NORTH SEA CIRCULATION

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Introduction

Currents in the North Sea, as in any continental shelf sea, occur in response to forcing by tides, winds, density gradients (arising from freshwater input), and pressure gradients. For most of the North Sea the dominant motion is tidal, with the next most significant motion generated by wind forcing. The response is determined by the sea's topography and bathymetry and is modified by, and modifies, its density distribution. Currents occur over a range of scales – a practical minimum is indicated in each case, ignoring waves and turbulence which are outside the scope of this article. For time the range is from minutes to years, horizontally in space from <1 km to basin-wide (1000 km), and vertically from 1 m to the full water depth. Current amplitudes range generally from $0.01\,\mathrm{m\ s^{-1}}$ to $2\,\mathrm{m\ s^{-1}}$ (in a very few places to in excess of $5\,\mathrm{m\ s^{-1}}$). The North Sea has been extensively studied for more than 100 years and its physical oceanography has been widely reviewed (see Further Reading section).

Topography

The North Sea is a semi-enclosed, wide continental shelf sea (**Figure 1**). It stretches southward for about 1000 km from the Atlantic Ocean in the north, and is about 500 km broad, from west to east. The northern boundary is composed of two connections. Firstly, the main connection with the ocean at the shelf edge is between the Shetland Islands and Norway. Secondly, from the mainland of Scotland to the Orkney and Shetland Islands via the Pentland Firth and the Fair Isle Channel, the connection is with the continental shelf seas to the west and north of Scotland. The North Sea has two other, narrow, connections. One is at its southern end, via the Dover Strait to the relatively salty English Channel (and ultimately again Atlantic) water. The second, on its eastern side, is via the Skagerrak and Kattegat to fresh Baltic water.

Topographically the North Sea can be split into three (**Figure 2**). In the south, bounded by about 54°N and the shallow Dogger Bank, depths are <40 m. Secondly, to the north of this the water depth increases from 40 m to 200 m at the shelf edge. Thirdly, the deep Norwegian Trench is in the north east, penetrating from the Norwegian Sea southward along the coast of Norway. The deepest depths in the trench, about 750 m, occur in the Skagerrak, off southern Norway and western Sweden, whilst the minimum axial depth is about 225 m off western Norway. This has a significant impact on the sea's dynamics.

Meteorology

The North Sea lies at temperate latitudes, between 51°N and 62°N, and so experiences pronounced seasonal changes in meteorological conditions. From September to April, in particular, it is exposed to the effect of a series of storms. These usually track eastward to the north of the British Isles, taking about a day to pass by the North Sea, accompanied by strong winds from the south west, west, and north west. Although these are the dominant wind directions, strong winds can blow from any direction. To some extent the British Isles shelter the North Sea from the wind's full effect since the only wind direction uninterrupted by land is from the north. (This is more significant for waves than currents.) The size of the storms is generally of the same order as that of the North Sea, or larger, and they can recur every few days. On average gale force winds blow on 30 days per year. The extreme 'one-in-50-year' hourly mean wind speeds are estimated to decrease from $39\,\mathrm{m\,s^{-1}}$ in the north to $32\,\mathrm{m\ s^{-1}}$ in the south, slightly stronger in the center of the North Sea compared with near the coast.

River Discharges

The main input of fresh water into the North Sea is from rivers, including the Rhine and Elbe, discharging along its southern coast (Belgium, The Netherlands, Germany). On average this input is $4000\,\mathrm{m^3\,s^{-1}}$, but it is highly variable from day to day and also from year to year. This fresh water has a significant impact on the salinity and density distribution (lower salinities along the continental coast and in the German Bight) and ultimately on the long-term circulation. A further $1500\,\mathrm{m^3\,s^{-1}}$ of fresh water on average is discharged from Scottish and English rivers. More fresh water flows into the Kattegat from the Baltic, on average $15\,000\,\mathrm{m^3\,s^{-1}}$

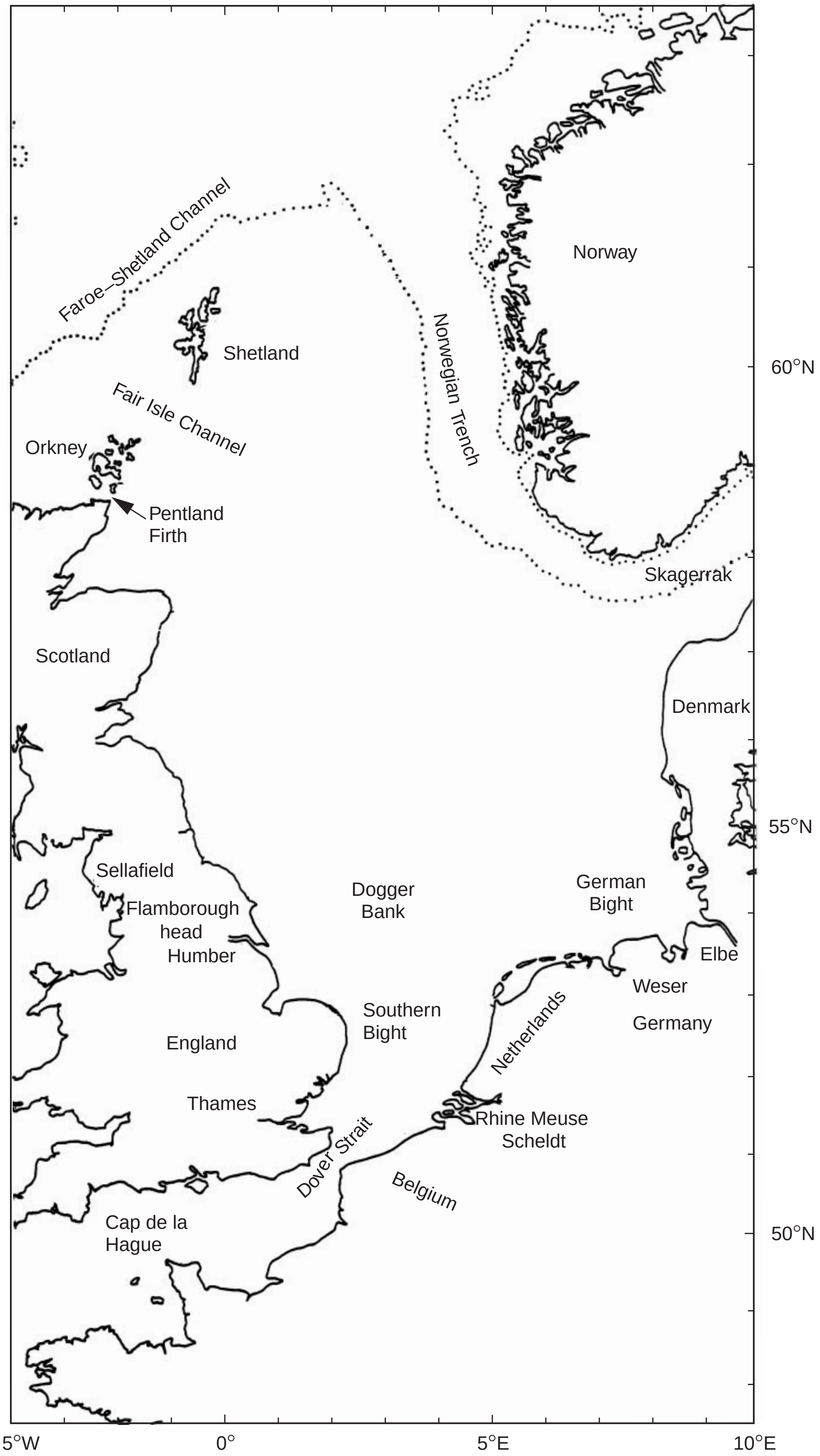

Figure 1 Map of the North Sea.

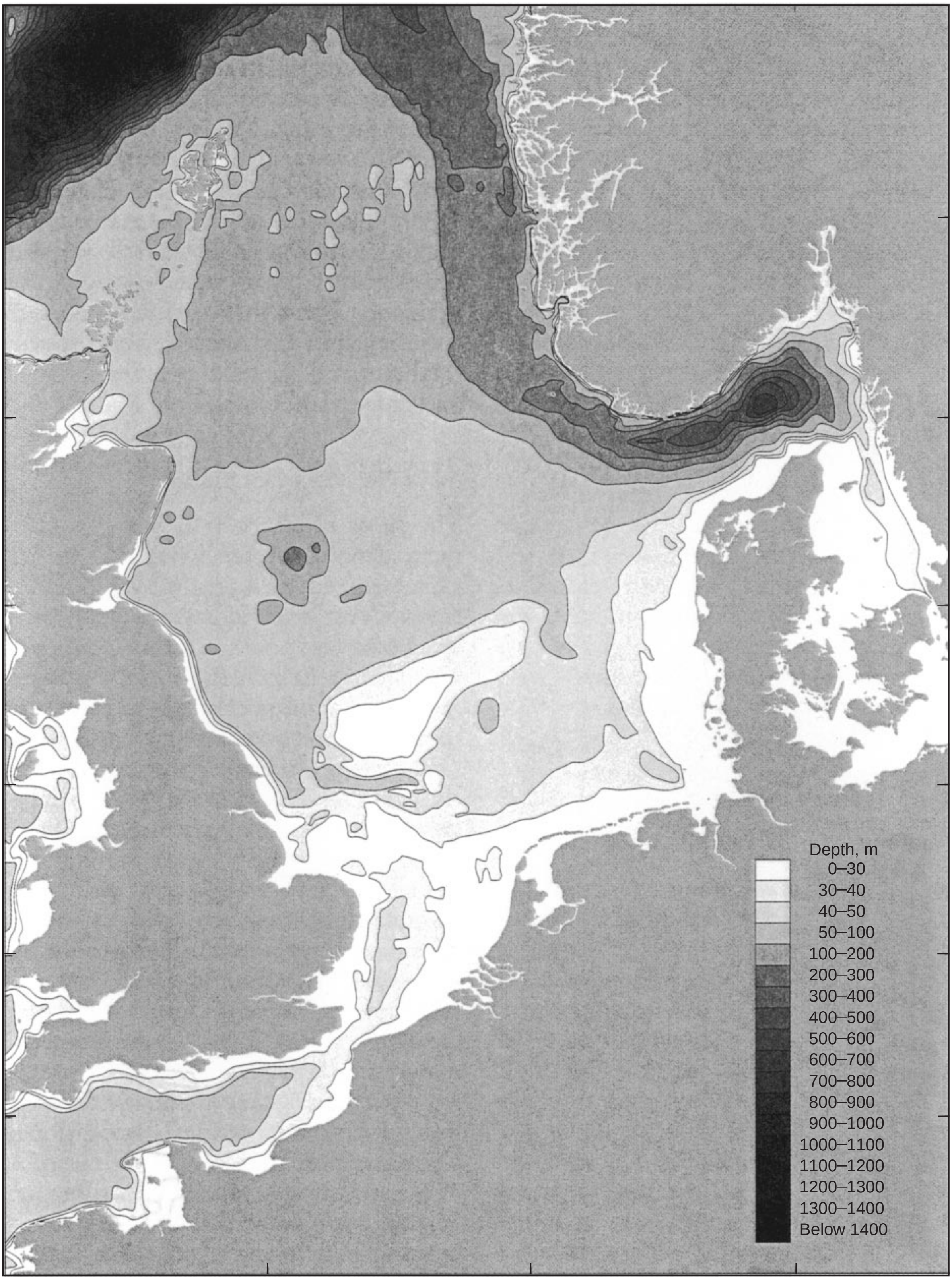

Figure 2 Bathymetry of the North Sea. (Reproduced with permission from North Sea Task Force, 1993.)

in the form of a low salinity (8.7 PSU) flow of 30 000 $m^3 s^{-1}$ in a surface layer partially compensated by a flow of 15 000 $m^3 s^{-1}$ of higher salinity (17.4 PSU) North Sea water into the Baltic in a near-bed layer. However, the instantaneous exchange between the Kattegat and the Baltic Sea is by no means a steady two-layer flow, but is predominantly barotropic (in response to wind forcing and the resulting sea level slopes) and can be up to 300 000 $m^3 s^{-1}$ in either direction. The fresher water flows into the Norwegian Coastal Current, a surface current following the Norwegian coast, and exits the North Sea. Generally there is little exchange with water in the rest of the North Sea, although on occasion a surface layer of low salinity water can spread westward across much of the northern North Sea. The boundary between the Norwegian Coastal Current and Atlantic water in the northern North Sea (*see* **Figure 3**) is not smooth but is subject to meanders with a wavelength of 50–100 km which can break off into gyres and vortex pairs generally propagating northward. Orbital speeds within the gyres are asymmetric; up to 2 m s^{-1} has been reported in the upper layer.

Stratification

The behavior of currents depends on whether the water column is well mixed or stratified. For some processes, for instance the response to wind forcing, stratification leads to the surface layer becoming decoupled from the bed layer – the sharper the transition from surface to bed layers (called the thermocline, for temperature) the greater the degree of decoupling. Well-mixed and stratified regions are separated by sharp fronts (*see* **Shelf-sea and Slope Fronts**). Stratification arises when mixing is insufficient to mix down lighter water at the sea surface – the water might be lighter either because of solar heat input during summer or because of freshwater river discharge. The energy available for mixing is primarily derived from the tides and its effect on the water column depends on the water depth. Hence the southern North Sea, where depths are shallow and tidal currents strong, tends to remain well mixed throughout the year, apart from regions close to the coast affected by river plumes.

Solar heat input causes most of the northern North Sea to stratify between April/May and October/December, with a well-mixed surface layer of about 30–40 m deep. In autumn heat loss at the surface leads to the surface mixed layer deepening and cooling until the bottom is reached.

Stratification caused by river discharge can occur at any time of the year, the fresher water tending to form a thin surface layer in a plume about 30 km wide which stays close to the coast. The nature of the plume is very variable, depending on freshwater discharge, wind, and tide (both during the semi–diurnal and the spring-neap cycles). Mean currents in the plume can be up to 0.2 m s^{-1}.

Measurements (*see* **Drifters and Floats; Moorings; Nuclear Fuel Reprocessing and Related Discharges; Profiling Current Meters; Single Point Current Meters**)

The long-term circulation (**Figure 3**) has been investigated since before 1900 by studying the returns of surface and seabed drifters and the distribution of tracers, initially salinity. More recently dissolved radionuclides have been used as tracers, primarily cesium-137 and technetium-99 discharged into the sea at very low levels in waste from nuclear fuel reprocessing plants, mainly at Sellafield on the west coast of the UK and Cap de la Hague on the north coast of France. These have given unambiguous confirmation of circulation paths.

Since the 1960s variations in currents on short time scales have been measured at fixed points by deploying moorings, often for about a month, with current meters, fitted with rotors or propellers, recording data every few minutes. In the 1990s a new instrument, acoustic Doppler current profiler (ADCP), became available which can measure the current profile throughout the majority of the water column in continental shelf seas. Frequently deployed in a seabed frame the current is determined from the Doppler shift in the back-scattered signal transmitted at 20° or 30° to the vertical. Currents at different depths are determined by chopping the return signal into segments. Another new technique is shore-based hf radar, where again the Doppler shift in a back-scattered signal is used to determine surface currents over a region, typically in 1 km cells, out to a range of about 30 km.

Numerical Models

At any one time measurements can give only an estimate of currents with very limited spatial coverage compared with the extent of the North Sea. However, these can be complemented by numerical models to give fuller spatial coverage (*see* **Regional and Shelf Sea Models**). The basic hydrodynamic equations are well known and have been solved on regular finite difference or irregular finite element grids. Currents vary in two horizontal directions and in the vertical, but the models are particularly quick if the equations are depth-averaged, which is

Figure 3 Schematic diagram of the circulation of the North Sea. The thickness of the lines is indicative of the magnitude of volume transport. (Reproduced with permission from North Sea Task Force, 1993.)

especially useful for the estimation of tide and storm surge elevations. Such models are now run operationally in association with meteorological models (the only sufficiently detailed source of meteorological forcing data to drive realistic sea models). Three-dimensional models are being developed which predict the tidal and wind-driven current profile and the effects of horizontal and vertical density gradients. Given the difficulty and expense of making accurate current measurements the future for prediction is via numerical models tested against a few critical measurements. Numerical models are also an integral component of process studies, since the significance of terms in the equations can be isolated and determined.

Tides

The dominant motion for most of the shelf seas around the UK is the semi-diurnal tides in response to the gravitational attraction of the moon and the sun. The tides (*see* **Tides**) are regular, repetitive, and predictable. Tidal currents control many physical and nonphysical processes and determine mixing, even though they are predominantly cyclical (to and fro or describing an ellipse) and tend to have small net movement, typically $0.01–0.03\,\mathrm{m\,s^{-1}}$, except near irregularities in the coastline such as headlands. In addition to the familiar basic M_2 12.4 hour cycle, the tides experience fortnightly spring–neap (on average spring tidal currents are twice as big as neap tidal currents), monthly, and 6 monthly cycles (larger spring tides usually occur near the spring and autumn equinoxes). Away from coasts the tidal currents can be accurately approximated (better than $0.1\,\mathrm{m\,s^{-1}}$) by just four constituents, or frequencies – M_2, S_2, N_2, and K_2, with periods between 11.97 and 12.66 hours. Near the shelf edge there can be localized amplification of the diurnal constituents O_1 and K_1. Only close to the coasts, in shallow water and near headlands, and in estuaries are distortions to the tides (represented by higher harmonics) significant. Clearly this is a very important region for predicting sea levels for navigation, but represents a small proportion of the area of the North Sea.

The tides enter the North Sea from the Atlantic Ocean north of Scotland and sweep round it in anticlockwise sense as a progressive (Kelvin) wave gradually losing energy by working against bottom friction. By the time Norway is reached tidal currents are relatively weak, $< 0.1\,\mathrm{m\,s^{-1}}$ at spring tides. Maximum currents occur in localized coastal constrictions, such as the Pentland Firth (in excess of $5\,\mathrm{m\,s^{-1}}$ at spring tides) and the Dover Strait ($2\,\mathrm{m\,s^{-1}}$). Elsewhere currents at spring tides rarely exceed $1\,\mathrm{m\,s^{-1}}$ (**Figure 4**).

The amplitude of tidal currents does not vary significantly with depth, except in a boundary layer near to the bed generated by friction, of the order of a few meters (up to 10 m) thick. Here the current profile at maximum flow is approximately logarithmic in distance from the bottom. Also due to the effects of bottom friction tidal currents near the bed are in advance of those near the surface, so that the tide turns earlier, by up to half an hour, near the bed compared with near the surface.

Wind Forcing

Wind forcing (*see* **Storm Surges**) is responsible for the second largest currents after tides over most of the region, and in areas where tidal currents are weak (for instance off Norway), the largest. By the very nature of storms the forcing is intermittent and seasonal. The largest storms tend to occur in winter, when the water column is homogeneous. Two effects are important. Firstly, sea level gradients are set up against a coast counterbalancing the wind stress, since the North Sea is semi-enclosed and so has no long approximately straight coasts, in contrast with many other continental shelf seas. Secondly there is the direct action of the wind stress at the sea surface.

The sea level gradients lead to storm surges at the coast, with the threat of coastal flooding. Sizeable currents can be generated during the setting up and relaxing of the sea level gradients. Measurement of these currents at depth is scarce not only because the environment is harsh during storms, although less severe than at the surface, but also because long deployments are required – at least over a 6 month period including winter to ensure an adequate sampling of storms. Seabed-mounted ADCPs are helpful, both because the storm environment is less likely to impinge on data quality and also because longer measurements are possible. The only feasible way of predicting extreme currents, for instance the 'one-in-50-year' current for the design of offshore structures, is via numerical models, either run for long periods or forced by a series of extreme events. The accuracy of extreme sea level estimates is better than that for extreme currents, because models can be validated against long records (many years) of coastal elevations from tide gauges.

The direct current response at the sea surface to the action of the wind stress is very difficult to measure, since waves tend to be large when winds are strong, but it appears to be limited to at most the top 25 m of the water column. (A very useful

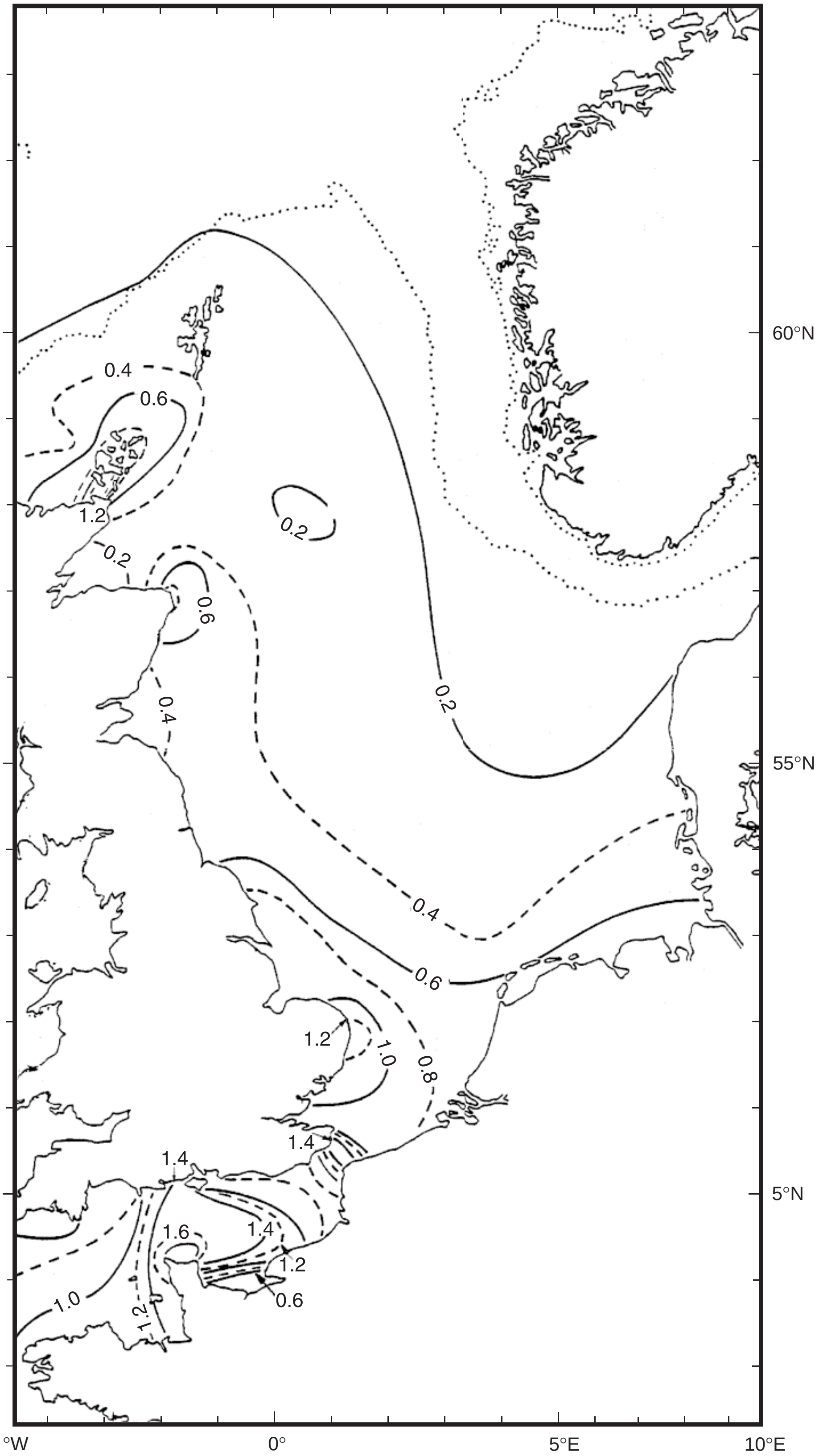

Figure 4 Estimate of the maximum depth-averaged currents for an average spring tide, in m s$^{-1.}$

remote sensing technique here is hf radar which measures surface currents.) The response is rapid, less than a few hours, and dependent on the roughness of the sea surface (i.e. on the waves and whitecapping). The surface current amplitude used, for instance in oil spill studies, is usually taken to be in the range 1–6% of the wind speed, with a typical value of 3%. The higher ratio appears to be more appropriate for developing seas. The direction of the wind drift is a few degrees to the right of the wind. Since there are very few accurate measurements to test models critically, the accuracy of models in this region is uncertain.

Circulation

Circulation is the long-term movement of water. Within the North Sea it is forced by the net tides (for instance, responsible for 50% of water transport in the western North Sea), the mean winds, and density gradients, principally caused by freshwater input from rivers and the Baltic. All these forces tend to act in the same sense, described below. There are seasonal variations, as storms mainly occur in winter, river discharge has an annual cycle, and in summer the water column stratifies in some regions. Over short periods the net movement of water is likely to be determined by the last storm or storms. The circulation pattern outlined below is enhanced by winds from the south west and can be reversed by strong winds from south and east. Although of considerable and long-standing interest to oceanographers – to physicists, fisheries biologists, and to those studying the movement of suspended sediments and pollution – it is difficult to measure and quantify since in most places its magnitude is $< 0.1\,\mathrm{m\ s^{-1}}$, much smaller than tidal or extreme wind-driven currents. It frequently has very short space scales, changing significantly in magnitude over a few kilometers and changing direction by 180° from the surface to the seabed.

There is, however, an overall long-term mean pattern (**Figure 3**), shown up clearly in the distributions of tracers whose major features in terms of direction have been known since the early 1900s. There are large uncertainties on estimates of amplitudes. The flow is broadly anticlockwise round the coasts of the North Sea, with weak and varied circulation in its center. The mean coastal flow is southward past Scotland and England into the Southern Bight, where there are inputs of salty water through the Dover Straits and of fresh water down the main rivers, all of which pass through large industrialized regions (Humber, Thames, Meuse, Scheldt, Rhine, Weser, Elbe) and on into the German Bight, flowing northward past Denmark in the Jutland current to join the Norwegian Coastal Current in the Skagerrak. The average input through the Dover Strait is about $0.1 \times 10^6\,\mathrm{m^3\,s^{-1}}$, but the flow there is strongly influenced by the wind and can reverse, moving south-westward out of the North Sea. There is also some flow from the coast of East Anglia to the north Dutch coast.

There are major inflows (in excess of $10^6\,\mathrm{m^3\,s^{-1}}$) of water of Atlantic origin across the northern boundary, but very little penetrates far into the North Sea. The larger portion flows in on the western side of the Norwegian Trench and recirculates in the Skagerrak, flowing out along the eastern side of the Norwegian Trench underneath the Norwegian Coastal Current. A smaller inflow of mixed Atlantic and shelf water flows in on either side of the Shetland Islands and turns eastward to follow the 100 m contour across the North Sea, eventually to flow out along the eastern side of the Norwegian trench. The majority of water passing through the North Sea goes through the Skagerrak. The only major outflow is along the eastern side of the Norwegian Trench, with magnitude of about $(1.3\text{–}1.8) \times 10^6\,\mathrm{m^3\,s^{-1}}$.

Effects of Stratification

Stratification profoundly affects the nature of currents in two ways. Firstly currents are driven by the density gradients associated with fronts – the sharp boundaries between stratified and well-mixed water. The currents tend to be along the fronts with transverse exchanges inhibited. Secondly, the structure of motion in the water column is affected by the region of vertical density change – either because the surface and bed layers are decoupled or because internal waves can propagate along the density interface. Theoretically there is no difference between stratification caused by heat input and that caused by fresh water; dynamically all that matters is the density difference. In practice the consequences of thermal stratification in summer can be easier to study because the extent of the surface mixed layer and of the water depth are more manageable and because regions of thermal stratification are predictable and dependable.

Fronts (*see* Shelf-sea and Slope Fronts)

The main front separating the thermally stratified water in summer to the north from the well-mixed water to the south starts from Flamborough Head, bifurcates around the Dogger Bank and passes to the north of the Frisian Islands. Tidal current speeds and water depths determine the front's position. Currents along the front in a west to east sense are typically about $0.05\,\mathrm{m\ s^{-1}}$ but can be up to $0.15\,\mathrm{m\ s^{-1}}$.

Inertial Currents

Inertial currents are generated by pulses of wind. The currents rotate clockwise in the Northern Hemisphere with a period in hours of 12/sine (latitude), which, in the North sea, is from 13.6 h at 62°N to 14.6 h at 55°N. In stratified water their vertical structure is primarily the first baroclinic mode; the currents are 180° out of phase above and below the thermocline and integrate to zero over the water column. Because of the phase reversal large shears can be generated across the thermocline – the largest in the water column. Their decay time, if not reinvigorated by another wind pulse, is of the order of days. ADCPs covering the majority of the water column are ideal instruments for measuring inertial currents, which can show all the characteristics indicated above. In the North Sea inertial current speeds up to $0.25\,\mathrm{m\,s^{-1}}$ have been observed in the surface well-mixed layer, which for most of the period of stratification is the shallower and hence the layer where inertial currents are stronger. During stratification some energy at or near inertial periods is present most of the time, but not always with a simple first baroclinic mode structure. The situation is different from the open ocean – in shelf seas the water depth is limited and tidal friction/mixing is ever present.

Internal waves (*see* Internal Waves)

Internal waves are ubiquitous in stratified water. They propagate along the thermocline density interface as a cyclical vertical movement of the density interface, which can be quite large, over 10 m, with only a 0 (1 cm) movement of the sea surface. The restoring force is primarily the buoyancy force. Internal interfacial waves are analogous to surface waves but their phase speed is less. They can have any period between the local inertial (see above) and the Brunt-Väissälä or buoyancy period, which depends on the degree of stratification and can be as short as a few minutes for sharp stratification. The corresponding currents are out of phase above and below the density interface and, for small amplitude waves, sum to zero in the vertical. It is only possible to give generalities since each situation is unique. Because vertical accelerations are significant, nonhydrostatic numerical models are required to reproduce the dynamics. These are rare for shelf-wide models.

Internal tides are often generated as the tides cross sharp changes in bathymetry, such as the shelf break. The internal tide then propagates both into the shelf sea and into the ocean, usually in the form of a pulse of waves with periods of order 30 minutes, repeated with a tidal periodicity.

Shelf Edge

The main distinguishing feature of the shelf edge is the pronounced change in water depth over a short distance, from shelf depths ($<200\,\mathrm{m}$) to oceanic (usually several thousand meters). At the shelf break between the North Sea and the Faroe–Shetland Channel water depths deepen from 200 m to 1000–1500 m over a distance of tens of kilometers. Compared with other shelf edges, even around the UK, this is relatively gentle and the gradients are relatively smooth. A mixture of dynamical processes can exist at the shelf edge involving a combination of stratification and steep bottom slope. Three relevant to the North Sea are internal tides (see above), the slope current flowing north-westward, and coastal trapped waves with super-inertial periods which can, for instance, lead to enhanced diurnal tides (see above).

Conclusions

The North Sea is a typical semi-enclosed continental shelf sea, with a wide range of tidal conditions, winds, circulation, and effects of stratification. To interpret and understand the dynamics it is not sufficient just to study the currents but also seabed pressures/coastal elevations, the (horizontal and vertical) density field which is not static, meteorological forcing (wind, atmospheric pressure, heat input at sea surface), and river discharges.

See also

Drifters and Floats. Moorings. Nuclear Fuel Reprocessing and Related Discharges. Profiling Current Meters. Regional and Shelf Sea Models. Shelf-sea and Slope Fronts. Single Point Current Meters. Storm Surges. Tides.

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NUCLEAR FUEL REPROCESSING AND RELATED DISCHARGES

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Introduction

Oceanographers have for some decades made use of human perturbations to the environment as tracers of ocean circulation and of the behavior of similar substances in the oceans. The study of the releases of anthropogenic radionuclides – by-products of the nuclear industry – by nuclear fuel reprocessing plants is an example of such an application. Other examples of the use of anthropogenic substances as oceanographic tracers addressed in this Encyclopedia include tritium and radiocarbon, largely resulting from atmospheric nuclear weapons testing in the 1950s and 1960s, and chlorofluorocarbons (CFCs), a family of gases which have been used in a variety of applications such as refrigeration and polymer manufacture since the 1920s. As outlined in this article, the source function of nuclear fuel reprocessing discharges, which is very different from that of either weapons test fallout or CFCs, is both a blessing and a curse, defining the unique applicability of these tracers but also requiring much additional and careful quantification.

The two nuclear fuel reprocessing plants of most interest to oceanographers are located at Sellafield, in the UK, which has been discharging wastes into the Irish Sea since 1952, and at Cap de la Hague, in north-western France, which has been discharging wastes into the English Channel since 1966. These releases have been well documented and monitored in most cases. It should be noted, however, that the releases of some isotopes of interest to oceanographers have not been as well monitored throughout the history of the plants because they were not of radiological concern, were difficult to measure, or both. This is particularly true for ^{99}Tc and ^{129}I, which are the isotopes currently of greatest interest to the oceanographic community but for which specific, official release data are only available for the last two decades or less. The radionuclides most widely studied by ocean scientists have been ^{137}Cs, ^{134}Cs, ^{90}Sr, ^{125}Sb, ^{99}Tc, ^{129}I, and Pu isotopes. The Sellafield plant has dominated the releases of most of these, with the exception of ^{125}Sb and, particularly in the 1990s, ^{129}I. In general, the Sellafield releases have been particularly well documented and are the easiest for interested scientists and other parties to obtain. The figures of releases presented in this article are based primarily on the Sellafield data, except where sufficient data are available for Cap de la Hague.

The location of the Sellafield and Cap de la Hague plants is important to the oceanographic application of their releases. As discussed below, the releases enter the surface circulation of the high latitude North Atlantic and are transported northwards into the Norwegian and Greenland Seas and the Arctic Ocean. They have been very useful as tracers of ventilation and deep water formation in these regions, which are of great importance to global thermohaline circulation and climate. In addition, the study of the dispersion of radionuclides from the reprocessing plants at Sellafield and Cap de la Hague serves as an analog for understanding the ultimate distribution and fate of other wastes arising from industrial activities in north-western Europe.

Much of the literature on reprocessing releases in the oceans has focused on, or been driven by, concerns relating to contamination and radiological effects, and they have not found the same broad or general oceanographic application as some other anthropogenic tracers despite their great utility and the excellent quality of published work. This may be attributable to a variety of factors, including perhaps (1) the contaminant-based focus of much of the work and its publication outside the mainstream oceanographic literature, (2) the complications of the source function as compared with some other