Introduction to the Assessment—Characteristics of the Region

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Abstract

This scene-setting chapter provides the basis for the climate change-related assessments presented in later chapters of this book. It opens with an overview of the geography, demography and major human activities of the North Sea and its boundary countries. This is followed by a series of sections describing the geological and climatic evolution of the North Sea basin, the topography and hydrography of the North Sea (i.e. boundary forcing; thermohaline, wind-driven and tidally-driven regimes; and transport processes), and its current atmospheric climate (focussing on circulation, wind, temperature, precipitation, radiation and cloud cover). This physical description is followed by a review of North Sea ecosystems. Marine and coastal ecosystems are addressed in terms of ecological habitats, ecological dynamics, and human-induced stresses representing a threat (i.e. eutrophication, harmful algal blooms, offshore oil and gas, renewable energy, fisheries, contaminants, tourism, ports, non-indigenous species and climate change). Terrestrial coastal range

Electronic supplementary material Supplementary material is available in the online version of this chapter at 10.1007/978-3-319-39745-0_1.

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M. Quante and F. Colijn (eds.), *North Sea Region Climate Change Assessment*, Regional Climate Studies, DOI 10.1007/978-3-319-39745-0_1

vegetation is addressed in terms of natural vegetation (salt marshes, dunes, moors/bogs, tundra and alpine vegetation, and forests), semi-natural vegetation (heathlands and grasslands), agricultural areas and artificial surfaces.

1.1 Introduction

To provide a sound basis for the climate change related assessments presented in later chapters of this book, this introduction to the North Sea region reviews both the natural features of the region and the human-related aspects. This overview includes a comprehensive description of North Sea hydrography, the current climate of the region, and the various marine and coastal ecosystems. The depth to which these topics can be addressed in this introductory chapter is limited, so additional reference material is provided in Annex 5 to this report. To date, there are few sources that cover the North Sea region as a whole and that address natural, social, and economic issues. Notable among those that are available are the OSPAR Quality Status Report for the Greater North Sea Region (OSPAR 2000) and a characterisation of the North Sea Large Marine Ecosystem by McGlade (2002). Comprehensive reviews of North Sea physical oceanography are provided by Otto et al. (1990), Rodhe (1998) and Charnock et al. (1994, reprinted 2012), and of physical-chemical-biological interaction processes within the North Sea by Rodhe et al. (2006) and Emeis et al. (2015).

1.2 North Sea and Bounding Countries—A General Overview

Markus Quante, Franciscus Colijn, Horst Sterr

1.2.1 Geography of the Region

The North Sea region is situated just north of the boundary (∼50°N) between the warm and cool temperate biogeographic regions, classified from north to south as Alpine North, Boreal, Atlantic North, Nemoral, and Atlantic Central (Metzger et al. 2005). The North Sea is a semi-enclosed marginal sea of the North Atlantic Ocean situated on the north-west European shelf. It opens widely into the Atlantic Ocean at its northern extreme and has a smaller opening to the Atlantic Ocean via the Dover Strait and English Channel in the south-west. To the east there is a connection with the Baltic Sea. The transition zone between the North Sea and Baltic Sea is located in a sea area between the Skagerrak and the Danish Straits, named the Kattegat. The continental bounding of the North Sea is well defined by the coastlines of the United Kingdom (Scotland and England) in the west, southern Norway, southern Sweden and Denmark (Jutland) in the east and Germany, the Netherlands, Belgium and France in the south (Fig. 1.1). The 'North Sea region' as defined in the NOSCCA context comprises the Greater North Sea and the land domains of the bounding countries, which form part of the catchment area. There are countries in the North Sea catchment area without a coastline, namely Liechtenstein, Luxembourg and larger parts of Switzerland and the Czech Republic. These countries are outside the scope of this assessment. A more formal definition of the boundary to the Atlantic Ocean may follow the internationally accepted setting proposed by the OSPAR Commission, where the western boundary of the so-called Greater North Sea (i.e. OSPAR Region II) is marked by the 5°W meridian and the northern boundary by the imaginary line along 62°N (OSPAR 2000). This definition encloses the

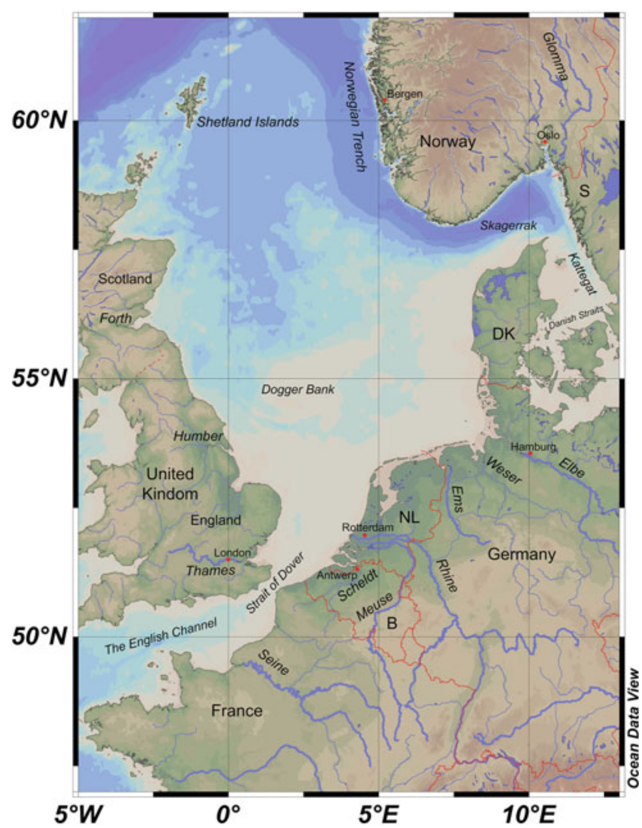


Fig. 1.1 North Sea region (map produced using Ocean Data View)

entire English Channel in the west. In the east, the Skagerrak and Kattegat are considered by OSPAR to be part of the Greater North Sea. Overall, the North Sea extends about 900 km in the north-south direction and about 500 km in the east-west direction. Including all its estuaries and fjords the Greater North Sea spans a surface area of about 750,000 km^2, the estimated water volume amounts to 94,000 km^3 (OSPAR 2000).

1.2.1.1 Catchment Area and Freshwater Supply

The total catchment area of the North Sea is about 850,000 km^2. Major rivers discharging freshwater into the North Sea are the Forth, Humber, Thames, Seine, Meuse, Scheldt, Rhine/Waal, Ems, Weser, Elbe, and Glomma. Some of these rivers form larger estuaries such as the Weser and Elbe in the German Bight and the Thames and Humber at the English east coast, while the mouth of the Rhine-Meuse-Scheldt system is more delta-like. The annual input of freshwater from all rivers is highly variable and within the range 295–355 km^3, with melt water from Norway and Sweden contributing about one third (OSPAR 2000). River runoff to the North Sea is considerably less than the freshwater input from the Baltic Sea. When runoff to the Danish Belts and Sounds is excluded, the net freshwater supply to the Baltic Sea is typically around 445 km^3 $year^{-1}$ (Bergström 2001). Overall, the salinity of Baltic Sea water is much lower than that of the North Sea. In the Kattegat, brackish water enters the North Sea in a surface flow with a counter flow of salty and oxygen-rich water to the Baltic Sea at depth (see Sect. 1.4.2). Total river runoff to the Baltic Sea is a good marker for the lower bound of freshwater delivered to the North Sea, since precipitation over the Baltic Proper is on average higher than evaporation, typically by about 10–20 % (e.g. Omstedt et al. 2004; Leppäranta and Myrberg 2009). According to Omstedt et al. (2004) the net outflow to the North Sea, excluding the Kattegat and Belt Sea water budget, is around 15,500 $m^3\ s^{-1}$ (or 488 $km^3\ year^{-1}$) with an interannual variability of $\pm 5000\ m^3\ s^{-1}$.

1.2.1.2 Coastal Types

The coasts of the North Sea display a large variety of landscapes, among the largest in the world. They vary from mountainous coasts interspersed by fjords and cliffs with pebble beaches to low cliffs with valleys and sandy beaches with dunes. There is a broad contrast between the northern North Sea coasts and the southern North Sea coasts; while the northern coasts are more mountainous and rocky the southern coasts are often sandy or muddy. This reflects regional differences in geology, glaciation history and vertical tectonic movements. The northern coastlines have experienced isostatic vertical uplift since the disappearance of the huge ice masses after the Weichselian glaciation (see Sect. 1.3.1).

The following description of the North Sea coastlines uses the morphological characterisation of the coastal landscapes by Sterr (2003). It should also be noted that the North Sea coast of the UK has been well documented in a set of dedicated volumes prepared by the UK Joint Nature Conservation Committee (Doody et al. 1993; Barne et al. 1995a, b, 1996a, b, c, 1997a, b, c, 1998a, b).

Starting in the northwest, the coasts of the Shetland and Orkney Islands and northern Scotland are mountainous showing a morphologically strongly structured rocky appearance. The area has a rugged and open character and predominantly comprises cliffed landscapes. The rocks of this region include some of the oldest in Great Britain.

The coasts of southern Scotland and northern England also feature cliffs of various sizes, which were shaped by several glaciation events and erosion. But in contrast to the northern part of Scotland, this region has a much gentler topography. Pebble beaches and intersections by river valleys are typical of this coastal region. The Firth of Tay and Firth of Forth are the most prominent features along the coastline; the latter being one of the major UK estuaries. The coast of northern England has fewer bays, headlands or estuaries compared to that of southern Scotland. Nevertheless it is still varied with cliffs alternating with stretches of lower relief.

The southern North Sea coast of the UK including the Humber and Thames estuaries comprises low-lying land that alternates with soft glacial rock cliffs. This makes it vulnerable to flooding and coastal erosion, and almost all of the open coast has some form of man-made defence along it (Leggett et al. 1999). Embedded in this area is a large indentation called the Wash—effectively a large bay into which four mid-sized rivers discharge. Most parts of the Wash are shallow and several large mudflats and sand flats are exposed at low tide. Much of the English Channel coast comprises cliffs, of both soft and harder rock. This results in a varied landscape with all the major coastal geomorphological structure types present. In the south-western segment the coast is punctuated by many narrow, steep-sided estuaries, with the River Exe the only typical coastal plain estuary in this region.

On the southern side of the North Sea especially between the Belgian lowland and the northern tip of Jutland an extended shallow coast has formed. The natural coastline of this region was strongly modified by storm floods during medieval times and has now changed considerably with the development of towns and harbours, land reclamation projects and coastal protection structures. The south-eastern North Sea coast of France, Belgium and the Netherlands is characterised by coastal dunes, sandy beaches and often a gentle shoreface. In the Delta area of the south-western Netherlands the straight coastline is interrupted by a complex of larger estuaries and tidal basins (Lahousse et al.

Fig. 1.2 Examples of the different types of coastline around the North Sea: cliff coast near St Andrews, Scotland (**a**), sandy beaches and dunes in Jutland, Denmark (**b**), tidal flats of the Wadden Sea, Germany (**c**), Norwegian fjord (**d**). *Photo copyright* T. Stojanovic (**a**), M. Quante (**b**, **d**), M. Stock (**c**)

1993). Some of these estuaries were closed in recent times. The subsequent Dutch coast, between Hoek van Holland and Den Helder is characterised by an uninterrupted coastal barrier with high dunes.

The Wadden Sea and barrier islands characterise the coast between the IJsselmeer in the Netherlands and the Blavandshuk peninsula *Skallingen* in Denmark. The Wadden Sea comprises a shallow body of water with tidal sand- and mudflats, which cover over two-thirds of the area, as well as salt marshes and other wetlands. The morphology of the Wadden Sea was described by Ehlers and Kunz (1993). It has the world's largest continuous belt of bare tidal flats, which are partially sheltered by a sandy barrier (Reise et al. 2010; Kabat et al. 2012). In 2009, the Wadden Sea was added to the UNESCO World Heritage List.

The West- and East Frisian barrier islands in front of the Dutch coast and the coast of lower Saxony in Germany are basically sandy dune islands and form an entity with the Wadden Sea and adjacent beaches of the mainland. Further north, the North Frisian and Danish islands have a different origin; they were originally parts of the mainland, their cores comprising glacial till from the Saalian Glaciation. Following Holocene sea-level rise, a north-south-trending barrier was formed from these islands, which fostered moorland growth and sheltered the mainland from medieval storm floods. Later, this segment suffered massive land losses during several disastrous medieval storm floods.

At the Danish west coast of Jutland large coastal dune areas have formed, some reaching several kilometres inland. There are no major estuaries along that coast and spits shelter former bays from the open sea. Overall, the graded shorelines of Jutland are similar in character to those in Belgium and the central part of the Netherlands.

In Sweden and in southern Norway up to Stavanger the typical skerry coasts are found, while the Norwegian coastline further north is mountainous and often dissected by deep fjords. The Norwegian and Swedish mainland is sheltered from the open ocean by a more or less continuous archipelago. Overall, the Swedish and Norwegian coast is strongly structured and dissected leading to a distinct interleaving of land and sea. The images in Fig. 1.2 show the diverse character of the different parts of the North Sea coast.

1.2.1.3 Demography

The North Sea plays a key role in one of the world's major economic regions, it is a place for settlement and commerce for millions of people and thus parts of its coastal area are densely populated. Establishing the overall population of the North Sea region without a strict geographical definition of the enclosed area is not straight forward. About 185 million people live within its catchment area (OSPAR 2000), which includes landlocked countries such as Liechtenstein, Luxembourg and larger parts of Switzerland and the Czech Republic. Although about 168 million people live within the catchments of countries bordering the North Sea, many probably consider they have no direct relation to the North Sea. Because a clear distinction between coastal zones and inland areas is difficult to perceive, to estimate population size for the North Sea region it may be more appropriate to include only those inhabitants whose daily living or economic activities are linked with the sea. The coastal regions as defined by the European Union (Eurostat 2011) could serve as a starting point for such a census. Here, a coastal region is a statistical region defined at NUTS level 3 (district level) that has a coastline or more than half of its population living within 50 km of the sea. According to Eurostat (2011) in 2008 about 205 million people lived in the coastal regions of the EU, of which 20.6 % or about 42 million lived in the North Sea maritime basin as defined by the EU (which excludes the Dover Strait, English Channel and Norwegian coast). Adding the number of people living in the relevant districts on both sides of the English Channel and the Dover Strait (about 18 million in 2008 according to Eurostat NUTS3) and an estimated 2.5 million Norwegians, it may be concluded that roughly 70 million people live in the North Sea region and use the coastline and marine environment in a number of ways. This estimate is reasonably close to an earlier estimate of 50 million people reported by Sündermann and Pohlmann (2011) and compiled in connection with the SYCON project (Sündermann et al. 2001a).

Population density varies widely around the North Sea, and is highest along the southern coast and lowest along the eastern coast. Heavily populated areas are found in the river basins of the Elbe, Weser, Rhine, Meuse, Scheldt, Seine, Thames, and Humber. The regions showing the highest population densities, with maxima exceeding 1000 inhabitants km^{-2} are found near the coast in the Netherlands and Belgium. In contrast, densities of less than 50 inhabitants km^{-2} are common along the coasts of Norway and Scotland. Four different types of region can be distinguished with respect to population density: the Netherlands and Belgium with very high density (>300 inhabitants km^{-2}), the UK and Germany with high density (>200 inhabitants km^{-2}), France and Denmark with medium density (>100–200 inhabitants km^{-2}), and Sweden and Norway with low density (<50 inhabitants km^{-2}). Along the North Sea coastline, the highest crude rates of population growth in recent years were in the English, Belgian and Dutch regions (Eurostat 2011).

Several large cities or agglomerations are situated in the North Sea region. In 2009, about 64 % of the population of EU coastal regions bordering the North Sea lived in predominantly urbanised areas (Eurostat 2011). Greater London with an official population of more than 8 million in 2012 is by far the most populous municipality, with the overall London metropolitan area having an estimated population of 12 to 14 million. Other large cities are Hamburg (1.77 million; metropolitan area 4.3 million), Amsterdam (0.75 million; metropolitan area 2.2 million), Oslo (0.61 million; metropolitan area 1.9 million), Rotterdam (0.58 million; metropolitan area 1.2 million), Bremen (0.55 million), Gothenburg (0.51 million), Edinburgh (0.48 million), The Hague (0.47 million), and Antwerp (0.47 million). In the Netherlands, the Randstad—a megalopolis comprising the four largest Dutch cities (Amsterdam, Rotterdam, The Hague and Utrecht) and the surrounding areas, including several midsize towns such as Haarlem, Delft, Leiden and Zoetermeer—has a population of 7.1 million and forms one of the largest conurbations in Europe. Another agglomeration has developed in northern England around the city of Newcastle; the Tyne and Wear City Region has more than 1.6 million inhabitants.

1.2.2 Major Human and Economic Activities

The North Sea region is a major economic entity within Europe and a very busy marine area with respect to human activities. The importance of the North Sea is determined by its geographic position off north-western Europe and the economic status of its surrounding countries. Its importance depends primarily on its transport function with several important harbours located on the North Sea coasts. This section provides only a few very general statements on coastal industries and agriculture in north-western Europe since detailed information on these sectors can be found in geography textbooks, such as that by Blouet (2012).

Various types of industry are established along the North Sea coasts, including metal and metal processing, chemicals, oil refineries, and shipbuilding, and these are mainly clustered in specific geographic locations. In the UK the coastal industries are found near the estuaries of the rivers Thames, Tyne, Tees and in the Firth of Forth as well as in the

Southampton area. On the French Channel coast industrial activities are concentrated in the Calais-Dunkerque region and around the Seine estuary. In Belgium the coastal industry is chiefly found in the Antwerp area near the Scheldt estuary. The estuaries of the Scheldt, Meuse and Rhine and the greater Amsterdam area are the major industrial regions in the Netherlands. German coastal industries are concentrated near the banks of the rivers Elbe, Weser, Ems and Jade. At the North Sea coast of Denmark, some industry occurs around the town of Esbjerg, more industrial activity is situated on the east coast of Jutland. In southern Sweden, major industrial activities settled around Gothenburg at the Kattegat. Along the southern and western coasts of Norway, industries developed in the innermost part of fjords, mostly connected to larger cities like Oslo, Stavanger and Bergen but also at sites where hydroelectric power is generated (OSPAR 2000). Most of these industrial activities are located either around an estuary or directly on the coast, and for efficient exchange of goods and materials several important harbours have developed.

Europe's busiest ports in cargo tonnage and container units are situated on the southern North Sea coast. Rotterdam (Netherlands) is the busiest reporting 291.1 million tonnes of bulk cargo throughput and over 12.3 million twenty-foot equivalent units (TEU) in 2014, followed by Antwerp (Belgium) with 62.8 million tonnes of bulk cargo and 9.0 million TEU and Hamburg (Germany) with 43.0 million tonnes of bulk cargo and 9.7 million TEU (Port of Rotterdam 2015). London and Felixstowe and several other British harbours together with Le Havre (France), Amsterdam (Netherlands), Bremen/Bremerhaven (Germany), and Gothenburg (Sweden) comprise the remainder. As these harbours play an important role in global trade the Straits of Dover and the North Sea proper contain some of the most heavily trafficked sea routes in the world. Several million tonnes of cargo are transported over the North Sea annually with about 280,000 ship movements a year (OSPAR 2000). At any given time, 900 to 1200 large ships are traversing the North Sea. The economy of north-western Europe depends strongly on the North Sea as a major transport corridor.

In north-western Europe there are several extended areas of intensive field-crop farming, these are concentrated in eastern England, northern Germany and large parts of the Netherlands. Areas of intensive animal production or fruit and vegetable farming are found in the coastal and southern areas of western Denmark and parts of Germany, the Netherlands, northern Belgium and northern Brittany. The main land areas in the North Sea region used for agriculture are introduced in Sect. 1.7.

The North Sea also fulfils a series of other economic, military and recreational functions. All coastal countries have declared an exclusive economic zone (EEZ); one of three area categories recognised by the United Nations Convention on the Law of the Sea (UNCLOS). An EEZ can extend from the territorial sea to 200 nautical miles from the baseline (commonly the low-water mark). Within this zone the coastal state has the sovereign right of exploitation of marine resources, including energy generation from water and wind.

All coastal states extract oil or natural gas from the North Sea with up to a thousand production platforms, depending on how they are counted; oil and gas are extracted in the northern North Sea and in the southern North Sea it is mostly gas. In 2007, production for the North Sea as a whole totalled 205 million tonnes of oil and 173 million tonnes of gas in oil equivalents (OSPAR 2010).

Although fisheries are a minor activity in terms of gross national product (GNP), thousands of fishing boats (over 5800) operate over the rich North Sea fishing grounds and are responsible for total landings of just over a million tonnes of fish and shellfish each year, primarily by British, Danish, French and Dutch fleets. In 2012, catches amounted to EUR 436 million (UK), EUR 327 million (Denmark), EUR 241 million (Netherlands), and EUR 196 million (France), together accounting for 81 % of the total value of landings in the North Sea (STECF 2014). Following a period of increasing depletion, fish stocks in the North Sea are now improving, owing to major reductions in the regional fishing industry five to ten years ago.

Exploitation of living resources other than from fin fisheries is restricted to the catch of shrimp and shellfish such as mussels and cockles in coastal seas like the Wadden Sea, although strong restrictions are in place in this area owing to its protected status as a World Heritage site. Mariculture is mainly restricted to coastal inlets, especially to fjords in Norway and Scotland.

A new economic activity in the North Sea is the establishment of large wind farms with up to 100 turbines per farm. A strong increase in the marine area covered by wind farms is expected especially in the German EEZ, but construction is occurring all along the coasts of Belgium, Denmark, the Netherlands and the UK. By 2015 there were 29 wind farms in the North Sea with a total installed capacity of 6000 MW, nine additional farms are under construction.[1]

Tourism is an important economic factor along the Belgian, Dutch, German, Danish and UK coasts. Tourists and daily visitors in the Wadden Sea region along the Dutch, German and Danish coasts are an especially important economic factor. Between 1998 and 2007 the annual number of visitors to the North Sea region increased from 50 million to 80 million (OSPAR 2010), potentially increasing pressure on the environment.

[1]Wikipedia, List of offshore wind farms in the North Sea. Accessed 15 October 2015.

Economic activities and the discharge of rivers draining extensive industrial and agricultural areas within the North Sea catchment, result in high nutrient and pollutant loads to the North Sea. Eutrophication has a long-term impact on the coastal regions of the North Sea, but some of its effects such as low oxygen levels in bottom waters in the German Bight have decreased over the past two decades. However, the North Sea coast remains on the list of OSPAR-designated eutrophication problem areas (OSPAR 2010). Riverine and direct pollution by heavy metals (cadmium, lead, mercury) also decreased substantially between 1990 and 2006 (OSPAR 2010). Polycyclic aromatic hydrocarbons (PAHs) and polychlorinated biphenyls (PCBs) are still widespread in the North Sea region (OSPAR 2010), with a large proportion of the sites monitored showing unacceptable levels. The burden of pollution by persistent organic pollutants continues albeit their character changes over time, owing to the phasing out of some compounds and the introduction of others such as flame retardants (Theobald 2011).

Nature conservation in the North Sea is based on the designation of EU protected areas. By the end of 2012, marine Natura 2000 sites covered nearly 18 % of waters in the North Sea region (EEA 2015).

The various and extensive uses of the North Sea collectively place a strong environmental pressure on the entire marine ecosystem.

1.3 Geology and Topography of the North Sea

Hartmut Heinrich

1.3.1 Geological and Climatic Evolution of the North Sea Basin

1.3.1.1 General Settings

The North Sea Basin in its present shape started to form after the end of the Variscian Orogeny during the Permian Period about 260 million years (Ma) ago. In a subsiding area between the Palaeozoic mountain chains with the Scottish and London Massifs in the west, the Brabant, Rhenohercynian and Bohemian Massifs in the south and Fennoscandia and Greenland in the north a tectonically very active basin formed which has accumulated about 10 km of sediments in certain locations (the Horn, Central and Viking Graben) that vary in character from terrestrial to fully marine. Over the same period, and as a consequence of plate tectonics Europe has drifted northwards from the equator towards its present position. In parallel, the climate of the area has successively evolved from extremely arid to subtropical, moderate, and finally over the last million years into the highly variable conditions of the glacial period (Ziegler 1990; Gatcliff et al. 1994; Balson et al. 2001; Lyngsie et al. 2006).

1.3.1.2 Permian to Holocene

During the **Permian [296–250 Ma]**[2] the North Sea region was situated close to the equator. To the North the desert-like hot and dry area was connected to the open ocean through a gap between Greenland and Norway leading to the deposition of different types of chemical sediments comprising carbonates, anhydride/gypsum and various types of salt that later formed structures that acted as traps for commercially exploitable hydrocarbons (Glennie 1984; Johnson et al. 1993). The paleogeographic setting is shown in Fig. 1.3.

At the onset of the **Triassic [250–200 Ma]** the region arrived in the zone of the northern trade winds. The marine basin began to rise culminating during the Lower Triassic in a desert-like landscape with fluvial deposits. Later, its southern part for roughly 10 million years [243–235 Ma, Muschelkalk] became part of the shallow marine German-Polish Basin where under subtropical climatic conditions mainly lime sediments were deposited.

During the **Jurassic [200–145 Ma]** the North Sea region was still located in the subtropical climate belt. This was a period of strong tectonic activity on Earth. The Tethys Ocean progressed from East Asia westward across the ancient Pangaea continent dividing it into the Gondwana continent (India-Africa-South America-Australia-Antarctica) and Eurasia. At the same time, in the south Gondwana began to split into an African and a South American part forming the Proto-Southern Atlantic. The growing mid-ocean ridges led to substantial sea-level rise.

As a result the North Sea basin developed wide connections to the Tethys Ocean and the Proto-Atlantic Ocean with far greater exchange of water than before. Within the North Sea area tectonic movements caused fluctuations in the distribution of land and sea that created a variety of depositional environments including floodplains and fluvio-deltaic to shallow marine systems. Towards the south as water deepened clays and limestone were deposited. These types of marine sediment indicate a warm productive environment with oxygen-depleted conditions at least in the bottom waters. The organic matter deposited during the mid-Jurassic is the source of most hydrocarbons in the North Sea exploited today.

The tectonic rise of the North Sea basin reached its greatest extent around the onset of the **Cretaceous [145–65 Ma]** and about half the area was dry land,

[2]All ages from Deutsche Stratigraphische Kommission (Menning and Hendrich 2012).

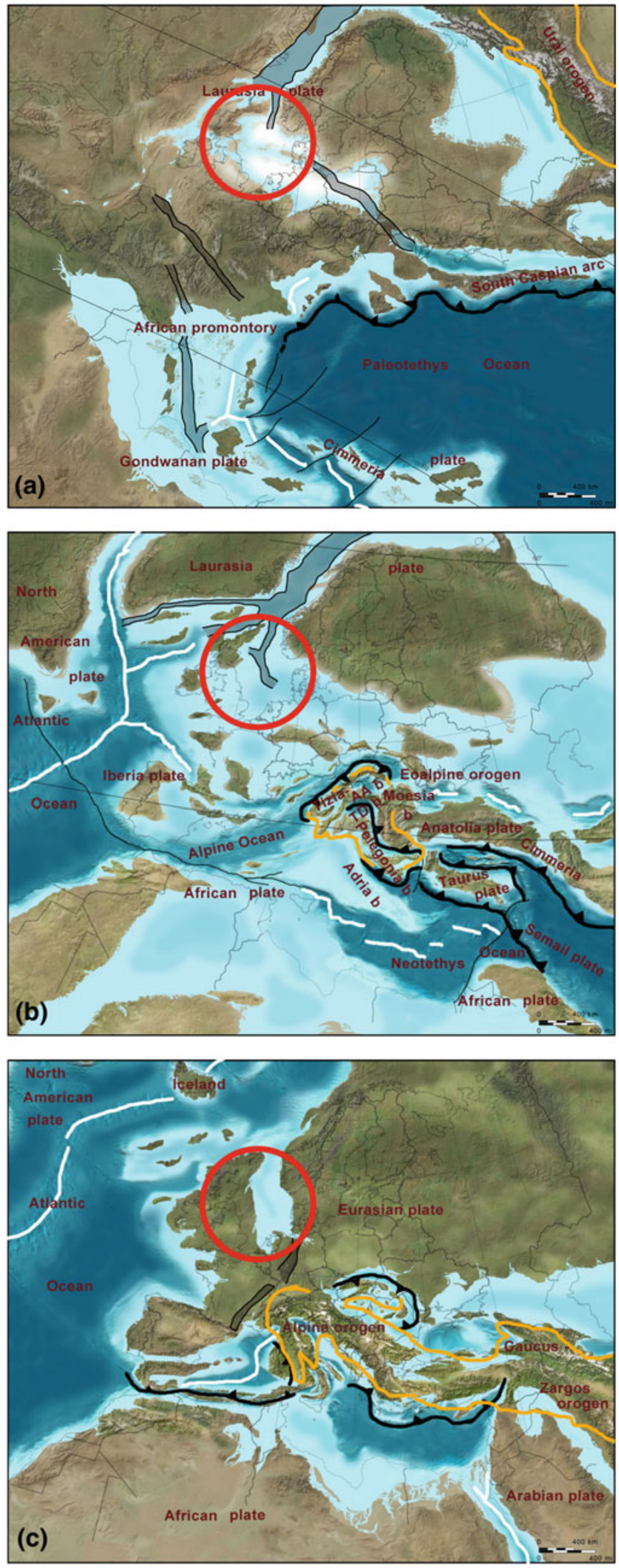


Fig. 1.3 Paleogeography of the European area during the Permo-Triassic (*upper*, ~250 Ma), the Upper Cretaceous (*middle*, ~75 Ma), and the Miocene (*lower*, ~13 Ma). The current position of the North Sea is marked by the *red circle* (graphical reproduction permitted by Prof. Blakey; http://cpgeosystems.com/paleomaps.html)

accompanied by a drop in global sea level (Haq et al. 1987). Continental rifting in the Atlantic Ocean began to separate North America from Europe (see Fig. 1.3). Uplift of the London-Brabant-Rhenish-Bohemian Massifs largely closed the connection to the Tethys Ocean in the south, whereas the connection via the Viking Graben to the Proto-Arctic Ocean remained open.

Later, when sea level started rising again a connection to the Proto-North Atlantic developed and, via the Paris Basin in the west and the Polish Straits in the east, water exchange with the Tethys again intensified. During the Lower Cretaceous [140–100 Ma] the fluctuating but generally rising sea level in conjunction with the warm climate generated a succession of clay and calcareous deposits. At the Lower-to-Upper Cretaceous boundary the North Sea Basin was fully flooded. In the Upper Cretaceous [100–65 Ma] continental rifting in the North Sea area accelerated leading to strong subsidence of the Central Graben.

During the period of high sea level water exchange between the North Sea area and the surrounding open oceans through the wide straits resulted in a warm and well oxygenated marine environment. Both the very warm climate and the high global sea level are linked with the development of a super plume in the Earth's mantle in the western Pacific Ocean that was accompanied by very strong volcanic activity from 120 to 80 Ma outgassing huge quantities of carbon dioxide (CO_2).

During the **Tertiary [65–2.6 Ma]** the North Sea region arrived in its present latitudinal position. The climate changed dramatically from relatively warm towards boreal conditions. Antarctica arrived at its present position at the South Pole and was climatically isolated from the rest of the globe. Huge ice sheets began to form in Antarctica as well as on Greenland and on high mountain areas leading to a global cooling and a notable drop in sea level. Connecting the Proto Atlantic Ocean with the now cold Arctic Ocean and in the North Sea the closure of the seaways to southern Europe at the Oligocene–Miocene boundary [24 Ma] enabled much cooler water to move into the North Sea Basin changing the climate in the northern half of Europe. The first ice-rafted debris appeared in the northern North Sea around the end of the Tertiary [2.4 Ma] (Rasmussen et al. 2008). Sea level was increasingly controlled by glacio-eustatic changes.

Increasing erosion in the rising land areas bordering the wider North Sea and the Polish Basin completely changed the coastal landscape. Extensive deltas developed at the mouth of river Rhine and on the present western Baltic Sea–Polish Platform areas; both deltas progressing slowly towards the centre of the North Sea basin. During the warm periods of the early Tertiary these deltas were covered with dense paralic forests and swamps that led to coal formation. At the Miocene–Pliocene boundary [1.8 Ma] the North Sea had reached a geographic and bathymetric size close to that of the present day.

In the southern and central parts of the North Sea area the deltaic regime of the Upper Tertiary proceeded into the **Quaternary [2.6–0 Ma]** with increasing rates of deposition, while the north comprised a deeper pelagic depositional environment. The faunal composition points towards water temperatures similar to those of today in the southern North Sea (Nilsson 1983).

The **Pleistocene [2.6–0.012 Ma]** in the North Sea area is a time of extremely variable climatic conditions. Beginning in the Middle Pleistocene [~1 Ma] glacial and interglacial types of sedimentary processes dominated the North Sea Basin. During glacial periods the sea level dropped several tens to hundred or more metres exposing a dry landscape, which was sometimes covered by ice sheets. These ice sheets usually originated in the Norwegian-Swedish-Scottish Mountains. They carried large amounts of eroded rock debris of varying grain size into the basin forming moraines and other glacigenic features. During the temperate interglacial periods the North Sea experienced repeated changes in sea level that led to brackish to marine deposits (Ehlers 1983; Schwarz 1991; Sejrup et al. 2000; Ehlers and Gibbard 2008; Gibbard and Cohen 2008).

As a result of erosion from the temporary ice covers and alternating transgressive and regressive sea levels the climatic record of the North Sea area is very fragmentary. The oldest traces of a glaciation in the North Sea area are reported from the Netherlands [1.8–1.2 Ma; MIS[3] 34–36] and Denmark [~0.850 Ma; MIS 22–19]. The first glaciation documented, which covered the southern North Sea as far south as 52°N was the Elsterian/Anglian glaciation [~0.48–0.42 Ma; MIS 12]. At the end of the glaciation [0.425 Ma] a catastrophic flood from a collapsed ice-damned lake in the southern North Sea area is deemed to have cut a first gorge into the Weald–Artois chalk range that is now Dover Strait. A second breach of that barrier occurred roughly 240,000 years later during the Saale/Wolstonian glaciation.

The subsequent Holstein/Hoxnian interglacial [0.424–0.374 Ma; MIS 11] in terms of water temperature and geographical extent is meant to be an analogue of the present North Sea. A very narrow Dover Strait did not allow a significant inflow of temperate water from the Bay of Biscay.

The Saale/Wolstonian Glacial complex [0.350–0.130 Ma; MIS 10–6] is a succession of cold and slightly milder periods mostly represented by glacio-marine deposits in the North Sea. There were two phases of greater ice advance, the Warthe and Drenthe stadials that formed moraines off the North Sea coasts.

[3]MIS: Marine Isotope Stage.

The most recent interglacial period was the Eemian/Ipswichian [0.130–0.115 Ma; MIS 5e]. The climate at that time is considered to have been similar to that of the present day, and possibly warmer for some period. The maximum global sea level was 4–6 m higher than today (Dutton and Lambeck 2012) such that marine sediments of Eemian age extend inland far beyond the present coastlines.

In the subsequent Weichselian/Devensian glaciation [0.115–0.017 Ma; MIS 5d − 2] the climate slowly cooled until 0.075 Ma [MIS 4]. At that time temperature dropped rapidly and initiated a first ice advance from the Scandinavian mountains towards the North Sea coasts. Within the next 50,000 years the climate switched on millennial time scales between cool (Dansgaard-Öschger events) and extremely cold (Heinrich events) until the maximum extent of inland ice was reached at about 0.020 Ma [MIS 2]. In parallel, sea level dropped discontinuously to 120 m below the present level. A pro-glacial landscape with rivers, marshes, lakes and lagoons subsequently developed in the North Sea Basin, as illustrated in Fig. 1.3. Sediments representing the coldest part of the Weichselian/Devensian in the southern North Sea are mainly of aeolian and riverine origin. There is still debate about a possible closure of the Norwegian and Scottish ice sheets. Closure of these ice sheets is supported by glacio-lacustrine sediments found in depressions on top of Dogger Tail End and in the Elbe Urstrom Valley area.

The melting of the ice sheets began at about 0.019 Ma. However, global warming was discontinuous and showed several rapid changes, such as cold excursions like Heinrich Event 1 [17.5–15.0 ka[4]] and the Antarctic Cold Reversal [14.7–14.2 ka] in the southern hemisphere. Warm excursions included the Bölling and Alleröd periods [14.7–12.7 ka]. The concomitant rate of sea-level rise changed abruptly. During the Bölling period, for example, sea level rose about 20 m within 500 years (Melt Water Pulse 1a). The Pleistocene ended with the Younger Dryas [12.7–11.7 ka], a cold spell of still unknown origin.

The **Holocene [0.012–0 Ma**] in the North Sea area is characterised by increasing warmth and a rising sea level that rapidly flooded the flat glacial landscape. The present sea level was reached about 2000 years ago, and continues to rise slowly.

The Holocene climatic warming following the Younger Dryas cold spell did not evolve continuously. During the Preboreal [11.6–10.7 ka] temperatures in the northern hemisphere rose rapidly. Temperate conditions developed in the North Sea region in the Boreal [10.7–9.3 ka]. The warmest period of the Holocene was the Atlantic [9–5 ka]. Temperatures and sea level were higher than today, as was precipitation. The composition of pollen in sediments shows the onset of extended human influence (Mesolithic) on the flora of north-western Europe. During the subsequent Subboreal [5–2.5 ka] the climate was slightly cooler than in the Atlantic period and drier. The final stage of the Holocene, the Sub Atlantic was a period of climatic oscillations with a general tendency to cooler and wetter conditions than in the Subboreal. Its warmest period was the medieval Climatic Optimum [900–1100 AD]. Temperatures then dropped towards the Little Ice Age [1300–1850 AD].

The post-glacial inundation of the North Sea north of the Dogger-Fischer Bank Ridge started at the end of the Younger Dryas [12.7–11.7 ka]. Along the northern margin of the North Sea rock debris was dumped by icebergs from the Scottish and Norwegian mountain glaciers. At about 9 ka sea water entered the southern North Sea through the gap that forms the northernmost parts of the Elbe Urstrom Valley between Dogger Tail End and Fischer Bank/Jyske Rev (Konradi 2000). At about 8.5 ka the Dogger Bank became an island owing to the flooding of the Silver Pit depression between England and the Dogger Bank. During this time the southern North Sea landscape evolved from dry land via a shallow swampy environment into a brackish lake or lagoon with lagoon-type sedimentation. Slightly later, at 8.3 ka the ingress of marine waters from the Northeast Atlantic through the English Channel established full marine conditions in the North Sea. The Dogger Bank Island with its Mesolithic settlements was finally drowned around 8.1 ka. During the short period between the first marine ingression through the Elbe Valley and the flooding of the Dogger Bank, sea level rose at an average rate of 1.25 m per century culminating in the latter half of this period at a rate of 2.1 m per century. Later the rate of rise slowed to 0.30–0.35 m per century. The rate of sea level rise finally approached present-day values at about 2.8 ka. A unique sea level curve for the North Sea is still not available due to very different and partly unresolved local effects of post-glacial rebound and other related tectonic movements (Shennan et al. 2006; Vink et al. 2007; Baeteman et al. 2011).

Although it is likely that Early Holocene hunter and gatherer communities occupied the vegetated landscape, apart from the Mesolithic human traces found on Dogger Bank evidence has not been found to support this. Settling along the coasts and in the marshlands started to increase with the onset of the Sub Atlantic (Iron Age), which included the building of simple dykes and terps as protection against storm surges and changes in sea level. Human settlements in the southern coastal area of the North Sea can be traced back to 3 ka.

[4]ka: calendar years before Present (absolute age).

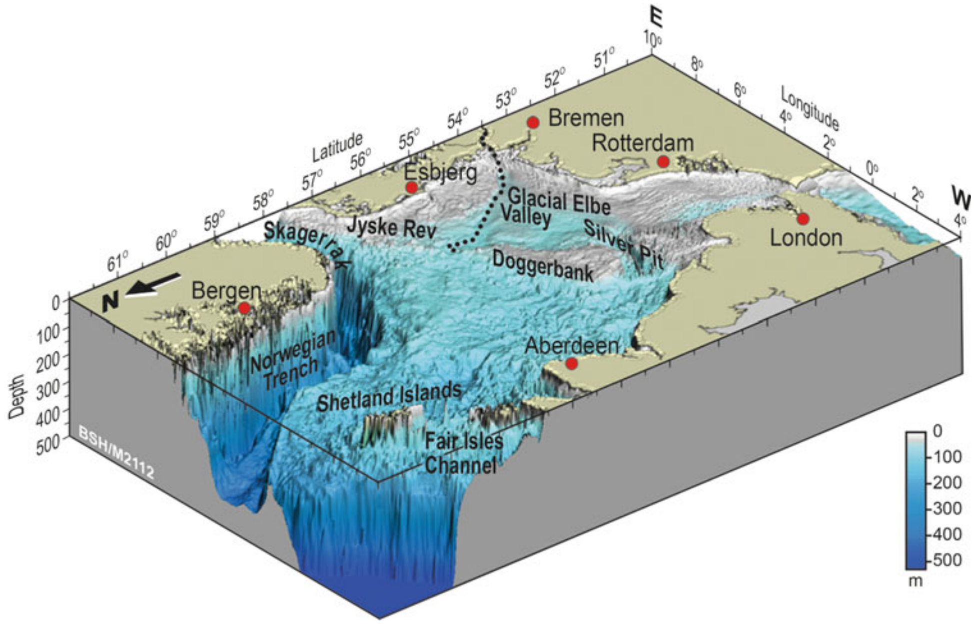


Fig. 1.4 Bathymetry of the North Sea

1.3.2 Topography of the North Sea

The North Sea is a continental shelf sea of the North Atlantic Ocean. It is bounded in the west by the British Isles, in the north by Norway, in the east by the Jutland Peninsula and North Frisia and in the south by the East and West Frisian Coast. In the north it is widely open to the deep Norwegian Sea. In its south-western corner the North Sea is connected to the Celtic Sea and subsequently to the Northeast Atlantic through the shallow Dover Strait/Pas de Calais with a minimum width of 30 km. A shallow connection to the Baltic Sea exists via the Skagerrak, Kattegat and Danish Belt Sea between the Jutland Peninsula, the Danish Islands and Scandinavia.

The North Sea dips gently from the shallow Frisian coasts in the south towards the continental margin along the deep Norwegian Sea. Average water depth in the North Sea is about 90 m. The present-day bathymetry of the North Sea is shown in Fig. 1.4. The western part of the northern basin has a trench 230 m deep, 30 km long, and 1–2 km wide, named the Devils Hole. Along the Norwegian coast into the Skagerrak spans a deep furrow, the Norwegian Trench which is up to 700 m deep.

The North Sea is mostly relatively flat. A ridge, the Dogger Bank–Jyske Rev subdivides the North Sea into a southern and a northern basin. The southern basin has a maximum depth of 50 m. North of this ridge the basin declines smoothly towards the shelf edge at about 200 m depth.

The Dogger Bank–Jyske Rev complex extends from east of Flamborough Head in England to the northern tip of the Jutland Peninsula. In the west the Silver Pit, a southeast-northwest trending gap about 100 km wide and up to 80 m deep separates the central Dogger Bank from its western part that extends to the coast of Norfolk and Suffolk. A smaller gap about 60 m deep right in the middle of the ridge, the breakthrough of the glacial Elbe Valley, separates the Dogger Bank/Dogger Tail End from the Jyske Rev. Minimum water depth on the Dogger Bank is 15 m below sea level. The Jyske Rev rises from 35 m at its western tip to the coast of northern Jutland. The two gaps enable deeper central North Sea water masses to pass from the northern basin to the southern basin.

1.4 Hydrography—Description of North Sea Physics

Jürgen Sündermann, Thomas Pohlmann

As generally in the ocean, the physical system of the North Sea is determined by the space-time distribution of seven macroscopic variables (Krauss 1973): temperature, salinity, density, pressure and the three components of the velocity vector. All additional physical quantities (such as water level elevation, thermocline depth, energy, and momentum) can then be calculated from the former. Current knowledge of all seven variables is based on field observations, remote sensing and model simulations.

The three-dimensional fields of temperature and salinity and their low-frequency variability are well-known, including statistical parameters such as error bounds, evidence, and confidence. Density can be calculated with high accuracy by means of the equation of state. Pressure can be related to sea-level elevation at the surface or within the water column,

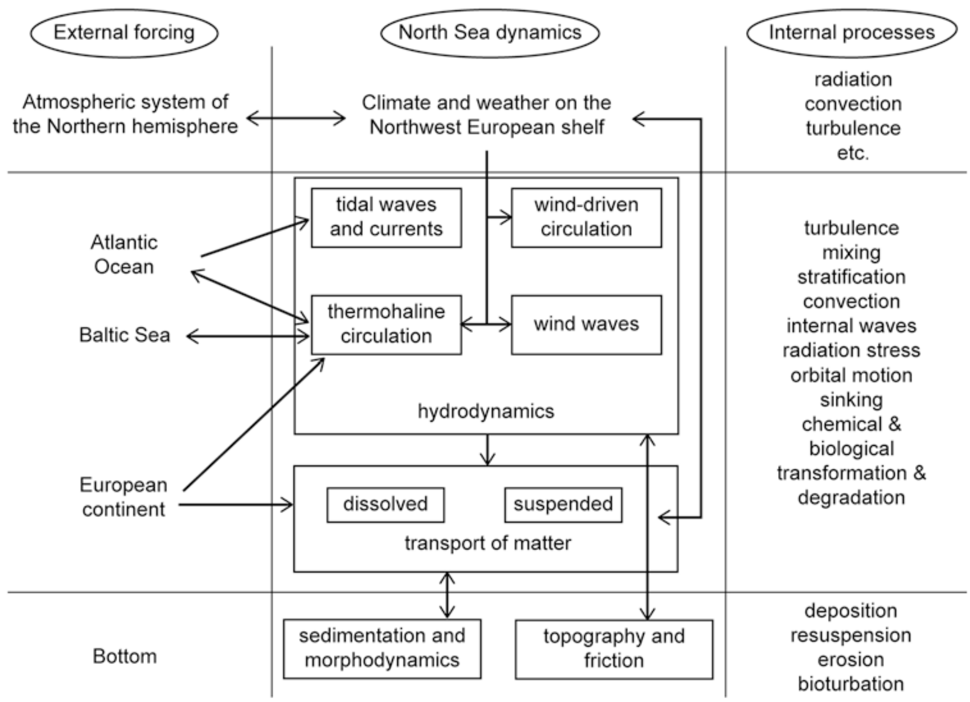


Fig. 1.5 Scheme of interactions within the physical system

which can be observed. Current velocities are only measured at certain points/sections and over defined periods. The best overall information today is given by hydrodynamic models combined with measurements assimilated into the model (Köhl and Stammer 2008).

Dissolved and suspended substances (such as nutrients, contaminants, and particulate material) may also be considered physical properties and their distributions are widely observed. Modelling requires knowledge of the sources and sinks of these substances.

To understand the physical system (and enable its simulation by models), knowledge of the interactions and processes within the current and transport regime including boundary forcing is also fundamental (Fig. 1.5).

North Sea dynamics are characterised by the regional interaction of the atmosphere, hydrosphere and lithosphere on the Northwest European shelf, and exhibit a broad spectrum of spatial and temporal scales (Fig. 1.6). Specific features of the physical system include turbulence, baroclinic eddies, internal waves, surface waves, convection, and tides.

Owing to the many interactions between them the physical, chemical and biological compartments of the North Sea system cannot be separated. Certainly, physics is essential for transport of chemical and biological substances and for the dynamics of the North Sea ecosystem as a whole. But there is also feedback depending on the scales considered, for example, in radiation flux, albedo, surface films, and surface roughness.

1.4.1 Boundary Forcing

The North Sea is part of the Northwest European shelf; its physical state is essentially determined by the adjacent Atlantic Ocean and the European continent including the Baltic Sea. Furthermore, the atmosphere of the northern globe is essential for the external forcing (Schlünzen and Krell 2004).

1.4.1.1 Atlantic Ocean

The open connection with the Atlantic Ocean allows the free exchange of matter, heat and momentum between the two seas. Planetary waves generated by astronomical and atmospheric forces in the ocean propagate over the shelf break into the North Sea generating changes in sea level, tides and water mass transport. In contrast, continental fresh water discharges influence the water characteristics of the North Atlantic (Figs. 1.7, 1.8 and 1.9).

There is an inflow of cold and salty Atlantic water into the deeper northern central basin of the North Sea and along the Norwegian Trench up to the Skagerrak. Less salty coastal waters circulate in an anti-clockwise gyre in the southern North Sea basin ultimately joining the Baltic Sea outflow (Winther and Johannessen 2006).

The total transport at the northern entrance exhibits a net outflow from the North Sea with an average of 2 Sverdrups (Sv) and annual variations of around 0.4 Sv (Fig. S1.4.1 in the Electronic (E-)Supplement, Schrum and Siegismund 2001).

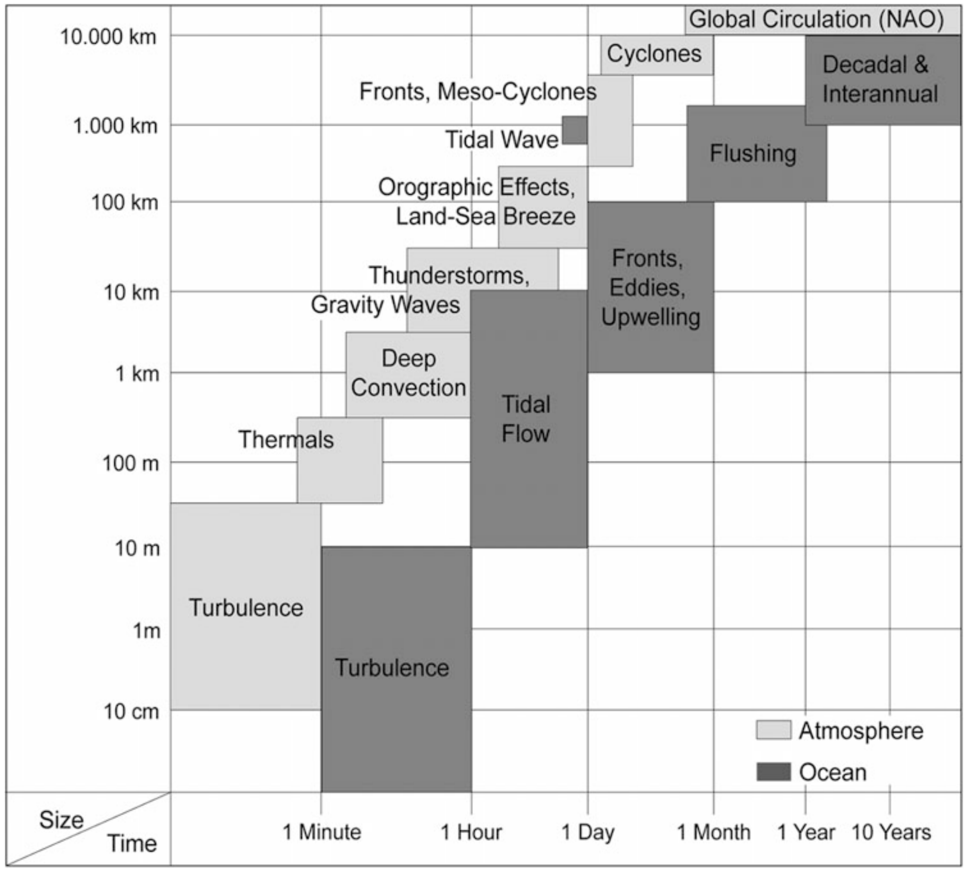


Fig. 1.6 Scale spectrum of the physical system (Sündermann et al. 2001b)

Decadal variability within the Atlantic Ocean, mainly driven by the North Atlantic Oscillation (NAO) (Hjøllo et al. 2009) and to a lesser extent by the Atlantic Multi-decadal Oscillation (AMO), is transferred to the North Sea. For heat this mainly occurs through the atmosphere, less through direct exchange of water masses, as is shown by the correlation pattern of NAO versus sea-surface temperature anomalies (Fig. S1.4.2 in the E-Supplement). High values in the central North Sea indicate this interrelation. Correlations reach their minimum at the north-western entrance and in the Southern Bight, indicating the influence of the advective heat transport from the Atlantic Ocean in these areas.

Net transport at the North Sea border is a superposition of continental outflow and Atlantic inflow. Substances moved by the respective currents enter the North Sea (salt, nutrients) or the Atlantic Ocean (fresh water, contaminants).

1.4.1.2 European Continent and Baltic Sea

The continental influence on the water characteristics of the North Sea comprises freshwater supply, and the input of dissolved and suspended matter: nutrients, contaminants, sediments.

Owing to continental freshwater discharge and the positive difference ‘precipitation minus evaporation’, the Baltic Sea exhibits a mass surplus resulting in a mean net outflow of 15,500 $m^3 s^{-1}$ (Omstedt et al. 2004). More precisely, from the North Sea perspective there is a permanent inflow of freshwater, superimposed by a weak outflow of saltwater. During episodes of decadal frequency this outflow can strongly increase (salt water intrusion events) and renew and ventilate the Baltic Sea deep water.

Through its geostrophic balance the Baltic Sea outflow causes an eastward elevation in sea level of the order of centimetres within the Kattegat.

1.4.1.3 Atmosphere

Through the downward flux of momentum the atmosphere significantly controls the general circulation of the North Sea as well as the vertical structure of the water column due to turbulence. The frequency distribution of the wind direction and speed determines the major current patterns in the North Sea (see Sect. 1.4.3). The wind forcing exhibits a predominantly southwestern direction with significant decadal variability.

The wind further controls the spectrum of surface waves in the North Sea, and cyclones can lead to strong storm surges. The atmosphere influences the heat budget via vertical heat fluxes and their variability. Precipitation on the Northwest European shelf influences North Sea salinity and its seasonal variability directly or via continental discharge (see Sect. 1.5.4).

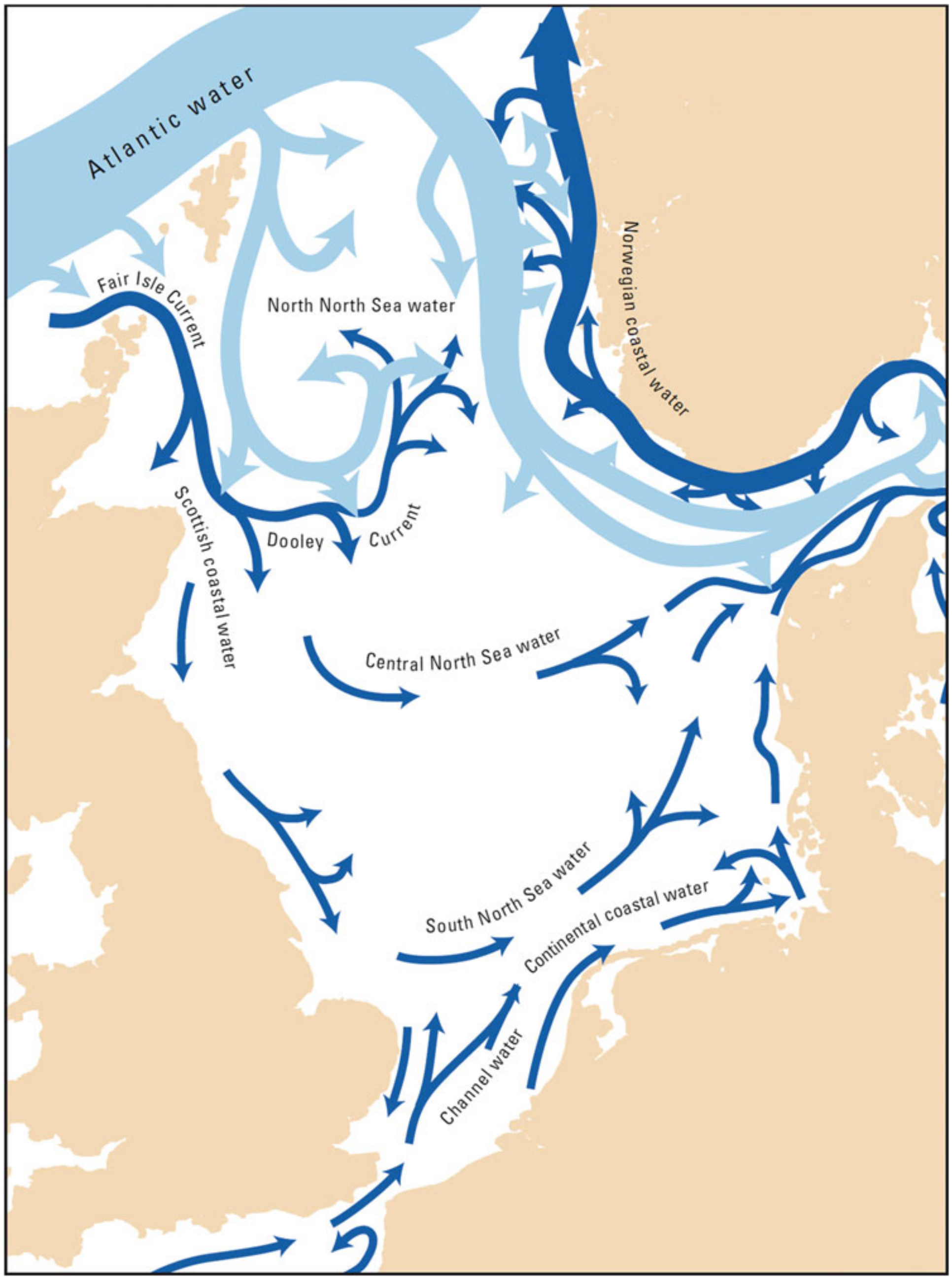


Fig. 1.7 Circulation system of the North Sea (after OSPAR 2000)

1.4.1.4 Seabed

The seabed represents a source or sink of sediment (by erosion, resuspension, or deposition) and associated substances. Related biogeochemical processes are important. Morphodynamics affect topography and as a consequence currents and waves.

1.4.2 Thermohaline Regime

The thermodynamic state of the North Sea is characterised by the 4-dimensional distributions of temperature and salinity (Figs. 1.8 and 1.9) and the related variable baroclinic circulation.

The strong seasonal variation in sea-surface temperature is the most evident low-frequency periodic feature in the North Sea. The annual mean shows a relatively homogeneous water mass with a tongue of warmer Atlantic water inflowing through the English Channel. Superimposed on this is the seasonal wave with amplitude increasing from northwest to southeast.

The annual mean salinity distribution reflects the inflow of Atlantic water through the northern entrance and the English Channel as well as the fresh water supply from the

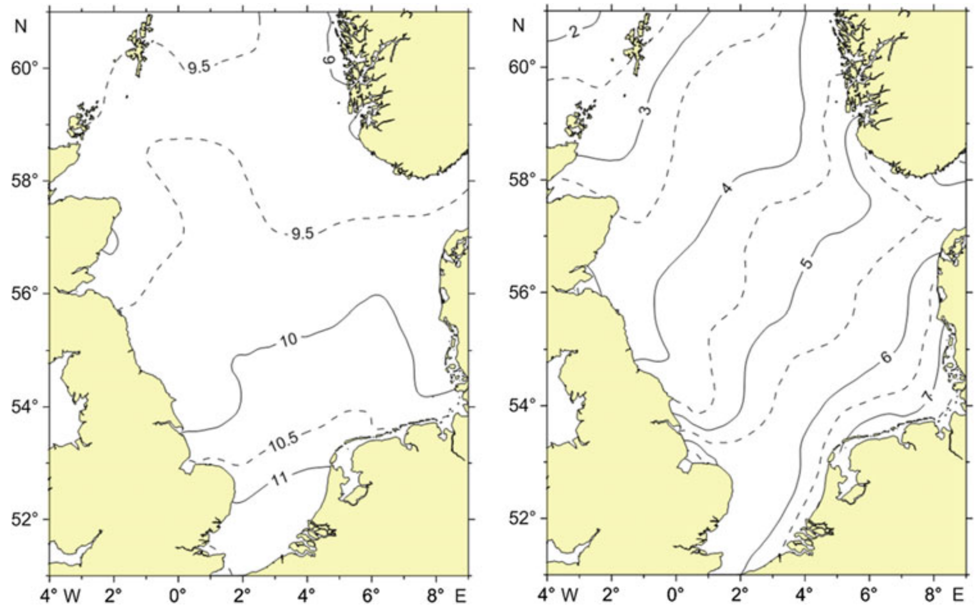


Fig. 1.8 Sea-surface temperature in the North Sea: annual mean (*left*) and seasonal variability (*right*) in °C, for the period 1900–1996 (data from Janssen et al. 1999)

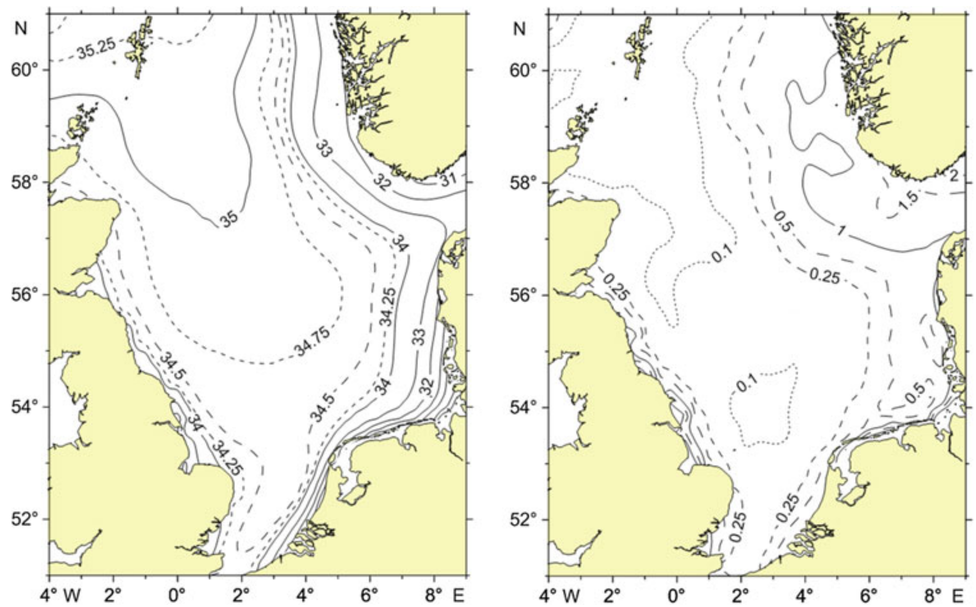


Fig. 1.9 Sea-surface salinity in the North Sea: annual mean (*left*) and seasonal variability (*right*) in psu, for the period 1900–1996 (data from Janssen et al. 1999)

European continent including the Baltic Sea outflow. Seasonal variation is most obvious in the southern and eastern coastal regions.

Figure 1.8 (right) shows the dominant seasonal temperature cycle. As explained in Sect. 1.4.1, temperature is mainly determined by heat exchange with the atmosphere. In the vertical, temperature development also shows significant differences between the southern and northern North Sea. While in the southern North Sea vertically homogenous conditions occur all year round, in the northern North Sea a summer thermocline develops in waters of around 30 to 40 m in depth (Fig. 1.10 and S1.4.3 in the E-Supplement).

Using the equation of state (Gill 1982), the baroclinic pressure gradients can be determined from the temperature and salinity fields and thus the geostrophic current system (Fig. S1.4.4 in the E-Supplement). This represents the density driven flow, which is superimposed by the wind driven current and the stronger tidal flow (see Sects. 1.4.3 and 1.4.4 and Pohlmann 2003). Tidal residual currents of the M_2 constituent are shown in Fig. S1.4.6 in the E-Supplement.

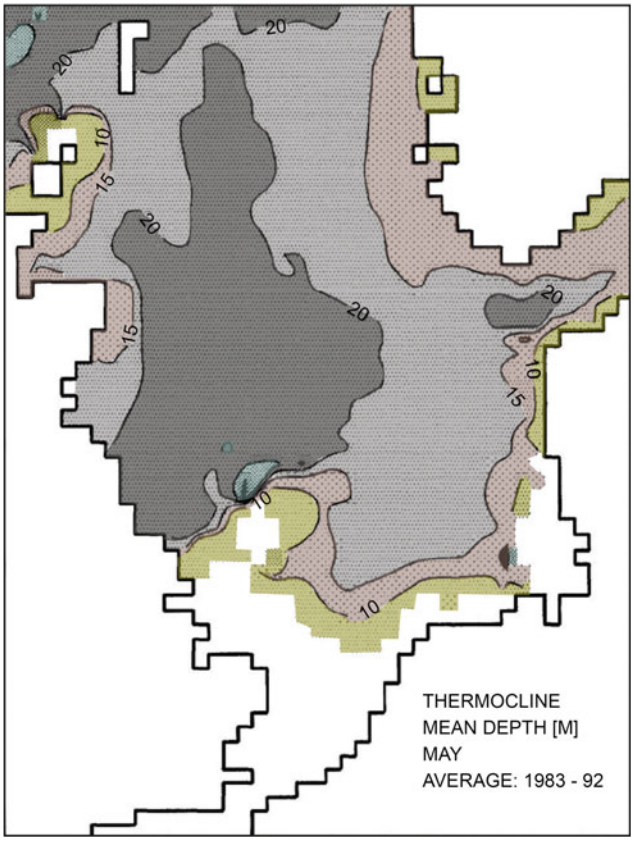


Fig. 1.10 Climatological monthly mean extension and depth of the thermocline in May (Pohlmann 1996)

For further studies on this topic see Luyten et al. (2003) and Meyer et al. (2011).

1.4.3 Wind-Driven Regime

The wind-induced circulation is clearly the dominant permanent regime, characterising the mean current system of the North Sea. Tidal currents may be stronger, but are almost periodic with relatively small net transports. Figure 1.11 shows the basic patterns of the wind-driven currents according to wind direction. Owing to the prevailing southwesterly winds on the Northwest European shelf an intense anti-clockwise circulation is dominant, which occasionally (in the case of easterly winds) reverses. For north-westerly and south-easterly winds, states of stagnation appear.

The NAO strengthens or weakens these patterns (see Fig. 1.12).

Storm surges constitute the greatest potential natural hazard for coastal communities in the North Sea region. An analysis of historical storm surges (Sündermann 1994) indicates that these extreme events fall into two classes:

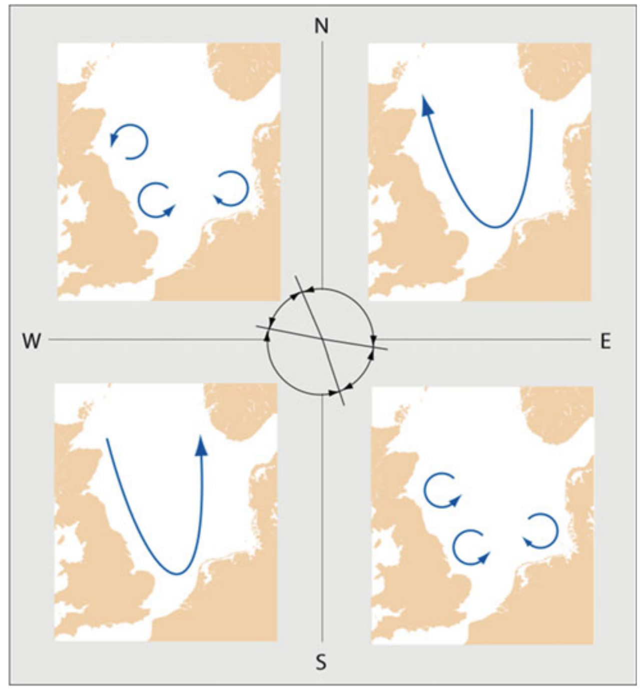


Fig. 1.11 Basic wind-driven circulation patterns in the North Sea. The four current states correspond to the four wind direction sectors in the central diagram (after Sündermann and Pohlmann 2011)

- Static type: low pressure track Iceland–northern North Sea–Scandinavia; extended, cold low; long-lasting, but not necessarily extreme winds push water into the German Bight. Example: 17 February 1962.
- Dynamic type: low pressure track Subtropical Atlantic–Great Britain–Denmark; small-scale, warm low; a short-lived, rotating extreme wind moves the North Sea water like a centrifuge raising sea level along all coasts. Example: 3 January 1976.

The storm surges mentioned are extreme, but not worst cases. Even under present-day conditions (i.e. without climate change) the full spectrum of possible surges allows for severely higher floods.

Surface waves are generated by the wind. Although their influence on large-scale circulation and transport is generally relatively small, it is significant for dynamical processes such as generation of turbulence, shear stress, radiation stress, sediment erosion, wave set-up in coastal areas, and extreme waves. The spectrum of wind waves is dependent on the fetch and duration of wind action (Fig. 1.13). Figure 1.14 depicts the first EOF pattern (Empirical Orthogonal Functions; represent the basic modes of the oscillation system) of the characteristic wave height. In combination with the time series of its principal component (not shown), it represents 82.5 % of total variance. Characteristic wave heights show the strongest variability in the open northern

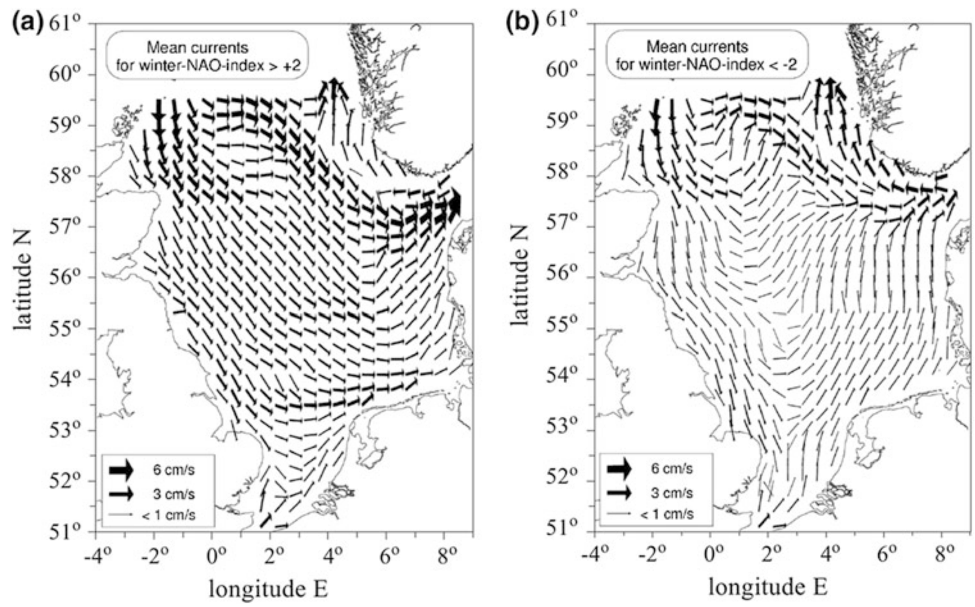


Fig. 1.12 North Sea circulation during prevailing positive winter NAO conditions (*left*) and negative winter NAO conditions (*right*) (Schrum and Siegismund 2001)

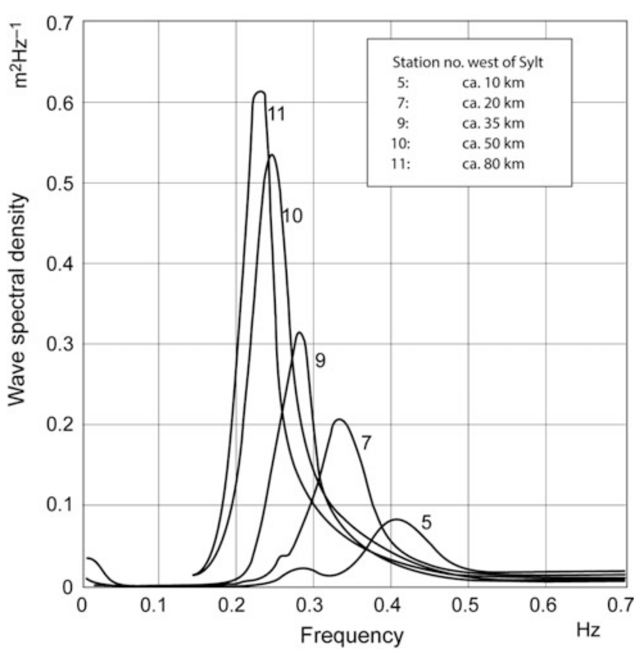


Fig. 1.13 JONSWAP spectrum (Hasselmann et al. 1973). Wave spectra of a developing sea for different fetches. Evolution with increasing distance from shore (numbers refer to stations off the island of Sylt)

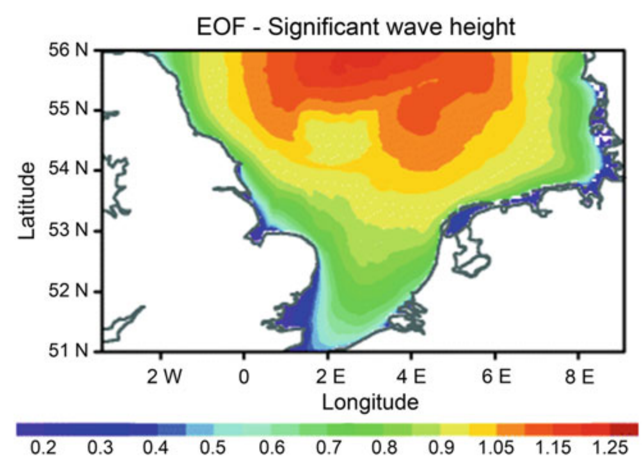


Fig. 1.14 Characteristic wave heights (m) in the North Sea (Stanev et al. 2009)

North Sea; in shallow regions and near the coast, variability is significantly reduced.

1.4.4 Tidally-Driven Regime

The North Sea dynamics are significantly influenced by astronomical tides. These are co-oscillations with the autonomous tidal waves of the Atlantic Ocean. The specific geometry of the North Sea basin implies eigen-periods and hence resonance in the semi-diurnal spectral range (Fig. 1.15). The superposition of the semidiurnal principal lunar and solar tides ($M_2 + S_2$) causes a significant spring-neap rhythm. The tidal currents may reach a speed of tens of centimetres per second and dominate any other flow, especially as they move the entire water column.

Tidal currents give rise to strong mixing of water masses, preventing thermohaline stratification in the shallow southern North Sea. In the Wadden Sea, tides cause the periodic exposure of large areas of seabed.

Tidal elevations penetrate from the Atlantic moving anti-clockwise as a Kelvin wave through the entire basin. There are three amphidromic points, i.e. points with zero

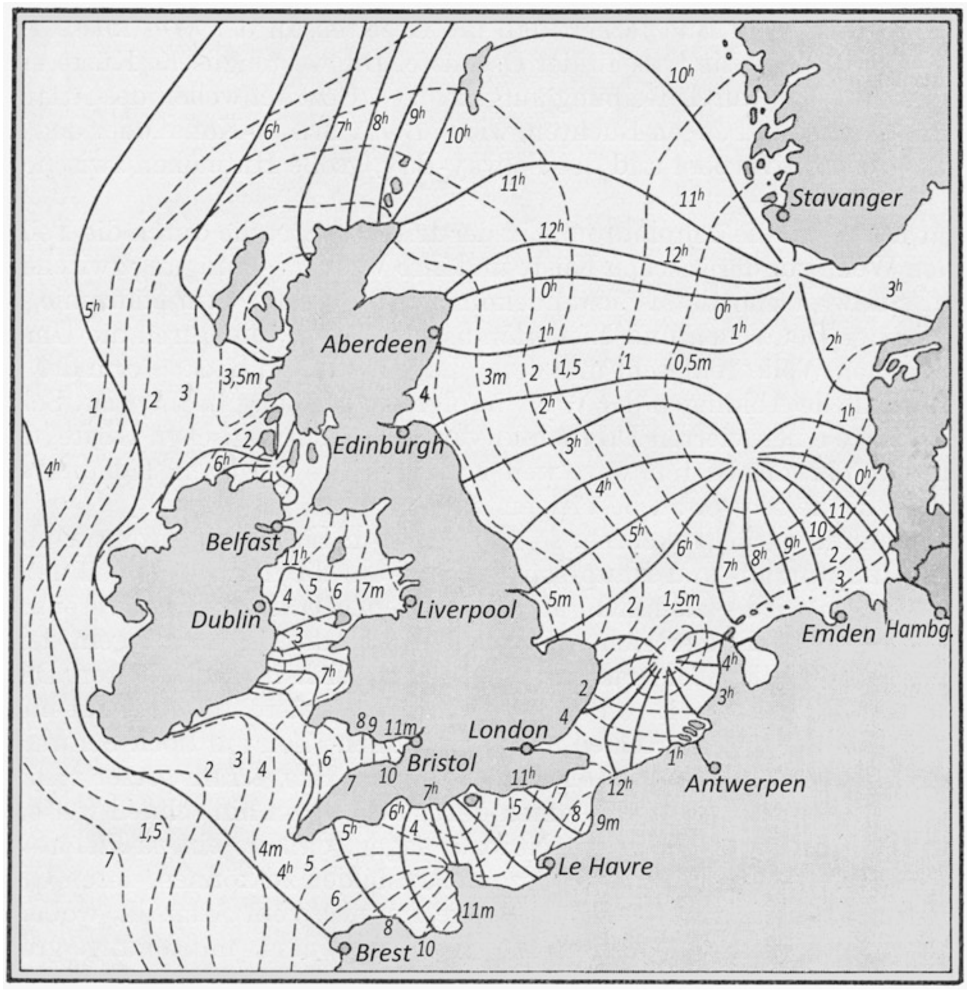


Fig. 1.15 Co-tidal lines for $M_2 + S_2$, the major tidal constituents in the North Sea (Sager 1959)

tidal amplitude around which the tidal wave rotates (see solid co-phase lines in Fig. 1.15 depicting the same phase of the tide). The co-range lines join places having the same tidal range or amplitude (dashed lines in Fig. 1.15).

Within one period the tidal currents form elliptic stream figures with positive or negative orientation (see Fig. S1.4.5 in the E-Supplement).

Nonlinear processes generate non-harmonic tidal motions and, as a consequence, non-vanishing residual currents with maximum values of the order of 10 cm (see also Fig. S1.4.6 in the E-Supplement).

Tides superimpose any other motion in the North Sea. They dissipate energy, mix water masses, and alter the coastline. Backhaus et al. (1986) showed that whenever a constant flow component is combined with a time-dependent periodic tide, there is a considerable reduction in the resulting residual flow.

Jungclaus and Wagner (1988) showed that sea-level rise leads to a shift in the central amphidromy towards the northwest and thus to higher tidal amplitudes in the southern North Sea.

1.4.5 Transport Processes

Dissolved and particulate inorganic and organic substances in the North Sea waters are transported by the current regimes as just described (Figs. S1.4.7 and S1.4.8 in the E-Supplement). Their spread and deposition control the biological and sedimentological systems of the North Sea.

The cyclonic current system of the North Sea means that as a generalisation substances entering the North Sea via river outflows are transported along the English, then Dutch, German, and Danish coasts into the Norwegian Trench, with significant scatter due to actual atmospheric conditions. Time integration yields residence times of the order of 6–12 months in the northern North Sea, to three years in the German Bight and along the north-eastern British coast (see Fig. S1.4.9 in the E-Supplement).

Besides advection in the flow field the concentrations of substances within North Sea waters are also the result of processes such as mixing, biogeochemical cycling, deposition, and resuspension. For particulate matter, sinking, flocculation, seabed processes such as bioturbation are also

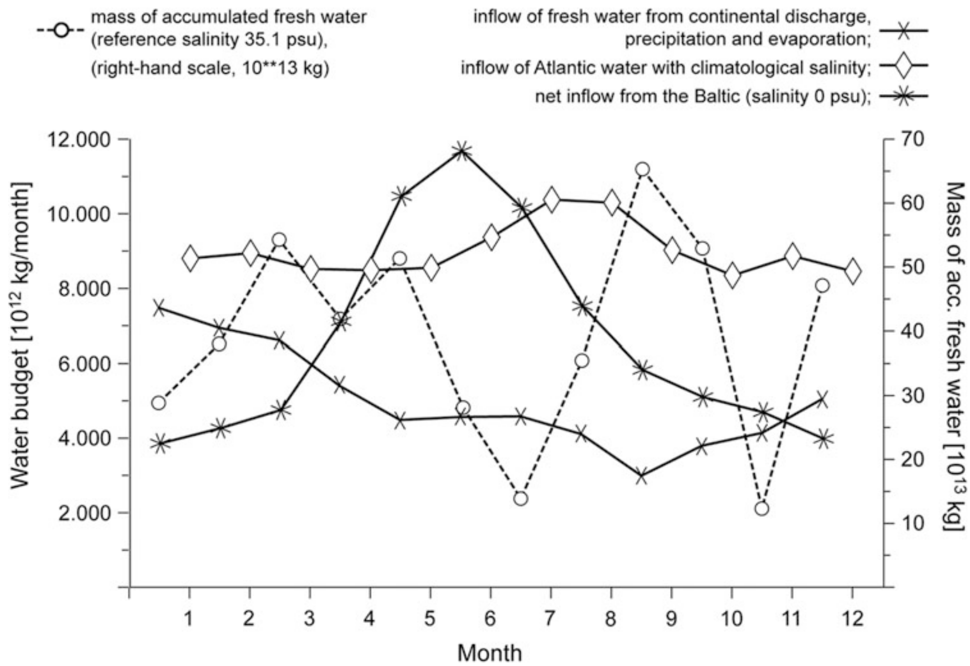


Fig. 1.16 North Sea water budget for one climatological year (Damm 1997)

important. Particulate transport drives the morphological changes occurring within the North Sea region.

Damm (1997) calculated the North Sea freshwater budget using the balance of inflows and outflows from long-term field records (Fig. 1.16).

1.5 Current Atmospheric Climate

Christiana Lefebvre

For climate descriptions, the data base should comprise a continuous period of at least 30 years in order to be representative in terms of variations and extremes. To account for climate change, the period 1971–2000 was chosen as the reference period for this study, because it seems to reflect features of the current climate better than the current World Meteorological Organization (WMO) climatological standard period 1961–1990. However, some analyses are also considered based on periods that differ slightly from 1971 to 2000. The current atmospheric climate as described in this section is based on analyses of observations for various climate parameters: air pressure, air temperature, precipitation, wind speed and direction, sunshine duration and cloud cover. In addition to analyses based on in situ data, for which coverage is poor in some sea areas, climate analyses are also based on the European Centre for Medium-Range Weather Forecasts (ECMWF) 40-Year Re-analysis (ERA-40; Uppala et al. 2005) and regional climate model (RCM) results from the ENSEMBLES project (Van der Linden and Mitchell 2009). Climatologies based on remote sensing from satellites are also used.

1.5.1 Atmospheric Circulation

The North Sea is situated in the west wind drift of the mid-latitudes between the subtropical high pressure belt in the south and the polar low pressure trough in the north. Westerly upper winds steer extratropical lows from the North Atlantic to northern Europe interrupted by relatively short anticyclonic periods. This is accompanied by frequent changes in air masses of different thermal and moisture-related properties, which drives continuous change in the synoptic-scale weather conditions over periods of days to weeks.

1.5.1.1 Sea-Level Pressure

Figure 1.17 shows the spatial distribution of the mean monthly sea-level pressure (SLP) across the North Sea region based on daily hemispheric analysis of SLP by the UK Met Office provided by the British Atmospheric Data Centre for the period 1971–2000 (Loewe 2009). Charts of the mean annual and mean monthly SLP for the period 1971–2000 based on data from the ERA-40 reanalysis and a hindcast of the ENSEMBLES RCMs forced by the ERA-40 reanalysis using a horizontal grid resolution of 25 × 25 km are reported by Bülow et al. (2013). The circulation pattern shows a distinct annual cycle that results from the interaction of the predominant air pressure centres across the North Atlantic: the Icelandic Low and the Azores High. On average, air pressure rises from northwest to southeast, while the standard deviation decreases. The strongest air pressure gradients are observed in autumn and winter. This is accompanied by the strengthening of low pressure systems due to a greater temperature difference between the polar and subtropical regions at this time of year. In the cold season, the direction of mean air flow varies between westerly in November and December and southwesterly from January to March. From March to April the intensity of mean air flow over the North Sea region decreases markedly. The Azores High starts to extend into parts of mid-Europe. In May, the air pressure gradient is weakest. In June and July, the extension of the Azores High causes on average a weak northwesterly air flow. In the English Channel and southwestern North Sea, mean air pressure is highest in July, while other regions have maximum air pressure in May (Fig. 1.18). Charts of mean SLP and standard deviation for the year as a whole, and for January and July from the ENSEMBLES RCMs and ERA-40 reanalysis for the period 1971–2000 are discussed by Bülow et al. (2013). The ERA-40 spatial air pressure distribution for January and July fits well with the corresponding analyses of UK MetOffice data in Fig. 1.17. The standard deviation derived from the ERA-40 reanalysis decreases in general from the northwest (area of the Orkney and Shetland Islands) to the southeast (southern Germany), for the annual mean (from 13–14 to 8–9 hPa), in January (from 16–17 to 10–11 hPa) and in July (from 8–9 to 4–5 hPa). The differences between the RCM SLP fields and ERA-40 reanalysis show a range of different patterns. The annual cycles of SLP from the ENSEMBLES RCMs and ERA-40 reanalysis for four North Sea subregions (northwest, northeast, southwest, southeast) show good agreement (Bülow et al. 2013), except for one RCM showing a permanent positive bias. Anders (2015) showed that the ERA-40 driven RCMs are able to reproduce different weather types, which were derived from the ERA-40 mean SLP field. Most of the RCMs reproduce the weather regime classification after Jenkinson and Collison (1977) centred over the North Sea with a coverage of 80–99 %. In general, agreement is better in winter than in summer.

1.5.1.2 North Atlantic Circulation

Circulation in the North Sea region is strongly influenced by the North Atlantic Oscillation (NAO). The NAO is described in detail in Annex 1 at the end of this report. The NAO is evident throughout the year, but it is most pronounced during winter and accounts for more than a third of the total variance in the SLP field over the North Atlantic (Hurrell and Van Loon 1997). During positive phases of the NAO, the meridional SLP gradient over the North Atlantic is enhanced. In the North Sea region, a positive NAO phase during the winter is usually accompanied by enhanced winter storm activity, above-average air temperatures and above-average precipitation in Scotland and Norway (Hurrell 1995; Hense and Glowienka-Hense 2008). Negative phases of the NAO, characterised by a weaker than normal Atlantic meridional SLP gradient are often linked with below-average air temperatures in northern Europe (Trigo et al. 2002). A prevailingly negative NAO phase influenced circulation from the mid-1950s to the 1978/1979 winter (Hurrell 1995). A period of high positive NAO in the late 1980s and early 1990s was connected with a high frequency of strong winter storms across the North Atlantic and high wind speeds across western Europe (e.g. Hurrell and Van Loon 1997). Figure 1.19 shows the frequency of extreme North Atlantic lows with core pressure of 950 hPa or less from November to March based on analysed weather charts (Franke 2009). Counts for November to March since 1956 show a sudden increase in winter 1988/1989 to 15 strong storms and a decrease since the late 1990s with the exception of the extraordinarily mild winter of 2006/2007 with 16 intense lows. The highest number occurred in winter 2013/2014 with 18 storms, causing severe damage along the western European coasts through storm surges.

1.5.2 Wind

Wind is the most important meteorological parameter for the North Sea and its coastal areas for two reasons. First, severe wind storms have the potential for high impact damage. They cause rough sea conditions, and increase risk of storm surges in coastal regions and thus damage to coastal settlements, infrastructure, agricultural land and forests, as well as increased coastal erosion in some areas. Second, wind is of increasing interest as a source of renewable energy. Widespread construction of onshore wind farms in coastal areas is now being followed by a significant increase in the development of offshore wind farms, and this requires reliable wind statistics for site identification and wind resource mapping as well as for user-specific forecasts of wind conditions for construction work and wind resource management.

Wind speed and direction across the North Sea area are driven by the large-scale pressure field and are modified at a local level by orographic effects caused by adjacent isles and coastal features. Wind speed is also affected by vertical temperature differences between the atmosphere and the sea surface, even for wind speeds of 7 Bft and above (Baas et al. 2015). The wind climate is characterised by pronounced seasonality. In general, the winds from November to March

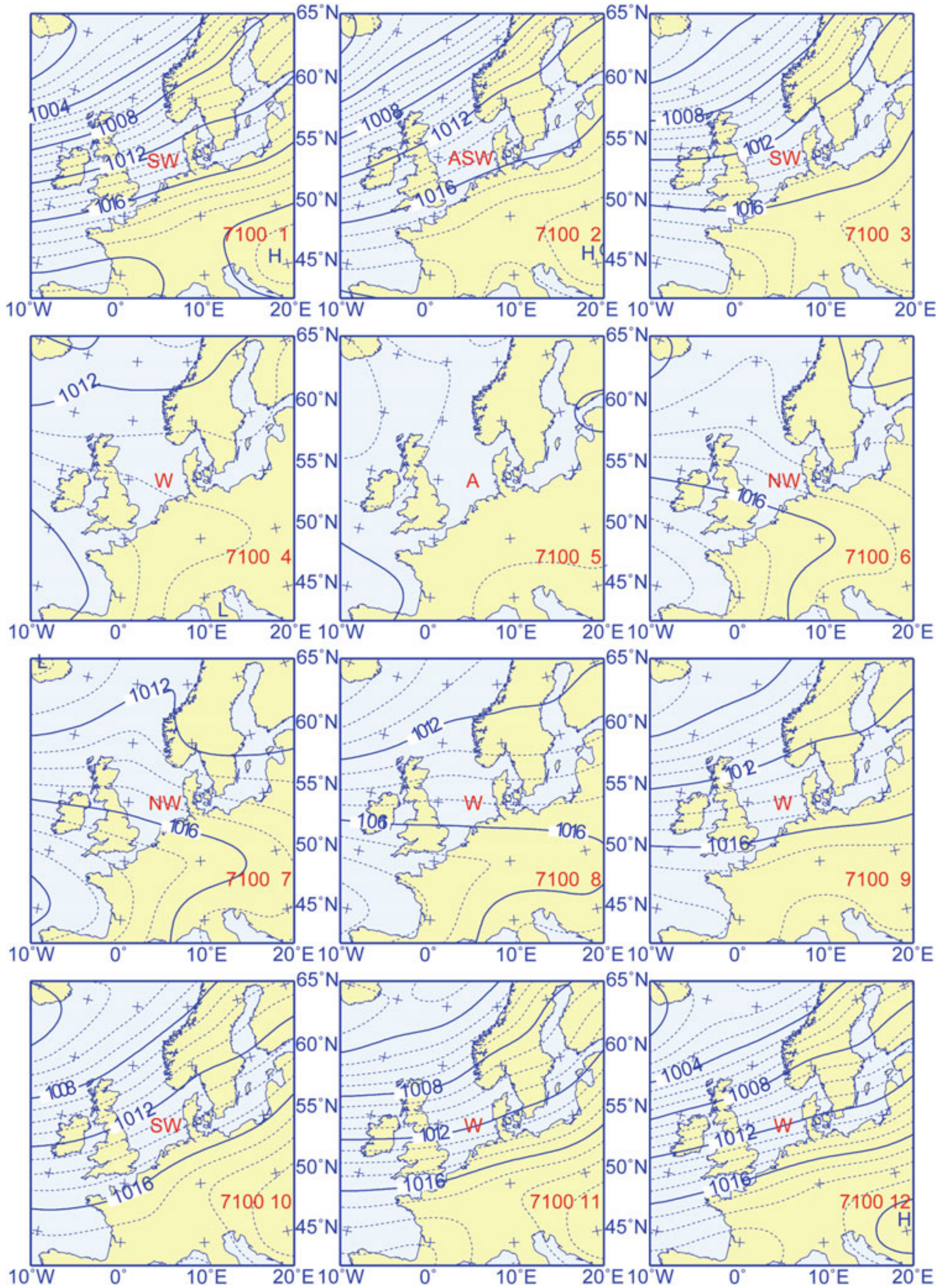


Fig. 1.17 Spatial distribution of mean monthly sea-level pressure (hPa) across the North Sea region for the period 1971–2000 (Loewe 2009). Numbers in the lower right of the subplots indicate time period and month

are stronger due to larger temperature differences between the subtropical and polar regions leading to more intense low-pressure systems.

1.5.2.1 Ship-Based Wind Speed Observations

The spatial distribution of mean monthly and annual wind speed based on ship observations was reported for the period 1981–1990 by Michaelsen et al. (2000), while Stammer et al. (2014) reported mean wind speed for June and December for the period 1981–2010. Due to uncertainties in wind data time series using ship-based observations arising from, among others, the switch from estimating wind speed from wave heights to direct measurements, no common measure height, and the effect of ship type and superstructure on measurements, it was decided to not include the results without further treatment into the KLIWAS North Sea Climatology (Stammer et al. 2014).

1.5.2.2 Remotely-Sensed Wind Speeds

In regions, where in situ observations are sparse, satellite observations with their extended spatial coverage are of great advantage. Satellite-based data sets covering long

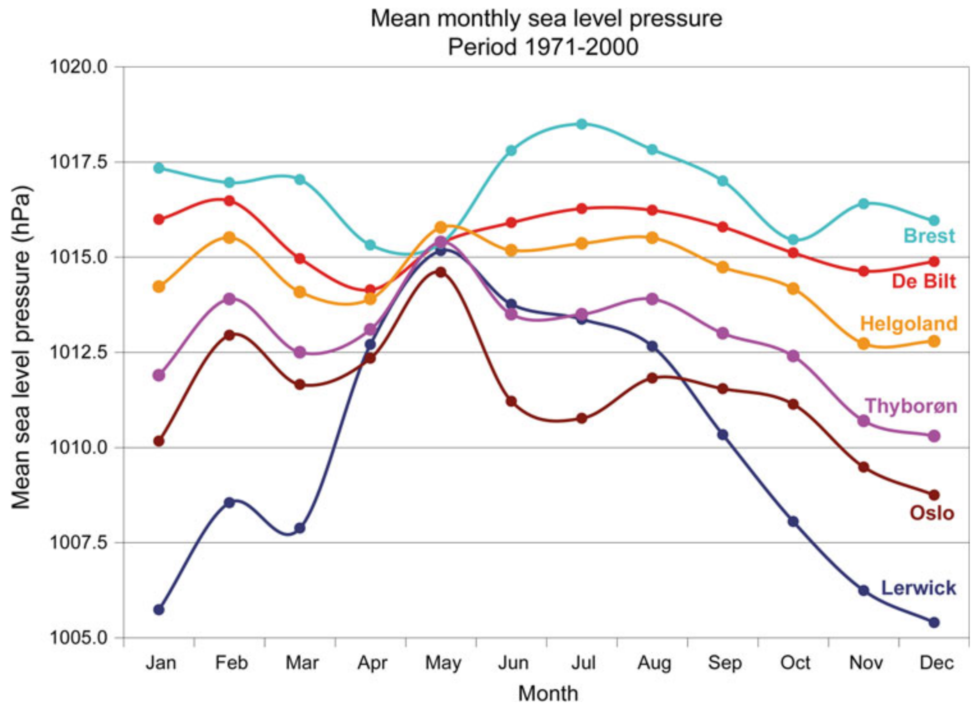


Fig. 1.18 Annual cycle of mean sea-level pressure (hPa) at selected land stations in the North Sea region for the period 1971–2000. Station positions are shown in the E-Supplement to this chapter (Fig. S1.5.1)

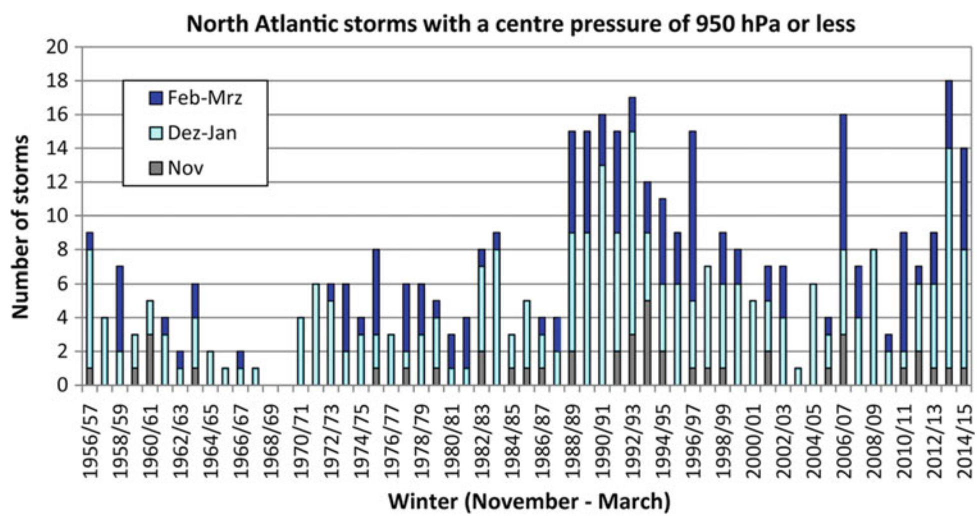


Fig. 1.19 Intense North Atlantic low-pressure systems with a core pressure of 950 hPa or less from November to March (Franke 2009, updated)

periods are also suitable for deriving climatologies. Figure 1.20 shows seasonal mean wind distributions developed from a 10-year data set of twice-daily (06:00 and 18:00 UTC) observations from NASA's QuikSCAT mission for the North Sea and Baltic Sea (Karagali et al. 2014). The data show equivalent neutral wind (ENW) at 10 m above the sea surface from rain-free observations assuming neutral atmospheric stratification. The ENWs originate from transmitted radar signals that are backscattered by small-scale waves at the sea surface, to which empirical algorithms are applied. The spatial distributions show higher wind speeds in winter and autumn as a result of increased storm activities as low-pressure systems cross the eastern North Atlantic and North Sea. In addition, the atmosphere in autumn and early winter is often colder than the ocean surface leading to prevailing unstable conditions that drive momentum transfer from higher atmospheric layers and result in higher wind speeds. Because neutral atmospheric stratification was assumed in the data processing, the satellite data may not exactly correspond to real conditions and may overestimate the true wind. In contrast, the strong lee effects in the western North Sea from the land effect of the British Isles may be less pronounced, because using ENWs leads to underestimation of true wind speed in the case of frequently stable atmospheric stratification. Besides atmospheric stability, rain affects the backscattered signal causing an

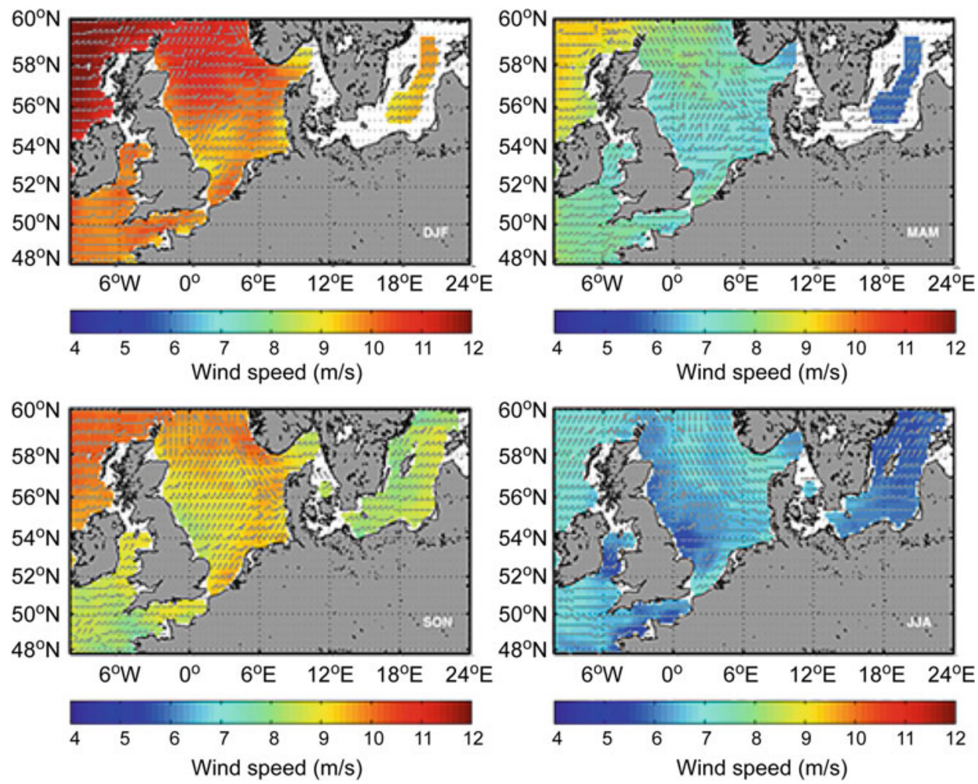


Fig. 1.20 Spatial distribution of seasonal mean wind speed (m s^{-1}) and the most frequently observed wind direction (*arrows*) derived from QuikSCAT satellite data for the period November 1999 to October 2009 (Karagali et al. 2014)

increase in retrieved wind speed. While rain-contaminated QuikSCAT winds could be excluded over sea areas but not always over coastal areas, wind speed estimates from QuikSCAT are higher than in situ observations in areas near land. Uncertainties in the QuikSCAT wind characteristics may also arise due to ice cover in the Baltic Sea, spatial differences in sea surface temperature and sea surface currents (Karagali et al. 2014).

Karagali et al. (2014) compared the QuikSCAT wind speeds with in situ measurements at three locations (platforms) in the North Sea: Greater Gabbard (off the Suffolk coast, UK), FINO 1 (north of the island Borkum, Germany) and Horns Rev 1 (off Esbjerg, Denmark). Owing to the mast's position relative to the wind farms and its proximity to land, only QuikSCAT and in situ winds from the south to north sectors (175°–13°) were considered. In this sector, wind speeds match well on average. The correlation is high (r 0.92) and the mean bias (in situ minus satellite) does not exceed −0.23 m s^{-1}. For wind speeds above 3 m s^{-1} the bias is close to zero with a standard deviation of 1.2 m s^{-1}. Figure 1.21 shows the change in in situ (all three stations) and QuikSCAT wind speeds over the year as well as wind speeds residuals (in situ minus satellite wind speeds). The mean wind speeds exhibit a pronounced annual cycle with a minimum (~7 m s^{-1}) in July and a maximum (~10.5 m s^{-1}) in December and January. Compared with in situ data, QuikSCAT winds are lower from April to July and higher from October to March. The residuals (which do not exceed ±0.5 m s^{1}) show the highest positive values in May and the highest negative values during October to December. For the North Sea area as a whole, an even stronger annual cycle but lower wind speeds results from the NCEP/NCAR reanalysis (Kalnay et al. 1996) for the earlier 40-year period 1959–1997. Siegismund and Schrum (2001) derived a mean wind speed of about 9 m s^{-1} for October to January from this dataset, which is about 50 % higher than for April to August.

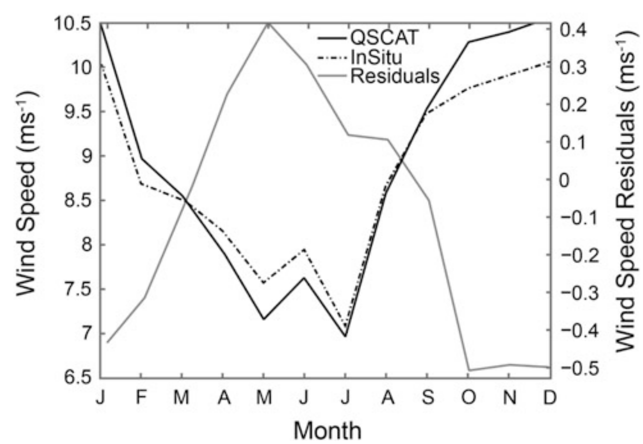


Fig. 1.21 Monthly variation of mean wind speed from QuikSCAT (*black line*), in situ observations from all stations (*dashed line*) and wind speed residuals (*grey line*) (Karagali et al. 2014)

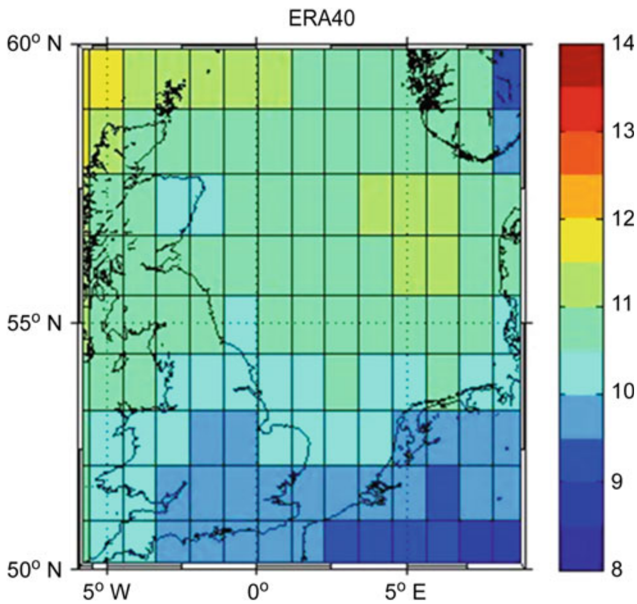


Fig. 1.22 Spatial distribution of mean annual geostrophic wind speed (m s^{-1}) for the period 1971–2000 determined from ERA-40 reanalyses of sea-level pressure data (figure prepared by A. Ganske, Federal Maritime and Hydrographic Agency, Germany)

1.5.2.3 Geostrophic Wind Speeds

Measurements of wind speed are usually insufficient for long-term wind analyses because they are easily affected by inhomogeneities, such as through changes in instrumentation, immediate surroundings, and location. To avoid such deficiencies, Schmidt and von Storch (1993) instead used geostrophic wind speeds derived from air pressure differences. This method is widely used and is often not only based on observed air pressure values but also on reanalysis data. Figure 1.22 shows the spatial distribution of mean annual geostrophic wind speed for the period 1971–2000 determined from ERA-40 reanalyses of SLP. The graphic shows a decrease in geostrophic wind speed from northwest to southeast and wind speeds of 10.5–11.5 m s^{-1} in the central North Sea. These wind speeds exceed those from ship-based observations for the shorter period 1981–1990 (Michaelsen et al. 2000) by more than 2 m s^{-1}.

A comparison of geostrophic wind fields derived from the ERA-40 reanalysis and the higher spatially resolved ERA-Interim reanalyses from the ECMWF (Berrisford et al. 2009) of SLP for the period 1981–2000 show greater spatial variation in the ERA-Interim fields, but differences relative to the ERA-40 geostrophic wind speeds of less than 1 m s^{-1} (Ganske et al. 2012). The shorter period used for this comparison shows higher wind speeds than seen in Fig. 1.22, because it is more influenced by the intensive wind phase from the late 1980s to the end of the 1990s. Additional graphics as well as a discussion of frequency distributions for wind speed in different sea areas and seasons are provided in the E-Supplement to this chapter (S1.5.3).

Evaluating the temporal and statistical characteristics of the coastal wind climate along the North Sea in the ERA-40 reanalysis and the ENSEMBLES RCMs by comparing them against wind measurements in the Netherlands and Germany, Anders (2015) found that ERA-40 reproduces the wind field very well in regions where high quality observational data were assimilated at high temporal frequency. Outside these areas, the RCMs mostly show better agreement with measurements over land. The correlation between ERA-40 and observations is between 0.75 and 0.95, and for most RCMs and observations is between 0.6 and 0.9. The models seem to overestimate mean wind speed at inland sites. For the North Sea region as a whole (but excluding coastal waters), five RCMs generate annual mean wind speeds that differ by less than ± 0.5 m s^{-1} from ERA-40 wind speeds while the remaining seven RCMs differ by ± 1.5 m s^{-1} at most. Six RCMs depict smaller wind fields than ERA-40, partly due to fewer wind speeds above 10 m s^{-1}. More detailed information is reported by Bülow et al. (2013).

The occurrence of high wind speeds across the North Sea from the end of the 1980s to the end of the 1990s agrees well with the increased frequency of strong North Atlantic winter storms (lows with a core pressure of 950 hPa or less—Fig. 1.19). Until 1974/1975 these extreme lows mainly occurred between December and January. Their occurrence has since increased in November as well as March (Franke 2009), which supports the results of Siegismund and Schrum (2001).

Studies estimating storminess from homogenous station pressure records show pronounced decadal variability but no robust sign of any long-term trend (WASA Group 1998; Bärring and von Storch 2004). This is not the case for results from studies using the 20CR reanalysis (Compo et al. 2011). For these, upper percentiles of daily wind speed (Donat et al. 2011) or geostrophic winds derived from air pressure (Krueger et al. 2013) indicate a significant upward trend in storminess in many parts of western and northern Europe. Figure 1.23 shows trends in the annual 95th percentile of daily maximum wind speed and trends in the days with gales during the period 1871–2008. Donat et al. (2011) assumed that the 20CR reanalysis may suffer from some inhomogeneities due to changes of station density.

1.5.2.4 Wind Direction

Wind direction across the different sea areas of the North Sea is determined by the large-scale air pressure distribution. Near islands and coasts winds are modified by orographic effects, depending on the shape and orientation of the adjacent coastlines. Figure 1.24 shows the annual frequencies of wind force as observed from ships in the period 1971–2000

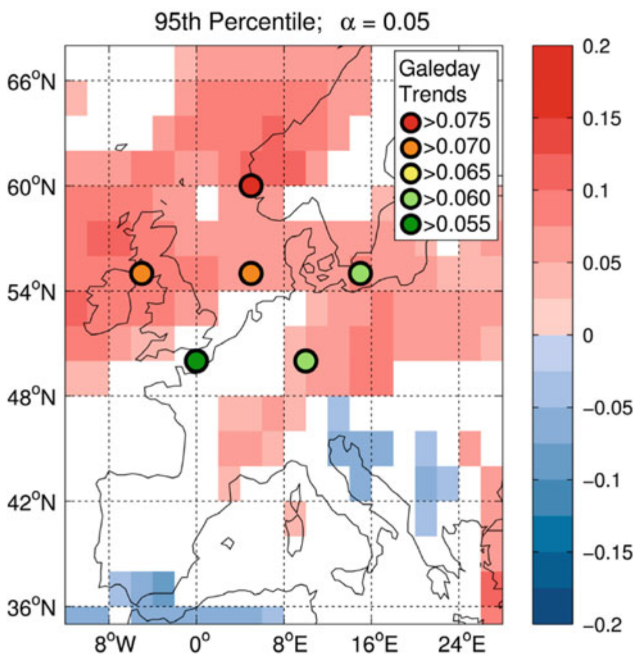


Fig. 1.23 Trends in the annual 95th percentile of daily maximum wind speed in the 20CR ensemble mean for the period 1871–2008 (*unit* standard deviation per 10 years). Only significant trends are plotted ($p \leq 0.05$, Mann-Kendall-Test). *Circles* indicate trends in gale day at that location (Donat et al. 2011)

for four categories (1–3, 4–5, 6–7 and 8–12 Beaufort scale) and eight directions. On average, winds from the southwest and west predominate. Owing to the orography, only in the sea areas between the Shetland Islands and the Norwegian coast (Viking, Utsira north) are winds most frequently from the south; west of the southern Norwegian coast (Utsira south) winds from the northwest predominate. A wind force of 8 Bft and above occurred in 6–9 % of observations for the central and eastern North Sea areas north of 56°N. While the prevailing wind directions from October to March are southerly to southwesterly, northwesterly to northerly winds predominate in the northern and central North Sea in spring and summer. Over the course of a year, easterly winds are most frequent in May, when the frequency of winds exceeding 6 Bft is lowest.

Frequency distributions of daily mean wind direction from the ERA-40 reanalysis and ENSEMBLES RCMs for the four sea areas considered for the period 1971–2000 are discussed by Bülow et al. (2013).

1.5.2.5 Sea Breeze

With calm conditions and strong insolation (i.e. high pressure situations), a local wind regime develops due to uneven heating of the land and sea surface in coastal areas. According to Steele et al. (2015), who referred to Atkinson (1981) and Simpson (1994) ‘The sea breeze is defined as a circulation which is induced by a thermal contrast, between the land and sea that overcomes the strength of the background or gradient wind’. The development of sea breezes occurs most often in spring and summer, when the North Sea is relatively cold and the sun reaches its minimum zenith angle (Tijm et al. 1999). At mid-latitudes, sea breezes usually have an inland penetration of 5–50 km (Atkinson 1981). In southern England (Simpson et al. 1977) and the Netherlands (Tijm et al. 1999), favourable conditions for sea-breeze development may result in inland penetration of 100 km or more. Offshore sea breezes can extend similar distances (Arrit 1989; Finkele 1998). Thus, sea breezes are an important component of the coastal wind climate and are of growing interest due to the development of wind farms in offshore and coastal areas and their need for reliable wind forecasts. Based on data from the Weather Research and Forecasting model (WRF, version 3.3.1; Skamarock and Klemp 2008), Steele et al. (2015) derived a sea-breeze climatology for five coastlines around the southern North Sea by considering three sea-breeze types (as described by Miller et al. 2003): a pure sea breeze (where the sea breeze forms in opposition to the gradient wind) and the corkscrew and the backdoor sea-breeze, where the gradient wind has an along-shore component. Pure sea breezes induce offshore calm zones, defined as regions where the 10-m simulated wind is <1 m s^{-1}. The corkscrew sea breeze is the strongest type of sea breeze. They induce coastal jets, which are defined as local wind speed maxima within 1 km of the coast (Capon 2003). The 10-m simulated wind speeds reach about 5 m s^{-1} and cause a net increase in wind energy on a given day of up to 10 % (Steele et al. 2015). The backdoor sea breeze is the weakest type of sea breeze. In many cases an intensifying backdoor sea breeze reduces the extent of the offshore calm zones. Table 1.1 shows the annual frequency of the different sea-breeze types for each coastline in the period 1 January to 31 December 2012. There is clearly significant variability between coasts and this is attributed to coastal orientation relative to the prevailing wind direction. Season length also differs between coasts; mostly extending from May to September, along the coasts of East Norfolk, Suffolk and Essex sea breezes can occur from March to October. Variations in coastal orientation or the presence of another coastline can cause interactions between sea breezes.

The magnitude of the differential heating and the strength of the opposing large-scale wind flow are important for the offshore extent and inland penetration of the sea breeze. Studies in southern England show that most sea breezes occur in conditions of near-calm or with offshore winds of less than 2–3 m s^{-1} at the surface (Tijm et al. 1999). Using two-dimensional model simulations, Finkele (1998) found the offshore sea-breeze propagation speed (−3.4 m s^{-1}) to be about double that for inland sea-breeze propagation (1.6 m s^{-1}) under light (−2.5 m s^{-1}) offshore geostrophic

Fig. 1.24 Annual distribution of wind forces in Beaufort (Bft) derived from ship observations for different sea areas of the North Sea in the period 1971–2000. The length of each branch is proportional to the percentage frequency of the respective wind direction and wind force class. *Numbers in circles* denote the frequency of calm conditions (courtesy of the German Meteorological Service)

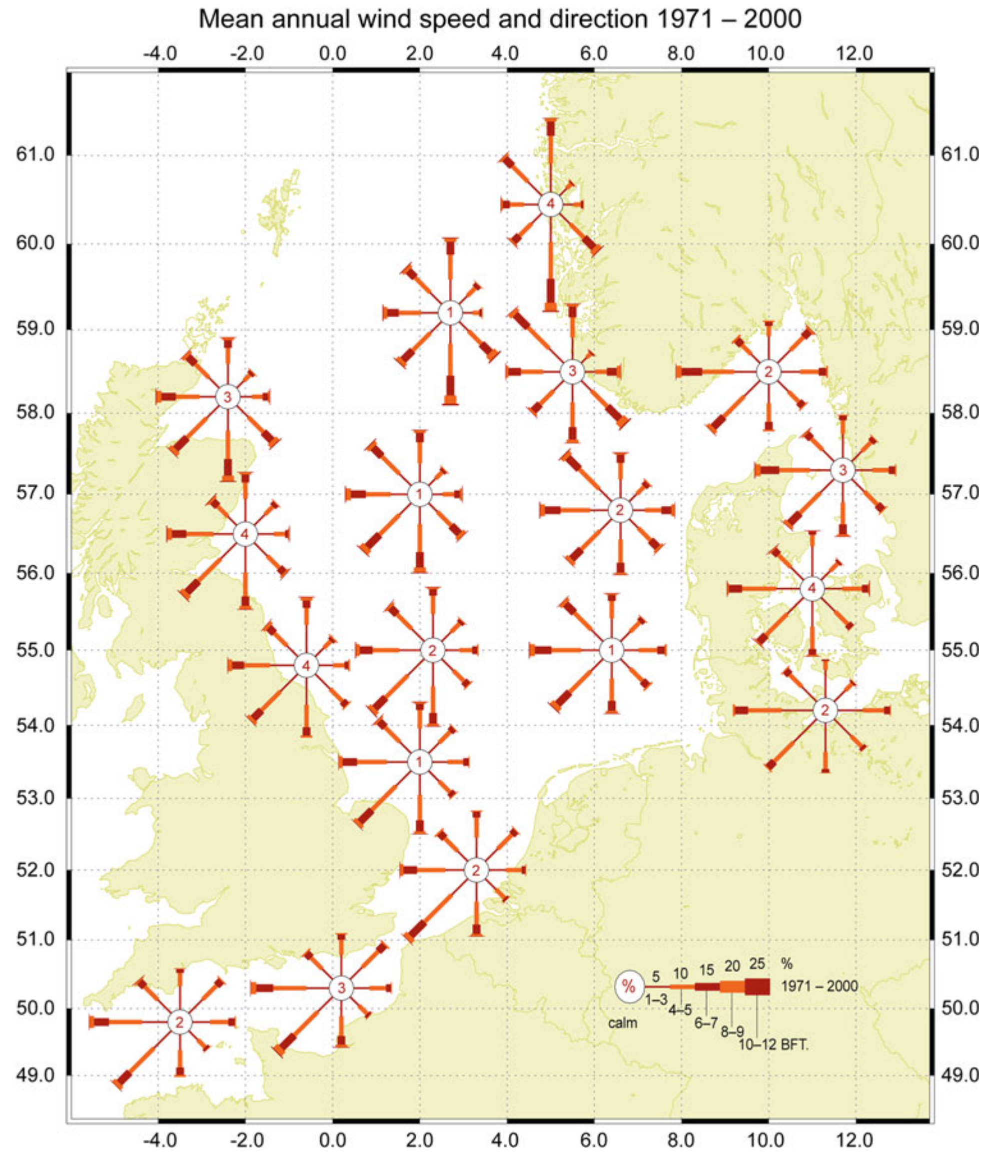


Table 1.1 Sea-breeze frequency (days) by sea-breeze type on southern North Sea coastlines between 1 January and 31 December 2012 (Steele et al. 2015)

Coast	Pure	Corkscrew	Backdoor	Total
North Norfolk	117	96	51	264
East Norfolk	166	169	0	335
Suffolk + Essex	46	167	13	226
Netherlands	146	76	71	293
South Kent	21	122	9	154
Total	496	630	144	1270

wind conditions (without a coast-parallel geostrophic wind component and a maximum sensible heat flux of about 380 W m^{-2}), which agreed well with measurements. The offshore sea-breeze propagation speed is defined as the speed at which the seaward extent of the sea breeze grows offshore. It is almost constant under light offshore geostrophic wind conditions and non-linear under moderate (−5.0 m s^{-1}) and strong (−7.5 m s^{-1}) geostrophic wind conditions. In the case of light offshore geostrophic wind conditions the inland sea-breeze propagation speed is almost constant until early afternoon and then increases during late afternoon and through the evening, which agrees with the findings of Tijm et al. (1999). Moderate geostrophic winds cause a non-linear inland sea-breeze propagation speed with the sea breeze slowing after having reached the coast. For strong geostrophic winds the sea-breeze circulation stays totally offshore.

The onshore sea breeze during the day alternates with the oppositely directed, but usually weaker, land breeze which develops during the night.

1.5.3 Air Temperature

1.5.3.1 Monthly and Annual Means

Offshore, the temperature of the lower atmosphere is mainly determined by sea surface temperature. For the North Sea, the two branches of the North Atlantic Current entering through the English Channel and between Scotland and the Shetland Islands respectively, have a significant influence (see Sect. 1.4). Air temperature is also influenced by the European land masses and latitude. The result is that mean air temperatures over the North Sea are above average for sea areas at similar latitudes elsewhere (Korevaar 1990). Spatial distributions of monthly mean air temperature across the North Sea region based on observations from ships and light vessels are available for the periods 1961–1980 (Korevaar 1990), 1981–1990 (Michaelsen et al. 2000) and 1971–2000 (Stammer et al. 2014). The latter are displayed in Fig. 1.25 and show only small differences relative to the climatology of Michaelsen et al. (2000), and for various periods the monthly means are highly correlated with the NCEP-RA1 (1950–2010), NCEP-RA2 (1979–2010), ERA-Interim (1979–2010), ERA-40 (1957–2002) and 20CR (1950–2010) reanalyses. The correlation coefficients of 0.98 and 0.99 exceed the 99 % level of significance (Stammer et al. 2014). Comparisons of the ERA 40 reanalysis with the ENSEMBLES RCMs for the period 1971–2000 are reported by Bülow et al. (2013). Annual air temperatures of the ERA-40 reanalysis are roughly 7.0–8.0 °C in the coastal areas of Norway and Sweden and 12–13 °C in the western English Channel. Due to differences in radiation absorption and heat capacity, the air over the North Sea is warmer than over the continent from autumn to spring and cooler from May to July. In winter (December to March), temperatures decrease from southwest to northeast, due to the declining influence of the warm North Atlantic Current and the advection of maritime air masses towards the east and the increasing influence of cold continental air masses. The lowest monthly means occur in February, ranging from below 0 °C in the Skagerrak and Kattegat area to 8–9 °C in the western English Channel. Towards summer, warming of the air over land proceeds faster and stronger than over the sea, leading to a shift in the orientation of the isotherms. The southern part of the North Sea is then warmer than the other regions. August is the warmest month of the year.

The annual cycle of mean air temperature at land stations in the North Sea region is shown in Fig. 1.26. Warming in summer is lowest in the far northwestern area (Lerwick on the Shetland Islands), where the highest mean monthly temperature is only 12 °C (August). The highest winter temperatures occur in Brest, in the western part of northwestern France, due to the influence of the North Atlantic Current.

The amplitudes of daily temperature as well as those of monthly mean temperature are more pronounced in coastal areas than in the central North Sea. Air temperatures show high variability, especially in winter, as reflected in a large standard deviation. In the period 1981–1990, the standard deviation increases from about 1 °C in the northwestern North Sea region, to about 3 °C along the western coast of Germany and Denmark and about 4 °C along the Swedish coastline in the western Baltic Sea region. The standard deviation is lowest from April to October and especially in summer with values mostly below 1.0 °C. In the inflow area between Scotland and the Shetland Islands it is about 0.4 °C in July (Michaelsen et al. 2000).

Figure 1.27 shows variation in air temperature over the course of a year from ship-based observations for the period 1950–2007 for different sea areas of the North Sea (BSH 2009). These distributions agree well with those for eight sea areas 2° × 2° in extent and four light vessels (Korevaar 1990), although the sea areas compared are not congruent. The coldest month is February with mean temperatures between 2 °C in the German Bight and 9 °C south of Scilly. The warmest month is August with mean temperatures between 13 °C in the area Shetland/Orkneys and about 15.5 °C in the German Bight and southern North Sea. Annual amplitude ranges from about 8 °C in the sea areas Shetland/Orkneys and South of Scilly and 14–15 °C in the sea areas Skagerrak and German Bight. The annual cycles for the northwestern, northeastern, southwestern and southeastern parts of the North Sea based on ERA-40 data and various ENSEMBLES RCMs show considerable deviations with differences of up to 2 °C in winter, but agree well in June and July.

1.5.3.2 Extremes

Significant deviations from the monthly mean are linked to specific air pressure patterns. The warmest European seasons since records began, autumn 2006 and winter 2006/2007 had temperature anomalies of up to 4 °C across the land areas surrounding the North Sea (WMO 2007, 2008). While the unusually warm autumn was linked to a negative NAO phase (−1.62 in September and −2.24 in October), the warm winter was associated with a positive

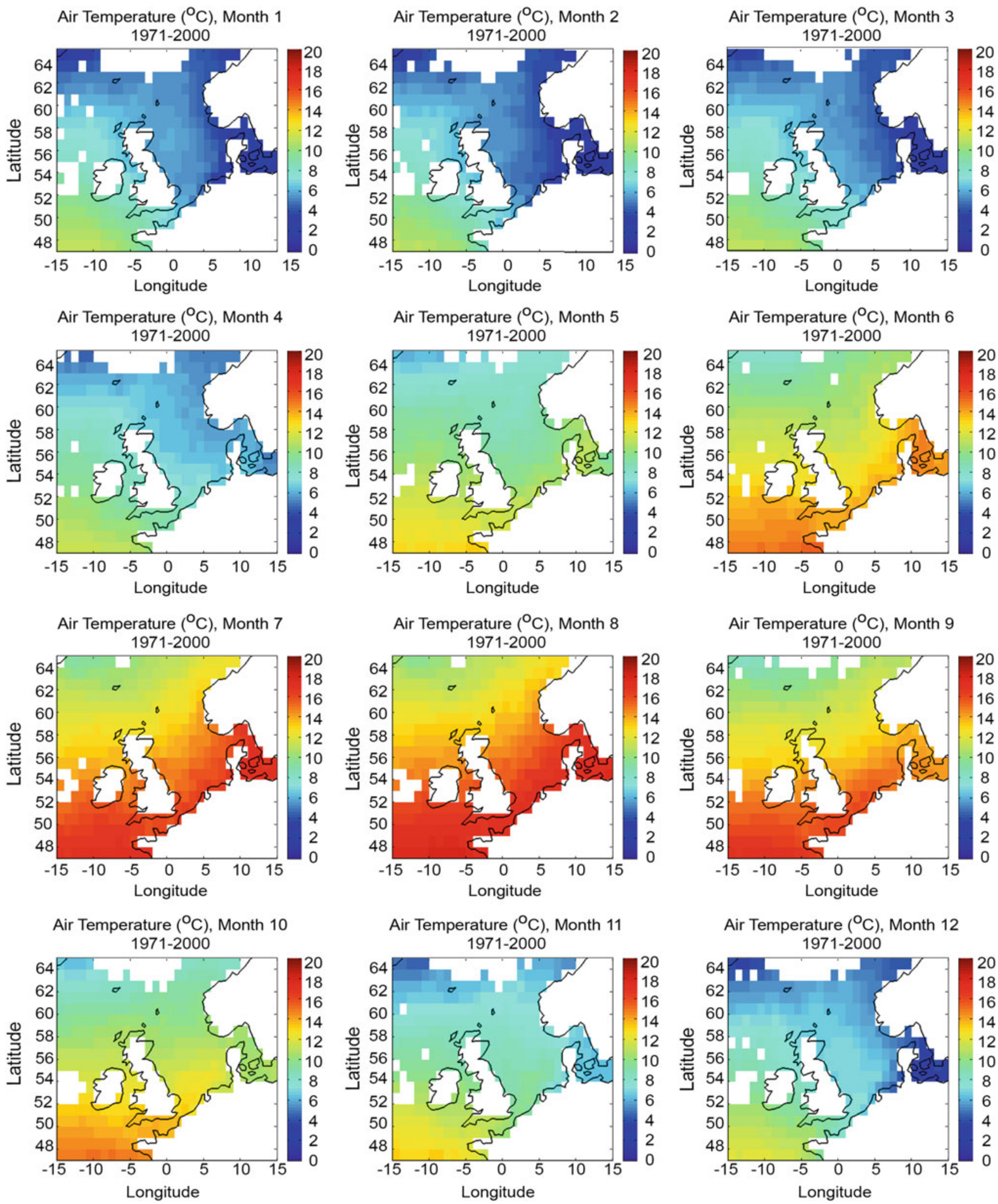


Fig. 1.25 Spatial distribution of monthly mean air temperature (°C) across the North Sea region based on in situ data for the period 1971–2000 (Stammer et al. 2014)

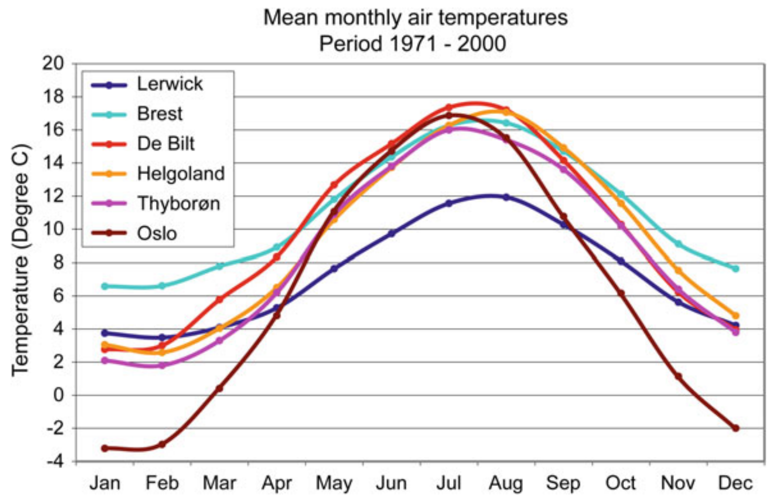


Fig. 1.26 Annual cycle in mean air temperature (°C) at land stations around the North Sea for the period 1971–2000. Station locations are shown in the E-Supplement to this chapter (Fig. S1.5.1)

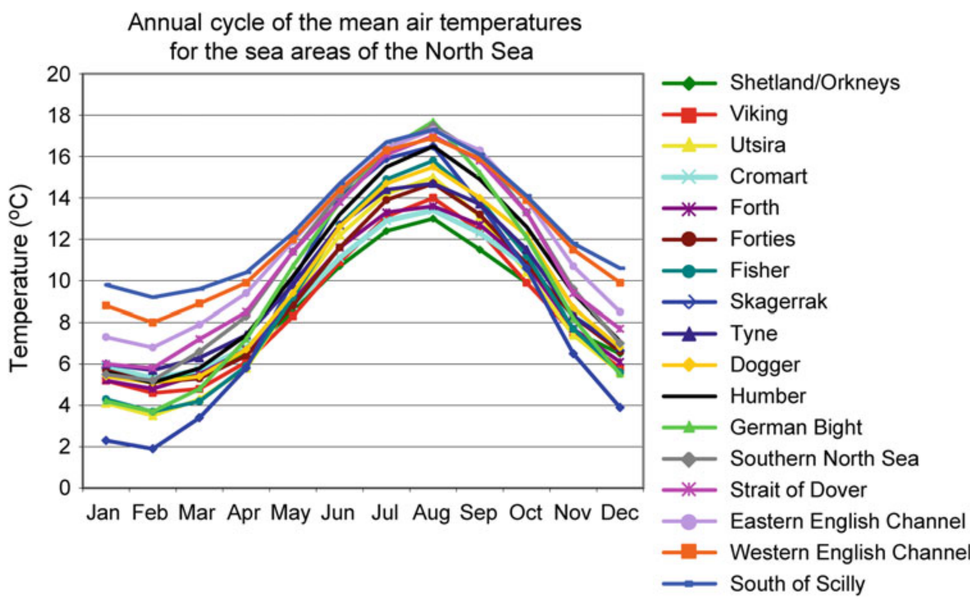


Fig. 1.27 Annual cycle in air temperature (°C) for the sea areas of the North Sea (BSH 2009). Sea area locations are shown in the E-Supplement to this chapter (Fig. S1.5.1)

NAO phase (+1.32 in December and +0.22 in January) (Luterbacher et al. 2007). The record negative NAO (−2.4) in winter 2009/2010 was linked to a cold and snowy winter influencing the area from northwestern Europe to central Asia (WMO 2010; Osborn 2011). By coupling mean SLP fields with temperature extremes (monthly occurrence of cold night and warm day temperatures) in Europe for the period 1961–2010, Andrade et al. (2012) found that in winter and spring the NAO is not only the major driver of mean temperature, but also of the occurrence of temperature extremes. Andrade et al. (2012) showed the leading modes for all four seasons. For winter, spring and autumn, there is coherent coupling for both extreme maximum and extreme minimum temperatures. The East Atlantic Oscillation defined by Barnston and Livezey (1987) also helps explain the occurrence of warm temperatures due to the advection of warm air with southwesterly winds into the region. This is the leading mode for temperature extremes in autumn. Cold air from the North and an absence of cloud cover are responsible for very cold nights on land. In summer, exceptionally long warm episodes are linked to a blocking high pressure system centred over the British Isles or over the European continent, stopping the westward propagation of North Atlantic pressure systems and leading to warm air advection and low cloudiness.

Table 1.2 shows extreme minimum and maximum air temperatures, determined from ship-based observations for the period 1950–2007 (99.9th percentile, the values were inferior to or exceeded, respectively, in 0.1 % of all measurements). Due to good data coverage, they can be considered more representative for the different North Sea areas than extreme temperatures derived from ERA records because ERA-40 temperatures are available at 6-h intervals only and are also smoothed by gridding.

Table 1.2 Extreme minimum and maximum air temperature (°C) for various sea areas from ship-based observations in the period 1950–2007 (BSH 2009)

Sea area	Extreme minimum temperature	Extreme maximum temperature
Shetland/Orkneys	−2	20
Viking	−4	21
Utsira	−8	23
Cromarty, Forth, Forties	−3	21
Fisher	−6	24
Skagerrak	−9	24
Tyne	−1	22
Dogger, Humber	−4	24
German Bight	−6	25
Southern North Sea	−5	25
Strait of Dover	−5	24
Eastern English Channel	−2	25
Western English Channel	0	25
South of Scilly	2	24

1.5.4 Precipitation

Precipitation across the North Sea is mainly supplied by Atlantic low pressure systems and their associated frontal systems. Their variation in occurrence and storm tracks causes regional and interannual variability. Strong positive phases of the NAO tend to be associated with above-average precipitation, especially over the northern North Sea area in winter (Trigo et al. 2002; Hense and Glowienka-Hense 2008).

1.5.4.1 Precipitation Frequency

In situ measurements of precipitation over the sea are extremely problematic. Many factors influence measurements, such as the movement and shape of the vessel, sea spray and wind. There are few measured precipitation data for sea areas. Those that are available are measured on light-vessels using a conical rain gauge, and on oil and gas platforms. The fleet of voluntary observing ships (VOS) does not measure precipitation amount, only information about the occurrence of precipitation. Analyses of data for different sea areas of the North Sea show precipitation frequency is mostly highest in November, sometimes in December or January (BSH 2009). Also, that precipitation frequency is higher over the northern North Sea (about 20–27 % of observations) than the English Channel, western North Sea and Skagerrak (10–16 % of observations), the latter due to lee effects of the Scandinavian mountains. The probability of precipitation is lowest in May.

1.5.4.2 Precipitation Amount

Prior to the satellite era, precipitation amounts across the North Sea were estimated in different studies by analysing and interpolating gauge measurements at coastal stations. As it was assumed that precipitation amounts for sea areas are generally less than over neighbouring land areas, different reduction factors were applied to coastal data leading to a broad range of estimates for the annual total for the North Sea area as a whole (440–800 mm; Barrett et al. 1991). Since the late 1970s, precipitation information has been remotely sensed from satellites. Their advantage is the provision of values for regions with few in situ measurements and the provision of spatially continuous data. However, satellite-based precipitation is not measured directly, but derived from radiance measurements. Validation of satellite-based data with in situ measurements from rain gauges on ships within the Baltic Sea shows precipitation is underestimated by remote sensing, because the detectability of small-scale precipitation typical of convective weather conditions is too low, although the detectability in cases of prevailing stratiform clouds fits well (Bumke et al. 2012). A first estimation for mean monthly, seasonal and annual precipitation totals was determined from the Scanning Multispectral Microwave Radiometer (SMMR) data on the Nimbus-7 satellite for the period 1978–1987 by retrieving the relationship of 37 GHz horizontal channel brightness temperatures to rain-rates (mm h^{-1}) from the calibration of the SMMR data by contemporaneous data from the Camborne radar station (Cornwall) of the UK Meteorological Office and published by Barrett et al. (1991). Barrett et al. examined the North Sea region from 47° to 63°N and 03°W to 13°E, excluding the land and mixed land/sea parts. Mean annual precipitation for the period October 1978 to August 1987 was estimated at 425 mm. Andersson et al. (2010) investigated monthly means of the quality-controlled

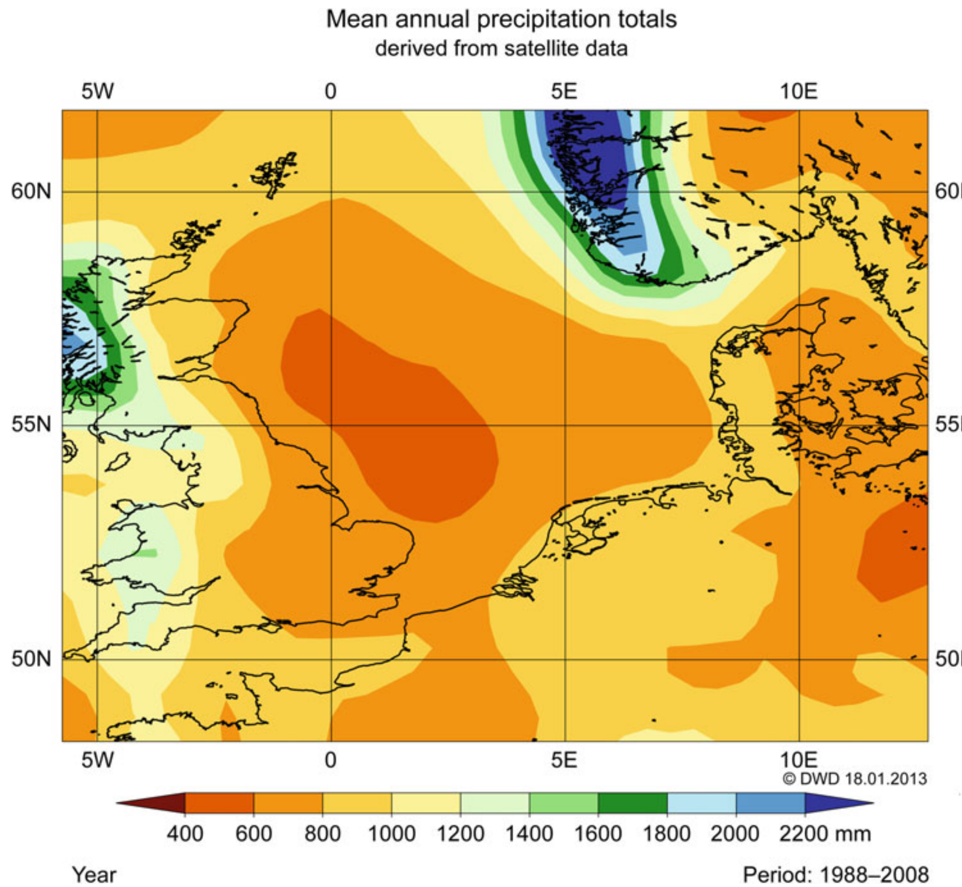


Fig. 1.28 Mean annual spatial distribution of precipitation (mm) across the North Sea region derived from the combined HOAPS-3 and GPCC data set for the period 1988–2008 (figure prepared by the German Meteorological Service, DWD)

HOAPS-3 (Hamburg Ocean Atmosphere Parameters and Fluxes from Satellite) data set with a grid resolution of 0.5° × 0.5° for the period 1988–2008. The data were derived from the Special Sensor Microwave Imager (SSM/I) operating on the polar-orbiting Defence Meteorological Satellite Program (DMSP) satellites for the sea area. For the land area this was completed with 'Full Data reanalysis Product Version 4' provided by the Global Precipitation Climatology Centre (GPCC; Rudolf and Schneider 2005), which only uses land-based rain gauge measurements. Figure 1.28 shows the annual spatial distribution of HOAPS precipitation data for the North Sea region calculated by the German Meteorological Service. Mean annual precipitation for the region from 50° to 62°N and 03°W to 13°E and excluding the land and mixed land/sea parts is 810 mm. This significant difference is partly explained by the different analysis periods (see below) and ongoing improvements in the instrumentation onboard satellites. But further research will be necessary, since comparisons of the ERA-40 reanalysis with the ENSEMBLES RCMs (Bülow et al. 2013) and those from different reanalyses with data sets of gridded observations from precipitation gauges (Lorenz and Kunstmann 2012) display considerable differences. An example for the central North Sea area (1.5–5.5°E, 54–58°N) is presented in Table 1.3 including a comparison of mean annual precipitation derived from the HOAPS satellite data and four reanalyses: ERA-Interim, ERA-40, NCEP/CFSR and MERRA.

Precipitation amount shows considerable intra-annual (see a selection of months in the E-Supplement Fig. S1.5.8) and interannual variability. For the reference period October 1978 to August 1987, February and/or April were the driest months. February 1986 was unusually dry with widespread means of less than 10 mm, even in coastal areas. Some areas were even rainless (e.g. in the region of De Bilt). Because February 1985 and 1986 received well below-average precipitation, the February mean for the period 1979–1987 was about 10 mm less than for the period 1971–2000 and about half the average for the period 1988–2008. The difference was greatest in the Shetland Islands. At Lerwick, the February mean was 62 mm for the period 1979–1987, 108 mm for 1971–2000 and 144 mm for 1988–2008. The HOAPS data show May as the driest month with average precipitation amounts of less than 25 mm in an extended area east and north of the British Islands. Spring is the driest season except in the western English Channel and the region around the Shetland Islands. Precipitation amount is mostly highest in autumn. The increase in precipitation amount in autumn is caused by the increase in low-pressure activity and convective rains due to the destabilisation of

Table 1.3 Mean annual precipitation (mm) for the central North Sea area (1.5–5.5°E, 54–58°N) derived from the satellite data set HOAPS and four reanalyses

Data set	1979–2001	1988–2008
HOAPS	–	643
ERA-Interim	812	800
ERA-40	691	–
NCEP-CFSR	966	1000
MERRA	754	772

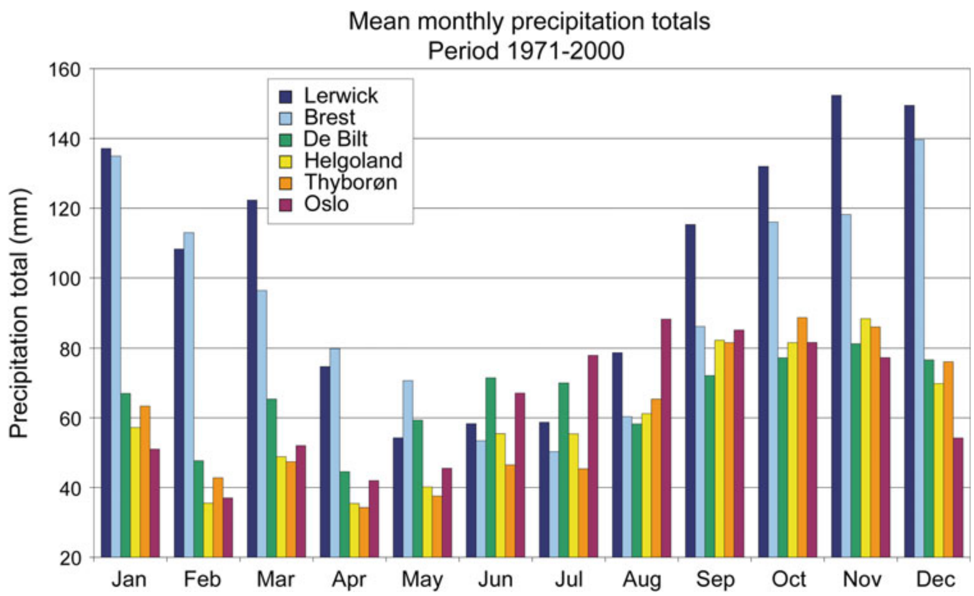


Fig. 1.29 Annual cycle in precipitation amount (mm) at selected North Sea stations for the period 1971–2000. Station locations are shown in the E-Supplement to this chapter (Fig. S1.5.1)

cold air masses moving over the warm North Sea (Lefebvre and Rosenhagen 2008).

In coastal areas, precipitation is intensified by coastal convergence and increasing friction effects. The annual cycle of the precipitation totals for stations in coastal areas of the North Sea region for the reference period 1971–2000 are shown in Fig. 1.29. There are significant differences in precipitation amount from October to April when the stations around the northern North Sea and the western part of the English Channel record about twice the amount of the other regions.

In winter, there is a pronounced correlation between precipitation amount in the northern North Sea region and the NAO. A positive NAO phase is linked to above-average precipitation, especially in Scotland and Norway and below-average precipitation in the Mediterranean region (Hense and Glowienka-Hense 2008). Studies for a box across northern Europe including the North Sea except for the southern part (10°W–20°E 55°–75°N) show the correlation between precipitation amount and NAO in winter (DJFM) seems to be stronger for the land area (correlation coefficient $r = 0.84$) than across the sea ($r = 0.38$), with all correlations statistically significant at the 99 % confidence level of the t-test (Andersson et al. 2010).

1.5.5 Radiation

1.5.5.1 Sunshine Duration

Sunshine duration depends on latitude and daytime cloud cover conditions. Measurements of sunshine duration are not included in the observational routine of the VOS fleet and statistics are not derived from measurements on light-vessels.

Annual cycles for some land stations in the North Sea region are shown in Fig. 1.30. Because there is a gradient in sunshine duration from land to sea, their representativeness for sea areas is limited. Change in daylength throughout the year shows a predictable pattern with sunshine duration in the North Sea region at a maximum in summer and a minimum in winter. On average May and July are the sunniest months with about 170 h of sunlight in Lerwick, 250 h in Helgoland and 290 h in Skagen Fyr (adjusted, not shown) for the period 1971–2000. Sunshine duration is lowest in

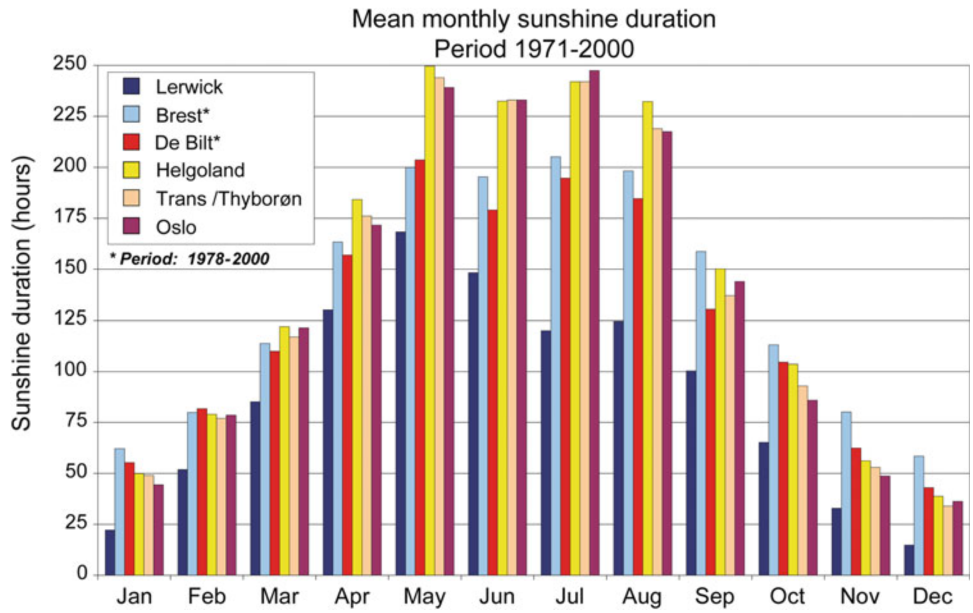


Fig. 1.30 Annual cycle of mean sunshine duration (hours/month) at selected land stations for the period 1971–2000. Station locations are shown in the E-Supplement to this chapter (Fig. S1.5.1)

December with mean values of 15 h in Lerwick to 60 h in Brest. From May to August, sunshine duration in the northern and western parts of the North Sea and the English Channel is about 20–50 h less than in the southern and eastern parts.

Recent research studies use various methods for deriving sunshine duration from satellite observations. For example, using cloud type data (Good 2010) or solar incoming direct radiation (Kothe et al. 2013), based on observations from the SEVIRI (Spinning Enhanced Visible and Infrared Imager) instrument on the Meteosat Second Generation satellite. A comparison of products generated by both methods for Europe with in situ observations showed that satellite-based sunshine duration is within ±1 h day^{-1} compared to the high-quality Baseline Surface Network or surface synoptic station measurements (Kothe et al. 2013). The procedure for deriving sunshine duration from satellite data for an area including the North Sea was recently established by the UK MetOffice, but the data have not yet been analysed from a climate perspective.

1.5.5.2 Global Radiation

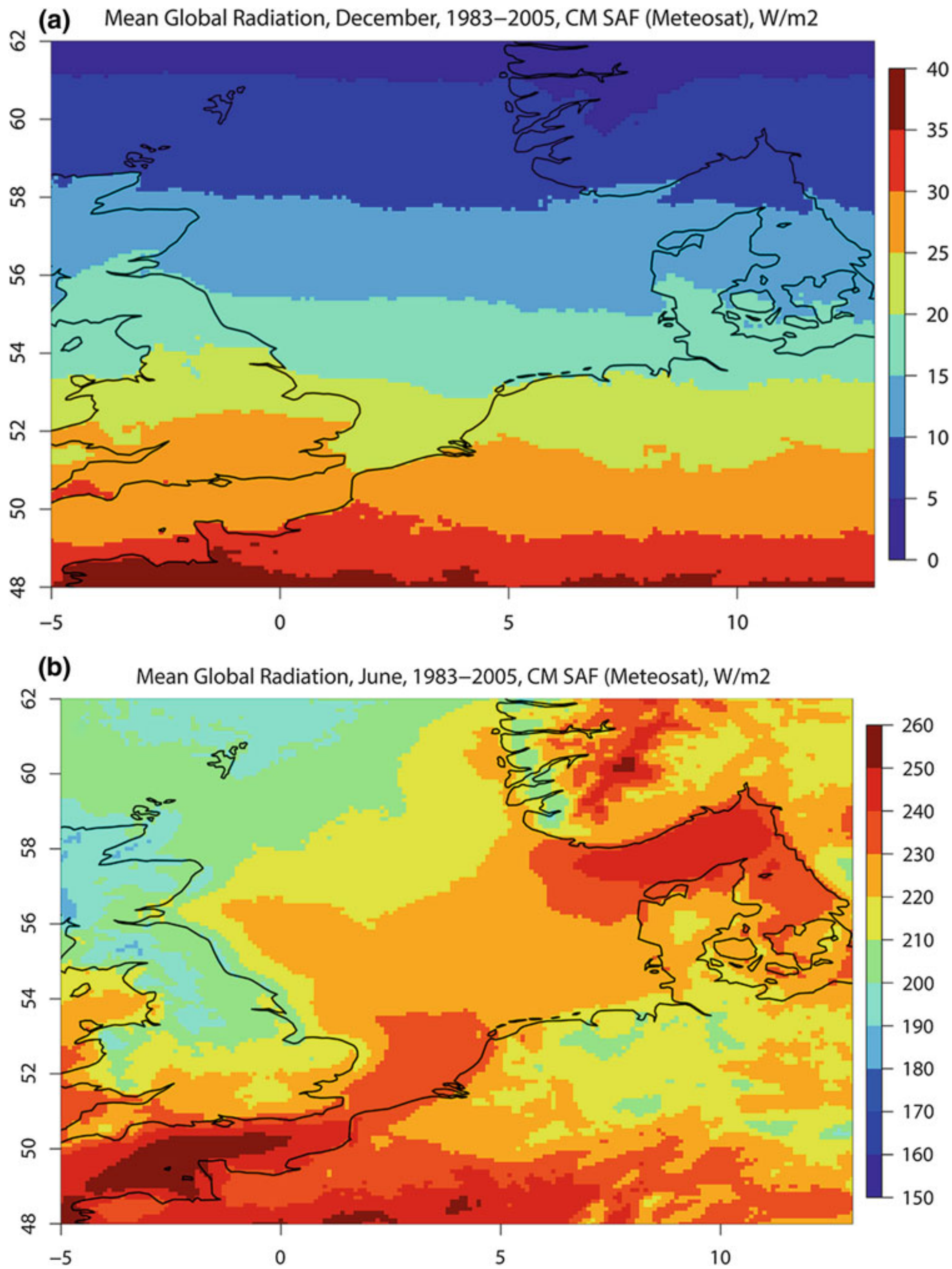
There is a strong relationship between sunshine duration and global radiation. Global radiation is the sum of direct solar radiation and diffuse sky radiation received by a unit horizontal surface. It is a function of latitude and depends on atmospheric scattering and absorption in the presence of clouds and atmospheric particles. More than 90 % of solar irradiance is absorbed by the ocean having an important impact on thermal structure and density-induced motions within the ocean (Bülow et al. 2013). In the network of EUMETSAT, the Satellite Application Facility on Climate Monitoring (CM SAF) provides a satellite-based data set of surface irradiance (Posselt et al. 2012). In the North Sea region, mean annual global radiation increases from north to south with the highest annual average irradiance of 130–140 W m^{-2} in the English Channel, for results derived from observations of the MVIRI instruments on the geostationary Meteosat satellites for the period 1983–2005 (compare Fig. S1.5.11 in the E-Supplement).

Global radiation exhibits a pronounced seasonal cycle with a minimum in winter shown by the December irradiance and a maximum in summer shown by that for June (Fig. 1.31). Over the course of a year, global radiation varies from about 5 to 200 W m^{-2} in the northern North Sea and between 25–30 and 230–240 W m^{-2} in the English Channel. The highest values are recorded in the Skagerrak (250 W m^{-2}) and English Channel (260 W m^{-2}) in June. In both areas, lee effects may account for this high irradiance as well as the influence of the ridge of the Azores High which stretches towards central Europe across the English Channel in summer (compare Fig. 1.17).

1.5.6 Cloud Cover

The spatial distribution of mean annual cloud cover for the period 1982–2009 is shown in Fig. 1.32 based on measurements by the Advanced Very High Resolution Radiometer (AVHRR) on the polar-orbiting NOAA and Metop satellites (CLARA data set). Cloud cover is highest in the northwestern sea areas and decreases southward. In coastal areas, cloudiness is affected by lee and luv effects depending on the exposure of the coastline to the prevailing

Fig. 1.31 Mean monthly global radiation (W m^{-2}) in December (*upper*) and June (*lower*) for the period 1983–2005 derived from satellite data by CM-SAF



wind direction. The Skagerrak is especially affected by a pronounced reduction in cloudiness due to the lee effect of the Scandinavian mountains. In particular, during weather situations with high reaching northerly airflow at the rear of large low pressure systems air humidity decreases significantly on their leeward side resulting in cloud dissolution as shown in Fig. 1.33. This Norwegian fohn effect is observed about 10 to 20 times a year. The mean monthly and annual cloud cover derived from ship observations (BSH 2009) shows cloud cover is generally lowest in May, the month with a high frequency of anticyclonic situations, and highest in winter, except for the sea areas along the northeastern coast of Great Britain where lee effects in the predominantly westerly air flow cause a reduction. The amplitude of the annual cycle is smallest (0.3 octa) in the sea areas Forth and Tyne and highest (1.5 octa) in the Skagerrak, where the cloud cover is lowest in summer.

A comparison of the mean annual cycle in cloud cover derived from the CLARA data set and ERA-40 over the German Bight for the period 1982–2002 shows an underestimation in the reanalysis data, which is smallest in winter and highest in summer (Bülow et al. 2014).

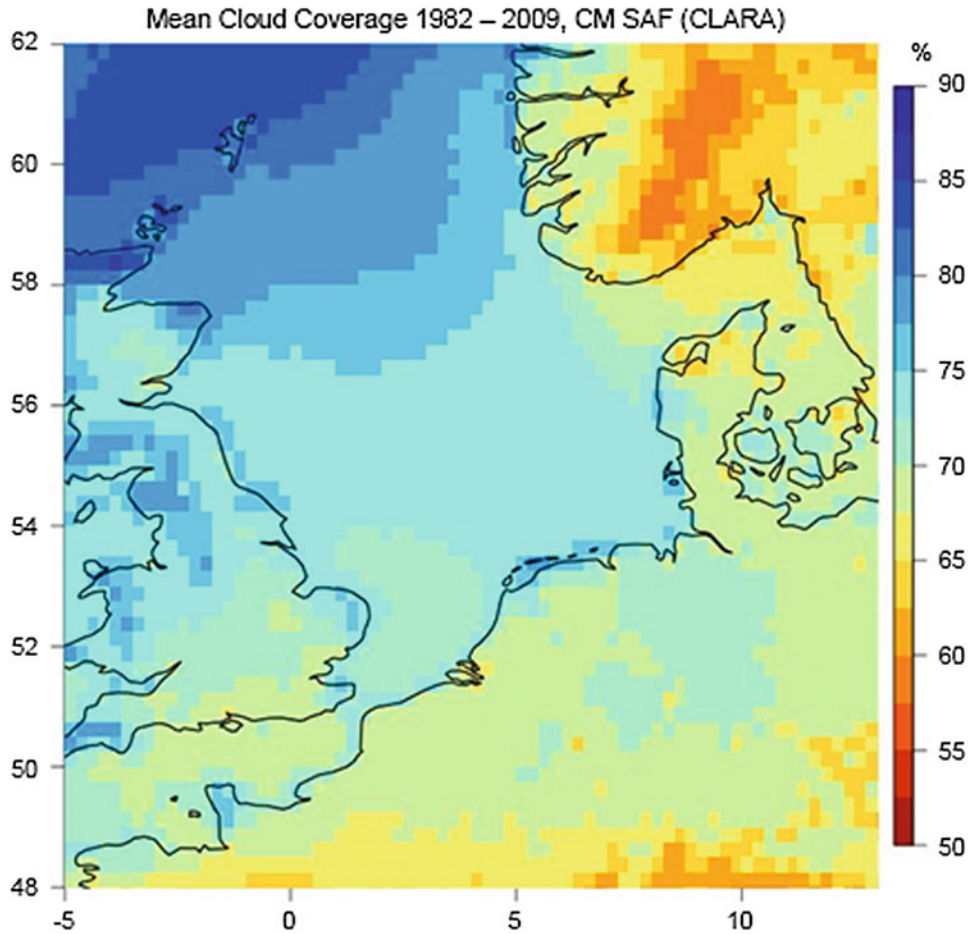


Fig. 1.32 Mean annual cloud coverage (in percentage) for the period 1982–2009 derived from satellite data by CM-SAF

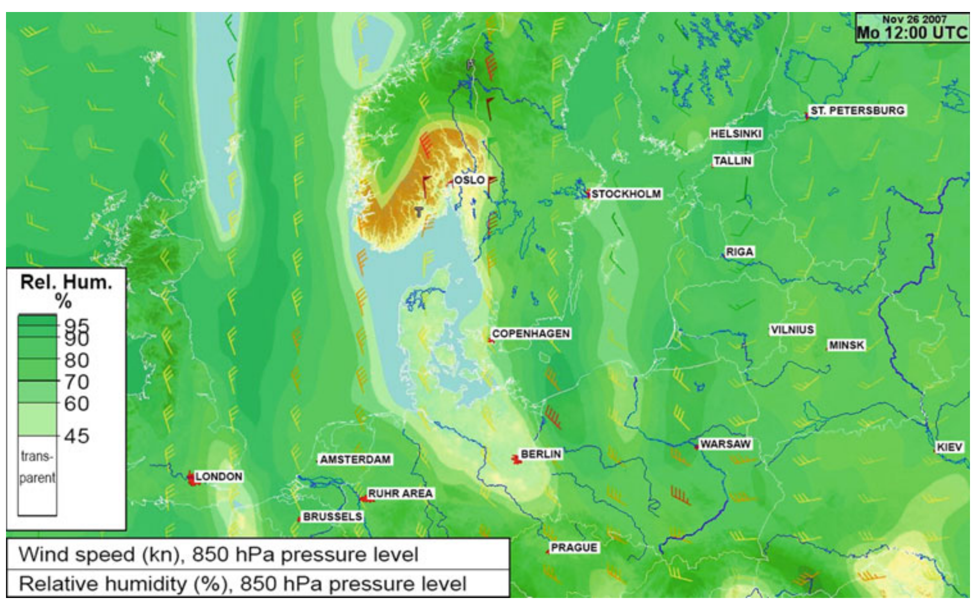


Fig. 1.33 Example of the lee effect off Scandinavia (Lefebvre and Rosenhagen 2008)

Spatial distributions of mean monthly cloud cover derived from satellite data across the eastern North Atlantic Ocean and Europe since 2009 are available.[5]

1.6 Marine and Coastal Ecosystems

Merja Helena Tölle, Franciscus Colijn

The semi-enclosed North Sea region is one of the biologically richest and most productive regions in the world (Emeis et al. 2015). Its ecosystem comprises a complex interplay between biological, chemical and physical compartments. Humans also play a major role in this system integrating social and economic activities (see Sect. 1.2). As is the case for most marine and coastal ecosystems the North Sea shows a high degree of natural variability, which hampers a distinction between human and natural causes of change. High nutrient loads from terrestrial and anthropogenic sources are one of the major contributors to the high levels of primary production in coastal waters. Fisheries and contaminant inputs constitute the main drivers of change in the North Sea biota. However, complex interactions within the food web make it difficult to discriminate between the effects of natural and anthropogenic factors.

1.6.1 Ecological Habitats

The North Sea is delimited by Dover Strait between the UK and France to the south (50°30′N 2°E), to the north by a line between Scotland and Norway north of the Fladen Ground (62°N), and by the Kattegat between Sweden and Denmark to the east (see Sect. 1.2 for more details). The North Sea can be subdivided into the shallow Southern Bight with vertically mixed water masses and a deeper, seasonally stratified northern part which is subject to significant nutrient-rich North Atlantic inflow. The southern North Sea receives warm oceanic water through the English Channel, experiences strong tidal currents, has a high sediment load, and receives large amounts of contaminants and nutrients from continental rivers discharging into the coastal zone. The whole North Sea is subject to atmospheric deposition from land- and ship-based sources.

The North Sea coastline includes a variety of habitats, such as fjords and rocky shores, estuaries and coastal deltas, beaches with dunes, banks including sandbanks, cliffs, islands, salt marshes and intertidal mudflats (see detailed review in Sect. 1.2). These coastal habitats are mainly characterised by a seabed covered by seagrasses and macroalgae or by sandy, gravelly or muddy sediments (ICES 2011). Coastal and estuarine habitats serve as spawning and nursery grounds for fish (Van Dijk 1994) and breeding grounds for coastal birds.

1.6.1.1 Wadden Sea

About 60 % of the intertidal area at the south-eastern North Sea shores occurs in the Wadden Sea (Reise et al. 2010). The Wadden Sea is a very shallow wetland area with a high sediment load in the channels due to strong tidal currents and waves. Consequently this region features sandy mud flats and shoals, seagrass meadows, and oyster and mussel beds. It serves as a rich food source and habitat for seals, waders, gulls, ducks and geese (Reise et al. 1994), provides a resting and feeding area for millions of migratory birds, and is used as a nursery ground by fish (e.g. plaice *Pleuronectes* spp. and sole *Solea* spp.). The appearance of the sandy tidal flats is shaped by the faecal mounds of the lugworm *Arenicola marina*. The Wadden Sea is characterised by a high biomass of benthic species (up to 100 g ash free dry weight m^{-2}) that can cope with tidal exposure and extreme changes in temperature, salinity and turbidity, due to tidal exposure and currents. Since 2009 the international Wadden Sea has been a UNESCO World Heritage Site (Reise et al. 2010).

1.6.1.2 Estuaries and Fjords

Estuaries of large rivers (e.g. Rhine, Meuse, Elbe, Weser, Ems, Tyne, Thames and Seine) extend along the North Sea coast and many harbour ports. All the estuaries have a characteristic turbidity maximum caused by the mixing of fresh and saline water. Due to their low and variable salinity the number of plant and animal species in the estuaries is reduced relative to sea and freshwater. There are some fully estuarine fish living almost their entire lifecycle in estuarine habitats (e.g. common goby *Potamoschistus microps* and European flounder *Platichthys flesus*).

A great variety of fjords can be found along the Norwegian coastline. These are typically deep, long and narrow, showing significant biological gradients from head to mouth. Plankton blooms in the coastal water may be passively transported into the fjords. The reefs of the upper sediment layers of these fjords (between 40 and 400 m) may comprise cold-water corals (e.g. *Lophelia pertusa* and *Gorgonocephalus caputmedusae*) and benthic communities including species such as sea stars, brittle stars and sea urchins.

1.6.1.3 Dogger Bank

The shallow Dogger Bank is a large sandbank situated east off the coast of England in the central North Sea and is influenced predominantly by Atlantic water from the north and Channel water from the south (Bo Pedersen 1994). Due

[5]http://www.dwd.de/DE/klimaumwelt/klimaueberwachung/europa/europa_node.html.

to year-round primary production this is a productive fisheries area (Kröncke and Knust 1995).

1.6.1.4 Helgoland, and the Shetland and Orkney Islands

The offshore island Helgoland in the Southern Bight and the Shetland and Orkney islands off the north-east of Scotland form rocky outcrops surrounded by soft sediments. Due to rich prey in the surrounding waters millions of seabirds use these islands for breeding. Sand dunes are inhabited partly by seals. The hard substrate around these islands serves as a holdfast for kelp (*Laminaria* spp.) (Lüning 1979).

1.6.2 Ecosystem Dynamics

1.6.2.1 Communities, Food Webs and the Seasonal Cycle

The North Sea is a temperate sea with a clear seasonal production cycle. In winter, most of the primary production is light-limited. In spring distinct phytoplankton blooms occur at the surface of the water column, mainly due to higher light levels and rising temperature. Carbon or energy is transferred from phytoplankton to herbivorous zooplankton to carnivorous zooplankton and finally to (jelly) fish, seabirds, and marine mammals. Figure 1.34 illustrates the trophic structure and energy flows of the North Sea food web. All organism groups discussed in later chapters of this report are shown in this schematic. Links between the pelagic and benthic components are indicated (i.e. settling detritus and suspension feeders). The spring phytoplankton bloom is initialised in the southern regions of the North Sea (south of Dogger Bank) in late winter/early spring, developing later in the northern part of the North Sea (Colebrook and Robinson 1965). The timing of the spring bloom depends primarily on increased light availability. The spring diatom bloom is responsible for a large proportion of the annual primary production which is succeeded by late summer and/or autumn blooms of dinoflagellates (Cushing 1959). Diatoms may bloom again in autumn but are then less numerous (Reid 1978). Grazing by secondary consumers occurs between May and September. Copepods consume about 10–20 % of the primary production of the spring bloom in the coastal zone (Baars and Fransz 1984). Roff et al. (1988) found the spring bloom is also grazed by heterotrophic protists which may provide an alternative food source for copepods. Pelagic herbivores such as copepods are preyed on by invertebrate carnivores (e.g. arrowworms and jellyfish). Meso- and macrozooplankton are also preyed on by pelagic fish, which are in turn consumed by larger fish, cetaceans and seabirds. A major proportion of the primary production, and the zooplankton and their faeces is transferred through sedimentation to benthic communities. There

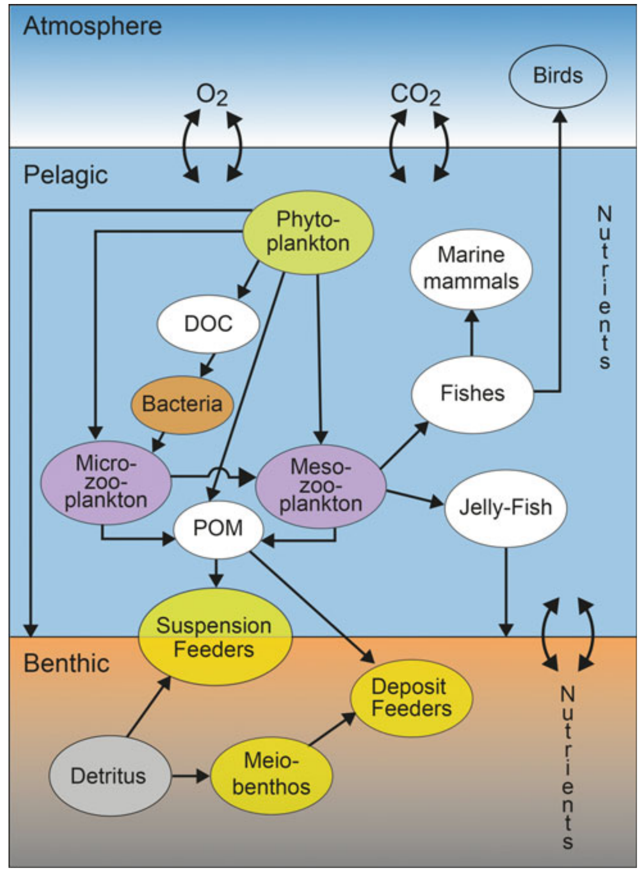


Fig. 1.34 Schematic overview of the trophic structure and flows of energy in the North Sea

they can be consumed by macrobenthos (shellfish, worms) and meiobenthos which serve as food for invertebrate carnivores (e.g. squid) and demersal fish (Dagg et al. 1982; Joris et al. 1982; Nicolajsen et al. 1983; Reid et al. 2009) or are mineralised by bacteria (Van Es and Meyer-Reil 1982). Invertebrate carnivores and demersal fish are in turn consumed by larger fish and other carnivores (such as seals) and some ultimately end up in the human diet. In the post-bloom period parts of the benthic biomass can be resuspended and remineralised by bacteria and protozoa. However, it should be noted that the actual North Sea food web is more complex than implied by this simple overview, owing to the large number of flora and fauna present in the North Sea and the many interrelations between these species and their various life stages.

Recruitment success of fish stocks and fisheries depends strongly on zooplankton production, and on their size and composition. Marine mammals and seabirds depend on fish stocks. Zooplankton peak abundance relies on primary production by phytoplankton. Complex interactions between the various components of the food web makes the North Sea ecosystem vulnerable to physical changes (such as in currents, salinity, mixing regimes or temperature; Schlüter et al. 2008, 2010) that affect energy flow through the food web.

1.6.2.2 Impacts of Stratification and Mixing

North of a rough line between Denmark and the Humber, the offshore central and northern North Sea becomes stratified in summer with a strong seasonal thermocline beginning in May (Becker 1981; Turrell et al. 1996). This leads to a rapid depletion of nutrients in the surface layer. The phytoplankton may be dominated by autotrophic nanoflagellates and other picoplankton at this time. Subsurface summer production may occur in these waters, based on new nutrients introduced into the pycnocline layer associated with fronts (Richardson et al. 2000; Weston et al. 2005). The coastal area of the North Sea including the shallow Dogger Bank, the Oyster Grounds and Dover Strait is generally vertically well-mixed due to tidal currents, leading to nutrient-rich conditions and high rates of primary production (Legendre et al. 1986). Nevertheless, surface stratification has also been observed in summer at the Oyster Grounds and on the northern slope of Dogger Bank (Greenwood et al. 2010). Fronts or frontal zones due to salinity and/or temperature gradients are frequently observed in the German Bight, off Flamborough Head, and along the coasts leading to high local phytoplankton biomass.

1.6.2.3 Carbon and Nutrient Cycles

A detailed North Sea field study initiated in 2001 revealed that bottom topography exerts fundamental controls on carbon dioxide (CO_2) fluxes and productivity, with the 50 m depth contour acting as a biogeochemical boundary between two distinct regimes. In the deeper northern areas, seasonal stratification facilitates the export of particulate organic matter (POM) from the surface mixed layer to the subsurface layer with the consequence that biologically-fixed CO_2 is replenished from the atmosphere. After entering the subsurface layer the POM is respired, releasing dissolved inorganic carbon (DIC) that is either exported to the deeper Atlantic or brought back to the surface during autumn and winter once the seasonal stratification has broken down (Thomas et al. 2004; Bozec et al. 2006; Wakelin et al. 2012), see Fig. 1.34. At the annual scale the northern parts act as a sink for atmospheric CO_2, and the high productivity driving the CO_2 fixation is largely fuelled by nutrient inputs from the Atlantic Ocean (Pätsch and Kühn 2008). In the southern part of the North Sea the shallow, well-mixed water column prevents the settling of POM from the euphotic zone, with the result that both production and respiration occur within the well-mixed water column. Except for a short period during the spring bloom, the effects of POM production and respiration cancel out and the CO_2 system appears to be temperature-controlled (Thomas et al. 2005a; Schiettecatte et al. 2006, 2007; Prowe et al. 2009). Productivity in this area relies on terrestrial nutrients to a far greater degree than in the northern North Sea, and nutrients are a limiting factor during the productive period (Pätsch and Kühn 2008; Loebl et al. 2009). Carbon cycling in the North Sea is dominated by its interaction with the North Atlantic Ocean, which serves as both a source and a sink for CO_2 transport due to the high rate of water exchange (Thomas et al. 2005b; Kühn et al. 2010). Thus, input from the Baltic Sea and river loads play a crucial role, since these constitute net imports of carbon (and other biogeochemical tracers) into the North Sea. As previously stated, nutrient concentrations are high in coastal areas relative to the offshore region and show considerable spatial variability. Concentrations decrease with distance from the shore. Riverine winter nutrient concentrations may be up to 50 times higher than offshore values (e.g. nitrogen in the river Ems; Howarth et al. 1994). In autumn and winter, nutrients accumulate due to intense mineralisation and peak in late winter. An average winter nitrate concentration in the central North Sea was estimated at about 8 μmol l^{-1} (Brockmann and Wegner 1996). In winter, nutrient concentrations in coastal waters are mostly influenced by river inputs and are only marginally influenced by biological processes. An exception is the Dogger Bank area where primary production continues all-year round and there is no winter peak in nutrient concentrations. Phosphate and silicate are usually the first nutrients to become depleted in coastal waters during spring slowing the growth of diatoms in the spring bloom. Excess nitrate is then taken up by flagellates and other plankton such as *Phaeocystis* sp. (Billen et al. 1991). In much of the North Sea, nutrients become depleted in the upper layer due to summer phytoplankton growth following stratification. An increase in surface nutrient concentrations can be seen in autumn after mineralisation has occurred in deeper water layers below the thermocline and when this nutrient-rich bottom water is brought up to the euphotic zone by stormy autumn weather. Nitrogen to phosphorus ratios show that nitrogen is a potential limiting factor in the central North Sea, whereas phosphate is a potential limiting factor in the coastal area and off England (Brockmann et al. 1990). The atmosphere, Atlantic inflow and several rivers contribute to the total nutrient load in the North Sea. Atmospheric nitrogen input to the North Sea is estimated at 300–600 kt (Richardson and Bo Pederson 1998). However, the spatial distribution of the atmospheric input is unclear. About 1411 kt N $year^{-1}$ is advected through the English Channel (Laane et al. 1993), with nutrient inputs entering the North Sea through the Atlantic Ocean estimated at 8870 kt N $year^{-1}$ and 494 kt P $year^{-1}$ (Brion et al. 2004). Total riverine inputs to the continental coastal zone are estimated to average 722 kt N $year^{-1}$ and 48 kt P $year^{-1}$ (Radach and Pätsch 2007).

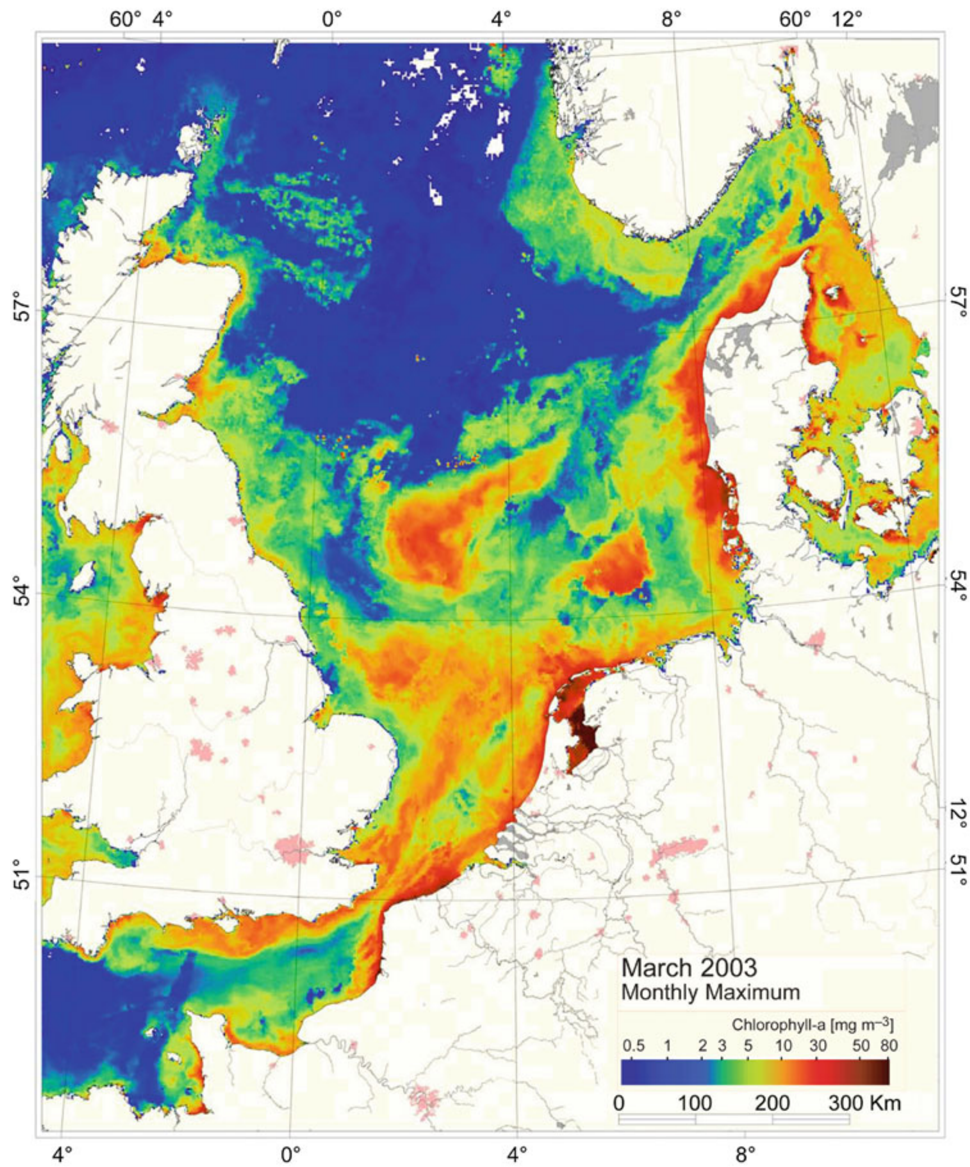


Fig. 1.35 Maximum chlorophyll-*a* concentration in the North Sea in March 2003, based on an ENVISAT/MERIS satellite image (Peters et al. 2005)

1.6.2.4 Production and Biomass

In addition to regulation by predators, phytoplankton growth and abundance are regulated by aspects of their physical and chemical environment, such as light intensity, wind, and nutrient concentration (e.g. Sverdrup 1953; Margalef 1997; Schlüter et al. 2012). Zooplankton biomass depends on the growth and quality of their food as well as on hydrodynamic and chemical factors.

Annual new production from the input of nitrogen to the North Sea is roughly 15.6 million t C (Richardson and Bo Pederson 1998). About 40 % of annual new production is estimated to be associated with the spring bloom in surface waters of the stratified regions of the North Sea, another 40 % with production in the coastal waters, and the rest with the deep chlorophyll maximum (Riegman et al. 1990).

There is a considerable variability in phytoplankton biomass across the North Sea with high values occurring inshore in the coastal regions of southern England, along the continental coast to Denmark and Norway, within tidal fronts, and at the Oyster Ground and Dogger Bank (Peters et al. 2005). The highest chlorophyll-*a* concentrations are observed along the southern coastal areas in spring (Fig. 1.35). The spatial distribution and productivity of benthic organisms in the North Sea are related to currents, and to variations in temperature and food availability (Heip and Craeymeersch 1995). High primary productivity in the eutrophic coastal zone is mostly due to terrestrial nutrient inputs from rivers and atmospheric deposition. Estimates of annual primary production in the North Sea are highest in coastal areas, and decrease northward from the southern to the northern North Sea (see Table 1.4).

Table 1.4 Estimates of primary production over an annual cycle for the North Sea and its subareas

North Sea area	Annual primary production, g C m^{-2}	Source
Coastal area	400	Cadee (1992)
Southern North Sea	150–200	Reid et al. (1990), Heip et al. (1992), Joint and Pomeroy (1993)
Offshore of Netherlands	375	Bot and Colijn (1996)
Northern North Sea	70–90	Steele (1974)

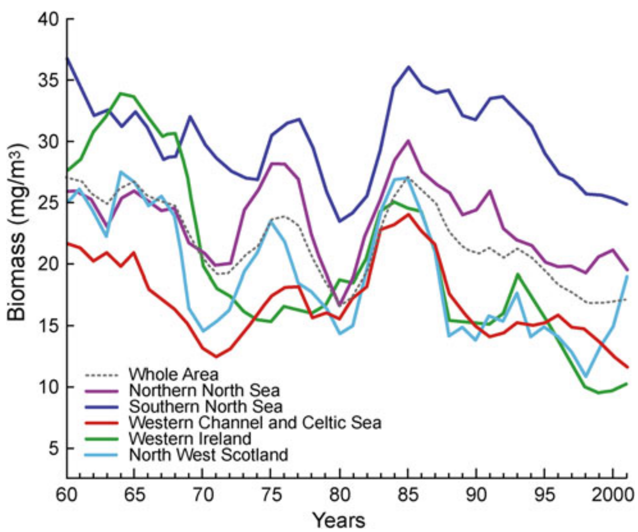


Fig. 1.36 Long-term trend in annual average biomass for 29 major copepods and cladocerans in five North Sea sub-areas and North Sea as a whole (Mackinson and Daskalov 2008)

Annual production of secondary producers (formation of heterotrophic biomass) is estimated at 2–20 g C m^{-2}, with higher production in the northern North Sea than the Southern Bight (Fransz et al. 1991). This gradient may be because large amounts of primary production in the shallow southern areas are transferred to benthic communities and so are unavailable for consumption by zooplankton. De Wilde et al. (1992) reported a significant decline in zooplankton abundance across the North Sea between 1960 and 1980. As shown in Fig. 1.36 this decline was followed by a subsequent recovery and then a new and ongoing decline. The long-term trend in zooplankton biomass for the North Sea as a whole is well documented through the variability observed in its sub-areas.

Estimates of annual secondary and higher production for the North Sea are given in Table 1.5. The benthic fauna production estimate for Oyster Ground (36 g C m^{-2} $year^{-1}$) includes 21 g C m^{-2} $year^{-1}$ for macrofauna and 6 g C m^{-2} $year^{-1}$ for meiofauna (De Wilde et al. 1984). Biomass of brown and green algae increased in the Wadden Sea and the Skagerrak-Kattegat area between 1960 and 1990 (Beukema 1989; Josefson et al. 1993). Kröncke and Knust (1995) found a decrease in total benthic biomass at the Dogger Bank between 1950 and the 1980s.

There are over 200 species of fish in the North Sea and their total annual productivity has been estimated at 1.8 g C m^{-2} (Daan et al. 1990). Cushing (1984) reported a large increase in the abundance of gadoids such as whiting *Merlangius merlangus*, haddock *Melanogrammus aeglefinus*, cod *Gadus morhua* and Norway pout *Trisopterus esmarkii* accompanied by a decrease in herring *Clupea harengus* in the 1960s, commonly referred to as the 'gadoid outburst'. Overall, demersal fish and their size composition have declined in the North Sea since the start of the 20th century (Pope and Macer 1996). The commercial fishery was heavily exploited in the 1960s, when landings peaked and then declined following a ban on herring in 1977 from a change in EU fisheries policy. The fishery reopened in 1981 and landings increased until 1988 followed by a record low in the 1990s.

Of the roughly 10 million t of fish and shellfish biomass produced each year in the North Sea, around 25 % is removed by the fishery, 50 % is consumed by predatory fish species, and the rest is consumed by birds and mammals or lost to disease (Daan et al. 1990).

About 2.3 million t of fish and shellfish were landed in the North Sea in 1999 (FAO 2003). Fish catches over the past 60 years seem strongly related to levels of primary production (Chassot et al. 2010). Pelagic species such as herring and mackerel are the most important in landings, as well as smaller species such as sardines, and anchovy. Demersal landings include cod, haddock, whiting, saithe *Pollachius virens*, plaice and sole. Detailed statistics of fish landings are available from the International Council for the Exploration of the Sea (ICES 2008; FAO Annual reports; see also Chaps. 8 and 12).

The sedimentary environment of the North Sea contains up to 5000 species of macrobenthic and meiobenthic invertebrates (Heip and Craeymeersch 1995). Total macrobenthic biomass decreases northward from 51.5°N while biodiversity and density increase (Heip et al. 1992). Rehm and Rachor (2007) also showed benthic biomass to decrease with distance from the coast. According to Heip and Craeymeersch (1995), northern species of the macrobenthic community extend southward to the northern slope of Dogger Bank and southern species extend northward to the 100 m depth contour. They also found the separation between northern and southern species to disappear at around the 70 m depth contour in the central North Sea.

Table 1.5 Estimates of annual secondary and higher production for the North Sea

Group	Annual secondary and higher production (g C m^{-2})	Source
Macrobenthos	2.4	Heip et al. (1992)
Fish	1.8	Daan et al. (1990)
Meiofauna	10	Heip and Craeymeersch (1995)
Phytobenthos	Negligible	Beukema (1989), Josefson et al. (1993)
Secondary production	2–20	Fransz et al. (1991)
Benthic fauna of Oyster Ground	36	De Wilde et al. (1984)

Several mammal species occur in the North Sea. The harbour seal *Phoca vitulina* is particularly abundant and there are estimated to be 4500–5000 in the German Bight, 6000 in the Wash, and 7000–10000 on the British east coast. For other common species such as harbour porpoise *Phocoena phocoena*, bottlenosed dolphin *Tursiops truncatus*, and less common species such as common dolphin *Delphinus delphis*, white beaked dolphin *Lagenorhynchus albirostris*, white-sided dolphin *L. acutus*, beluga *Delphinapterus leucas*, pilot whale *Globicephala melas* and minke whale *Balaenoptera acutorostrata* all populations are either stable or are declining due to pollution, fewer prey or accidental bycatch by the fishing fleet (FAO 2003).

Bellamy et al. (1973) listed 71 species of bird in the North Sea coastal and offshore areas.

1.6.3 Current Status and Threats

Human-induced stresses represent major threats to the North Sea ecosystem. These include overfishing, eutrophication, ocean acidification, climate change, recreation, offshore mining, wind farms, shipping, dumping of waste, changes in food web dynamics, and the introduction of non-indigenous species (Richardson et al. 2009). Potential threats on the North Sea ecosystem could be reduced by better management based on a concept of zones with different utilisation levels (Fock et al. 2014).

1.6.3.1 Eutrophication

Sewage effluents, leaching from agricultural land, and atmospheric nitrogen deposition are responsible for the high nutrient input to the North Sea (Druon et al. 2004). Aquaculture is another important factor. Enrichment by nitrates and phosphates may encourage blooms of particular phytoplankton species, such as *Phaeocystis* sp. or *Noctiluca* sp. in the coastal area. Under calm weather conditions massive algal blooms may settle on the sediment surface and cause hypoxia in the near-bottom water as seen in the German Bight and at the Danish Coast (De Wilde et al. 1992) resulting in mass mortality of macrobenthos. Present conditions reflect a strong decrease (70 %) in phosphate input since 1985 and a moderate reduction (about 50 %) in nitrogen for two major rivers Rhine and Elbe (van Beusekom et al. 2009).

1.6.3.2 Harmful Algal Blooms

Harmful algal blooms (HABs) have been reported in several regions of the North Sea and linked to changes in nutrients, temperature, salinity, and the North Atlantic Oscillation (ICES 2011). Their relation to anthropogenic drivers is unclear. Harmful algal blooms may impact ecosystem function and thus influence economic functions, including human health. However, several species known to cause HABs (e.g. *Phaeocystis* spp., and several dinoflagellates and raphidophytes) were already present in the North Sea at the beginning of 20th century (Peperzak 2003). Laboratory studies indicate that a rise in temperature may enhance growth, but that not all species tested responded in the same way (Peperzak 2003).

1.6.3.3 Offshore Oil and Gas

Vast oil and gas reserves formed during the North Sea's long geological history are currently being exploited. A large number of oil and gas production platforms widely distributed over the North Sea are responsible for supplying energy to European countries. Waters around the platforms are sometimes contaminated by chemicals including substances that affect benthic communities. Detailed studies showed effects of drilling activities (discharge of oil-based muds) only up to about 1 km from the platform (Daan and Mulder 1996).

1.6.3.4 Renewable Energy

As the use of renewable energy from offshore wind farms and from wave/tidal power plants increases, so the threat to seabirds and marine mammals will increase. The long-term impacts of renewable energy infrastructure on the North Sea ecosystem are not yet clear. Initial studies based on a UK wind farm show that plant and animal growth on piles may offer a substantial additional food supply for marine mammals. Studies by Garthe (Kiel University, unpubl.) on telemetered northern gannet *Morus bassanus* from Helgoland show birds can avoid wind farms to some extent.

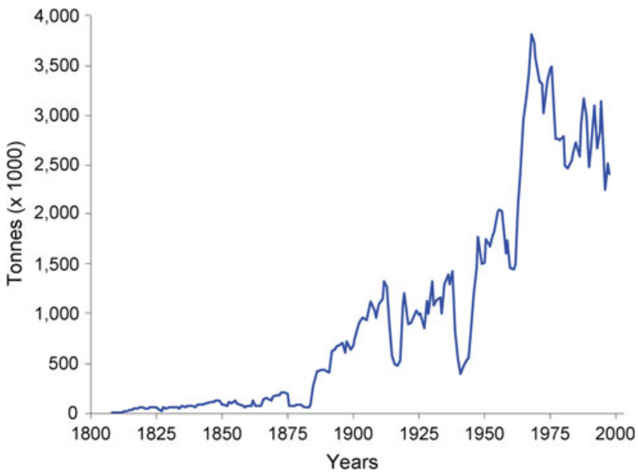


Fig. 1.37 Long-term trend in North Sea fish catches since the 1800s (Mackinson and Daskalov 2008)

Long-term avoidance of wind farms by marine mammals such as harbour porpoise is still debated (Dähne et al. 2013). To date, only a small number of the planned wind farms have been realised (see also Sect. 1.2).

1.6.3.5 Fisheries

The North Sea ecosystem is overfished (Cury et al. 2000; FAO 2012). Bottom and beam trawling are a major threat for marine organisms because they damage the seabed and alter mature benthic communities. Based on long-term data, Fock et al. (2014) stated that the age, volume and size composition of commercial fish stocks has shifted since 1902. As a result, species composition has shown significant changes in recent decades. For example, slow-reproducing fish such as sharks and rays declined and may only be encountered in areas with low fishing density. With beam trawling, the benthic community structure has changed from long-lived species (e.g. sharks and rays) to short-lived opportunistic and scavenging species (e.g. crabs and shrimps). Seagrasses declined along the Dutch, German and Danish coasts as a result of bottom trawling fisheries and an epidemic of wasting disease in the 1930s. Exploitation of North Sea fish stocks has increased since 1945 as shown by trends in fishery mortality among all groups of exploited fish species (Daan et al. 1990). As a result of measures to allow fish stocks to recover, total catches have declined since the late 1960s (Fig. 1.37). Even though pollution and overfishing in the North Sea (Cabeçadas et al. 1999) have resulted in major changes in species composition and shifts in species distribution, species richness based on International Bottom Trawl Survey (IBTS) data has increased over the past 30 years (ICES 2008); see

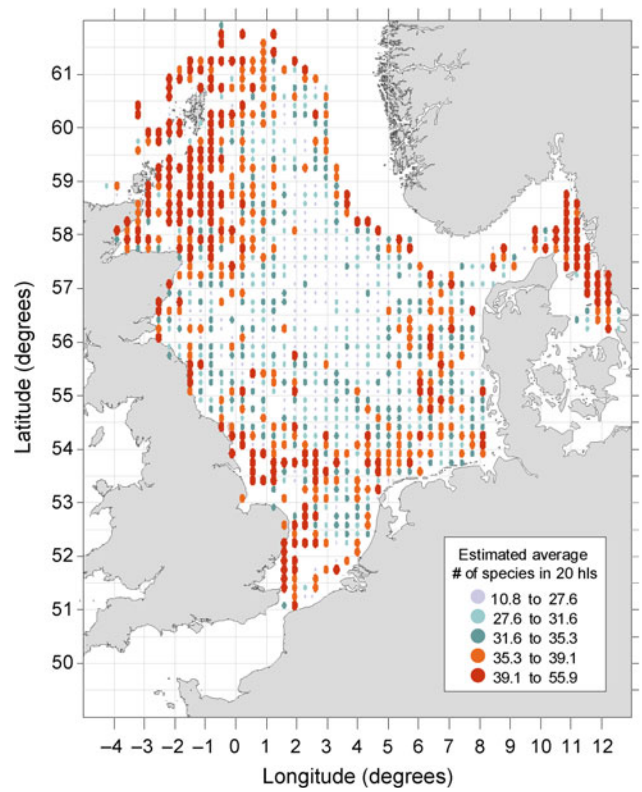


Fig. 1.38 Spatial distribution of species richness (1977–2005) for all North Sea fish species based on International Bottom Trawl Survey (IBTS) data (ICES 2008)

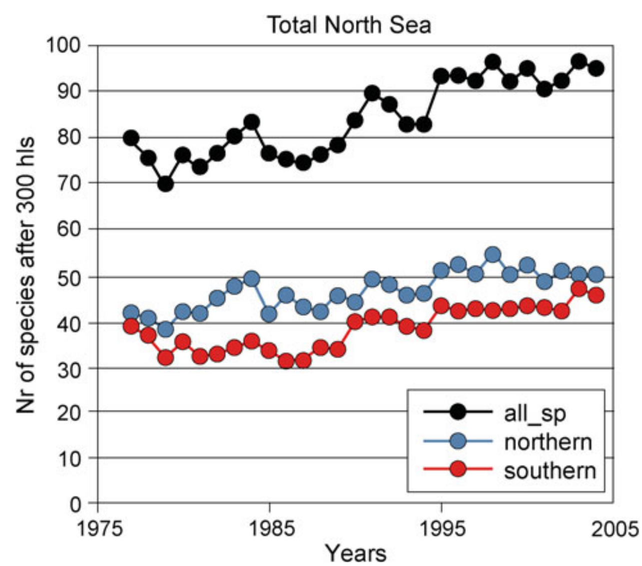


Fig. 1.39 Trends in species richness for all North Sea fish species: for the northern North Sea, the southern North Sea and the North Sea as a whole based on International Bottom Trawl Survey (IBTS) data (ICES 2008)

Fig. 1.38 for the spatial distribution of fish species richness and Fig. 1.39 for the long-term trend.

1.6.3.6 Contaminants

Contaminants enter the North Sea through various pathways and have had adverse and toxic effects on many species including cold-water corals, seabirds and marine mammals. Oil and oily wastes enter the North Sea from drilling operations, activities on platforms, shipping, harbours and ports, tanker spills and illegal discharges. Tankers and cargo vessels discharge ballast water containing non-indigenous species into the North Sea potentially with severe consequences for the ecosystem. Heavy metals and persistent organic pollutants enter the North Sea via atmospheric deposition and discharges from coastal industries and rivers (Chester et al. 1994). The quantities of most contaminants reaching the North Sea have decreased substantially since around 1985 (OSPAR 2010; Laane et al. 2013).

After entering the marine environment, contaminated particles mix with non-contaminated particles. Depending on the transport mechanism associated with seasonal and short-term variations in waves and primary productivity these particles can be widely dispersed or be deposited and so remain within the area. At the seabed older material becomes contaminated by mixing with newly supplied material. Thus, after sedimentation contaminants may be resuspended and redistributed. This causes a long-term transport of toxic persistent compounds towards the North Atlantic up to the Arctic Ocean. Apart from physical mechanisms, bioturbation by infaunal communities may also redistribute pollutants into overlying waters (Kersten 1988).

Chlorinated hydrocarbons (such as polychlorinated biphenyls; PCBs) were responsible for a dramatic reduction in the numbers of harbour seals in the Wadden Sea (Reijnders 1982), but after a ban on hunting and a strong reduction in the use of PCBs the population has since increased strongly (Wolff et al. 2010). Exposure to tributyltin (TBT) and polycyclic aromatic hydrocarbons (PAHs) also resulted in adverse effects on organisms (Laane et al. 2013). Some of the persistent organic pollutants entering the North Sea are biomagnified through the marine food web.

1.6.3.7 Tourism

Tourism is exerting high pressure on some coastal areas. Species and habitats could be affected by those activities that disturb wildlife, damage seabed habitat, and which cause noise disturbance and pollution.

1.6.3.8 Ports

Port development is expected to continue as a result of increasing ship traffic in the short-sea and containerised cargo markets. An example is the new deep water Jade-Weser-Port in the Southern Bight, which is accessible by the largest container vessels. A recurring issue with major harbours is the need for dredging and then disposal of the often contaminated sludge. Such as occurs with the deepening of the Elbe river with the port of Hamburg.

1.6.3.9 Non-indigenous Species

Many studies report the occurrence of non-indigenous species in the North Sea that may have been introduced via ballast water from cargo ships, shipping or mariculture. Some new species are also reported that were misidentified in the past (Gómez, 2008). Two examples of imported species are the American comb jelly *Mnemiopsis leidyi* first recorded in the North Sea in 2006 (Faasse and Bayha 2006) and the Pacific oyster *Crassostrea gigantea* which was introduced in the 1980s on selected plots in the Wadden Sea used for cultivation of shellfish (Drinkwaard 1998). A combination of over-exploitation of native oyster *Ostrea edulis* and import of the Pacific oyster has almost driven the former to vanish (Reise et al. 2010). Jellyfish concentrations are expected to increase across the entire North Sea in the next 100 years, owing to the projected rise in water temperature and fall in pH (Attrill et al. 2007; Blackford and Gilbert 2007). The ability of jellyfish to reproduce in a short time may affect pelagic and coastal ecosystems (Purcell 2005; Schlüter et al. 2010). An example of a non-indigenous phytoplankton species that is now well established in the North Sea is the diatom *Coscinodiscus wailesii*, which originated in the Pacific Ocean (Edwards et al. 2001; Wiltshire et al. 2010).

1.6.3.10 Climate Change

Chapters 3 and 6 provide a detailed description of climate change in the marine system. The following examples show that biological and physical effects of climate change are probably already being observed within the North Sea.

Major south-north changes in distribution and abundance related to rising temperatures have been detected for two key calanoid copepods, the cold-water species *Calanus finmarchicus* and the warm-water species *C. helgolandicus* (Planque and Fromentin 1996). Annual abundance of *C. finmarchicus*, which was usually high in the northern North Sea, decreased and the population has shifted north out of the North Sea (Beaugrand et al. 2009). Former high abundance of *C. helgolandicus* in the central and southern North Sea declined in that area and higher abundances were found further north (Helaouët and Beaugrand 2007).

During the summer period after the onset of stratification decreased dissolved oxygen concentrations in the bottom water at the North Dogger and Oyster Grounds were observed related to an increase in seasonal bottom water temperature (Greenwood et al. 2010).

1.7 Terrestrial Coastal Range Vegetation

Werner Härdtle, Jan P. Bakker, Jørgen Eivind Olesen

1.7.1 Natural Vegetation

1.7.1.1 Salt Marshes

Coastal salt marshes (also tidal marshes) are natural or semi-natural (non-grazed or grazed, respectively) halophytic ecosystems. They are habitats of the upper coastal intertidal zone of the North Sea and thus represent the transition between marine and terrestrial ecosystems (Ellenberg and Leuschner 2010).

Salt marshes establish in areas where plants that can trap sediment are inundated by water carrying suspended sediment. Salt marshes are often associated with muddy substrates and occur as 'foreland salt marshes' at the mainland coast (including sheltered estuaries and inlets), as well as in the lee of some North Sea islands (such as the Frisian Islands).

Salt marshes are highly dynamic ecosystems, and sites are characterised by daily inundation with salt water, sedimentation, and (locally) erosion processes. Species diversity is low and the vegetation comprises halophytic plants with life forms such as grasses, dwarf shrubs and herbs. Species composition and zonation are mainly determined by inundation frequency and soil salinity. Based on their topography, salt marshes are classified as low, medium or high salt marshes. A low salt marsh has more than 200 inundation events per year. Typical plant species include glassworts (*Salicornia* spp.), the dwarf shrub *Halimione portulacoides* and the grass *Puccinellia maritima*. High salt marshes, in contrast, are only flooded during extremely high tides and during storms. Typical species include black rush *Juncus gerardii* and grasses such as *Festuca rubra* agg. and *Agropyron repens* agg.

Salt marshes are highly productive ecosystems. They serve as a sink for organic matter and sediments, and play a crucial role in the littoral zone food web. In the past, most salt marshes were cut for hay and grazed by livestock, and so can be considered semi-natural. To maintain biodiversity, these semi-natural systems are often managed by livestock grazing for nature conservation purposes.

1.7.1.2 Dunes

Dunes are present on shorelines where fine sediments (mainly sand) are transported landward by a combination of wind and waves. Large dune areas occur on the North Sea coast, for example, in Denmark (to the north of Esbjerg), in the Netherlands (to the west of Den Helder) and on the Frisian Islands (Ellenberg and Leuschner 2010).

From an ecological perspective dunes are extreme habitats. Important stressors include water and nutrient shortage, unstable substrate, and salt spray. Dune formation is closely associated with plant succession and pedogenetic processes that occur with dune ageing. The natural succession starts with an embryo dune, where soils have low humus contents but are buffered due to the presence of calcium carbonate from seashells. Embryo dunes become foredunes as sand is accumulated by dune grasses such as *Ammophila arenaria* and *Elymus europaeus*. Further developmental stages are grey dunes (dominated by grasses or sedges such as *Carex arenaria*) and brown dunes (often characterised by dwarf shrubs such as *Calluna vulgaris* and *Empetrum nigrum*). Dune ageing is accompanied by soil acidification, the accumulation of humus and decreasing impact of wind and salt spray. In many places, eutrophication and dune disturbance have led to the establishment and proliferation of shrub species such as sea-buckthorn *Hippophae rhamnoides* and bramble *Rubus fruticosus*.

These successional stages often form a mosaic with duneslacks, low lying inter-dune areas protected from inundation and often separating foredunes from older phases of dune development, where a near-surface (brackish) water table favours a diverse and species-rich community, including bog-stars *Parnassia palustris*, marsh helleborine *Epipactis palustris*, marsh pennywort *Hydrocotyle vulgaris*, various other marsh orchids, rushes, sedges, and in mature stages also creeping willow *Salix repens*.

In the past, most dunes (except foredunes) were grazed by livestock and so can be considered semi-natural. To maintain biodiversity and prevent bush encroachment, dunes are often managed by livestock grazing for nature conservation purposes.

1.7.1.3 Moors (Bogs)

Moors, such as bogs (or mires) are wetlands that accumulate peat (i.e. organic matter originating from dead plant material). In bogs, peat is often formed by mosses (bryophytes), as well as grass species or sedges (Dierssen 1996). Waterlogged soils, in which the breakdown of (dead) organic material is inhibited by a lack of oxygen, are an important prerequisite for peat formation. The gradual accumulation of decayed plant material in a bog functions as a carbon sink and so provides an important ecosystem service.

Bogs are widely distributed in the temperate and boreal zone and are particularly well developed under an oceanic climate with high precipitation and low evapotranspiration (e.g. Scotland, western Scandinavia; Dierssen 1996; see Fig. 1.40).

In bogs the interstitial water of the peat body is acidic and low in nutrients (particularly nitrogen). Where the water supply is from precipitation, bogs are termed as ombrotrophic. If peat formation takes place under the influence of a

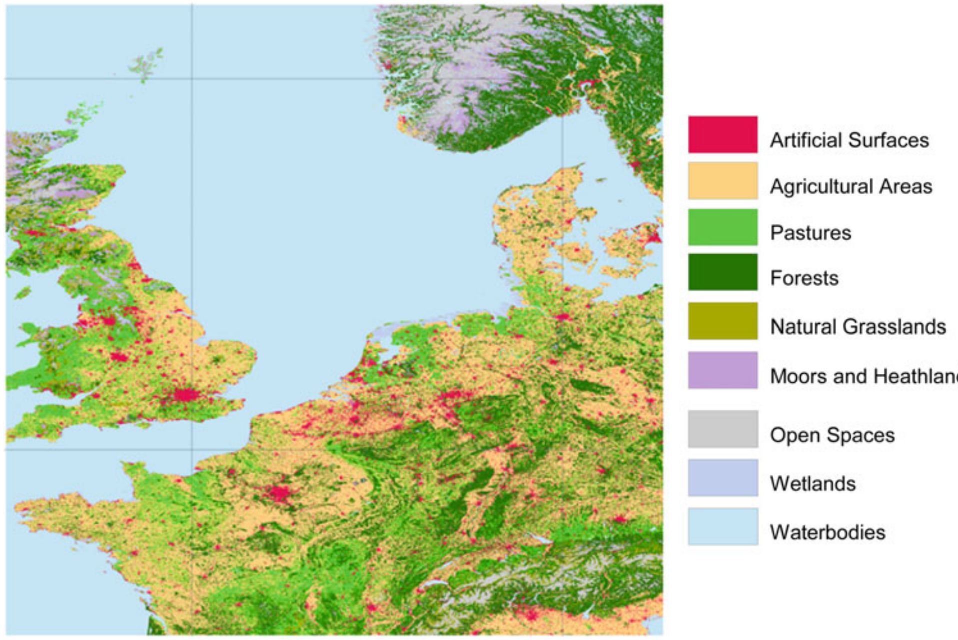


Fig. 1.40 Current (2006) land cover in the North Sea region according CORINE, a programme initiated by the EU to unify the classification of vegetation types and the description of different forms of land use (www.eea.europa.eu/data-and-maps/data/corine-land-cover-2006-raster-2)

high groundwater table, habitats are termed 'fens'. Low soil fertility and cool climates contribute to slow plant growth, as well as to low decomposition rates of organic material. In many bogs, the peat layer is 10 m thick or more.

Species typical of bogs are highly specialised. Most are capable of tolerating the combination of low nutrient levels and waterlogging. Dominant species include mosses of the genus *Sphagnum* and dwarf shrubs of the Ericaceae. Bogs are susceptible to fertilisation and drainage. Both factors may cause rapid and irreversible shifts in species composition.

1.7.1.4 Tundra and Alpine Vegetation

Tundra (including alpine vegetation types) occurs above the timber line and so is typical of the alpine zone in Scotland and Scandinavia (roughly between 1200 and 1700 m above sea level). Sites are mostly acidic and growing seasons are between 45 and 90 days long. The vegetation comprises perennial (mostly tuft forming) grasses, sedges, and dwarf shrubs of the Ericaceae. Cryptogams such as bryophytes and lichens are also very common (Dierssen 1996).

1.7.1.5 Forests

Forests are an important habitat type in the coastal range vegetation of the North Sea region. Under natural conditions forests would cover more than 90 % of this region, but currently cover only about a third (Bohn et al. 2002/2003).

Birch forests (with *Betula pubescens* agg.) are the dominant forest type in western Scandinavia (so-called western boreal and nemoral-montane birch forests) but are also developed as pioneer stands under temperate conditions in north-western parts of central Europe and in Great Britain (Dierssen 1996; Bohn et al. 2002/2003). Soils are mostly acidic (podzolic) and poor in nutrient supply (particularly for nitrogen). In the canopy, birch is the dominant trees species but pine trees (*Pinus sylvestris*) and willows (*Salix glauca*) may also be present. In contrast to the low number of vascular plants, birch forests are characterised by a highly diverse moss flora, among which species such as *Rhytidiadelphus loreus*, *Hylocomium umbratum* and *Rhodobryum roseum* are particularly typical.

Natural spruce forests are typical of central and southern parts of Scandinavia (western boreal and hemiboreal spruce forests; Dierssen 1996). In the canopy, spruce *Picea abies* is the dominant tree species, but pine trees (*Pinus sylvestris*) in the boreal zone and fir (*Abies sibirica*) and some broad-leaved trees in the hemiboreal zone may form mixed species stands. Soils are acidic, but base and nitrogen supply is better than in birch forest ecosystems. In the understorey, grasses (e.g. *Deschampsia flexuosa*) and bryophytes such as *Barbilophozia lycopodioides* and *Hylocomium umbratum* are common.

Forests dominated by European beech *Fagus sylvatica* are typical of large areas of temperate Europe (Ellenberg 2009; Ellenberg and Leuschner 2010). Beech trees cover a wide range of ecological site conditions; from strongly acidic soils (e.g. Podzols) to neutral soils (e.g. Luvisols) (Härdtle et al. 2008). The extreme shade tolerance of beech is a key factor in its competitive advantage over other European broad-leaved tree species. As a result, many natural beech stands are monospecific. In the understorey, typical herb species include *Anemone nemorosa*, *Viola reichenbachiana*, and *Galium odoratum* (Härdtle et al. 2008). Beech forests are the prevailing forest type in north-western parts of central Europe, in southern Great Britain, and in Denmark (Bohn et al. 2002/2003; Rodwell 2003). The northern range limit of beech forests roughly coincides with 58°N (e.g. in northern Denmark and southern Sweden; Diekmann 1994). At acidic sites (such as soils originating from sediments from the Saalian glaciation), oak trees (*Quercus petraea*, *Q. robur*) may become co-dominant, but these structural patterns often are attributable to (former) silvicultural practices.

Mixed broad-leaved forests dominated by oak trees (*Quercus robur*, *Q. petraea*) and ash *Fraxinus excelsior* are the prevailing natural coastal range vegetation of Great Britain and so are developed under an oceanic climate (Bohn et al. 2002/2003; Rodwell 2003). Oak and ash trees form the canopy layer, and elm *Ulmus glabra* may be present in some stands (but has dramatically decreased in recent years due to elm disease). Sites are well supplied with nutrients and water, and nutrient-demanding species such as *Sanicula europaea*, *Brachypodium sylvaticum*, and *Primula acaulis* are frequent in the understorey vegetation.

1.7.2 Semi-natural Vegetation

1.7.2.1 Heathlands

Heathlands (including heather moorland) constitute one of the oldest cultural landscapes in north-western Europe (Gimingham 1972). In the 18th century, they were widespread throughout Great Britain, Belgium, the Netherlands, northwest Germany, Denmark, and Norway, and were the product of long-lasting extensive heathland farming systems (Sutherland 2004). In many regions, heath areas declined by more than 30 % during the 20th century, mainly due to afforestation activities and the conversion of heaths to arable land. Heaths are typical of strongly acidic soils (e.g. Podzols) and their structure is characterised by a dominance of dwarf shrubs such as *Calluna vulgaris*, *Empetrum nigrum*, and *Erica tetralix*. Heaths are today considered habitats of high conservation value, since they host a large proportion of the biodiversity typical of open landscapes in north-western Europe.

1.7.2.2 Grasslands

Grasslands (low-intensity pastures and meadows) are areas where the vegetation is dominated by grasses (Poaceae) and other herbaceous (non-woody) plants (forbs, sedges, rushes). The majority of grasslands in temperate climates are 'semi-natural', since their maintenance depends on human activities such as low-intensity farming (Ellenberg and Leuschner 2010). Thus, grasslands are subject to grazing and cutting regimes, which in turn keep the landscape open and prevent the encroachment of trees or shrubs. Unfertilised grasslands are characterised by a large diversity of plants and insects. Although intensification in land-use management (due to drainage and fertilisation) has improved the productivity of grasslands (in favour of cultivated varieties of grasses), this has in turn caused a significant decline in total grassland biodiversity. In central Europe, for example, the proportion of low-intensity pastures and meadows is below 6 % of the total agricultural landscape.

1.7.3 Agricultural Areas

Agricultural landscapes comprise areas that are primarily used for food production (i.e. arable land and grasslands with varying intensity of use). In north-western Europe, for example, about 50 % of the total area is currently in agricultural use (for which the proportion of arable land ranges from 30 to 70 %). Arable land is primarily associated with highly productive soils, for example in southeast England, northern France and Denmark (see Fig. 1.40), whereas grasslands are located in areas with high rainfall and/or at sites that are less suitable for cultivation. Much of the agricultural land in north-western Europe is artificially drained, either by ditches or tile drains, to ensure that the land can be farmed.

A major proportion of the agricultural area is used for livestock production, and many different production systems are applied. This covers purely grassland-based beef or dairy farming systems in the wetter western part of the region, intensive dairy farming systems based on grass and maize in large areas along the North Sea, and intensive pig and poultry farming systems in areas where arable agriculture dominates.

The countries in north-western Europe have economically well performing agricultural sectors that have a high value addition per farm (Giannakis and Bruggeman 2015). This is due to well-trained farmers supported by a highly competitive agricultural sector that supplies inputs and processes and markets the agricultural products. The productivity of the agricultural systems increased greatly over the 20th century and a high proportion of the produce was used for food production (Gingrich et al. 2015). Current trends in agricultural land use in north-western Europe are primarily driven by the globalisation of agricultural markets and a transition from a rural to an urban society (van Vliet et al. 2015).

Use of the agricultural area for producing bioenergy is growing, either by using existing crops for biofuel (e.g. rapeseed for biodiesel or maize for biogas) or by growing dedicated biofuel crops (e.g. *Miscanthus* or willow as biomass crops). There is also increased consideration for using crop residues for bioenergy purposes, although this competes with the need for organic matter input to soils to maintain fertility.

1.7.4 Artificial Surfaces

The area covered by artificial surfaces (e.g. for residential areas, industrial and commercial sites) amounts to about 4 % and is mainly related to urban centres (Fig. 1.40).

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