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RELATIONS BETWEEN NORTH SEA AND ATLANTIC OCEAN

A LITERATURE STUDY

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SAMENVATTING

De Noordzee is een randzee van de Noordatlantische Oceaan (NAO) en in vergelijking met deze klein, zowel qua oppervlakte als qua waterinhoud. Een ander belangrijk topografisch verschil, dat grotendeels de hydrografische en biogeochemische eigenschappen bepaalt, is dat de Noordzee ondiep is (tot ca. 200 m, met alleen een klein deel Noorse Geul en Skagerrak tot ongeveer 700 m), terwijl in de NAO de diepte kan oplopen tot enkele kilometers. In de NAO speelt zich een essentieel deel van het wereldwijde circulatiesysteem af. In het noorden vindt de vorming van diep water plaats, die de watercirculatie in de werelddoceanen aandrijft.

Noordzee en Atlantische Oceaan zijn geen gesloten systemen. De Noordzee wordt gevoed met water van de NAO. Dit betekent dat de NAO van nature grote invloed op de Noordzee uitoefent, hetgeen beschouwd kan worden als het achtergrondsignaal voor alles wat zich verder op en in de Noordzee afspeelt. Het Atlantische achtergrondsignaal is echter niet constant, maar vertoont alle mogelijke (natuurlijke) variaties, op tijdschalen van dagen tot eeuwen. Dit compliceert de interpretatie van wat zich op de Noordzee afspeelt nogal. De Atlantische invloed op de Noordzee is grofweg onder te verdelen in fysische- (watertransporten), chemische- (im- en export van chemische verbindingen, zowel natuurlijke als kunstmatige), en biologische invloed (uitwisseling van organismen). Deze onderverdeling wordt dan ook aangehouden in dit rapport.

-FYSICA

Het Atlantische water heeft een eindige verblijftijd binnen de Noordzee en wordt ook daarbinnen gemodificeerd, o.a. door bijmenging van zoet water. Gemiddeld wordt in ongeveer één jaar het complete volume van de Noordzee vervangen. Echter, verschillende gebieden binnen de Noordzee hebben ook verschillende verblijftijden van het erin aanwezige water. Water uit de Duitse Bocht bijvoorbeeld heeft gemiddeld zo'n 3 jaar nodig om de Noordzee te verlaten, terwijl water in de noordelijke Noordzee dit in slechts 6 maanden realiseert.

Het getij van de Noordzee wordt opgewekt in de Atlantische Oceaan. De water dynamiek in de Noordzee wordt grotendeels bepaald door dat getij, nl. door het heen en weer bewegen van het water, waarbij echter opgemerkt dient te worden dat na een volledige getijdencyclus het water niet meer op z'n oorspronkelijke positie zal zijn teruggekeerd. Zo ontstaat menging, waarbij verder ook de wind betrokken is. Naast het getij dragen ook stormgolven (Engels: storm surges) bij tot de water dynamiek. Het gaat hier om gebeurtenissen die geen vaste regelmaat hebben en ontstaan door atmosferische oorzaken (hoewel ook verstoringen in de diepzee een rol zouden kunnen spelen). Stormgolven ontstaan voornamelijk in de Atlantische Oceaan en worden aan de Noordzee doorgegeven. Als resultante van alle water dynamiek, die overigens ook nog van andere factoren afhankelijk is, bestaat er een gemiddelde reststroom voor de Noordzee (Fig. 2.8). De grootschalige circulatie van de Noordzee is tegen de wijzers van de klok in gericht. De Atlantische Oceaan is voor een belangrijk deel verantwoordelijk voor de gemiddelde reststroom van de Noordzee.

De oppervlaktecirculatie in de NAO wordt gedomineerd door de Golfstroom. Deze ontstaat uit de subtropische reuzewervel (Engels: gyre) in het zuidwesten van de NAO, vanwaar hij warm water transporteert langs de Amerikaanse oostkust en vandaar richting NO Atlantisch bekken loopt. Wanneer de Golfstroom de Amerikaanse kust verlaten heeft gaat hij verder als Noordatlantische Stroom. De drijvende kracht achter het circulatiesysteem in de NAO is de wisselwerking tussen de atmosfeer en het oceaanooppervlak: afkoeling van het oppervlaktewater in de Poolzeeën in het noorden doet dit water afdalen naar de diepte, hetgeen compenserende stromen van andere watermassa's tot gevolg heeft. Echter, ook het stabiele windsysteem in het gebied waar de Golfstroom ontspringt draagt in belangrijke mate bij aan de uiteindelijke vorm van de circulatie. Op grond van de intensieve wisselwerking tussen atmosfeer en oceaan zouden reeds seizoensafhankelijke variaties in de NAO verwacht mogen worden. Dit blijkt echter niet alleen voor de oppervlaktetemperatuur te gelden, maar ook voor de stroomsterkte van de Golfstroom (Fig. 2.3). Verder kon aangetoond worden dat lange- termijn temperatuurvariaties in het zuidwesten van de NAO zich omgekeerd evenredig verhouden tot die in het noordoosten. Bovendien bestaat er een relatie (langjarig) tussen de stroomsterkte van de Golfstroom en de temperatuur in het noordoosten (Fig. 2.5). Het mechanisme dat hierachter schuil gaat is waarschijnlijk dat een grote stroomsterkte van de Golfstroom leidt tot het vasthouden van water in de reuzewervel, waardoor de Noordatlantische Stroom met minder water gevoed zal worden. Dit betekent vervolgens dat er minder relatief warm water in het noordoosten terecht komt, waardoor de temperatuur daar afneemt.

Het lijkt erop dat (natuurlijke) klimaat variaties uiteindelijk achter alle lange termijn veranderingen in de NAO zitten. Het blijkt dat een toename van de passaatwinden gepaard ging met een toename van het Golfstroom debiet en met een afname van de temperatuur in de NO Atlantische Oceaan. Tevens bleek dat een abrupte beëindiging van een volhardende afwijking in het druksysteem boven Groenland in 1971 vergezeld ging van een verandering van de positie van de Golfstroom naar een meer noordelijke ligging. Ook veranderingen van saliniteit en temperatuur vonden plaats gedurende die periode.

Een kleine vertakking van de Noordatlantische Stroom gaat de Noordzee in (Fig. 2.1). De instroming van Atlantisch water in de Noordzee vindt zowel in het zuiden, via Het Kanaal, als in het noorden, tussen Schotland en Noorwegen, plaats, waarbij de laatste gemiddeld ongeveer 10 keer zo groot is als de eerste. De uitstroming uit de Noordzee gebeurt bijna volledig in een relatief smalle strook langs de Noorse kust naar de Noorse Zee (Fig. 2.8). De instroming is uitermate variabel, voorzover dit is na te gaan. Variatie is er zelfs van dag tot dag, maar ook op basis van perioden van enige dagen. De reden van deze variaties is grotendeels gelegen in de variabele wind over de Noordzee en z'n omgeving. Voor het transport door de Straat van Dover is bekend dat tijdens perioden met een noordelijke component in de wind dit zelfs kan omkeren. Ook gedurende het jaar is de instroming variabel. Gemiddeld gezien vertoont de toevoer van water vanuit Het Kanaal een maximum in november en een minimum in de periode februari-april. In het noorden is de Fair Isle Stroom (tussen de eilandengroepen van de Orkneys en de Shetlands) het sterkst in de zomer. Dit wordt niet alleen veroorzaakt door de wind, maar ook door externe factoren (op de NAO). In de noordelijke Noordzee wordt verder waargenomen dat de 35-isohaline (=lijn van gelijk zoutgehalte) z'n meest zuidelijke uitbreiding bereikt in februari en z'n noordelijkste terugtrekking in de periode juli-september. Dit duidt op een sterke seizoensafhankelijke invloed van het water van de Atlantische Oceaan op de Noordzee. Het mechanisme dat dit veroorzaakt is waarschijnlijk van plaatselijke hydrografische aard.

De meeste kennis die verband houdt met de veranderlijke invloed van het Atlantische water op de Noordzee is gebaseerd op (indirecte) waarnemingen van de saliniteit en de temperatuur, en niet op stroomsnelheidsmetingen die een veel beter beeld zouden opleveren. Zo volgt uit de lange-termijn trends van de saliniteit en de temperatuur in de Noordzee dat er dus ook op de lange termijn (jaren tot decennia) variaties plaatsvinden in de instroming (en ook in de uitstroming) van Atlantisch water. Zo zijn in het bijzonder de fluctuaties in saliniteit met een frequentie van 4 tot 6 jaar opvallend, hetgeen doet vermoeden dat ook de toevoer van Atlantisch water met deze frequentie minima en maxima vertoont. De veronderstelde verklaring voor deze fluctuatie voert uiteindelijk terug op een atmosferisch proces dat sterke invloed uitoefent op de wind in de oostelijke Atlantische Oceaan. Hierdoor zou er ofwel periodiek een grotere toevoer van water naar de Noordzee kunnen plaatsvinden, ofwel, onder overigens ongewijzigde watertoevoer, zou de herkomst van het water uit de Atlantische Oceaan zuidelijker kunnen zijn dan normaal (zuidelijker water heeft een hogere saliniteit).

In het midden van de jaren-70 werd een opvallend grote afwijking naar beneden van de gebruikelijke saliniteit in de noordelijke Noordzee geconstateerd. Ook in de NAO werd zo'n afwijking gevonden, maar niet geheel gelijktijdig. De saliniteitsafwijking bewoog zich als het ware door de Atlantische Oceaan volgens het bekende stromingspatroon (Fig. 2.12). Juist in dezelfde periode werden andere opvallende variaties gemeld, waaronder die van de stroomsterkte en de positie van de Golfstroom (Fig. 2.7), en een verplaatsing van het Subpolaire Front (dat warm en koud water in de NAO van elkaar scheidt). Het verschijnsel dat zoveel processen min of meer gelijktijdig zulke opvallende variaties vertonen wijst in de richting van een mechanisme dat van invloed is op de gehele oceaan, en klaarblijkelijk ook de lange-termijn variaties (van saliniteit, temperatuur, en water- instroming) in de Noordzee bepaalt.

-BIOLOGIE

Het Atlantisch water dat de Noordzee instroomt bestaat niet alleen uit H₂O. Zeewater is de drager van vele chemische verbindingen, zowel opgelost als in particuliere vorm, en daarnaast bevinden zich in het water organismen die voor hun verplaatsing in meerdere of mindere mate afhankelijk zijn van de waterbewegingen. Een nogal directe relatie tussen de Noordzee en de NAO wordt onderhouden door dieren die actief tussen beide bekken bewegen. Van sommige plankton soorten, zowel fyto- als zooplankton, is bekend dat ze min of meer passief met de heersende waterstromingen de Noordzee in of uit getransporteerd worden. Plankton is voor de voortbeweging nagenoeg geheel afhankelijk van waterbewegingen. Het gaat hier om gebeurtenissen die optreden met onregelmatige tussenpozen, en soms een jaarlijks terugkerend verschijnsel vormen. Een andere vorm van migratie is die van exotische (indicator) soorten die zo nu en dan buiten hun gebruikelijke verspreidingsgebied aangetroffen worden. Ook zij maken gebruik van de heersende stromingen.

Wanneer we de mogelijke indirecte invloed van de Atlantische Oceaan op het ecosysteem van de Noordzee willen achterhalen, dan zijn lange-termijn trends een bijna onontbeerlijk hulpmiddel. Correlaties tussen trends van biotische en abiotische factoren kunnen dan misschien iets zeggen over gemeenschappelijke oorzaken. Gelukkig zijn er enige tijdseries bekend. Zowel de hoeveelheid zooplankton (sinds 1948) als fytoplankton (sinds 1958) hebben een neerwaartse trend vertoond tot ongeveer 1980 en dit werd gevonden zowel in diverse gebieden van de NO Atlantische Oceaan als in de Noordzee; na 1980 is overigens weer een stijging geconstateerd (Fig. 3.1). Het opvallende is dat een gelijke trend gevonden werd voor vele soorten zooplankton en fytoplankton (Fig. 3.2 en 3.3). Er moet bedacht worden dat de grootste variaties die plankton vertoont nog steeds die van seizoensafhankelijke aard zijn; de lange termijn-trends zijn hieruit gefilterd met behulp van wiskundige methoden.

Wanneer gepoogd werd de lokale zeewater temperatuur variaties (langjarige trend) te correleren aan de variaties van de hoeveelheid zooplankton, dan bleek dit te mislukken. Wanneer echter de gemiddelde temperatuur over de hele NAO genomen werd, dan was er wel degelijk een goede correlatie mogelijk tussen zooplankton en zeewater temperatuur (Fig. 3.4). Ook de eerder genoemde wijziging van de positie van de Golfstroom bleek samen te vallen met veranderingen in de hoeveelheid zooplankton (Fig. 3.5). Deze feiten wijzen erop dat de langjarige variaties van het zooplankton en fytoplankton in de NAO gestuurd worden door veranderingen in de Noordatlantische circulatie, en uiteindelijk door klimatologische fluctuaties. Omdat de lange termijn trends van het plankton in verschillende delen van de NAO en de Noordzee grote gelijkenis vertonen, lijken ook lange termijn variaties van de plankton populaties van de Noordzee door deze klimatologische factoren bepaald.

Ook buitengewone variaties in de vispopulaties in de Noordzee doen het vermoeden rijzen dat de Atlantische Oceaan hierop z'n invloed doet gelden. Hoewel de Noordzee populaties zwaar bevestigd worden en dat in principe de grootste invloed vormt, zijn er toch verschijnselen waargenomen die hiervan los lijken te staan. Dit geldt met name de veranderingen van positie van de paaigronden en de onverklaarbare explosie van de populatiegrootte van de sprot en de makreel. Opmerkelijk genoeg vonden deze veranderingen plaats tijdens de periode dat de buitengewone afwijking van de saliniteit in de NAO en de Noordzee ook opgeld deed. Het verband was snel gelegd, maar het precieze mechanisme dat deze veranderingen in vispopulaties moet bewerkstelligen is niet duidelijk.

-CHEMIE

De intensieve fysische wisselwerking tussen de NAO en de Noordzee is, vanuit chemisch oogpunt bezien, van groot belang voor de waterkwaliteit. Snelle verdunning van Noordzee-water wordt bewerkstelligd door continue aanvoer van Atlantisch water en snelle menging daarvan, hetgeen tot gevolg heeft dat de concentratie van verontreinigende stoffen over het algemeen onder het nivo blijft dat grootschalige milieuschade veroorzaakt.

De produktiviteit van de Noordzee is hoog te noemen, hetgeen evenzeer te danken is aan de Atlantische invloed. Factoren die hierbij een rol spelen zijn de goede menging in de Noordzee en de rijkelijke aanvoer van voedingszouten (nutriënten) door de NAO. Hoewel het antropogene deel van de aanvoer van nutriënten sterk is toegenomen, wordt nog steeds 80-90% van de opgeloste stikstof en fosfor in de Noordzee door de NAO ingebracht. Plaatselijk kan dit anders liggen, in het bijzonder in de zuidelijke Noordzee, waarin de belangrijkste rivieren uitmonden die grote hoeveelheden nutriënten meevoeren.

De toevoer en afvoer van nutriënten door de NAO is zeer variabel. Dit komt in de eerste plaats doordat de watertoevoer variaties vertoont. Maar ook de concentratie van nutriënten in het instromende water is niet constant. Het binnenstromende water vindt z'n oorsprong in de oppervlakte- lagen van de oceaan en daarin voltrekt zich jaarlijks de biologische cyclus van primaire produktie en remineralisatie met de daaraan gepaard gaande afname en toename van de nutriënten concentraties. Een lange-termijn serie van nutriënten, net zoals voor plankton en hydrografische parameters, bestaat jammer genoeg niet, zodat de langjarige invloed van nutriëntvariaties op de primaire produktie en het Noordzee ecosysteem niet bekend is. Uit metingen in Het Kanaal komen echter aanwijzingen dat de concentratie van nutriënten in het instromende Atlantische water langjarige variaties kunnen vertonen die samenvallen met variaties van plankton en vispopulaties (Fig. 4.2). Als achterliggende oorzaak worden klimatologische variaties verondersteld, die uitwerken op de Noordatlantische circulatie.

De hoeveelheid zwevende stof die met het Atlantisch water de Noordzee binnenkomt is vergelijkbaar met de hoeveelheid die de Noordzee weer verlaat. Echter, de samenstelling kan verschillend zijn: naast de oceanische aanvoer van zwevende stof zijn er ook andere bronnen van zwevende stof, waaronder een

terrestrische (met een antropogene component), en daarnaast vindt permanente depositie van zwevend materiaal plaats binnen de Noordzee. Bovendien kunnen spoormetalen en organische verontreinigingen aan zwevende deeltjes ad- of absorberen. Op macroschaal kan dus gesteld worden dat de Noordzee een modificatiebekken is voor de zwevende stof van de NAO. De import en export van zwevende stof van de Atlantische oceaan is eigenlijk alleen in de winter goed bekend. In andere jaargetijden maakt ook organische stof (dood of levend) deel uit van de zwevende stof, maar dit is een grote, veranderlijke hoeveelheid. Het percentage organische stof kan wel oplopen tot bijna 100%. Omdat de mineralisatie van de organische stof plaatsvindt binnen de tijdschaal die typisch is voor watertransporten in de Noordzee (dat is, binnen een jaar), komt die organische stof uiteindelijk slechts als een kleine post in het zwevende stof budget van de Noordzee voor. Toch is het mogelijk dat de export van organisch materiaal vanaf het continentale plat naar de oceanhelling een belangrijke zinkput ('sink') is in de mondiale koolstofkringloop.

De concentratie van spoormetalen in de Noordzee is meestal hoger dan in de oceaan. Voor vele spoormetalen is de concentratie in de particulaire fase vergelijkbaar met hun vrij-opgeloste concentratie, maar plaatselijk kunnen verschillen optreden. Spoormetalen verlaten de Noordzee zowel met het water in opgeloste vorm als geadsorbeerd aan deeltjes. Voor de meeste metalen is de invoer in particulaire vorm vergelijkbaar met de uitvoer (in de winter). Aan de (continentale plat) rand van de Noordzee kunnen echter nog processen optreden die metalen tegenhouden voordat ze naar de Atlantische Oceaan kunnen "verdwijnen". Dit geldt voor metalen die ook biologisch een rol spelen, zoals Fe, Cd, Zn, Co, Cu, en Ni. Aan de rand vindt in de zomer continue primaire productie plaats door de aanvoer van voldoende nutriënten vanaf de oceaan. Daarbij worden de metalen ingebouwd en verwijderd naar de particulaire fase, waardoor ze minder snel, of niet uit de Noordzee verwijderd zullen worden. In de winter spelen zich mogelijk hele andere processen af aan de rand, waarbij juist sterk verhoogde concentraties aan metalen zouden ontstaan door remobilisatie van metalen van het sediment (Fig. 4.3). Of dit laatste werkelijk gebeurt is nog onzeker.

Organische microverontreinigingen komen ook in opgeloste en in particulaire vorm voor, hoewel qua absolute hoeveelheid toch het meest opgelost. Hun herkomst is voornamelijk antropogeen. De concentraties die gevonden worden zijn zeer laag. De zeer persistente verbindingen, zoals PCB's en gechlloreerde koolwaterstoffen, zullen met het water de Noordzee verlaten en hebben inmiddels in de oceaan een meetbare concentratie bereikt.

Menselijke activiteiten hebben zo'n grote invloed op de aarde gekregen dat zelfs het gigantische waterareaal van de oceanen wereldwijd aangedaan is. Dit geldt bijvoorbeeld voor de concentratie van lood die sterk verhoogd is ten opzichte van het natuurlijke nivo (factor 10). Maar ook het nivo van radioactiviteit in de oceanen is verhoogd. (De natuurlijke achtergrondstraling maakt nog altijd het overgrote deel van de gemeten radioactiviteit in de oceanen uit.) In de eerste plaats is die verhoging veroorzaakt door radioactieve neerslag ("fallout") van atoombomproeven uit de jaren-50 en -60, en door het ongeluk met de kerncentrale van Tsjernobyl. Daarnaast is in de NO Atlantische Oceaan een deel van de verhoging toe te schrijven aan de lozingen van de opwerkingsfabriek Sellafield (Groot Brittannië), vroeger Windscale, aan de Ierse Zee. Deze verhoging van de radioactiviteit, waarvan het meeste door cesium-137, wordt in een vrij smalle stroom de Noordzee in getransporteerd en veroorzaakt daar sterke verhoging van de concentratie van cesium-137. Zo'n 10% van het nivo van radioactiviteit van cesium in de Noordzee wordt na 1-3 jaar terug gevonden bij Spitsbergen en na 3-5 jaar nog 1-2% ten oosten van Groenland (Fig. 4.7).

Olieresten komen ook in alle oceanen voor en zijn sterk geassocieerd met menselijke activiteiten. Er zijn echter ook natuurlijke bronnen van petroleum koolwaterstoffen in de oceanen, maar die worden toch lager ingeschat (tot ca. 20%). Olieresten komen in verschillende vormen voor, en kunnen ten dele vrij persistent zijn. Plaatselijk kan de invloed groot zijn, in het bijzonder op zeevogels.

De biologische hulpbronnen en het ecosysteem van de oceanen zijn op wereldwijde schaal inmiddels ook door menselijk handelen aangetast. Voor een gebied als de Noordzee was aantasting al vroeg duidelijk, de activiteit die daarvoor zorgde was de visserij. Van vele vissoorten zijn de populaties gedecimeerd en is de leeftijdsopbouw binnen de populatie zo scheef gegroeid dat de populatie zeer kwetsbaar is geworden. Ook de zeezoogdierenstand in de Noordzee is achteruit gegaan ten gevolge van menselijke activiteiten. Op de oceanen is op het ogenblik de drijfnet visserij de grootste bedreiging op verschillende nivo's van het ecosysteem. Het is een zeer niet-selectieve manier van vissen die naast vispopulaties ook de zeezoogdierenstand bedreigt. Hoewel de exacte kennis over de negatieve invloed van drijfnetvisserij ontbreekt kan in ieder geval gesteld worden dat het potentieel van deze methode om wereldwijd schade aan te richten in het oceanische ecosysteem enorm is. De eerste tekenen van overexploitatie van de oceanen worden al zichtbaar.

SUMMARY

Being a marginal shelf sea of the North Atlantic Ocean, the North Sea is much smaller both in surface area and water contents. Apart from that, the North Sea is shallow, whereas the North Atlantic is up to several kilometers deep and this difference is crucial for the different biogeochemical properties of both basins. In the northern North Atlantic Ocean large-scale formation of deep water takes place, which in itself drives the world-wide ocean circulation. The North Sea is flushed with water from the N Atlantic in about one year. However, different parts of the North Sea also have different residence times, for example, for the German Bight this is 3 years and for the northern North Sea about 6 months. The tide in the North Sea is generated in the Atlantic Ocean. Tidal currents cause turbulence which, together with the wind, efficiently mixes the water. Extreme wind events such as storm surges also determine part of the water dynamics of the North Sea. Most surges originate on the Atlantic Ocean. The resultant of the water dynamics is a mean residual current pattern in the North Sea. Although many factors contribute to this current pattern as well, the N Atlantic is largely responsible for it.

The surface water circulation in the N Atlantic is dominated by the Gulf Stream, which originates from the Subtropical Gyre in the southwest of the N Atlantic. It transports relatively warm water towards the NE Atlantic and Polar Seas. After having left the U.S. east coast the Gulf Stream proceeds as the North Atlantic Current (NAC). The driving force of the circulation system is the interaction between atmosphere and ocean surface: By cooling the surface waters in the Polar region sink down to deeper layers, and this causes compensating surface flows. Also the steady wind system in the area where the Gulf Stream originates contributes to the ultimate configuration the circulation has. From long-term records of sea surface temperature an inverse relationship was deduced between the temperature anomalies in the southwestern (Gulf Stream) parts of the N Atlantic and those in the NAC. Moreover, there is a correlation between the current strength of the Gulf Stream and the temperature in the NE Atlantic. The mechanism probably is that a large current strength of the Gulf Stream leads to a retention of warm water in the Subtropical Gyre, and accordingly a smaller transport to the NAC. This in turn means that a smaller amount of relatively warm water will end up in the NE Atlantic, and thus the sea surface temperature decreases. Apparently, climate variations ultimately cause the long-term variations in the N Atlantic. It was found that an increase of the Trade Winds was associated with an increase of the Gulf Stream transport and with a decrease of the temperature in the NE Atlantic. Also the abrupt change of a persistent atmospheric pressure anomaly over Greenland in 1971 was accompanied by changes in the position of the Gulf Stream to a more northerly position. Marked changes of salinity and temperature also occurred during this period.

A small branch of the NAC enters the North Sea. The inflow of Atlantic water takes place both through the northern boundary of the North Sea between Scotland and Norway and through the south via the English Channel, whereas the former flow is about ten times as large as the latter. The outflow occurs in a relatively small strip along the Norwegian coast to the Norwegian Sea. Inflow is quite variable, even on a daily basis, and this is mainly caused by the variable wind field. There is also a seasonal variation of the inflow, which is again largely brought about by the wind, but also by external factors (originating on the N Atlantic). Most knowledge which is concerned with the variable influence of the N Atlantic on the North Sea is based on (indirect) observations of salinity and temperature, and not on measurements of the current velocity, which would give a much better picture. Thus, from the long-term trends of salinity and temperature in the North Sea it follows that there are marked fluctuations in the inflow and outflow with a frequency of 4-6 years. The starting point of explanation would be that atmospheric processes cause persistent changes in the wind field over the eastern Atlantic.

In the mid-1970s a marked salinity decline was observed in the northern North Sea. It was found in the N Atlantic as well, but for different areas it was found in different years, as if to move through the N Atlantic according to the known current pattern. In the same period other phenomena were signalized, such as changes in the current strength and the position of the Gulf Stream. The fact that so many processes coherently showed such conspicuous variations points to a common mechanism that influences the whole ocean. Apparently, long-term changes in the North Sea hydrography are also mediated by such ocean-wide processes.

Not only physically, but also chemically and biologically there are interactions between the North Sea and the N Atlantic Ocean. Some plankton species are known to be transported between both basins along with the water. Also exotic indicator species, which are incidentally encountered in the North Sea, use the prevailing currents. Indirect biological interactions between the North Sea and the N Atlantic are deduced

from long-term time-series. Many species of both zooplankton and phytoplankton in different regions of the NE Atlantic and the North Sea showed a similar downward trend in abundance since the middle of this century, and an increase again after about 1980. There is a good correlation between this general plankton trend and the mean seawater temperature trend for the N Atlantic, while on the other hand the local plankton trends did not show a significant relationship with the local temperature. The interannual changes in the Gulf Stream position were also similar to the plankton variations in the NE Atlantic. These facts indicate that the long-term changes of the plankton in the N Atlantic are mediated by variations in the N Atlantic circulation system, and ultimately by climatic fluctuations. Since the long-term variations of the plankton in the NE Atlantic and the North Sea are very similar it appears that also variations in the North Sea plankton populations are generated by climatic factors. Some unusual changes in fish populations in the mid-1970s were attributed to hydrographic factors as well, because they occurred contemporaneously with the great salinity anomaly. The mechanism that should cause these variations is unclear, though.

Through the intense physical interaction between the North Sea and the N Atlantic a fast dilution is effectuated, which is of utmost importance for the water quality in the North Sea. The high productivity of the North Sea is the consequence of the Atlantic influence as well. Factors that play a role here are the abundant supply of nutrients by the Atlantic (80-90% of all nutrients originate from the Atlantic) and the rapid mixing in the North Sea. The nutrient supply of the Atlantic is seasonally variable. This is caused by the fact that the inflow derives from the surface layers of the oceanic water column where nutrients had been extracted and supplied accompanying the cycle of biological activity during the year. It is not clear if there are trends in the long-term variation of nutrient inflow from the N Atlantic into the North Sea. From the English Channel there are indications that this might happen, and that this might influence the ecosystem.

With respect to the suspended matter the North Sea can be regarded as a modification basin. The amount of suspended matter that enters and leaves the North Sea from and to the N Atlantic, respectively, is comparable, only the composition may be different. This finds its cause in that there are additional sources of suspended matter to the North Sea, and that part of the particulates are deposited within the North Sea. Besides that, metals or contaminants may be incorporated in the particles by sorption processes, which of course changes their composition. In the growing season the major part of the suspended matter fluxes may consist of organic matter. Possibly, the export of organic material from the shelves to the oceanic slopes constitutes an important sink in the global carbon cycle.

Trace metals occur in enhanced concentrations in the North Sea compared with the N Atlantic, because most of them have an anthropogenic source. Export to the ocean takes place both as dissolved species with the water as well as in the particulate phase. In winter the inflow and outflow of particulate trace metals is of the same order of magnitude. In summer the shelf-edge may constitute a barrier, especially for trace metals that have a nutrient-type distribution, such as Fe, Cd, Zn, Co, Cu, and Ni: As a consequence of continuous primary production at the shelf-edge the metals are extracted from the seawater and transferred to the particulate phase, through which leaving the North Sea gets more difficult. Human interference has also brought organic micropollutants in the North Sea. They are strongly hydrophobic, but nevertheless the amount of dissolved micropollutants is generally higher than the particulate fraction because of the relatively low amount of suspended matter. If persistent, they will eventually leave the North Sea following the water flows. Some persistent compounds, such as PCB's and chlorinated hydrocarbons, meanwhile have accumulated in measurable concentrations throughout the oceans.

Human activities are having a world-wide impact on the oceans. The level of radioactivity is somewhat higher than the natural background level. This is mainly caused by fallout as a consequence of early atmospheric atomic bomb tests. In the NE Atlantic, part of the enhancement is attributed to the discharges by the nuclear fuel reprocessing plant Sellafield. This radioactive flow, mainly consisting of caesium-137, derives from the Irish Sea, crosses the North Sea and from there is traced to Spitsbergen and Greenland. Petroleum hydrocarbons in all kinds of states can be found all through the oceans as well. The biological resources of the oceans are threatened on a world-wide scale because overexploitation is dawning. Large-scale fisheries, especially driftnetting, have caused a dramatic decline of the fish stocks in the oceans, but have also been affecting the abundance of sea mammals. Much knowledge has to be obtained yet to assess the real impact on the ocean ecosystem.

1. INTRODUCTION

The North Sea is a marginal shelf sea of the North Atlantic Ocean. It is continuously supplied with water from the N Atlantic as it is part of the current system of the latter. Generally stating, the water from the N Atlantic resides on the North Sea shelf for a while and then leaves again for the Atlantic. Meanwhile many processes occur within the North Sea that can modify the contents of the seawater (see Hoppema & De Baar, 1991), seawater being the carrier of all kinds of chemical substances, suspended particles and organisms. There are different processes at work on the shelf than there are in the open ocean, but also processes may run at different rates. Besides that, the material input and output from the Atlantic are not constant, they may show diurnal, seasonal, interannual, long-term or other variations.

Hence, it is manifest that the N Atlantic Ocean has a great natural influence on the North Sea. This influence can be considered as serving as the background signal for all possible phenomena and states occurring within the North Sea. For assessing the real impact of secondary disturbances on the North Sea the background level should definitely be known. These disturbances are frequently of anthropogenic nature, since the North Sea is heavily exploited by the dense population that surrounds it. On the other hand, the anthropogenic impact may reach so far as to affect the open ocean directly. These lines of impact should of course be separated during the analysis and identified as being different.

The Tidal Waters Division (Dienst Getijdewateren) of the Ministry of Transport and Public Works (Rijkswaterstaat) is responsible for the policy of the Netherlands part of the North Sea. Also they are involved in the international deliberation on issues concerning the North Sea. Owing to the internationalisation of the approach of (marine) environmental problems it is essential for management and policy strategies to place the area under review in the context of large-scale occurrences. The present report is meant to be a background document addressing the connection between one of the major and most influential ocean basins, the N Atlantic, and its, at least from an anthropogenic (economic) point of view, not less important marginal area the North Sea.

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2. PHYSICAL OCEANOGRAPHY OF THE NORTH SEA AND THE NORTH ATLANTIC OCEAN

2.1. THE NORTH ATLANTIC OCEAN

By volume the North Atlantic Ocean is the smallest of the six ocean basins (Wright & Worthington, 1970), the volume being $137 \cdot 10^6 \text{ km}^3$, which is one-tenth of the world ocean. Geographically, it is quite different from the other basins, a fact that has great consequences for the circulation pattern in the N Atlantic. An outstanding topographical feature is the Mid-Atlantic Ridge, which divides the basin in an eastern and western part. In the northeast another important ridge system is formed by the Greenland-(Iceland)-Scotland Ridge. This ridge, which is everywhere shallower than ca. 900 m separates the NE Atlantic proper from the North Polar Sea, including the Norwegian, Greenland and Iceland Seas. Indirectly, through the Polar Sea and Bering Straits there is a small, shallow connection with the North Pacific Ocean, but the associated water flow is only minor (Worthington, 1976). In the east the N Atlantic is bordered by the European shelf, including the North Sea. The N Atlantic has the most distinct characteristics of all oceans: It is the warmest and most saline, and appears to be geologically the "youngest" (Worthington, 1976). In addition, by acting as a reception reservoir of new deep and bottom water it has the highest oxygen and lowest nutrient concentrations. To the north of the N Atlantic there are the world's most important sites for deep and bottom water formation, which influence most of the global ocean (Reid & Lynn, 1971). The N Atlantic receives this cold deep and bottom water from the Polar Seas and in turn supplies as compensation the Polar Seas with warm surface water in a self-perpetuating way. Considering the size difference between the N Atlantic Ocean and the North Sea, the former being 3240 times larger than the latter, it is evident that the former will have influence on the latter to a much greater extent than the other way round.

2.1.1. THE NORTH ATLANTIC CURRENT

The general picture of the large-scale circulation pattern of an ocean basin is one of a subtropical anticyclonic gyre and a subpolar cyclonic gyre, separated by an area with predominantly westerly winds (Munk, 1971; Stowe, 1983). In the N Atlantic a different picture arises. Indeed, there is a subtropical gyre, but instead of a subpolar gyre there is a surface water flow to the northeast out of the subtropical gyre to replace the water that leaves the N Atlantic basin towards the Polar Seas. This surface flow, so typical for the N Atlantic and its surroundings, is commonly known as the Gulf Stream. Actually, in an oceanographical sense the Gulf Stream is only a part of the Subtropical Gyre and its extension along the eastern American coast, further to the east and north the flow is called the North Atlantic Current. Warm and saline water is transported from the southwestern part of the basin towards the northeast. The release of the advected heat to the atmosphere in the northeast in winter is largely responsible for the relatively warm winters in Europe.

The North Atlantic Current (NAC), also known as the North Atlantic Drift, is part of the Gulf Stream system (Fig. 2.1). The Gulf Stream commences its course near Florida, moves along the eastern coast of the U.S.A. until south of Newfoundland (Iselin, 1936; Defant, 1941; Mann, 1967). At this point the Gulf Stream splits in different branches (Clarke et al., 1980). The southern branch returns to the western subtropical Atlantic to participate in the subtropical gyre, whereas the northern branch continues its path, looping northeast of Newfoundland, along the continental slope. After the looping the northern branch is joined by the slope water current and together they form the NAC (Dietrich et al., 1975; Krauss, 1986). Further on, some water of the Labrador Current joins in. East of Newfoundland the NAC has its greatest strength of about $1 \text{ m} \cdot \text{s}^{-1}$. At about 52° N the NAC crosses the Mid-Atlantic Ridge to enter the east Atlantic basin. Further to the east another branching may occur. However, the exact hydrographical regime there is still unclear due to conflicting observations (Dietrich et al., 1975; Saunders, 1982; Krauss, 1986).

Between 30° W and 23° W the NAC turns northward (Helland-Hansen & Nansen, 1926). With some minor modifications and branching this water is further transported to form the Norwegian Current. The inflow of water to the Norwegian Sea occurs along the continental slope NW of Shetland and over the Iceland-Faroe Ridge (e.g. Helland-Hansen & Nansen, 1909; Dooley & Meincke, 1981). An important branch with reference to the present report is the one circulating in the North Sea, which joins the Norwegian Coastal Current (see Fig. 2.1). For the eastern shelf boundary of the N Atlantic a poleward northeast Atlantic slope current has been suggested (Swallow et al., 1977; Dickson et al., 1985). Such a current would be

important in terms of North Sea exchanges with the Atlantic Ocean. This slope current is said to be related to the very well-defined Mediterranean outflow into the eastern Atlantic, which occurs at intermediate depths (e.g. Maillard, 1984). However, it is asserted by the above authors that it is not confined to these depths but also extends to the layers above and below the Mediterranean Water.

It should be realised that the NAC is not a very coherent entity. It may consist of several smaller parallel meanders and branches that exhibit a varying spatial expansion (Sy, 1988). Krauss (1986) presumes the NAC to be associated with a broad eddy field, having a width of 1500 km (Fig. 2.1). This causes intensive mixing of warm Atlantic water and cooler water from the north. The mean drift to the east superimposed on this field is $5\text{--}10\text{ cm.s}^{-1}$. To the north the boundary of the NAC appears to be sharper, because there the Subpolar Front (or Subarctic Front) separates the warm NAC waters from the cold water from the north. It manifests itself by a strong temperature gradient. By the way, the position of the Front is neither firm but varies in space and time (e.g. Harvey, 1982).

Huge amounts of water are transported to the NE Atlantic. This implicates that there should be a return flow from the northeast. Indeed, at 2000 m depth Olbers et al. (1985) found a strong return flow nearly opposite to the NAC. This water flows south of Iceland and crosses the Mid-Atlantic Ridge between 45°N and 55°N .

The driving force of the large-scale circulation pattern in the N Atlantic is plainly the interaction between the atmosphere and the ocean surface. In the Mediterranean and the Polar Seas (the "Arctic Mediterranean") excessive evaporation and cooling occur, respectively. These processes create the conditions for dense water mass formation, and these water masses flow into the N Atlantic causing compensating flows of other water masses.

Alternatively, the definitive form the circulation system has imprinted, i.e. the Gulf Stream system as it is, is generated by the steady wind system at its place of origin. The mechanism is that the winds create a high-pressure cell in the western Sargasso Sea around which the Gulf Stream system revolves anticyclonically (Worthington, 1976). The course of the warm water flow through the N Atlantic is furthermore influenced by the dynamics imposed by the rotating earth (Coriolis Force) and, of course, by the bottom topography of the N Atlantic and by its boundaries (Dietrich et al., 1975).

2.1.2. WATER BUDGET

The N Atlantic is a very complicated system for which it is very difficult providing a closed water budget. The reason is the great variability of the circulation pattern and the corresponding insufficient sampling frequency till now. Therefore, the large-scale pattern is essentially qualitative and the figures given for the water flows are mainly intelligent estimates. In Fig. 2.2 such a scheme is depicted. It shows the most important surface water flows and their approximate sizes. Like before emphasis will be on the eastern basin of the N Atlantic, which is the most important for the European continental shelf, including the North Sea. Within this eastern basin the budget will be confined to the upper water layer.

Some simple budgets have been constructed and they were brought together by Otto (personal communication, see Table 2.1). The budgets by Worthington (1970, 1976) are very deviating from the other two, in particular since he assumes that no water flows in with the NAC. In his general circulation pattern he postulates the existence of a second anticyclonic gyre east of Newfoundland instead of the NAC. Other scientists, however, have revealed the inconsistency of this theory (e.g. Clarke et al., 1980). This leaves us with two budgets for the N Atlantic surface water. The inflow by the NAC is compensated by outflow towards the Norwegian Sea (Faroe-Shetland Channel) and Iceland Sea. The outflow into the North Sea is not included in these budgets because it is quite small compared with the other entries. As noticed before there may also be an inflow from the south along the European continental slope, but this flow is not quantified. In addition, up- or downwelling, entrainment, vertical mixing or convection are processes that provide ways of water exchange between the upper and lower water column, but their contribution is largely unknown (Otto, personal communication).

The overflow over the Iceland-Scotland Ridges is certainly a very important entry in a deep water budget (e.g. Tait, 1967; Worthington, 1969). This is likely for the deep outflow via the Gibbs Fracture Zone as well. However, there is a great lack of quantitative data to construct a reasonably reliable deep water budget.

2.1.3. VARIATIONS IN THE NORTH ATLANTIC OCEAN

The current strength of the Gulf Stream in its Florida approaches shows a seasonal cycle with highest values in July/August and lowest in November (Fuglister, 1951). This seasonal cycle correlates closely with that of the wind velocity and the sea level difference off the Florida coast (Fig. 2.3; also see Dietrich et al., 1975).

Not surprisingly, the sea surface temperature in the N Atlantic shows a pronounced seasonal cycle. At all nine Ocean Weather Stations, spreaded over the N Atlantic, a peak temperature (long-term monthly mean) is found in August and a minimum in February-March (Colebrook & Taylor, 1979). All seasonal curves are remarkably similar, only the seasonal amplitude differs, generally decreasing from south to north.

The salinity cycles at the weather stations in the N Atlantic (Fig. 2.4) vary considerably both in amplitude and phase (Taylor & Stephens, 1980a, also Smed, 1943). The seasonality in the salinity is only partly explained by the cycles of evaporation and precipitation. Advective processes appear to be the major cause of the variability. As noticed earlier, the Labrador Current injects (low salinity) water into the NAC. This flux is strongest in the summer. Subsequently it is mixed and advected to other regions in the N Atlantic, causing drops in salinity (Taylor & Stephens, 1980a; Defant, 1961).

There are several ways by which variations in the characteristics of the Atlantic and European shelf waters can be generated. As referred to above, exchanges of heat and water between the ocean and the atmosphere are processes that result in major fluctuations, particularly on a seasonal scale. Secondly, fluctuations in the horizontal exchange between water masses may cause substantial variability, and thirdly, variations may arise because of variability in the relative contributions of the various source waters that determine the water characteristics at a given place. Source waters that are meant here are, for example, Gulf Stream Water, Labrador Sea Water, and Mediterranean Water.

A sea surface temperature record in the NE Atlantic from 1854 onwards enables us to investigate long-term trends (Martin, 1972; Colebrook, 1976; Folland et al., 1981). In the area southwest of England the period from about 1885 is especially remarkable, with first a rather sudden, pronounced decrease and from about 1895 a nearly continuous warming until 1960. After 1960 cooling appears to occur. In an area west of Ireland a similar general trend of temperature was observed, the warming being only more pronounced from 1915-1920 onwards. Martin (1972) observed a similar trend in the area northwest of Scotland during the same time period. These trends fit in the worldwide sea surface temperature trend very well (Folland et al., 1981). Colebrook (1976) and Martin (1972) demonstrated the relationship between the magnitude of the Gulf Stream flow (indirectly via the water level near Florida) and the water temperatures in the NE Atlantic (Fig. 2.5). They based their explanation on the theory of Iselin (1940) saying that a strong Gulf Stream flow leads to a retention of warm water in the Subtropical Gyre and a reduction of the NAC with accordingly a cooling of the latter.

Both Maximov et al. (1972) and Colebrook (1976) further found a highly significant 11-year periodicity in the sea surface temperature trend. This cycle may be caused by atmospheric alterations induced by varying solar activity, as also demonstrated by the 11-year sun-spot cycle (Maximov et al., 1972). Also periodicities with other frequencies were found, but their origin is not always clear.

Colebrook & Taylor (1979) examined the changes in the geographical distribution of sea surface temperature anomalies (in the period 1949 to 1974). Their results agreed with those of the earlier authors in that there is an inverse relationship between temperature anomalies in the central (NAC) and southwestern (Gulf Stream) parts of the N Atlantic. Comparison with earlier temperature changes in the late 19th and early 20th century (Bjerknes, 1964) revealed similar patterns. These results are in keeping with the explanation according to Iselin (1940).

The temperature of the surface water is not only dependent on the processes described above but evidently also on atmospheric exchange and vertical mixing. These factors complicate the interpretation of long-term trends. Salinity is only slightly affected by interactions with the atmosphere, and thus salinity changes may be more indicative for internal oceanographic trends and changes. Unfortunately, salinity data are much less abundant than those of temperature. There are some indications that west of Scotland a rise occurred of 0.1 ‰ S from the beginning of this century to 1930 (Martin, 1972). From 1928 onwards there is no clear long-term trend, but instead there are two periods, one in the 1930s and a smaller one in the 1950s when the salinity was higher than normal. During the mid-1970s the salinity declined to relatively very low levels (Dooley et al., 1984) while in the 1980s the values returned to 'normal' again. Salinity measurements at several Ocean

Weather Stations in the period 1954 to 1974 show that the interannual variability at one particular station may be as large as 0.4 ‰ S (Taylor & Stephens, 1980a). The stations mutually showed great differences in their long-term trends.

According to Colebrook & Taylor (1979) and Taylor & Stephens (1980a) the general trends of temperature and salinity changes in the NE Atlantic matched in many cases, rather than changes in individual years (Fig. 2.6). This would indicate that displacements of currents and water masses play a role. Moreover, they found that temperature and salinity anomalies were transported through the N Atlantic according to the known current system. Frequently however, other processes would also contribute to the variations such as evaporation and precipitation, and the seasonal dispersion of low salinity water (see also earlier this section). The displacements could have been caused by large-scale variations in the ocean circulation. It should be mentioned that other authors did not find a correlation between surface temperature and salinity changes (e.g. Martin, 1972).

Actually, it is expected that advective processes (and variations thereof) are important in determining changes in temperature (and salinity) since at latitudes higher than of 45° N there is a net loss of heat to the atmosphere against which the ocean temperature is maintained by heat advection (Taylor & Stephens, 1980b).

Apart from long-term changes in salinity and temperature there is also evidence for longer-period changes in the Gulf Stream position near the east U.S. coast (Taylor & Stephens, 1980b). During the years 1970-1974 the Gulf Stream had a more southerly position than in the years 1966-1969 (Fig. 2.7). Associated with it were changes in salinity and temperature in the NE Atlantic. The cause for this displacement was unclear. Long-term changes in the Gulf Stream strength are observed as well. In the mid-1970s the lowest Gulf Stream transport ever was measured, while only 2 years later there was a record high (Worthington, 1977).

It would be interesting to know the long-term variations in the deeper waters of the Atlantic since they may give better indications for large-scale oceanographic climate variations. However, long-term records are scarce or absent. Some indications were found through the occurrence of periods with high-salinity water at depth in the Faroe-Shetland Channel (e.g. Martin, 1972; Alekseev et al., 1961), which may be caused by a stronger water flow from the south (Mediterranean Water).

2.2. THE NORTH SEA

The North Sea has existed in approximately its present form for about 6000 years. A continuous (relative) sea level rise has occurred, however, since that time amounting to 5-6 m (Eisma, 1987). The North Sea is bordered by land at three sides, except in the north. The entire northern boundary is formed by the NE Atlantic Ocean, i.e. the Norwegian Sea. In the south there is a narrow connection with the English Channel via the Dover Straits, and in the east with the Baltic via the Skagerrak. The North Sea is a shallow shelf sea, which means that it is an intermediate between a mediterranean sea (where internal dynamics determine the circulation) and a coastal open oceanic shelf region (Otto et al., 1990). The rectangular-shaped basin has a surface area of 575 300 km², a volume of 42 294 km³ and a mean depth of 74 m (ICES, 1983), including the Skagerrak, which is a natural extension of the North Sea. The southern part is shallower (30-40 m) than the central and northern part (up to 200 m). A remarkable feature in the east is the Norwegian Trench (or -Through, -Rinne, or -Channel) and its extension the Skagerrak, where water depths up till 710 m can be found. Some other holes deeper than 200 m are found in the central North Sea, but they are too small to be of more than local importance.

The shallowness of the North Sea largely determines its properties. For this reason a subdivision should be made between the southern part, and the central and northern (deeper) part. Another reason for making this subdivision is that the central and northern parts receive major oceanic influence, whereas in the southern part the continental influence via rivers and atmosphere plays a significant role. Some minor oceanic influence, though, is exerted from the south via the Channel water that flows in through the Dover Straits.

2.2.1. WATER MOVEMENTS

The dynamics in the North Sea are mainly determined by the tides, and to a lesser extent by external surges (Huntley, 1980) and variabilities in the inflow from the N Atlantic Ocean. Below, these features will shortly be discussed.

Because of its relatively small size compared to the oceans the tides in the North Sea cannot be generated locally. Instead, the Atlantic tides intrude. The Atlantic tidal waves enter through the northern opening of the North Sea, mainly between Scotland and Shetland (Sager, 1962), but also through the English Channel. The dominant tidal motion in the North Sea is by the semi-diurnal M_2 lunar tide. The tidal current strength is strongly dependent on water depth. This implies that from north to south this current increases. Tidal currents cause (quasi) turbulence which is an important agent for mixing of water masses. By non-linear interactions between the essentially harmonic tidal currents and the irregular topography of the North Sea the former induce residual currents. Also interactions between various tidal components and between the tide and meteorological effects contribute to this phenomenon. In coastal areas and areas with sharp depth gradients these residual currents may be as high as 15 cm.s^{-1} (Backhaus, 1979).

Storm surges are abnormal changes in "expected" sea level. They occur with large atmospheric pressure anomalies as a result of storms (Huntley, 1980). The North Sea is rather susceptible to storm surges due to its shallow depth and the relatively large area over which wind stress can be developed. In addition, the facts that the North Sea is a nearly closed box, and that the northern entrance is lying in the track of many atmospheric depressions coming from the N Atlantic towards Europe also contribute to this susceptibility (Huntley, 1980). The surges of the North Sea can be divided between internal and external surges (Heaps, 1969). External surges probably originate off northern Scotland. They proceed southwards as tidal waves do with only minor loss of amplitude, but they differ from the latter in that they move across the whole width of the sea and not in a circular pattern. Although mainly meteorological causes for surges are thought to be effective, also deep ocean disturbances generated in the Atlantic Ocean may be important (Huntley, 1980). Internal surges occur as a result of local and regional storms on the North Sea. However, surges frequently are the result of combined internal and external causes. Surges generated in the English Channel do contribute to sea level changes in the Southern Bight, but only to a minor extent.

There is a gigantic inflow of seawater from the N Atlantic Ocean. The inflow appears to be subject to substantial seasonal variations (e.g. Dickson, 1971; Dooley, 1983). The main reason for inflow variations is probably a rapidly changing wind field (Furnes & Saelen, 1977). The day-to-day variability is very high, frequently greater than the mean. This varying advective water displacement has its greatest dynamic influence on the waters in the northern North Sea.

The overall effect of these dynamical water movements is a thorough stirring of the water masses in the North Sea. Tidal mixing of water masses is generally most effective near the bottom, whereas wind has its major influence on the stirring of surface waters. The southern North Sea in particular is vertically well-mixed. In the northern approaches of the North Sea stratification of the water column occurs, partly only in the summer season. Remind that in the northern part the tidal currents are weaker than in the south. This stratification is important for the water flow since water movements in the upper and lower water column can have different directions.

As stated before, the tides give rise to residual currents. Water masses are horizontally dispersed by residual currents, which therefore are important for their distribution (and everything contained in them). However, the residual currents in the North Sea are furthermore determined by:

- meteorological effects (wind- and pressure induced)
- topography
- influence of the Atlantic circulation (advection)
- density-induced currents

(Becker, 1981; Otto et al., 1990). Observations and mathematical modelling have shown that for the North Sea there is a mean residual circulation pattern (Fig. 2.8, Böhnecke, 1922; Dooley, 1974; Lee & Ramster, 1976; Maier-Reimer, 1977). Generally, the circulation is anti-clockwise. Along the Scottish and English coasts water of Atlantic origin is transported in a weak current in southeastern direction where it ultimately turns to the east towards the German Bight. The water from the Dover Straits moves in a restricted band along the continental coast towards the Skagerrak, where it joins the N Atlantic (deeper) inflow from the north. Via the Skagerrak loop the water, together with the Baltic outflow, leaves the North Sea again through the Norwegian Channel. There are, however, many secondary systems imposed upon this general circulation, and even some areas with no predominating current direction exist (see Fig. 2.8).

Analysis of data shows that the residual circulation pattern is mainly wind-driven (and only partly tidal). The average circulation pattern, as discussed above, can be understood in terms of a predominant (westerly) wind direction over the North Sea. In addition, the topography will constrain water flows, in this way mitigating the wind-induced variations. On the other hand, this concept implies that different patterns of

residual currents may occur for short periods of time (Rieppma, 1980; Pingree & Griffiths, 1980). For example, during prolonged periods of winds with a northern component a reversal of the water flow through the Dover Straits has been found (Ramster et al., 1976). The reliability of the indicated mean circulation pattern is limited. Especially when shorter time intervals are considered (days) very deviating flow patterns occur. Over longer periods (months to years) the distribution of radio-active nuclides, however, confirm the general picture of the mean circulation (Kautsky, 1973). Although wind effects are the main determinants of the observed typical mean residual circulation pattern of the North Sea, calculations show that also tidal residuals, the large-scale North Sea topography and baroclinic effects promote the pattern (discussed in Otto et al., 1990). The same holds for the advective currents originating in the Atlantic Ocean.

2.2.2. WATER BUDGET AND WATER MASSES

In a recent review (Otto et al., 1990) all fluxes with their likely ranges were gathered. Table 2.2 is taken from this review; the budget is also shown on a spatial chart (Fig. 2.9); the latter contains approximately the same figures, as agreed upon by an ICES Study Group (ICES, 1983). The time scale for which the budget is valid is necessarily one year or a period of more years; on shorter time scales large temporal variations may occur. Unfortunately, far from sufficient knowledge concerning this variability especially is available to confine the uncertainty ranges to more acceptable levels.

The main freshwater fluxes derive from the Baltic and NW continental Europe (rivers Rhine, Meuse, Elbe). The total freshwater runoff that ends up in the North Sea is about $900 \text{ km}^3 \cdot \text{y}^{-1}$, which is more than 2% of the total world runoff. The inflow of Channel water through the Dover Straits is relatively well-known (Otto, 1976; Prandle, 1978; Postma, 1990), but the variations are large. The inflow from the North Atlantic Ocean is partitioned between several different regions, related to the topography (Dooley, 1974). Most water enters over the Shetland-Shelf and along the western slope of the Norwegian Trench. The former flow is not well-defined because it is a slow flow over a large area (e.g. Otto, 1983). The latter, called the slope current, is mainly a sub-surface one (Dooley, 1974), and is a branch of the North Atlantic Current system. More to the west, Atlantic water flows in by the Pentland Firth Flow (between Scotland and the Orkneys) and the Orkney-Shetland Flow (or Fair Isle Current). The latter is by far the more important one and is confined to a quite narrow zone (Prandle, 1980).

The outflow essentially occurs along the Norwegian coast, commonly known as the Norwegian Coastal Current. It is confined to the eastern part of the Norwegian Trench and considered as the continuation of the Baltic Current (Otto et al., 1990). The outflow is completed by unquantified turbulent exchanges across the northern boundary, and by some exchange across the Dover Straits.

Two entries that may substantially contribute to the water budget of the North Sea, precipitation and evaporation, have not been included in Table 2.2. Although there are indications for a slight excess of the former over the latter (Becker, in ICES, 1983), the overall effect on the budget is negligible (Grindley, 1972; Otto, 1976). All figures given above are highly uncertain. This is caused by the high variability of the fluxes in combination with the insufficient temporal coverage of the observations. The seasonal variation of the fluxes is possibly of the order of 50% of the annual mean (Otto, 1983), and on a shorter time scale even more.

Because of the different inputs and outputs which are spatially separated it is convenient to introduce hydrographic regions for the North Sea within which certain water masses occur (Fig. 2.10, Dietrich, 1950; Lee, 1980). Following the latter author six basic water masses can be distinguished on the basis of their physical and chemical characteristics (Table 2.3): North Atlantic, Channel, Skagerrak, Scottish Coastal, English Coastal, and Continental Coastal. Of course, the limits of the regions are not firm, they are for instance certainly dependent on the season. So, North Atlantic water can predominantly be found in region B, Skagerrak water in C, and Channel water in A3 (see Fig. 2.10). The coastal water masses self-evidently are found in their respective geographical areas. Other regions are intermediates which contain mixtures of some of the basic water masses (Lee, 1980).

For defining time-scales diverging terminology is used. The turn-over time for the North Sea as a whole, obtained by dividing the total mass of water by the total of advective mass fluxes amounts to about one year (Otto et al., 1990; Zimmerman, 1976). However, more useful concepts for the study of concentrations and inputs of substances are the 'age' and the 'residence time'. The 'age' is the time a parcel of water has remained in the area and the 'residence time' is the time the parcel of water needs to leave the area (Otto et al., 1990). Ages can be estimated by using radio-active tracers, discharged by the nuclear plants at Sellafield (Irish Sea)

and La Hague (English Channel), of which the former is the most important source. Water from the Irish Sea was traced to enter the northern North Sea via the Pentland Firth between Scotland and the Orkneys (Jefferies et al., 1973). In Fig. 2.11 (Prandle, 1984) the age distribution for North Sea water is shown. It is evident that ages differ very much for different North Sea regions. For example, a water parcel in the German Bight on average only leaves the North Sea after about 3 years, whereas in the northern North Sea the equivalent figure is 6 months. Turn-over times very much depend on the wind stress. As the latter exhibits a substantial variation, the turn-over time will also be highly seasonally dependent.

2.2.3. VARIABILITY

On a time scale of hours the tides constitute the main source of variation of water movements in the North Sea. Variations with a frequency of an order of days are mainly brought about by varying wind fields over the North Sea and its surroundings. For periods of days, for example, the fluctuations of the water inflow through the Dover Straits can typically be of the order of the mean (Hainbucher et al., 1986), and even reversal can occur. Also the inflow through the Pentland Firth varies on the time scale of days, which is suggested to be caused by external surges (Prandle, 1980). The inflow and outflow along the Norwegian Trench appear to vary at time scales of 10 days (Riepmann, 1980), which may be explained by meteorological forcing (Furnes, 1980).

On an annual basis the seasonal variations are the most conspicuous. The Fair Isle Current velocity is the highest in summer. Wind effects play an important role in this flow pattern, but Dooley (1983) states that there is a non-wind driven component as well. The inflow through the Dover Straits shows a seasonal variation with a maximum in November and a minimum from February-April (Prandle, 1978). Apart from temporal variations, the flows also show variations in their spatial expansion (e.g. ICES, 1983).

Long-term variations in the North Sea hydrography may also occur. Although the direct evidence for such long-term trends in the inflow or outflow are virtually absent, the trends in salinity and, to a lesser extent in temperature, suggest that variations are taking place. Especially the interannual fluctuations with a 4 to 6 year frequency are prominent (e.g. Hill & Dickson, 1978), which thus suggests that the Atlantic inflow roughly varies with this frequency. Also irregular long-term trends occur with largely unknown influences on the circulation of the North Sea.

Related to the inflow-outflow variations is the variation of the North Sea volume. The annual and seasonal volume variations are only minor compared to the uncertainty of the water fluxes. As a result of density (=temperature) variations the volume response is about 15 km^3 , for annual variations of atmospheric pressure and wind the equivalent figure is 50 km^3 , and irregular month-to-month meteorological effects produce volume changes of 100 km^3 (ICES, 1983).

2.3. DIRECT PHYSICAL INTERACTIONS BETWEEN NORTH SEA AND NORTH ATLANTIC OCEAN

In the previous sections the relation between the North Sea and the N Atlantic has already implicitly been discussed, the North Sea being fed with saline water of Atlantic origin and in turn feeding the N Atlantic with somewhat modified 'North Sea water'. However, it would be useful to focus on cases where the specific influence of the one body of water on the other is evident.

In the northern North Sea the 35-isohaline reaches its most southern extension in February and its maximum northern retraction in the period July-September. This seasonal variation is interpreted as being the result of the seasonal variation of the N Atlantic inflow (Steele, 1957). It is suggested that in the northern approaches of the North Sea Atlantic water that is already present cools down during the winter, becoming more dense than "new" water flowing in from the N Atlantic. Consequently, the "new" Atlantic water is hampered to flow in and thus the inflow is reduced in winter and spring. In the course of the spring and the summer the relatively dense Atlantic water warms up and is reduced in spatial extent by mixing with North Sea water masses. In autumn then, when the size of the dense water mass has sufficiently decreased, a new pulse of saline, dense Atlantic water can flow in.

The process described above concerned the seasonally varying influence of the N Atlantic water on the North Sea. Dickson (1971) and Hill & Dickson (1978) observed interannual variations in the salinity (see also section 2.2.3), and attributed this to anomalies in the inflow of N Atlantic water, lasting for periods of 4 to 6 years. The underlying causes are anomalous atmospheric processes which result in a higher frequency of

winds with a southerly component. This in turn causes a northward advection in the eastern part of the N Atlantic along the British Isles (Namias, 1965), which brings warmer and more saline water to the area where water is recruited to the inflow into the North Sea. A complex air-sea interaction loop is able to maintain this situation for a prolonged time span (Namias, 1965). The atmospheric forcing mechanism described by Namias can actually explain the periods of increased salinity in the North Sea in two ways, 1) by causing an increased current strength of the N Atlantic inflow, and 2) under "normal" inflow conditions by the fact that the inflowing Atlantic water originates more southerly and thus inherently has a higher salinity than normal. Dickson (1971) furthermore showed that the interannual salinity variations recurred in the deep water of the Skagerrak, which was observed to be accompanied by deep inflow to the Baltic. Thus salinity variations indeed appear to be associated with water flows in the North Sea.

In another analysis of the salinity anomalies, Schott (1966) found that freshwater runoff variations from the European continent were the main determinant. However, as Dickson (1971) pointed out, the reduced runoff may be a secondary effect of the anomalous atmospheric conditions. Circumstantial support for Dickson's analysis further comes from salinity and temperature time series in the Norwegian and Barents Seas, where roughly the same trends are found in the surface waters (Dickson & Blindheim, 1984).

There are some studies in which the fluctuations and long-term trends in the temperature and salinity in the NE Atlantic and the North Sea were suggested to run parallel (Goedecke, 1952; Tomczak, 1967; Taylor, 1978). The conspicuous salinity decline in the mid-1970s was found both in the North Sea and in the NE Atlantic Ocean (Dickson et al., 1984; Ljøen & Sætre, 1987). Actually (Fig. 2.12), the salinity anomaly was found in the Faroe-Shetland Channel in 1976 (Dooley et al., 1984), at the Ocean Weather Station M at 66°N in 1977 (Gammelsrød & Holm, 1984), in the Barents Sea in 1978/1979 (Dickson & Blindheim, 1984) and in the North Sea in 1978 (Ljøen & Sætre, 1987). Thus, from the Faroe-Shetland Channel the occurrence of the salinity anomaly in the northern North Sea was delayed for two years. The fact that these long-term trends and events occur coherently in such wide and different areas strongly suggests that they were caused by an ocean-wide mechanism. This may have resulted in changes in the Gulf Stream-NAC system (see section 2.1.3). Changes in the strength of the Gulf Stream (Worthington, 1977), the position of its north wall (Taylor & Stephens, 1980b), an eastward shift of the Subpolar Front and other anomalous events in the N Atlantic (Dooley et al., 1984) have actually accompanied the mid-1970s salinity decline. Thus, the hydrographic regime in the North Sea, and in particular its long-term fluctuations are very likely to be determined by processes of Atlantic origin, where changes in advection are probably the conveying agents. In January 1990 the highest salinity ever was measured in the northern North Sea (Heath et al., 1991). This may be a signal of another period of changing current patterns in the Atlantic, which will also affect the North Sea.

As regards temperature, Becker & Kohnke (1977) demonstrated that the long-term temperature trends for the Bay of Biscay correlated well with those in the southern North Sea, but not with those in the northern North Sea and the Faroes. The latter two areas mutually did neither show a correlation. These facts imply that in the southern North Sea it cannot be ruled out that the temperature (~heat content) is influenced by advective currents from the English Channel, whereas the northern North Sea is not or insubstantially influenced by the advection of heat from the N Atlantic or Norwegian Sea (Becker, 1981). For the North Sea the direct heat exchange with the atmosphere is the major way of surface temperature control, while in the N Atlantic temperature variations relate to changing advective surface currents (Colebrook & Taylor, 1979).

The North Sea, although having a small volume of water compared to the Atlantic Ocean, does have demonstrable influence on the latter. The water leaving the North Sea as the Norwegian Coastal Current towards the Norwegian Sea and Barents Sea (Kautsky et al., 1980; Livingston et al., 1982) is shown to contribute to the low salinity of the surface waters in these Polar Basins. Mosby (1963) estimates that the contribution is 15-20% of the local runoff. Relying on artificial radioactive nuclides, North Sea water can be traced into the East Greenland Current 3-5 years after it left the North Sea (Dahlgaard et al., 1986; Kautsky, 1987).

2.4. CONCLUSIONS

About the hydrographic and current regimes of the North Sea and the N Atlantic much knowledge has been obtained. However, the relation between the processes that have been identified and the observed variability is largely qualitative, and still needs a lot of research. Long-term time series revealed a link between climate and the major current system in the N Atlantic, the Gulf Stream- North Atlantic Current. Because of the observed

parallelism in the changes in the NE Atlantic and the North Sea it is presumed that variations in the hydrographic regime of the N Atlantic influence the water characteristics of the North Sea. How exactly the Atlantic influence works out on the North Sea is unclear, and neither is the extent of such influence compared with other possible factors such as changes in runoff or local wind fields. It is fairly well established now that possible climate variations or changes (by natural cause or anthropogenically) will modify the N Atlantic and, through the prevailing current system there, also the North Sea.

It is of utmost importance that all the links and connections between the various subsystems in the N Atlantic become clear for a proper assessment of the consequences of climatic changes. Obviously, this also pertains to regional areas like the North Sea. To investigate and understand large-scale processes we will need large-scale research programs as the World Ocean Circulation Experiment (WOCE) and the Joint Global Ocean Flux Studies (JGOFS), which are already underway and are supported by many countries.

3. IMPACT OF THE NORTH ATLANTIC OCEAN ON BIOLOGICAL COMPONENTS IN THE NORTH SEA AND ANTHROPOGENIC INFLUENCE ON THE OCEAN

When considering the biological variability of the North Sea in relation to the variability in the N Atlantic Ocean one is inclined to think in terms of Atlantic water masses introducing organisms into the North Sea directly. Organisms are indeed brought into the North Sea by the prevailing currents, e.g. species of zooplankton (*Calanus*) are known to be periodically imported into the North Sea via the Fair Isle Current and the inflow along the Norwegian Trench (Fransz et al., 1991). But it also concerns the invasion of exotic (indicator) species, which visit areas outside their normal geographical distribution area only exceptionally. This is the simplest way to detect changes in the ecosystem. Exotic invaders visited the North Sea and surrounding waters frequently (Cushing & Dickson, 1976; Cushing, 1982), the record goes back some centuries. They are possible indicators of large-scale, long-term changes, for example, in the early 1930s many uncommon invaders from the south were additional signals for major oceanic changes. They supported the observation of salinity anomalies in the NE Atlantic and its shelf areas (Dickson & Lee, 1969). This was probably associated with the world-wide increase of the air temperature, which also affected the oceans and took place during the first half of this century (Cushing, 1982).

Causal relationships that relate events in the N Atlantic with those in the North Sea are best identified during extremities or during prolonged periods of a sustained trend. But even when these ideal conditions are fulfilled it will not be simple to obtain relationships, for there may be many causes contributing and feedback mechanisms complicating the interpretation. Whilst extremities cannot be created, long-term time series can. The existence of a long time series of temperature and salinity was referred to earlier, and has proved to be very helpful in identifying large-scale processes in the N Atlantic Ocean. Since 1945 moreover, data are available on plankton abundances, as collected by the Continuous Plankton Recorder (CPR) Survey (Glover, 1967). From this extremely valuable data set many publications evolved. They largely provide the clues for unravelling the influence of the N Atlantic Ocean on the North Sea ecosystem, particularly on zooplankton and phytoplankton.

The most outstanding temporal changes in populations of organisms are the seasonal variations. When long-term time series are considered these variations are the most conspicuous, for instance, Colebrook (1978a) demonstrated that about 60% of the variability of a zooplankton species in the North Sea was of seasonal origin, while the amplitude of variability associated with the long-term trend was only 5%. Fortunately, sophisticated mathematical methods have been developed to detect these relatively small variations and trends in time series.

3.1. LONG-TERM PLANKTON CHANGES

In the N Atlantic south of 59°N and in the North Sea an analysis of CPR data showed that from 1958 onwards an overall decline in the phytoplankton abundance occurred (Reid, 1977; 1978; Colebrook, 1982b) to approximately 1980, and since then there was a reversal of this trend (Fig. 3.1, Colebrook et al., 1984; Owens et al., 1989; Aebischer et al., 1990). The observed trends for the N Atlantic and the North Sea are very similar. Note that this is about abundances and not about phytoplankton primary production. About the latter no convenient time series are available in the North Sea or Atlantic Ocean; some time series exist for near coastal areas which indicate an increase of primary production in the period 1970-1985 (Cadée, 1986), but this should be considered a typical coastal phenomenon probably associated with eutrophication.

The general trend of phytoplankton abundance obscures deviating changes for certain separate species or for certain areas. Not only the abundance of the phytoplankton changed but also the composition of the population. For example, in the North Sea *Ceratium* species did not show a progressive trend (Fig. 3.2). They mainly varied about the mean value with a pronounced maximum or minimum in certain years (Colebrook, 1982b). Only from 1975 there is a steady decrease as other phytoplankton species did many years before. Diatoms declined dramatically from 1966 on, whereas the autumn bloom disappeared. Also the phytoplankton colour index of the CPR (a measure of the standing crop of all phytoplankton species) in the North Sea increased markedly since 1958 as opposed to the nearly general decline of all other plankton species. This is possibly explained by unidentified components of the phytoplankton in the CPR, notably microflagellates (Reid, 1978). According to Colebrook (1982b) species of phytoplankton with similar geographical distributions do not necessarily show similar annual variations, whereas the same holds for

different species occurring at the same time of the year. This complicates the drawing of general conclusions from long-term trends. Finally, accompanying the decline of abundance of a great number of species was a shortening of the production season: While the range of variation of the onset of the phytoplankton bloom is about two months a progressive delay of about 3 weeks has occurred in 22 years of sampling from 1948 to 1969 (Glover et al., 1972).

The trend of the zooplankton abundance from 1946 to 1987 is downward in the first decades with a trough around 1980 (Fig. 3.1), very much like the general phytoplankton trend. This holds for many zooplankton species and for all areas of the NE Atlantic and the North Sea (Fig. 3.3, Colebrook, 1978a, b; 1986; Colebrook & Taylor, 1984; Owens et al., 1989; Aebischer et al., 1990). As for phytoplankton, some individual zooplankton species may exhibit deviating behaviour (Glover et al., 1972; Colebrook, 1982b). For example, the trend of *Calanus* differs from the general one. This might have been caused by anomalous advective import of *Calanus* from the Norwegian Sea in periods when the Arctic influence is large (Cushing, 1982). It was furthermore demonstrated that species which show similar annual fluctuations in abundance tend to have similar geographical distributions but do not necessarily have similar seasonal cycles (Colebrook, 1978a). There were also long-term trends found for these seasonal cycles: The production of zooplankton biomass has gradually been reduced from 7/8 months to 5/6 months, which means that one or two generations of zooplankton were lost in a period of nearly 3 decades (Cushing, 1982).

3.2. INTERPRETATION OF PLANKTON CHANGES

The fact that there are similar, persistent trends in the long-term changes of phytoplankton and zooplankton abundances is in itself a good reason to suspect long-term climate variations as the ultimate cause, the more so because these long-term trends are uniform for many different species of plankton and because these trends have an ocean-wide range, including the N Atlantic and its shelf areas like the North Sea. But there are actually more direct indications for a relation between these biological changes and the physical environment (climate).

Colebrook (1978a, b) proved that there is a correlation between the zooplankton decline in N Atlantic and North Sea and the sea surface temperature (SST) at the Ocean Weather Stations throughout the N Atlantic (Fig. 3.4). In addition, during the same period the frequency of days per year of westerly weather over the British Isles was observed to have decreased (Garrod & Colebrook, 1978; Colebrook, 1982b). The best correlation of the latter with the zooplankton decline was achieved with a two-year lag of the westerly weather. These results indicate that there is a tendency for these zooplankton species to be less abundant when the temperature is low, i.e. when the influence of the NAC is weak (see also Chapter 2).

According to Garrod & Colebrook (1978) no correlation existed between the local SST variations in the NE Atlantic and the coincident variations of the zooplankton. If, however, the SST variations were considered occurring over the entire N Atlantic (as represented by the Ocean Weather Stations) the long-term trend was very similar with that of the zooplankton abundance. Moreover, the SST changes appeared to be determined to a considerable extent by variations in the north-east trade winds and the mid-latitude westerlies (Colebrook, 1978a). This provides a possible connection between climatic variations and the SST. The 'medium' to convey these temperature changes is presumably the Gulf Stream-NAC system. Thus zooplankton changes were probably mediated by fluctuations in advection.

Taylor & Stephens (1980) produced indications that relate hydrographic conditions in the N Atlantic with changes in biological parameters. In the time span 1966-1977 there were two pronounced periods, one in which the (north wall of) the Gulf Stream had a southerly position (1970-1974) and another (1966-1969) with a more northern position (see also section 2.1.3). The more southerly position was moreover accompanied by stronger atmospheric circulation, i.e. the Gulf Stream position appeared to be associated with the atmospheric regime. The Gulf Stream position showed a very similar trend as compared to the long-term SST trend as represented by the Ocean Weather Stations in the N Atlantic (Fig. 3.5). This long-term temperature trend, by the way, has been accompanied by similar long-term changes in the salinity (Taylor, 1978; Colebrook & Taylor, 1979). Also depicted in Fig. 3.5 is that the pattern of fluctuation of a number of zooplankton species in the NE Atlantic shows some similarities with the Gulf Stream position. It is therefore suggested that the oceanographic changes in the N Atlantic might be the result of the latitudinal displacement of the Gulf Stream, whereby advection plays a major role. The mechanism through which advection could cause changes in zooplankton abundances might involve overwintering stocks. Small

advected changes in winter populations may be magnified into substantial changes the following summer (Colebrook, 1979; 1985a).

Climatic changes (through changed advection) can also directly be linked to local changes in biological components in the North Sea. In 1971 in the southern North Sea the phytoplankton colour index increased markedly in January and February compared to the annual mean, early diatom blooms occurred, and the blooms of several *Ceratium* species advanced by periods up to 6 weeks (Colebrook et al., 1978). At the same time a persistent salinity increase was only shortly going on in the English Channel (Garrod & Colebrook, 1978). These events were associated with a sudden reversal of a long-term pressure anomaly over Greenland (Dickson et al., 1975), which was made responsible for a change of wind direction in the NE Atlantic to westerlies. This in turn caused the inflow of water up the English Channel and into the southern North Sea to increase. The exact mechanism which caused the biological changes in response to the enhanced inflow is less clear. Dickson & Reid (1982) suggest that in the 1970s the North Sea circulation became more under the influence of winds with a southerly component (instead of a northern one in the 1960s), which made the water in the southern North Sea less turbid. Related to the changes in wind direction (and reduced wind strength) was a concomitant decrease in river runoff which acted in the same way on the turbidity.

In the North Sea significant correlations were calculated between phytoplankton and zooplankton on the one hand and salinity on the other (Reid & Budd, 1979). For SST no such correlations were found. As salinity changes in the North Sea can be positively related to environmental changes on an ocean-wide scale (Garrod & Colebrook, 1978; Taylor, 1978) this indicates that, through modified currents in the N Atlantic, climatic variations cause long-term changes in the plankton. The relationship between the frequency of occurrence of westerly weather over the U.K. and the plankton abundance, as referred to before, is another link in this connection (also Colebrook, 1985b). Applying a different atmospheric index, Dickson et al. (1988) furthermore demonstrated that the long-term increase in the northerly wind component over the NE Atlantic during the 1950-1970 period was associated with the decline of the plankton population in the central North Sea. A possible reason for the phytoplankton decline therefore is the vigorous spring mixing of the oceanic surface layer, which leads to a delay of the spring outburst because the phytoplankton is mixed to below the photic zone (Mann & Lazier, 1991).

A case should be mentioned concerning the concurrent changes of four marine trophic levels and climate. In the northwestern North Sea the long-term trends from 1955 to 1987 of phytoplankton, zooplankton, herring, and kittiwake breeding variables were very similar to each other and to the occurrence of westerly weather over the British Isles (Fig. 3.6, Aebischer et al., 1990). The relationship between the plankton and climate (through advective currents) seems well established and possibly for fish (i.e. certain life stages, for example larvae) this may apply as well, though we should be cautious deriving too simple relations for the life cycle of fishes. The trends exhibited by the kittiwake may reflect the predator-prey relationship between bird and fish. This study clearly demonstrates that climate changes and associated changes in the water movements in the N Atlantic could have impact on all levels within the North Sea ecosystem.

3.3. CHANGES IN NORTH SEA FISH STOCKS AND THEIR POSSIBLE ATLANTIC CAUSE

The fish population of the North Sea has displayed dramatic changes during this century (e.g. Hempel, 1978; Daan et al., 1990). Undoubtedly, fisheries contributed strongly to this phenomenon. Many species have shown a decline in population in recent years. Some aspects of the issue are treated in section 3.4.

The total fish biomass in the North Sea shows both seasonal as well as interannual variations (Daan et al., 1990). Particularly notable is the biomass increase of about 50% towards the end of the summer, which is predominantly caused by the invasion of the horse mackerel (*Trachurus trachurus*) from the NE Atlantic (Sparholt, 1987). To a smaller extent there are also other immigrants from the Atlantic. These movements into the North Sea are usually associated with spawning and feeding, but may also be linked to the seasonal changes in water temperature (Daan et al., 1990). Amongst the species that now and then invade the North Sea are the pilchard (*Sardina pilchardus*), sea bream (*Pagellus centrodontus*), Ray's bream (*Brama brama*) and Arctic skate (*Raja hyperborea*) and others (Postuma, 1978; Hempel, 1978; Daan et al., 1990).

Fluctuations in fish abundance were also found that could not be contributed to common causes. Corten (1990) mentions some of these for the North Sea. Between 1972 and 1979 a decline in the recruitment to North Sea herring (*Clupea harengus*) stocks took place. The course of the subsequent recovery did not have an obvious explanation (Corten, 1986). In addition, a shift of the herring spawning grounds between the Shetland/Orkney area and the Aberdeen Bank occurred since 1983. This was exactly the opposite shift that

occurred some decades ago. The sprat (*Sprattus sprattus*) stock size boomed between 1972-1975, and the spawning grounds moved towards the north. In the late 1970s the sprat stock started to decline again. As a third case the mackerel (*Scomber scombrus*) fisheries shifted northward in the period 1974-1985 (Walsh & Martin, 1986) and the timing became later. After 1981 juvenile mackerel had been migrating from the English Channel to the west of Scotland and even into the northern North Sea. These changes could not be explained by internal dynamics in the fish populations. Rather, Corten (1990) assumes that they were caused by a large-scale change in the North Sea circulation, and "if such changes exist they are not likely to originate locally since the North Sea conditions are too variable to create sustained anomalies over longer periods of time". Changed water characteristics are known to have a direct influence on the behaviour of fish (abundances). Therefore, changing the inflow of water from the N Atlantic into the North Sea could be the ultimate cause of the observations: Herring spawning north (since 1983) or more southerly (in the 1970s) would parallel the (possible) extension or retraction of the Atlantic water mass in the northwestern North Sea, since herring always tends to spawn in water with the same characteristics (i.e. temperature and salinity). Reduced inflow of Atlantic water may also change or diminish the prevailing water movements from the northwest towards the German Bight, with the concomitant transport of herring larvae to their nursery grounds disrupted; this could be the cause of the recruitment failure in the 1970s. Also for the sprat and mackerel peculiarities as referred to above, realistic changes in the flowing pattern could be the direct cause. Additional evidence that the fish abundance (i.e. recruitment to fish stocks) is linked to the physical environment (climate) can be found in Garrod & Colebrook (1978) and Shepherd et al. (1984). Therefore, the cause of the changes in fish stocks as discussed by Corten (1990) must be sought in processes in the N Atlantic Ocean. Although the direct evidence of hydrographic changes in the 1970s is poor, Corten (1990) suggests that the mid-1970s salinity anomaly in the North Sea (Dooley et al., 1984) and in many adjacent areas of the N Atlantic and Arctic basins (Dickson & Blindheim, 1984) might be a signal of ocean-wide anomalies in currents (see also Chapter 2). The change in the Gulf Stream position referred to above (Taylor & Stephens, 1980) also occurred in the period under review.

3.4. ANTHROPOGENIC INFLUENCE ON THE BIOLOGICAL RESOURCES OF THE OCEANS

The anthropogenic influence on the world oceans reaches farther than only biologically. In section 4.3.3 the case of lead is mentioned, which demonstrates that increased concentrations are found now throughout all oceanic surface waters. Lead is not the only chemical substance that shows anthropogenic enrichment in the remote marine environment. However, the concentration of these substances in oceanic waters is almost always low in comparison with the level where organisms are negatively affected. Another kind of human impact on the oceans and the life therein evolves from our continuous attempts to modify the climate on earth, notably by burning fossil fuels and unnatural land use (deforestation). Actually, the oceans play an important role in this set-up, because they compensate the emission of CO₂ into the atmosphere by absorbing part of it. The most striking feature of the so-called greenhouse effect is expected to be a global warming. The life in the oceans will definitely be affected by temperature increases. One can imagine changing of the geographical distribution of organisms, but organisms that are not able to keep pace with the velocity of the movement of climatic zones will most probably perish. Temperature changes will also affect the general ocean hydrography, which in turn will have influence on the biota. A possible other effect is associated with the acidification of the surface waters of the oceans through their uptake of CO₂. This could perhaps be deleterious to the carbonate tests of organisms. We do not even come near when trying to see into the consequences of the greenhouse effect on the world oceans and everything that is in it. Our scientific basis is far too small to go beyond speculations, but nevertheless an excellent account on all known aspects and an ordering of all intelligent speculations of the greenhouse effect was given by a large group of top scientists in the Intergovernmental Panel on Climate Change (Jäger & Ferguson, 1991). It is beyond the framework of the present report to discuss extensively this speculative future scenario for the oceans, for this constitutes a study on its own. Moreover, until now no signals have been detected that could possibly relate biological changes to (anthropogenic) global warming.

For the anthropogenic impact on the oceans attention will be paid to fisheries effects, for they are the most outstanding. This does not mean, however, that a complete account of fisheries effects for the oceans is available. Actually, we cope with a high degree of uncertainty regarding fish resources, i.e. we lack the necessary background level against which the modifications on the system should be placed. This situation

even holds more for the marine mammals, a group of animals that is tremendously being affected by human activities.

With respect to fisheries the North Sea is a relatively well-studied area compared with the oceans. In section 3.3 the effects of fisheries on the North Sea fish population was shortly mentioned. It should be noted that even in this well-studied area the knowledge is mainly confined to some commercially exploited fish species. Through the very intensive fisheries in the North Sea, especially since 1945, the spawning stock of many fishes has declined, amongst which are the herring, mackerel, sole, cod, haddock and whiting. The herring and mackerel population decline is a particularly illustrative example of how overfishing could bring a fish population on the verge of extinction in a certain region (Daan et al., 1990). Obviously, the species that are commercially sought after are severely under pressure. But the fisheries also affect the non-targeted fish stocks, either through by-catches or destruction of essential habitats by fishing gear (Bergman et al., 1991). All this led to the virtual extinction of some species in the North Sea, for example the greater weever and the blue tuna (Daan, 1989). In the 1960s the bluefin tuna (*Thunnus thynnus*) disappeared from the North Sea as well, but Hempel (1978) suggests that this was caused by heavy exploitation of the tuna stock in the Atlantic!

Fisheries cause changes throughout the entire ecosystem. This may either occur through the direct by-catch of other marine organisms, for example the zoobenthos in shallow seas such as the North Sea, or through shifts in the ecosystem structure, for example through the filling up of holes left behind by species that have been caught away. An extensive review on the effects caused by North Sea fisheries at the different trophic levels of the ecosystem is documented by Bergman et al. (1991). When considering the human impact on the different levels of the marine ecosystem in the oceans it is undoubtedly the most severe on the level of the marine mammals. This contention can be made even though the size of the populations of many species of cetaceans (whales and dolphins) are generally only sparsely known. These animals are at the end of the food chain, which implies that their abundances are by nature already much lower than those at the lower trophic levels. This, together with their slow reproduction cycle, makes them very vulnerable to disturbances.

For a restricted area as the North Sea it is generally assumed that the populations of marine mammals have declined during this century (e.g. Reijnders & Lankester, 1990). Without much speculating the same contention could be made for the open ocean. There are several possible causes for the decrease of the numbers of marine mammals. Obviously, the intense hunting on whales has been one of the major causes of decline. Secondly, marine pollution, particularly with polycyclic aromatic hydrocarbons and chlorinated hydrocarbons is a possible cause of reproduction failure in marine mammals, which could lead to a reduction of the population size. This mechanism was demonstrated convincingly for common seals by Reijnders (1986), but Reijnders & Lankester (1990) question if this conclusion can be extrapolated to other marine mammals, such as the harbour porpoise. Thirdly, the marine mammals suffer from competition with fisheries for their prey. This mechanism is particularly effective because fisheries have caused the fish population to be consisting mainly of smaller individuals while marine mammals preferentially prey on larger fish.

The most severe threat to marine mammals at the moment - and to the entire oceanic ecosystem - is the large-scale driftnetting in the oceans. A driftnet is a sort of gill-net that was originally used to catch salmon, squid and tuna. The length of the nets are up to 40 km, and they are set at the migration routes of the fishes. These driftnets are so sheer, however, that they cannot be seen or otherwise detected by the animals. In other words, they are very non-selective in catching. All kinds of larger marine animals are caught as by-catch, for example whales, dolphins, seals, birds, sea turtles and sharks. Recently, catch data have been published (as quoted in Muntingh, 1991), giving (only) an indication of the immense amounts of animals that are caught. About 80,000 blue sharks, 30,000 marine birds, 1700 whales, 250,000 tuna and 3 million sea breams are reportedly caught annually by Japanese driftnetting for squid in the N Pacific only, whereas it is estimated that the actual amounts are at least ten times higher. Additional catches stem from predominantly Taiwanese and South Korean driftnet fisheries. Other sources (Anonymous, 1991) report a total cetacean by-catch of between 315,000 and 1 million per year as a lower limit (the Atlantic Ocean fisheries not included and neither the unknown pirate driftnetting operations). In a preliminary quantitative assessment on the number of by-catches it was found that in the Tasman Sea albacore fisheries one dolphin was caught per 11 km of net during haulage (Coffey & Grace, 1990). The latter authors quote another figure of one marine mammal per 23 km of net in the N Pacific Ocean. With a total length of driftnets in the N Pacific only (about 40,000 km) this implies that 1750-3600 marine mammals are killed per day. This has to be raised with an unknown amount for the other oceans. An additional problem caused by driftnet fisheries is that broken nets are

abandoned and thus keep on 'fishing' as 'ghost-nets'. This results in even more catches and cetacean by-catches of an unknown amount.

Driftnetting started in the N Pacific but has spreaded to all world oceans now. In the Pacific the catch data of fish recently revealed the first signs of overfishing, that is, catches declined and the young year classes were represented to a lesser extent than normally (Anonymous, 1991; see also Muntingh, 1991). For the NE Atlantic it is as yet unclear how much driftnetting occurs and what its effects are on the fish stocks and numbers of marine mammals (McDonnell, 1990). It is thought, however, that driftnet fisheries in this area is actually still expanding.

3.5. CONCLUSIONS

The many studies relating hydrographic variables to biological ones have proved to be extremely valuable in detecting the climatic influence on the biology of the N Atlantic, including its boundary areas such as the North Sea. This shows once more how important the CPR time series is. Recapturing, a general picture may be given of the way the N Atlantic influences the biology in the North Sea. The picture is to some extent speculative since the mechanisms to convey climate changes and current fluctuations to biological fluctuations are largely unknown. On the other hand, there are strong indications given by causal relations between climatic variables and biological parameters.

The Gulf Stream-NAC system is thought to respond to and interact with the atmosphere. Actually, correlations have been found between atmospheric indices and Gulf Stream parameters. The Gulf Stream-NAC system represents a (relatively) warm water flow and determines the temperature regime of the N Atlantic to a great extent. In fact, the SST in the NE Atlantic tends to be inversely related to the strength of the Trade and Westerly winds, which indicates that the fluctuations in the seawater temperature in the NE Atlantic are some sort of indicator of changes in the Gulf Stream-NAC system. In the NE Atlantic the long-term trends of salinity are very similar to those of temperature. Thus the SST and salinity changes observed in the NE Atlantic (including the North Sea) are interpreted as resulting from shifts in the Gulf Stream-NAC system. The temperature and salinity fluctuations show a great deal of similarity over large areas, including the N Atlantic and the North Sea. This suggests that the long-term hydrographic changes in the North Sea are mediated by the large-scale ocean currents in the N Atlantic, and through these by climate changes. It should be noted that the time taken for the effects of current changes to become manifest over the entire N Atlantic will certainly be one or more years. That is why the year-to-year changes of temperature and salinity do not match well, but the general long-term trends of them do.

The long-term trends of the plankton in the NE Atlantic and the North Sea appear to be very similar. In addition, the time series of the plankton and of SST (whole N Atlantic) were correlated. Further, the long-term trend of the plankton abundance was associated with the long-term changes in the occurrence of certain wind components in the NE Atlantic which in turn are related to atmospheric pressure distributions. Hence, it is strongly implicated that an appreciable proportion of the long-term fluctuations of the plankton abundance in the NE Atlantic and North Sea are determined by large-scale climatic changes through changes in the advective currents. In a way this is curious because the importance of processes within the plankton ecosystem is great and variations associated with this are large. The fact that changes as a result of climate variations are detectable implicates that the ecosystem processes must be extremely stable and that long-term changes are merely perturbations on this.

Largely unsolved until now is how the mechanism acts that causes the changes in plankton abundance associated with changes in currents and advection. It is certain that a direct effect of the temperature is not the cause. It was suggested (and there is some evidence for it) that overwintering stocks of the zooplankton could provide a clue, whereby relatively small advected changes in winter will become marked ones in the following summer.

Evidence has been put forward that also fish recruitment is subjected by ocean-wide climatic processes, as this is the case for plankton. It was shown that long-term changes in the behaviour and abundance of several species of fish in the North Sea were most likely of Atlantic origin, notably by changes in the NAC. In the northwestern North Sea the similarity of long-term trends extended over four marine trophic levels and altogether they showed similar characteristics as a climate parameter. Albeit the plankton trends were likely the result of advective changes in the N Atlantic, this is not necessarily the case for the higher trophic levels. The parallelism between the bird variables and fish stocks may find its origin in the predator-prey

relationship between them. Nevertheless, the climatic influence on the North Sea through the N Atlantic apparently has great consequences for the entire ecosystem by causal interactions.

4. CHEMICAL ELEMENTS IN THE NORTH SEA AND THE ATLANTIC OCEAN

In seawater almost all chemical elements occur naturally, some in high and some in (extremely) low concentrations. They can be in all kinds of states, free dissolved or bound to other constituents or suspended particles. In marine science suspended matter is operationally defined as what is retained on a 0.45 µm filter and what passes through is 'dissolved'. In reality there is a continuous spectrum of particle sizes to be found in seawater. For the behaviour of a chemical species in seawater it is very important if it is in the dissolved or in the suspended phase: Species in solution follow the water movements closely, while suspended particles, although their general circulation is mediated by the water circulation, can be temporarily (or permanently) deposited and resuspended. This means that the fate of suspended particles in the North Sea not always needs to be the Atlantic Ocean; there are some areas where (semi)permanent deposition occurs, of which the Norwegian Trench and the Skagerrak are the most important (Eisma, 1990).

The interaction between dissolved species and suspended particles occurs through processes such as adsorption/desorption, remobilization from the sediments and active uptake by living organisms. The sources and sinks of dissolved and suspended chemicals in the North Sea are partly the same, again demonstrating the strong impact of the general water circulation. There are, however, additional sources of suspended particles within the North Sea such as coastal and seafloor erosion, the rivers, atmospheric (= aeolian) input and primary production (Eisma & Irlon, 1988). Some dissolved species also have a significant atmospheric source, especially those of anthropogenic origin.

Several chemicals or groups of chemicals will be considered in the present report. Most of them are occurring naturally in oceanic waters, some have increased by anthropogenic causes, and some have been introduced by mankind. In the following sections the starting point will be the distribution and concentrations of the species in the North Sea which will be compared with those in the adjacent NE Atlantic.

4.1. THE INORGANIC NUTRIENTS

With the term nutrients usually the inorganic forms of phosphorus, nitrogen and silica are meant. They are essential for all living organisms (with the exception of silica, which is needed only by some species of phytoplankton) and are major constituents of them. On occasion, these nutrients may become limiting for further growth of the phytoplankton, and therefore they are important in determining the level of primary production. In this section the term nutrients refers to the dissolved free state of these. Nutrients are also occur in suspended particulate and dissolved organic matter.

As a consequence of them being the building blocks of phytoplankton, the nutrient concentrations exhibit a pronounced seasonal variation. In winter, when the water is cold and the light regime is poor, the plankton production is low and consequently the nutrient concentrations are high. In spring and summer nutrients are gradually depleted through extraction by the phytoplankton. If no new nutrients are supplied the concentrations decrease. Remineralization causes the nutrients finally to return from the organic to the inorganic pool. Another process that plays a role in determining this seasonal behaviour is that in winter advection by deep water is more important than in summer.

The winter distribution of phosphate in the North Sea and a small part of the adjacent NE Atlantic is shown in Fig. 4.1 as an example. The distributions for the other nutrients are quite similar (Brockmann et al., 1988, 1990; Gerlach, 1990). Features in these distributions are, 1) the nutrient contents of the inflowing water from the NE Atlantic across the northern boundary is approximately twice as high as in the central and southern North Sea, and 2) in the inshore areas of the continental and British coasts the concentrations are markedly higher than further offshore.

The latter feature is caused by the discharge of nutrients by rivers where due to restricted mixing the fresh water remains along the coast, and by sediment-water exchange of remineralized nutrients. The decrease from the north towards the south with the minimum in the Southern Bight is according to Postma (1978) caused by the nutrient extraction of the previous year which is not fully restored and secondly by the "sweeping away of organic matter towards the edges" (i.e. the coastal areas) through the strong tidal currents, upon which little nutrients are remineralized in the offshore waters.

The influence of the NE Atlantic Ocean on the nutrient budget of the North Sea is evident from Table 4.1 (Gerlach, 1990). Although the anthropogenic influence (through rivers and the atmosphere) has increased,

the natural contribution (through the NE Atlantic and the English Channel) is still about 80% for nitrogen and 90% for phosphorus. Earlier budget calculations arrive at quite similar relative contributions of the N Atlantic to the North Sea nutrient input (James & Head, 1972; Ursin & Andersen, 1978; Nelissen & Stefels, 1988). This budget may be crude with some questionable assumptions, but it is certainly adequate to make the point that the Atlantic nutrient supply is of utmost importance for the North Sea.

On a seasonal scale the oceanic input and output of nutrients is quite variable, although the extent to which is uncertain. This is mainly caused by the lack of knowledge about the water transport. The concentration of the nutrients in the inflowing water is variable because the inflowing water is derived from the top layers of the oceanic water masses (Postma, 1978). In the course of the year the nutrient concentration in the top (euphotic) layer gradually decreases because the produced organic material with its fixed nutrients sinks down towards the deeper layers where most of the nutrients will be remineralized; these remineralized nutrients are, however, not readily available for primary production in the upper layers because the seasonal thermocline prevents vertical exchange. In this way the nutrients get depleted in the top layers during the growing season, and the concentrations in the inflowing Atlantic water thus decrease in the course of the growing season. A higher nutrient content is restored in the winter due to wind-induced vertical mixing, which reaches down to about 500 m.

The vertical nutrient gradients in the oceanic water masses (which are most pronounced in summer) imply that for the proper inflow and outflow calculations, different layers should be distinguished. Reliable transport data of the water masses at different depths (and in different seasons), however, are lacking (Chapter 2) which makes the nutrient input data very approximate. As referred to in Chapter 2 the Atlantic inflow into the northern North Sea is divided between three areas. For the annual input of nutrients the following general picture can be drawn. First, the water that enters along the western Norwegian Trench contains water from the upper 500 m and is consequently relatively rich in nutrients. However, its influence on the North Sea is limited to the northern part, where it circulates and leaves again in about half a year. The second water inflow is the Fair Isle Current which derives water from the upper 100 m of the NE Atlantic (e.g. Rogalla, 1959); the water is somewhat poorer in nutrients, but its influence extends over a larger North Sea area (central and northwestern part). Third, through the Pentland Firth the smallest water flow enters the North Sea. This water flow also contains the lowest nutrient concentrations (Johnston, 1973), because this current contains shelf water from the west British coast. The outflow water along the Norwegian coast is firmly divided between a surface and a deep layer. Already in winter the surface layer is lower in nutrient content than the incoming water from the NE Atlantic between Shetland and Norway (Johnston, 1973; Postma, 1978), which is possibly caused by a progressive depletion as the water mass follows its course along the Norwegian coast; the nutrients cannot be replenished from the deeper water masses due to the permanently stratified water column. The deep water of the Norwegian Coastal Current derives from the Atlantic inflow between Scotland and Norway and is consequently nutrient-rich.

The Atlantic influence on the nutrient contents of the southern North Sea is proportionally much smaller than in the north, because all major rivers discharge their nutrients in the south. Compared with the water inflow from the English Channel the total freshwater discharge of all southern rivers is small, but the concentration of dissolved nutrients in the river water is much higher than in the inflowing Channel water. Meanwhile, the terrestrial input of dissolved nutrients to the southern North Sea is larger than the oceanic input owing to the anthropogenic enhancement of the nutrient loads (Table 4.1). However, the total amounts of nitrogen and phosphorus (that is, including the organically bound nutrients) coming in through the Dover Straits is still higher than those from the rivers (Sydow et al., 1990). The oceanic nutrient load of the southern North Sea is furthermore rather modified by processes within the English Channel. The winter concentrations in the Channel are generally lower than those in the Atlantic water near the northern boundary (Russell et al., 1971; Butler et al., 1979). The distribution of nutrients in the Channel is rather patchily (Armstrong et al., 1974) which results in a variable input into the south of the North Sea. In Chapter 2 it was shown that the water transport through the Dover Straits is considerably variable as well, which reinforces the variation of the nutrient input.

It should be noted that in a season not being winter the nutrient input from each of these external sources is quite different. Not only the nutrient concentrations in the inflowing water are lower, but also the water transports are different. Moreover, *in situ* biological activity in the North Sea strongly influences the nutrient concentration which altogether results in quite different distributions (e.g. Johnston & Jones, 1965).

The main long-term loss of nutrients from the North Sea is the transport to the Atlantic Ocean via the Norwegian Trench. Other sinks are the burial of particulate matter (with fixed nutrients) within the North Sea, the transport of suspended particles to the Atlantic, and the loss to the atmosphere after transformation into the gaseous phase.

The North Sea is considered to be a productive sea. The reason is that it is a rather shallow and turbulent sea, but above all that there is an adequate supply of nutrients. Although the anthropogenic nutrient load has increased dramatically during the last decades, the nutrient input from the NE Atlantic is still by far the most important for large parts of the North Sea. In a very general way one can state that changes in nutrients will affect the primary production because production is limited by one of the nutrients. Since the annual primary production in the North Sea seems to be variable and long-term trends in the abundance of phytoplankton were observed (Chapter 3), the question is qualified what causes this, and in our particular case, what is the role the nutrient supply from the Atlantic. The best way to answer this question would be using a long-term nutrient time-series accompanying the plankton and meteorology series. Unfortunately, such does not exist for the NE Atlantic. There are some nutrient series in the coastal North Sea, the most outstanding one in the German Bight (Radach & Berg, 1986; Radach et al., 1990). In the latter area it was found that a strong phytoplankton increase between 1962 and 1984 was accompanied by increases of nutrients (except silicate). However, it was concluded that these observations were dictated by anthropogenic causes (eutrophication), through enhanced nutrient discharges by the river Elbe.

A long-term study in the western English Channel off Plymouth provides some clues for the changes of the biology related to nutrients changes. Because the region is comparable these findings may also pertain to the North Sea. Continuous observations from 1924 onwards showed that there is a notable similarity of the course of the phosphate concentration and some biological parameters (Fig. 4.2). In the 1930s, amongst others, there was a marked decrease of the winter maximum of phosphate together with a decline of the quantity of zooplankton and of the herring fishery (Russell et al., 1971; Southward, 1980). In the 1960s a conspicuous reversal of the events from the 1930s occurred. Since the 1960s primary production was measured concurrently and a concomitant rise in primary production was thus found during the 1960s (Boalch, 1987). There is general agreement that these observations are broadly related to climatic changes (Cushing & Dickson, 1976; Southward, 1980). They thus demonstrate the "nutrient connection" with large-scale climatic changes. However, it remains unclear whether the changed nutrient input from the Atlantic triggered these biological changes or, the other way round, the biological changes were the cause of the observed nutrient trend. The mechanism through which all of these observations are linked to climate is unclear, possibly due to a different response at different rates of changes of the various chemical and biological components of the intricate ecosystem. Sure is that the climatic change is conveyed through the incoming Atlantic water. Oceanic variability of nutrients and associated changes in biology may also be transferred through the Channel towards the southern North Sea. No direct evidence exists for this assertion, but the long-term influence on the physical properties of the southern North Sea was convincingly demonstrated (Chapter 2). The observations so far indicate that the long-term trend of nutrients in the Dover Straits is one of an increase by a factor 2-3 between the 1930s and 1986/1988 (Sydow et al., 1990), but probably this increase can be attributed to anthropogenic causes and is not of Atlantic origin. In addition, the winter levels of nutrients at the entrance of the North Sea may vary by a factor 3-4 between years (Carlson, 1986). Van Bennekom & Wetsteijn (1990) concluded that the true variations of the winter levels of nutrients through the years in the water flowing into the southern North Sea were only minor. Dickson et al. (1988) claim a long-term trend of nitrate in the western North Sea which could be caused by climatic factors, but the method with which this trend was established is debatable.

4.2. SUSPENDED PARTICLES

Suspended matter does not represent a single chemical species. The biogenic suspended matter derives predominantly from phytoplankton production, and consists of organic matter, carbonate or opal (SiO_2) particles. Besides, there are contaminant single particles, such as fly ash, coal or organic waste, which are introduced through human activity. Contaminants which are originally in solution (heavy metals, chlorinated hydrocarbons) also may become adsorbed onto (scavenged onto) suspended particles and they may be actively extracted from the water by organisms when these take up essential nutrient elements. Subsequently those contaminants will also get incorporated into the particulate matter. It is clear that suspended matter may be an important transport route for certain chemicals, especially those that have a preference to be adsorbed

rather than remain in solution (i.e. those which are hydrophobic). Suspended matter is also important because its concentration and size distribution influences the amount of sunlight that is able to penetrate the water column, i.e. the sunlight which is available for primary production. Furthermore, suspended particles are a source of food for benthic organisms; microorganisms may be transported by being attached to the particles (Eisma, 1990).

The concentration of suspended matter in the surface water of the Atlantic Ocean is very low (Jacobs & Ewing, 1961), while on the continental shelves it is generally higher (e.g. Eisma, 1981). In the North Sea in winter the concentration generally increases from north to south and from offshore to inshore. The reason that the suspended matter concentration of oceanic surface waters is so much lower than of water on the shelf is that there are no nearby sources on the ocean, such as the rivers and the seafloor, where resuspension may occur, whereas the particulate organic matter produced by phytoplankton sinks out of the surface layer.

The suspended matter concentration is much higher in the oceanic water that enters the southern North Sea through the Dover Straits than in the N Atlantic water at the northern boundary. Most of this material is picked up from the Channel coasts and seafloor and therefore is not of oceanic origin (Eisma, 1981). Thus, although the water inflow from the south is relatively small, the input of particulate matter is higher than from the northern boundary (Table 4.2). Other important sources of suspended matter are as shown in Table 4.2 the rivers (which account for the concentration increase towards the coasts) and the atmosphere. In spring and summer the concentration of suspended matter is much higher because of primary production; then up to nearly 100% of the suspended matter may be organic.

The concentration of suspended matter flowing in and out at the northern boundary between Scotland and Norway is approximately the same and taking into account the small excess of the water outflow over the inflow this implicates that only a little more suspended material is exported than imported (Table 4.2). However, the composition of the imported and exported material is probably not the same (Eisma, 1990). Part of the exported material had been introduced from other sources (see Table 4.2), but this is 'compensated for' by material which is deposited within the North Sea and which originally came from the N Atlantic. In addition, the elemental and chemical composition of the particles will have changed after entering the North Sea because of sorption processes and exchange of particles between bottom sediments and those in suspension in the water column (Eisma, 1990). The North Sea is thus a gigantic modifier of particles of N Atlantic origin. But the other way round, particles of the North Sea and of terrestrial (or anthropogenic) origin may find their way to the N Atlantic Ocean, with their possible load of heavy metals and chlorinated hydrocarbons (e.g. pesticides).

The supply of organic matter from the NE Atlantic can be estimated from the inflow of suspended matter and its organic content. Eisma & Kalf (1987) found that the organic content of the suspended inflow in winter from the NE Atlantic is 40% and from the English Channel the equivalent figure is 15%. For the rest of the year no reliable data are known and therefore the total import from the NE Atlantic is $10 \cdot 10^6 \text{ ton} \cdot \text{y}^{-1}$ together with an unknown amount coming in during spring, summer and autumn. Likewise, the export along the Norwegian coast is $5 \cdot 10^6 \text{ ton} \cdot \text{y}^{-1}$ increased with an unknown amount for the spring, summer, and autumn (Eisma, 1990). Walsh et al. (1981) asserted that the transport of organic particles from the continental shelves to the slopes of the oceans could be a significant sink in the global carbon cycle. In a later paper Walsh (1991) contended that the continental margins are as important as the deep sea in the global carbon and nutrient cycles. Possibly the North Sea-NE Atlantic system is a link in this world-wide process.

4.3. TRACE METALS

In the ocean trace metals occur naturally. Some of them, such as manganese, iron, cobalt, nickel, copper and zinc are essential elements for primary producers in very low amounts, where they are needed in certain metal-requiring enzyme systems (Bruland, 1983; Sunda, 1991). Consequently, their distributions are influenced by biological processes, and vice versa they influence biological processes. Their concentrations and distributions are also determined by other processes. These may be chemical such as precipitation/dissolution, oxidation/reduction or hydrolysis (Abdullah, 1985). Most metals possess the capacity to adsorb on or absorb in suspended particles, evidenced by the fact that their concentration in the particulate phase ($\mu\text{g} \cdot \text{g}^{-1}$) is usually much higher than in the dissolved phase ($\mu\text{g} \cdot \text{dm}^{-3}$) (Kersten et al., 1988). In shallow areas, such as the continental shelves, there is an intense interaction with the sediments involving adsorption, but also remobilization and reductive dissolution from the sediments.

Sources of trace metals to the oceans are the rivers and the atmosphere (and some deep sea sources, hydrothermal and geothermal activity). The former sources contain a substantial anthropogenic component, for some metals human activity is the principle component. There are many metals of which the concentrations are very low in oceanic waters (pmol.kg^{-1} range). For many of these no data are available for the North Sea, or for the adjacent NE Atlantic. For the oceanic behaviour, or what is known from it, one is referred to the extensive reviews by Bruland (1983) and Chester (1990).

Measurements of trace metals in very low concentration ranges poses strict requirements on contamination control during sampling, sample handling and analysis. Only after about 1976 accurate data sets started to become available which were produced in clean room conditions. Before that time the comparability between the different data sets was insufficient (Topping et al., 1980; Jones, 1982). It is illustrative to note that within one decade the concentration range of some metals was adjusted downwards by some 3 orders of magnitude! Now many vertical profiles have been found to be consistent with the present knowledge about the biology, physics and biogeochemistry of the oceans (Bruland, 1983).

It should be realised that because of the many processes and sources and sinks for trace metals, combined with the fact that larger data sets are only emerging recently and are far from complete, mass-balances for the North Sea are very difficult to construct. Therefore, in the following the general distributions of some trace metals will be treated as far as these are known, focussing on differences between the North Sea and the N Atlantic Ocean. Also, in the light of the present state of development, it seems appropriate to discuss generally the trends rather than the absolute concentrations. Further it should be kept in mind that the enrichment of trace metals in the North Sea in comparison with the open ocean does not necessarily indicate pollution since the natural level on the shelves might be higher than at the open ocean due to the intense interaction with the shallow sediments (Kersten et al., 1988).

4.3.1. Cd, Cu, Ni

Cadmium (Cd), copper (Cu) and nickel (Ni) exhibit a nutrient-type distribution in the oceans (Bruland, 1983), which means that their vertical profiles correlate to a high degree with those of the nutrients. They appear involved in the uptake by phytoplankton and are regenerated at depth and in the sediment during remineralization.

The surface concentrations of these three metals in the central North Sea and the English Channel are 3-5 times higher than in the open N Atlantic Ocean (Kremling, 1983; 1985; Danielsson et al., 1985). In the nearshore Southern Bight and the German Bight the concentrations are again typically a factor 2 higher than in the offshore North Sea (Duinker & Nolting, 1982), which is clearly caused by river discharges. Notable in the observations of Kremling (1983; 1985) is the dramatic increase of the metal concentration at the shelf-edge (Fig. 4.3). This is explained by Kremling through the diagenetic remobilization of the metals from the partly reduced sediments with subsequent mixing into the surface layers by the strong tidal currents in that area. According to Kremling (1983) the processes must be variable which is connected with the seasonal variability of the currents and mixing characteristics. Possibly, the long-term variations in the hydrography and currents will also have impact on the trace metal concentrations at the shelf-edge. In a later study Kremling & Hydes (1988) indeed did not find the front-like distribution of the metals; a slight increase of a factor <2 from the open Atlantic towards the shelf, though, was found for Cd, Cu and Ni. Balls (1985a, b) did also observe trace metals fronts for Cd and Cu accompanying a salinity frontal structure around Scotland, but on the ground of the vertical profile of Cu which did not display an increase towards the bottom, he concluded that the high trace metal concentration at the shelf-edge was caused by freshwater runoff.

4.3.2. Al, Mn, Co

The distributions of aluminium (Al), manganese (Mn) and cobalt (Co) are strongly influenced by external sources. Co is moreover biologically mediated, being present in the centre of vitamin B₁₂. Its concentration in oceanic waters is very low ($<0.010 \text{ nmol.kg}^{-1}$), which implies that it is rapidly removed from seawater (Bruland, 1983). Mn generally shows a maximum in the surface layers, while in the deeper layers it is scavenged; the same holds for Al (Hydes, 1983). Al is also involved in shell formation.

Mn shows the same behaviour at the shelf-edge as Cd, Cu and Ni as referred to above (Kremling, 1985). For Al this behaviour is even more pronounced, going from the open ocean towards the English Channel the concentration increases by a factor 10-20. In the southern North Sea the values are comparable with those in

the Channel. Probably the Al distribution on the shelf is determined by river runoff or sediment releases and not by biological shell formation (Kremling, 1985). In the N Atlantic the vertical distribution of Al is typically influenced by the input of Al from the North Sea (Measures et al., 1986). In the NW Atlantic there is a surface maximum and mid-depth minimum, whereas in the NE Atlantic there is no deep water increase (which would result in the mid-depth minimum). The explanation for this difference is that North Sea water, which is enriched in Al, is advected to the southern Greenland Sea where it participates in the formation of water that, via the Greenland-Scotland overflows, is the source of the deep water in the N Atlantic. Thus, the deep water in the N Atlantic at high latitudes becomes enriched in Al. However, because the deep water circulation at lower latitudes in the eastern N Atlantic is more sluggish than in the western N Atlantic, different profiles are found in the two basins (see also Chester, 1990). The concentration of Co decreases with the distances from the continents (Bruland, 1983). On the NW European shelf the concentration is clearly the highest closely to the coasts (Kremling & Hydes, 1988). Lowest values were indeed measured at the outer shelf-edge. The central and northern North Sea occupy intermediate positions in the concentration range.

4.3.3. Hg, Pb, Zn

Zinc (Zn) has a typical nutrient-type distribution in the ocean, it particularly correlates favourably with silicate (Bruland & Franks, 1983). Zn is strongly depleted in the surface waters and is transported to deeper waters probably as a trace constituent of biogenic particles, such as opal. Lead (Pb) and mercury are known biological inhibitors (Sunda, 1991). The general distribution pattern of Hg is not completely clear. Part of the Hg might be associated with organic matter (Ólafsson, 1983). The major input source for Hg is the atmosphere, whereas in the seawater it is scavenged (Gill & Fitzgerald, 1988). Pb is an outstanding example of an element whose world-wide distribution and biogeochemical cycle is markedly influenced by man (Schaule & Patterson, 1980; Ng & Patterson, 1982). Pb has been brought into the environment mainly through automobile exhausts. It is transported atmospherically to the open ocean, of which a 15-fold enrichment in the surface compared to the deep waters is the result. Due to more extensive anthropogenic activity the lead content of the N Atlantic Ocean is about 2.5 times higher than in the Pacific Ocean (Schaule & Patterson, 1983).

The Zn depletion in the NE Atlantic is less pronounced than in other ocean areas (Danielsson et al., 1985). In the North Sea the surface values are variable, but considerably higher (about 5 times) than in the NE Atlantic. The vertical profiles in the northern North Sea are quite variable. Zn sources are the rivers and the atmosphere together, for there is no relationship between the Zn concentration and salinity.

The concentration of Hg in the North Sea is about twice as high as in the adjacent N Atlantic (Lee & Ramster, 1981). The distribution in the North Sea is irregular with generally low values ($<2 \text{ ng} \cdot \text{dm}^{-3}$) (Schmidt & Dicke, 1987 as cited in Kersten et al., 1988). Elevated levels at some spots in the North Sea and near the shelf-edge may be attributed to an enhanced suspended load (Baker, 1977).

The Pb concentration in the NE Atlantic is lower than in the offshore North Sea (Brügmann et al., 1985). According to the latter authors within the North Sea the concentration in the north is higher than in the central part. Balls (1985c) finds that the levels in the northern North Sea are twice as low as those of Brügmann et al. (1985), and moreover, his results do not show great differences with values from the southern North Sea. Dicke et al. (1987, as cited by Kersten et al., 1988) found still another Pb distribution in the North Sea with a maximum in the central North Sea. Kersten et al. (1988) attribute the observations of the latter authors to Pb being considerably associated with particulate matter. This statement is corroborated by Brügmann et al. (1985) who found that up to 40% of the total Pb is in particulate form. On the other hand, Balls' (1985c) data show a much smaller fraction of the total Pb to be represented by particulates. Brügmann et al. (1985) state that the Pb concentration in the North Sea is relatively low when compared with the great input through the atmosphere and the rivers. The explanation must be that intensive particle scavenging occurs within the North Sea, but also that the water exchange with the N Atlantic is fast. As a consequence of the intense scavenging the North Sea must accumulate much Pb at its deposition sites. In the NE Atlantic Pb accumulation in the bottom sediments was established as well (Veron et al., 1987) but this is certainly caused by atmospheric deposition of Pb directly into the oceanic environment as well. Contrasting views indicate that the behaviour of Pb is not unequivocally established.

4.3.4. Fe

Iron (Fe) is a biologically very important metal, with a functional role in oxygen transporting enzymes and electron transfer systems. It is also essential for enzymes in the synthesis of chlorophyll as well as in the enzymatic reduction of nitrate and nitrite, as required for utilizing ambient nitrate as substrate for protein synthesis. Fe is a candidate to be considered as a limiting element for primary production (Martin & Fitzwater, 1988; De Baar et al., 1990), and therefore has drawn major attention. Still, its oceanic distribution is poorly known. Contamination problems during analysis and sampling are undoubtedly responsible for this. Gordon et al. (1982) found a nutrient-type distribution for dissolved Fe. The concentration of particulate Fe is generally higher than the dissolved.

In the NE Atlantic and in the North Sea rather scattered profiles were reported by Danielsson et al. (1985). The authors attributed this partly to the method of analysis and to contamination. Despite these problems the Fe concentration in the North Sea is several times higher (and in the Southern Bight up to orders of magnitude) than in the NE Atlantic. These very high values in the North Sea are possibly caused by the high suspended load, because with their methodology probably total Fe (=dissolved + particulate) was measured. According to Danielsson et al. (1985) the particulate-bound form of Fe constituted the major fraction of the total Fe content. This is confirmed by Nolting (1986) for the southern North Sea, where particulate Fe is about 2 orders of magnitude higher than dissolved Fe.

4.4. TRACE ELEMENTS ON PARTICLES

The elementary composition of suspended matter is dependent both on its origin and on its organic content (Nolting & Eisma, 1988). For many trace metals their particulate concentration is comparable to or lower than their dissolved concentration, examples are Cu, Zn, Cd, and Ni (Danielsson et al., 1985; Nolting, 1986); the spatial distribution of the ratio particulate:dissolved may vary considerably, though. In estuaries and coastal zones many metals are retained, but also many metals are deposited on the seafloor at some deposition areas in the North Sea.

The amount of particulate metals leaving the North Sea to the NE Atlantic could broadly be estimated by comparing the concentrations in the inflowing and outflowing water at the northern boundary, taking into account that the concentration of suspended matter in the inflow and outflow is approximately equal and that there is only a slight excess of outflow water. According to Nolting & Eisma (1988) the influence of the southern North Sea on the northern part with respect to particulates is negligible.

The elemental composition of suspended matter for the North Sea as a whole was studied by Wirth & Seifert (1988), Hölemann & Wirth (1988) and Nolting & Eisma (1988). The latter authors performed the most extensive measuring campaign and their results are displayed in Fig. 4.4. The situation depicted in Fig. 4.4 applies to winter conditions. It appears that for most elements the particulate concentration in the inflow and outflow are comparable, only for Mn the outflowing water contains substantially more and for Si, Ti, Ca and Zn it contains less. (Note that Si is no trace element). This is only part of the story. Particularly for metals which are biologically involved (Fe, Cd, Zn, Co, Cu, Ni) there may be an effective trapping mechanism at the shelf-edge, especially in the summer. The nutrient-rich inflow from the NE Atlantic sustains a high primary productivity with a concomitant removal of dissolved metals to the particulate phase. The increased vertical mixing intensity at the shelf-edge completes the 'nutrient pump' (Sandstrom & Elliott, 1984). This process stands in contrast to the enhanced dissolved metal concentrations at the shelf-edge (Kremling, 1983), observations of which were done in winter.

Thus, the mixing zone of Atlantic and North Sea water represents a last biogeochemical barrier for dissolved species from escaping to the ocean (Kersten et al., 1988). Particulate metals possibly escape to some extent, but may partly be deposited as well, for example in the Norwegian Trench.

4.5. ORGANIC MICROPOLLUTANTS

There is an enormously large range of organic chemicals synthesized by mankind, most of which have the possibility to reach the sea eventually. What holds for metals also holds for these organics: They are transferred between different phases, i.e. they are dissolved, and adsorbed on particles or in organic matter. But more than metals organic micropollutants can be transformed or degraded in the water or within

organisms (Ernst et al., 1988). Some compounds, however, such as chlorinated hydrocarbons are very persistent in the environment because they are hardly degraded. Others form degradation products that may be even more toxic than the parent compounds. Because of the high degradability many compounds will not reach the ocean, whereas they might still occur in the coastal waters.

Some groups of organic pollutants that occur in the marine environment can be discerned (Preston, 1989). *First* the pesticides, which are further subdivided into chlorinated and other species. Of the first subdivision the DDT family is the most widely distributed; other organochlorine pesticides are for example dieldrin and endrin. Generally, these chlorinated compounds are very persistent in the marine environment. The other species of pesticides include organophosphorus- based and carbamate pesticides. These are short-lived in seawater, because they are easily degradable. The *second* group of organic pollutants consists of polychlorinated biphenyls (PCBs) and other halogenated hydrocarbons. These too are very persistent. *Thirdly*, there is a rest group, with for example phthalate esters, C_1 and C_2 halocarbons, dibenzofurans and dioxins.

Organic micropollutants are known to cause deleterious effects on marine organisms. Bioaccumulation and biomagnification are the processes that effectuate concentrations within the organisms that override the ambient concentration by several orders of magnitude, especially at the higher trophic levels, where birds and marine mammals are struck.

All organic compounds have in common that their concentration in seawater is very low (in the $ng \cdot dm^{-3}$ range or sub-range), and many of them occur below the detection limit in large parts of the oceans. They are land-derived, the main sources being the rivers and the atmosphere, but also dumping and shipping activities bring organic contaminants into the seawater. Therefore, their concentration is usually the highest on the continental shelves, in coastal areas. The distributions of the different organic compounds are compound-specific, which implies that it is not possible to use one particular substance as indicator species (Gaul & Ziebarth, 1983). For example, PCB-species of low chlorination are transported as dissolved species, while PCB-compounds with a high chlorination level are attached mainly to particulate matter (Ernst et al., 1988). This will of course determine their distribution to a great extent. It should be noted that most organochlorine compounds are highly hydrophobic, which means that they are preferentially present in the particulate phase rather than in the dissolved phase. According to Eisma (1990) most organic contaminants by amounts occur mainly in the dissolved phase with the exception of the already mentioned PCBs and HCB (hexachloro benzene). This is caused by the fact that the particulate concentration is so low. Other compounds which are taken up by organisms and tend to accumulate in them, are returned to the dissolved state upon decomposition of the organic matter.

Of all possible organic micropollutants, the distribution extending over the whole of the North Sea and part of the NE Atlantic is known for only an insignificant number. Sometimes only regional studies exist. Fig. 4.5 displays the distribution of lindane (= γ -HCH, hexa chloro cyclohexane), which has a clear north-south structure within the North Sea. It is also clear that the inflowing N Atlantic water contains a significant background concentration of this artificial chemical substance. The surface water that flows out of the North Sea along the Norwegian coast, has a much higher concentration than the adjacent water masses; this indeed holds for the surface water which partly derives from the Baltic, the deeper outflow water has predominantly the similar characteristics with respect to lindane as the inflow. This distribution clearly demonstrates the export of lindane towards the N Atlantic. In the same study by Gaul & Ziebarth (1983) other organic pollutants (HCB, PCB-compounds and others) did not show such a structured distribution. It is certain, however, that water exchange between the North Sea and the NE Atlantic is the transport pathway of many persistent micropollutants towards the ocean, because the residence time of many organic chemicals is much longer than the time-scales associated with the water exchange. Transport from the North Sea to the Atlantic also occurs atmospherically for compounds with high volatilities, i.e. compounds of low chlorination.

4.6. MISCELLANEOUS

A separate class of substances that should be considered are the radioactive nuclides. In the natural ocean many radionuclides occur, such as tritium, potassium-40, rubidium-87, uranium, radium, and the nuclides of the decay series of uranium and thorium (Kautsky, 1988). All these isotopes are long-lived and represent the background radioactivity. Through mankind the so-called artificial radio nuclides have been added to this pool, and these are isotopes with relatively short half-lives. Originally these nuclides may have been present in the oceans, but because of their short life-times on a geological time-scale they have decayed to more stable

isotopes (which are the 'natural' nuclides as mentioned above). For any given radio-isotope its potential harm for biota not only depends on its activity but mostly on the nature (α , β or γ -radiation) and energy of its decay. Artificial nuclides derive from (Kautsky, 1988; Preston, 1989):

1. atmospheric atomic bomb testing, the so-called fallout. This source was largely discontinued in 1963, and presently still gives rise to an enhanced background level.
2. nuclear power generating plants.
3. nuclear accidents, of which the one in Chernobyl in 1986 had a high public profile.
4. nuclear fuel reprocessing plants.

On a long-term basis the reprocessing plants produce by far the largest inputs of radioactivity to the oceans (Preston, 1989). In the North Sea the radioactivity concentration is 10-20% higher than the natural background level, while in the N Atlantic and other oceans the relative increase is much smaller (Kautsky, 1987; 1988; Dahlgaard et al., 1986). The normal nuclear power generating plants, of which there are many situated around the North Sea, discharge only small amounts of radioactivity so that the radioactivity increase from this source would hardly rise above the ambient level (Kautsky, 1988); that is, with the exception of tritium which is not radio-toxic, however. The distribution of radioactivity within the North Sea shows typical features, high values in the northwest and central parts and low in the south and southeast (Fig. 4.6), and this reveals the most important sources. Most radioactivity enters the North Sea through the Pentland Firth and comes from the Irish Sea, wherein it is discharged by the nuclear fuel reprocessing plant Sellafield, formerly Windscale (Great Britain). A much smaller, but significant (few percent of Sellafield) source outside the North Sea as well is the reprocessing plant at La Hague (France) in the English Channel. The most abundant artificial radioactive isotopes occurring in the North Sea are caesium-137, caesium-134, strontium-90, ruthenium-106, antimony-125 and tritium, of which the first is by far the most abundant. Many other radionuclides occur as well; of these the transuranics are the most conspicuous, but the quantity of discharged plutonium-239/240 lies more than two orders of magnitude under that of caesium-137 (Kautsky, 1988).

The distribution of caesium-137 within the North Sea reflects the mean circulation pattern. This is because caesium-137 is predominantly present in the dissolved phase and behaves chemically essentially conservative, which makes it a good tracer of water masses (Jefferies et al., 1982). The half-life of caesium-137 is about 30 years. Investigations on radionuclides in the N Atlantic have revealed that the discharges from the Sellafield Works, after passing through the North Sea were transported alongside the Norwegian coast to the Barents Sea and along with the West-Spitsbergen Current to the east of Greenland (Fig. 4.7). Thus, of the radio-caesium within the North Sea 10% is found west of Spitsbergen after 1-3 years and 1-2% east of Greenland after 3-5 years (Aarkrog et al., 1983; Dahlgaard et al., 1986; Kautsky, 1987). The transport of radionuclides in the NE Atlantic is astoundingly confined to the upper 200 m of the water column (Kautsky, 1987).

Finally, it can be concluded that the North Sea is an important recipient of artificial radionuclides, which are further transported towards the NE Atlantic. The level of radioactivity in the NE Atlantic has been enhanced through anthropogenic impact, firstly as a consequence of fallout from atmospheric atomic bomb tests and secondly by advection of water masses with increased radioactivity concentration from the European shelf via the North Sea.

Another group of chemicals that occurs worldwide in the oceans and poses a worldwide threat are the petroleum hydrocarbons. Sources are both natural (seeps) and anthropogenic. Recent estimates of the total amount of petroleum compounds that reach the oceans annually lie around 3 million tonnes (Preston, 1989), but this includes natural seeps which may account for up to 600,000 tonnes.y⁻¹. Anthropogenic sources include (Preston, 1989): Offshore operations (drilling, routine operation, production water, displacement water, accidental discharges), transportation (operational and deliberate discharges, tanker accidents), land-based sources (oil refineries, oil ports/bulk oil handling), the atmosphere and dumping. Oil moves through the seawater as oil slicks, tar balls, or dissolved and dispersed residues. The distribution of tar balls in the N Atlantic is shown in Fig. 4.8. It is correlated with high tanker activity, but is also associated with the current system. The concentration of tar balls seems to decrease along the Gulf Stream-North Atlantic Current track, and in the North Sea the concentration is low. The amount of dissolved petroleum residues in the North Sea was also found to be surprisingly low, in 81 out of 90 samples it was zero (Preston, 1989). This may, however, also be caused by erratic sample collection.

Once in the sea oil undergoes 'weathering processes'. Depending on the conditions oil can be degraded within a short time, or a more persistent foamy emulsion, or 'chocolate mousse', may be formed. The impact

of petroleum contamination is very dependent on the site where it occurs. Estuaries and special coastal areas are much more vulnerable than the open ocean. This holds equally well for the recovery after the oil spill. Marine life that is most affected by oil contamination are seaweeds and marine birds.

4.7. CONCLUSIONS

The interaction between the N Atlantic Ocean and the North Sea is in the first place of a physical nature, which was comprehensively addressed in Chapter 2. However, water exchange between both areas does not only involve H_2O : Seawater contains both dissolved and suspended chemical substances. The intense physical interaction is the key to the issue of water quality in the North Sea. Through the rapid rate of dilution of water in the North Sea by the inflowing Atlantic water and the strong tidal mixing, the levels of toxic or harmful chemicals - that mostly derive from the land through river water - generally remain low. Of course the levels of these substances are still higher than at the open ocean, but they are not, or only exceptionally, higher than the level at which effects for organisms become apparent (Carlson, 1986).

As regards the useful substances, i.e. nutrients, the N Atlantic also plays the leading part. The N Atlantic water is rich in nutrients which is to the benefit of the primary production of the North Sea. The other important factor to sustain a high primary production is again the intense mixing by the tidal currents. The variability in the input of nutrients is large, firstly on a seasonal scale, which is associated with the extraction of the nutrients by the phytoplankton, but also on an interannual scale. The extent of interannual variability of nutrients and the effects of it on the primary production of the North Sea are not sufficiently known. Indications for a long-term trend of nutrient input from the Atlantic which is accompanied by trends in biological parameters (amongst others primary production) were obtained from the English Channel. This research area is wide open to be filled in by an extensive North Sea-North Atlantic project.

The North Sea is a rather large intermediate basin between terrestrial inputs and the ocean for many substances, both natural and anthropogenic. Surely many substances are exported towards the NE Atlantic, but the specific conditions in the North Sea determine the rate and extent to which this happens. The shelf-edge with its typical hydrographic regime may be an effective barrier for trace metal transport to the NE Atlantic, especially for those that possess nutrient-type characteristics. For particles of oceanic origin the North Sea is a gigantic modifying reservoir: It brings about a change in composition between entering and leaving particles through the northern boundary. Although the North Sea water outflow is small the trace metal output to the Atlantic can significantly influence the vertical profile in the N Atlantic, as demonstrated to be the case for Al.

According to recent insights the continental margins might be equally important in the global carbon and nutrient cycle as the open ocean (Walsh, 1991). Within this framework the North Sea-NE Atlantic may be an important link in the global carbon cycle through the net export of organic matter from the shelf to the NE Atlantic slope. To test this important contention explicitly for the North Sea-NE Atlantic specific research needs to be performed, for example within the targeted North Atlantic project of the MAST-E.C. programmes.

5. SCIENTIFIC FRAMEWORK AND RECOMMENDATIONS

5.1. SCIENTIFIC FRAMEWORK

Funding of scientific research in oceanography is predominantly executed by national governments. In The Netherlands this is done by NWO and affiliated organizations. Only a small part of the research is sponsored by private companies. There is merely one international organization that on a large scale supports research financially and that is the Commission of the European Community (EC). Geographically, this support is limited to European countries and the research is restricted to the European region. For the period 1991-1994 the Marine Science and Technology programme (MAST-II) provides funding for international cooperation in research within the marine science community. Several Netherlands institutions have been involved in MAST projects. Actually, within MAST-II there is a targeted project embracing the North Atlantic, and in particular the European shelf-break, which appears to be a major area of relevance for the present report.

All other international organizations do not provide substantial financial support of research projects, but merely serve as a forum for bringing together scientists of a particular research area or interest, for coordinating large research efforts, for disseminating publications, for acting as a central data centre, or just for representing scientists as a counterpart of governmental organizations. On European level there is the European Science Foundation (ESF), which is a non-governmental organization and is the representative of 53 member research councils and academies (Posner, 1990), including the KNAW. Recently, ESF and EC founded the European Committee on Ocean and Polar Sciences (ECOPS), which is meant to be a body that looks after the interests of oceanography within the EC. For the (near) future it is expected that the latter organization will be marking out the lines of European oceanographic research. Also active within Europe but not restricted to the EC is the North Sea Task Force (NSTF). Members are all riparian countries and the (Commission of the) EC. This is an intergovernmental bureau which evolved from the Ministers Conferences on the Protection of the North Sea. The NSTF is primarily involved in policy questions, but also to some extent in stimulating and supporting scientific research of the North Sea.

On a wider international level, that is, not only confined to Europe, two kinds of organizations are active, to be distinguished as (inter)governmental and non-governmental (or scientific). Both types of organizations have only a limited budget available, which is not used for direct support of active research. Falling under the United Nations (UN) there are several intergovernmental organizations that are of importance for oceanography. These include (the Netherlands ministry that is responsible for maintaining contacts is marked in parentheses):

- International Atomic Energy Agency - IAEA (Economische Zaken). For radioactivity in the sea.
- International Maritime Organization - IMO (Verkeer en Waterstaat). Involved in sea water pollution questions.
- United Nations Environmental Programme - UNEP (Milieu, VROM). Concerned with pollution as well, but also with other environmental questions like global change.
- Food and Agriculture Organization - FAO (Visserij, LNV). Where fisheries research is concerned.
- World Meteorological Organization - WMO (Verkeer en Waterstaat). Involved in seawater surface parameters, such as temperature, salinity, waves.
- United Nations Educational, Scientific and Cultural Organization - UNESCO (Onderwijs en Wetenschappen). Within UNESCO was founded the Intergovernmental Oceanographic Commission (IOC), which is the main governmental forum for oceanography and oceanographic research.

Apart from this there is the non-UN organization ICES (International Council for the Exploration of the Sea) (Netherlands ministry: Visserij, LNV), which is influential. ICES is geographically restricted to the North Atlantic Ocean, and has been employing many activities on the North Sea as well. Traditionally ICES was strongly directed at fisheries research, but it has environmental branches as well.

NATO (North Atlantic Treaty Organization) being an intergovernmental military alliance, has a Science Committee as well which also gives support to (marine) science in the form of subsidizing conferences, disseminating publications and allotting grants to researchers. Support is restricted to the NATO member states.

More or less as a counterpart of the intergovernmental organizations there are the non-governmental or scientific organizations. The one organization covering all basic natural sciences in all of its aspects is the International Council of Scientific Unions (ICSU). An impressive amount of both national and international scientific unions and associations operate under the aegis of ICSU (Ernster, 1991). Many other scientific communities are adhering to one of the unions participating in ICSU and so more than 120 national scientific organizations are in some kind of relation to ICSU. This makes ICSU the main representative of the scientific world on international fora. Being part of ICSU different unions that have common interests in a certain field of science or geographical area have founded Scientific and Special Committee's and Commissions. For the oceanographic science community the Scientific Committee on Oceanic Research (SCOR) is of importance, but also the Scientific Committee on Problems of the Environment (SCOPE). Unlike IAPSO (International Association for the Physical Sciences of the Ocean), which was already part of ICSU, SCOR is concerned with all aspects of ocean science.

There are many cross-links between ICSU and its affiliated unions and associations on the one hand and the UN organizations on the other hand. In the first place the ICSU budget depends substantially on the contribution from UNESCO. Many joint committee's were established, for example, the Committee on Climatic Changes and the Ocean (CCCCO) by SCOR and the IOC, and the World Climate Research Programme (WCRP) by ICSU and WMO. The most recent world-wide programmes where ICSU is involved are the International Geosphere-Biosphere Programme (IGBP) and WCRP. IGBP is the major body that fosters large-scale efforts to understand the earth in all of its interactive physical, chemical and biological processes, where the emphasis lies on integration. Attention of the international organizations involved in oceanographic research has recently very strongly been focussed on programmes addressing issues on global change. The world-wide problem of the greenhouse effect, which has a high public profile, is definitely responsible for this. Large-scale long-term cooperative projects, of which JGOFS (Joint Global Ocean Flux Study) is the most important, have found shelter under the umbrella of IGBP (JGOFS is actually carried out by SCOR). In 1989-1990 the North Atlantic Pilot Programme of JGOFS has been executed. The Netherlands participates in JGOFS through the following institutes and universities: Nederlands Instituut voor Onderzoek der Zee (NIOZ), VU Amsterdam, RU Groningen, RU Leiden, TU Delft, RU Utrecht. The other major international programme in which the oceanographic community is strongly involved is the World Ocean Circulation Experiment (WOCE). This is a CCCO project, which has the function to improve the understanding of the role of the oceans in climatic change. Institutes in The Netherlands taking part in WOCE are the NIOZ, IMAU of the RU Utrecht, and the KNMI.

Finally, many scientific and governmental organizations are active in oceanography and related fields and the cross-links are numerous. As an example Table 5.1 is given where all ICSU bodies that are involved in priority areas designated by the United Nations Conference on Environment and Development (Brazil 1992) (La Rivière, 1990).

5.2. RECOMMENDATIONS

The long-term time series of hydrographic and biological parameters strongly suggest that the Gulf Stream-North Atlantic Current system responds to climatic fluctuations and that through these the plankton and possibly the fish stocks in the Atlantic and the North Sea are affected. Whilst this picture is only qualitative, it is absolutely necessary in the light of probable anthropogenic climate modifications in the near future, that the mechanism of the climatic impact on the long-term variations in hydrography and biota be unravelled. For this purpose it is essential that the large-scale sampling by the Continuous Plankton Recorder continues and it would thereby be helpful if more biological and chemical samples could be taken regularly on an ocean-wide scale to come to additional long-term time series. Process studies are important as well for the correct interpretation of the long-term records. There is moreover a great need to give much more attention than previously to the relation between physics on the one hand and chemistry and biology on the other, preferentially in large-scale multidisciplinary research projects.

The North Atlantic circulation is the pivotal point in the whole question. More quantitative knowledge should be obtained about it and the coherence between all of its aspects should firmly be established. This could partly be accomplished by modelling exercises of the N Atlantic, where ocean-atmosphere interactions will have to be included. More understanding of the (natural) variability of the circulation needs to be obtained, for this is a basic question that is still largely unsolved. The need to understand variability emerges from the fact that it forms the background of long-term variations, and if this is not sufficiently resolved it

will always stay the bottleneck for obtaining proper knowledge of the long-term development of the ocean system. The lack of knowledge about ocean variability, its mechanisms and controls is something that applies for most ocean processes. It is important that the emphasis of scientists shifts from single-event research to time-dependent aspects of the oceanic processes under study.

A field that has received too little attention in the past is the direct interaction between the margins and the open ocean. The importance of the margins has been greatly underestimated and now it is suggested that 50% of the fixation of all organic matter occurs on the margins. The extent to which the shelves, and in particular the North Sea, are a trap for chemical elements is the great unknown that should be exposed. The trapping capacity may be varying on a seasonal scale or could be depending on other factors, and so time-dependent research is has to be executed. Targeted research is needed specifically aimed at processes which occur right at the transition between the shelf and the open ocean. Questions to be answered are what processes are specific for the shelf-break and how important they are for the budgets of elements. The exchange of particles and their composition across the shelf-break should be established by way of a seasonal record. About the dominant processes that are known now, understanding has to be expanded so that predictions become possible. There is a basic knowledge about water exchanges between the North Sea and the N Atlantic which should be greatly improved for it is essential in all other elemental budgets. Correct balances of water and salt, and their fluctuations, should be constructed against which chemical changes can be assessed. Especially about the influence of nutrients supply from the Atlantic to the North Sea little is known.

On a world-wide scale a reliable inventory of the ecosystem structure with its many interlinks is urgently needed to be able to signalize major perturbations of it. This especially holds for the higher trophic levels within the ecosystem, like the marine mammals. This will, however, be a gigantic effort which could take many decades and therefore it is worthwhile to stop all major impact on the oceans at least until more understanding has come available.

Climate plays a major role in determining the (long-term) conditions on the oceans. There are strong indications that through climate the oceanic biota are influenced. This raises the crucial question what would happen if man continues modifying the global climate, as we are doing at the moment by increasing the concentration of atmospheric CO₂ significantly ('the greenhouse effect'). This question can only be answered when a major research effort is made to obtain a complete understanding about the mechanisms that relate climate to ocean variability and to variability of the biota. This research target is probably too ambitious to be realised within the near future. Furthermore, the way climate will change in turn depends to some extent on the reaction of the oceans to the CO₂ increase, which brings us in a complicated interaction loop.

However, for realistically assessing the consequences of the anthropogenic influence on climate and through this on the oceans and the life therein, this knowledge has to be available. This presents us therefore with an unsolvable problem which should not and cannot be decided upon by scientists alone.

In the meantime a wealth of organizations has come into being that in some way has something to do with oceanography and management questions concerning the oceans and its margins. This particularly holds for the North Sea, although on the other hand it is understandable that it has come this far since the North Sea has a function for many different kinds of users. Still, for a greater efficacy it would be useful if more structure could be brought into the efforts to manage the North Sea in a responsible way and to obtain a better knowledge of its functioning.

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5. SCIENTIFIC FRAMEWORK AND RECOMMANDATIONS

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TABLES AND FIGURES

Table 2.1: Some estimated NE Atlantic water budgets, in Sv (from Otto, personal communication)

	Dietrich et al. 1975	Worthington 1970	Worthington 1976	McCartney and Talley, 1984.
N.Atlantic Current	11	–	–	14.1
Labrador Current	–	–	2	–
Southern (slope) Current	–	13	6	–
Faroe-Shetland outflow	7	8	8	4.7
Outflow south of Iceland	4	5	–	9.4

Table 2.2: Summary of fluxes in the North Sea area. Given are ranges as found in the literature (from Otto et al., 1990)

	<i>fresh-water $10^3\text{m}^3/\text{s}$</i>	<i>flux $10^6\text{m}^3/\text{s}$</i>	<i>net flux $10^6\text{m}^3/\text{s}$</i>	<i>references</i>
Baltic fresh-water influx	14	0.01		(a)
Baltic-Kattegat flux		0.06-0.03		(a)
Kattegat-Baltic flux		0.05-0.01		
net			0.014	
Kattegat fresh-water influx	1			(a)
Kattegat-Skagerrak flux		0.08-0.07		(a)
Skagerrak-Kattegat flux		0.07-0.06		(a)
net			0.015	
Skagerrak fresh-water influx	2			(a), (b)
Skagerrak-North Sea flux		1.00-0.50		(a), (b), (c)
Jutland current flux		0.22-0.18		(b), (c)
Norw. Channel-Skagerrak flux		0.80-0.13		(b), (c)
net			0.017	
Orkney-Shetland flux		0.40-0.30		(b), (c)
Shetland-Orkney flux		0.03-0.00		(b)
Scotl-Engl. fresh-water influx	2			
sub-total		0.43-0.30		
Straits of Dover flux		0.17-0.10		(b), (c)
Continental fresh-water influx	4			(b)
sub-total		0.17-0.10		
Norw. coast fresh-water influx	11	0.01		
Norwegian Channel influx		1.11-0.70		(b)
Shetland shelf influx		0.60-(0.22)		(b)
sub-total		1.73-(0.93)		
Norwegian Channel outflux		1.80-1.34		(b), (c)
			0.034	

Figures are maximum and minimum values cited from different publications that are mentioned in references (a) or (b), or from modelling results given in (c). The sum of the three sub-totals should be equal or more than the outflux (maxima) or equal or less than the outflux (minima). (a) SVANSSON, 1975; (b) ICES, 1983 (c) HAINBUCHER, BACKHAUS & POHLMANN, 1986.

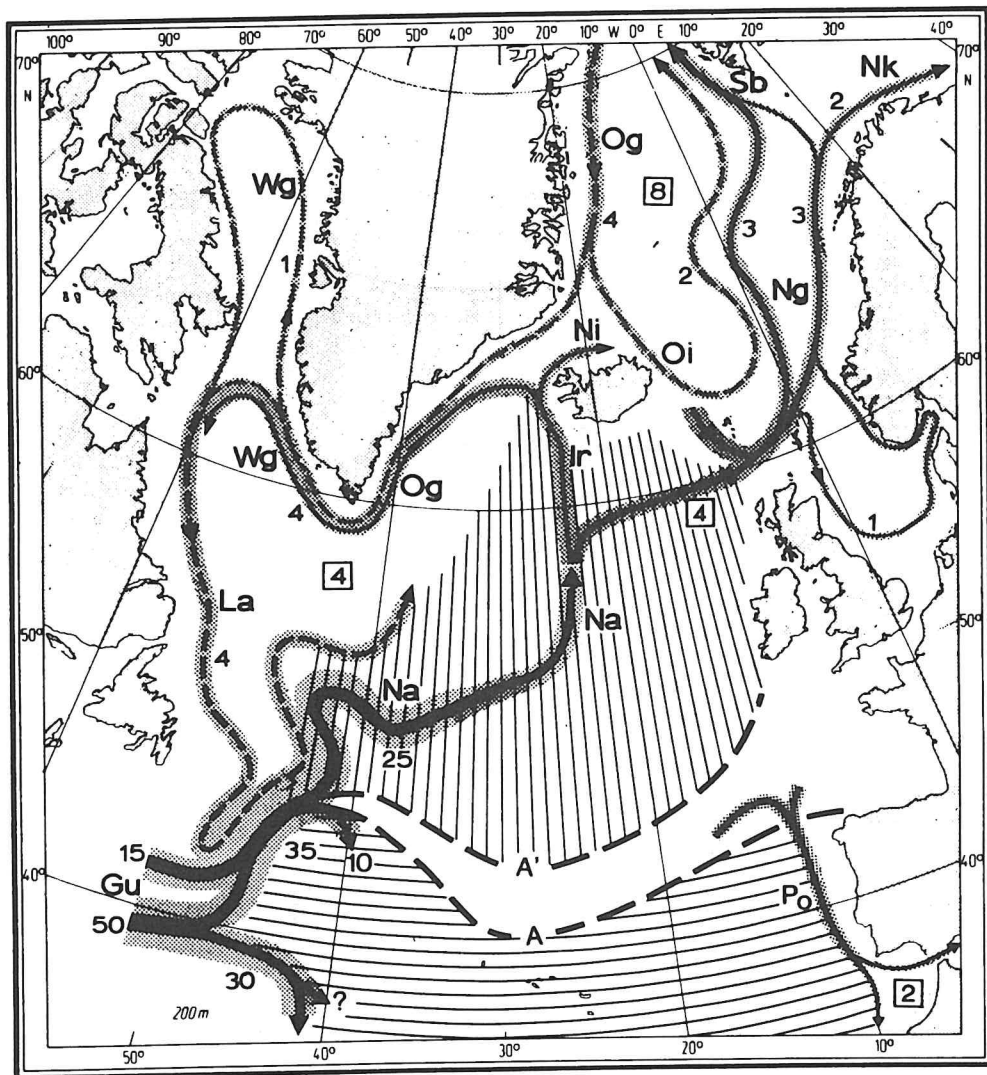
Table 2.3: Characteristics of water masses of the North Sea (from Lee, 1980)

Water mass	Temperature		Salinity	Winter maximum: inorganic nutrients			Summer minimum: inorganic nutrients			‘Dissolved’ trace metals*				
	winter	summer		phosphate PO ₄ -P	nitrate- nitrogen NO ₃ -N	soluble silicate SiO ₂ -Si	free phosphate PO ₄ -P	nitrate- nitrogen NO ₃ -N	soluble silicate SiO ₂ -Si	Cu	Zn	Cd	Ni	Hg
	°C	°C		μmol·l ⁻¹	μmol·l ⁻¹	μmol·l ⁻¹	μmol·l ⁻¹	μmol·l ⁻¹	μmol·l ⁻¹	10 ⁻⁹ g/l	10 ⁻⁹ g/l	10 ⁻⁹ g/l	10 ⁻⁹ g/l	10 ⁻¹² g/l
North Atlantic	6-8	12-14	>35	0.6-0.8	10	4-6	0.1-0.4	1-4	2	0.2-0.5	1.5-4	<0.1	<0.5	2
Channel	5-7	16-17	>34.75	0.3-0.5	7	6	<0.1	<1	<1	0.25-0.5	2.4	0.1-0.3	0.5-1	<2
Skagerrak	2-5	14-17	<34	<0.4	<7	<4	0.1-0.2	-	-	0.5-0.75	-	-	-	1-2
Scottish Coastal	4-6	12-14	34-35	0.6	-	-	0.2	0.5-1	2	0.2-1.5	4-8	<0.1-0.4	<0.5-1	2-4
English Coastal	4-6	14-18	<34-34.5	0.7-1.2	35	14	0.1-0.4	1-4	<1	0.5-1.0	2-6	0.1-0.5	2-5	3-10*
Continental Coastal	2-4	17-19	<34	2.0-3.0	45	20-30	0.1-0.4	10-20	1-2	0.5-2.0	4-6	0.1-0.8	>2	3-4

* Values for Cu, Zn, Cd and Ni refer to water passed through 0.22 μm membranes. Analyses by atomic adsorption method.

Values for Hg refer to unfiltered water and are for ‘inorganic’ mercury. Asterisked value is based on Baker’s [1977] estimate of ‘reactive mercury’.

Fig. 2.1: Schematic picture of the North Atlantic circulation. Flow data in Sv. Horizontally shaded area belongs to the Subtropical Gyre. Meridionally shaded area where flow is associated with the North Atlantic Current towards the north. Area between A and A' belongs temporarily to the northern or southern area (from Krauss, 1986)



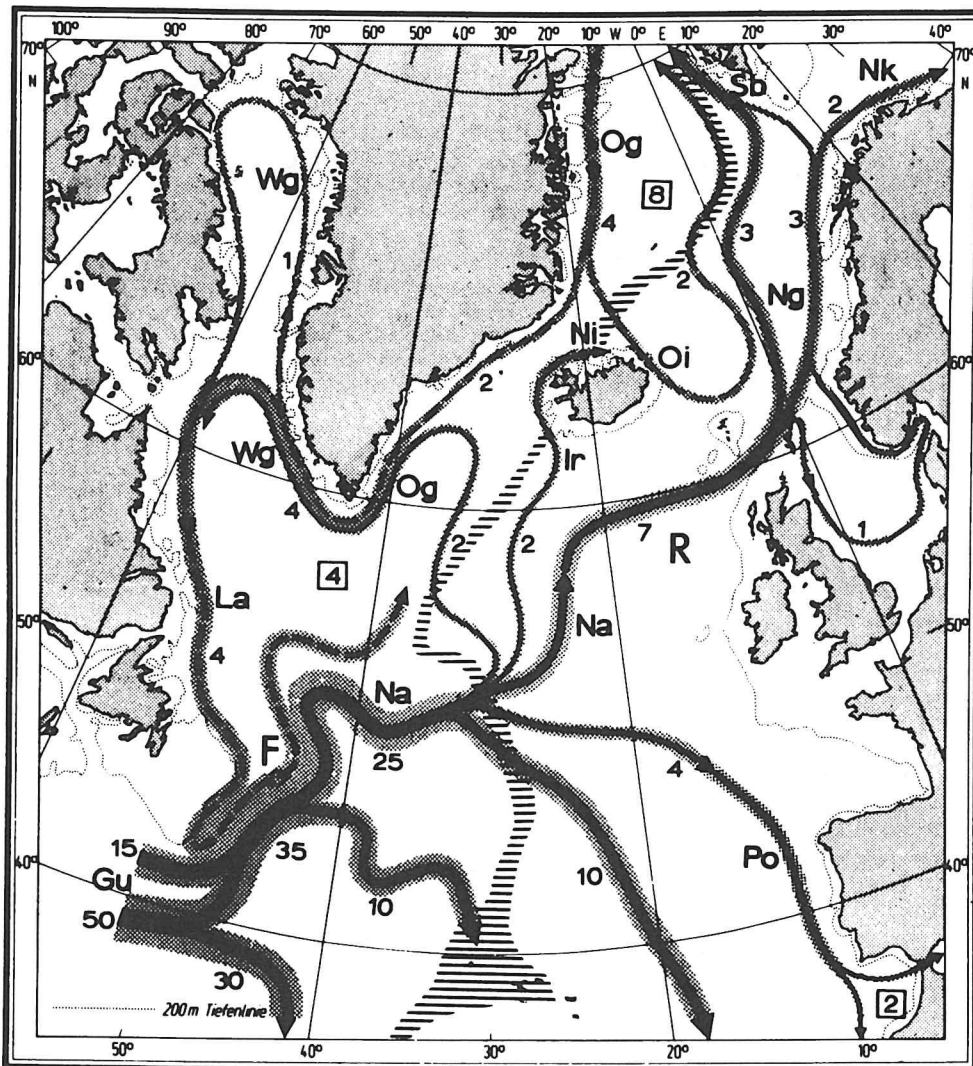


Fig. 2.2: Scheme of the water transport (in $10^6 \text{ m}^3 \cdot \text{s}^{-1} = 1 \text{ Sv}$) in the top 1000 m of the northern North Atlantic (from Krauss, 1986)

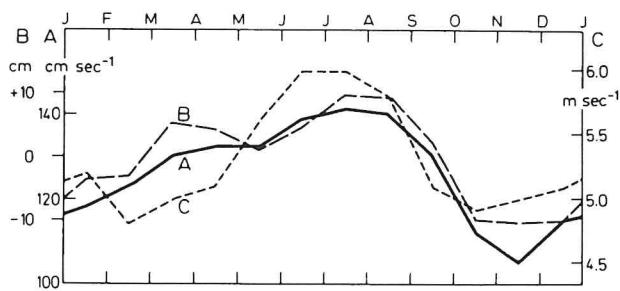


Fig. 2.3: Seasonal cycle of A) the current strength of the Gulf Stream off Florida, B) of the water level difference in the Gulf Stream off Florida, and C) of the wind velocity of the Trade Winds (from Dietrich et al., 1975)

Fig. 2.4: Long-term monthly mean sea surface salinities at the nine Ocean Weather Stations A to M, which are scattered over the North Atlantic Ocean (from Taylor & Stephens, 1980a)

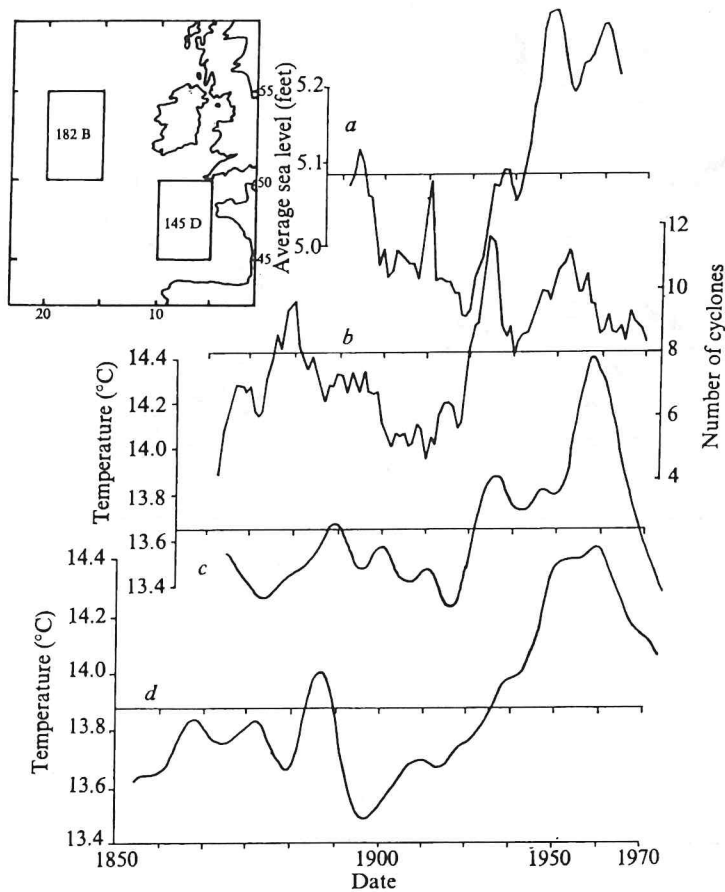
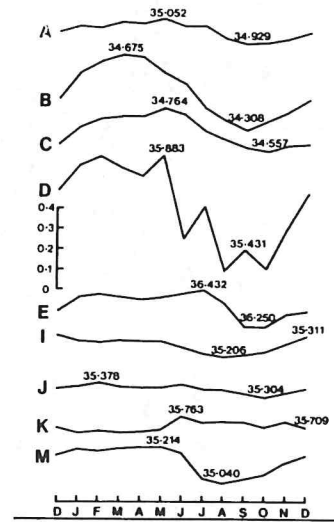


Fig. 2.5: A) 5-year running mean of average sea level along the coast off Florida, B) 7-year running mean of number of Atlantic tropical cyclones, C) smoothed variations of the sea surface temperature for area 182B, D) smoothed variations of sea surface temperature for area 145D (from Colebrook, 1976)

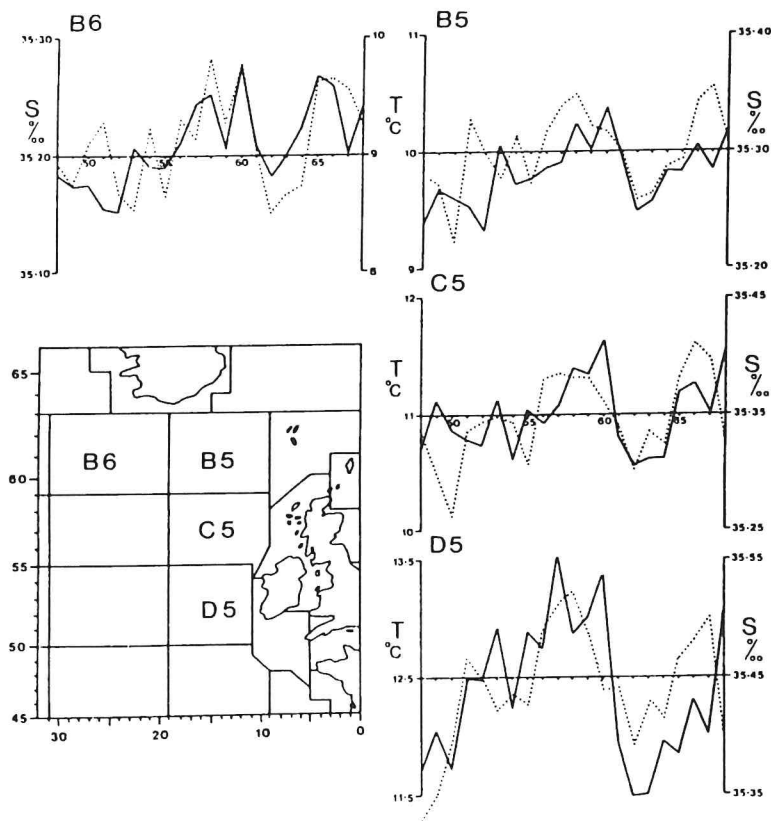


Fig. 2.6: Time series of temperature and salinity for selected areas of the North Atlantic: Temperature (solid lines), salinity (dotted), (from Colebrook & Taylor, 1979)

Fig. 2.7: Annual means of the Gulf Stream position and several atmospheric indices (from Taylor & Stephens, 1980a)

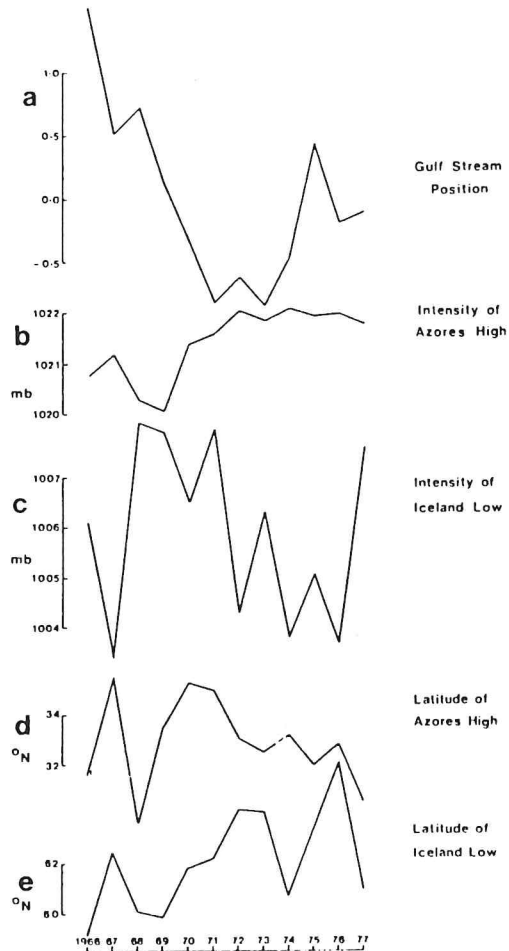
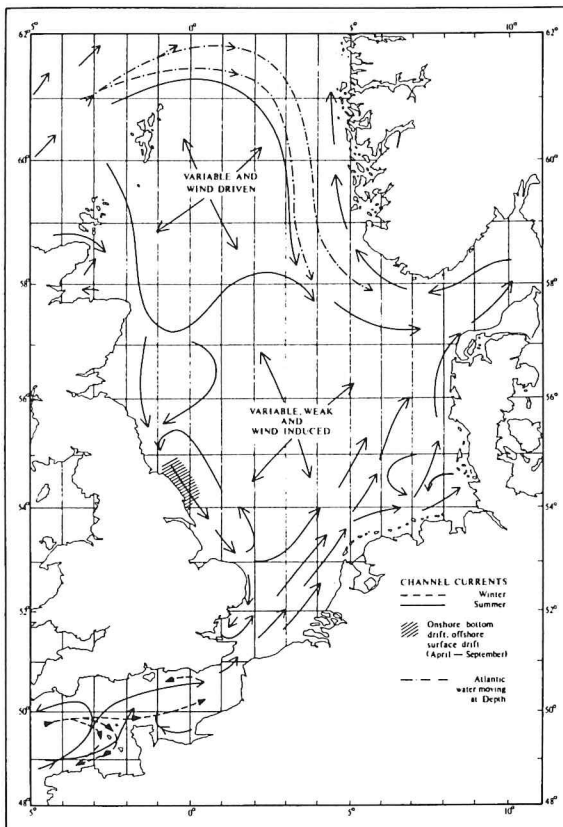


Fig. 2.8: Surface current pattern of the North Sea (from Lee, 1980)

Fig. 2.9: Schematic water budget of the North Sea (from Otto, 1983)

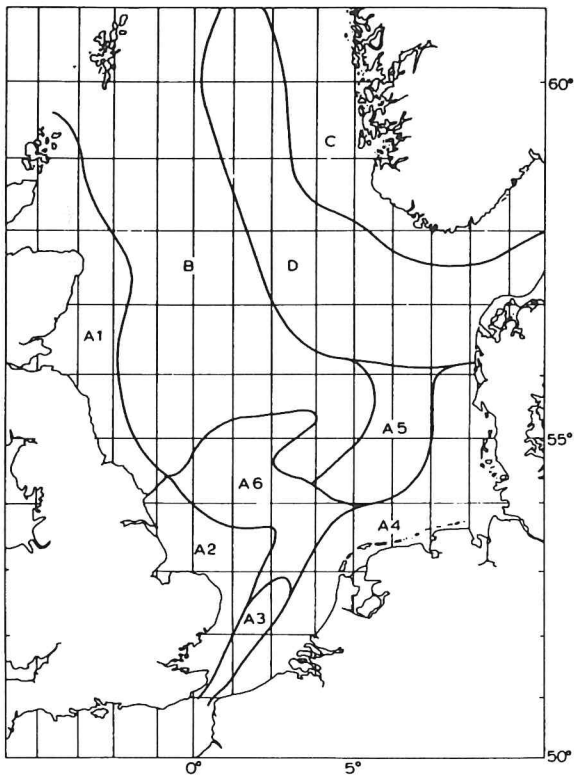
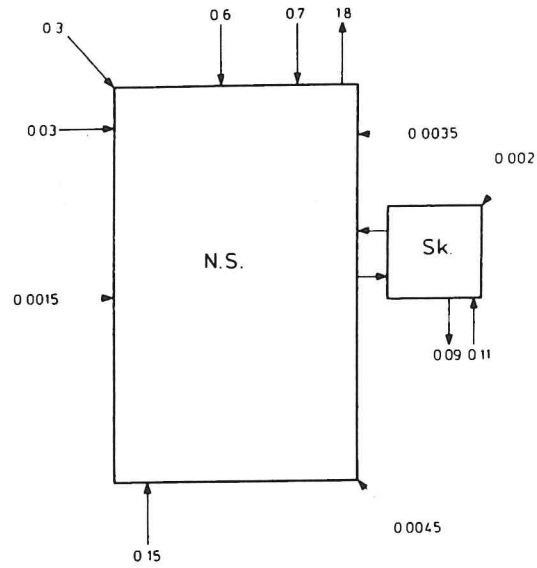


Fig. 2.10: Hydrographical regions of the North Sea (from Lee, 1980)

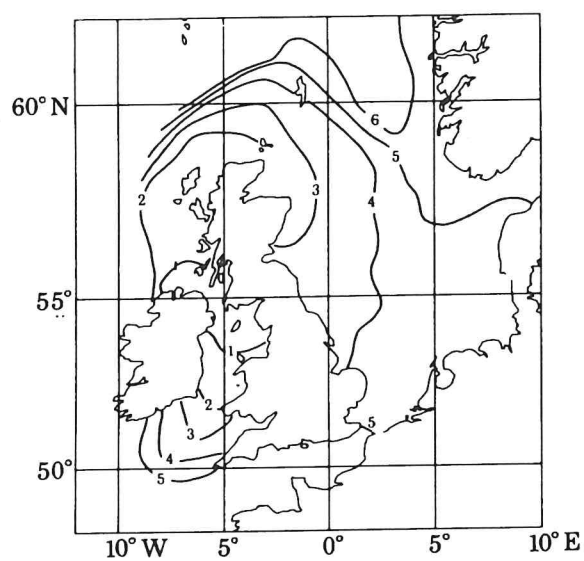


Fig. 2.11: Age (years) of material discharged from Sellafield, derived from model calculations (from Prandle, 1984)

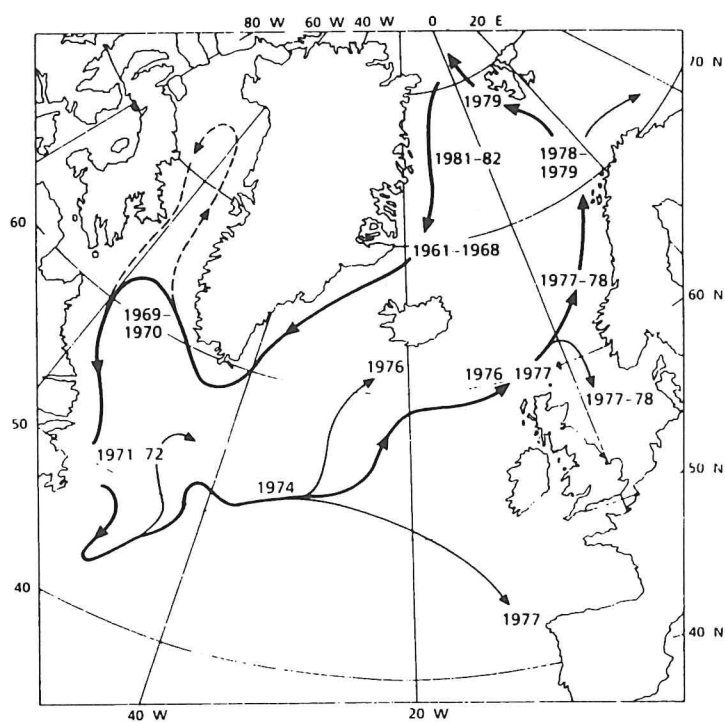


Fig. 2.12: Route followed by the great salinity anomaly, from its formation north of Iceland in 1961/1962 to its return to the east coast of Greenland in 1981 (from Mann & Lazier, 1991)

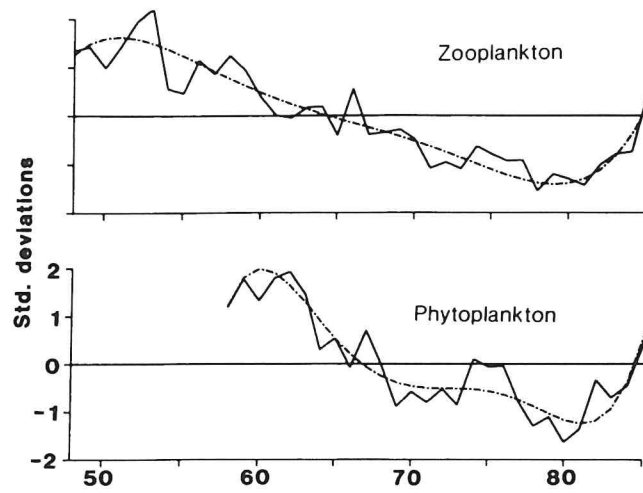


Fig. 3.1: Mean trends in the abundance of zooplankton and phytoplankton, 1948-1983 in the NE Atlantic and the North Sea (from Colebrook et al., 1984)

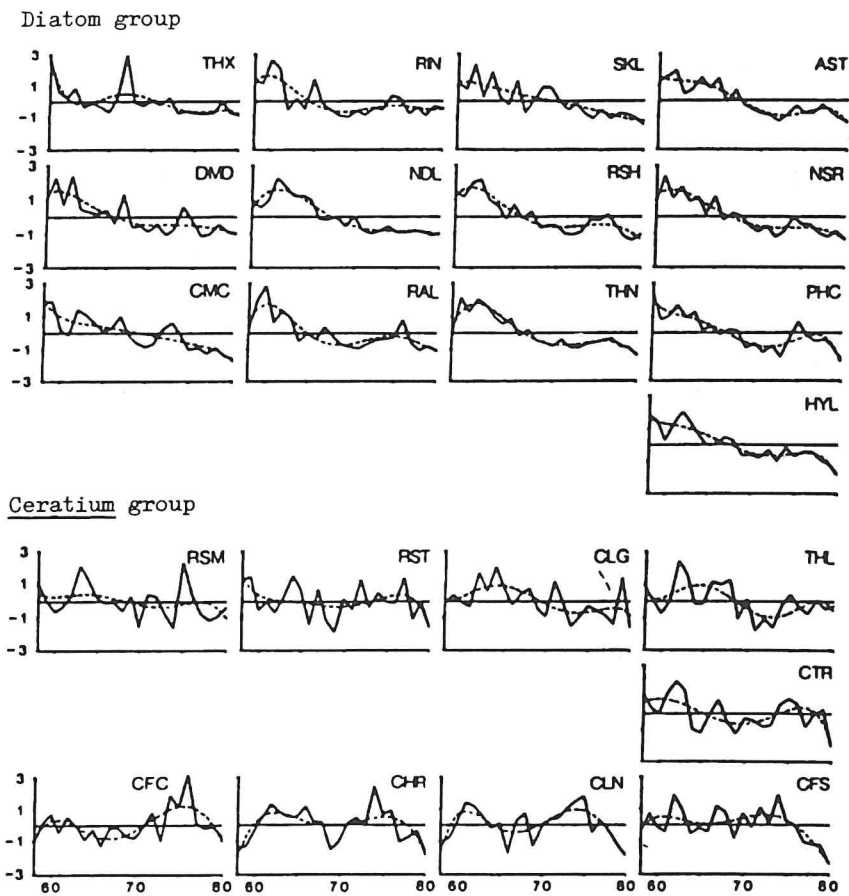


Fig. 3.2: Mean trends of different species of phytoplankton (diatoms and ceratium) in the NE Atlantic and the North Sea. For details see Colebrook, 1982b. Taken from Radach (1984) (after Colebrook, 1982b)

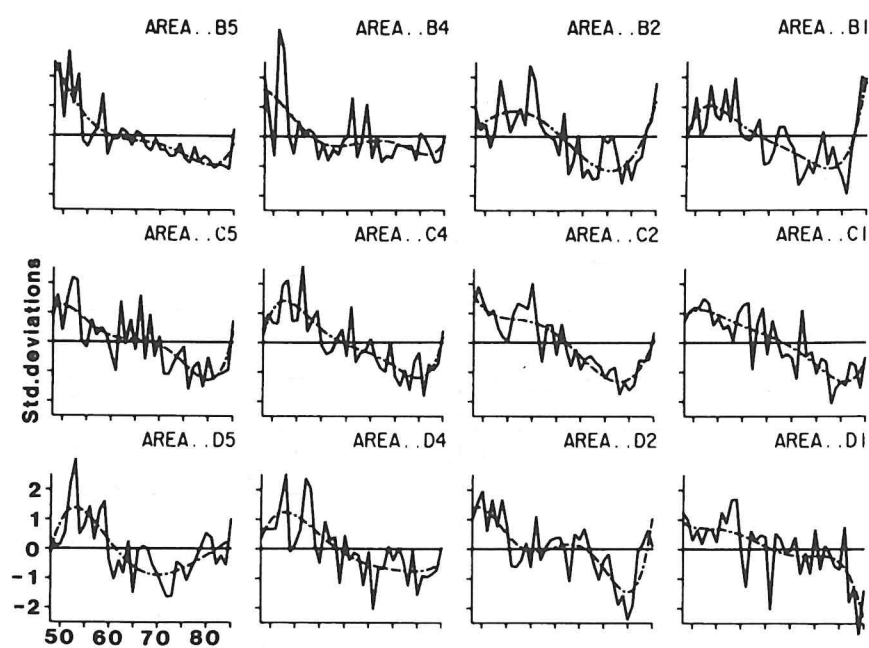


Fig. 3.3: Trends of zooplankton abundance in 12 different areas in the NE Atlantic and the North Sea. Key to the areas in Figure 3.4 (taken from Dickson et al., 1988)

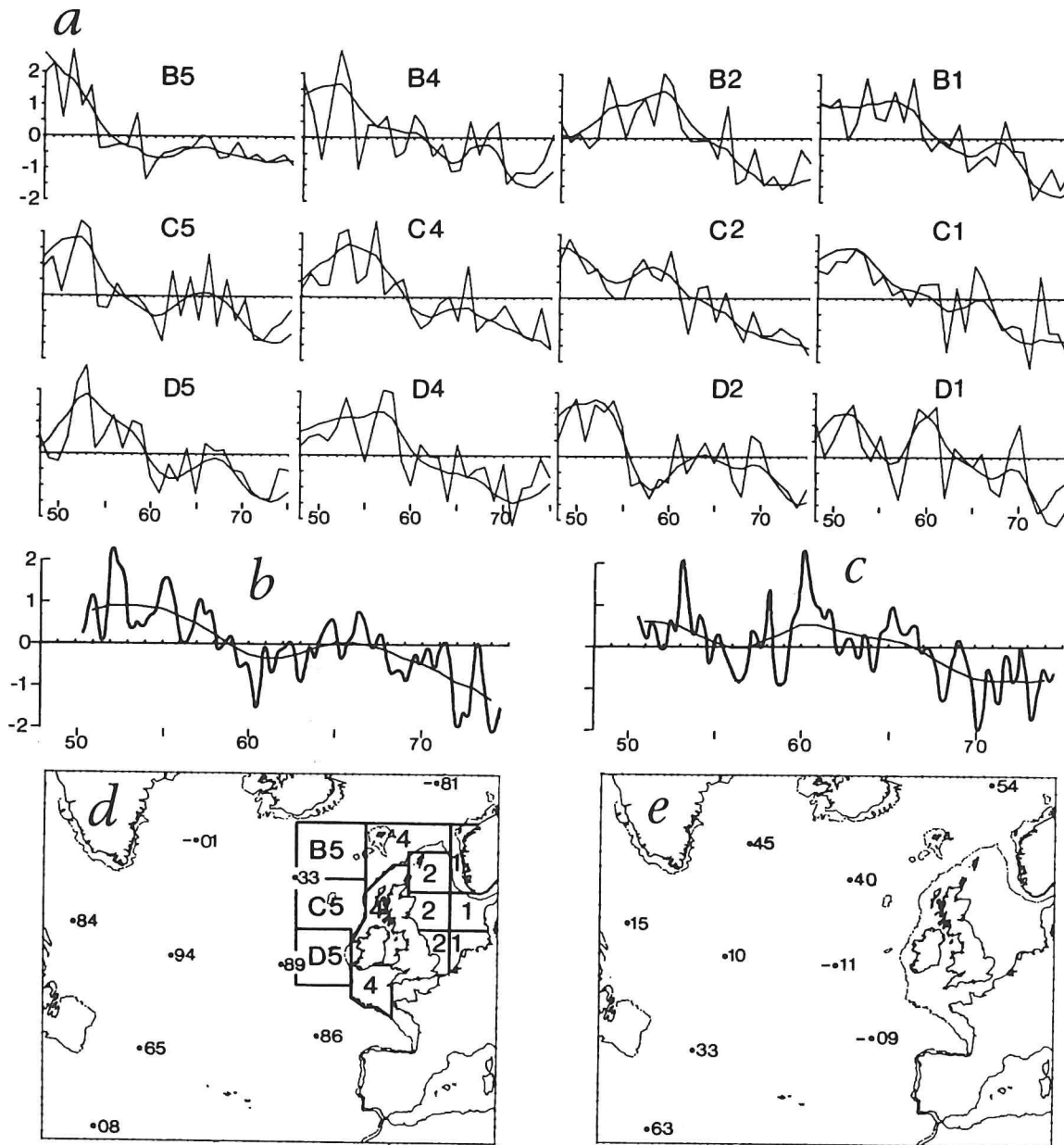


Fig. 3.4: A) Smoothed long-term trends of the annual fluctuations of zooplankton sets in each of the areas in D); B) and C) smoothed graphs of the sea surface temperature anomalies emphasizing the long-term trends at the nine Ocean Weather Stations indicated in D); in B) the mean of the first and second principal component is given and in C) the third (from Garrod & Colebrook, 1978)

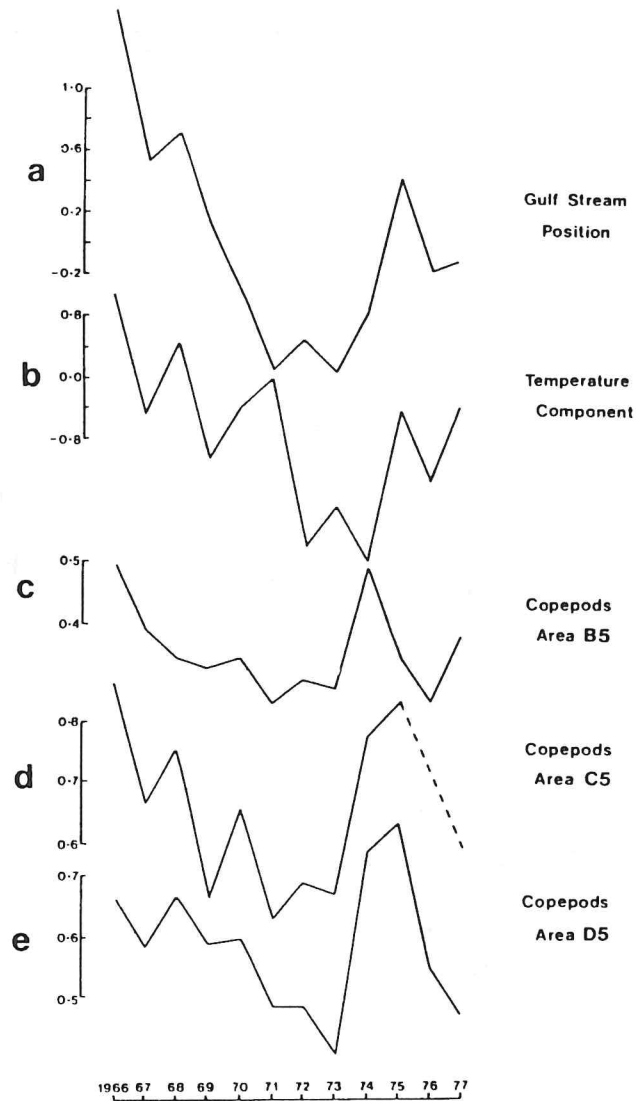


Fig. 3.5: Annual means for 1966-1977 of A) the position of the Gulf Stream, B) the sea surface temperature anomaly at the Ocean Weather Stations, and C), D), E) numbers of copepods (zooplankton) in selected areas of the NE Atlantic. Key to areas in Figure 3.4 (from Taylor & Stephens, 1980)

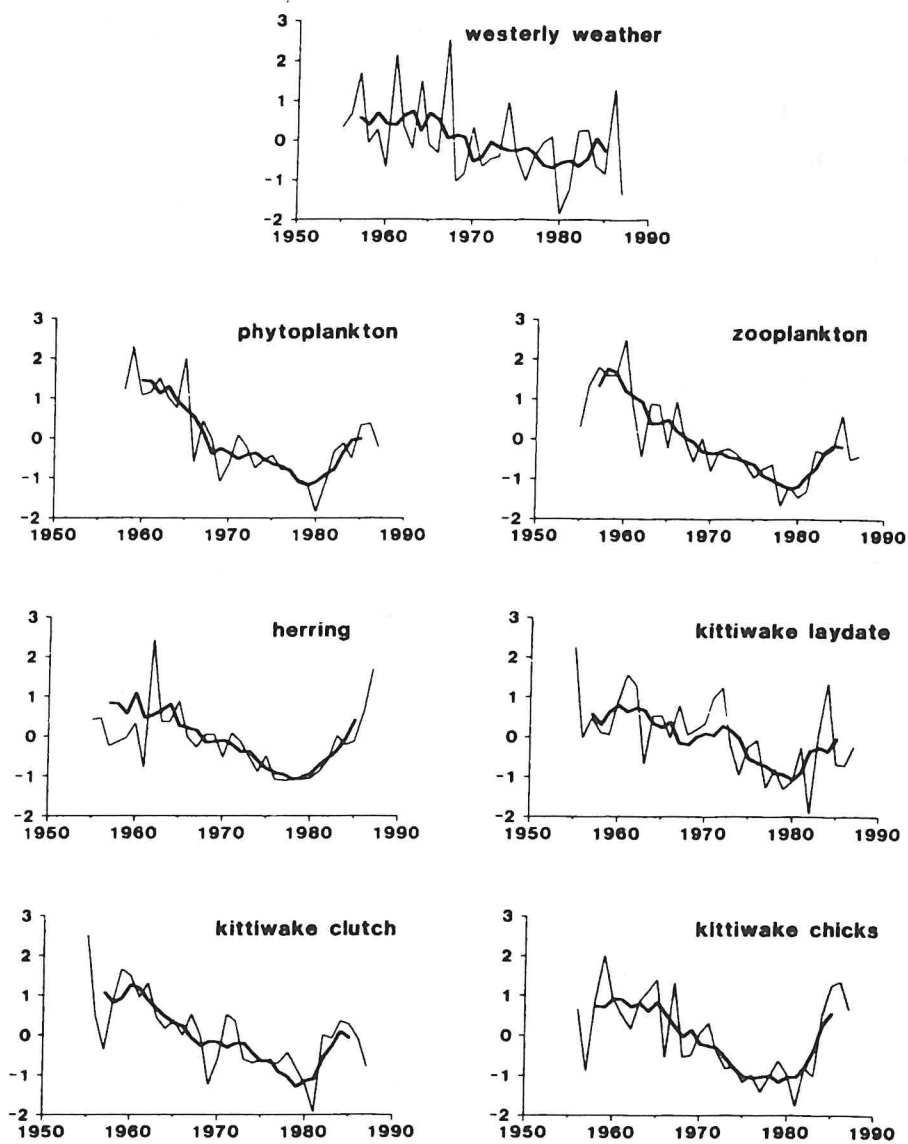


Fig. 3.6: Trends (5-year running means) for phytoplankton, zooplankton and herring abundance, kittiwake laying date, clutch size and chick production, and for the frequency of westerly weather, 1955-1987 in the northwestern North Sea (from Aebischer et al., 1990)

Table 4.1: Annual sum of inputs of nitrogen and phosphorus into the North Sea (from Gerlach, 1990)

	1950		1980	
Inputs of nitrogen	t N/year		t N/year	
From North Atlantic	7 000 000	86%	7 000 000	74%
From English Channel	705 000	9%	705 000	7%
From atmosphere (1 g N/m ²) 1950 = 33 % of 1980	170 000	2%	520 000	6%
From rivers, discharges, dumping 1950 = 22 % of 1980	264 000	2%	1 202 000	13%
Inputs, sum total	8 099 000	t/y	9 427 000	t/y
Inputs of phosphorus	t P/year		t P/year	
From North Atlantic	1 085 000	90%	1 085 000	83%
From English Channel	82 000	7%	82 000	6%
From atmosphere (35 mg P/m ²) 1950 = 50 % of 1980	9 000	1%	18 000	6%
From Rivers, discharges, dumping 1950 = 15 % of 1980	22 000	2%	146 000	11%
Inputs, sum total	1 198 000	t/y	1 331 000	t/y

Table 4.2: Estimated supply, outflow and deposition of suspended matter in the North Sea (from Eisma, 1990)

Supply	10 ⁶ t · year ⁻¹	Outflow + Deposition	
North Atlantic Ocean	10.4	Outflow	11.4 + <3
Channel	17	Deposition	
Baltic	0.5	Estuaries	1.8
Rivers	4.8	Waddensea + the Wash	5
Seafloor erosion	9—13.5 (+ ?)	Outer Silver Pit	1—4
Coastal erosion	2.2	Elbe Rinne	?
Atmosphere	1.6	Oyster Grounds	2 (+ ?)
Primary production	1	German Bight	3—7.5
		Kattegat	8
Total	46.5—51.0 (+ ?)	Skagerrak + Norwegian Channel	17 (+ ?)
	Av. 48.7	Dumped on land	2.7
		Total	51.9—62.4 (+ ?)
			Av. 57.2

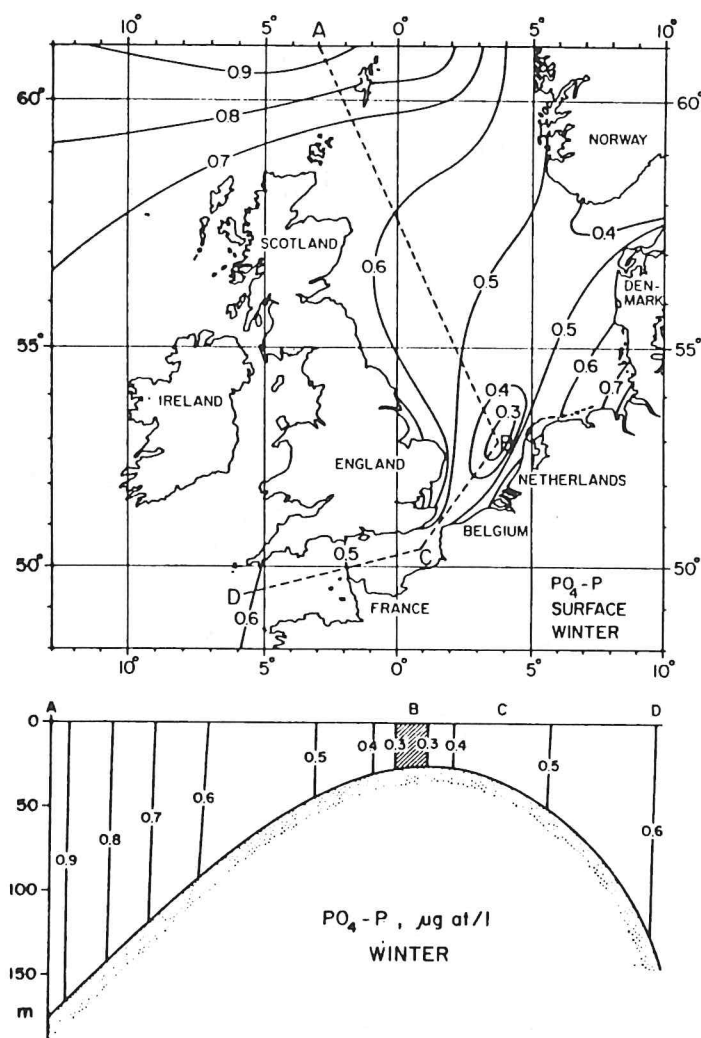


Fig. 4.1: Distribution of phosphate in the North Sea and part of the NE Atlantic (from Postma, 1978)

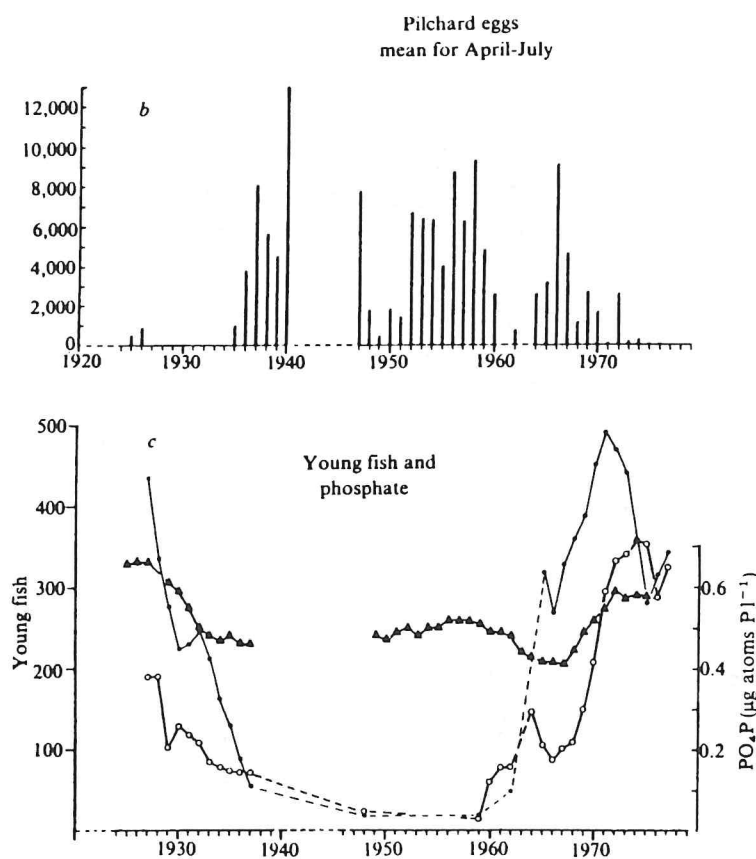


Fig. 4.2: (from Southward, 1980)

Examples of some of the biological changes off Plymouth, based on weekly samples with the 2 m net at station L5 (2 miles east or 2 miles west of the Eddystone reef). The standard oblique haul filters about 5,000 m³ of water⁶⁹. As indicated by the broken line for the ordinates, sampling was not possible in certain years; the broken columns or broken trend lines show years when sampling was incomplete. *a*, Numbers of the chaetognath *Sagitta elegans* Verrill, expressed as the average per haul for the summer months (May to August inclusive) when the offshore water is stratified. *b*, Numbers of eggs of pilchard (*Sardina pilchardus* (Walbaum)) expressed as the average per haul during the spring/summer spawning season from April to July inclusive. The number of eggs is assumed to be an index to the numbers of mature adults¹⁶. *c*, Comparison of smoothed values (5-yr running means) of inorganic phosphate (▲) at station E1 (50°02'N, 4°22'W), with 5 yr running means of post-larval teleosts (excluding clupeids) in the 2 m net samples at L5. The young fish are divided into spring-spawners (●), taken as the sum of the monthly means for March to June, and summer-spawners (○), taken as the sum of the monthly means for July to September. Phosphate is expressed as the 'winter maximum' of 'reactive' inorganic phosphate in μg atoms P l⁻¹. The winter maximum can be found variously from December to early March, and is allocated here to the spring of the following year if found in December.

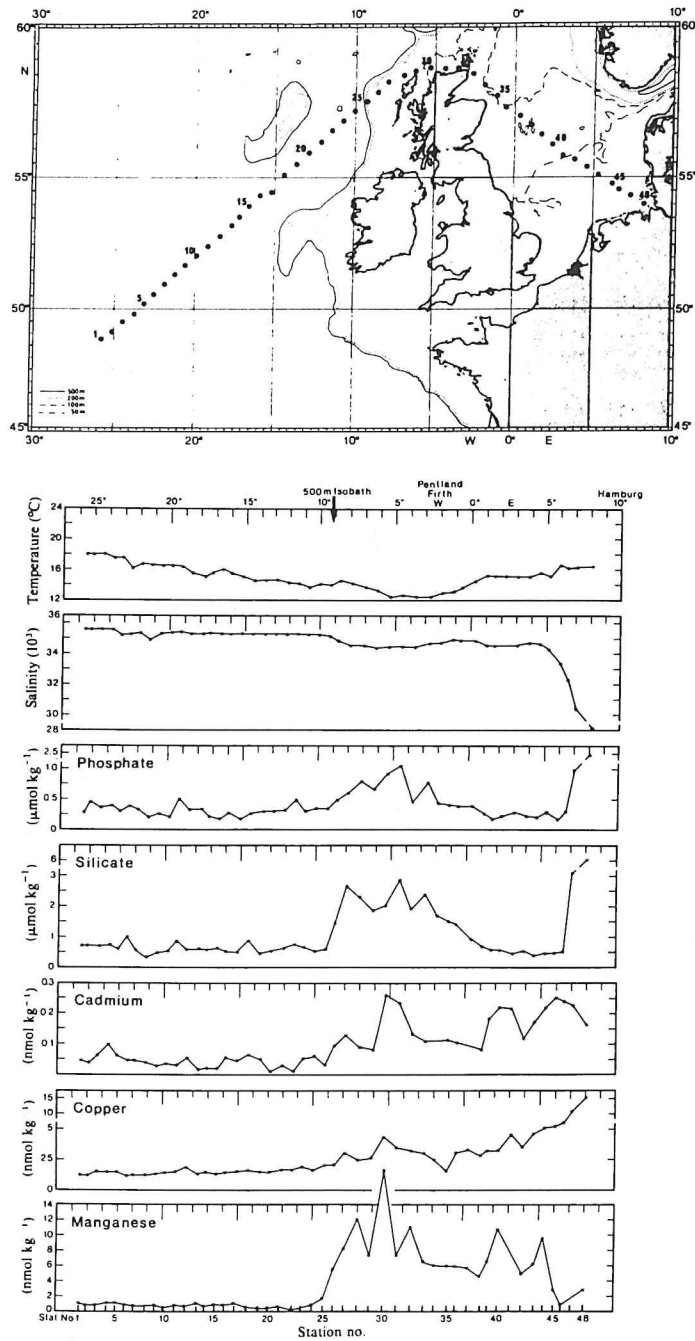


Fig. 4.3: Surface water data for temperature, salinity, nutrients and trace metals from a transect in the NE Atlantic Ocean and the North Sea (from Kremling, 1983)

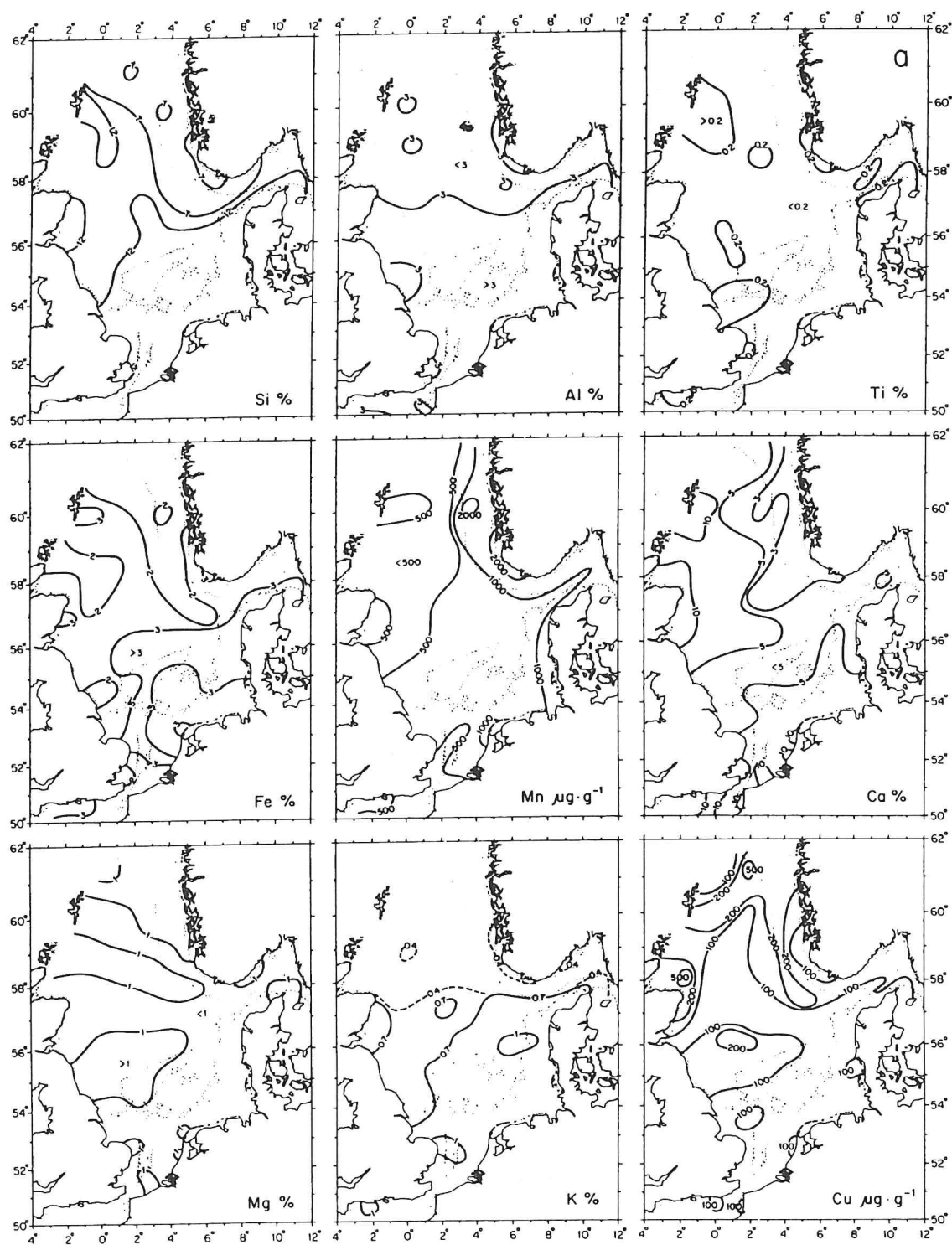


Fig. 4.4: Distribution of various trace elements and particulate organic carbon in suspended matter in the North Sea, January 1980 (from Nolting & Eisma, 1988)

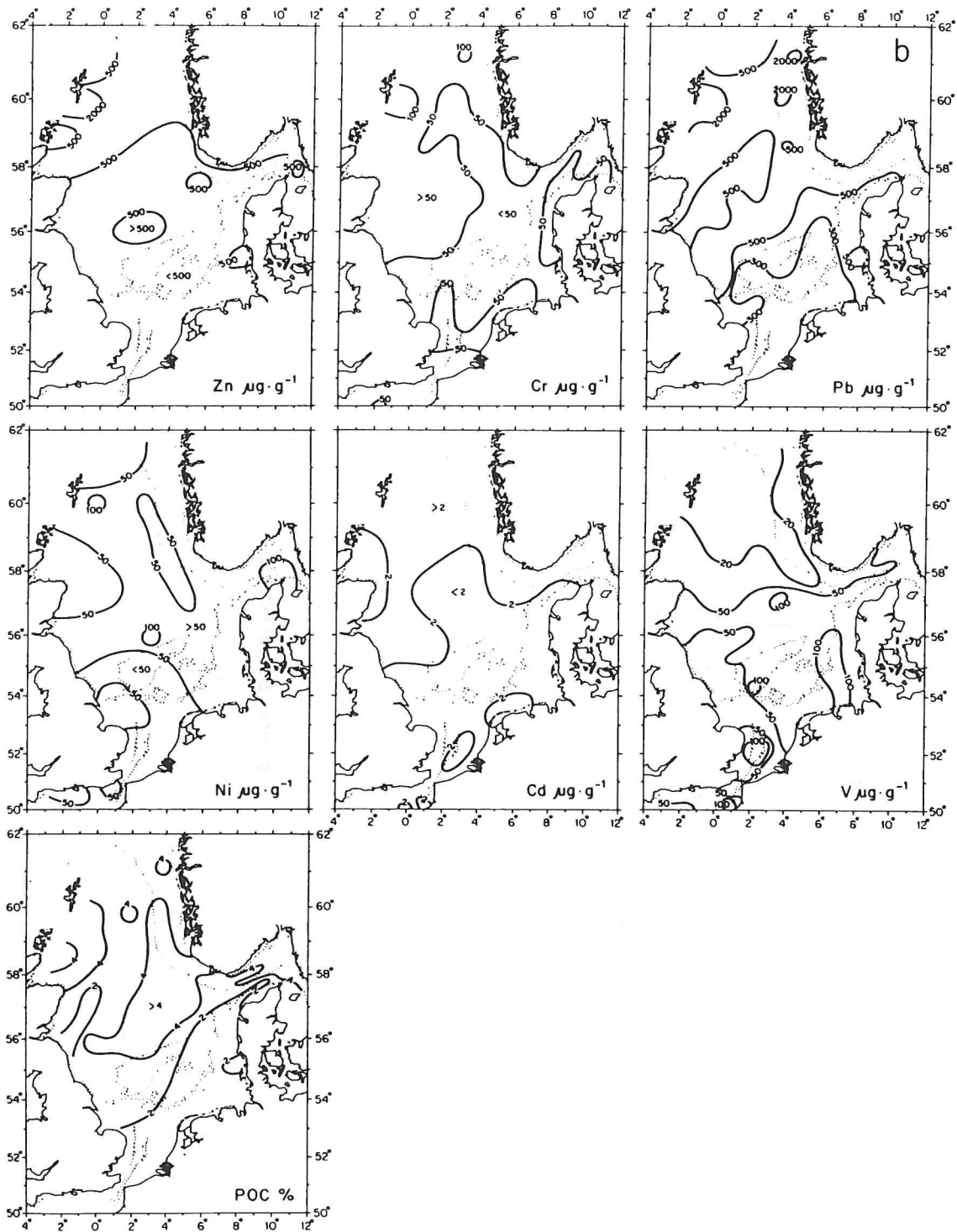


Fig. 4.4: (continued)

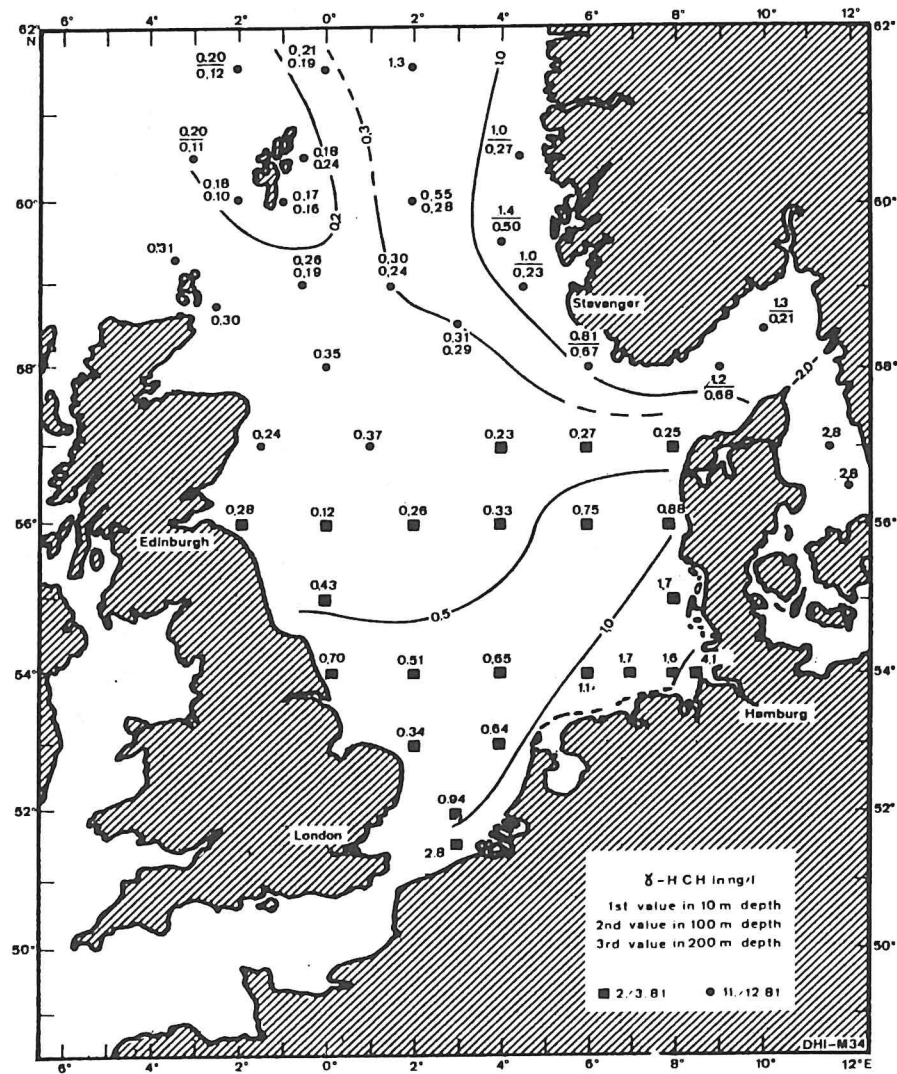


Fig. 4.5: Distribution of lindane (γ -HCH) in the North Sea (from Gaul & Ziebarth, 1983)

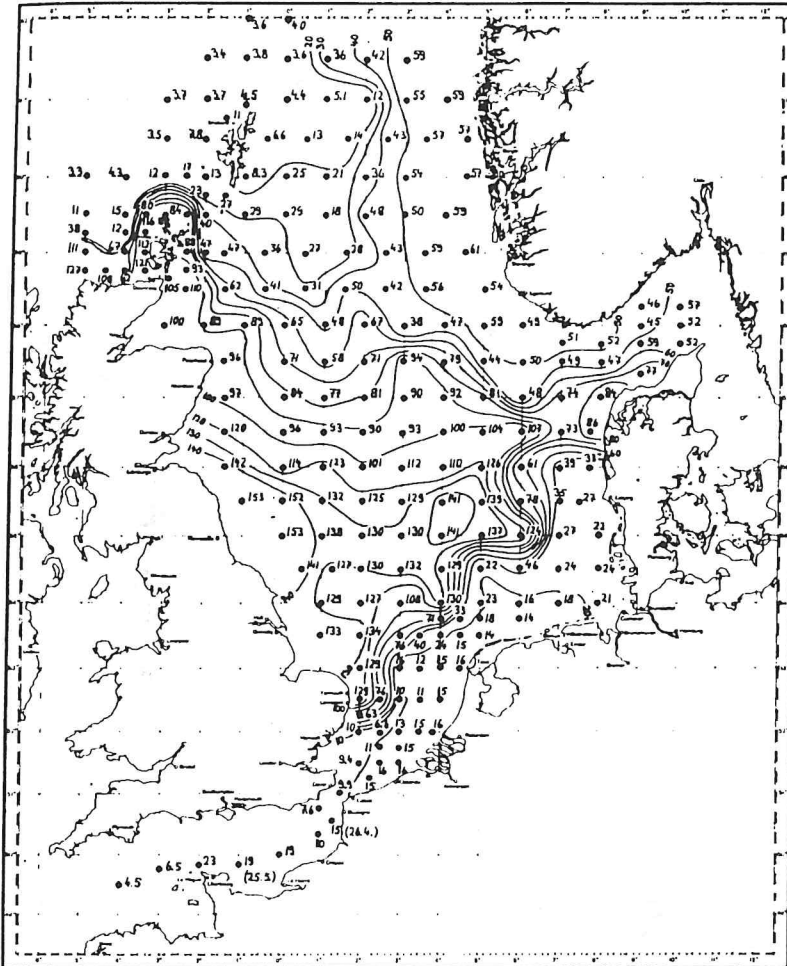


Fig. 4.6: Distribution of caesium-134+137 in North Sea surface water (Bq.m⁻³) in April/June 1984 (from Kautsky, 1988)

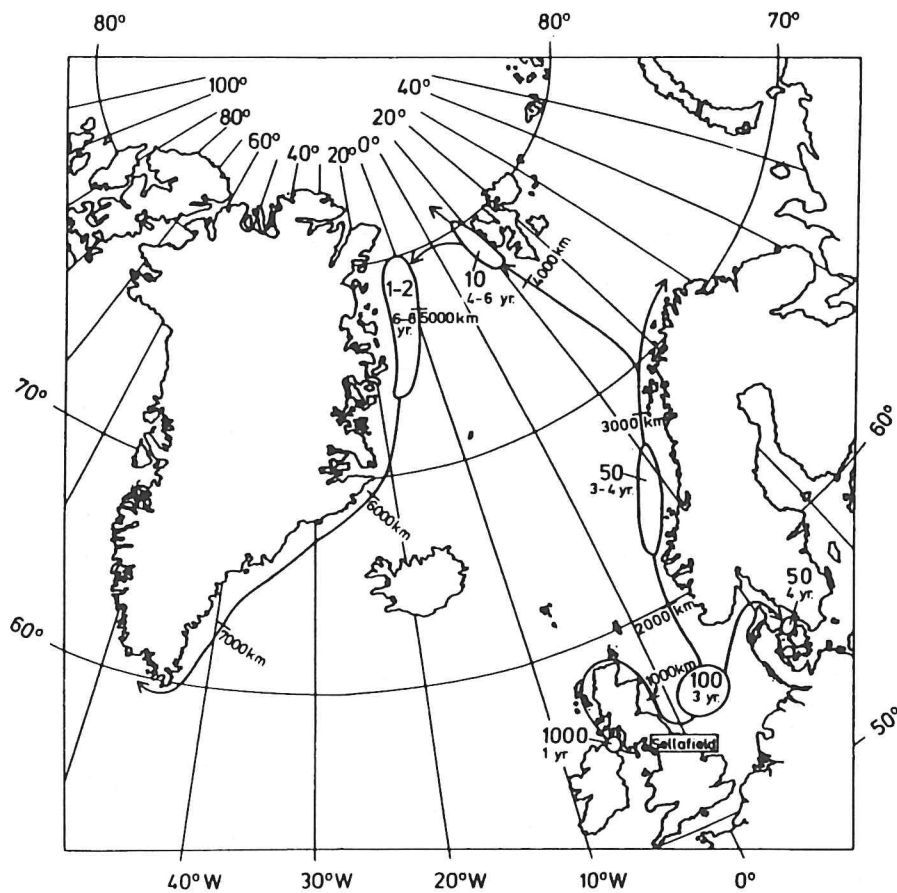


Fig. 4.7: Approximate route for the transport of radionuclides from Sellafield to east Greenland. Relative concentrations and approximate transit times are shown. Distance along the track in kilometers. Relative concentrations can also be read as percentages of the concentration of any almost-conservatively behaving pollutant in the North Sea (from Dahlgard et al., 1986)

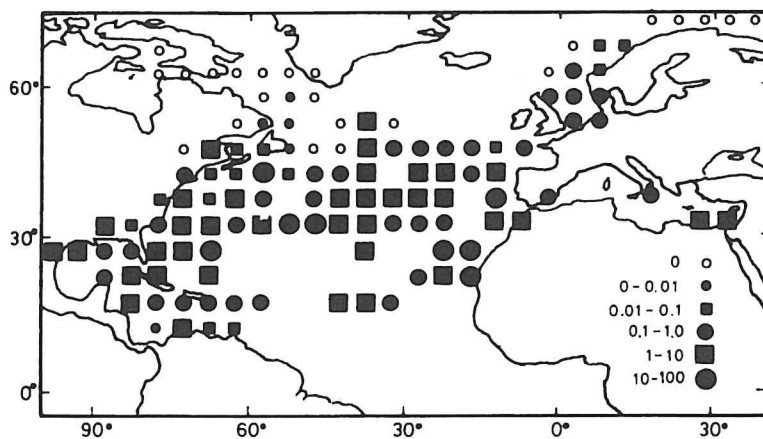


Fig 4.8: Distribution of tar ball concentrations in the North Atlantic (from Preston, 1989)

Table 5.1: Tentative list of ICSU bodies carrying out studies relevant to priority areas of the UN Conference on Environment and Development (Brazil 1992) (reproduced from La Rivière, 1990)

1. Protection of the atmosphere by combatting climate change, depletion of the ozone layer and trans-boundary air pollution	WCRP, IGBP, SCOPE, IUGG (IAMAP), ISSS
2. Protection of the quality and supply of freshwater resources	COWAR, SCOPE, IUGS (IAH), IAWPRC, IUGG (IAHS)
3. Protection of the oceans and all kinds of seas, including semi-enclosed seas, and of coastal areas and the protection, rational use and development of their living resources	SCOR, SCAR, SCOPE, IUBS, IUGG (IAPSO), IGBP
4. Protection and management of land resources by, inter alia, combatting deforestation, desertification and drought	IUBS, CASAFA, IBN, SCOPE, IGBP, ISSS
5. Conservation of biological diversity	IUBS, SCOPE, IBN, IGBP
6. Environmentally sound management of biotechnology	IUMS, COGENE, COBIOTECH, SCOPE
7. Environmentally sound management of wastes, particularly hazardous wastes, and of toxic chemicals, as well as prevention of illegal international traffic in toxic and dangerous products and wastes	IUPAC, IUGG, SCOPE

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