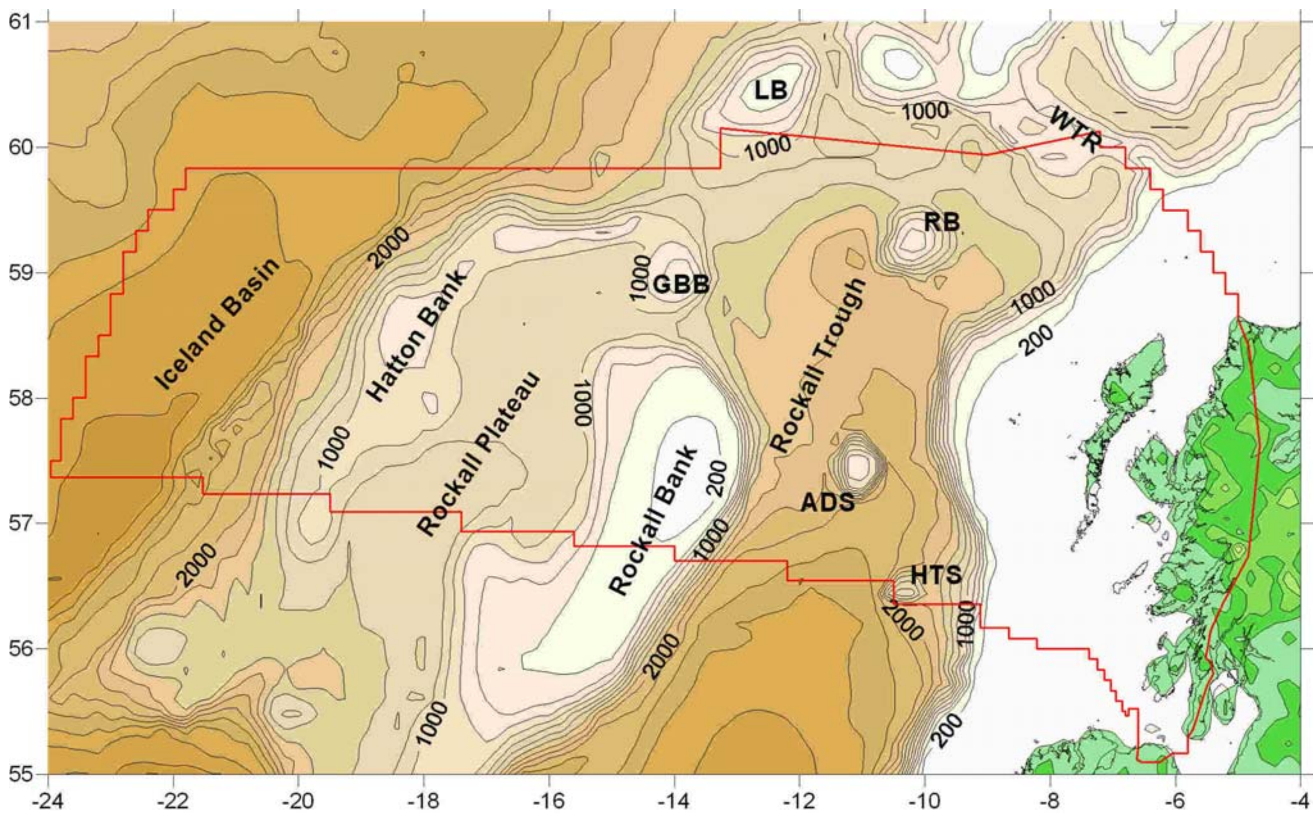
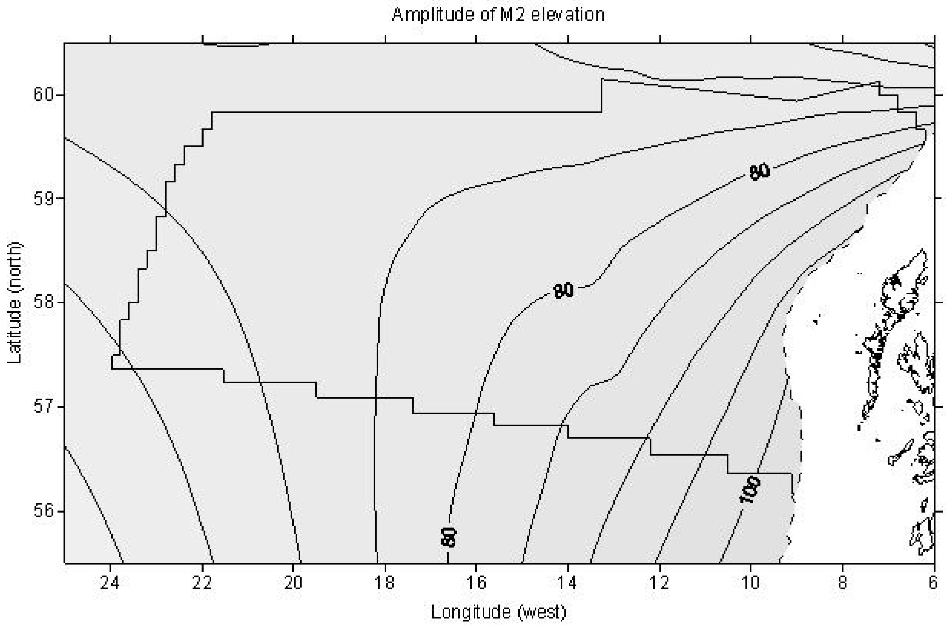


Figure 2.1. The SEA7 oceanic region. Contour interval 200 m. ADS - Anton Dohrn Seamount; LB - Lousy Bank; GBB - George Bligh Bank; HTS - Hebrides Terrace Seamount; RB - Rosemary Bank; WTR - Wyville-Thomson Ridge.



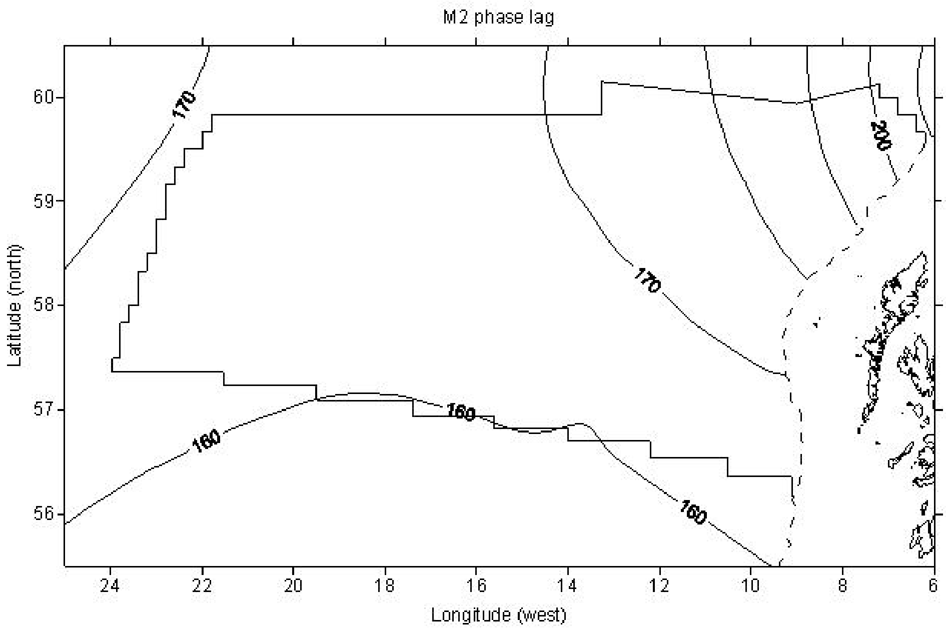
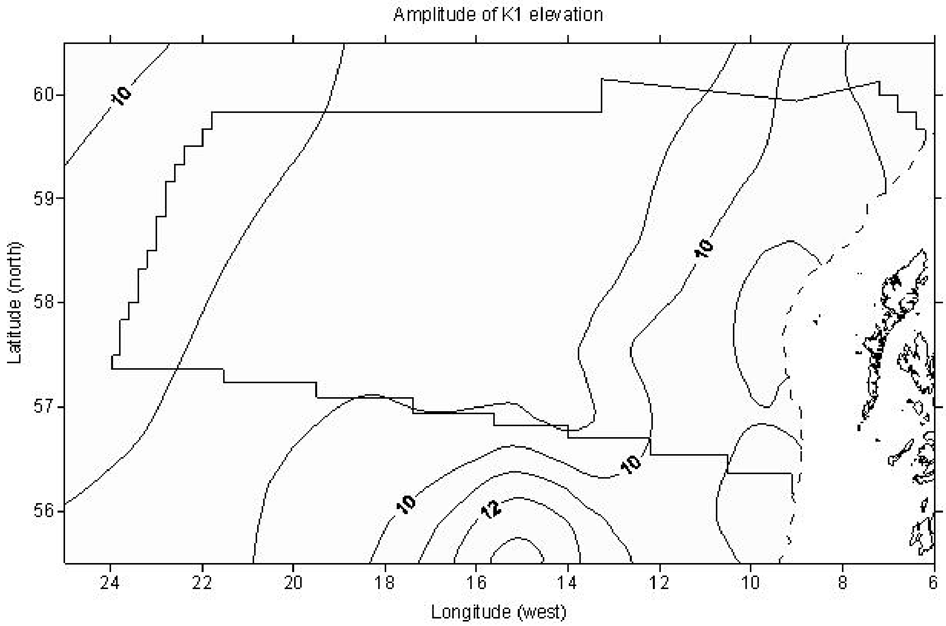


Figure 2.2. M2 elevation amplitude (cm) and phase lag (º).



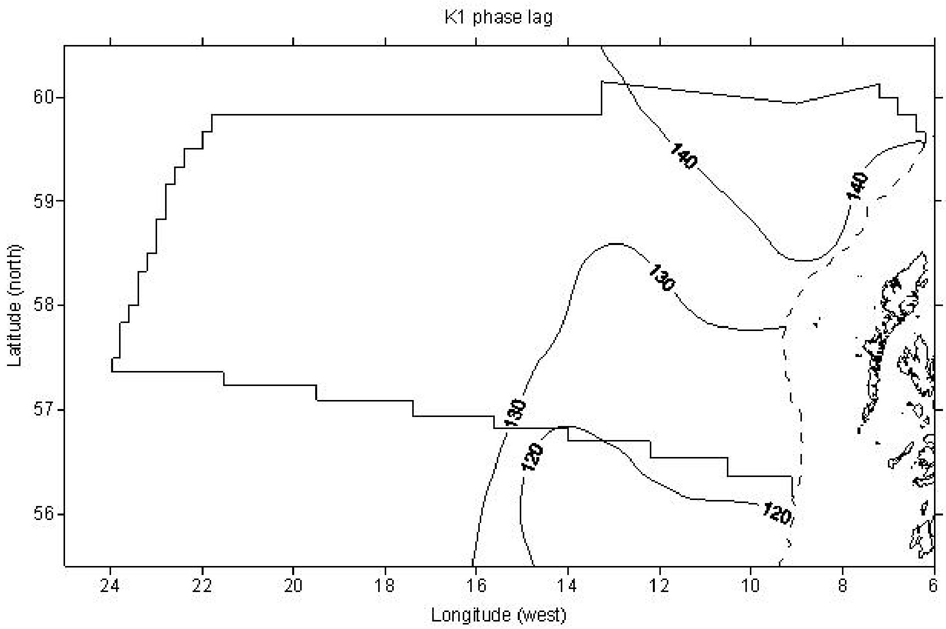
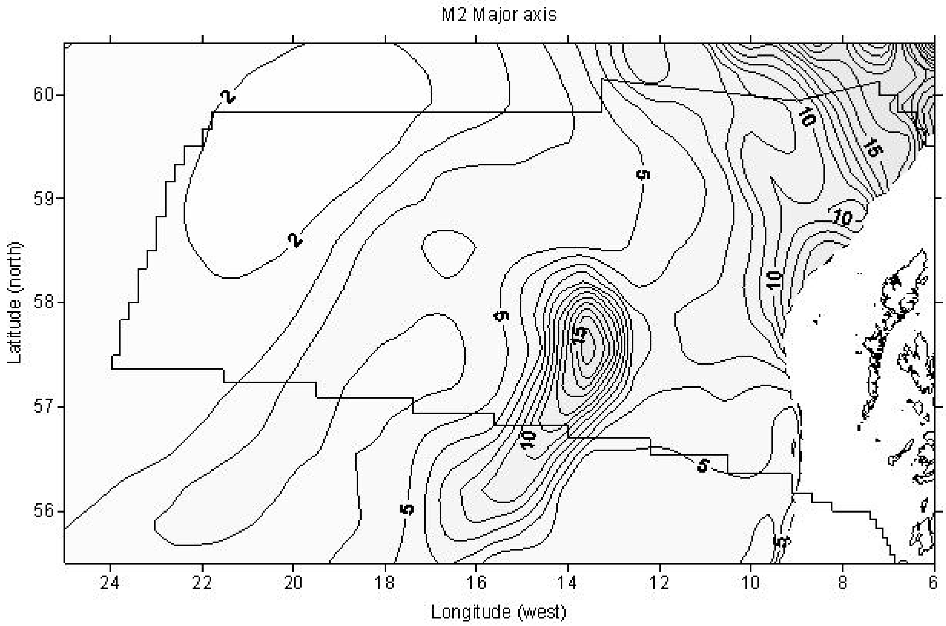


Figure 2.3. K1 elevation amplitude (cm) and phase lag (º).



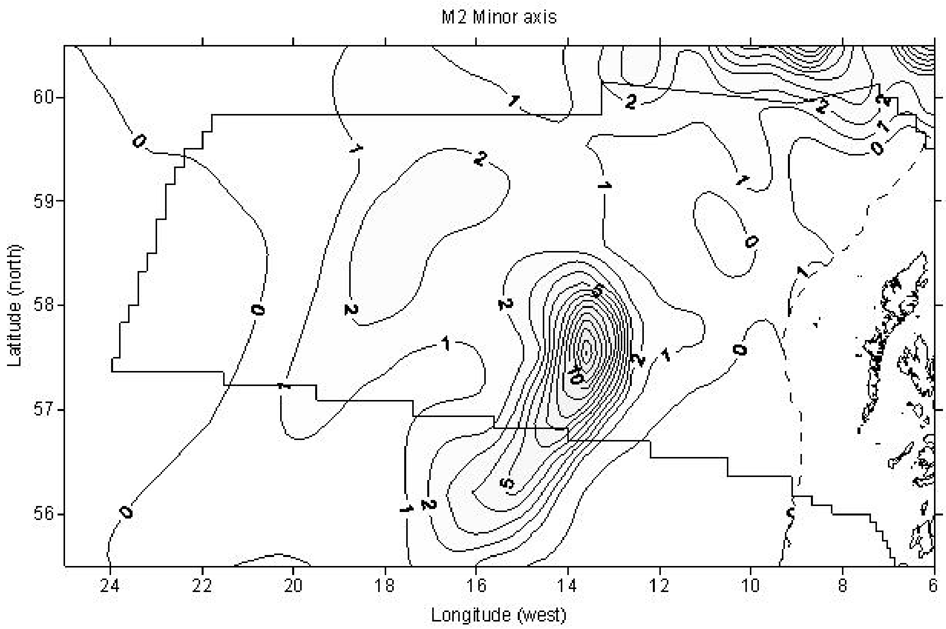


Figure 2.4. M2 major and minor axis current amplitudes (cm s^{-1}).

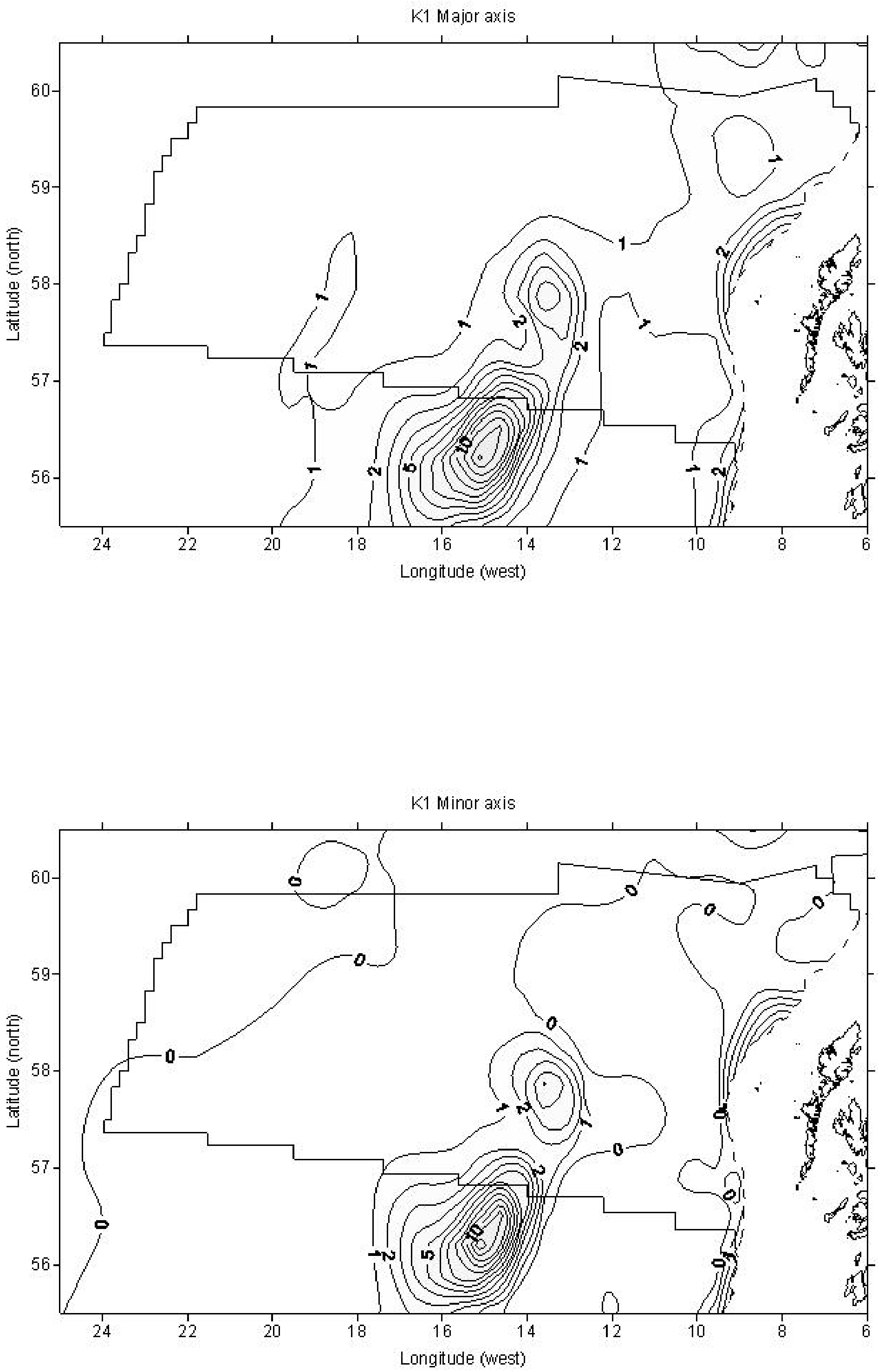
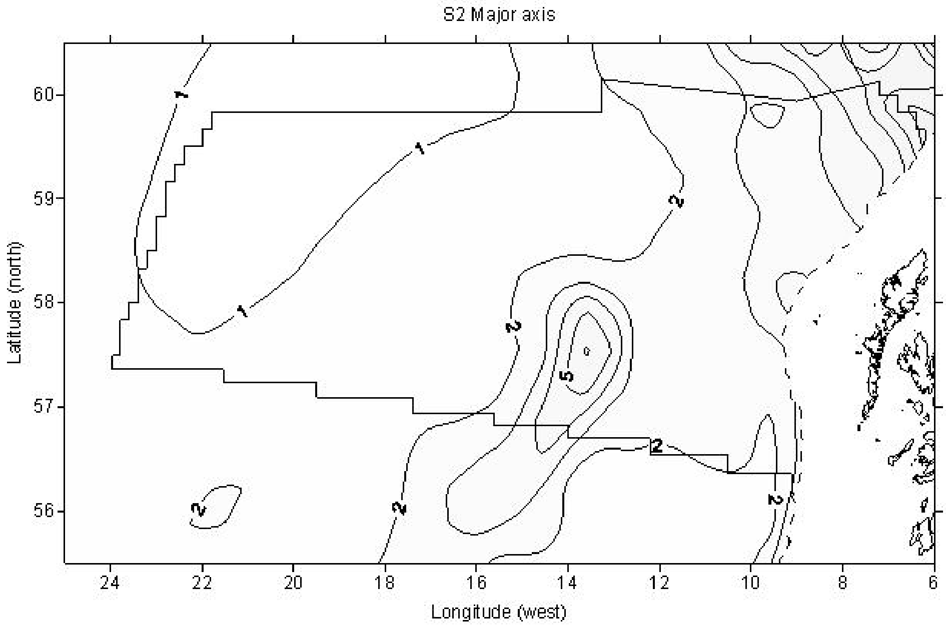


Figure 2.5. K1 major and minor axis current amplitudes (cm s^{-1}).



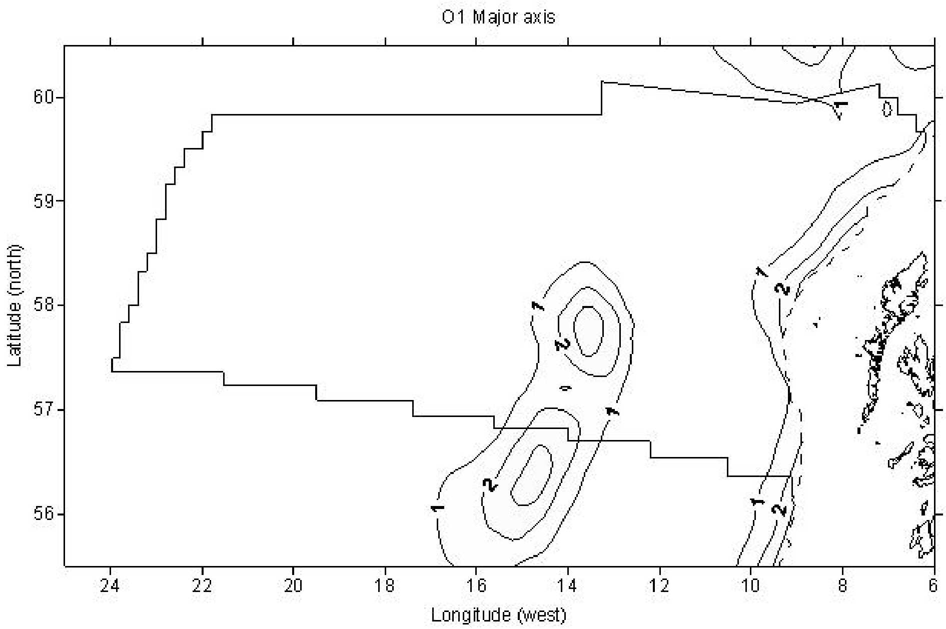


Figure 2.6. Major current axis amplitudes for S2 and O1 (cm s^{-1}).

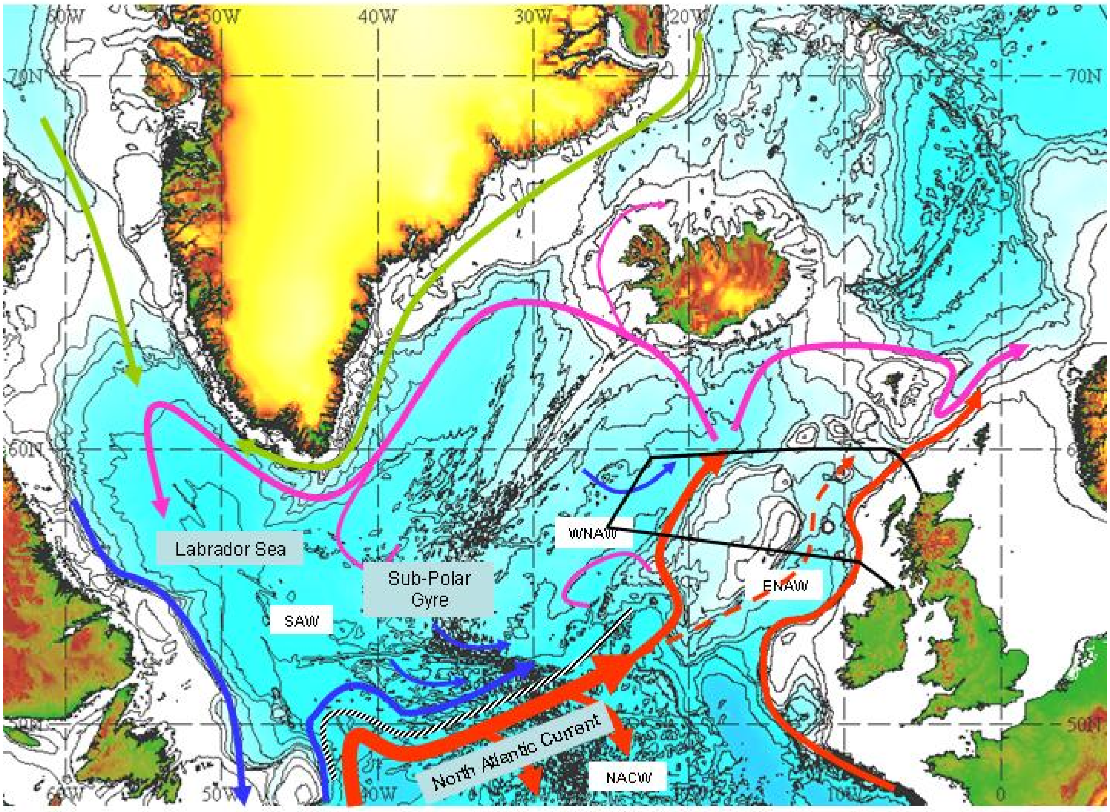


Figure 2.7. Circulation of the surface waters of the North Atlantic. Relative current strength is suggested by line thickness. Relative current temperature is indicated by colour: red - warm; purple - cool; blue - cold; green cold and relatively fresh. The hatched line shows the sub-polar front. The black line gives the approximate outline of the SEA7 area. SAW - Sub-Arctic Water; WNAW - Western North Atlantic Water; ENAW - Eastern North Atlantic Water; NACW - North Atlantic Current Water.

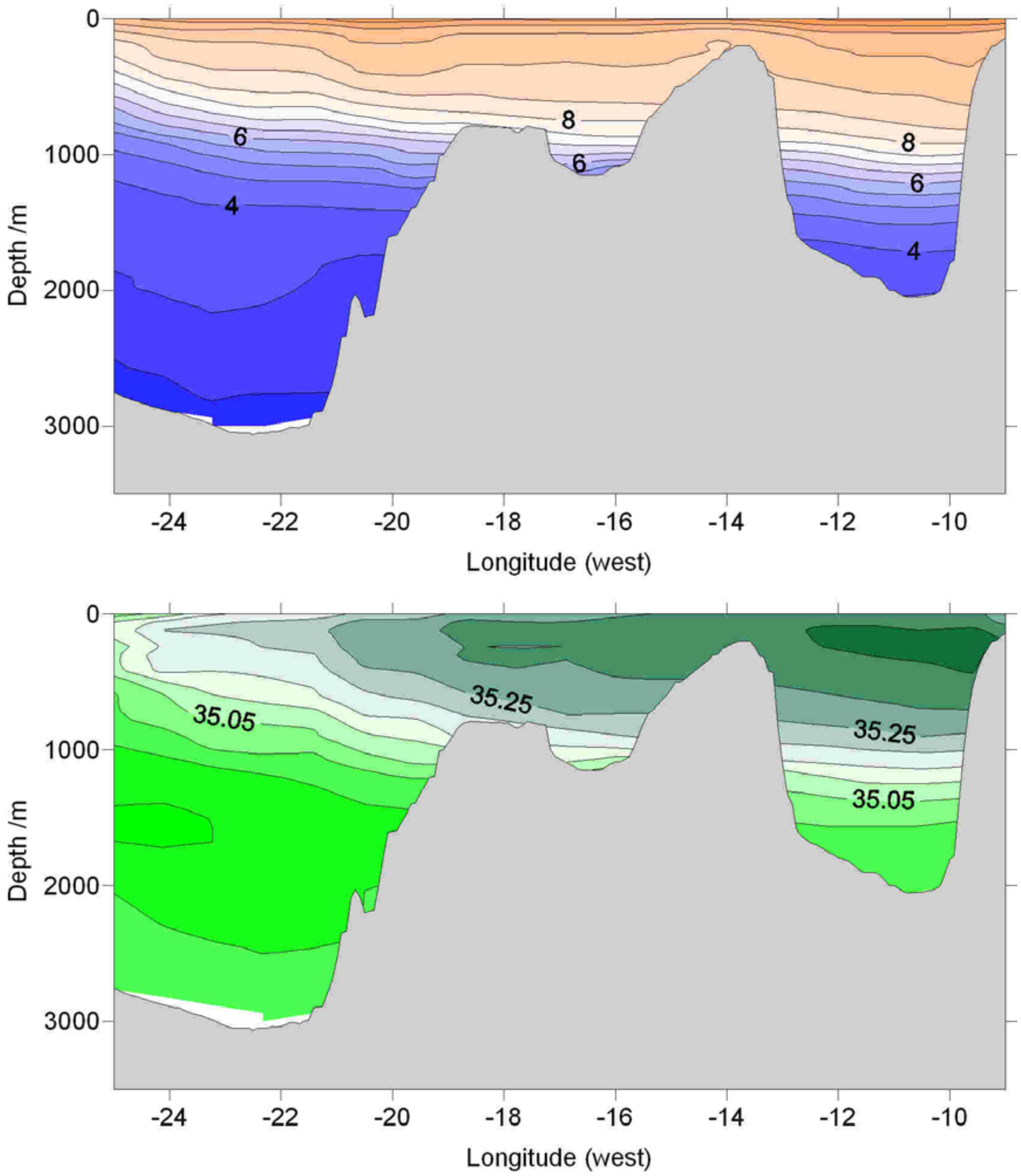


Figure 2.8. Annual mean temperature (above) and salinity (below) sections along 57.5º N. Units are ºC and practical units respectively. Source: World Ocean Atlas 2001.

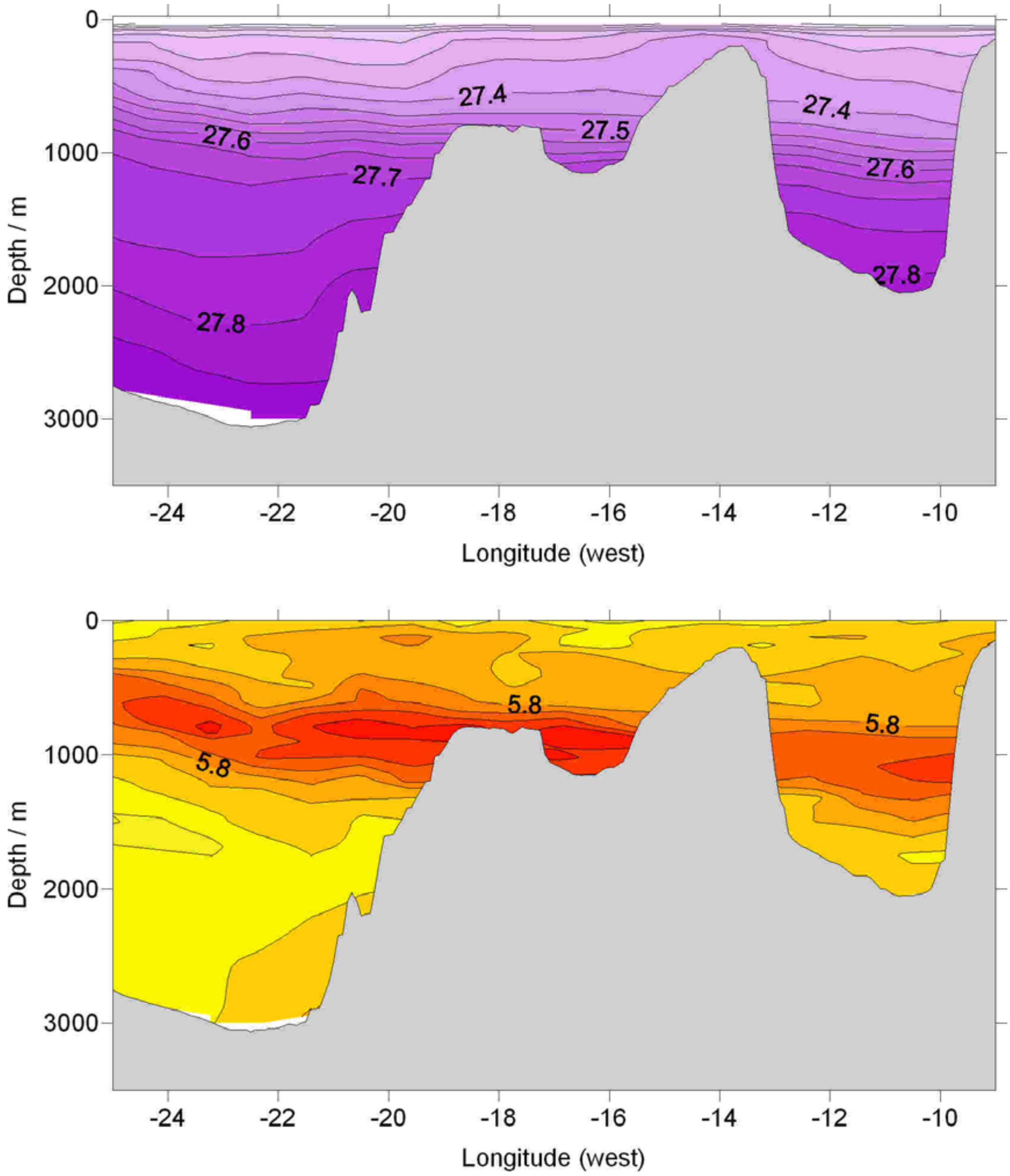


Figure 2.9. Annual mean density anomaly, σ_t, (above) and dissolved oxygen (below) sections along 57.5º N. Units are kg m^{-3} and ml l^{-1} respectively. Source: World Ocean Atlas 2001.

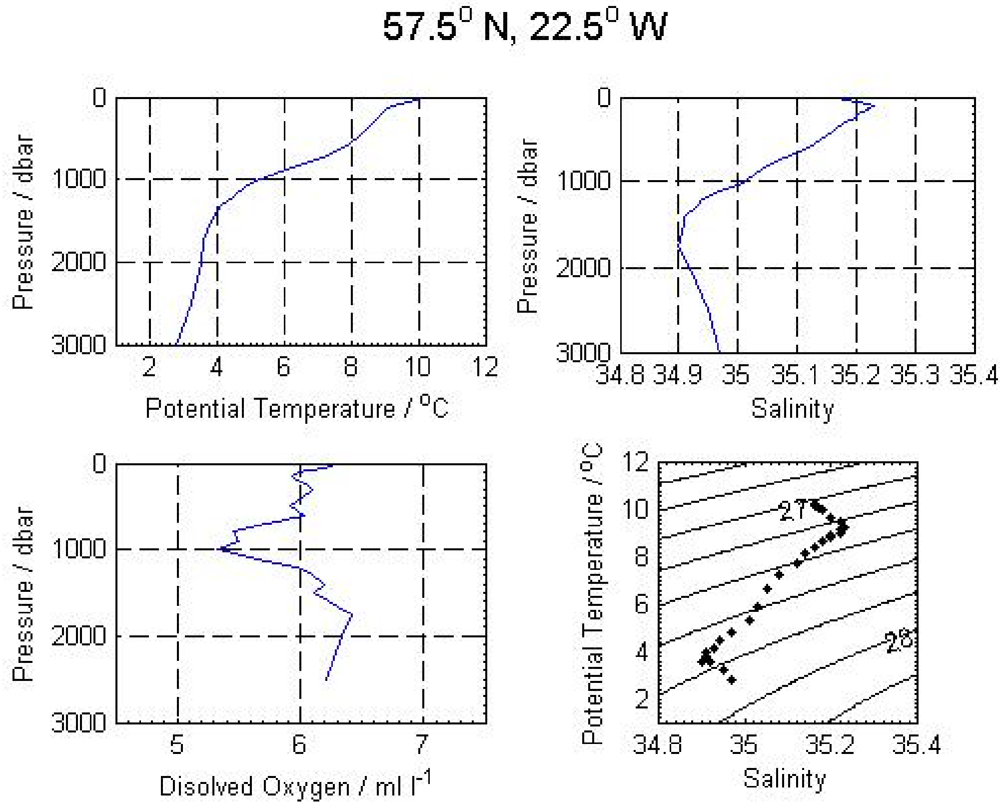


Figure 2.10. Annual mean profiles and TS plot at 57.5º N, 22.5º W in the Iceland Basin.

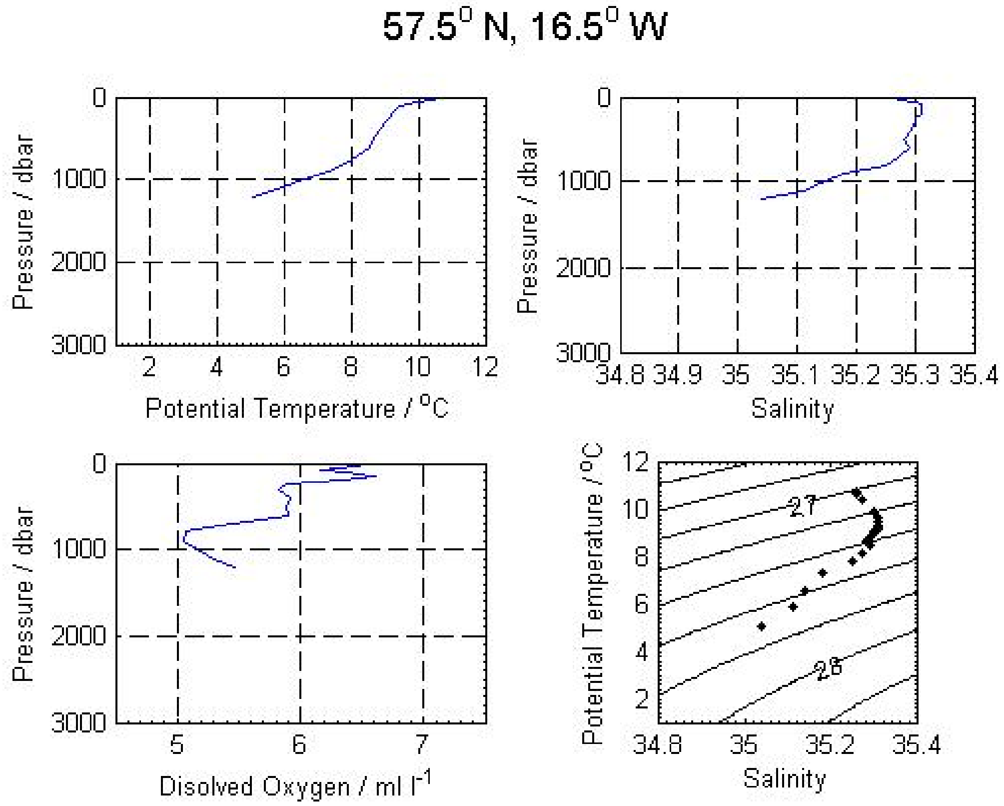


Figure 2.11. Annual mean profiles and TS plot at 57.5º N, 16.5 W on the Rockall Plateau.

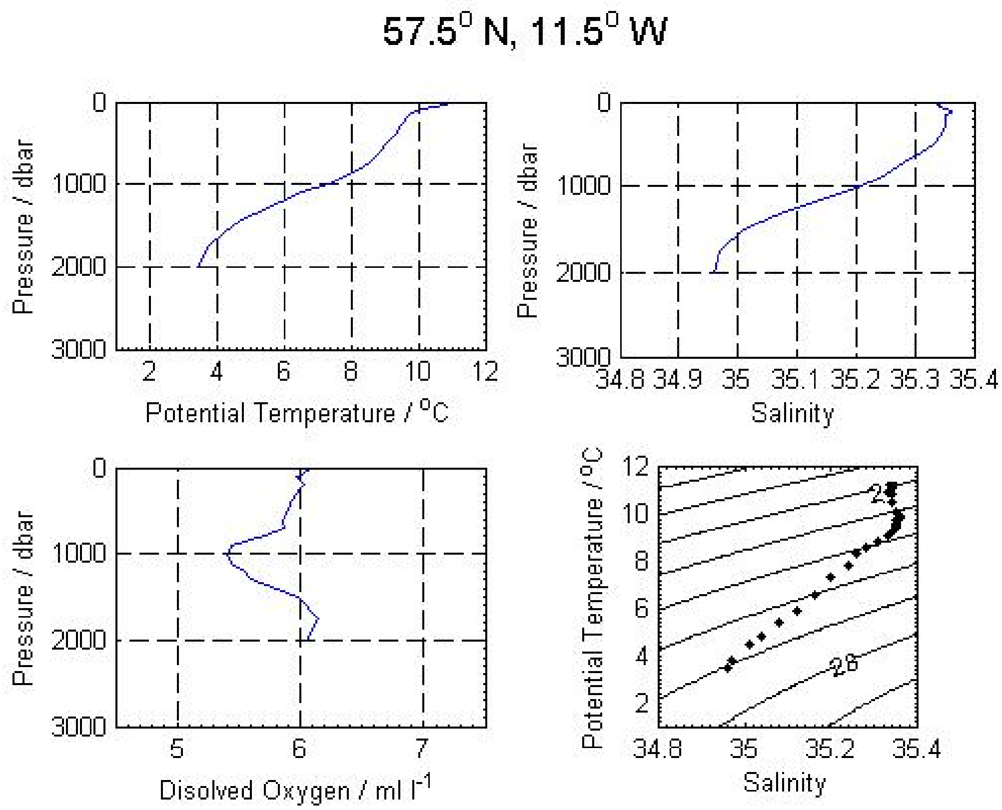


Figure 2.12. Annual mean profiles and TS plot at 57.5º N, 11.5º W in the Rockall Trough.

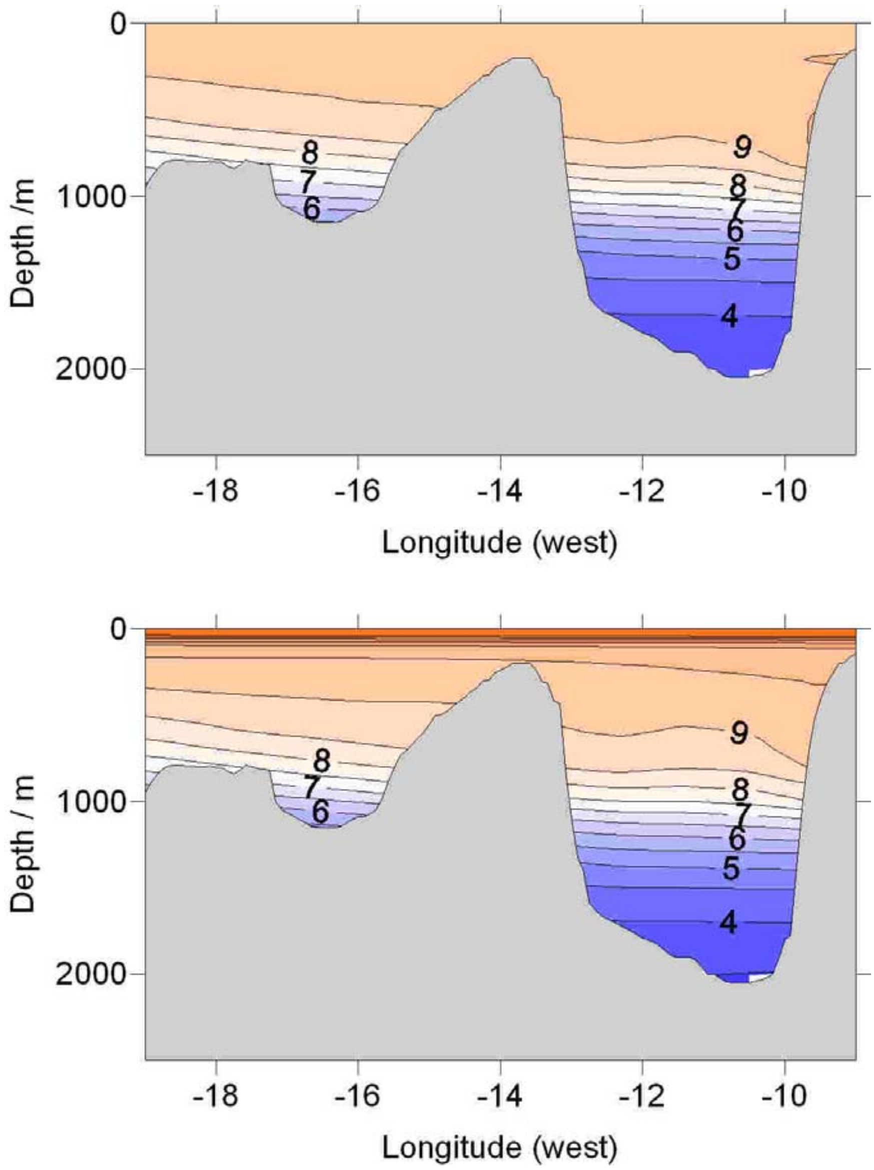


Figure 2.13 Temperature sections in ºC across the Rockall Trough and Plateau in winter (above) and summer (below). Source: World Ocean Atlas 2001.

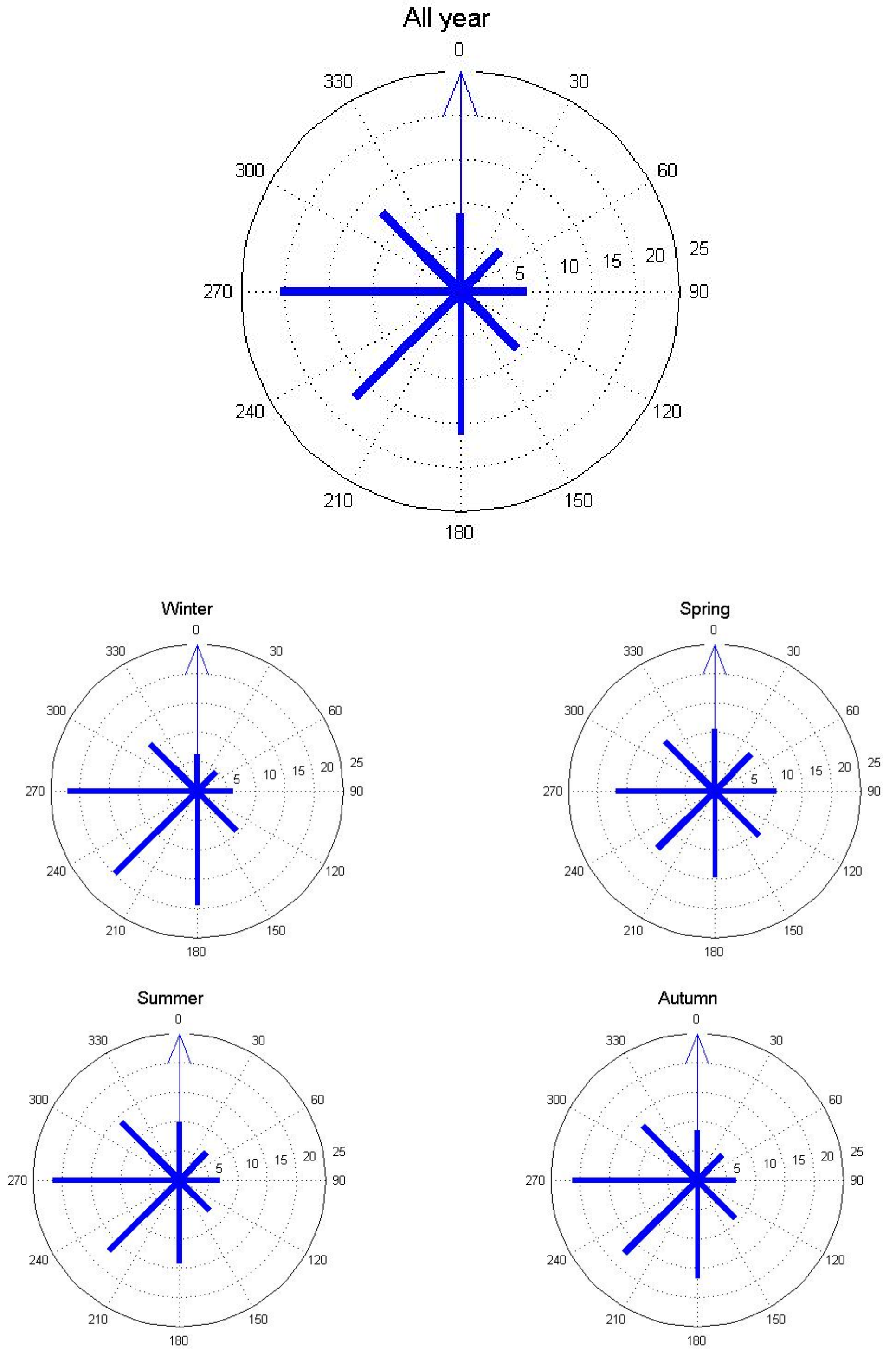


Figure 2.14. Compass roses showing the distribution of wind direction averaged over a year and for each season.

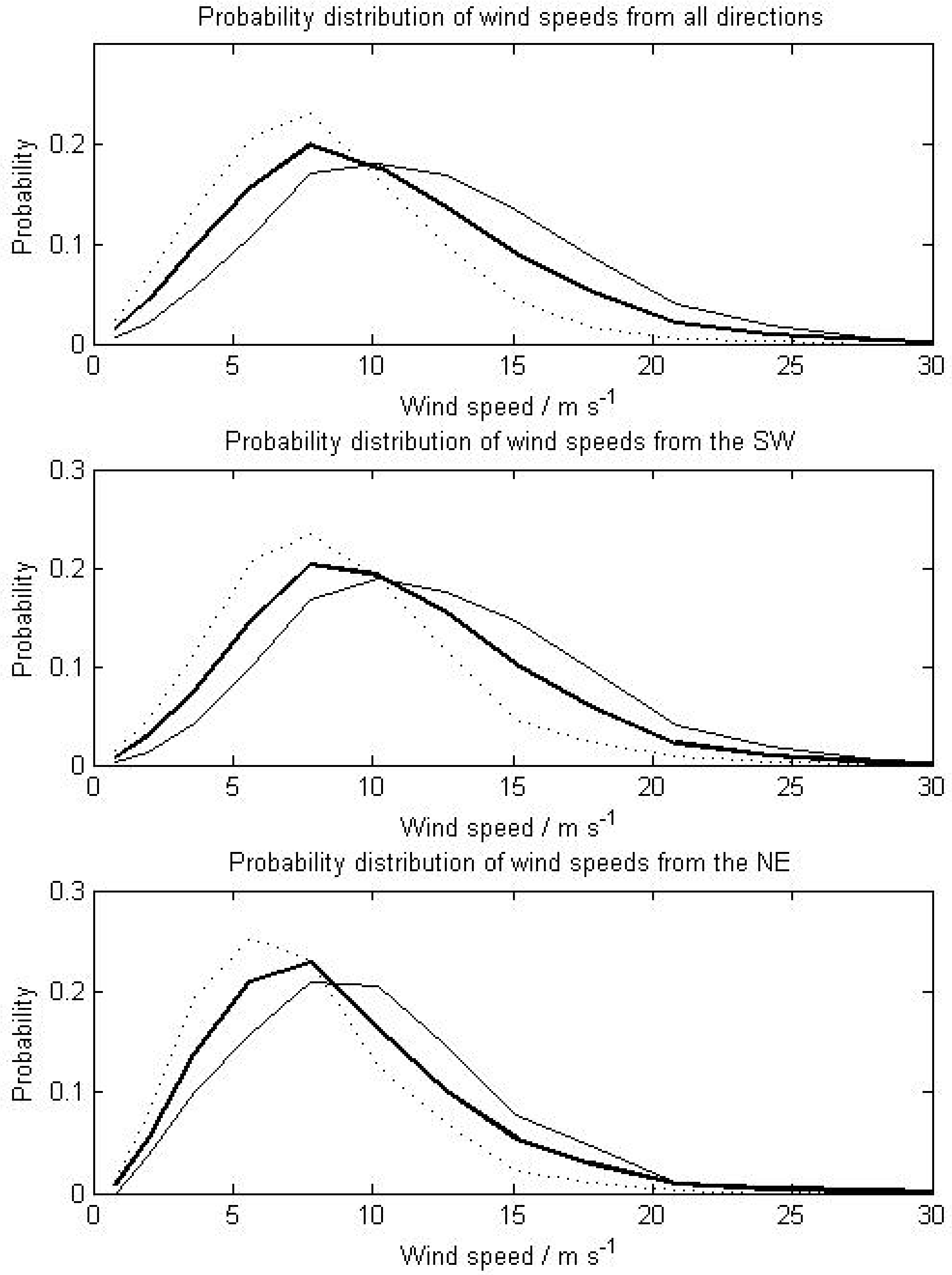


Figure 2.15. Probability distribution of wind speeds when the wind is blowing from the specified direction, averaged over a year.

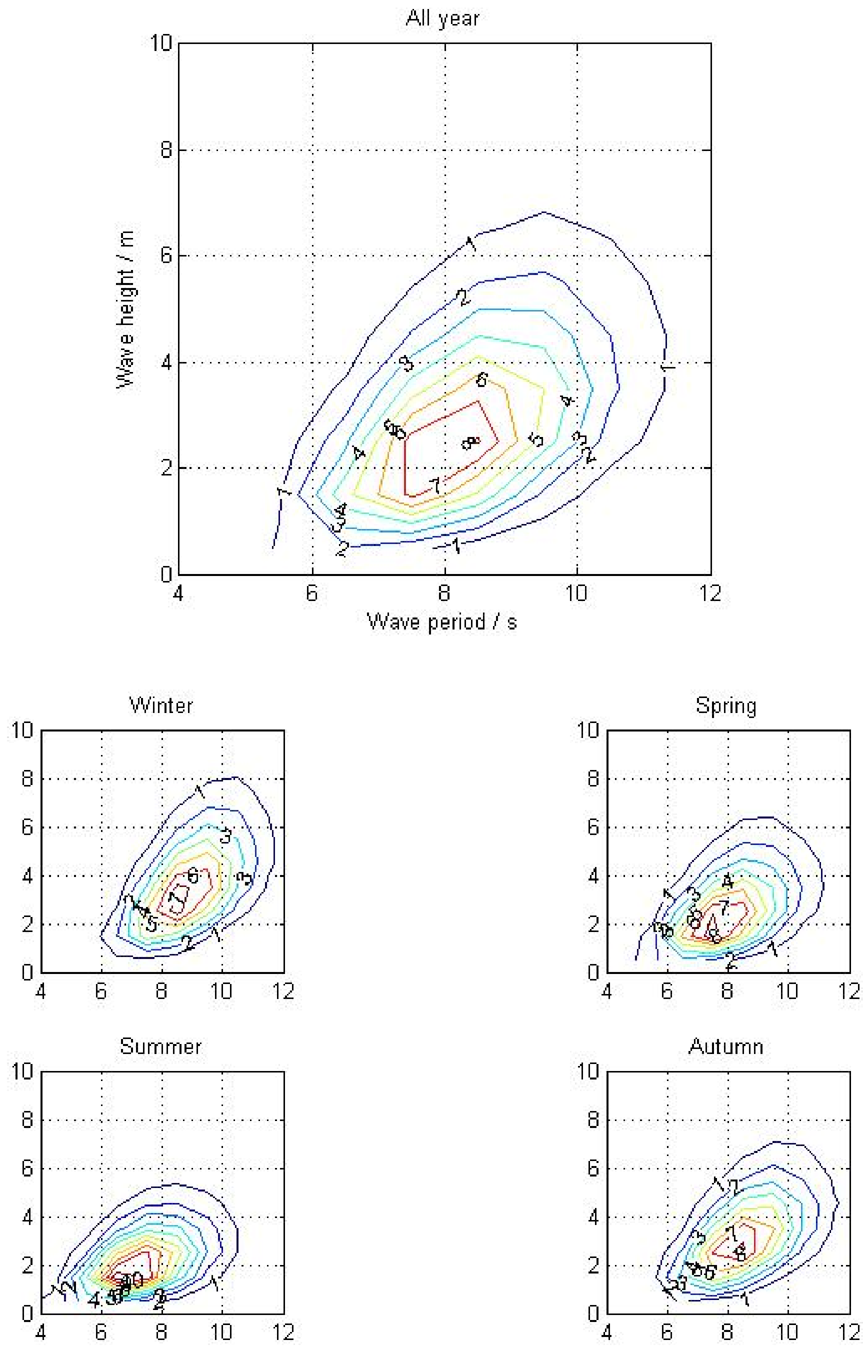


Figure 2.16. Wave scatter plots, averaged over a year and for each season.

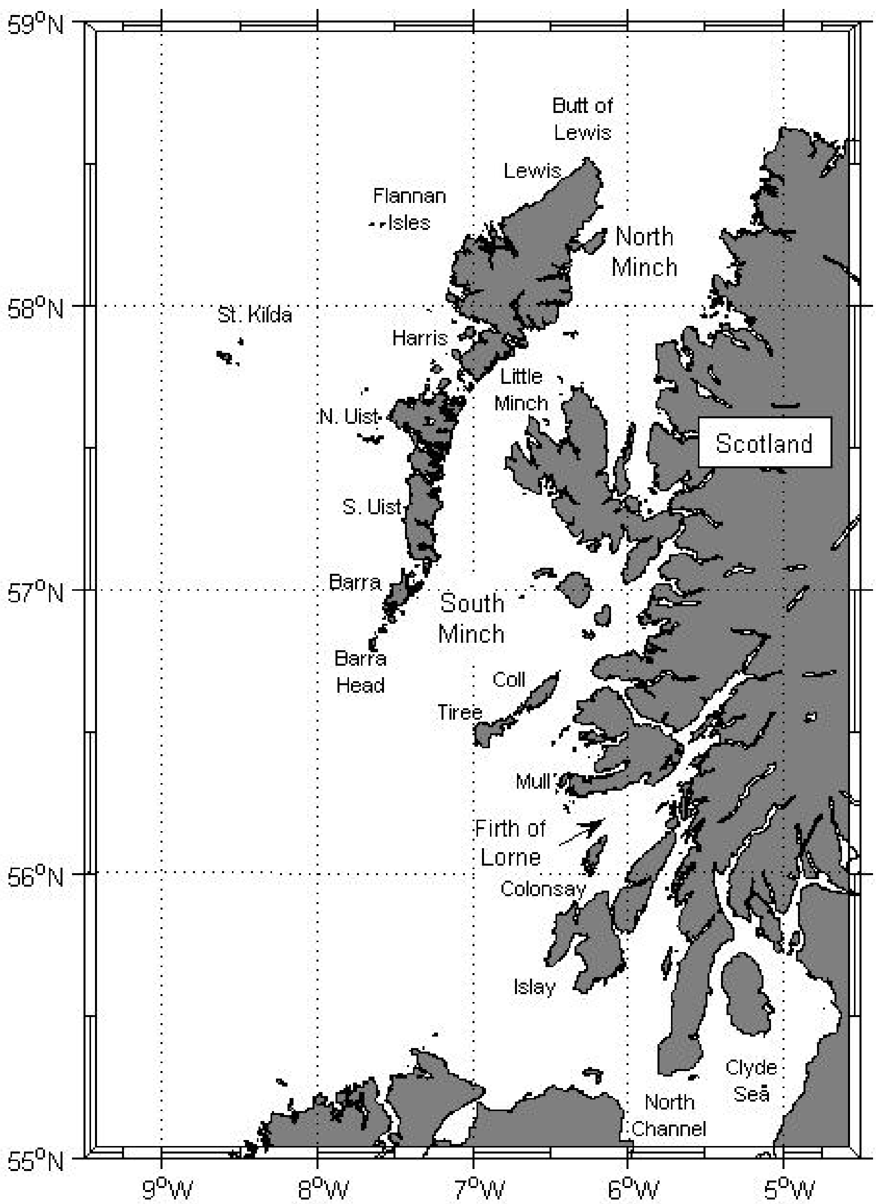


Figure 3.1: Coastline of the SEA7 area, with the main Islands and sea areas marked.

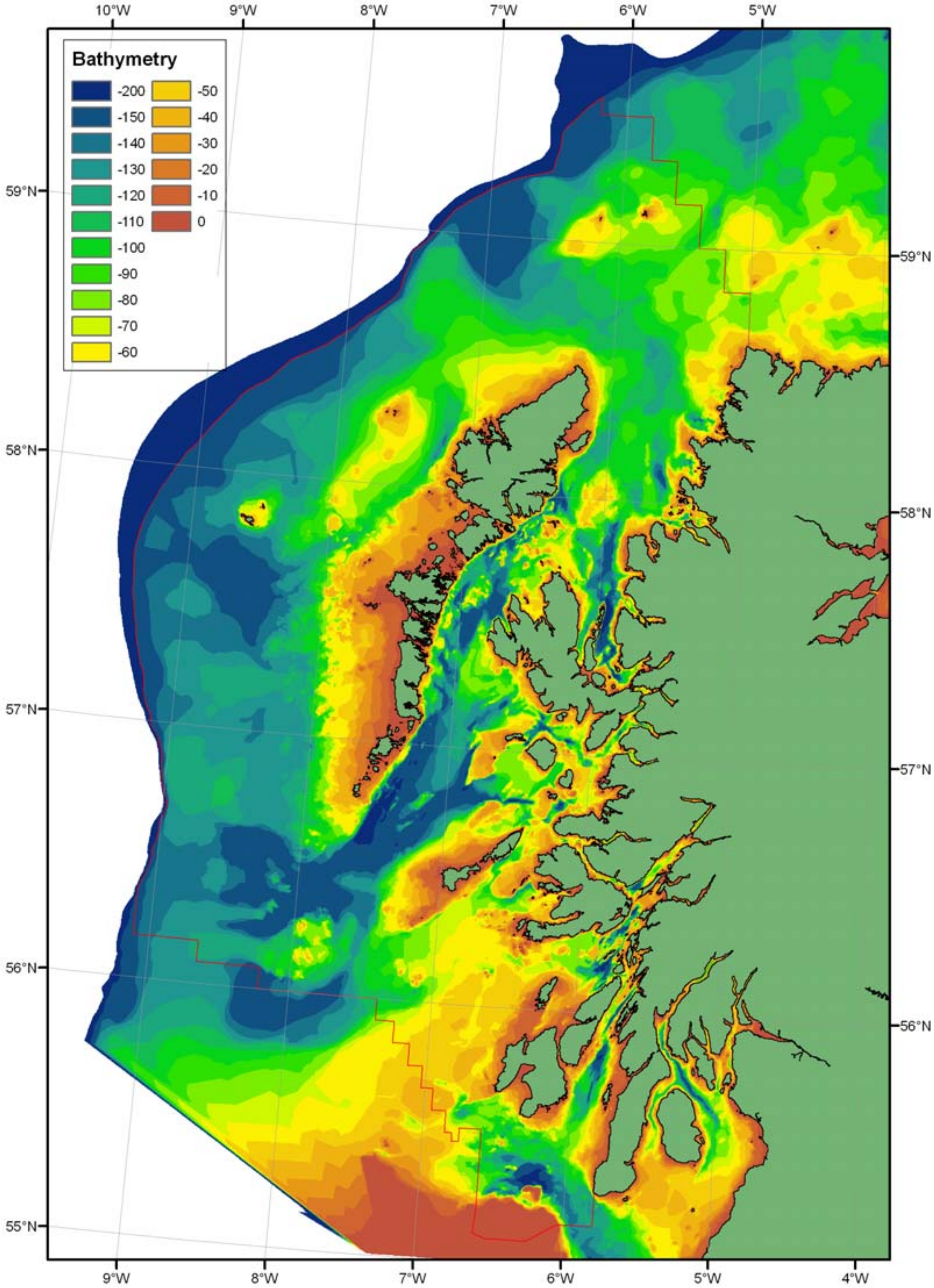


Figure 3.2: Bathymetric map of the coastal and shelf portion of the SEA7 area. Drawn from the 250m horizontal resolution bathymetric database.

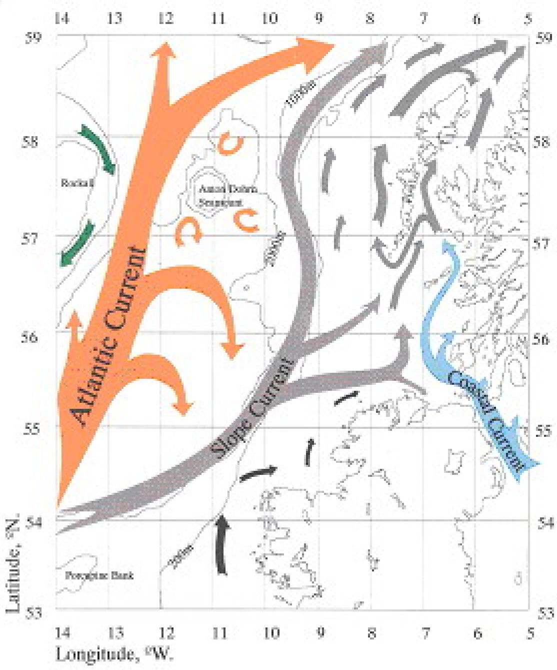


Figure 3.3: Schematic of residual circulation pattern, Courtesy of A. Edwards.

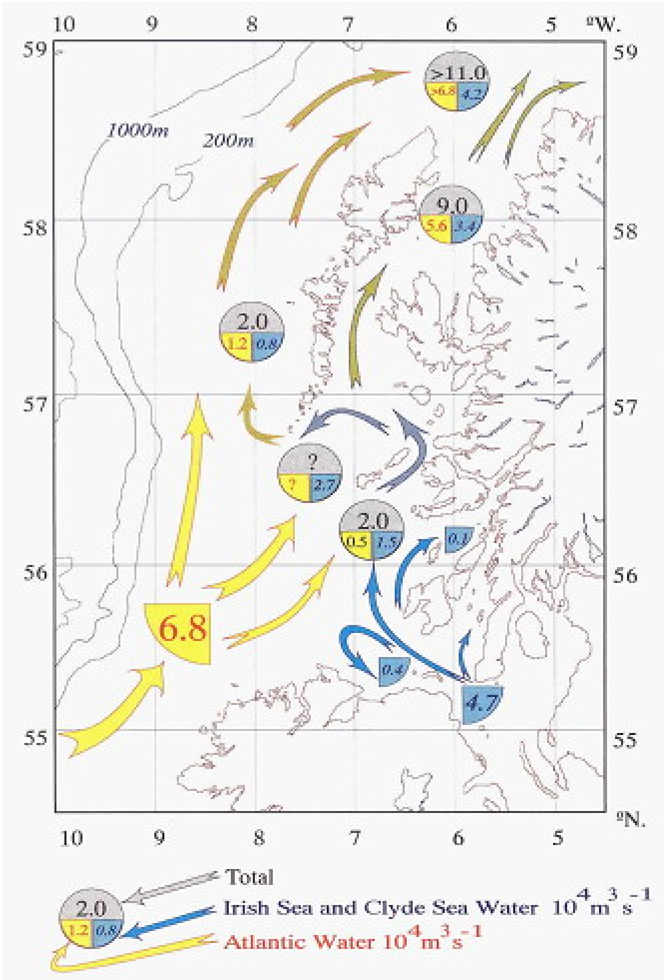


Figure 3.4: Circulation pattern and approximate volume fluxes, drawn from a variety of sources. Courtesy of A. Edwards.

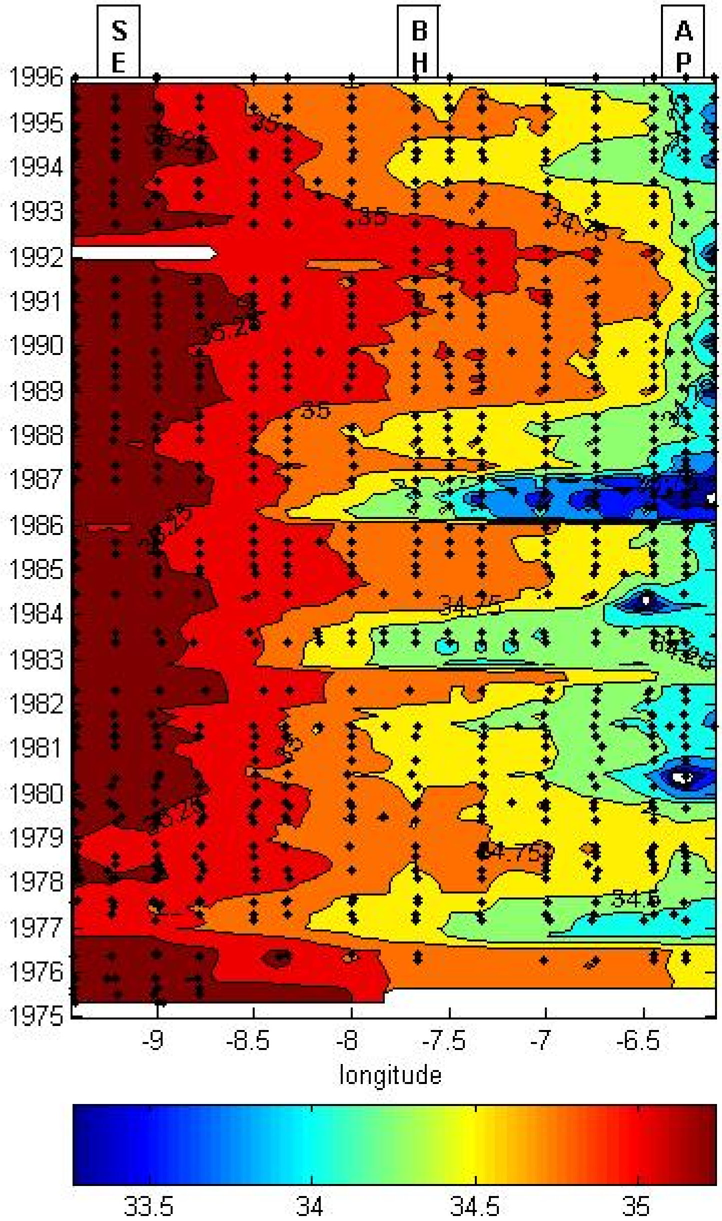


Figure 3.5: Surface salinity hodogram from Ellett Line CTD data. Longitudinal positions of Shelf Edge (SE), Barra Head (BH), and Ardmor Point (AP) indicated. Black dots indicate data points.

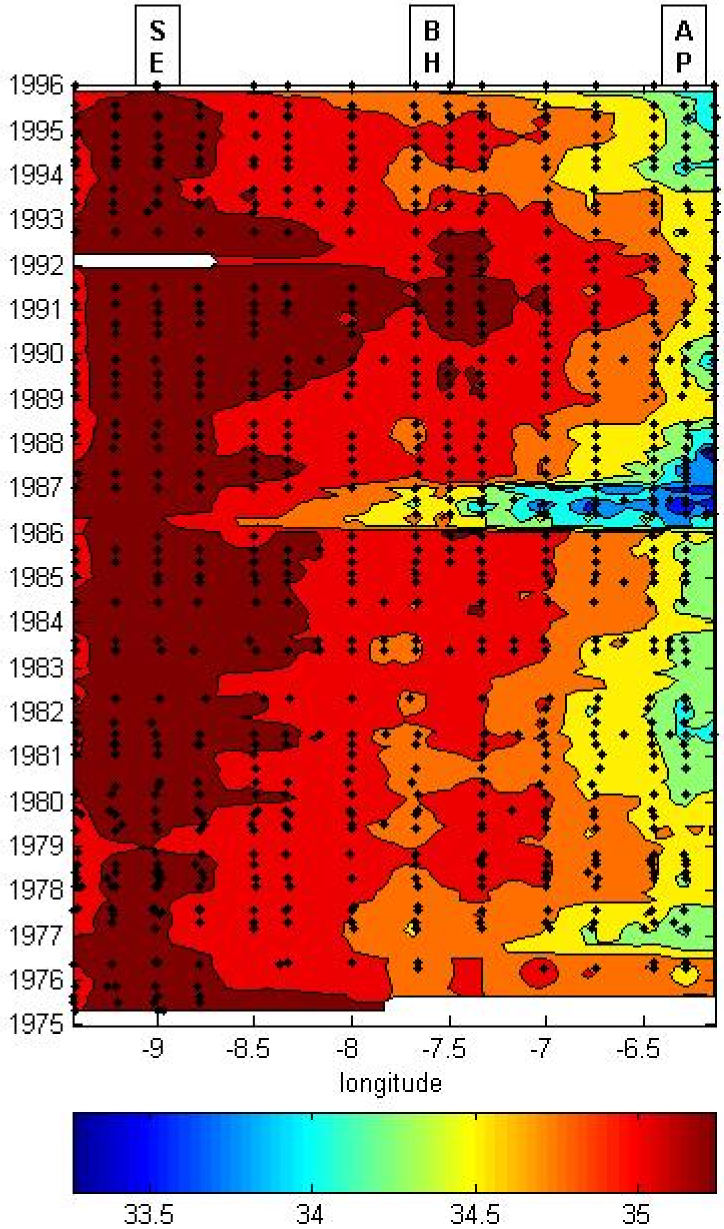


Figure 3.6: Bottom salinity hodogram from Ellett Line CTD data. Longitudinal positions of Shelf Edge (SE), Barra Head (BH), and Ardmor Point (AP) indicated. Black dots indicate data points.

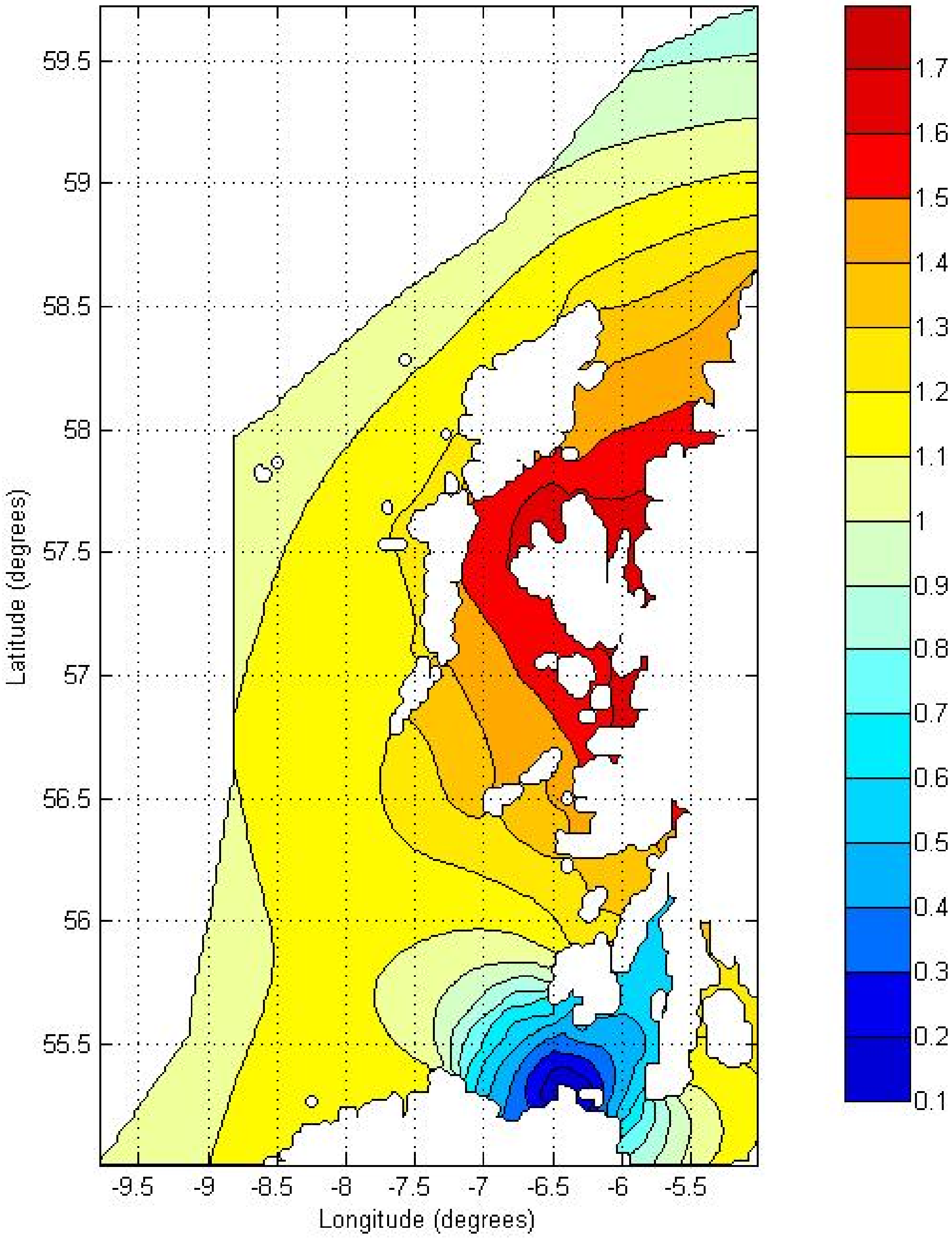


Figure 3.7: M2 tidal elevation amplitude (metres).

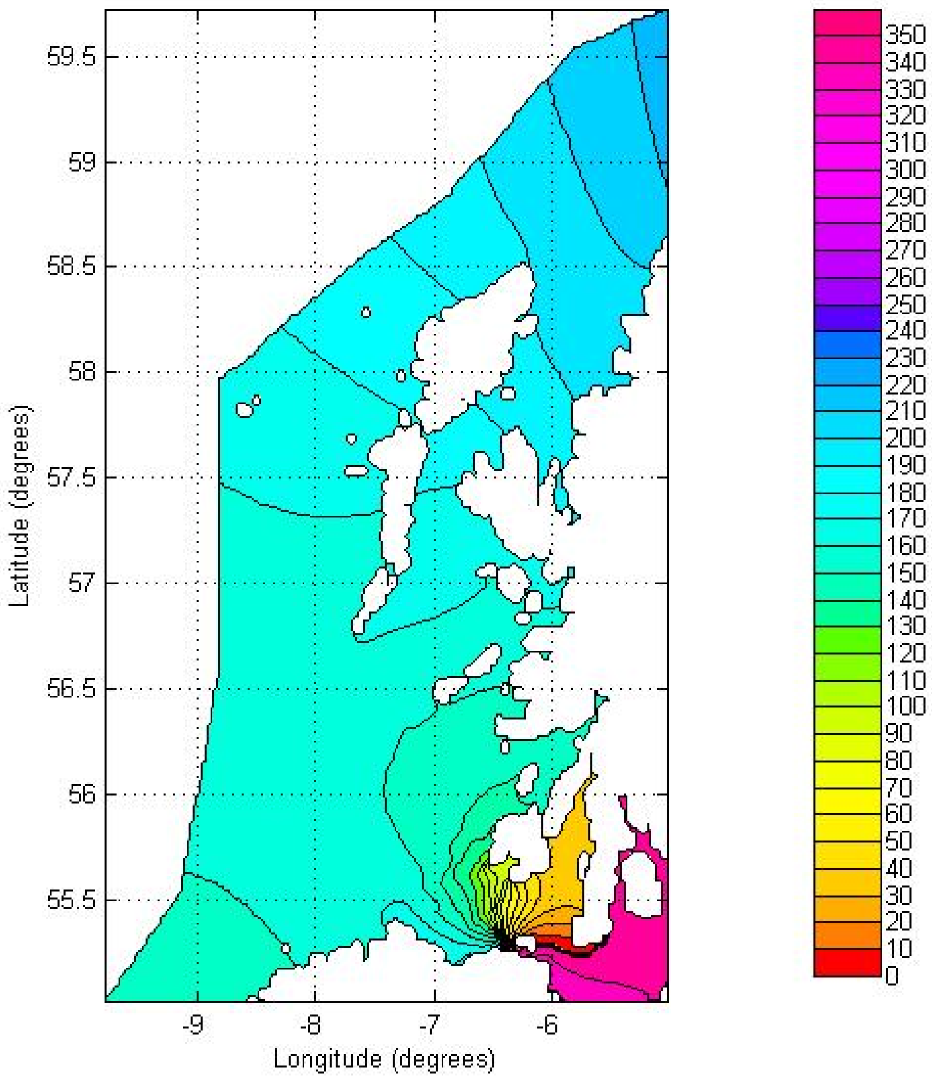


Figure 3.8: M2 tidal elevation phase (degrees).

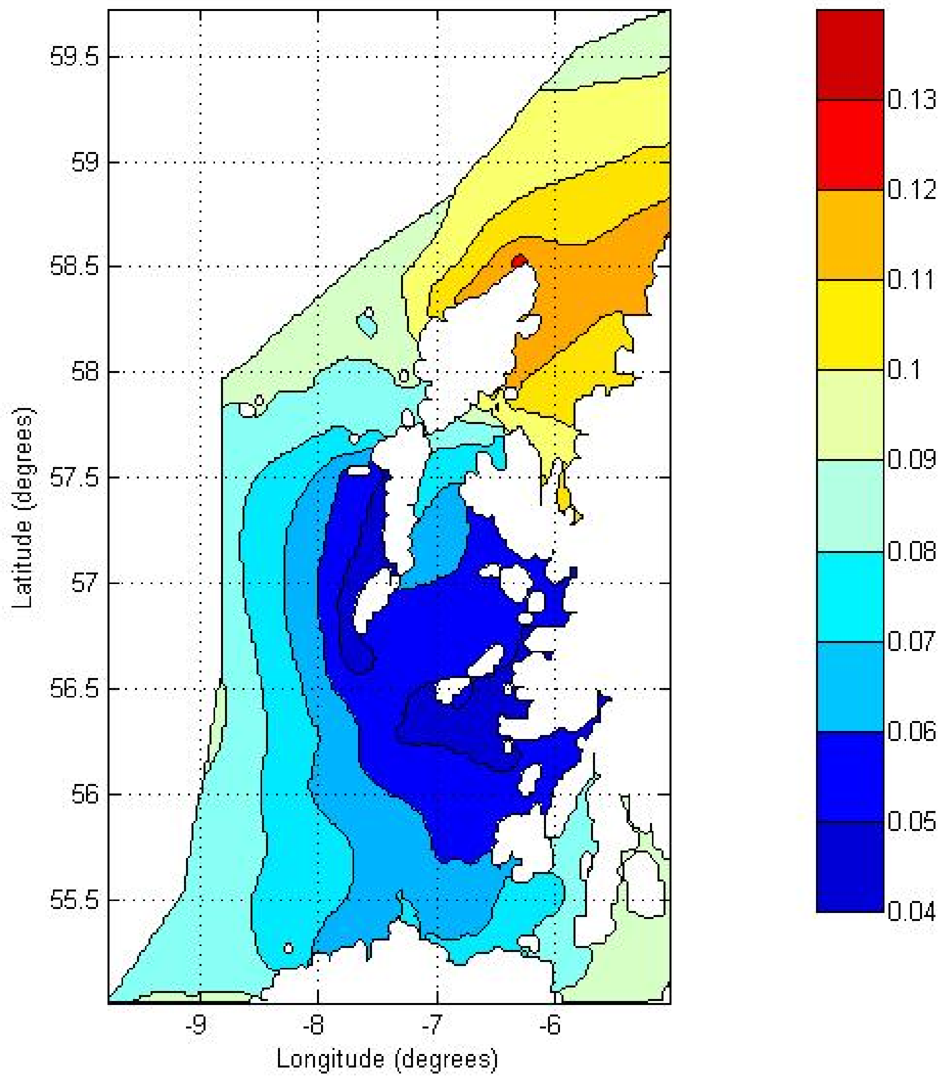


Figure 3.9: K1 tidal elevation amplitude (metres).

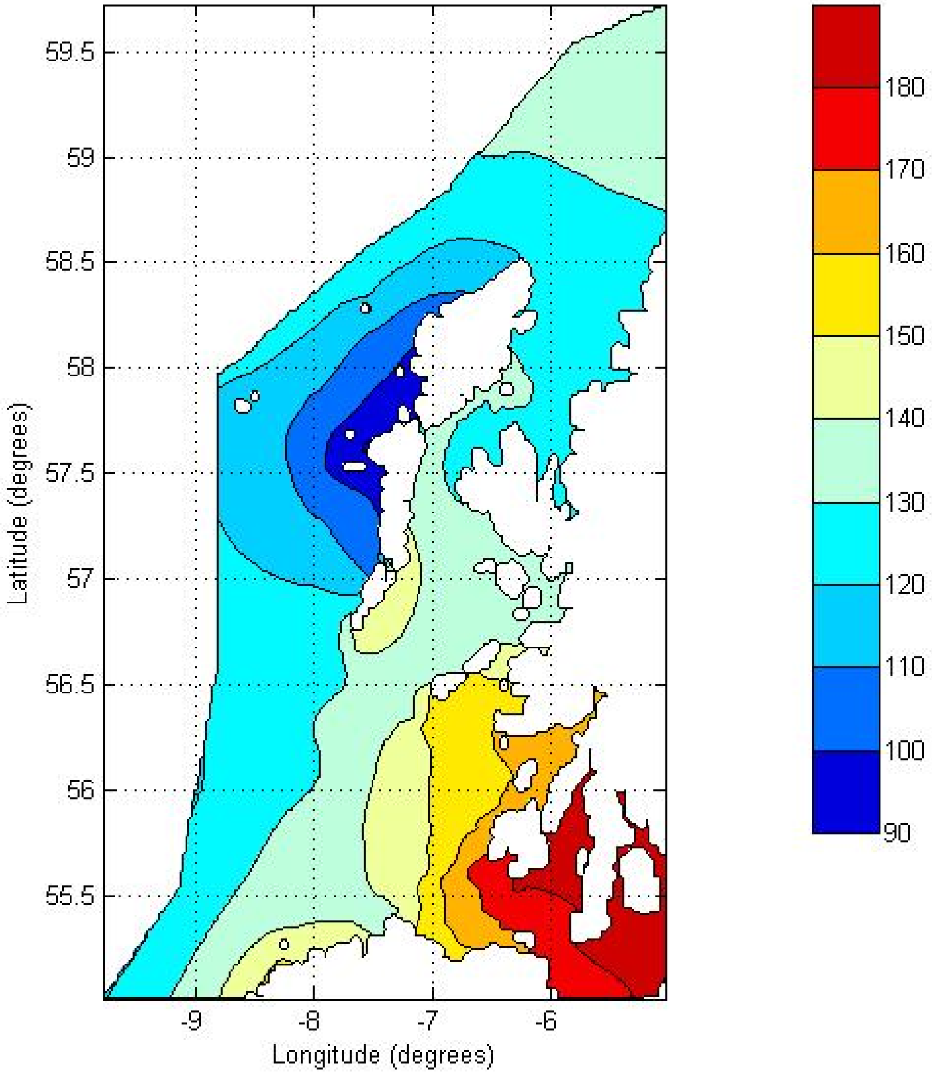


Figure 3.10: K1 tidal elevation phase (degrees).

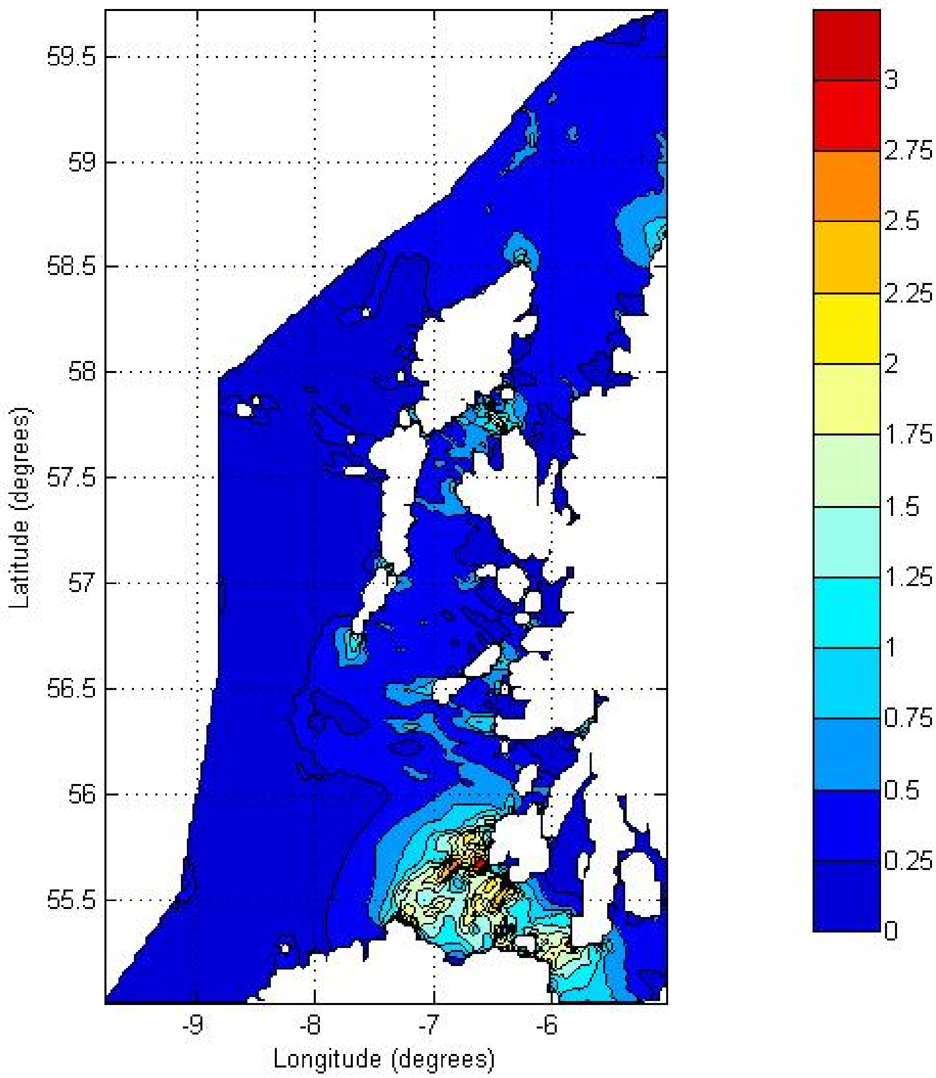


Figure 3.11: Maximum amplitude of the depth-averaged current for a mean spring tide (ms^{-1})

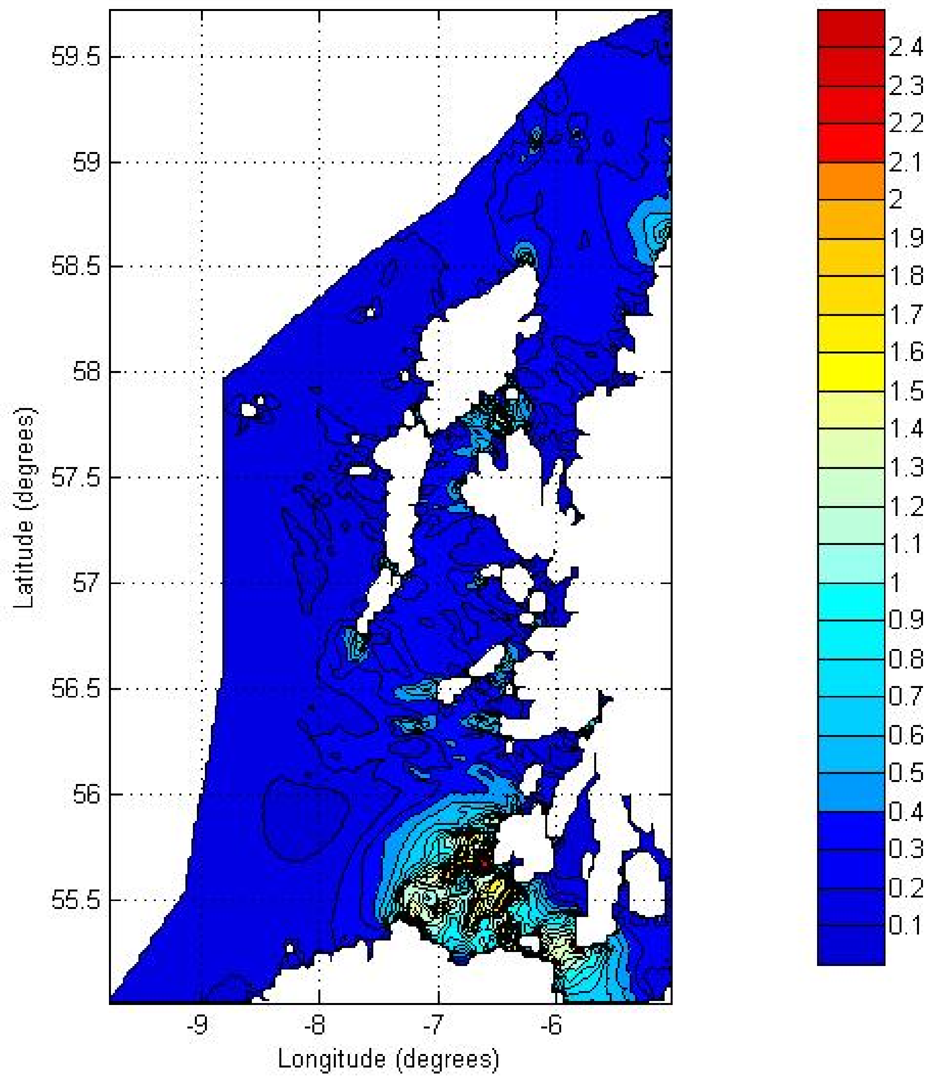


Figure 3.12: M2 semi-major axis depth-averaged current speed (ms^{-1}).

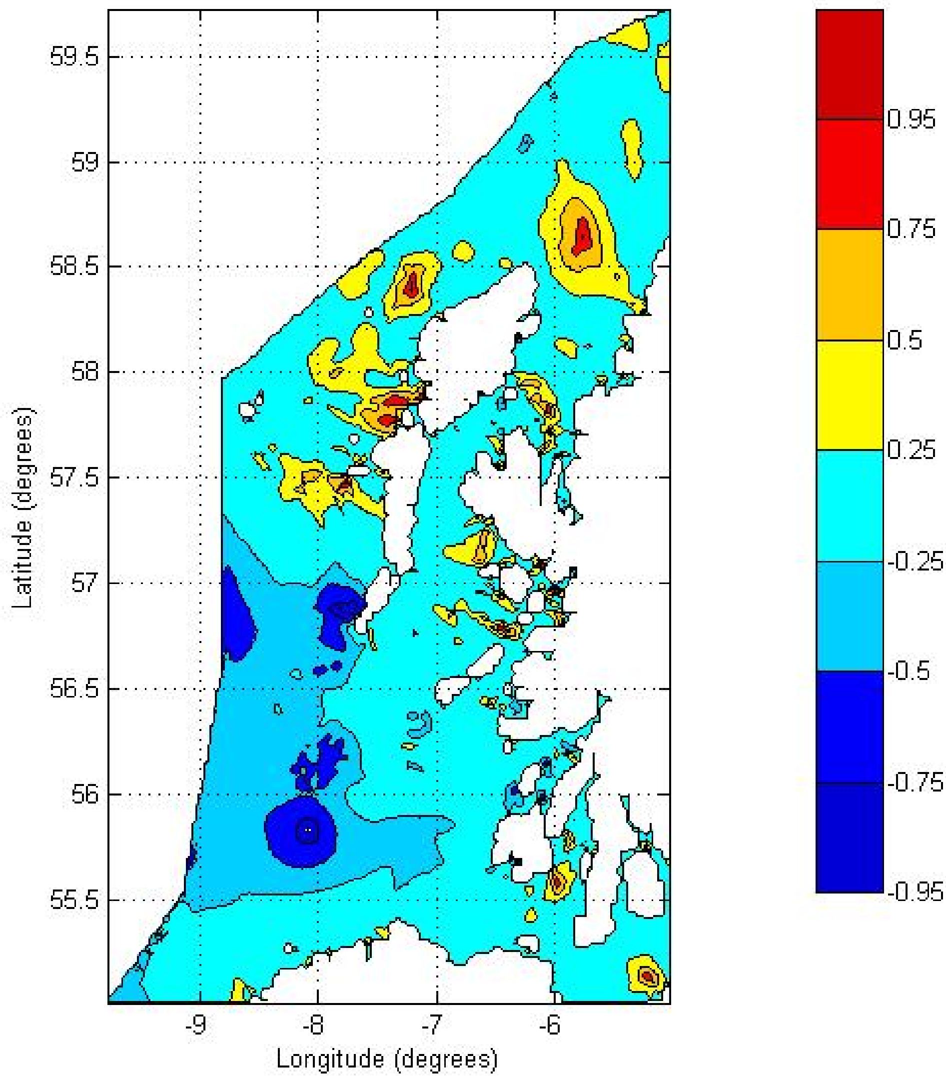


Figure 3.13:. M2 tidal current ellipse eccentricity (ratio of semi-minor to smei-major current amplitude. Positive represents anti-clockwise rotation of tidal current vector and negative represents clockwise rotation of tidal current vectors with time.

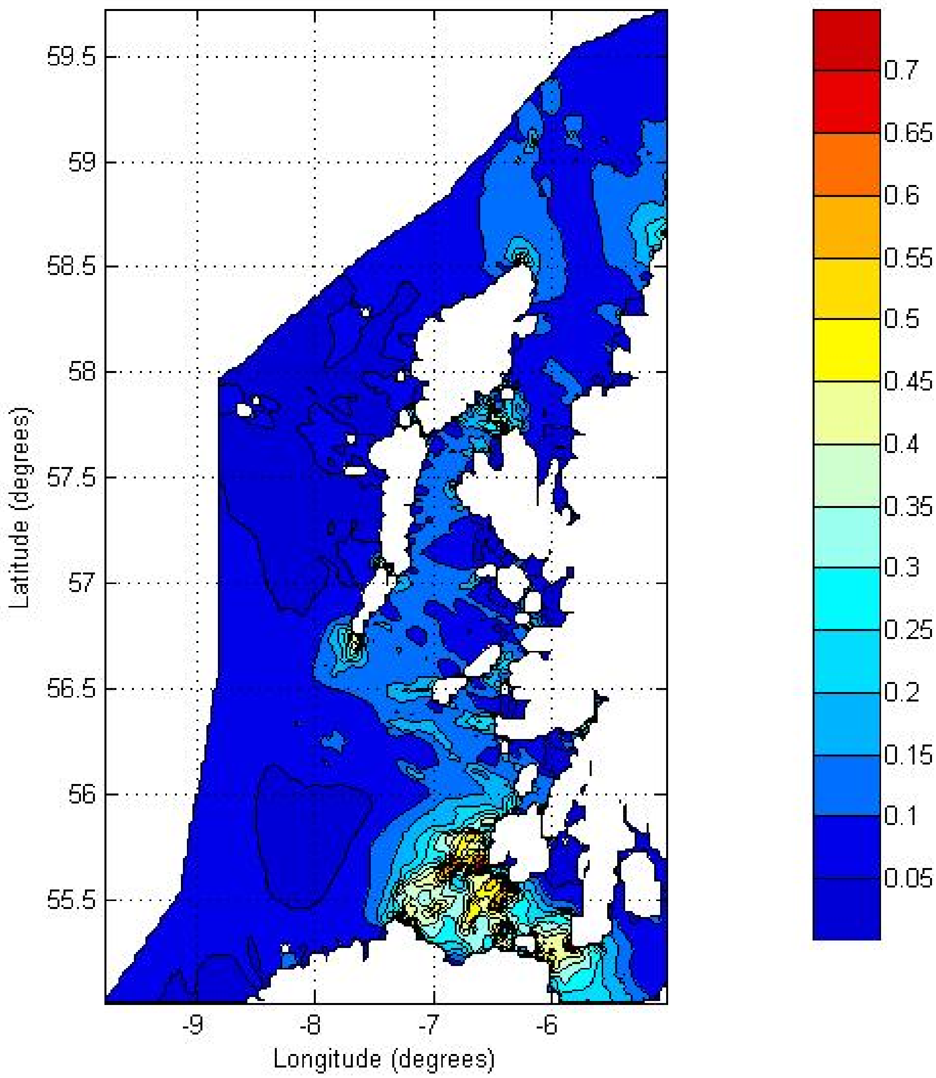


Figure 3.14: S2 semi-major axis depth-averaged current speed (ms^{-1}).

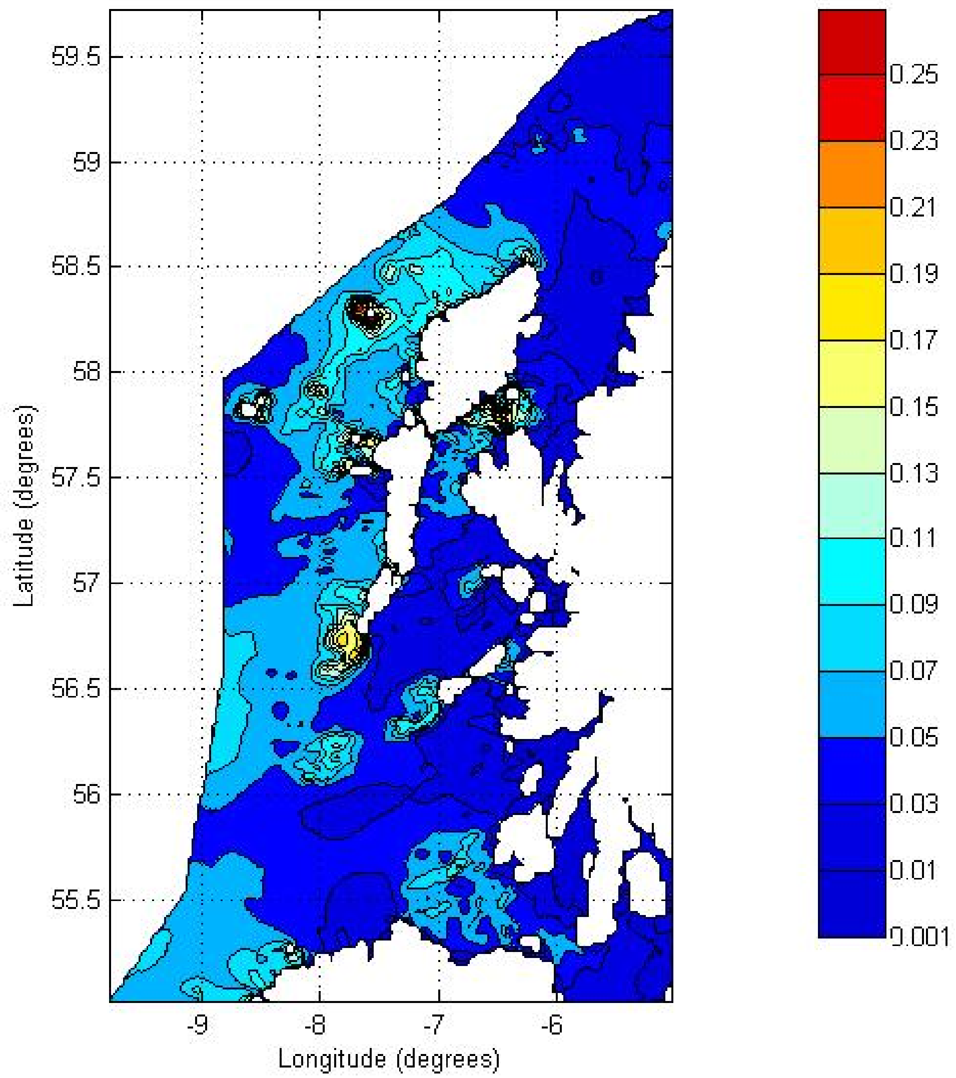


Figure 3.15: K1 semi-major axis depth-averaged current speed (ms^{-1}).

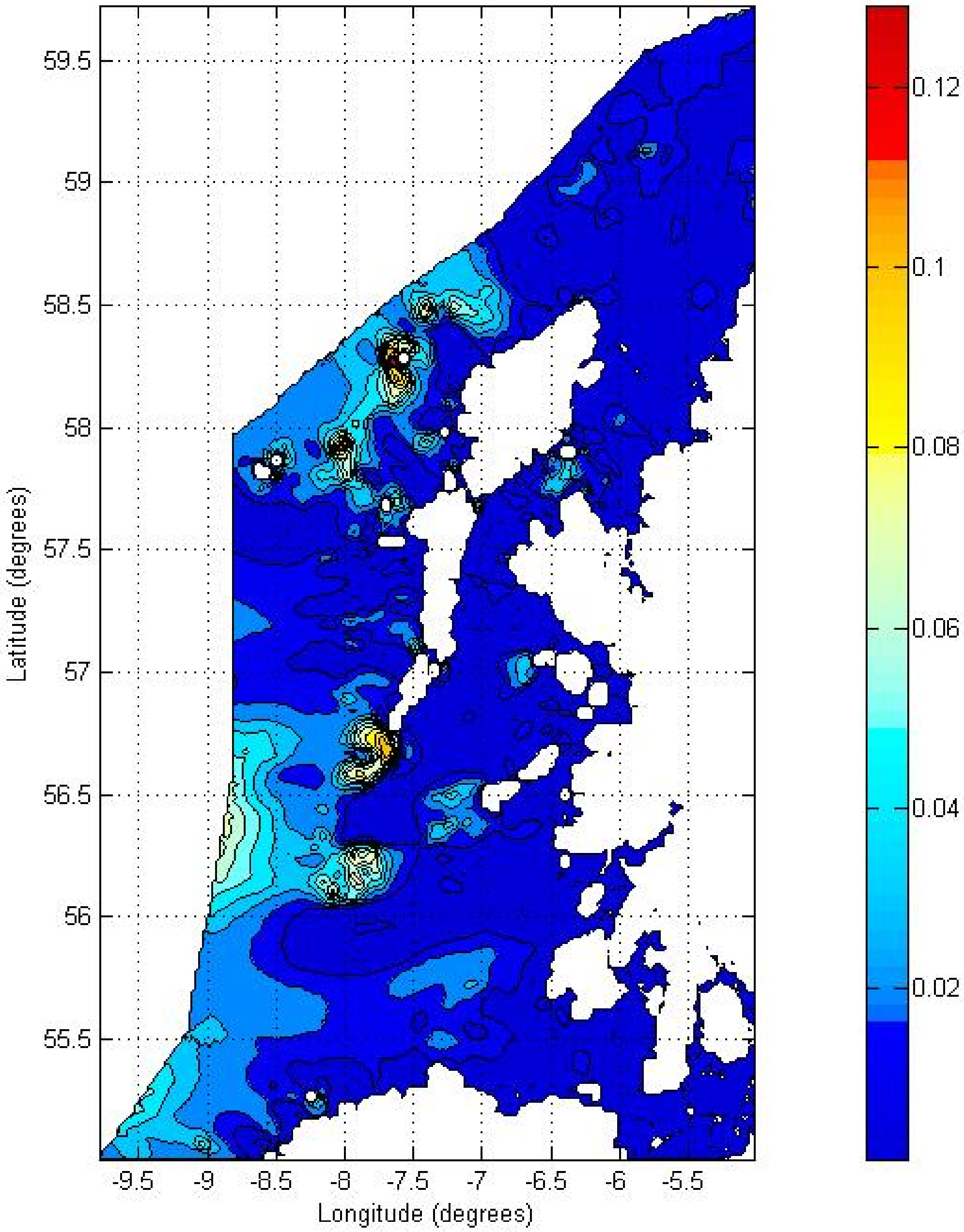


Figure 3.16: K1 semi-minor axis depth-averaged current speed (ms^{-1}).

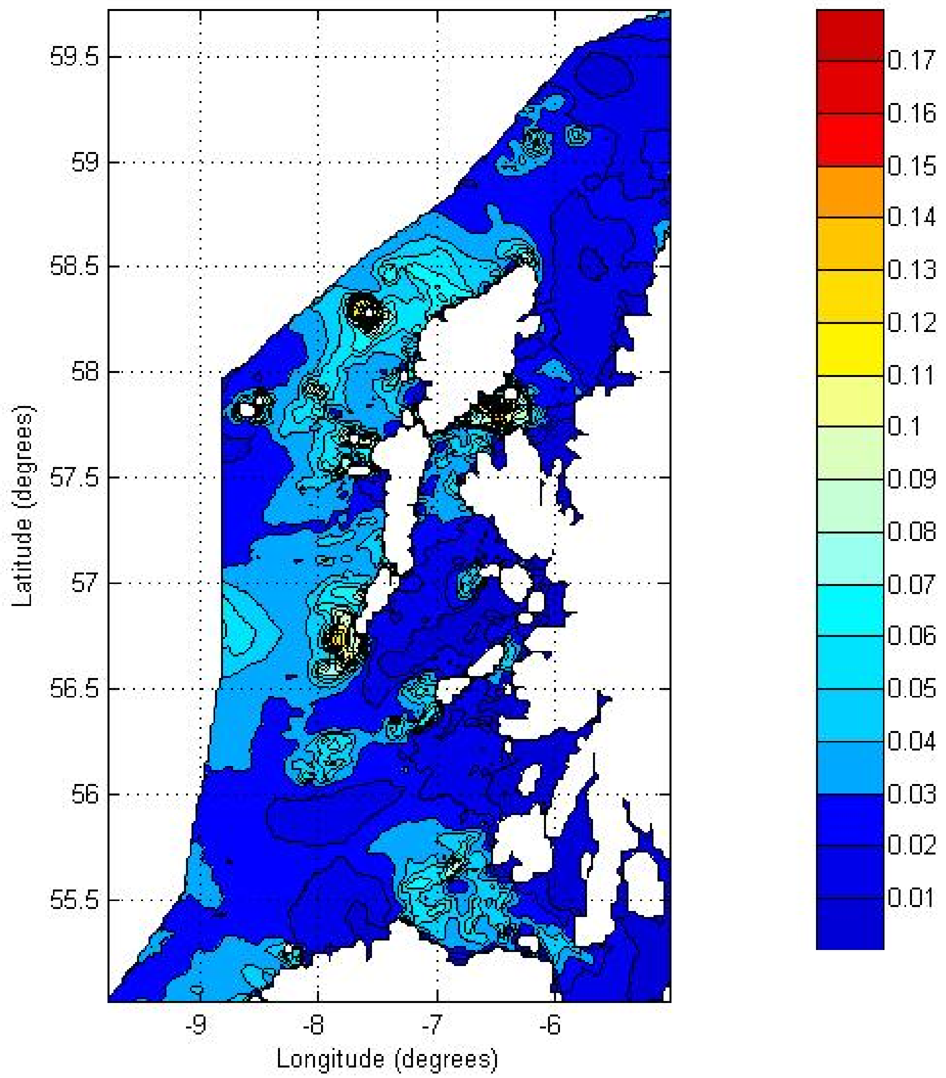


Figure 3.17: O1 semi-major axis depth-averaged current speed (ms^{-1}).

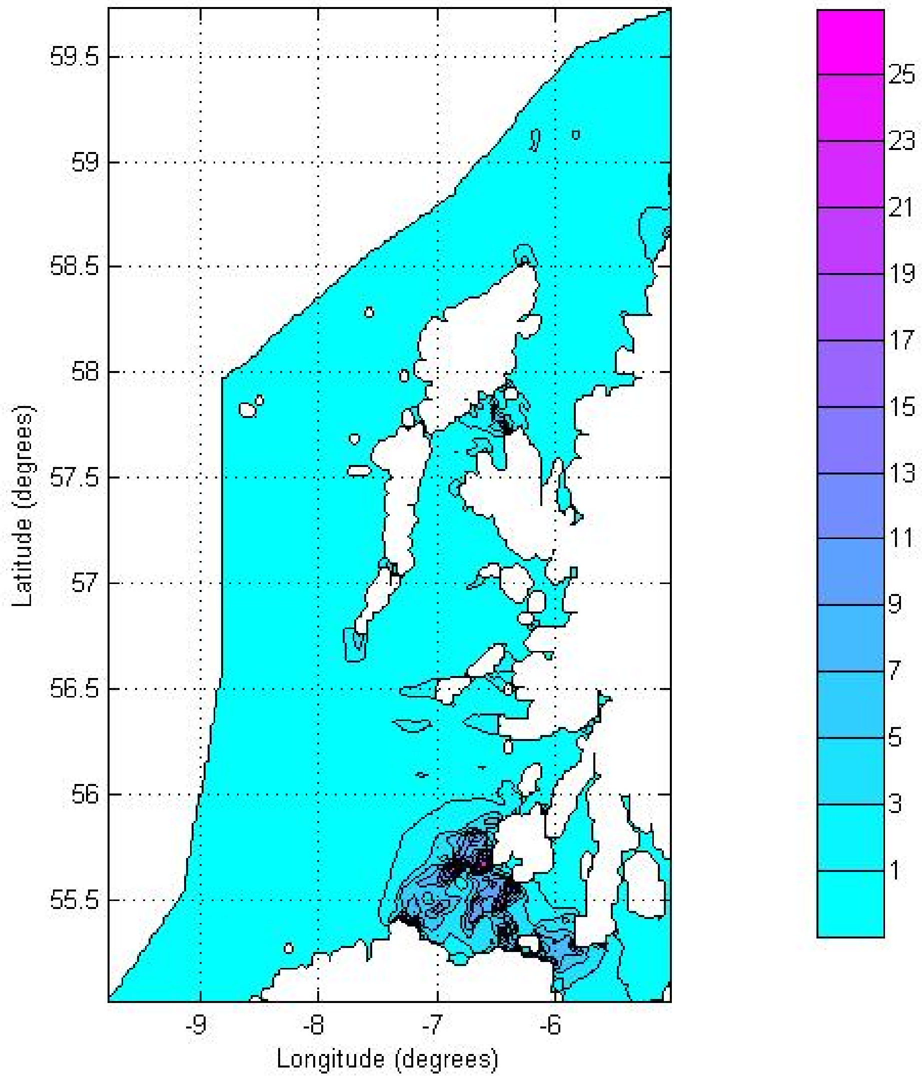


Figure 3.18: Maximum tidal bed stress in Pa (Nm^{-2}) from the POL CS20 numerical model.

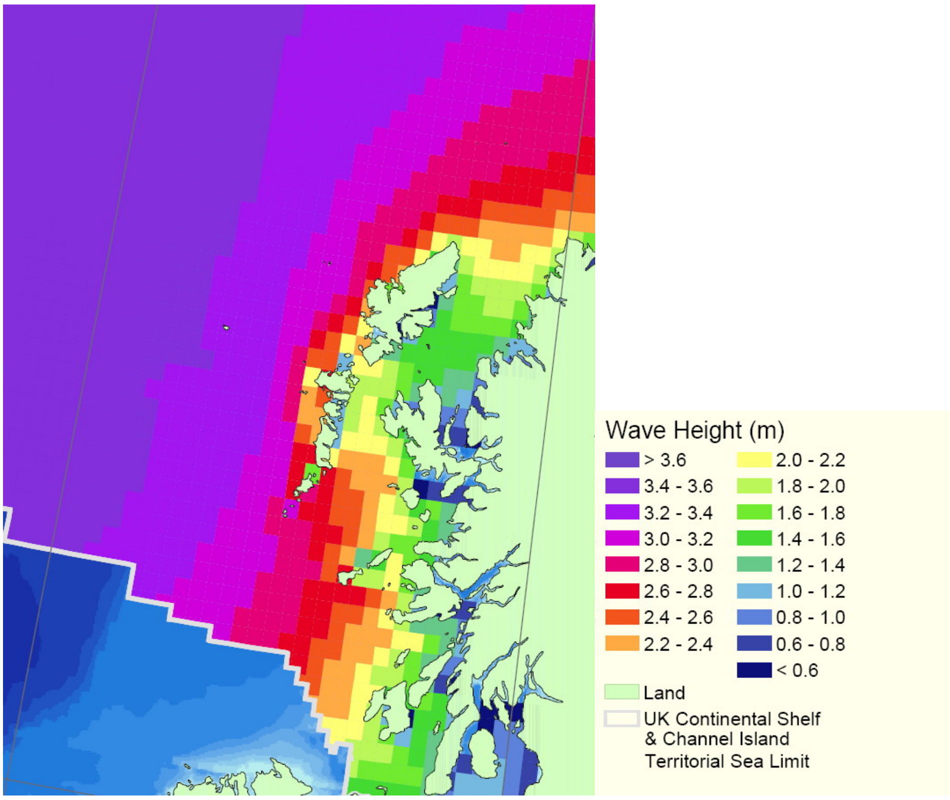


Figure 3.19: Significant wave height (m), reproduced from *ABPmer et al. 2004*.

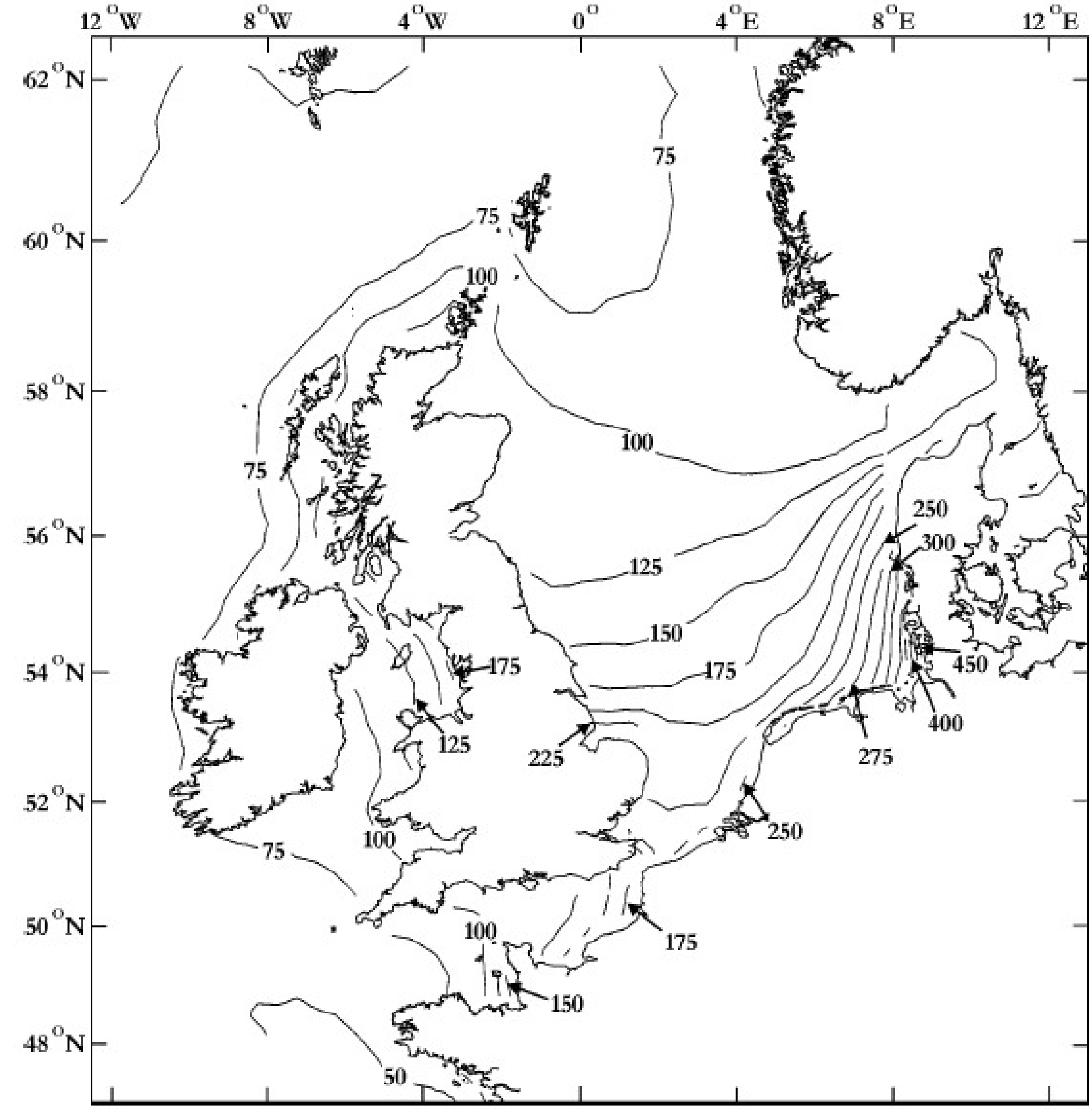


Figure 3.20: 50-year return period storm surge elevations (cm), reproduced from *[Howarth, 2005]*, and taken originally from *[Flather, 1987]*.

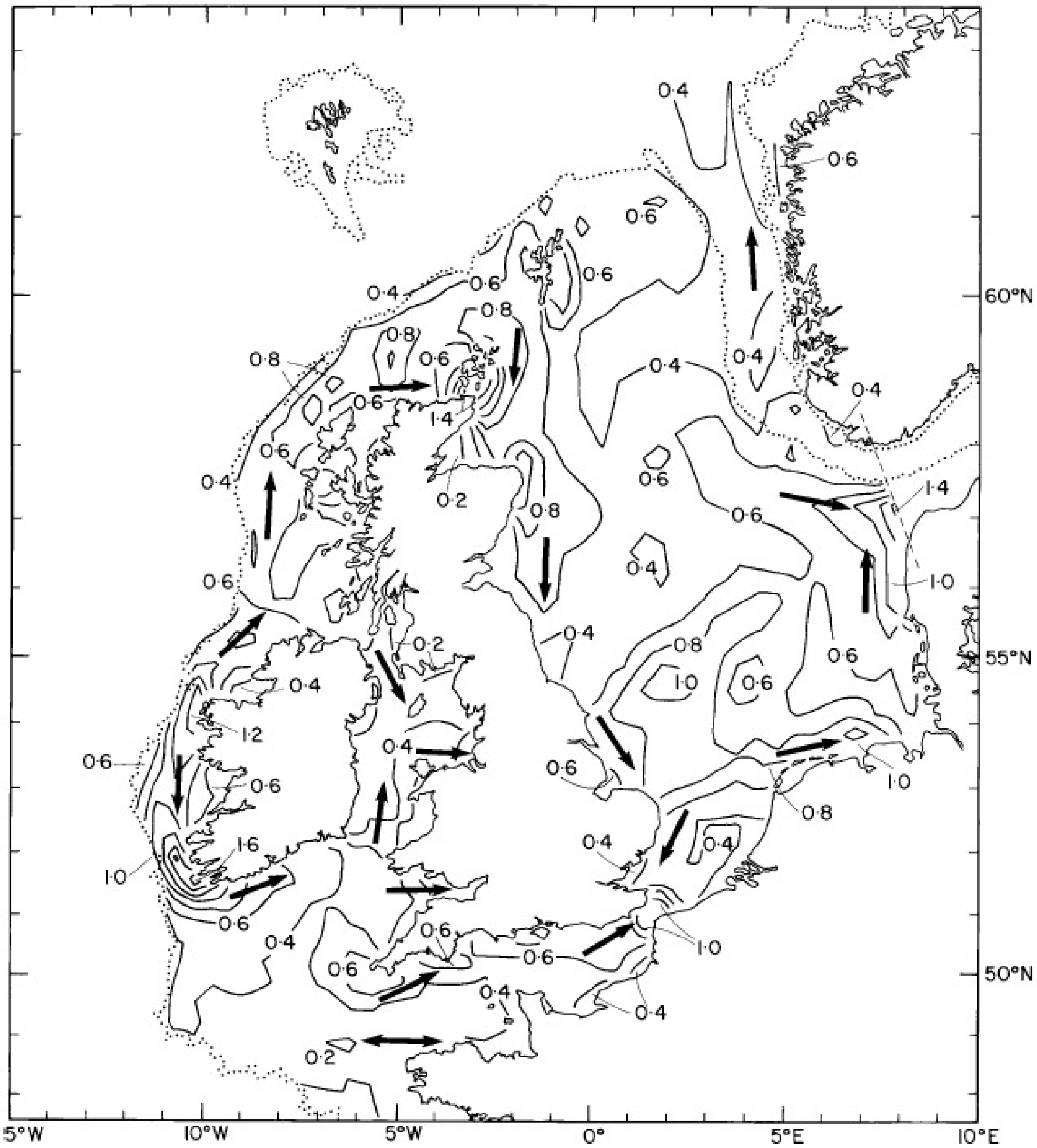


Figure 3.21: 50-year return period storm surge currents (ms^{-1}), reproduced from *[Howarth, 2005]*, and taken originally from *[Flather, 1987]*.