Hydrography of the Irish Sea

SEA6 Technical Report

POL Internal Document 174

M.J. Howarth

"This document was produced as part of the UK Department of Trade and Industry's offshore energy Strategic Environmental Assessment programme. The SEA programme is funded and managed by the DTI and coordinated on their behalf by Geotek Ltd and Hartley Anderson Ltd.

Figure captions

Figure 1. Map of the Irish Sea.
Figure 2. Bathymetry with contours at 20, 40, 60, 80, 120 and 160 m.
Figure 3. A) M_2 tidal elevation amplitude in metres. B) M_2 elevation phase in degrees.
Figure 4. Maximum amplitude of the depth-averaged current for a mean spring tide (m s^{-1}).
Figure 5. Phase difference between M_2 currents and elevations (degrees).
Figure 6. M_2 tidal current ellipse eccentricity (ratio of minimum to maximum amplitude).
Figure 7. Maximum bed stress in Pa from a numerical model run for the years 1995 to 1997 forced both by tides and winds, but with no wave contribution (JNCC, 2004).
Figure 8. Variation with height above the bed of the M_2 current amplitude (m s^{-1}) at the Mersey Bar Light a) Maximum b) Minimum, positive anti-clockwise.
Figure 9. Variation with height above the bed of the maximum M_2 current amplitude (m s^{-1}) in the North Channel, 54º 46´N 5º 24´ W in 142 m of water.
Figure 10. The North Atlantic Oscillation index from 1864 to 2004 (data from http://www.cgd.ucar.edu/cas/jhurrell/indices.html).
Figure 11. Measurements of significant wave height at the Mersey Bar Light for 21 months plotted against direction and mean period.
Figure 12. Map of indicative values of 50-year return period significant wave height (m) (Carter and Challenor, 1989).
Figure 13. 50-year return period storm surge elevations in centimetres (Flather et al., 1998).
Figure 14. 50-year return period storm surge currents in (m s^{-1}) (Flather, 1987).
Figure 15. Discharge (m^3 s^{-1}) by Mersey (red) and the sum of the Clwyd, Dee, Mersey and Ribble (blue) for 2002 and 2003.
Figure 16. Map showing number of days in a year in which the water column is thermally stratified (JNCC, 2004).
Figure 17. Map showing areas where the water column remains well-mixed throughout the year (blue, dark - high salinity; pale – low salinity) and areas where stratification occurs (green, - high salinity; pale – low salinity) (JNCC, 2004).
Figure 18. Concentration (Bq kg^{-1}) of Caesium-137 in filtered water from the Irish Sea, May 1978 (Hunt, 1980).
Figure 19. Mean surface currents in the North Channel based on a year's of hf radar measurements (Knight and Howarth, 1999).
Figure 20. Progressive vector diagram showing mean currents from a 2-year record by the Mersey Bar Light. The figures denote measurement height (m) above the bed. The water depth at the site varies between 17 and 27 m, depending on the tide. (In one year water moving at 0.01 m s^{-1} will travel 315 km.)

1. Introduction

The SEA6 area stretches from the Mull of Kintyre in the north to St. David's Head in the south, encompassing several geographic regions, Figure 1.
the Clyde Sea
the North Channel, between the Mull of Kintyre and the Mull of Galloway
the Irish Sea proper, between the Mull of Galloway and Holyhead / Dublin, including
    the eastern Irish Sea, to the east of the Isle of Man and Liverpool Bay.
the St. George's Channel, as far south as St. David's Head.
There are two large islands within the region – the Isle of Man and Anglesey, although the latter is only separated from north Wales by the narrow Menai Strait.

The whole of the region will be presented, although Irish waters are excluded from SEA6, since scientifically this is the only sensible approach. The region encompasses as wide and interesting a variety of continental shelf sea regimes as anywhere. The predominant dynamical process is the semi-diurnal tides, with areas of both high and low energy embraced. Superimposed on this is the full range of water column structure – areas that are well mixed throughout the year; areas that stratify thermally in summer; areas of freshwater influence from river discharges, leading both to nearshore density gradients and stratification; frontal regions between the well-mixed and stratified regions. Finally there are regions of restricted exchange, principally sea lochs where a sill inhibits mixing with the outside waters, such as the Clyde Sea, but also Belfast Lough. There have been several general reviews of the physical oceanography of the Irish Sea – Bowden (1980), Dickson & Boelens (1988), Sweeney (1989), Simpson (1998) in addition to various status reports - and for the Clyde Sea Edwards et al. (1986). This report covers the shape and depth, the tides, the impact of storms, stratification and its consequences and the mean circulation, all with a view to mean and extreme conditions.

The physical oceanography (hydrography) of the area determines the movement of the water and the amount of mixing, prescribing physical effects such as forces on structures and the movement and dispersion of contaminants, but also significantly influencing biogeochemical processes including sediment erosion / deposition and movement, particularly of suspended sediment, benthic exchanges and primary productivity (via stratification, nutrient exchanges and light levels).

The two sources for many of the figures in this report are a three-dimensional hydrodynamic numerical model of the continental shelf seas around the United Kingdom with a horizontal resolution of 1.8 km, and long term measurements from a site less than a mile west of the Mersey Bar Light, at 53º 32´ N 3º 21.8´ W. The water depth at the site is 18.5 m below chart datum, with a tidal range at equinoctial spring tides of about 10 m. The site is part of a project started in August 2002 and expected to last for 5 – 10 years. Measurements include current profiles, waves and surface and bed salinities and temperatures (for more details see http://cobs.pol.ac.uk). Since there are very few such long term measurements, because of the expense, effort and commitment required, the measurements are used to test the models and the models then used to estimate spatial (horizontal and vertical) variations.

2. Topography

The Irish Sea consists of a deeper channel in the west, with shallower embayments in the east, Figure 2. The channel is open-ended, forming part of a loop connected at both ends to the Atlantic Ocean, in the south via the Celtic Sea and the St. George's Channel and in the north, via the North Channel and the Malin Shelf Sea. Hence the Irish Sea receives Atlantic water and influences through both entrances. The channel is about 300 km long and 30 – 50 km wide, with a minimum depth of 80 m and a maximum exceeding 275 m in the Beaufort's Dyke in the North Channel. The two principal shallower embayments, each with depths less than 50 m are Cardigan Bay in the south and the eastern Irish Sea (to the east of the Isle of Man) in the north, and there is also the smaller Caernarfon Bay. The width of the Irish Sea varies between 75 and 200 km but decreases to 30 km in the North Channel. Its volume is 2,430 km^3, 80% of which lies to the west of the Isle of Man, and its surface area is 47,000 km^2. It receives fresh water run-off from a large area of land; the catchment area is about 43,000 km^2, with the majority of the run-off arriving in the eastern Irish Sea, down the Ribble, Mersey and Dee estuaries and into the Solway Firth and Morecambe Bay. The region is also affected by significant freshwater input from the south via the Bristol Channel. As well as the shallow estuaries like the Solway Firth, Morecambe Bay and the Dee estuary there are extensive sanbanks to the north and east of the Isle of Man, including the Bahama and King William Banks, and off the Irish Coast south of Dublin – the Kish, Codling, Arklow and Blackwater Banks. The Clyde Sea, extending north-east from the North Channel, is like a loch with a shallow (~45 m) sill at its mouth and maximum depth 170 m further inland.

3. Tides

The semi-diurnal tides are the dominant physical process in the SEA6 region, propagating into the Irish Sea from the Atlantic Ocean through both the North Channel and the St. George's Channel. (The diurnal tides, also forced by the gravitational action of the Sun and the Moon, are very weak in this area.) An understanding of their dynamics and consequences are therefore prerequisites to understanding both physical and non-physical, including biological, processes. The tides have a basic period of 12.4 hours but also exhibit variations on fortnightly (spring / neaps, with spring tides occurring on average two days after Full and New Moon and nearly twice as large as neaps), monthly, 6 monthly (equinoctial spring tides) and yearly time scales. The full span of possibilities occurs within the region, from areas with very large tidal range (the range in Liverpool Bay exceeds 10 m on the largest spring tides and is the second largest in the British Isles) to regions of very small tidal range (amphidromic points, in the vicinity of Arklow in the St. George's Channel and between Islay and the Mull of Kintyre in the North Channel), Figure 3a, showing the amplitude (equals half the range) of the main tidal constituent. The progression of the tides through the North and St. George's Channels is illustrated in Figure 3b, showing the phase, or timing, of the tide. In addition, the time of high water varies little over a wide area to the east and west of the Isle of Man, where the two waves meet, forming a standing wave.

3.1 Tidal currents

There is also a wide range of tidal current strength, Figure 4, which exhibits greater variation on shorter space scales compared with elevations. Depth-averaged values exceed 1 m s^{-1} at spring tides generally throughout the St. George's Channel, north-west of Anglesey, north of the Isle of Man and in the North Channel. Within these areas particularly high values can be found locally near headlands, for instance exceeding 2 m s^{-1} at spring tides northwest of Anglesey. Areas of very weak tidal currents, less than 0.25 m s^{-1} at spring tides, occur to the south-west of the Isle of Man, towards Dundrum and Dundalk Bays, and slightly less weak, 0.5 m s^{-1}, between the Isle of Man and the Cumbrian coast, both as a consequence of this being the region where the two tidal waves meet. Another consequence of this standing wave region is that in the Irish Sea proper slack water occurs approximately at high and low water (a phase difference between currents and elevations of ±90º, Figure 5), whereas in the North Channel and the St George's Channels maximum currents occur at about high or low water. The Clyde Sea is a further area of very weak tidal currents. Tidal ellipses are approximately rectilinear in most localities but in a few tend towards circular, for instance where the tidal currents are weak to the east and west of the Isle of Man, in the entrance to the Clyde Sea and the southern end of Cardigan Bay, Figure 6. Where the ellipses are circular there is no slack water. Both the amount of mixing and the bed shear stress, which drives sediment resuspension and hence also influences scour are related to the currents and so show similar distribution, but with more pronounced variations, Figure 7. This figure is based on the response to both tidal and wind forcing but the distribution of bed shear stress is clearly dominated by the tides. It does not contain any wave effects, which may significantly increase bed shear stresses in shallow water.

Throughout most of the water column the tidal current speed changes little with depth; the largest changes occur in a high shear layer a few metres thick near the sea floor in which the velocity decreases to zero at the bed. Compared with mid-depth values, the amplitude at 1 m above the bed is about a half and the maximum current occurs a few minutes earlier, Figure 8a, 9. (Traditionally the depth-averaged value is taken to occur at 0.4 times the water depth, above the bed.) As the bed is approached the anti-clockwise component of the tidal ellipse tends to become more important, changing the shape of the ellipse and in some case reversing its sense of rotation, for instance Figure 8b where the (nearly rectilinear) tidal ellipse rotates clockwise near the surface and anti-clockwise near the bed.

The daily tides are small by comparison, current amplitudes are less than 0.1 m s^{-1} everywhere, again with a minimum to the south-west of the Isle of Man. Higher frequency tides are generated in shallow water and where the water depth or topography changes abruptly. The largest component is the four-times-daily which has mean spring current amplitudes up to 0.15 m s^{-1} to the east of the Isle of Man, but locally these high frequency currents can be enhanced near headlands, islands and estuaries. The effects of the higher harmonics are apparent as distortions to the sinusoidal shape of the tidal wave, for instance in estuaries leading to shorter floods and longer ebbs. The consequences can be significant if the peak ebb and flood currents have different amplitudes, which can be caused by even harmonics (principally the sixth diurnals). In addition, the flood / ebb inequality occurs for the combination of the semi-diurnal component with its first harmonic (four-times daily) for a set phase (timing) difference (if the phase of the four-times daily component of current minus twice the phase of the twice daily equals 0º or ±180º). (In elevations this is analogous to the double high water in the tides near Southampton.) Then not only will there be large differences between the peak ebb and flood bottom stresses but also a mean bottom stress, both significant for sediment transport. In the eastern Irish Sea this is directed eastward, in the southern St. George's Channel southward, in the northern St. George's Channel northward and in the North Channel northward (Pingree and Griffiths, 1979; and the sediment transport technical report).

4. Impact of storms

4.1 Winds

The maximum 50-year period return values of the hourly-mean wind speed at 10 m height are in the region of 34 – 36 m s^{-1} (about 65 knots),with gusts up to 50 m s^{-1} (93 knots). Most frequent winds are from between the west and north-west and also from the south-east but gales only occur from the west and north-west. Winds of Force 6 or stronger (greater than 11 m s^{-1}, 22 knots) can occur at any time of the year but are commonest between December and March and scarcest between April and August, with considerable year-to-year variability. The year-to-year variability of the strength of westerly winds has been characterised by the North Atlantic Oscillation (NAO) Index, based on the winter atmospheric pressure difference between Iceland and Lisbon or the Azores. A positive NAO (a large pressure difference) is accompanied by strengthened westerlies and a negative NAO (weak pressure difference) is accompanied by weaker winter westerlies; Figure 10 shows how the Index has varied since 1864.

4.2 Waves

The magnitude of surface waves depends on the duration and fetch of the wind. Since the Irish Sea is sheltered with only two relatively narrow 'windows', along the axes of the St. George's and North Channels, the majority of waves are locally generated, of fairly short period and hence steep. Swell waves are only present near entrances, at the southern end of the St. George's Channel (although these can propagate as far as the Lleyn peninsular in North Wales) and the northern end of the North Channel. Hence, the wind direction leading to the largest waves will depend very much on the locality, for instance in Liverpool Bay winds from between west and north-west cause the largest waves, Figure 11, and waves from the north causing most damage on the North Wales coast. The maximum 50-year return value of the mean zero-up-crossing period varies between 10 s within the Irish Sea to about 15 s at its outer entrances. Similarly, the 50-year return value of significant wave height varies between 8 m within the Irish Sea to about 12 m at its outer entrances, Figure 12. There is a suggestion that the Irish coast to the west of the Isle of Man is least affected by large wave activity. The effect of waves on other processes will be significant during storms and especially on sediment movement, in the shallow areas of the eastern Irish Sea and Cardigan Bay. The impact on the coast of a given wave field depends critically on the local topography with channels enabling wave energy to approach the coast. There are no long-term records of wave heights in the Irish Sea but data from a variety of sources indicate that between the 1960s and through into the 1990s wave heights have increased in the north-east Atlantic.

4.3 Surges

Surges are generated by storms, both locally through the action of wind stress on the sea surface piling up water at the coast and, on the scale of the depression, through the action of atmospheric pressure - high pressure depresses the sea surface and low pressure raises it, by about 0.01 m for each millibar deviation from the mean (about 1012 mb). Once generated storm surges travel in the same manner as the tides. Hence, Irish Sea surges have an external component, propagated via the St. George's and North Channels, and a locally generated component, each of comparable significance. Surges and tides can interact leading to intermittent oscillations with a twice-daily frequency in the tidal residuals. In the Irish Sea this interaction appears to be associated with the surge's external component. The largest surges are generally associated with storms, secondary depressions, tracking eastward between Inverness and Shetlands. The largest surges occur in the eastern Irish Sea, with maximum 50-year return period surge levels, based on a 12 km grid numerical model simulation, estimated to be less than 2 m for the Lancashire and Cumbrian coasts, associated with westerly winds, Figure 13, whilst the maximum surge levels are between 1.25 m and 0.75 m on the Irish coast and across the St. George's Channel (Flather et al, 1998). (Note however that these levels may be exceeded at the coasts, for instance based on 17 years of observations the 50-year return period surge elevation at Heysham, Lancashire, is estimated to be 3.16 ±0.55 m.) The impact of a surge will depends critically on the state of the tide with the biggest risk of flooding occurring if the surge peak coincides with high water on a spring tide, and conversely the maximum risk of a ship grounding occurring if a negative surge coincides with low water at a spring tide.

Since the Irish Sea is semi-enclosed the associated surge currents are weak, arising both directly from the wind drag at the sea-surface and also related to the sea surface gradients. The former are limited to a surface layer of order 10 m thick, with a maximum speed at the surface of about 3% of the wind speed, decreasing rapidly with depth. The latter are predicted, based on a numerical model simulation, to have a maximum 50-year return period depth-averaged current away from the coast of 0.5 m s^{-1} (Figure 14, Flather, 1987). Their direction is largely determined by topography not wind. This figure is only indicative since the vertical structure of wind-driven currents will in many places be more pronounced than for tidal currents, and may even involve flow reversal at depth. In the eastern Irish Sea the prevailing storms generate an anti-clockwise movement of water, in opposition to the longer period density driven (clockwise) movement. Flows of water through the North Channel are correlated with the component of wind blowing along the channel's axis ($r^2 = 0.44$). The largest depth-averaged non-tidal flow at a site in the middle of the North Channel in a year long measurement was 0.65 m s^{-1}. (The largest depth-averaged total measured current for this period was 1.6 m s^{-1}). In contrast, sea level variations there are correlated with the wind blowing perpendicular to this, parallel to the Scottish and Irish west coasts (Knight and Howarth, 1999).

4.4 River flows

River discharges are highly variable – on a daily basis the peak flow down a major river during a flood can be up to 400 times the flow during dry weather. Since floods last at most a few days and the mean is the average of a series of such events there is often a large difference between an actual daily measurement and the long term average figure for that day. The largest monthly discharge occurs between December and February and the smallest in July. From year to year the total river flow can vary by a factor of three. Discharges from the Mersey, Dee andn Ribble contribute an average freshwater input to the eastern Irish Sea of about 220 $m^3 s^{-1}$, Figure 15 and Table 1.

Table 1. Annual average river discharge ($m^3 s^{-1}$) into the Irish Sea by regions.

Bristol Channel	600
Mid Wales	176
Eastern Irish Sea	659
Clyde	284
Northern Ireland	144
Irish republic	934

5. Density

5.1 Temperature

The Irish Sea's temperature distribution is dominated by vertical exchanges and heat input at the sea surface leading to a pronounced seasonal cycle. The annual mean temperature decreases northward from a little over 11ºC at the southern end of the St. George's Channel to 10ºC in the North Channel and it also decreases towards the sides. The water is coolest in February or March with temperature decreasing from the deeper channel towards the coasts. A warm tongue, with a temperature above 7.5ºC, extends up to the North Channel. The coolest water is towards the coast in the eastern Irish Sea – between the Solway Firth and Liverpool Bay the temperature is below 5ºC. Temperatures also decrease slightly towards the Irish coast – the 7ºC isotherm runs parallel to the east coast of Ireland. At this time of year the temperature is uniform with depth everywhere.

The situation in the warmest month, August, is contrasting, with the coolest surface water in the deep channel (13 – 13.5ºC) and the warmest water close to the coasts, exceeding 16ºC in Liverpool and Cardigan Bays. Again there is only a small change in temperature (this time a rise) towards the Irish coast. Hence the magnitude of the seasonal cycle is largest in Liverpool Bay (12.1º) and about half as big (6.4ºC) between Holyhead and Dublin, where the maximum temperatures occur about a month later. All the figures here are based on averages over many years and so there will be some year-to-year variations. The longest temperature record in the region is from the breakwater at Port Erin, Isle of Man. The record shows a large degree of variability in the seasonal cycle, although a general increasing trend is apparent, indicating a rise of around 0.6ºC over the last 70 – 100 years, and particularly an increase in winter temperatures since 1990.

5.2 Salinity

The annual mean salinity decreases from south to north and from the centre of the channel to the sides. The salinity decreases from 34.9 at the southern end of the St. George's Channel to 34.0 in the North Channel. Lowest values, less than 32.5 are found in the north-east, from the Solway Firth to Liverpool Bay, and in the Clyde Sea. (Values for salinity are a dimensionless ratio of grams of salt in a kilogram of water). In the eastern Irish Sea there is often an abrupt change in salinity, running approximately north/south lying east of 4ºW, between the fresher coastal water and the saltier offshore water (Foster et al, 1985). The position of this front is greatly affected by wind stress. Seasonal variations are much less pronounced than for temperature, especially away from the coasts. Near the coasts the annual cycle is related to the river flow, with minimum salinity occurring in spring and maximum in late summer or autumn. At the Mersey Bar Light, where the mean is 31.9, the annual range is 0.7. There is some evidence that surface salinity has decreased slightly over the last 50 years, although as for temperature there is much year-to-year variability.

5.3 Stratification

Throughout most of the region tidal mixing is sufficiently intense to ensure that the water column remains well mixed throughout the year. However in the regions of weak tidal currents to the east and west of the Isle of Man and in Cardigan Bay stratification (warm lighter water on top of cool, denser water) occurs in summer. To the east of the Isle of Man conditions for this are only marginal so that stratification is only likely to develop during hot, calm conditions and can easily be mixed away by storms or spring tides. Stratification is more dependable in the deep waters to the west of the Isle of Man, Figure 16, starting in April – May and continuing through to October, with a maximum surface to bed temperature difference of about 5ºC. The change in temperature from surface to bed is not gradual but occurs abruptly, at the thermocline, which is about 20 – 30 m below the surface. Even here stratification is not as robust or as well developed as in some other areas in the seas around the British Isles, such as the Celtic Sea and the northern North Sea. One of the effects of stratification is to isolate the near bed waters from the near surface, although the isolation is not complete as the near bed waters warm up continuously throughout this period, from about 8º to 12.5ºC. An interesting and unusual feature of this region is that it is entirely surrounded by water well-mixed in the vertical or by a coast.

Near to estuaries and especially in Liverpool Bay the water column can also stratify because fresh water is lighter than salty; conditions are most suitable at neap tides, when the weather is calm and when river discharges are large. Once the water column has stratified surface to bed temperature differences can also occur in summer, Figure 17.

5.4 Inertial currents

Inertial currents, episodic currents usually generated by wind impulses, can occur when the water column is stratified, especially in the surface mixed layer. The currents rotate clockwise in an inertial period (14.8 hours) and have slowly varying amplitudes. The inertial current beneath the thermocline is out of phase with the surface current, so that there is minimal energy at this frequency in the depth-averaged current. These have been observed in the western Irish Sea with amplitudes up to 0.2 m s^{-1} in the surface layer (comparable with the tidal currents there) and a decay time scale of about three inertial periods (Sherwin, 1987).

5.5 Fronts

The transitions between mixed and stratified regions are in many cases marked by sharp fronts which may be manifest at the surface and / or near the bed and which have an important influence on the dynamics and inhibit mixing across the fronts. In addition to fronts in the Irish Sea there are fronts in summer between the St. George's Channel and the Celtic Sea and also between the North Channel and the Malin Shelf Sea (the Islay front) and along the Clyde Sea sill. A particular feature of the flow associated with the stratified region of the north-western Irish Sea is a closed circulation cell which can retain material within the cell for as long as stratification persists. Measurements show narrow currents up to 0.2 m s^{-1} circulating anti-clockwise round the edge of the patch.

5.6 Clyde Sea

A pronounced front separates the stratified regime of the Clyde Sea from the well-mixed waters of the North Channel and mediates the density-driven exchange over the sill which is responsible for deep-water renewal. Input from the river Clyde and other freshwater sources at a rate of 60 – 700 m^3 s^{-1} into this partially enclosed basin tends to promote a stratified system throughout the year. During the summer months, stratification induced by the freshwater buoyancy is reinforced by strong thermal stratification. In winter months, cooling and enhanced wind mixing work to erode stratification but are generally insufficient to surmount the increased freshwater input. The result is a rather specialized regime, which maintains a stable structure throughout the annual cycle, except for infrequent episodes of complete mixing and bottom water renewal (Rippeth and Simpson, 1996).

6. Circulation

The mean flow is generally weak, by and large less than 0.1 m s^{-1} and about 0.01 m s^{-1} in many places, resulting from the sum of events (storms, peak river discharges) plus density gradients. The long term average (in time and across the cross-section) flow in the deeper western channel has long been deduced to be from south to north, based initially on the salinity distribution. More recent measurements support this, for instance of Caesium 137 discharged from the nuclear reprocessing plant at Sellafield, Cumbria, since the 1950s and peaking in the mid 1970s (now orders of magnitude less) and of Technetium 99, for which discharges have increased significantly since 1994 (McCubbin et al. 2002). Both these radionuclides are soluble in water and are detectable at very low levels, and hence are tracers of water movement. For instance, the distribution of Caesium at the period of peak discharge showed levels 50 – 100 times lower in the St. George's Channel compared with the North Channel, Figure 18. Care is necessary converting tracer distributions into current values since the distribution results both from advection (water movement) and mixing. Transit times from Sellafield to the North Channel have been estimated in the range 6 to 12 months and a mean residence time for the Irish Sea of 1 – 2 years, although the uncertainties associated with these estimates are large. Even though the average flow is northward it should be remembered that water movement is strongly influenced by the wind, so that this flow can be reversed for months at a time.

However, there is an unambiguous measurement of flow through the North Channel from a year's deployment of a shore-based hf radar system, measuring surface currents, supported by an in situ Acoustic Doppler Current Profiler, measuring the vertical distribution of current at a point, from July 1993 to August 1994 (Knight & Howarth, 1999). These gave an outflow of 0.08 x 10^6 m^3 s^{-1}, equivalent to a cross-sectional average of 0.025 m s^{-1}. This is similar to values calculated from salinity and Caesium distributions, although the latter do show variability by a factor of two from year to year, and implies that the average residence time for the Irish Sea is about one year. The current was not, however, distributed uniformly across the channel – the strongest mean surface outflow was close to the Mull of Galloway, inshore of the Beaufort's Dyke, with current speeds up to 0.15 m s^{-1}, Figure 19. This flow through the North Channel forms the basis for the Scottish Coastal Current which flows northward past the west coast of Scotland. Drifter tracks support a clockwise flow round Ireland, implying that water may flow southward on the Irish side of the North Channel. The south to north flow also implies that discharges into the Bristol Channel could well enter the Irish Sea. The measurements showed that the flows through the North Channel are related to the wind.

The circulation in the regions away from the western channel is less clear. In Liverpool Bay the density gradients drive a circulation offshore at the surface and onshore near the bed (predicted both by theory (Heaps, 1972) and observed, Figure 20). Overall the density gradients tend to drive a clockwise circulation around the coasts of the bay, in opposition to the winds. Accordingly a clockwise flow is found during periods of light winds, especially when the horizontal density gradients are strongest in winter and spring, but at wind speed > 5-10 m s^{-1} from between south-west and north-west this pattern is reversed.

Weak mean transport does not preclude moderately energetic closed circulation cells present for only part of the year which need not contribute to the net transport of water. It is the weak mean flow that is crucial in controlling the long-term distribution of conservative (and near conservative) substances, which are input within the Irish Sea or through its boundaries. Because of the time scales involved the dispersion of such substances is reasonably well described by two-dimensional models, which do not explicitly include vertical exchange processes.

References

Bowden, K.F., 1980. Physical and Dynamical Oceanography of the Irish Sea. In The North-West European Shelf Seas: The Sea Bed and Sea in Motion. Vol. II Physical and Chemical Oceanography and Physical Resources. Eds. F.T. Banner, M.B. Collins and K.S. Massie; Elsevier Oceanography Series Vol. 24B, pp 391-413.

Carter, D.J.T., Challenor, P.G. 1989. Estimation of extreme waves. Metocean Parameters – wave parameters, Dept. of Energy report OTH 89 300, 7-66.

Dickson, R.G., Boelens, R.G.V. (eds), 1988. The status of current knowledge on anthropogenic influences in the Irish Sea. ICES co-operative report No. 155, I.C.E.S., Copenhagen, 88pp.

Edwards, A., Baxter, M.S., Ellett, D.J., Martin, J.H.A., Meldrum, D.T., Griffiths, C.R., 1986. Clyde Sea hydrography. Proceedings of the Royal Society of Edinburgh, 90B, 67-83.

Flather, R. A., J. A. Smith, J. D. Richards, C. Bell and D. L. Blackman (1998). "Direct estimates of extreme storm surge elevations from a 40-year numerical model simulations and from observations." The Global Atmosphere and Ocean System, 6: 165-176.

Flather, R.A., 1987. Estimates of extreme conditions of tide and surge using a numerical model of the north-west European continental shelf. Estuarine, Coastal and Shelf Science, 24, 69-93.

Foster, P., Beardall, J., Voltolina, D., Savidge, G., 1985. The effects of wind, phytoplankton and density discontinuities upon ammonia distribution in Liverpool Bay. Estuarine, Coastal and Shelf Science, 20, 463-475.

Heaps, N.S., 1972. Estimation of density currents in the Liverpool Bay area of the Irish Sea. Geophysical Journal of the Royal Astronomical Society, 30, 415-432.

Hunt, G.J., 1980. Radioactivity in surface and coastal waters of the British Isles, 1978. Aquatic Environment Monitoring Report, MAFF Directorate of Fisheries Research, Lowestoft, 4, 1-37.

JNCC, 2004. Irish Sea Pilot. Joint Nature Conservation Committee Report, Peterborough, pp 172.

Knight, P. J., Howarth, M.J., 1999. The flow through the North Channel of the Irish Sea. Continental Shelf Research, 19, 693-716.

McCubbin, D., Leonard, K.S., Brown, J., Kershaw, P.J., Bonfield, R.A., Peak, T., 2002. Further studies of the distribution of technetium-99 and Caesium-137 in UK and European coastal waters. Continental Shelf Research, 22, 1417-1445.

Pingree, R.D., Griffiths, D.K., 1979. Sand transport paths around the British Isles resulting from M_2 and M_4 tidal interactions. Journal of the Marine Biological Association of the UK, 59, 497-513.

Rippeth, T.P., Simpson, J.H., 1996. The frequency and duration of episodes of complete vertical mixing in the Clyde Sea. Continental Shelf Research, 16, 933-947.

Sherwin, T.J., 1987. Inertial oscillations in the Irish Sea. Continental Shelf Research, 7, 191-213.

Simpson, J.H., 1998. The Celtic Seas, in The Sea Vol.11. Eds A.R. Robinson, K.H. Brink; John Wiley and Sons, pp 659 – 698.

Sweeney, J.C. (ed.), 1989. The Irish Sea: a resource at risk. Geographical Society of Ireland, special publications no. 3.

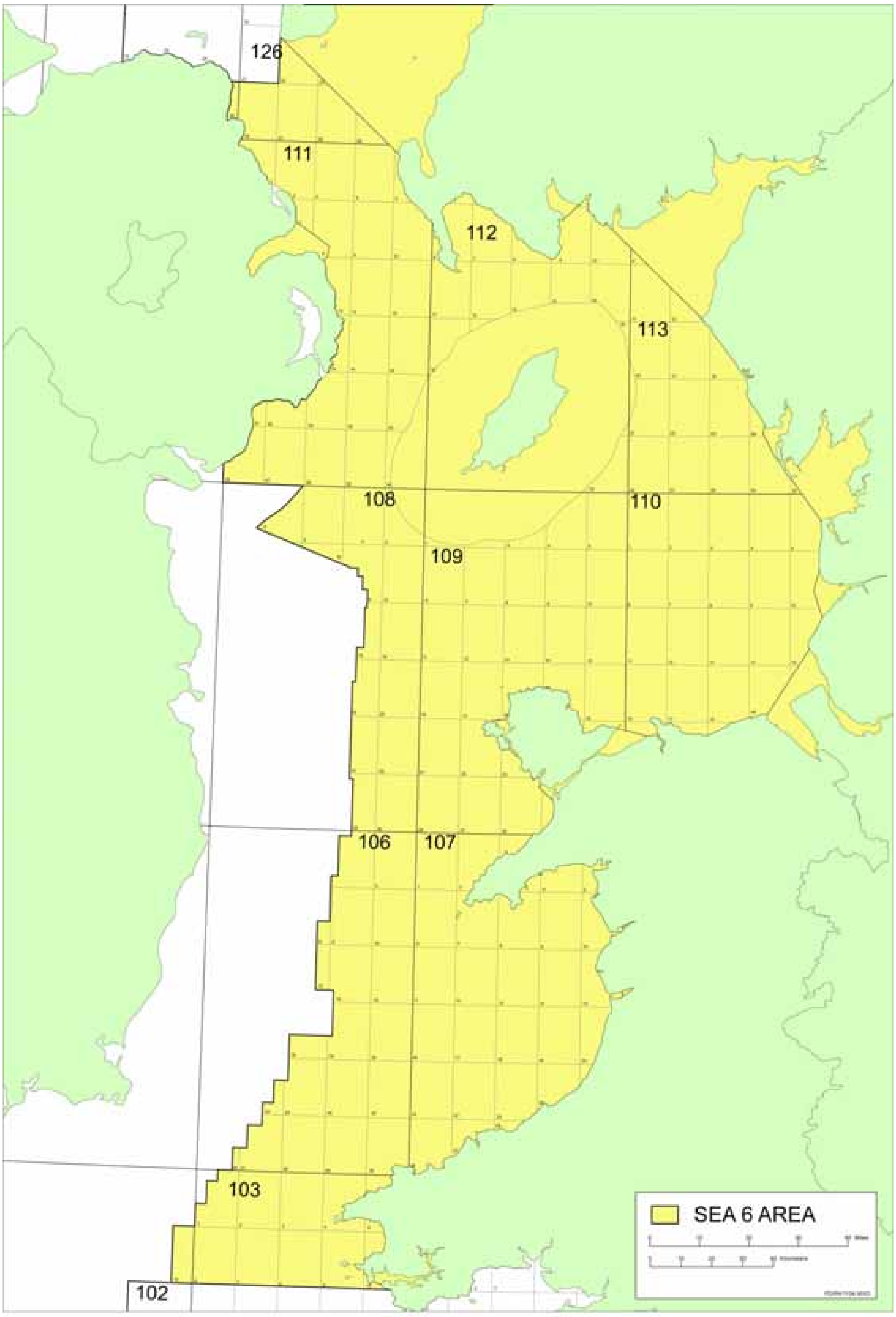


Figure 1. Map of the Irish Sea.

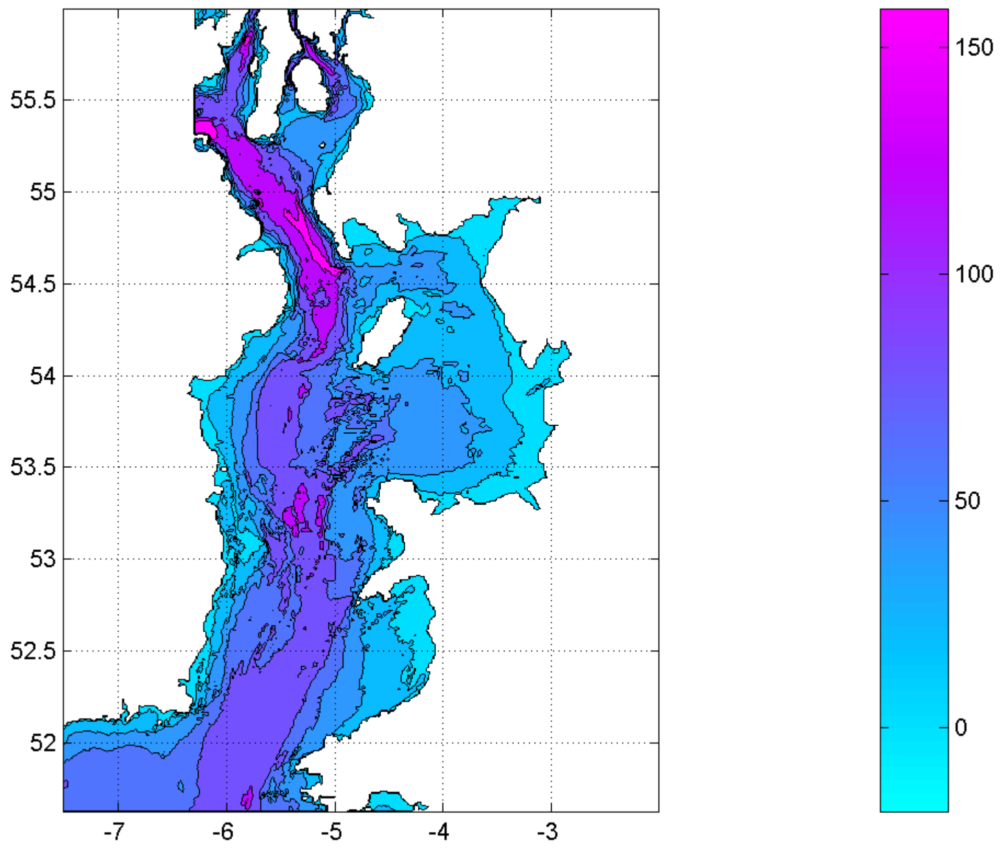
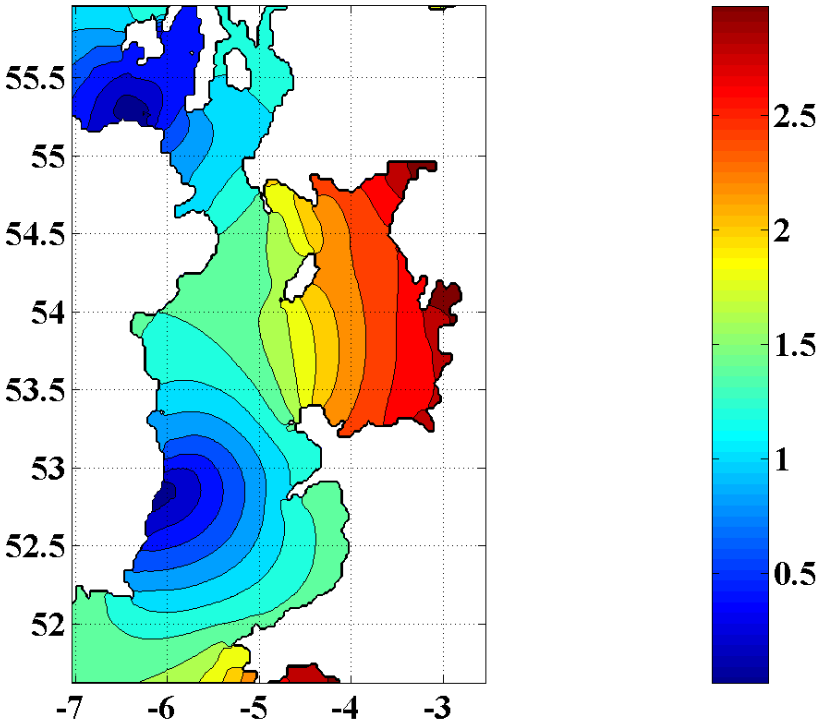
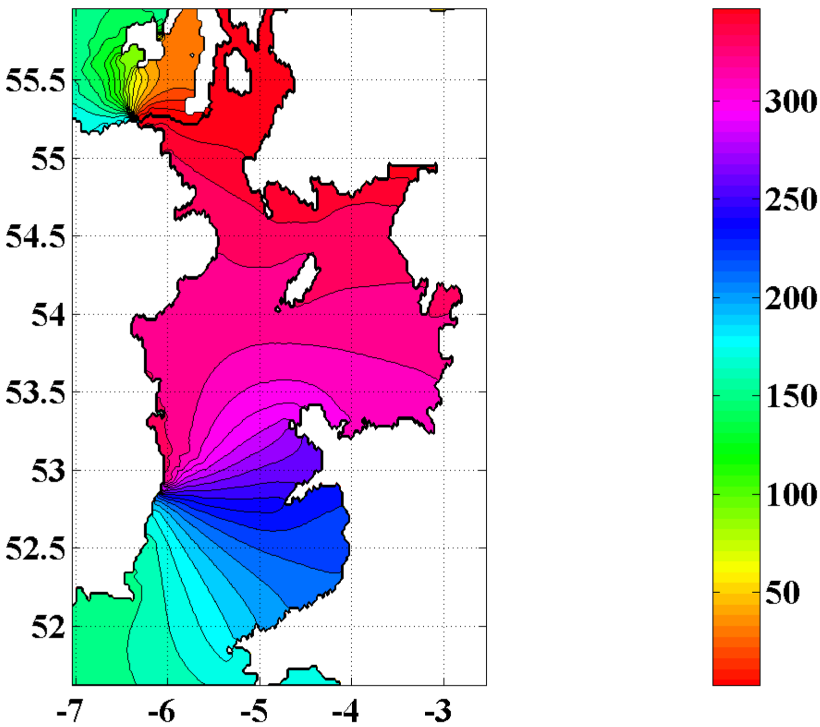


Figure 2. Bathymetry with contours at 20, 40, 60, 80, 120 and 160 m.



A



B

Figure 3. A) M_2 tidal elevation amplitude in metres. B) M_2 elevation phase in degrees.

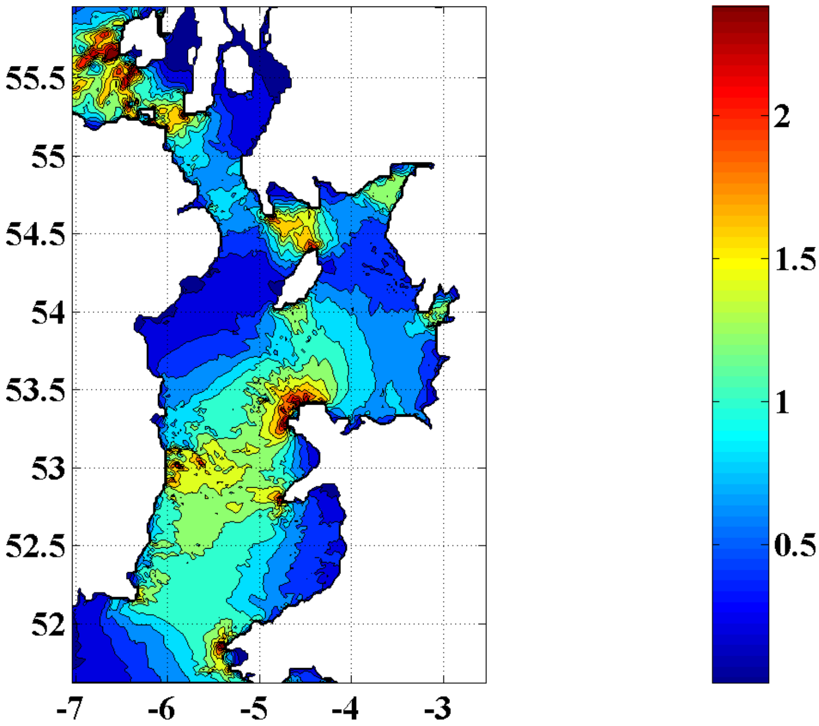


Figure 4. Maximum amplitude of the depth-averaged current for a mean spring tide ($m\ s^{-1}$).

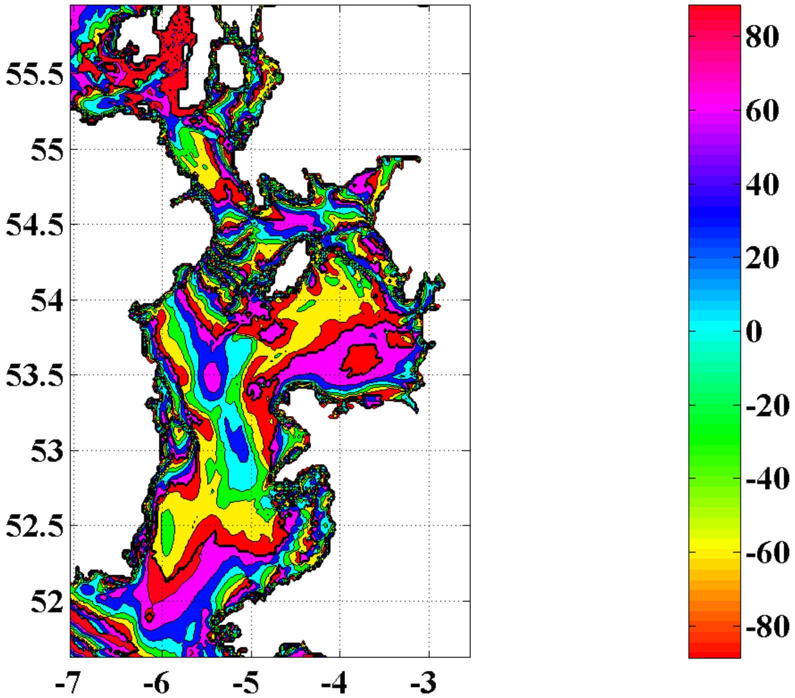


Figure 5. Phase difference between M_2 currents and elevations (degrees).

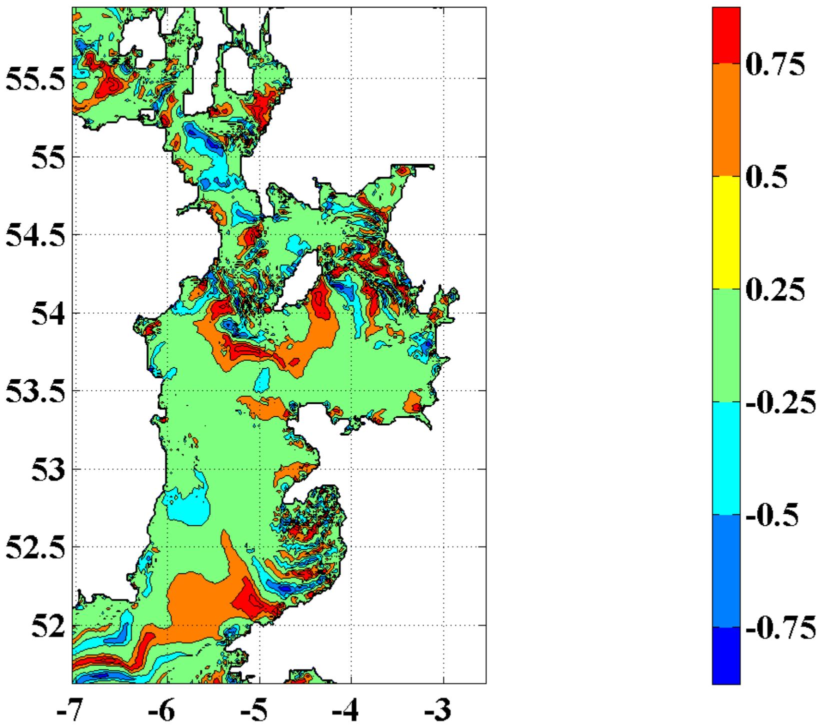


Figure 6. M_2 tidal current ellipse eccentricity (ratio of minimum to maximum amplitude).

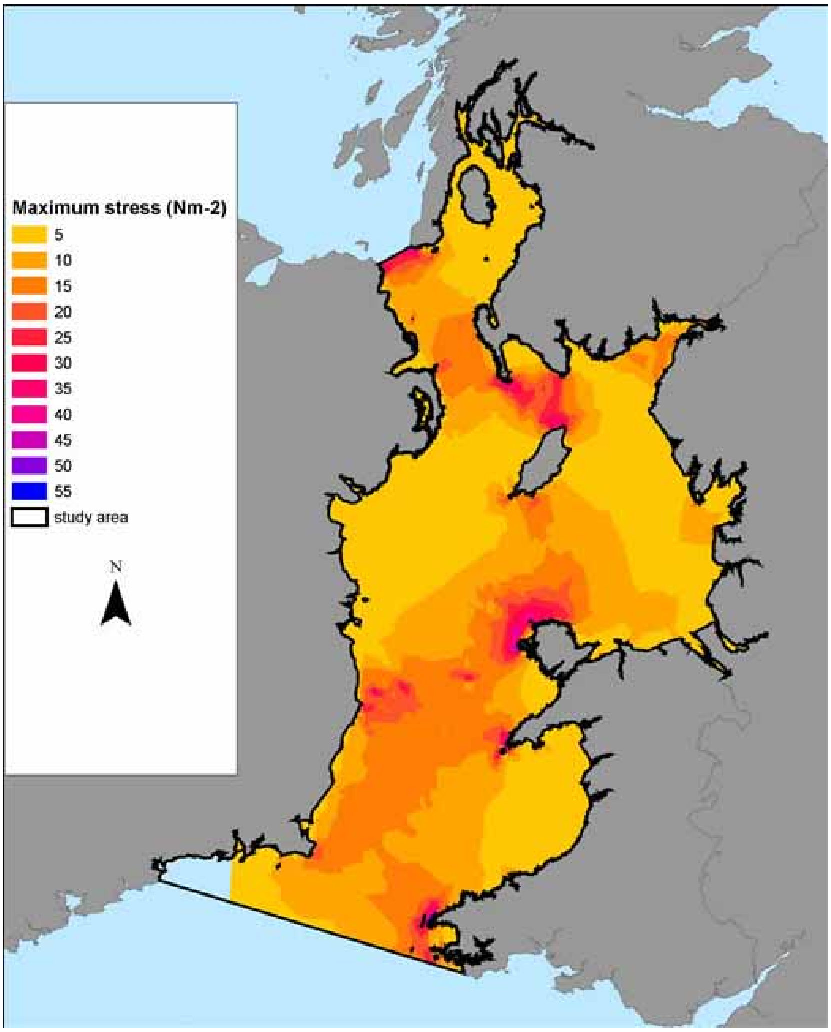
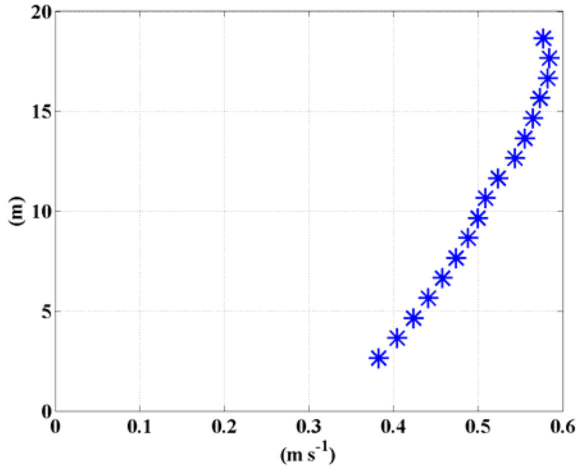
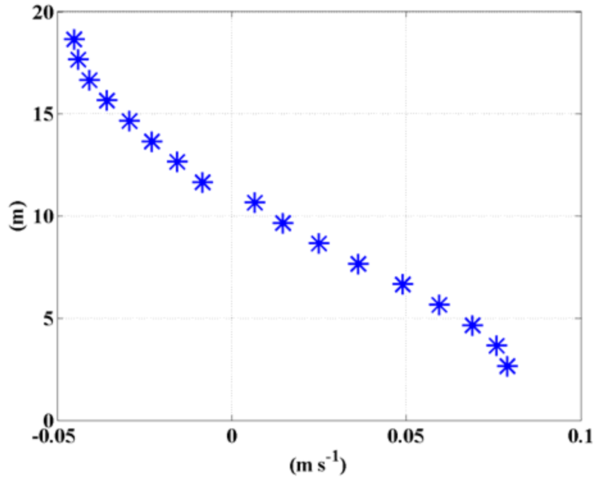


Figure 7. Maximum bed stress in Pa from a numerical model run for the years 1995 to 1997 forced both by tides and winds, but with no wave contribution (JNCC, 2004).



A



B

Figure 8. Variation with height above the bed of the M_2 current amplitude (m s^{-1}) at the Mersey Bar Light a) Maximum b) Minimum, positive anti-clockwise.

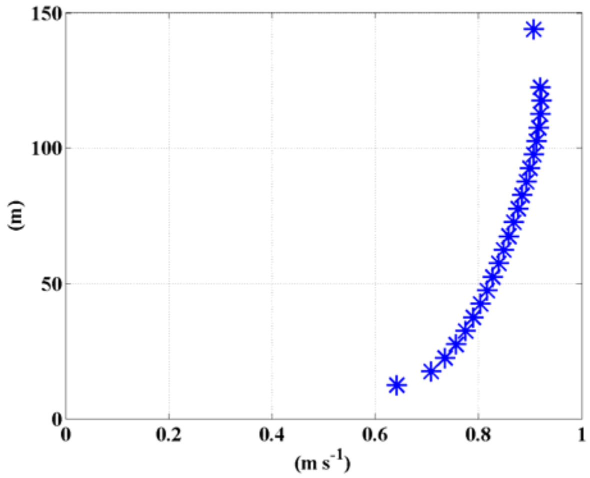


Figure 9. Variation with height above the bed of the maximum M_2 current amplitude (m s^{-1}) in the North Channel, 54° 46´N 5° 24´ W in 142 m of water.

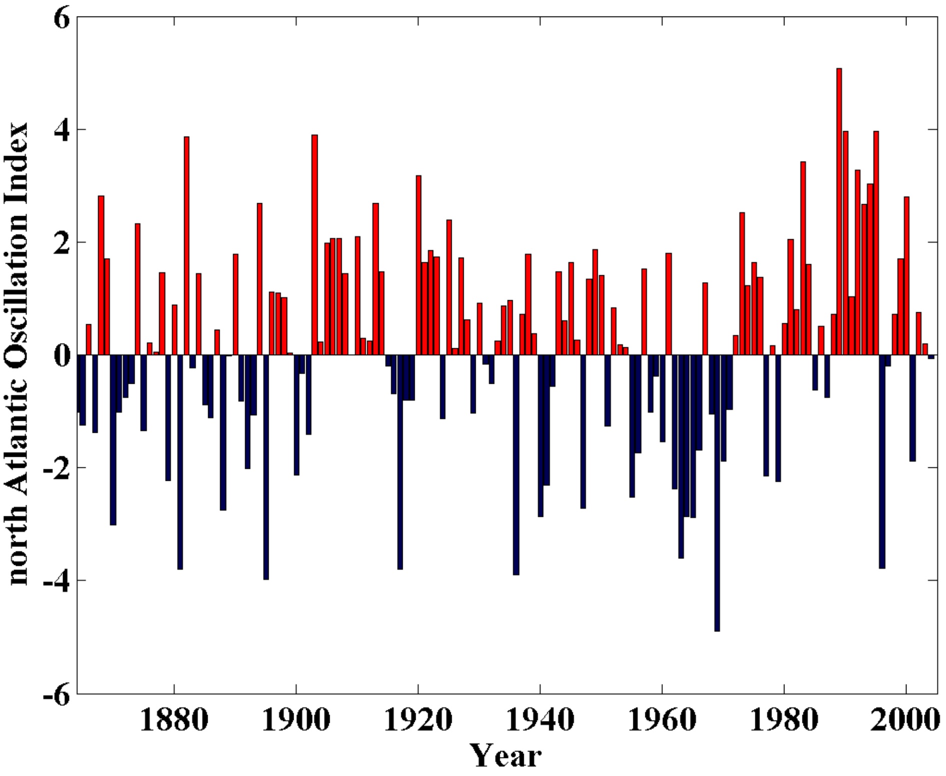


Figure 10. The North Atlantic Oscillation index from 1864 to 2004 (data from http://www.cgd.ucar.edu/cas/jhurrell/indices.html).

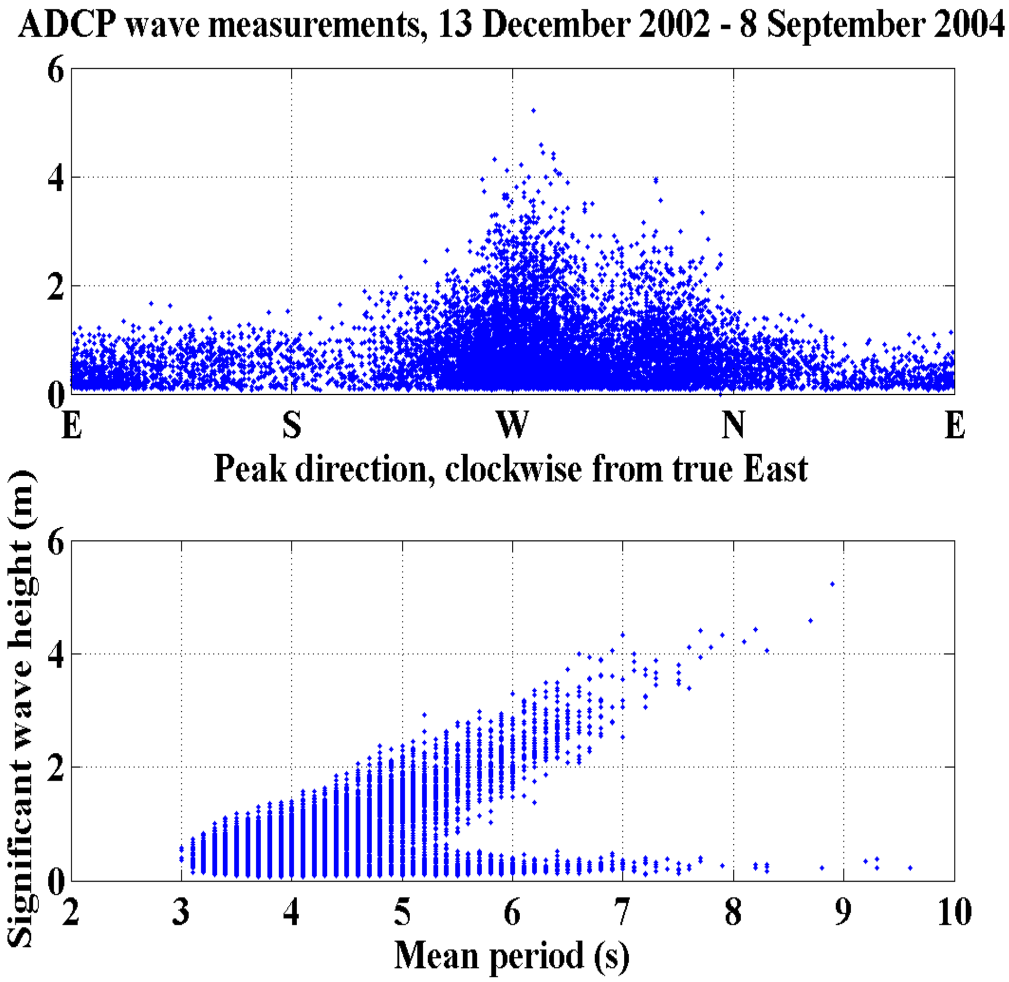


Figure 11. Measurements of significant wave height at the Mersey Bar Light for 21 months plotted against direction and mean period.

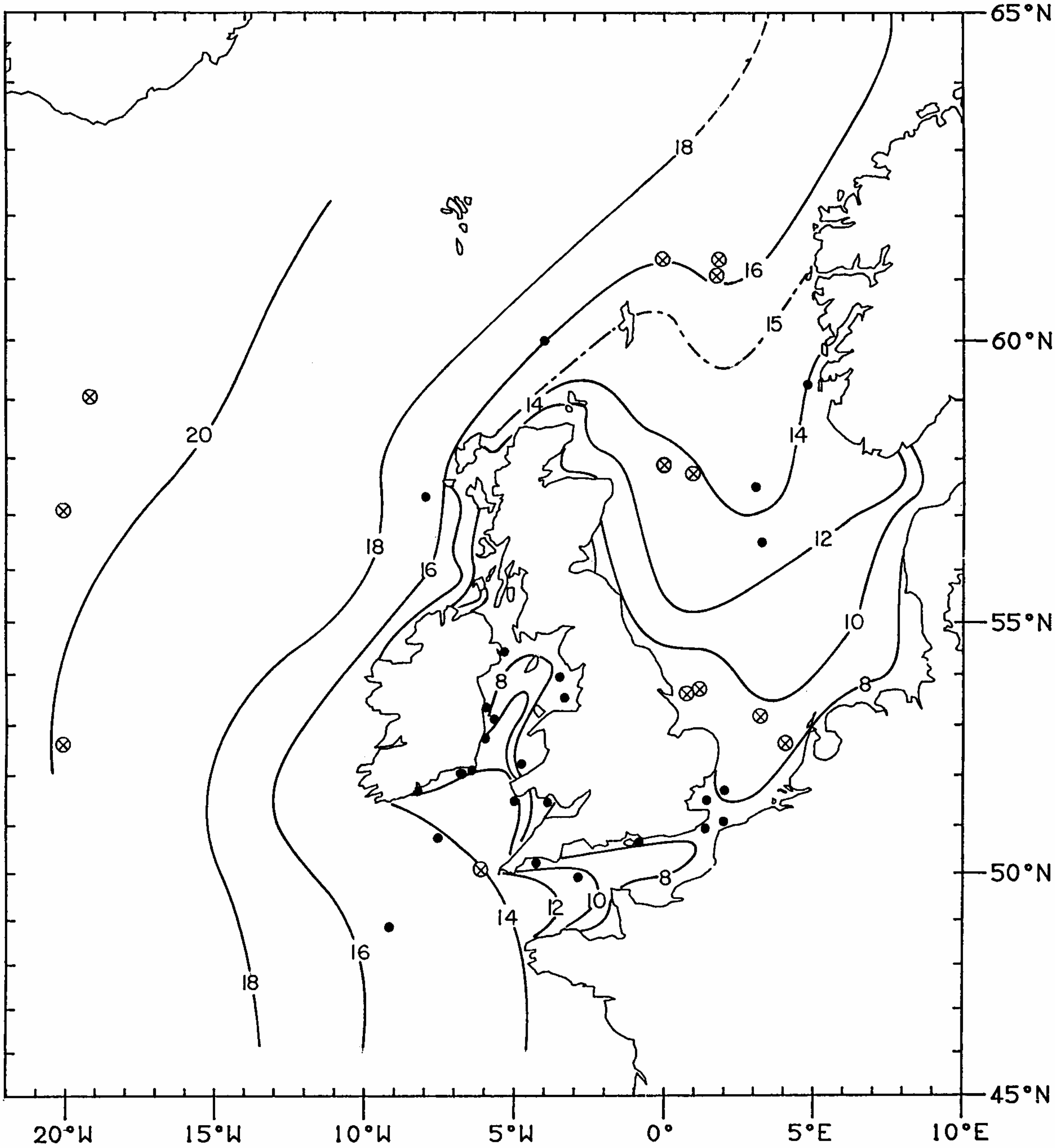


Figure 12. Map of indicative values of 50-year return period significant wave height (m) (Carter and Challenor, 1989).

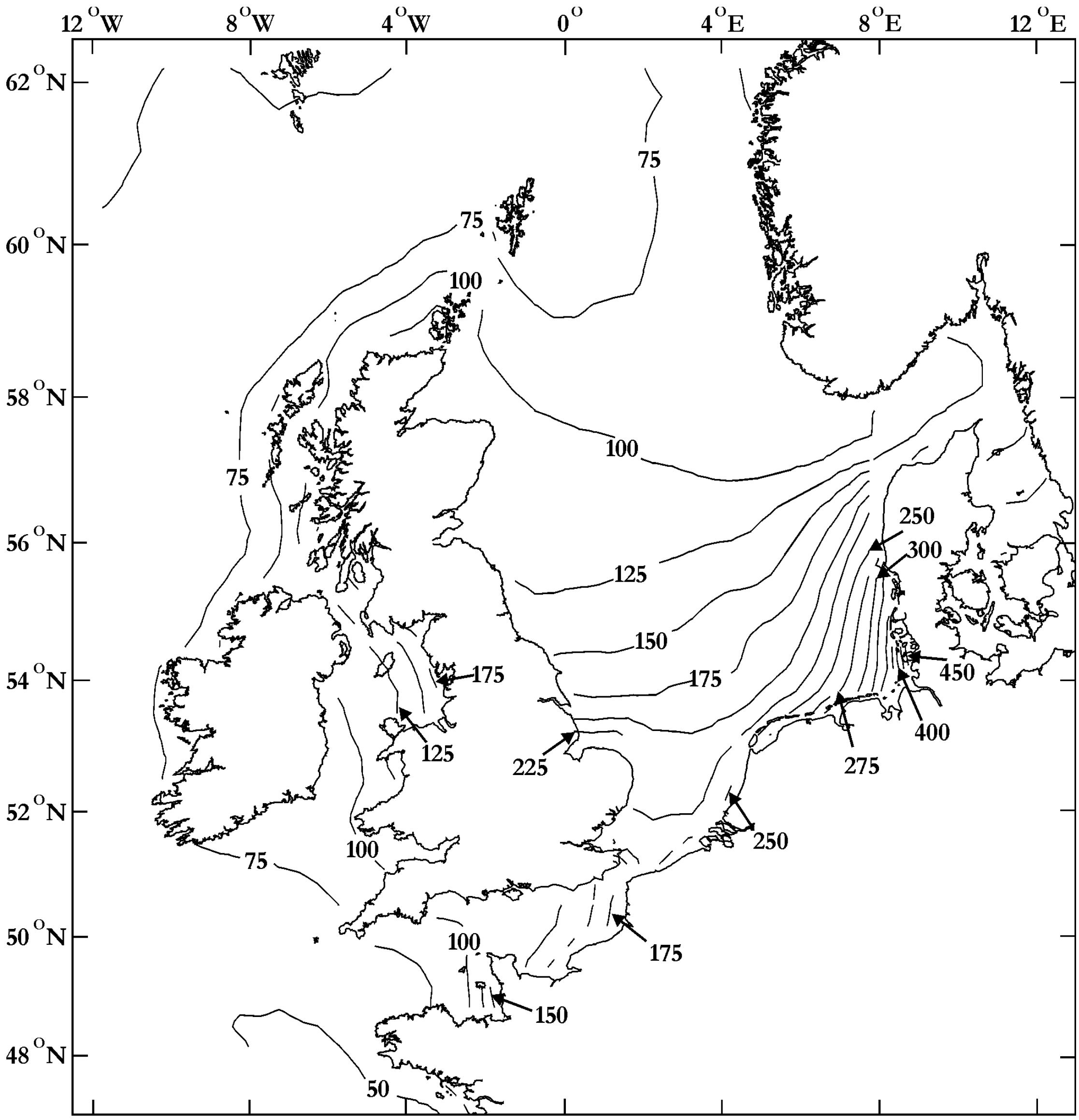


Figure 13. 50-year return period storm surge elevations in centimetres (Flather et al., 1998).

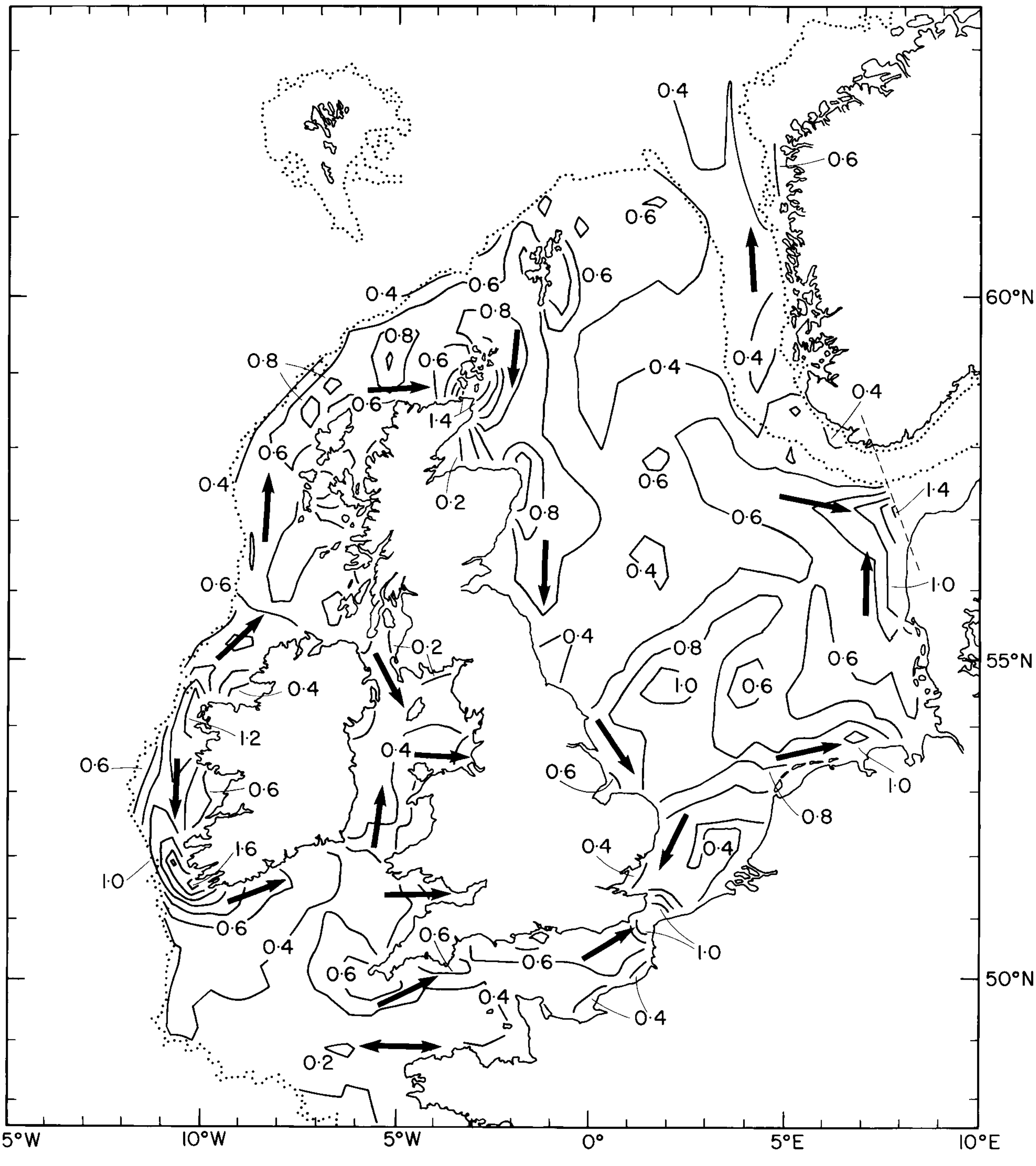


Figure 14. 50-year return period storm surge currents (m s^{-1}) (Flather, 1987).

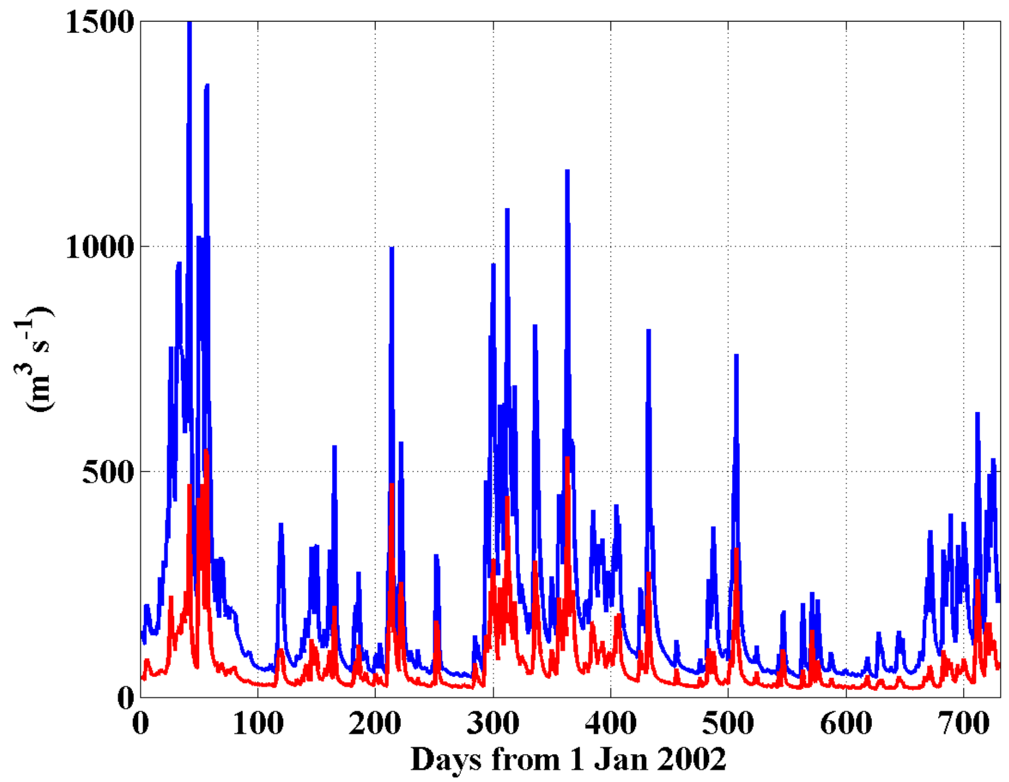


Figure 15. Discharge ($m^3\ s^{-1}$) by Mersey (red) and the sum of the Clwyd, Dee, Mersey and Ribble (blue) for 2002 and 2003.

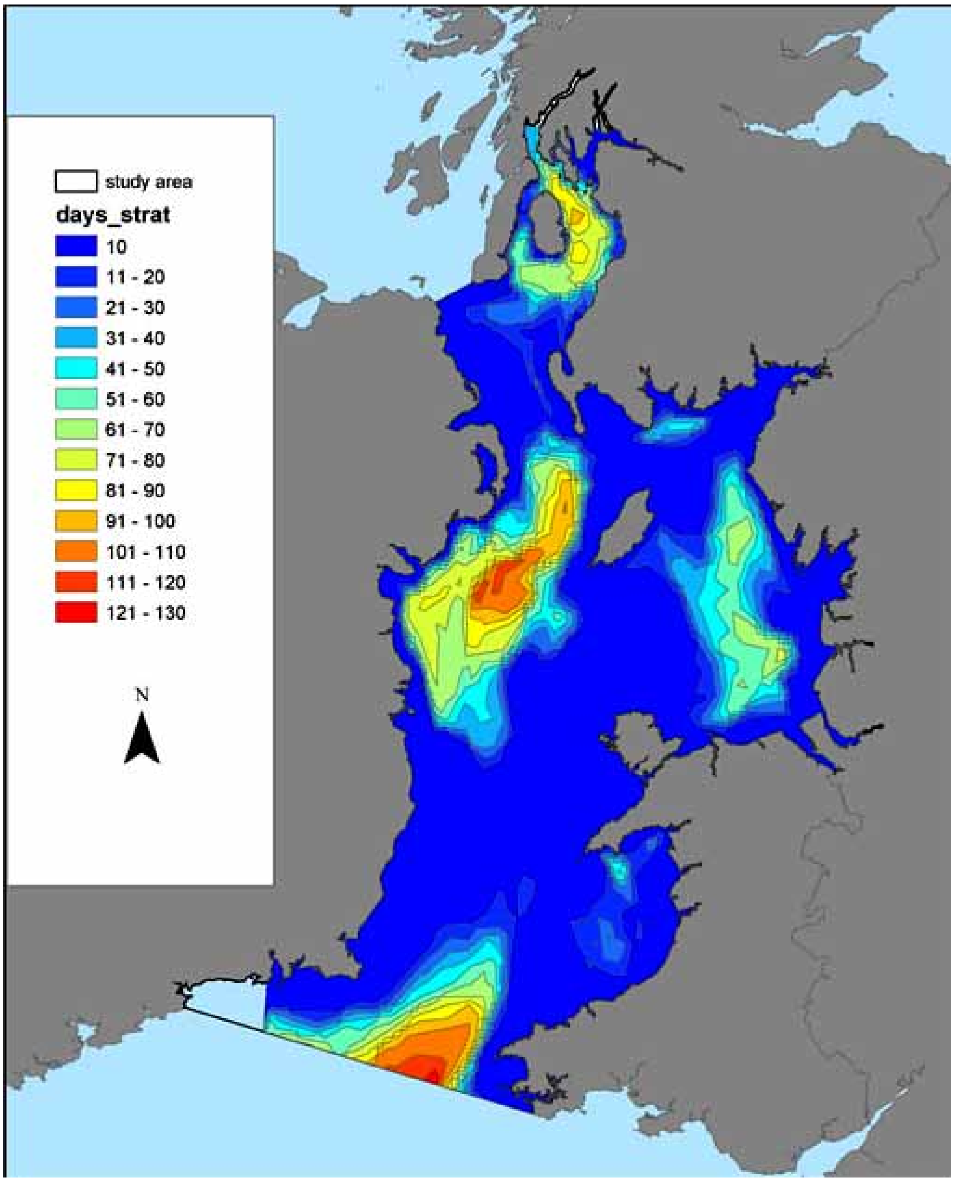


Figure 16. Map showing number of days in a year in which the water column is thermally stratified (JNCC, 2004).

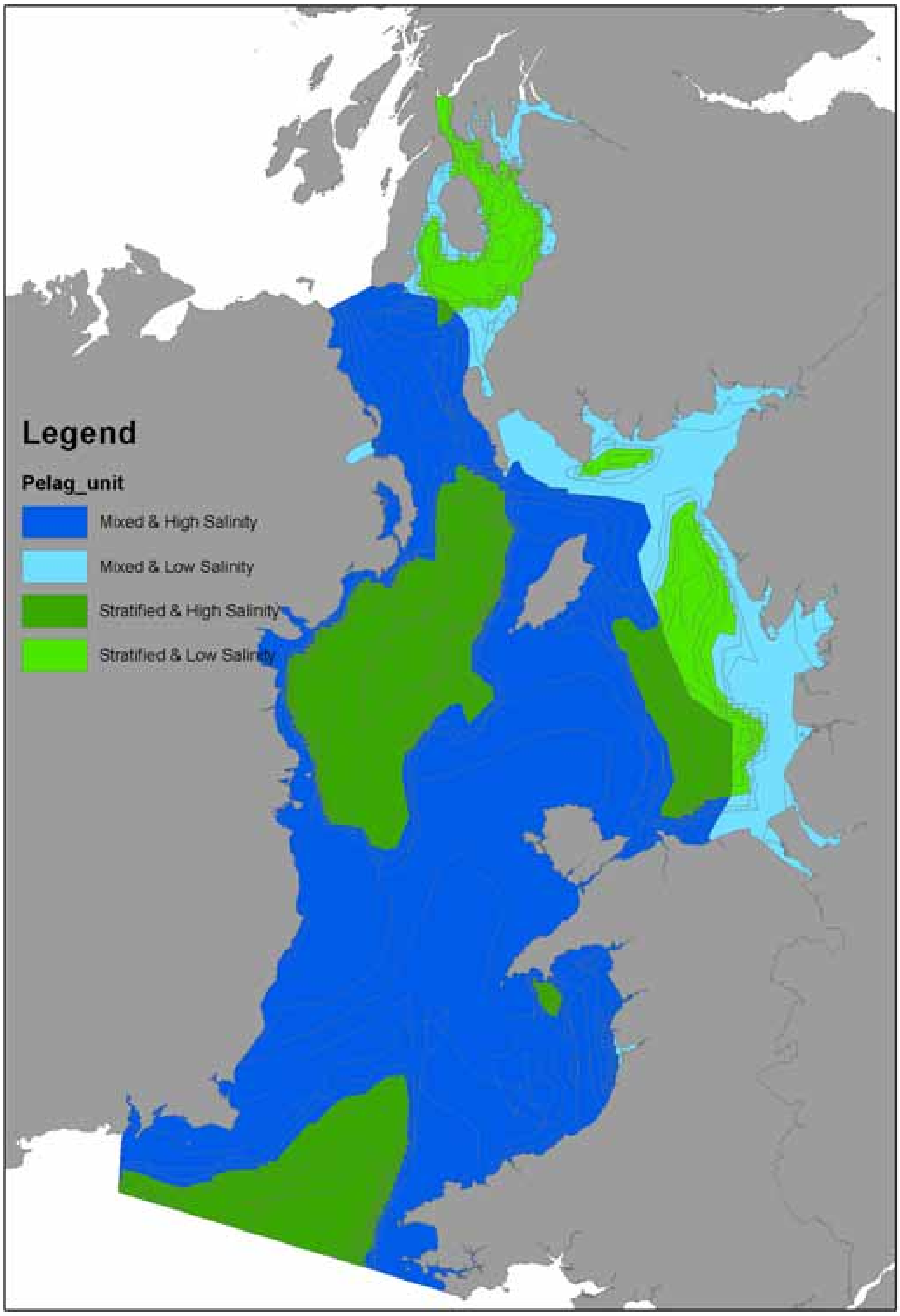


Figure 17. Map showing areas where the water column remains well-mixed throughout the year (blue, dark - high salinity; pale – low salinity) and areas where stratification occurs (green, - high salinity; pale – low salinity) (JNCC, 2004).

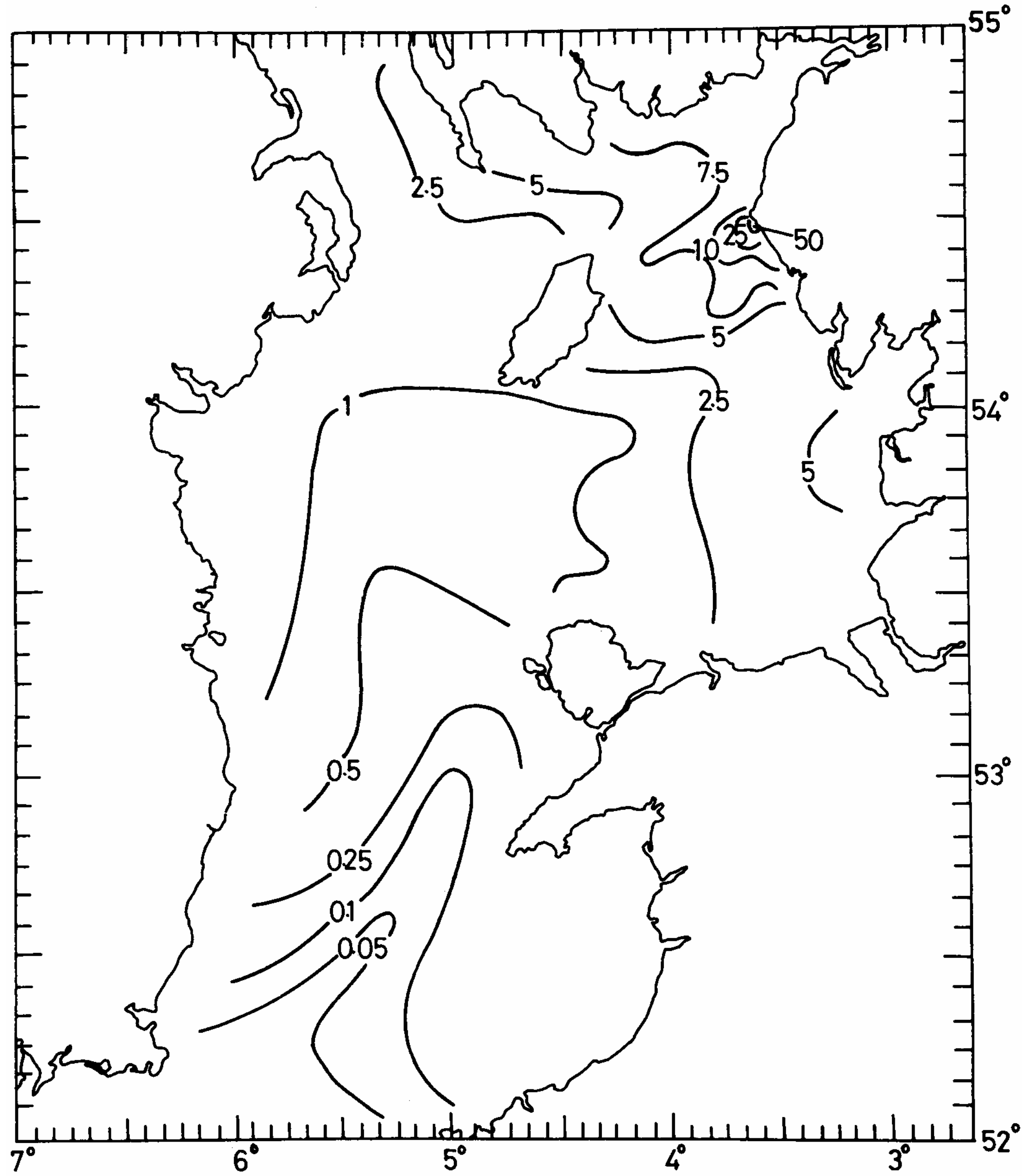


Figure 18. Concentration (Bq kg^{-1}) of Caesium-137 in filtered water from the Irish Sea, May 1978 (Hunt, 1980).

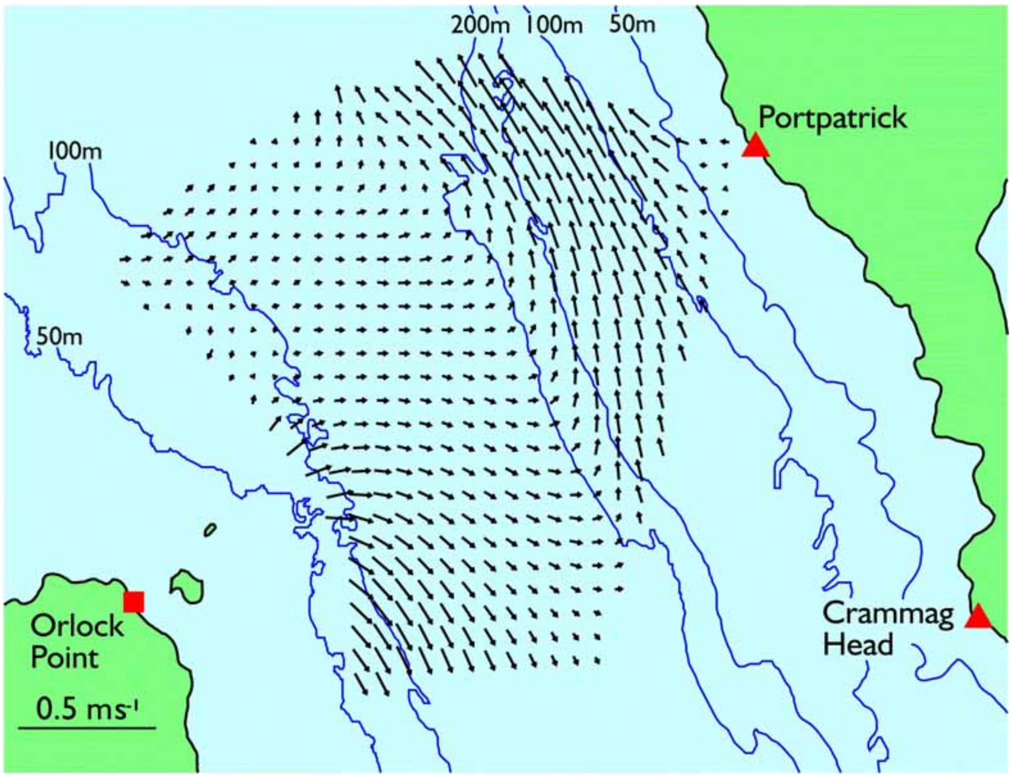


Figure 19. Mean surface currents in the North Channel based on a year's hf radar measurements (Knight and Howarth, 1999).

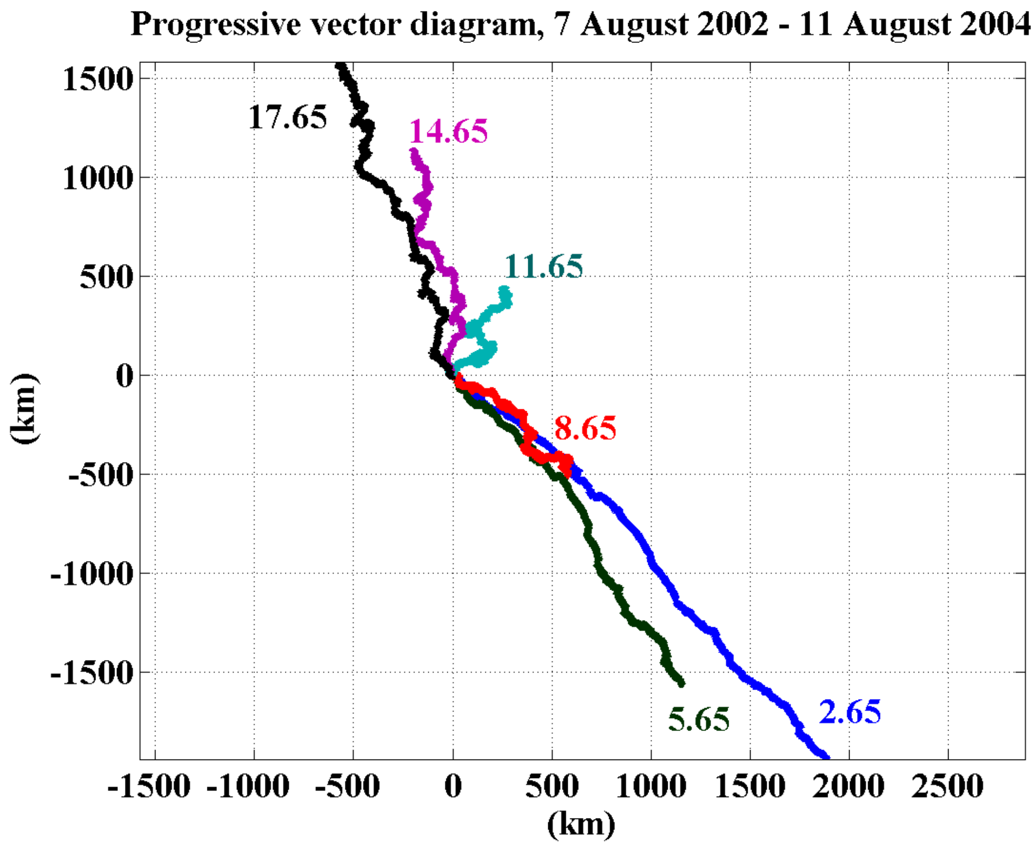


Figure 20. Progressive vector diagram showing mean currents from a 2-year record by the Mersey Bar Light. The figures denote measurement height (m) above the bed. The water depth at the site varies between 18.5 and 28.5 m, depending on the tide. (In one year water moving at 0.01 m s^{-1} will travel 315 km.)