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Report

Microplastic in global and Norwegian marine environments: Distributions, degradation mechanisms and transport

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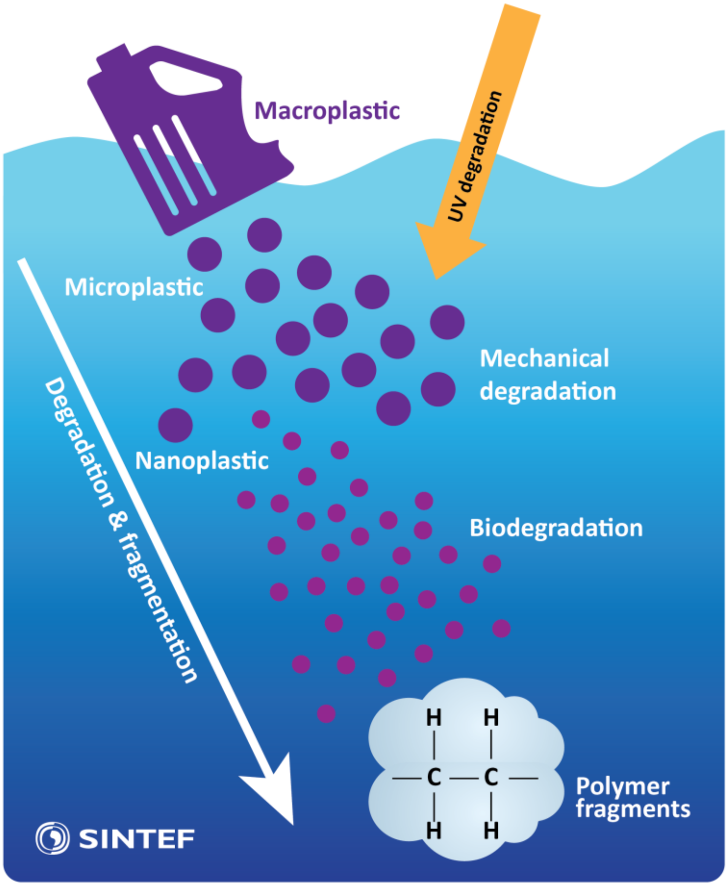

Report

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Summary

Small items of plastic under five millimetres in size are called microplastic. They are an important component of marine litter, being ubiquitous across all global marine environmental compartments. To develop strategies for reducing plastic inputs into the ocean, it is essential to understand the distribution, degradation and transport of macroplastic (i.e. large plastic items) and microplastic particles. This report addresses these three topics, which are necessary for understanding the potential exposure of microplastic in the marine environment. Together with hazard identification, exposure is a fundamental component in conducting risk assessment.

We review the available literature reporting on the distribution of microplastic in key marine environmental compartments, including water, sediments and biota. These data are then used to estimate microplastic concentrations and the total load of microplastic in the different compartments at both the Norwegian and global scale. The degradation pathways of macroplastic litter into microplastic are reviewed and the relative influence of environmental parameters and climatic conditions are considered. The knowledge is then used to identify environmental compartments representing the highest and lowest potential for macroplastic degradation, and to estimate the relative importance of macroplastic degradation in the marine environment as a source of microplastic. The transport of microplastic into and through the Norwegian marine environment, defined here as the Norwegian Exclusive Economic Zone (EEZ), is modelled using Lagrangian particle tracking methods and an overall Lagrangian analysis called "Lagrangian Coherent Structures (LCS). LCS analysis is used to investigate the transport barriers and potential for microplastic accumulation in different regions of the Norwegian EEZ. Finally, we combine the information summarised for each of the focus areas, and use this to identify where most microplastic accumulates in the marine environment and to estimate microplastic concentrations in the Norwegian environment ten years from now. This work contributes to understanding the current and future conditions in the Norwegian marine environment, and highlights knowledge gaps and research topics that require further study.

When the microplastic distribution is estimated, over 90% is expected to be in the world's sediments, supporting previous conclusions that marine sediments act as a sink and accumulation zone. Approximately 8% of microplastic is in the water column, 0.2% is in surface waters and less than 0.001% is predicted to be in marine fish (other classes of biota were not included in the estimation). Global microplastic concentrations are similarly estimated to be highest in sediment compartments. Shorelines and coastal sediments have higher microplastic concentrations than deepsea sediments, but account for only a small percentage of the global sediment area and volume. The limited data for polar regions suggests microplastic concentrations in all compartments are comparable to global values, indicating an active transport of microplastic to these regions. Microplastic concentrations estimated in marine organisms (fish, non-fish pelagic and benthic) compare favourably with the concentrations in the respective environmental compartments in which the organisms live. Benthic species (i.e. seafloor dwellers) have the highest microplastic concentrations, reflecting the higher concentrations estimated for sediments than in the water

column. However, these data suggest that microplastic is not accumulated in most marine organisms, as the concentrations do not appear to be significantly higher than the surrounding environmental concentrations.

There are very limited data on microplastic concentrations in the Norwegian marine environment. However, we estimate that microplastic concentrations in Norwegian compartments are comparable (e.g. for biota and sediments) or lower (waters and shorelines) to average global values. The distribution of microplastic across the different Norwegian environmental compartments is largely similar when this is estimated using either Norwegian or global microplastic concentrations. The estimated distributions suggest that over 90% of microplastic currently present in the Norwegian marine environment will be in the sediment, mirroring global distributions.

The process of plastic degradation leads to a transformation in material structure, typically characterised by a change of properties (e.g. integrity, molecular mass or structure, mechanical strength) and/or fragmentation. Plastic degradation is highly influenced by polymer type, physicochemical properties and the presence of additives, and can proceed by either abiotic (e.g. photodegradation, mechanical, hydrolysis) or biotic pathways (biodegradation). Abiotic degradation, initiated hydrolytically (water) or by UV radiation (sunlight) in the marine environment, must occur before significant biodegradation begins. Microorganisms will then mineralise the already physically and chemically degraded polymeric material into methane, CO_2 and water, which represents the endpoint of the degradation process. The kinetics of polymer degradation in the environment depends on the specific combination of environmental conditions: oxygen concentration, water chemistry, temperature, presence of other chemicals, sunlight, and the community dynamics of degrading microorganisms. Therefore, degradation will proceed at different rates in different environmental compartments (e.g. shorelines vs deepsea). Degradation typically starts at the polymer surface, and over the course of the degradation process macroplastic will disintegrate into smaller and smaller pieces, i.e. meso-, micro- and nanoplastic, ultimately forming polymer fragments. Due to a higher surface to volume ratio, the degradation of microplastic proceeds faster than meso- and macroplastic.

Owing to the large variability in the process of macroplastic transformation into microplastic, it is not possible to estimate a single overall degradation rate that is representative of all plastics and all environmental compartments and conditions. For the current study, we assumed macroplastic items in the marine environment lose approximately 0.5% (most likely an overestimate) of their mass annually due to degradation, and all this mass is converted into microplastic. Due to the greater potential for abiotic degradation of macroplastic to occur in coastal regions and along shorelines, it is suggested these areas are the main source of marine generated microplastic. This allows us to estimate that globally, degradation of macroplastic marine litter produces 0.23 million tonnes of microplastic annually. Based on literature values for the total amount of microplastic entering the marine environment annually from terrestrial sources, we estimate macroplastic degradation in the marine environment accounts for 20% of the microplastic entering the global marine environment annually.

The distribution of microplastic between marine organisms, the sea bed, and the different ocean compartments in the Norwegian marine environment depends on (i) the origin and circulation of water off the Norwegian coast, (ii) large-scale and local winds, and (iii) the local ecology. The principal factor in the transport and accumulation of plastic and microplastic litter is the sedimentation rate to the seafloor. Plastic will sink if it has a higher density than seawater, or if becomes associated with other particles or organisms in the ocean that sink (e.g. accumulation in marine snow, colonisation by organisms). Particle tracking simulations can determine the transport of microplastic by moving the particles according to ocean currents and the sinking speed of individual particles, where sinking can be determined from the plastic size and density. We have used this approach to model the transport of microfibres (a class of microplastic) released from several European countries, including Norway, tracking these particles to see if they reach Norwegian coastal water or the larger area of the Norwegian EEZ. The results of the simulations indicated ~90% of the microfibres settled to the sediment during a time frame of 5 months. Combining the simulation result with historical data for synthetic fibre production, we estimate that close to 23000 tonnes of microfibre could be present in sediments (~200 fibres kg^{-1}) in the Norwegian EEZ today. This compares to only 20 tonnes in the water column (~3.9×10^{-5} fibres kg^{-1}), and shows that the sediments represent the major accumulation zone, in agreement with observations and conclusions in this report. Extrapolating our numbers based on estimated increase in synthetic fibre production, we estimate that up to 38000 tonnes of microfibre will be present in the sediment (~330 fibres kg^{-1}) and 29 tonnes in the water column (~5.7×10^{-5} fibres kg^{-1}) 10 years from now.

Plastic debris can enter the Norwegian EEZ from the western North Atlantic, North Sea, Baltic Sea, Greenland Sea and Barents Sea. The transport of microplastic between different marine water bodies was simulated by looking at the occurrence of oceanic transport barriers using LCS; lines in the sea that water does not cross because of the local circulation dynamics. Calculating LCS monthly examples over one year of ocean current data, we conclude that microplastic in seawater on the Norwegian EEZ continental shelf will tend to stay on the shelf in winter. However, the winter transport barrier along the continental shelf break disappears during oceanographic summer, allowing microplastic to spread more easily beyond the shelf. Analysis of the LCS calculations also showed that the Norwegian Sea is unlikely to become a perennial collection zones of macro- and microplastic. We have shown that Lagrangian approaches can be used to study the transport and accumulation of microplastic.

Existing data indicate overall microplastic concentrations in the major oceans gyres are no longer increasing, while they continue to increase in coastal regions such as the Norwegian EEZ. This supports the literature evidence and modelling work conducted in this report that microplastic is removed from the sea surface rather rapidly (close to the source of entry into the marine environment). Using estimates for today's load of microplastic in combination with estimated plastic production volumes since 1950 and values predicted until 2027, we have estimated the total load of microplastic in the Norwegian marine environment in 10 years' time. The results suggest an increase in the total load of microplastic from 1.77 x10^{18} to 2.91 x 10^{18} particles, which represents an 64% increase over the next decade. Based on our previous calculations, we can assume that 80% of this increase will be due to new microplastic from terrestrial sources, with 20% coming from degradation of macroplastic already in marine environment. Our estimates assume that the current quantities of plastic being released into the environment will remain constant over the next 10 years (no increase or decrease in the annual levels). The results show that new inputs of microplastic from terrestrial sources, together with microplastic formed through degradation of existing macroplastic litter, will contribute to increasing the amount of microplastic in the marine environment for decades to come.

All calculated values presented in this report are based on a high degree of uncertainty, which comes from the limited amount of published data, differences in sampling and analysis techniques, and the need to use assumptions to convert the data to a common SI unit for comparative purposes. As it is not possible to calculate the levels of uncertainty, these data should be viewed as a simplified understanding of global microplastic concentrations, loads and distributions in the global and Norwegian marine environment. There is also a high degree of uncertainty associated with the plastic degradation rate estimation presented in the report. Plastic degradation rates vary considerably due to key factors (e.g. polymer type, environmental conditions, presence of additive chemicals). As a single degradation rate that is representative of all plastics and all environmental compartments and conditions cannot be accurately determined, we employed a general figure of 0.5% degradation per year. This is likely to represent an overestimation and can be considered a best-case scenario. Particle modelling of microplastic is still in its infancy, though rapidly advancing, so as we understand more about the characteristics of microplastic formation, transport and degradation, model predictions will improve. Our sampling of a single year for the LCS study does not contain information related to climatic inter-annual variability. Crucially, the highlighted areas of uncertainty represent key knowledge gaps and future research needs that should be addressed to improve our understanding of microplastic distributions, degradation and transport in the global and Norwegian marine environment. Such future studies would benefit from increased international cooperation to regarding sample access, data exchange, creation of standard sampling and analysis approaches, data nomenclature and reporting protocols.

Sammendrag

Mikroplast er definert som små plastbiter mindre enn 5mm i størrelse. En stor del av den marine forsøplingen består av mikroplast, og er å finne i alle verdenshav. For å utvikle metoder og tiltak som kan redusere mengden plast som havner i det marine miljø, er det viktig å forstå fordelingen av store og små plastpartikler i havrommet, hvordan plasten transporteres i havet og hvordan den brytes ned i det marine miljøet. Denne rapporten adresserer disse tre temaene, som tilsammen gir mulighet for å forstå i hvilken grad marint dyreliv blir eksponert for partikler av mikroplast og makroplast i havet i dag. Grad av eksponering kan videre danne grunnlag for risikovurdering av plast i det marine miljøet.

Vi har undersøkt litteraturen som beskriver fordelingen av mikroplast i sentrale marine miljøer, slik som vann, sedimenter, og biota. Resultatene er brukt for å estimere konsentrasjonen av mikroplast og total mengde mikroplast i disse miljøene, både i Norske farvann og på global skala. Større plastbiter, også kalt makroplast, kan brytes ned til mikroplast. Vi har gjennomgått dagens forståelse av hvordan denne nedbrytingen skjer, med hensyn på forskjellige klimatiske omgivelser. Denne kunnskapen er brukt for å identifisere de ulike miljøene i havet (vannkolonnen, havbunnen, sedimenter, strandsone, […]) hvor nedbryting av makroplast til mikroplast har størst og minst potensiale for å skje. Transporten av mikroplast til det norske marine miljøet, her definert som Norges økonomiske sone (NØS), er modellert ved bruk av partikkel-modeller og såkalte Lagrangian Coherent Structures (LCS). LCS-analysen brukes for å undersøke transport-barrierer og muligheten for akkumulering av mikroplast i NØS. Vi har sammenfattet kunnskapen fra de tre undersøkte temaene for å peke på hvor mikroplast har størst potensiale for opphoping, og estimert hvor stor konsentrasjon vi kan ha av mikroplast i det marine miljøet om 10 år. Dette arbeidet kan bidra til økt forståelse av mikroplast i det norske marine miljøet i dag og i framtiden, og peker på hvor vi mangler kunnskap og hvilke forskningstemaer som bør prioriteres/jobbes videre med.

Vi estimerer at mer enn 90 % all av mikroplast i det marine miljøet befinner seg i sedimenter på havbunnen, i tråd med tidligere rapporter og konklusjoner. Ca. 8 % befinner seg i vannkolonnen, 0.2 % i overflatevann, og mindre enn 0.001 % er estimert til å befinne seg i fisk (andre biota var ikke inkludert i undersøkelsen). Konsentrasjonen av mikroplast globalt er estimert til å være høyest i sedimentet. Kysten og sedimentlaget langs kysten har høyere konsentrasjoner enn sedimenter på dypvann, men representer kun en liten andel av totalt volum og areal av sediment i verdenshavene. De begrensede observasjonene som eksisterer for polare områder indikerer at konsentrasjonen av mikroplast er tilsvarende det som måles ellers på kloden, noe som indikerer en aktiv transport av mikroplast til de polare områdene. Konsentrasjonen av mikroplast i undersøkte marine organismer (fisk, pelagiske arter (ikke-fisk), og bentiske arter) er funnet å være sammenlignbar med konsentrasjonen i de respektive miljøene. Bentiske arter, som oppholder seg hovedsakelig på havbunnen, har de høyeste konsentrasjonene av mikroplast, som er i tråd med at det er en høyere konsentrasjon av mikroplast i sediment sammenlignet med vannkolonnen. Vi finner at mikroplast tilsynelatende ikke akkumuleres i stor grad i de fleste marine biota, ettersom konsentrasjonene i biota ikke er signifikant høyere enn i omgivelsene.

For det norske marine miljø er det begrensede observasjonsdata for mikroplast. Basert på det som finnes av data estimerer vi at konsentrasjonen av mikroplast i norske farvann er lik (for biota og sedimenter) eller lavere (for vannkolonne og kyst), sammenlignet med gjennomsnittlige globale data. Bruker vi globale data for mikroplastkonsentrasjoner endrer ikke fordelingen av mikroplast i det norske marine miljøet seg vesentlig i forhold til om vi benytter norske data til beregningene. Begge estimater indikerer at mer enn 90 % av all mikroplast i det norske marine miljøet befinner seg i sedimenter, likt det som er vist globalt.

Når plast brytes ned endres ofte plastmaterialets struktur seg slik at også egenskapene til materialet endres (som integritet, molekylmasse, molekylstruktur, og mekanisk styrke), og/eller fragmenteringen endres. Nedbrytingen er avhengig av typen polymer, dens fysiokjemiske egenskaper, samt tilstedeværelse av tilsetningsstoffer i plasten. Plastnedbryting kan foregå abiotisk ved hjelp av UV-stråling (sollys), hydrolyse eller mekanisk nedbryting, eller den kan foregå biotisk ved biologisk nedbryting. Abiotisk nedbryting, som initieres hydrolytisk (vann) eller med UV-stråling, må skje før biologisk nedbryting kan begynne. Mikroorganismer vil deretter mineralisere det allerede fysisk og kjemisk nedbrutte materialet til metan, CO_2, og vann, som er siste trinn i nedbrytningsprosessen. Kinetikken til nedbrytningsprosessen bestemmes av kombinasjonene av spesifikke forhold i omgivelsene: konsentrasjon av oksygen, vannkjemi, temperatur, tilstedeværelse av andre kjemikalier, sollys, og dynamikken i det mikrobielle samfunnet til nedbrytningsorganismene. Derfor vil nedbryting foregå i forskjellige hastigheter i de forskjellige miljøene, for eksempel raskere i kyst-sedimenter enn i dyphavssedimenter. Nedbryting begynner ofte på polymeroverflaten, og vil over tid bryte makroplast ned i mindre og mindre deler, til meso-, mikro-, og nanoplast, og til slutt til polymerfragmenter. Overflatearealet av mikroplast partiklene er relativt sett større i forhold til volum enn for meso- og makroplast og nedbrytningen av mikroplast vil foregå raskere enn for de større plastpartiklene.

På grunn av den store variasjonen i måten mikroplast dannes fra makroplast, er det ikke mulig å tilordne en enkelt nedbrytingsrate som er gyldig i alle marine miljøer og under alle forhold. I dette arbeidet har vi antatt at 0.5% av makroplastmassen i det marine miljøet transformeres til mikroplast hvert år. Dette er sannsynligvis et høyt estimat. På grunn av det relativt høye potensialet for abiotisk nedbryting av plast i strand- og i kyst-sonen, antas det at det er i disse miljøene brorparten av marin mikroplast dannes. Med denne antakelsen estimerer vi at det globalt nedbrytes 0.23 millioner tonn makroplast til mikroplast årlig. Dette tilsvarer ca 20 % av den antatte totale årlige tilførselen av mikroplast til havet.

Hvordan mikroplast fordeles mellom marine organismer, havbunnen, og resten av det marine miljøet avhenger av (i) kilden til og strømningen av vann langs norskekysten, (ii) global og lokal vind, og (iii) den lokale økologien. Den viktigste faktoren som innvirker på spredning og opphoping av plast og mikroplast er plastens synkehastighet. Plast vil synke hvis den har en tetthet som er større enn tettheten til sjøvann, eller hvis den kommer i kontakt med og synker sammen med andre partikler med større tetthet, som ved aggregering med marin snø, eller at plastpartiklene blir kolonisert av marine organismer. Ved å modellere plast som partikler kan vi simulere transport og sedimentering av mikroplast. Modellerte havstrømmer brukes for horisontal transport, mens vertikal transport beregnes fra partiklenes størrelse og tetthet. Vi har brukt denne metodikken til å modellere transport av mikrofibre (som er en type mikroplast) som slippes ut i havet fra flere Europeiske land, inkludert Norge. Målet var å finne ut av hvor mye av mikrofibrene som slippes ut i Nord- og Vest-Europa havner i norske kystområder og i NØS. Resultatene viser at ~90 % av mikrofibrene endre opp i sedimentet i løpet av de 5 månedene simuleringen varte. Kombinerer vi resultatene med historiske data for global produksjon av syntetiske fibre estimerer vi at nærmere 23000 tonn mikrofiber (~ 200 fiber kg^{-1}) er til stede i sedimenter i NØS i dag. Dette vises i sammenheng med at kun 20 tonn (3.9×10^{-5} fiber kg^{-1}) er estimert til å være i vannkolonnen, i tråd med observasjoner og konklusjonen i denne rapporten om at sedimentet er det største akkumuleringsområdet for mikroplast. Når vi ekstrapolerer disse resultatene basert på global historikk for produksjon av syntetiske fibre finner vi at så mye som 38000 tonn mikrofiber (330 fiber kg^{-1}) vil være i sedimentet i NØS, og 29 tonn mikrofibre i vannkolonnen (5.7×10^{-5} fiber kg^{-1}) om 10 år.

Plast kan følge havstrømmene inn i NØS fra vestre Nord-Atlanteren, Nordsjøen, Østersjøen, Grønlandshavet, og Barentshavet. Vi undersøkte potensialet for transport av mikroplast mellom forskjellige deler av disse havene ved å bruke en LCS-teknikk for å se etter transportbarrierer, som er linjer i havet som vann ikke går over på grunn av lokale strømningsforhold. Ved å undersøke representative LCS for hver måned i året konkluderer vi med at mikroplast i NØS som er i vannkolonnen på kontinentalsokkelen generelt vil holde seg på sokkelen om vinteren. Transportbarrierene bryter sammen om sommeren og tillater at mikroplasten kan spre seg forbi sokkelen i denne perioden. LCS-analysen viser at Norskehavet ikke er et sannsynlig oppsamlingsområde for makro- og mikroplast. Vi har vist her at lagrangske analysemetoder kan brukes til å undersøke transport og potensiale for akkumulering av mikroplast.

Eksisterende data kan tyde på at konsentrasjonen av mikroplast i de store havvirvlene ikke lenger øker, mens den fortsatt øker i kystnære områder som en stor andel av NØS. Dette støttes av den litteraturen som er gjennomgått i dette arbeidet og gjennom modelleringsarbeidet som viser at mikroplast fjernes fra overflaten relativt hurtig (nært utslippspunktet i det marine miljøet). Ved å sammenfatte estimater for dagens mengde mikroplast med global produksjon av plast siden 1950 og forventet produksjon fram til 2027, har vi estimert total antall mikroplastpartikler 10 år framover i tid. Resultatene antyder en økning i antall partikler fra dagens 1.77×10^{18} til 2.91×10^{18} partikler. Det representerer en økning på 64 % de neste 10 årene. Basert på våre tidligere beregninger kan vi anta at 80 % av denne økningen kommer fra ny mikroplast fra kilder på land, mens 20 % kommer fra nedbryting av makroplast som allerede befinner seg i det marine miljøet. Estimatene antar at andelen av dagens plastproduksjon som ender opp i havet vil holde seg konstant de neste 10 år. Dette viser at framtidige utslipp av mikroplast fra land, samt mikroplast fra nedbryting av makroplast, vil bidra til å øke mengden mikroplast i det marine miljøet i tiden framover.

Alle beregnede verdier i denne rapporten er forbundet med et høyt nivå av usikkerhet som stammer fra begrenset mengede tilgjengelig informasjon i publiserte data, forskjeller i prøvetaknings- og analyseteknikker, og i konvertering mellom rapporterte enheter og standard SI-enheter for å kunne sammenligne observasjoner som er rapportert på forskjellig måte. Siden det ikke er mulig å kvantifisere usikkerheten, bør disse beregningene anses som en forenklet forståelse av konsentrasjoner av mikroplast, partikkelantall, og fordelinger i det globale og norske marine miljøet. Det er også stor usikkerhet heftet til nedbrytingsraten brukt i denne analysen. Nedbrytingsrater er forventet å variere stort ut fra type polymer, miljø, og tilleggsstoffer i plasten. Da det ikke finnes en enkelt rate som beskriver degradering for alle typer plast i alle deler av miljøet har vi anslått et gjennomsnitt på 0.5 % per år, som ses på som et høyt anslag. Modellene som er brukt støtter seg på flere forenklende antagelser. Feltet innenfor partikkel-modellering av mikroplast er i en tidlig fase, men er i hurtig utvikling. Med en bedre forståelse av egenskapene til mikroplast, samt hvordan den dannes og brytes ned, vil modell-beregningene forbedres. I arbeidet med LCS undersøkte vi ikke mellomårlige klimavariasjoner. De omtalte usikkerhetene i denne rapporten representerer gap i dagens kunnskap om mikroplast som er viktige å lukke, og framtidig forskning bør fokusere på disse: fordeling, nedbryting, og transport av mikroplast i globale og norske marine miljøer. Framtidige studier vil styrkes ved internasjonalt samarbeid rundt prøvetakning og utveksling av observasjonsdata, samt utvikling av standarder for prøvetakning, analysemetoder, metadata og protokollføring av data.

1 Introduction

Microplastic is used in consumer products and may enter the environment; however, it is widely acknowledged that microplastic formed through abiotic and biotic degradation processes are the major source of microplastic in the marine environment[1]. Further degradation into nanoplastic (<100 nm in size) has been observed in laboratory systems, and is expected to occur in the environment[2, 3]. Degradation processes are also thought to generate polymer chain fragments, chemical fragments and serve as a mechanism for the release of plastic additive chemicals[4, 5]. However, the chemicals generated by degradation of the plastic polymers themselves have not been well studied from an environmental perspective. Recent studies estimate that there could be five trillion pieces of plastic in the global ocean, with an estimated 4.8 to 12.7 million metric tons entering the ocean annually[6-8]. Microplastic (particles < 5 mm in diameter) has been found everywhere in the world that has been investigated, including the most remote parts of the earth[9]. These small fragments vastly outnumber larger, more visible pieces of plastic debris in the environment[6, 9-11] due to the slow degradation and mineralisation rates for the most commonly used plastics (i.e. such as polyethylene (PE), polystyrene (PS), polypropylene (PP), polyvinyl chloride (PVC) and polyethylene terephthalate (PET))[8, 12]. Existing macroplastic litter in the marine environment will continue to present a major source of microplastic formation for decades to come, and may increase by up to an order of magnitude between 2015 and 2025[8].

Plastic and microplastic ingestion has been demonstrated for marine species representing most trophic levels, but few studies have reported impacts associated with ingestion[13-17]. Microplastic has also been identified as a vector for the transport of absorbed pollutants (e.g. persistent organic pollutants and metals)[18, 19] and pathogens[20, 21]. Unfortunately, microplastics are currently impossible to remove *en masse* from the open ocean due to their small size, chemical inertness, and vast distribution. To develop strategies for reducing plastic inputs into the ocean, it is essential to understand the distribution, degradation and transport of plastic particles[8].

2 Aim and objectives of the study

Aim

The aim of this work is to review the established and recent literature concerning the transport, accumulation, fragmentation, and degradation of plastics and microplastic particles. This knowledge will contribute to understanding the current and future conditions in the Norwegian marine environment, and highlight knowledge gaps and research topics that require further study.

Objectives

- Assess the distribution of macro- and microplastic in the various marine compartments by identifying the main transport and sedimentation pathways and rates.

- Estimate the quantity of microplastic (and nanoplastic) formed by degradation of macroplastic marine litter.
- Conduct a preliminary assessment of new-generation plastic materials with oxo-degradable and biodegradable properties for their potential to mitigate or contribute to the problem of microplastic pollution in the marine environment.
- Estimate the amount and fate of microplastic in the ocean, with a focus on the Norwegian coastal environment.

The following sections summarise data available in the literature and its contribution towards the current state of knowledge pertaining to the transport, distribution and degradation of macro- and microplastic in the marine environment. This data will be used, in conjunction with reported methods and approaches, to estimate key parameters relevant to the Norwegian marine environment. The information and data collected will be summarised in a final report, together with relevant estimates for Norway, addressing the needs of Miljødirektoratet.

3 Distribution of microplastic in environmental compartments

3.1 Introduction

Marine litter results from the indiscriminate disposal of waste items that are either directly or indirectly transferred to our seas and oceans[22]. Early estimates suggested up to 10% of plastics produced end up in the oceans, where they may persist and accumulate. The percentage of plastic fragments that exist in marine debris increases as the distance from the debris source increases[23]. Of the plastic litter entering the marine environment, it is estimated that 15% is floating on the surface, 15% is washed ashore and up to 70% of all plastic debris eventually settles onto the benthos[23, 24]. Sources of macro- and microplastic litter in the marine environment have been extensively studied and reviewed[14, 25-27]. An increasing number of environmental studies have estimated or quantified the environmental occurrence of microplastic in surface waters[28, 29], shorelines[30, 31], coastal sediments[25], beach sands[32], fjords[33], arctic waters[34] and deep-sea environments[35-37]. There have also been a significant number of studies identifying microplastic particles present in wild-caught marine organisms representing pelagic and benthic species[38-40]. Furthermore, several recent review articles and books have summarised current knowledge regarding the sources, temporal distributions, fate, effects, and potential solutions of microplastic pollution in the marine environment[16, 25, 31, 41-45].

The reported concentrations of microplastic in the current literature was used as a basis for estimating the relative distribution of microplastic. The influence of key parameters (e.g. climatic conditions and plastic transport/global dispersion) is highlighted and combined with Norwegian data to estimate the likely environmental distribution of microplastic in the Norwegian marine environment. By calculating the distribution of microplastic in different environmental compartments, especially that associated with biota, we estimate the respective proportion that is entering the marine food chain. Importantly, we have opted to use only data reported since 2000 to try and provide an assessment of the current environmental loadings. Furthermore, only studies reporting specific concentrations and amounts of microplastic in environmental compartments are included in this report. **We strongly acknowledge the literature review work conducted by others which has been used as much of the basis for the literature data presented here[16, 25, 31, 41-47]. These review documents have been supplemented with a selection of the most recent data reported in the scientific literature.**

This section summarises the available literature reporting quantities and types of microplastic in various compartments of the global marine environment. The environmental compartments identified are:

- Surface waters
- Water column
- Shorelines and beaches
- Coastal sediments
- Deep-sea sediments
- Fish
- 'Non-fish' pelagic organisms
- Benthic organisms

We have decided to group data reported for marine biota into three categories: fish species, pelagic species and benthic species, to see if this correlates with the corresponding values for microplastics in these environmental compartments (water column and sediments, respectively).

From a Norwegian perspective, we will also summarise any data specifically related to the following environmental compartments:

- Fjords
- Polar waters and sediments

3.2 Distribution of microplastic across the global marine environment

Microplastic contaminates shorelines worldwide, from pole to pole in six different continents[25]. Floating plastic and microplastic debris appears to accumulate in oceanographic convergence areas, enclosed seas, and ocean currents[23]. A global study of microplastic occurrence on shorelines worldwide found more material in densely populated areas[25]. However, many unknowns exist regarding the relative distributions of microplastic in different marine compartments and we are still lacking a clear idea of the importance of each compartment as a sink for microplastic.

3.2.1 Data collection, interpretation and assumptions

Due to the diversity of reporting and the need to bring a large and diverse literature into a single framework, there were three key challenges to address: (i) how to describe a diverse sample for "concentration", (ii) bring the diverse units used among various groups into a single framework, and (iii) creating a single metric for microplastic concentration. Our process is described below:

1. In the vast majority of studies, the concentration of microplastic is reported as the number of particles present in a specific matrix (e.g. water, sediment, biota). In contrast, only a small number of studies reported the concentration of microplastic as mass of plastic. We have therefore opted only to use data from studies reporting the number of microplastic particles to allow for an inclusive comparison between studies.

2. Microplastic concentrations are frequently reported with a wide variety of different SI units describing the matrix (water, sediment biota etc). This not only varies between different environmental compartments (e.g. water vs. sediment), but also within the same environmental compartment. In surface waters, for example, microplastic measurements are frequently reported as a concentration (i.e. mass per volume) or an area density (mass per area). To be able to directly compare data available for the same environmental compartment and across different environmental compartments, we have opted to normalise all concentrations to the number of microplastic particles per kg of matrix (kg^{-1}). A mass-based unit was selected for comparison because many of the environmental matrices are either reported in mass or can be converted to a mass relatively easily. Specific assumptions and calculations are described in the relevant sections below.

3. Most studies either reported an average microplastic concentration derived from all the samples analysed, or presented a concentration range representing the samples analysed. Having the data presented in these two ways also makes it more challenging to interpret and compare values from different studies. Both methods of reporting have value, but it is difficult to compare an average value with a concentration range. In an attempt to utilise all the available data, we have calculated median values from concentration ranges. We have then combined these median values with the average values reported from the other data sets. We acknowledge that this approach introduces uncertainty to our calculations.

In addition, several other issues became evident when evaluating the available microplastic concentration data for different environmental compartments. The reliability of microplastic identification presents a significant issue for all environmental compartments. Identification methods range from diagnostic approaches to light microscopy and/or visual identification with the naked eye. The latter approach presents significant limitations and has likely led to either an over estimation or underestimation of the microplastic content in many environmental samples reported in the literature. Only analytical chemical techniques such as ATR-FTIR, µFTIR and Raman spectroscopy can definitively identify microplastic from naturally occurring particulates. We have included data for which there is a high confidence in the identification of microplastic particles.

An important note is that the microplastic concentrations used in this report have been estimated using a variety of techniques and represent a time range of 17 years (2000-2017). Therefore, an important consideration is that *the increased focus on microplastic in environmental samples in recent years has led to better and more robust approaches for determining concentrations*. As a result, recent studies may have utilised technology that more accurately defined differences between microplastic particles and naturally occurring particles. Whether this represents a potential underestimation or overestimation in older studies is not clear. Likely, these newer approaches allow for the identification of much smaller particles (using advanced instrumentation), which are considered to present in a higher abundance than larger particles. Finally, environmental samples may be easily contaminated by microplastic in the laboratory (e.g. fibres from clothing), and the level of contamination is likely to vary from study to study.

3.2.2 Marine waters

Different plastics have different densities which helps to determine where in the world's oceans and seas they are likely to occur. Plastics comprised of polymers with low densities are typically expected to float and would therefore spend a significant period of time at the same surface[48]. Plastic types with densities higher than seawater would be expected to immediately sink through the water column towards the seafloor[35, 49]. In reality, the processes are slightly more complicated. Buoyant plastic items can also be transported to the seafloor when natural processes alter their relative density. For example, biofouling by bacteria, algae and large marine organisms can promote sinking[50, 51]. In the case of small buoyant microplastic particles, heteroaggregation with other dense particulate matter and repackaging in faecal materials after ingestion by organisms may also promote sedimentation. In contrast, the sinking of dense microplastic particles may be significantly slowed by frictional forces, especially for very small particles. As a result, microplastic particles are likely to be present in both surface waters and the water column, with some particles potentially having long residence times in the water column. The following section has been divided into two sub-sections looking at the concentrations of microplastic in global surface waters and in global water columns, respectively.

Different studies report the concentration of microplastic in marine waters with different SI units. The most commonly used is m^{-3}, but some studies have also reported in L^{-1}, m^{-2} or km^{-2}. For this report, we have made the following conversions:

- L^{-1} converted to kg^{-1}: Direct conversion
- m^{-2} converted to m^{-3}: Multiply by 0.2 (previously described[52])
- km^{-2} converted to m^{-3}: Division by 1,000,000, multiply by 0.2 (previously described[52])
- m^{-3} converted to kg^{-1}: Divide by 1000

The conversion from m^{-3} to kg^{-1} is based on 1 m^{-3} containing 1000 L, where 1 L of seawater is assumed to be 1 kg in mass. We acknowledge that there may be significant levels of uncertainty introduced by these estimation approaches.

3.2.2.1 Surface waters

Marine surface waters are easily accessible and water samples can be collected quickly and simply using manta nets or similar techniques Figure 1. Furthermore, this environmental matrix is relatively simple in composition, which is reflected in the basic sample processing required for quantifying microplastic content. As a result, there is currently much data available that reports on the concentrations of microplastic in global marine surface waters. A summary of selected reported concentrations of microplastic in global marine surface waters is presented in Appendix 1, Table A1. The data presented are almost exclusively collected using a form of plankton net trawl. All data are summarised as the number of particles kg^{-1} (Appendix 1, Table A1).

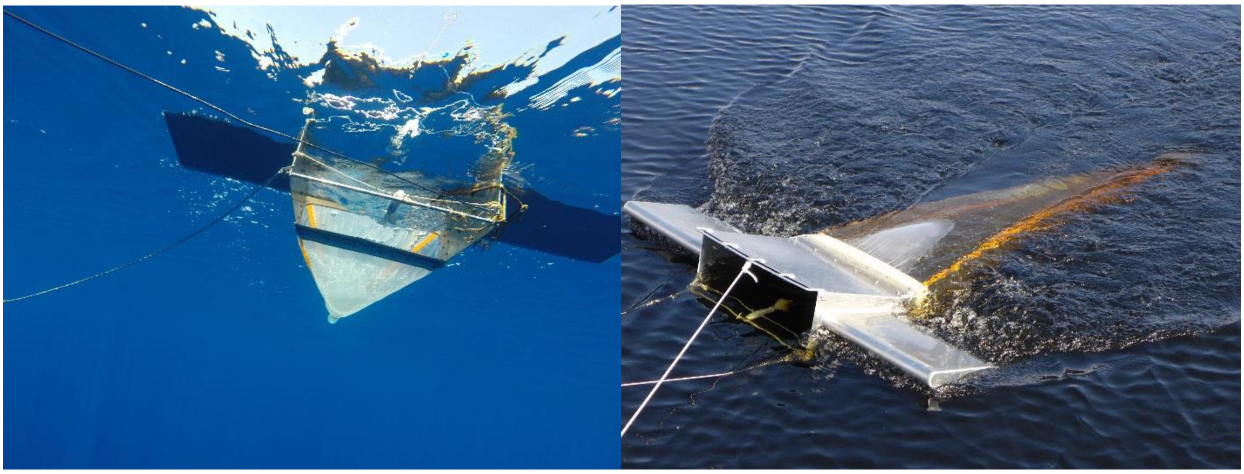


Figure 1. Example of a manta net sampler. Photo Julia Farkas, SINTEF Ocean.

Note that all studies found microplastic in many of their samples, but some studies also found individual water samples that contained no microplastic. However, these are rarely included when average microplastic concentrations are calculated. Instead, most studies simply report an average microplastic concentration across all samples or present a concentration range. In one case[53], the reported concentration is simply >200 particles m^{-3}, and again these data are not included in our calculations. When looking at the final values for all the data sets presented in Table A1 (Appendix 1), we see that values for the number of microplastic particles in surface waters ranges from 8.5 x 10^{-7} kg^{-1} to 16 kg^{-1}, with a global average of 0.79 particles kg^{-1}. The lowest concentrations were reported off the Australian coast in the South Pacific[51], whilst the highest concentrations are reported off the South Korean coast in the North Pacific[54]. Interestingly these values are both reported in different parts of the Pacific Ocean, and they represent a difference in particle concentration of over 7 orders of magnitude. These two areas also represent a range from extremely high human populations in southeast Asia, to very low human populations in eastern Australia and vicinities.

An important consideration is that the microplastic concentrations reported have been almost exclusively determined or estimated from samples collected by filtration of seawater. As a result, one of the main limitations with the available data is that filtered samples are typically collected using nets with a mesh of approximately 300 µm. This is because smaller pore sizes remove too much biomass from the water column (e.g. planktonic organisms such as algae and zooplankton), meaning they clog very quickly and the resulting samples need much more extensive processing before the microplastic content can be determined. Collecting fixed volumes of water is also not feasible owing to the low concentration of microplastic. As a result, there is virtually no data on the concentrations of microplastic <300 µm in surface waters, and we consider that this fraction is critically under-represented in the available literature. In terms of the number of particles present, it is also expected that the fraction of microplastic <300 µm is likely to be significantly higher than the fraction 300 µm – 5 mm. This is due to the fact there it is estimated that the number of particles present in environmental samples increases almost exponentially with decreasing size. Furthermore, smaller particles are typically sediment more slowly than larger particles as the friction processes begin to dominate over density processes. Variations in sampling approaches in the different studies are also likely to mean that the type of microplastic particles, especially the size-range, that was collected in each study may differ, with some approaches favouring larger size ranges than others. This is likely to lead to a significant differences in the reported microplastic concentrations, with samples encompassing smaller size particles more likely to show higher numbers of particles.

3.2.2.2 Water column

In situ observations and measurements of microplastic concentrations in the water column remain scarce[55]. This is largely due to the challenge in collecting volumes of water from the water column that are sufficient for determining the concentration of microplastic present. Most studies report the use of a bongo net to collect sub-surface water samples, but other approaches are also reported (e.g. epibenthic sled[56], multi-level trawls[55] and pumping water up from the water column onto a ship for filtration[57]). Owing to the lack of data available for the marine water column, we suggest it is difficult to accurately estimate relevant global concentrations of microplastic in this environmental compartment. This is further limited in an equivalent way to the surface water samples, which are collected with some form of plankton net with a typical pore size of approximately 300 µm. The approaches used will miss capturing any microplastic particles below 300 µm and is therefore likely to significantly underestimate the number of particles present in the water column, as this is believed to be dominated by increasingly sampler particle size ranges. A summary of the reported concentrations of microplastic in the global water column is presented in Table A2, Appendix 1. Again, some studies report average particle concentrations, whilst others report concentration ranges. When looking at the final values for all the data sets presented in Table A2 (Appendix 1), we see that values for the number of microplastic particles in the water column ranges from 1.7 x 10^{-5} kg^{-1} to 0.279 kg^{-1}, with a global average of 4.2 x 10^{-2} particles kg^{-1}. The lowest concentrations were reported North Pacific central gyre (10-30 m sampling depth) [58], whilst the highest concentrations are reported in sub-surface waters (4.5 m sampling depth) of the north eastern Pacific Ocean and coastal British Columbia[37]. Again, both values are reported for different parts of the Pacific Ocean, with different circulation regimes, and they represent a difference in particle concentration of over 4 orders of magnitude.

3.2.3 Marine sediments

Microplastics with a density greater than that of seawater will sink to sediments, where they are expected to accumulate [35, 49, 59]. There are also acknowledged transport mechanisms for buoyant microplastic to marine sediments (e.g. biofouling, heteroaggregation and repackaging in faecal material). As a result, marine sediments have been proposed as long-term sinks for microplastic[60], with high concentrations of microplastic reported (up to 3% of sediment weight on highly contaminated beaches)[61-63]. A global study of microplastic occurrence on shorelines worldwide found more material in densely populated areas[25], so it may be expected that sediments in densely populated coastal areas may exhibit higher concentrations of microplastic than in remote deepsea areas. Furthermore, the sedimentation process indicates that higher concentrations might be found in coastal areas compared to deepsea areas, as most sources of plastic to the marine environment come from terrestrial sources. An interesting comparison are the distributions found on (1) beaches and shorelines (including intertidal zones) with those in (2) coastal and (3) deepsea sediments. Microplastic is expected to be present at different concentrations in different sediment compartments. The following section looks at the concentrations of microplastic on global beaches and shorelines, coastal sediments, and deepsea sediments, respectively.

Different studies report the concentration of microplastic with different SI units, including L^{-1}, m^{-3}, m^{-2} or kg^{-1}. The situation is further complicated by some studies reporting values for dry weight sediment, some reporting values for wet weight sediment and others not specifying. Although this makes a direct comparison of the reported values almost impossible, so we have attempted to normalise all data using a series of assumptions and calculations. We have decided not to distinguish between dry weight data and wet weight data as it is impossible to introduce a conversion factor owing to the water content varying highly in different sediment samples. Again, some studies report average particle concentrations, whilst others report concentration ranges. In the current document, we have made the following calculations to convert all reported data into kg^{-1}:

- L^{-1} converted to kg^{-1}: Direct conversion (previously described[52])
- g^{-1} converted to kg^{-1}: Multiply by 1000
- m^{-3} converted to kg^{-1}: Divide by 1000 (we have assumed that 1 m^{-3} is equivalent to 1000 L)
- m^{-2} converted to kg^{-1}: Divide by 100

Where data are reported in m^{-2}, we have assumed that the particles identified come from the upper 10 cm of the area surveyed. This means that every observation in units of m^{-2} can be considered as a volume of 0.1 m^{-3} or 100 L, which we directly converted to kg. We acknowledge that there may be significant levels of uncertainty introduced by these estimation approaches.

3.2.3.1 Shorelines and beaches

Marine sediments along beaches and shoreline waters are easily accessible and samples can be collected quickly and simply. Despite this environmental matrix having a more complicated composition compared to water samples, many approaches are available for isolating the microplastic content from the naturally occurring particulate fraction. Simple density separation can be achieved by adding water and shaking, although this methodology is not particularly robust. More recently, elutriation techniques (e.g. Figure 2) have been employed with a high degree of success[64-66]. Elutriation is a process for separating particles based on their size, shape and density, using a stream of gas or liquid flowing in a direction usually opposite to the direction of sedimentation. As samples are easily collected and relatively simple to process, there is currently much data available reporting concentrations of microplastic on global beaches and shorelines.

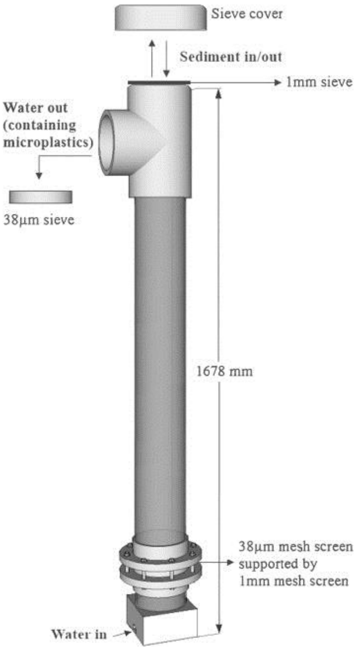


Figure 2. Schematic representation of the elutriation column used for separating microplastic from heavier sand particles. Reproduced from Claessens et al., 2013[64].

A summary of the reported concentrations of microplastic on global shorelines and beaches is presented in Table A3, Appendix 1. Where studies report the concentrations of different types of particles (e.g. spheres, fibres, fragments)[67, 68], we have combined these numbers to give a total number of microplastic particles. When looking at the final values for all the data sets presented in

Table A3 (Appendix 1), we see that values for the number of microplastic particles on beaches and shorelines ranges from 1.52 x 10^{-2} kg^{-1} to 4340 kg^{-1}, with a global average of 334.23 particles kg^{-1}. The lowest concentrations were reported in the North Pacific on Coastal beaches in Japan[69], whilst the highest concentrations are reported for the Burrard Inlet, British Columbia, Canada[63]. These values are both reported in different parts of the Pacific Ocean, and they represent a difference in particle concentration of over 5 orders of magnitude. Interestingly, the lowest concentration is found on a Japanese beach, which represents one of the most densely populated countries in the world, whereas the highest concentration was found within the proximity of the large city of Vancouver, Canada. Japan has a strong ethic of cleanliness, so there is no litter found on the streets. It is interesting to note that these studies were conducted 13 years apart, with the highest concentrations reported in the most recent study (2016). This may reflect the increased improvements in sample analysis or an increase in plastic inputs into the environment over the last 10 years. Table A3 (Appendix 1) also shows that a range of microplastic types were observed in the different studies, with fibres being increasing reported in more recent studies. One study also investigated season differences in microplastic concentrations at a beach in South Korea[70], observing a 3-fold increase during the rainy season compared to the dry season.

3.2.3.2 Coastal sediments

Collecting samples from coastal marine sediments presents significantly more challenges than collecting samples from shorelines and beaches. Sampling typically requires access to a boat and more advanced sample collection equipment (e.g. sediment grabs). As a result, there are significantly fewer studies in the literature focusing on this environmental compartment. However, once samples have been collected, processing and analysis is essentially the same as for beach and shoreline samples outlined in Section 3.2.3.1 above. A summary of the reported concentrations of microplastic in global coastal sediments is presented in Table A4, Appendix 1. Again, there are some significant challenges with different studies reporting microplastic concentrations with different SI units, but these have been converted to kg^{-1}.

When looking at the final values for all the data sets presented in Table A4 (Appendix 1), we see that values for the number of microplastic particles in coastal sediments ranges from 3.91 kg^{-1} to 3320 kg^{-1}, with a global average of 473.17 particles kg^{-1}. The lowest concentrations were reported at the Mackellar Inlet, South Shetland Islands, Southern Ocean[71], whilst the highest concentrations are reported for an Industrial harbour sediment sample collected in Sweden[72]. The values represent a difference in particle concentration of approximately 3 orders of magnitude, despite representing very different environments (industrial harbour vs. sediment from the Southern Ocean). Again, it is interesting to note that these studies were conducted 10 years apart, with the study from the Southern Ocean being the most resent (2017). Table A4 (Appendix 1) also shows that a range of microplastic types were observed in the different studies, with fibres being increasing reported in more recent studies.

3.2.3.3 Deepsea sediments

Collecting samples from deepsea marine sediments is time consuming, expensive and complicated. Unsurprisingly, there are very few studies in the literature which focus on this environmental compartment. However, once samples have been collected, processing and analysis is essentially the same as other sediment samples. The typical methods and considerations are outlined in Section 3.2.3.1 above. A summary of the reported concentrations of microplastic in global deepsea sediments is presented in Table A5, Appendix 1.

When looking at the final values for all the data sets presented in Table A5 (Appendix 1), we see that values for the number of microplastic particles in deepsea sediments range from 0.4 kg^{-1} to 10.3 kg^{-1}, with a global average of 69.78 particles kg^{-1}. The lowest concentrations were reported for the Porcupine abyssal plain in the Atlantic and a location from the Southern Atlantic[36], whilst the highest concentrations are reported for the Kuril-Kamchatka Trench in the north west Pacific Ocean (collected from 4869-5766 m)[73]. A final study by Woodall et a (2013)[35] reports an average concentration of 268 kg^{-1} for microplastic in deepsea sediment samples collected from 12 locations worldwide, including subpolar North Atlantic, North East Atlantic, Mediterranean, South West Indian Oceans (collected from 300-3500 m depth). The values represent a difference in particle concentration of approximately 3 orders of magnitude, despite representing very different geographical locations. The studies included in this report were published between 2013-2015, which suggest knowledge and access to more advanced sample processing and sample analysis techniques which would increase the accuracy of these data. The Kuroshio Current travels past the large population centres of southeast Asia before traveling over the Kuril-Kamchatka Trench on the way eastward, while the water in the Gulf Stream Extension traveling over the Porcupine abyssal plain left the east coast of the USA and travelled across an ocean basin. Table A5 (Appendix 1) also shows that a range of microplastic types were observed in the different studies, with fibres being reported as the dominant form.

3.2.4 Polar regions

The plastic flux into the Arctic Ocean has been calculated to range between 62,000 and 105,000 tons per year, with variation due to spatial heterogeneity, temporal variability and different sampling methods[74]. Owing to the costs and logistics involved with collecting samples from polar regions the limited data currently available is not unsurprising. Prior to 2014, there had been no direct studies of microplastic in either the Arctic Ocean or the Southern Ocean surrounding Antarctica[52]. Since 2014, a small number of studies have focused on microplastic in polar regions, and available data has been recently reviewed[71]. As there is so little data available, we have grouped all of the available data for sea ice[75, 76], polar waters[6, 34, 60, 77, 78], and polar sediments[71, 79] into a single section. A summary of the reported concentrations of microplastic in global polar environmental compartments is presented in Table A6, Appendix 1.

When looking at the final values for all data sets presented in Table A6 (Appendix 1), we see that values for the number of microplastic particles in polar compartments range from 2 x 10^{-9} kg^{-1} (sea ice) to 33.19 kg^{-1} (sediment), with a global average of 6.58 particles kg^{-1}. The values represent a difference in particle concentration of approximately 10 orders of magnitude. In sea ice, concentrations range from a minimum of 2 x 10^{-9} kg^{-1} to a maximum of 1.36 x 10^{-1} kg^{-1}, with a global average of 5 x 10^{-2} particles kg^{-1}. The minimum and maximum values determined come from samples collected in the Arctic[75, 76]. The values represent a difference in particle concentration of approximately 8 orders of magnitude. In polar surface waters and the water column, concentrations range from a minimum of 1.45 x 10^{-5} kg^{-1} to a maximum of 22 kg^{-1}, with a global average of 5.50 particles kg^{-1}. The minimum and maximum values determined come from samples collected in the Southern Ocean[77, 78]. The values represent a difference in particle concentration of approximately 6 orders of magnitude. The minimum concentration reported for polar sediments is 3.91 kg^{-1} (Antarctic)[71] and the maximum being 33.19 kg^{-1} (Arctic)[79], with a global average of 18.55 particles kg^{-1}. The values represent a difference in particle concentration of only 1 order of magnitude.

3.2.5 Marine organisms

Marine organisms are grouped into three separate categories: marine fish species, 'non-fish' pelagic species (water column dwelling) and 'non-fish' benthic species (sediment dwelling). The fish group includes all species regardless of which part of the water column they inhabit (e.g. both pelagic and demersal). The pelagic group includes squid, mammals (seals, whales) and reptiles (turtles). The benthic group includes all species which live either within the sediment (e.g. worms) or are sedentary by nature (e.g. mussels, oysters). The main reason for grouping the marine organisms in this way is so that we can compare water column microplastic concentrations with organisms that live in that environmental compartment, whilst sediment microplastic concentrations can be compared to corresponding benthic organisms. By placing all the fish into a single group, we can compare this specific class of marine organisms, important from a human food perspective, to all other environmental compartments. Furthermore, there are published estimates for the global biomass of fish that are not available for other species. The following section has been divided into three sub-sections looking at the concentrations of microplastic in global fish, pelagic and benthic marine organisms, respectively.

The microplastic concentrations reported for different marine organisms have been estimated using a variety of techniques. In addition to the techniques used to identify the microplastic particles, methods used to extract microplastic from the target organism may vary between studies and represents a potential source of uncertainty when comparing values (reviewed by Miller et al., 2017)[80]. Most approaches involve some form of laboratory digestion using an acid, a base or enzymes to remove the biological material and release the microplastic. Some of the methods are considered more effective than others, whilst some are considered to be more damaging to the microplastic present. Choice of extraction method may therefore lead to underestimation of microplastic concentrations. It is also important to note that in most cases only the digestive organs were removed from each organism and subjected to the microplastic extraction/digestion process, and not the whole organism. This reflects the understanding that microplastic is generally too large to transfer through the gut wall of an organism and into the tissues. Small microplastic particles and nanoplastic particles may be sufficiently small to be transferred, but this requires further study.

Most reported concentration data for marine species is presented as the number microplastic particles per individual organism. This number is typically presented as an average derived from analysis of multiple organisms representing the same species. In a few studies, a concentration range per individual is reported. Having these data presented in two ways makes it more challenging to interpret and compare values from different studies. To utilise all the available data, we have opted to calculate median values for the data sets where concentration ranges are presented. We have then combined these with the average values from the other data sets, but acknowledge there are limitations to this approach and that it introduces a degree of uncertainty.

3.2.5.1 Marine fish species

There are a considerable number of studies reporting the concentration of microplastic in fish species, with fish representing the most commonly studied group of marine organisms. A summary of the reported concentrations of microplastic in global marine fish is presented in Table A7, Appendix 1. One significant challenge is to present the reported data in a way that it can be directly compared to the microplastic concentration data for other environmental compartments. As previously stated, our goal is to convert all reported data into microplastic concentration kg^{-1} of a specific matrix (e.g. water, sediment etc). As a result, we have attempted to convert all data into values representing the number of microplastic particles per kg of fish. To do this we have had to estimate an average mass for an individual from each species. As so many different fish species are included in the report, we were not able to determine average weights for each individual species. We have therefore opted to define a common weight of 1 kg for every individual, irrespective of the species type. We acknowledge that this will underestimate the weight of individuals from certain species and overestimate the weight of individuals from other species. As a result, this is a potentially significant uncertainty in our calculations.

When looking at the final values for all the data sets presented in Table A7 (Appendix 1), we see that values for microplastic particles across all fish species range from 3×10^{-2} kg^{-1} to 7.2 kg^{-1}, with a global average of 1.46 particles kg^{-1}. The lowest concentrations were reported in blue jack mackerel (*Trachurus picturatus*) from the Portuguese coast[81], whilst the highest concentrations are reported for a species of lantern fish (*Myctophum aurolaternatum*) from the north Pacific central gyre[82]. The blue jack mackerel typically grow to about 25 cm, whilst the lantern fish typically grows to about 10 cm, with the latter known to be planktivorous. As both species are relatively small, our normalisation approach, which assumes individuals weigh 1 kg is likely to significantly under estimate the average microplastic concentration in these two species.

3.2.5.2 Pelagic organisms

The number of studies reporting microplastic concentrations for pelagic organisms other than fish species is rather limited. A summary of the reported concentrations of microplastic in global pelagic marine organisms is presented in Table A8, Appendix 1. To directly compare the concentration of microplastics in pelagic marine organisms to organisms from other environmental compartments, we have attempted to convert all data into values representing the number of microplastic particles per kg of biota. To do this we have had to estimate an average mass for an individual from each species. This approach is difficult as there is typically significant variation in organism mass across a single species (e.g. males vs females, juveniles vs. adults). In the case of Humboldt squid (25 kg), Harbour seals (66 kg), True's Beaked whale (1200 kg) and Green sea turtles (129 kg), we could find average weights for full grown adults (e.g. from Wikipedia and scientific reports). We acknowledge that this may underestimate or overestimate the weight of some individuals, and therefore represents an uncertainty in our calculations. When looking at the final values for all the data sets presented in Table A8 (Appendix 1), we see that values for the number of microplastic particles in 'non-fish' pelagic organisms ranges from 2.5 x 10^{-3} kg^{-1} to 0.44 kg^{-1}, with a global average of 0.16 particles kg^{-1}. The lowest concentrations were reported in sea turtles[83], whilst the highest concentrations are reported for squid[84].

3.2.5.3 Benthic organisms

There are many fewer studies reporting the concentration of microplastic in benthic marine organisms than there are for pelagic species. Filter feeders such as mussels and oysters represent the most commonly studied species. A summary of the reported concentrations of microplastic in global benthic marine organisms is presented in Table A9, Appendix 1. The reported concentration data for benthic species is presented as either the number microplastic particles per individual organism or the number of microplastic particles per mass of tissue. We have converted all data into values representing the number of microplastic particles per kg of biota. For data presented as the concentration of microplastic per mass of tissue, this is straightforward as these data are reported as per gram (g^{-1}) or per 10 gram (10 g^{-1}), which is readily converted to kg^{-1} by multiplying by 1000 and 100, respectively.

In the case of data reported as microplastic concentrations per individual, we have had to estimate the average mass for an individual of that species. We were unable to find reliable adult masses for any of the species (blue mussels, Pacific oysters, Gooseneck barnacles), but in the case of the lugworm *Arenicola marina* 100 g appears to be suitable. We have therefore opted to define a common weight for an individual of each species, with individual mussels (*Mytilus edulis*) as being 10 g, Pacific oysters (*Crassostrea gigas*) as being 20 g, and Gooseneck barnacles (*Lepas* spp.) as being 10 g. We acknowledge that this may underestimate or overestimate the weight of individuals from certain species and that this represents a significant uncertainty in our calculations. When looking at the final values for all the data sets presented in Table A9 (Appendix 1), we see that values for the number of microplastic particles in benthic organisms ranges from 12 kg^{-1} to 10600

kg^{-1}, with a global average of 1724.44 particles kg^{-1}. The lowest concentrations were reported in *A. marina*[61], whilst the highest concentrations are reported for *M. edulis*[85].

3.3 Relative distributions of microplastic at the global scale

Using data presented in Appendix 1 and summarised in Section 3.2 above, we have attempted to estimate the relative distributions of microplastic in the different environmental compartments. The aim of this section this to try and identify which of the environmental compartments contain the greatest proportion of microplastic currently present in the marine environment. Table 1 summarises the global microplastic concentration ranges and average concentrations estimated for the different environmental compartments. The level of the variation is indicated by showing the number of orders of magnitude between the lowest and the highest concentrations for each compartment. These data highlight the significant differences in microplastic concentrations within individual environmental compartments and, importantly, across different environmental compartments. At the same time, we are also able to see consistencies between concentration ranges for different environmental compartments.

Table 1. Summary of the global minimum and maximum microplastic concentrations reported for each of the main environmental compartments and the calculated average concentration

Environmental compartment	Minimum concentration (particles kg^{-1})	Maximum concentration (particles kg^{-1})	Order of magnitude across range	Average concentration (particles kg^{-1})
Surface waters	8.5×10^{-7}	16	~7	0.79
Water column	1.7×10^{-5}	0.28	~4	4.2×10^{-2}
Beaches and shorelines	1.5×10^{-2}	4340	~5	334.23
Coastal sediments	3.91	3320	~3	473.17
Deepsea sediments	0.4	268	~3	69.78
Polar sea ice	2×10^{-9}	0.136	~8	5×10^{-2}
Polar waters	1.45×10^{-5}	22	~6	5.50
Polar sediments	3.91	33.19	~1	18.55
Fish species	3×10^{-2}	7.2	~2	1.46
Pelagic species (non-fish)	2.5×10^{-3}	0.44	~2	0.16
Benthic species (non-fish)	12	10600	~3	1724.44

3.3.1 Water compartments

Although there are a very small number of reported values for the water column relative to the amount of data available for surface waters, the concentration range for the water column (8.5×10^{-7} – 16 kg^{-1}) is generally similar in distribution to the equivalent range estimated for surface waters (1.7×10^{-5} – 0.28 kg^{-1}) (Table 1). The average microplastic concentration determined for surface water (0.79 kg^{-1}) is approximately one order of magnitude greater than the average concentration estimated for the water column (4.2×10^{-2} kg^{-1}). The highest and lowest concentrations are reported for surface waters, with the concentration range for the water column lying between these two values. Although concentrations vary by many orders of magnitude within both environmental compartments, there is no clear difference in concentrations between the two. The range of concentrations reported for global surface waters covers approximately 7 orders of magnitude, indicating just how varied microplastic concentrations are at the global scale within this environmental compartment. Although the concentration range is narrower for the water column, being approximately 4 orders of magnitude, this also highlights significant variation in microplastic concentrations at global level.

It is estimated that the world's oceans and seas have a surface area of approximately 360 million km^{-2}. If we apply in reverse the approach we have used previously to convert km^{-2} to kg^{-1}, then we are able to estimate that the total number of microplastic particles in world's surface waters ranges from 1.53×10^{12} – 2.88×10^{19}; with an estimated average of 1.42×10^{18}. It is estimated that the world's oceans and seas have a volume of approximately 1.335 billion cubic kilometres (1.335×10^{18} m^3), which corresponds to approximately 1.335×10^{21} kg. Similarly, if we apply in reverse the approach we have used previously to convert m^{-3} to kg^{-1}, then we are able to estimate that the total number of microplastic particles in world's ocean water column ranges from 2.27×10^{16} – 3.74×10^{20}, with an estimated average of 5.61×10^{19}. These very crude estimates suggest that there is a slightly higher quantity of microplastic particles are present in the marine water column than at the surface. This is not unsurprising considering that the volume of water comprising the surface layer is vastly smaller than the total volume comprising the water column, despite the lower microplastic concentration estimated for the water column compared to surface waters.

3.3.2 Sediment compartments

The number of studies reporting microplastic concentrations is highest for beaches and shorelines, followed by coastal sediments, and finally deepsea sediments, for which there are very little data available. Beaches and shorelines also have the largest variation (approximately 5 orders of magnitude) in the determined concentration range (1.5×10^{-2} – 4340 kg^{-1}), but this high variation is likely caused by the number of studies included in the analysis ($n = 39$). Beaches and shorelines have the highest and lowest concentrations, with the concentration range for coastal (3.91 – 3320 kg^{-1}) and deepsea (0.45 – 268 kg^{-1}) sediments located within these two values and having less variation (approximately 3 orders of magnitude in both cases). The average microplastic concentration estimated for beaches and shorelines (334.23 kg^{-1}) is within one order of magnitude of the average value estimated for coastal sediments (473.17 kg^{-1}). The average microplastic concentration estimated for deepsea sediments is approximately one order of magnitude lower (69.78 kg^{-1}). Importantly, the data suggest that there is not a significant difference ($p < 0.05$) between the different sediment compartments, indicating that all are potential sinks for microplastic. This is consistent with previous suggestions that global sediments are likely to be major sinks and accumulation zones for microplastic[35, 49, 86]. The lower average concentration estimated for the deepsea sediments may reflect their remote location from terrestrial sources.

It is estimated that the world's oceans and seas have a surface area of approximately 360 million km^2. If we assume that the total area of marine sediments is similar, and apply in reverse the approach we have used previously to convert the number of particles km^{-2} to kg^{-1}, then we are able to crudely estimate that the total number of microplastic particles in worlds sediment compartments (beaches, shorelines, coastal sediments and deepsea sediments) ranges between 2.70×10^{16} and 7.81×10^{21}. For this calculation, we have used the microplastic concentration range estimated for beaches and shorelines, as the concentration ranges estimated for coastal and deepsea sediments fall within this range. The average number of microplastic particles in global sediments is estimated as 6.30×10^{20}, based on combined data from all 3 sediment compartments.

3.3.3 Polar compartments

Although there are an extremely small number of studies reporting microplastic concentrations in polar compartments, it is still possible to present some tentative concentration ranges and average concentrations. The concentration range for polar waters (surface and water column combined) is 1.45×10^{-5} - 22 kg^{-1}, with the average concentration estimated to be 5.50 kg^{-1} (Table 1). Only a single average concentration for microplastic in the polar water column has been reported (2.68×10^{-3} kg^{-1})[34], which is insufficient to provide the basis for an accurate assessment of water column concentrations. However, this value falls in the middle of the microplastic concentration range for the global water column, but is below the average. The concentration range for Arctic sea ice is 2×10^{-9} - 0.136 kg^{-1}, with the average concentration estimated to be 5×10^{-2} kg^{-1} (Table 1). The average concentration of microplastic in sea ice is approximately two orders of magnitude lower than that estimated for polar waters. The concentration range for polar sediments is 3.91 - 33.19 kg^{-1}, with the average concentration estimated to be 18.55 kg^{-1}. This value is similar to the average microplastic concentration estimated for polar waters. However, it is very important to note that the concentration ranges and average values presented are based on a very small number of data points.

Although the Arctic and Antarctic marine systems are often considered pristine compared to other regions around the globe, microplastic is clearly present and at concentrations comparable to those found in marine waters and sediments elsewhere. Microplastic concentrations observed in Antarctic areas appear to be comparable with those observed in Arctic regions[78]. Crucially, local sources do not account for the reported concentrations, indicating one or more transport mechanisms from other regions (e.g. via global ocean wind driven surface circulation[79]). Current microplastic data supports prior reports of polar regions acting as major sink and accumulation areas, despite their remoteness from the main sources of plastic. Furthermore, an increase in abundance of small-sized plastic in Arctic deepsea sediments from the HAUSGARTEN Observatory between 2002 and 2014 indicates degradation of plastic litter[87]. However, available data for polar regions are extremely limited and further studies are necessary to accurately determine the distribution of microplastic in different polar environmental compartments, and how this relates to concentrations found in non-polar regions.

3.3.4 Biota compartments

Fish are by far the most studied class of organisms in the marine environment in terms of microplastic occurrence. Outside of fish species, there are a relatively small number of studies quantifying microplastic concentrations in other pelagic and benthic species, with benthic species such as mussels and oysters also represent common human food species. The microplastic concentration range estimated for fish species is 3×10^{-2} – 7.2 kg^{-1}, with an average concentration of 1.46 kg^{-1}. This is approximately an order of magnitude higher than the concentration range (2.5 $10x^{-3}$ – 0.44 kg^{-1}) and average concentration (0.16 kg^{-1}) estimated for other 'non-fish' pelagic organisms. Interestingly, the variation in microplastic concentrations is only two orders of magnitude for both groups, indicating consistency across species. Although the number of studies relevant to 'non-fish' pelagic organisms is much lower than the number of studies used to estimate the equivalent range for fish, the numbers indicate that fish species may take up microplastic more readily than other pelagic organisms.

There also remains a relatively small number of studies reporting the concentrations of microplastic in benthic organisms (Table A9). The microplastic concentration range estimated for benthic species is 12 – 10600 kg^{-1}, with an average concentration of 1724.44 kg^{-1}. This is approximately 3 orders of magnitude higher than the average concentration estimated for fish (1.46 kg^{-1}) and approximately 4 orders of magnitude higher than the average concentration estimated for 'non-fish' pelagic organisms (0.16 kg^{-1}). Although the variation in microplastic concentrations is slightly higher at 3 orders of magnitude, this may reflect the inclusion of filter feeders and true sediment dwellers within this group of organisms. Crucially, the estimated average concentration of microplastic in benthic organisms suggests that these species are exposed to, and ingest, much higher quantities of microplastic than fish species and other pelagic organisms. It may also reflect different feeding strategies and food size ranges for these benthic species compared to fish and other pelagic species. Organisms such as mussels and oysters actively filter small particulate material from the water column, while sediment dwelling worms process enormous quantities of inorganic sediment particles.

A 2009 paper in Science estimated, for the first time, the total world fish biomass as somewhere between 0.8 and 2.0 billion tonnes (average 1.4 billion tonnes)[88]. If we simply convert the microplastic concentrations determined in pelagic fish from the number of particles kg^{-1} to the number of particles tonne^{-1}, and multiply by 1.4 billion, we can crudely estimate that the total number of microplastic particles in the worlds fish ranges from 4.2 x 10^{10} and 1.0 x 10^{13}. We were unable to find estimated values for the global biomass of benthic organisms and other pelagic species, so we are unable to generate global microplastic values for these environmental compartments/biota groups.

3.3.5 General comparison

This section attempts a comparison of the different environmental compartments based upon the estimated concentration ranges and averages shown in Table 1 and the estimated total number of microplastic particles present in key environmental compartments (summarised in Table 2). The estimated concentration of microplastic in all sediment compartments is orders of magnitude higher than the estimated concentration of microplastic in marine waters (surface water and water column). The lowest average concentration reported for any sediment compartment (deepsea: 69.78 kg^{-1}) is two orders of magnitude greater than the average concentration reported for global surface waters (0.79 kg^{-1}), and three orders of magnitude greater than the average concentration reported for the global water column (4.2 10^{-2} kg^{-1}). The highest average concentration of microplastic estimated for sediments (coastal sediments; 473.17 kg^{-1}) is approximately three orders of magnitude greater than the average concentration reported for global surface waters (0.79 kg^{-1}), and four orders of magnitude greater than the average concentration reported for the global water column (4.2 10^{-2} kg^{-1}). While these average concentrations include a high degree of uncertainty, the differences between the two compartments are highly significant and support the mechanism of sedimentation of microplastic when released to marine waters.

Table 2. Summary of the estimated total number of microplastic particles present in key environmental compartments (minimum and maximum based on reported microplastic concentrations)

Compartment	Minimum number of microplastic particles	Maximum number of microplastic particles	Average number of microplastic particles	Minimum percentage distribution	Maximum percentage distribution	Average percentage distribution
Surface waters	1.53 x 10^{12}	2.88 x 10^{19}	**1.42 x 10^{18}**	3.1 x 10^{-3}	0.35	**0.21**
Water column	2.27 x 10^{16}	3.74 x 10^{20}	**5.61 x 10^{19}**	45.67	4.55	**8.16**
Sediments	2.70 x 10^{16}	7.81 x 10^{21}	**6.30 x 10^{20}**	54.33	95.10	**91.63**
Fish	4.20 x 10^{10}	1.01 x 10^{13}	**2.04 x 10^{12}**	8.5 x 10^{-5}	1.2 x 10^{-7}	**3 x 10^{-7}**
Total	4.97 x 10^{16}	8.21 x 10^{21}	**6.87 x 10^{20}**	100.00	100.00	**100.00**

The average concentration of microplastic in polar waters (5.50 kg^{-1}) is approximately 1 order of magnitude higher than the average concentration estimated for global surface waters (0.79 kg^{-1}) and two orders of magnitude higher than the average concentration estimated for the global water column (4.2 x 10^{-2} kg^{-1}). The average concentration of microplastic in Arctic sea ice (5 x 10^{-2} kg^{-1})

is more comparable to the average concentration estimated in the global water column (4.2 x 10^{-2} kg^{-1}), and approximately one order of magnitude lower than global surface waters (0.79 kg^{-1}) (Table 1). It has been suggested that the scavenging phenomenon that accompanies ice growth is the process driving this and that the Arctic Sea ice represents a major global sink for microplastic particles[75, 76]. The average microplastic concentrations estimated for Arctic sediments (18.55 kg^{-1}) are comparable with the values estimated for deepsea sediments elsewhere in the world (69.78 kg^{-1}), being an order of magnitude lower than the estimated values for beaches, shorelines and coastal sediments (Table 1). The microplastic quantities in Arctic deepsea sediments from the HAUSGARTEN Observatory are among the highest recorded from benthic sediments across the globe[79]. This suggests a strong transport of microplastic from source areas to polar regions where there are limited sources of microplastic. This also suggests that microplastics are already ubiquitously found around the global marine environment (though at different concentrations), which is consistent with a pollutant that is both widely used and which has also been emitted for a prolonged period.

The estimated average concentration of microplastic in benthic organisms (1724.44 kg^{-1}) compares quite closely with the concentration of microplastic estimated in coastal sediments (473.17 kg^{-1}). This is significantly higher than the average concentration of microplastic estimated for fish (1.46 kg^{-1}) and other pelagic organisms (0.16 kg^{-1}). However, the average microplastic concentration estimated for fish (1.46 kg^{-1}) compares favourably with the average concentration estimated surface waters (0.79 kg^{-1}). It is approximately 1-2 orders of magnitude greater than the average microplastic concentration estimated for the water column (4.2 x10^{-2} kg^{-1}). The estimated average microplastic concentration for non-fish pelagic species (0.16 kg^{-1}) lies in between the average concentrations estimated for surface water and the water column (0.79 kg^{-1} and 4.2 x 10^{-2} kg^{-1}, respectively).

The microplastic concentrations estimated in marine organisms (fish, non-fish pelagic and benthic) generally compare favourably with the microplastic concentrations estimated in the respective environmental compartments in which the organisms are found. In many cases, the average concentrations estimated for the 3 biota compartments are slightly higher than the estimated concentrations for their respective environmental compartment (e.g. waters or sediments). Perhaps unsurprisingly, this suggests that ingestion of microplastic by marine organisms is influenced by the concentration in their surrounding environment. It also suggests that microplastic is not accumulated in most marine organisms, as the concentrations do not appear to be significantly higher than the surrounding environmental concentrations. This is consistent with previous studies, which have shown that microplastic ingestion is typically followed by rapid excretion for most organisms, with no clear evidence of microplastic passing through the gut wall and undergoing true uptake and accumulation.

When looking at the crude estimates for the total number of microplastic particles in key environmental compartments (Table 2), we can use these numbers to tentatively estimate the percentage distribution of total microplastic particles for the minimum and maximum range values, as well as the average values. This estimation assumes a uniform distribution of particles across each environmental compartment, which we acknowledge is unrealistic. Nonetheless, it affords the opportunity to loosely estimate which of the world's environmental compartment(s) contains the majority of marine microplastic.

Although there are some differences in the percentage distributions between the minimum and the maximum values estimated for each compartment, over 99% of microplastic in the marine environment is likely to be present in either the water column or sediments (Figure 3). When the percentage distribution is calculated using average concentration values for each environmental compartment we see that over 90% is estimated to be in the world's sediments. The values support the theory that sediments act as a sink and accumulation zone for microplastic entering the marine environment. As surface waters represent a very small percentage of the total seawater volume, it is not surprising that this environmental compartment contains only a small percentage of the total microplastic load. It is also unsurprising that the quantity of microplastic estimated to be present in fish is very small compared to the water column and sediments. However, it should be noted that the number of microplastic particles present in marine biota is only represented by fish species and that no other marine organisms are considered in these estimates. As a result, the percentage of microplastic particles in biota may be considerably higher, but it is proposed that that the total global marine biomass (at least that capable of ingesting microplastic) is almost negligible compared to the total amount of seawater and sediment mass.

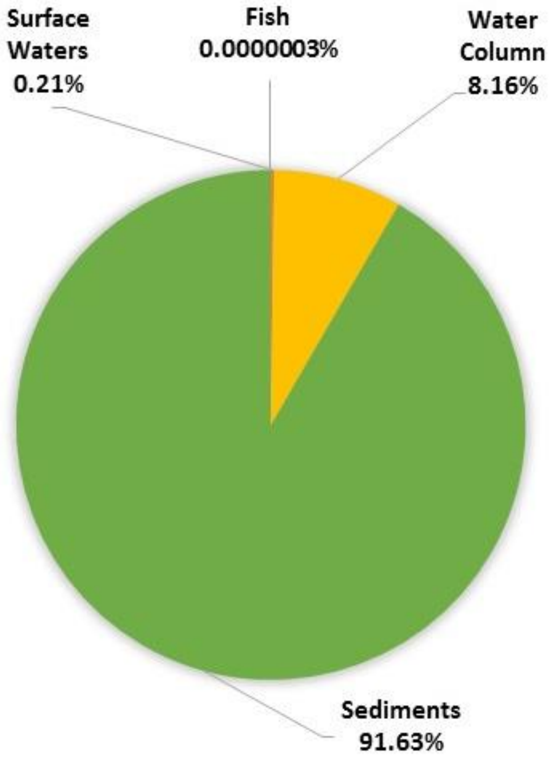


Figure 3. Percentage distribution of microplastic in global environmental compartments.

It is also important to stress how much uncertainty there is in reaching the values presented in Table 2. The first level of uncertainty comes from the raw data published in each of the studies used as the basis for this report. In addition, we have made many assumptions and generalisations to allow us to calculate and convert the data into a common SI unit for comparison. We then had to introduce another level of uncertainty when estimating global quantities of microplastic in different environmental compartments. Unfortunately, it is not possible to calculate the levels of uncertainty in the estimated values. Therefore, more data is necessary to confidently estimate global microplastic concentrations and distributions. **It is important to view the numbers estimated in this report for what they are; a simplified understanding of global microplastic concentrations and distributions in the marine environment.**

3.4 Distribution of microplastic in the Norwegian marine environment

3.4.1 Values reported in the literature

In 2014, a report by the Norwegian Environment Agency acknowledged major knowledge gaps concerning plastic litter in the Norwegian marine environment, and recognised that levels of microplastic pollution in this area were virtually unknown[44]. In the period since 2014, detailed literature searches, which were conducted specifically for this report and another recent report[45], have identified a slowly growing body of data related to the distribution of microplastic in the Norwegian marine environment. These sources of data included peer-reviewed publications, reports, theses, and conference presentations. Most of the available literature is in the form of reports and has therefore not been subject to a peer-review process. A recent report has provided a comprehensive review of the available data for macro- and microplastic in the Nordic environment (Norway, Sweden, Denmark, Finland, and Iceland)[45]. The report includes the coastal areas of Norway, but also studies from the Baltic Sea and the southern regions of the North Sea. We have included only data specific to the Norwegian environment in this report and refer the reader to the report by Bråte et al.[45] for a detailed overview of the broader Nordic region.

Despite a slight increase in the number of studies reporting on the concentrations of microplastic in different compartments across the Norwegian marine environment, the amount of data remains extremely limited. This lack of data means that it is impossible to present an accurate estimate of microplastic pollution. However, we have utilised what is available to try and look at how the few reported values compare to the global values presented in Sections 3.2 and 3.3. As with the global data, some studies could not be included as they did not report concentrations of microplastic.

3.4.1.1 Norwegian surface waters and water column

Despite an extensive literature search, there appears to be virtually no reported data concerning microplastic concentrations in marine water samples (surface or water column) from the Norwegian coastal region. A pilot study performed in 2010 and 2011 investigated the occurrence of anthropogenic particles (between 10 and 500 µm) in Norwegian waters (Skagerrak between Arendal and Hirtshals).[89] Although microscopic litter (not separated as plastic particles) was found across the Skagerrak, no specific microplastic concentrations were determined, as the concentration of textile fibres and microplastic particles could not be qualitatively distinguished from the control samples. A 2011 study from Sweden collected water samples from around the entire Swedish coastline, including a small number of locations close to the Norwegian border[90]. Since microplastic data pertaining to Norwegian waters does not yet exist, , data from this 2011 Sweden report have been included in the current report (stations 1-5). The only other study reporting microplastic concentrations in Norwegian waters relates to the coastal area around Svalbard[34]. Data from this study have already been utilised in the section on the polar compartment above (Section 3.2.4), and are also included in this section focusing on Norwegian environmental compartments. In total, we were only able to identify two studies reporting microplastic concentrations in surface waters and one study reporting microplastic concentrations in the Norwegian water column[34, 90]. A summary of the reported concentrations of microplastic in Norwegian marine surface waters and water column is presented in Table B1 (Appendix 2).

When looking at the final values for all the data sets presented in Table B1 (Appendix 2), the number of microplastic particles in Norwegian marine waters ranges from 3.4 x 10^{-4} kg^{-1} to 3.2 x 10^{-3} kg^{-1}, with an average of 1.8 x 10^{-3} particles kg^{-1}. The minimum and maximum values reported are for surface waters, while the only value for the water column (2.68 x 10^{-3} kg^{-1}), lies between these two values. The values are approximately within one order of magnitude of each other.

3.4.1.2 Norwegian beaches, shorelines and sediments

There are a very limited number of studies reporting the concentration of microplastic in sediment samples (beaches, shorelines, coastal and deepsea) collected from the Norwegian marine environment. To our knowledge, there is only a single report documenting the concentration of microplastic from shorelines and beaches in Norway, which focuses on sediments collected outside of Longyearbyen in Svalbard [91]. We have only been able to find microplastic concentration data in Norwegian coastal sediments from two sources[91, 92]. The first study reports the concentration of microplastic in sediments collected in Adventfjord, close to Longyearbyen in Svalbard[91]. A second study, conducted as part of the long-term MAREANO project, has recently published preliminary microplastic concentration data for sediment samples collected from around the western and northern coast of Norway[92]. As minimal data are currently available for microplastic in Norwegian sediments, this preliminary data has been included in the current report. The data are presented in Figure 4, which shows the sampling locations and concentration ranges of microplastic in collected sediments. A summary of the reported concentrations in Norwegian shorelines, beaches and coastal sediments is presented in Table B2 (Appendix 2).

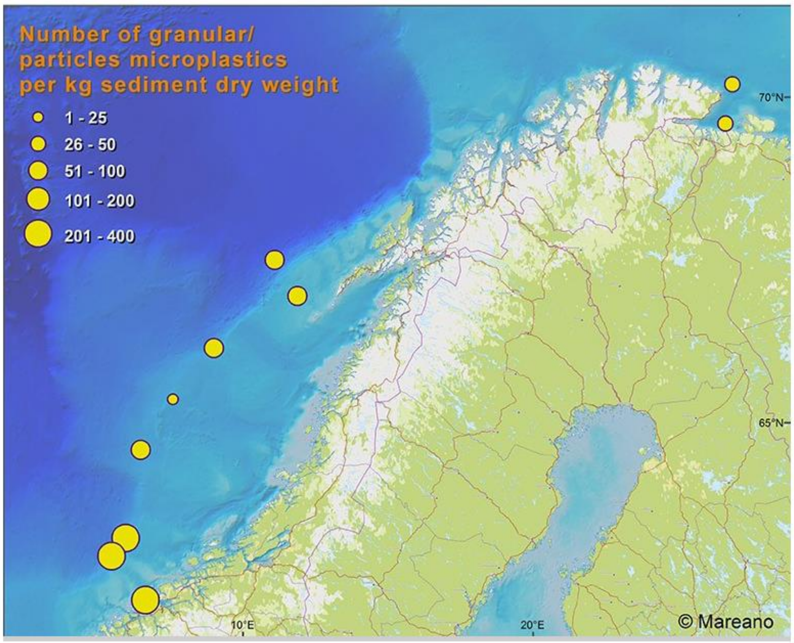


Figure 4. Map showing the number of particles per kg of sediment at sampling locations around the Norwegian coast, determined as part of the MAREANO project[92]. Map reproduced from the Geological Survey of Norway webpage (http://www.ngu.no/nyheter/mikroplast-spredd-til-havbunnen).

When looking at the final values for all the data sets presented in Table B2 (Appendix 2), we see that values for the number of microplastic particles across all Norwegian marine sediments range from 6.3 kg^{-1} to 300.5 kg^{-1}. The lowest concentration reported (6.3 kg^{-1}) is from a beach in Longyearbyen, Svalbard, while the highest concentration (300.5 kg^{-1}) is for 3 coastal sediment samples collected off the coast of the county of Møre og Romsdal. The average concentration of microplastic in coastal marine sediments is 122.62 kg^{-1}, whilst the average in beach sediments is 6.3 kg^{-1} (based on a single data point). The values are approximately within one order of magnitude of each other. It is also interesting to note that the preliminary results from the MAREANO project show a general trend of higher concentrations being present in sediments from the Norwegian Sea compared to those collected from locations further north (Figure 4)[92].

We were also able to find two MSc theses which have looked at microplastic in freshwater sediments collected from in the two main rivers (Alnaelva and Akerelva) in Oslo, Norway[93, 94]. One study[94] reports a concentration 202 microplastic particles L^{-1} (approximately 202 kg^{-1}), whilst the other study[93] reports finding 15 microplastic particles in 9 kg of sediment collected at 6 different locations (average concentration 1.7 particles kg^{-1}). However, both studies used approaches that did not allow for measuring particles under 500 µm in size and so is likely to have resulted in a significant underestimation of the true microplastic concentration. As the data is from the freshwater environment, we have not used them in the current study.

3.4.1.3 Norwegian marine organisms

A comprehensive overview of macroplastic and microplastic occurrence and ingestion by Nordic species has been presented in a recent report.[45] The report presents all known data for the Nordic regions up to and including 2017. Here, we summarise the available data concerning the ingestion of microplastic by organisms collected specifically from the Norwegian marine environment. There has been a decades-long study of the ingestion of macroplastic by seabirds in Nordic regions[95, 96], and there is some limited data available concerning macroplastic occurrence in marine mammals (e.g. whales) and sharks[45]. However, there are currently no available data on microplastic distributions in such organisms. The available data on microplastic occurrence in marine organisms from the Norwegian environment is predominantly related to fish and invertebrate species. Most of the available data for microplastic in Norwegian fish comes from reports, with only four peer-reviewed publications[97-100]. In the case of invertebrates, there are only two peer-reviewed studies of plastic ingestion by invertebrates from the Nordic environment, but these specifically focus on a fjord in Denmark[101] and the Baltic Sea[100].

Microplastic concentration data for fish caught from Norwegian waters is available from three individual studies, and represents six different fish species[97, 99, 102]. Two reports include information on the occurrence of microplastic in benthic organisms collected in Norwegian waters. The first report focuses on the occurrence and sources of microplastic in sediment and invertebrates in Svalbard, presenting data for Iceland cockles (*Clinocardium ciliatum*) and Blue mussels (*M. edulis*)[91]. The second report focuses on the Snow Crab (*Eriocheir sinensis*) collected near Varangerhalvøya[103]. Approximately 20% of crab stomachs contained plastic, but it is not stated if this is macro or microplastic, and the quantities were not reported. Finally, the preliminary microplastic concentration was reported in lugworms (*A. marina*) collected from Byfjorden (Bergen, Norway) has been presented at a scientific conference[104]. This study also reports microplastic in a range of other polychaete species, *Malacoceros fuliginosus*, *Chaetozone jubata*, *Pectinaria belgica*, *Terebellides stroemi*, *Pista cristata* and *Pectinaria auricoma*, but concentrations have not yet been published. There do not appear to be any studies investigating the occurrence of microplastic in 'non-fish' pelagic organisms. A summary of the reported concentrations of microplastic in marine organisms collected from Norwegian waters is presented in Table B3 (Appendix 2).

Microplastic particles in fish species caught in Norwegian waters ranged from 0.5 kg^{-1} to 2.5 kg^{-1}, with an average of 1.14 kg^{-1}. The minimum and maximum values are approximately within one order of magnitude of each other. The lowest microplastic concentration reported is common to three different fish species, Atlantic cod (*Gadus morhua*)[97], haddock (*Melanogrammus aeglefinus*)[99] and horse mackerel (*Trachurus trachurus*)[99], while the highest concentration is reported for *G. morhua*[102]. In the study presented by Foekema et al., 2013[99], no microplastic was observed in Atlantic mackerel (*Scomber scombrus*) or Gray gurnard (*Eutrigla gurnardus*). Norwegian values for the number of microplastic particles in benthic species ranges from 0 kg^{-1} to 950 kg^{-1}, with an average of 483.33 kg^{-1}. The values do not show any significant difference from each other. Of the benthic species for which there is data available, microplastic was only found in *M. edulis* and *A. marina*, with none observed in *C. ciliatum*.

3.4.1.4 Norwegian fjords

Although there are a small number of studies currently ongoing in Norway[33, 105], to date there are no detailed reports into the concentration of microplastic in Norwegian fjord systems. A report by Sundet et al.[91], presents microplastic concentrations for a small number of sediment and biota samples collected from Adventfjord, Svalbard. One ongoing study has begun to quantify microplastic in sediment and biota, in a sampling gradient from the discharge sites for untreated sewage to the deep hollows in the urban Byfjorden in Bergen, Norway (https://web.whoi.edu/ocean-outlook/microplastic-in-a-norwegian-urban-model-fjord-2/). Preliminary findings show coloured fibres in some species of polychaeta (sediment dwelling worms) at the investigated discharge points and the deep sites in the urban fjord, but to date no detailed microplastic concentrations have been published.

Outside of Norway, a small study conducted in Limfjord, Denmark reported that a sample of five mussels (*M. edulis*) contained no microplastic[101]. The only other documented report of microplastic concentrations in fjord systems is an MSc thesis from Canada[106]. In the thesis, samples were collected in both an urbanised (Puget Sound, Washington State, USA) and a non-urbanised (Nootka Sound, Vancouver Island, British Columbia, Canada) both north-eastern Pacific Ocean fjord estuaries. The average microplastic concentrations at the surface ranged from 0 - 102 particles m^{-3}, from 0 - 44 particles m^{-3} at 5 m depth, and from 0 - 5300 particles m^{-3} at 10 m depth. This suggests deepwaters and sediments in fjord systems may act as sinks for microplastic. Microplastic fibres had a higher concentration at most sampling points than those in pellet or fragment form.

3.4.2 Relative distributions of microplastic at the Norwegian scale

Using these data presented in Appendix 2 and summarised in Section 3.4.1 above, we have attempted to estimate the relative distributions of microplastic in the different environmental compartments. The aim of this section is to identify which of the environmental compartments contain the highest concentrations of microplastic currently present in the Norwegian marine environment. Table 3 summarises the microplastic concentration ranges estimated for the different marine environmental compartments in Norway and highlights the level of variation by showing the number of orders of magnitude between the lowest and the highest concentrations for each compartment. The data in Table 3 indicate that the differences in microplastic concentrations within individual environmental compartments are quite small. These data also show differences and similarities between the different environmental compartments; however, it is very important to note that these numbers are based on an extremely limited set of studies.

Table 3. Summary of the Norwegian average minimum and maximum microplastic concentrations reported for each of the main environmental compartments

Environmental compartment	Minimum concentration (particles kg^{-1})	Maximum concentration (particles kg^{-1})	Order of magnitude across range	Average concentration (particles kg^{-1})
Surface waters	3.4×10^{-4}	3.2×10^{-3}	~1	1.8×10^{-3}
Water column	2.68×10^{-3}*	2.68×10^{-3}*	-	2.7×10^{-3}
Beaches and shorelines	6.3*	6.3*	-	6.3*
Coastal sediments	9.2	300.5	~2	122.62
Fish species	0.5	2.5	~1	1.14
Benthic species	0	950	-	483.33

* Single data point, so no variation can be estimated.

From Table 3 we can see that the concentration of microplastic reported in surface waters and the water column are all within an order of magnitude of each other (range: 3.4×10^{-4} - 3.2×10^{-3} kg^{-1}). Although this indicates similarity between surface water and the water column, this is based on data from only two different studies and cannot be considered representative of concentrations across the entire Norwegian coastal environment. Only two studies report microplastic concentrations for sediments from the Norwegian marine environment. One of the studies contains preliminary data from nine separate locations around the Norwegian coast, while the other study presents data from Svalbard. As a result, these data offer a small insight in the distribution of microplastic in Norwegian sediments. The microplastic concentration ranges from 6.3 particles kg^{-1} in beach sediment from Svalbard, to approximately 300.5 kg^{-1} in sediment samples collected off the coast of Møre og Romsdal. These limited data suggest that there are higher concentrations of microplastic in Norwegian sediments than in Norwegian waters, indicating sediments represent sinks for microplastic. Fish are again the most studied class of organisms in the marine environment in terms of microplastic occurrence. Outside of fish species, there are a relatively small number of studies quantifying microplastic concentrations in benthic species, and no studies into other pelagic organisms. The microplastic concentration range estimated for fish species caught in Norwegian waters (0.5 – 2.5 particles kg^{-1}) suggests a small variation between different studies and species, but this observation is based on a very small number of studies and samples and two species were found to contain no microplastic. The microplastic concentration range estimated for benthic species (500 – 950 particles kg^{-1}) also indicates minor variation, but is based on a very limited number of studies and species and one species did not contain microplastic.

The estimated average concentration of microplastic in Norwegian sediment (122.62 kg^{-1}) is approximately 5 orders of magnitude greater than the estimated average concentration of microplastic in marine waters (surface water and water column: 1.8×10^{-3} kg^{-1}). The lowest concentration reported for any sediment compartment (beaches and shorelines: 6.3 kg^{-1}) is still approximately 4 orders of magnitude greater than the highest concentration reported for marine waters. Whilst it is important to remember that the estimated concentration ranges are determined with a high degree of uncertainty and from very small data sets, the numbers support the mechanism of sedimentation of microplastic when released to marine waters. The estimated average concentration of microplastic in Norwegian benthic organisms (483.33 kg^{-1}) compares closely with the average concentration range estimated in Norwegian sediments (122.62 kg^{-1}), being within an order of magnitude. The average concentration in benthic organisms appears to be over 2 orders of magnitude greater than that observed for fish species (1.14 kg^{-1}). Interestingly, the average microplastic concentration in fish (1.14 kg^{-1}) is 3 orders of magnitude higher than that estimated for Norwegian waters (1.8×10^{-3} kg^{-1}). This may reflect the fact that seven of the eleven microplastic concentrations reported for Norwegian fish are for demersal species. Demersal fish species live and feed on or near the sediment, and may therefore be exposed to higher concentrations of microplastic than pelagic species, which live and feed in the water column.

3.5 Norwegian microplastic distributions relative to global values

Table 4 summarises the estimated average microplastic concentrations for specific environmental compartments at the global and Norwegian levels. Although the concentrations ranges presented contain significant levels of uncertainty, especially for the Norwegian values, this allows us to tentatively compare Norwegian values with global values. The average microplastic concentration estimated for Norwegian surface waters (1.8×10^{-3} kg^{-1}) is 2-3 orders of magnitude lower than the average concentration estimated at the global level (0.79 kg^{-1}). The average microplastic concentration estimated for the Norwegian water column (2.7×10^{-3} kg^{-1}) is approximately one order of magnitude lower than the average concentration estimated at the global level (4.2×10^{-2} kg^{-1}), although this is based on a single value for the Norwegian compartment. Similarly, the average microplastic concentration estimated for Norwegian coastal sediments (122.62 kg^{-1}) is comparable to the average concentration estimated at the global level (473.17 kg^{-1}). The average microplastic concentration estimated for Norwegian beaches and shorelines (6.3 kg^{-1}), is two orders of magnitude lower than the average concentration estimated at the global level (334.23 kg^{-1}), although this is based on a single value for the Norwegian compartment. The average microplastic concentration estimated for fish species caught in Norwegian waters (1.14 kg^{-1}) is comparable to the estimated value at the global level (1.46 kg^{-1}). The average microplastic concentration determined for benthic organisms from Norwegian waters (483.33 kg^{-1}) is similarly comparable to the estimated value at the global level (1724.44 kg^{-1}). Whilst it is difficult to draw any significant conclusions owing to the uncertainty in the estimated values shown in Table 4, it is very interesting to note that the limited data available for Norway appears to be generally comparable with the global average estimates for most environmental compartments. It is important to note that for certain environmental compartments (e.g. surface water, water column, beaches and shorelines), the global average concentrations are derived from ranges covering many orders of magnitude. Importantly, sediments appear to be sinks for microplastic both globally and within the Norwegian marine environment. Furthermore, benthic organisms consistently appear to have higher concentrations of microplastic than pelagic species, most likely reflecting their increased level of exposure to organisms inhabiting the benthos.

Table 4. Comparison of the average global and Norwegian microplastic concentrations reported for each of the main environmental compartments

Environmental compartment	Average concentration globally (kg^{-1})	Average concentration in Norway (kg^{-1})
Surface waters	0.79	1.8 x 10^{-3}
Water column	4.2 x 10^{-2}	2.7 x 10^{-3}
Beaches and shorelines	334.23	6.3*
Coastal sediments	473.17	122.62
Fish species	1.46	1.14
Benthic species	1724.44	483.33

* Single data point

There is no doubt that microplastic is widely distributed throughout the marine food chain. It has been found in a broad range of pelagic and benthic marine organism, including many species caught and sold for human consumption. Microplastic has been found in very small organisms, as well as some of the largest species inhabiting the world's oceans. However, there remain questions concerning the occurrence of microplastic in marine organisms. More knowledge is needed to understand clearly whether microplastic is present due to true accumulation (i.e. translocation to tissues and organs) or whether its presence is transitional (i.e. present temporarily in the digestive tract). There appears to be limited evidence of larger microplastic particles traversing the gut walls of most species, a process considered necessary for true accumulation by an organism. However, there are limited data for very small microplastic particles (and nano-sized plastic particles), which may pass through biological barriers more easily.

3.6 Knowledge gaps

Here we provide a summary of the knowledge gaps that we believe are currently preventing an accurate assessment of microplastic distributions in the Norwegian marine environment. As we have seen in the sections above, the most critical knowledge gap is the lack of data concerning the concentration of microplastic in different marine environmental compartments. For some environmental compartments (e.g. non-fish pelagic species), there is simply no data available at the Norwegian level. For the others (surface waters, water column, shorelines, coastal sediments, fish, benthic species), there is currently insufficient data for an accurate determination of environmental concentrations in the Norwegian marine environment. There remains an urgent need for more information about microplastics concentrations in all environmental matrices along the Norwegian coast, although several projects by Norwegian institutions are ongoing and may contribute to this knowledge gap. In line with the generation of new data, an efficient system for compiling new and existing data is necessary, so that it may be archived and utilised more readily in the future. Furthermore, we are currently lacking sufficient data in Norway to be able to reliably comment on how the concentrations of microplastic change over time. From a monitoring perspective, there needs to be recurrent sampling of locations to document potential changes in concentrations over time. Furthermore, the relative concentrations of plastic and microplastic at the same location have been found to vary significantly over time and can be influenced by natural events such as storms[56]. Documenting these differences and variations in different locations will assist the accuracy and understanding of plastic concentrations.

One of the biggest issues regarding current data on the occurrence and accumulation of microplastic in marine environmental compartments is the accuracy and comparability of the reported data. Some degree of standardisation is necessary with respect to collecting environmental samples, processing of samples and analysing microplastic content. Already at the sample collection stage, we see that there is a broad range of approaches and equipment used to collect samples which influences the quality of the final data generated. From a monitoring perspective, it is important that all data produced is comparable. It has been shown that studies relying solely on visual identification of microplastic in environmental samples may significantly overestimate the plastic load [107]. Future studies and monitoring regimes should therefore aim to implement methodologies that minimise the uncertainty in microplastic identification, e.g. use of instrumentation that is capable of unequivocally identifying microplastic particles from other naturally occurring particles. As a result, it is recommended that all future studies and monitoring approaches employ diagnostic characterisation techniques such as Fourier transform infrared spectroscopy (e.g. ATR-FTIR and µFTIR) and pyrolysis GC-MS techniques. Furthermore, the high proportion of microfibres reported in an increasing number of studies, suggests that this group of microplastic particles should be a focus in future research and monitoring activities. Until recently, many studies highlighted the presence of microfibres in environmental samples, but had problems quantifying them due to contamination issues (e.g. from clothing or dust in the laboratory). Contamination will remain a challenge in the analysis of microplastic in environmental samples, especially in environmental samples that contain low concentrations of microplastic.

The number of plastic fragments in the marine environment is considered to increase almost exponentially with decrease in particle size[6, 9-11]. Sea surface water and water column samples are typically collected using in-field filtration techniques (e.g. manta trawl nets and bongo nets) with a minimum pore size of 300 µm, which has the potential to miss a considerable proportion of microplastic with particle size <300 µm. It is difficult to collect such small particles from marine waters as the filtration requires a very small pore size that will also collect any other natural particulates and organisms (e.g. algae and zooplankton) that are of a comparable size. Furthermore, separating, recovering and characterising such small particles from complex sample matrices such as sediments and biota presents a big challenge. Measuring the concentrations of such small particles in environmental samples is therefore very difficult, time consuming and expensive. As a result, the concentrations of low micron-sized plastic particles (<300 µm) and nanoplastic particles in the environment are virtually unknown at present. This means that we are potentially missing data and knowledge about the bulk of the particles in the marine environment (in terms of particle number). It is unlikely that such particles will be included in monitoring programmes in the near future, but methods for estimating their concentrations based on empirical data for large microplastic particles may serve to address this knowledge gap. One approach may be to use microplastic (>300 µm) concentrations as a proxy for estimating the concentrations of smaller particles, but this requires methodology development.

While current expert reviews suggest that microplastic in fish and shellfish pose a negligible risk to human health, it has been proposed that consumption of food items contaminated by microplastic may facilitate the transfer of plastics-associated chemicals (e.g. plastic additives and pollutants) to humans. However, further knowledge is required about this process, and it remains to be conclusively proven. It is also important to note that the degradation processes that generate microplastic from macroplastic debris are also considered to produce smaller and smaller fragments, ultimately forming nanoplastic. There is increasing evidence from the large body of research into the environmental and human health studies of nanoparticles, that they are sufficiently small to traverse the gut wall in many species. Therefore, knowledge is urgently needed on the exposure, uptake, accumulation and hazards associated with nanoplastic and organisms.

4 Degradation of plastic in the marine environment

4.1 Introduction

Degradation is an irreversible process leading to a significant change in the structure of a material, typically characterised by a change of properties (e.g. integrity, molecular mass or structure, mechanical strength) and/or fragmentation, affected by environmental conditions[108]. The degradation of plastics is highly influenced by polymer composition and the presence of additives, and can proceed by either abiotic or biotic pathways[109]. Generally abiotic degradation precedes biodegradation, and is initiated hydrolytically (water) or by UV-light (sunlight) in the environment. The kinetics of polymer degradation in the environment depends on the specific combination of conditions in that environment: oxygen concentration, water chemistry, temperature, presence of other chemicals, sunlight (UV), degrading microorganism community dynamics[110]. Figure 5 illustrates the degradation process of plastics in the marine environment.

Most plastics degrade first at the polymer surface, which is exposed and available to UV, chemical or enzymatic attack. This process is also known as surface erosion. In the course of the degradation process macroplastic will disintegrate into smaller and smaller pieces, i.e. meso-, micro- and nanoplastic, ultimately forming polymer fragments. This fragmentation of macroplastic into increasingly smaller pieces is an indispensable part of the degradation process, caused by the material becoming brittle during degradation and losing its physical integrity. Due to a higher surface to volume ratio, the degradation of microplastic proceeds faster than meso- and macroplastic[4]. It is still uncertain how fast macroplastic is transformed into microplastic through degradation processes (e.g. photodegradation, mechanical, hydrolysis and biodegradation)[12]. At a certain point in the degradation process, when the material properties and environmental conditions are appropriate, biodegradation will start. Microorganisms will then convert the already degraded polymeric material into methane, CO_2 and water. This conversion is called mineralisation and represents the endpoint of the degradation process. There is currently a need for greater understanding of the long-term, natural weathering of microplastic and the variables that influence the weathering process[8, 111]. Knowing how microplastic particles weather (i.e. degrade) is important for understanding the ecological impacts of the most common type of marine debris.

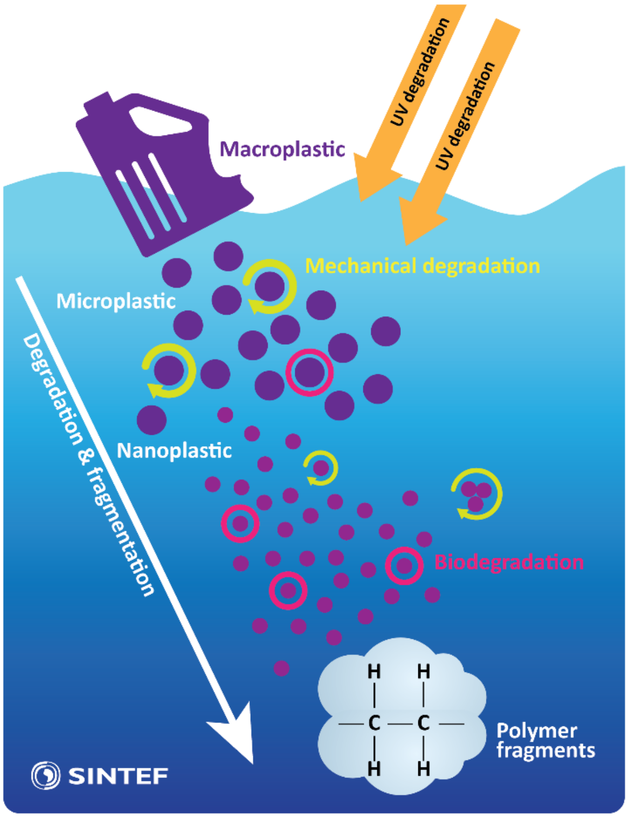


Figure 5. Overview of the main degradation processes and the fragmentation of plastic items in the marine environment.

In general, plastics in the marine environment will ultimately enter one of three different marine environmental compartments; the sea surface, the shoreline, and the seabed. In which environmental compartment a material ends up depends primarily on its buoyancy and the point it enters the environment (e.g. at sea vs. onshore). Furthermore, the surface of plastic rapidly becomes coated with inorganic and organic compounds and biofilms when immersed in seawater. This process may alter the overall material density and cause floating plastic objects to sink. The environmental conditions in each of the marine zones are different with respect to temperature, light, oxygen, and biota. Hence, the conditions for degradation of plastics are very different. In general, lower temperatures, less oxygen, less light and less biota will slow down the process of degradation. In addition to the various environmental factors, the degradation of plastics is also influenced by additives incorporated in the plastic material, such as fillers, pigments, and antioxidants. Hence, the degradation process of plastic is complex and therefore difficult to predict. Numerous studies of the degradation behaviour of various plastics under different environmental and laboratory conditions have been conducted in recent years[4, 110, 112-115]. Here we conduct a thorough review of the available literature with the goal of identifying the main degradation pathways of macroplastic into microplastic/nanoplastic in the ocean and coastal zones. We will also attempt to estimate degradation rates under typical Norwegian climatic conditions. Furthermore, we will conduct a preliminary assessment of new-generation plastic materials with oxo-degradable and biodegradable properties for their potential to mitigate or contribute to the problem of microplastic pollution in the marine environment.

4.2 Degradation pathways of macroplastic into microplastic and nanoplastic

Plastics can degrade through many different degradation pathways, acting either consecutively or simultaneously. Importantly, plastics can be fragmented through physical forces, which typically play a key role in the early stages of other degradation processes.[116] This section will review the current literature and knowledge regarding the main degradation mechanisms for plastics in the marine environment (ocean and coastal zones). This review will focus on both abiotic and biotic pathways:

- Photodegradation
- Hydrolysis
- Mechanical degradation
- Thermal degradation
- Biodegradation

4.2.1 Photodegradation

Photodegradation, also called photo-oxidative degradation, occurs when plastics are exposed to UV radiation (usually sunlight in outdoor exposure) and oxygen. To be able to absorb light energy and thus start the reaction, the polymer structure of the plastic must contain unsaturated chromophoric groups. However, in most cases it is not the polymer chain itself absorbing UV light, but additives and impurities such as pigments and catalyst residues. The photodegradation mechanism of polymers is highly dependent on the type and concentration of chromophores present[117]. This degradation pathway often triggers an auto-oxidation reaction, which follows a free radical mechanism containing three steps; initiation, propagation and termination. In the initiation step, free radicals are formed when UV light is absorbed by the material. These primary radicals can then react with oxygen to form peroxy radicals, or more complex radicals. During the propagation step, peroxy radicals extract hydrogen from the polymer by breaking C-H bonds and thus form new alkyl radicals. The propagation ultimately leads to chain scission or crosslinking, which reduces the molecular weight of the polymer and widens the molecular weight distribution. The last step, termination, will occur when two radicals combine to an inert product, and the propagation stops. The termination step can form and introduce new functional groups, such as olefins, aldehydes, ketones and carboxylic acid. These groups are even more susceptible to photoinitiated degradation and therefore accelerate the plastic degradation process. Introduction of carboxylic and hydroxy groups during the oxidation process will also increase the hydrophilicity of the polymer, making it more available for biodegradation.

Polymer additives such as UV stabilisers are used to prevent photodegradation and guarantee a certain service life of a plastic material. In contrast, pro-oxidants are used to increase the rate of degradation in so-called oxo-degradable plastics. Photodegradation will reduce the polymer size and increase the chance of further degradation. Albertsson et al.[118] described a photodegradation study of PE over 10 years in an inert system. It was discovered that the degradation rate of PE was not constant over time, but characterised by three different steps. The first step involves a constant rate of degradation and depended on the environment. In this step, CO_2 is evolved, oxygen uptake is rapid and a rapid change of the mechanical properties of the material was observed. This change occurs until a certain equilibrium is achieved. The second step involves a parabolic decline of the degradation rate and showed low evolution of CO_2, low oxygen uptake and small changes in the mechanical properties, crystallinity and molecular weight. The third step indicated a rapid deterioration of the structure and the degradation rate increased again, but the mechanical properties appeared already lost due to the final collapse of the structure. This study was performed on PE and other polymers may behave differently and not necessarily go through all three steps. However, they might show the same trend with a non-linear degradation rate even in an inert environment. For most polymers, 10 years is a very short time with respect to degradation and in the study by Albertsson et al.[118], only steps one and two could be clearly observed. In a natural, non-inert environment, the degradation rate is expected to be even more complex.

In the marine environment, photodegradation occurs widely at the sea surface, in shallow waters and on shorelines, where oxygen and sunlight (UV) is readily available. In the water column and on the seafloor below the photic zone, there is no UV and oxygen concentrations are typically low, meaning the photodegradation process will stop entirely. Certain plastic products with a high buoyancy, such as empty bottles, containers and Styrofoam, will have rather long residence times at the sea surface, thus experiencing a higher degree of photo-oxidative degradation. In contrast, less buoyant products and plastic materials will sink relatively quickly to the seafloor where the photodegradation stops due to the lack of UV light. Furthermore, the formation of a biofilm on the surface of the floating plastic material may increase its density and promote sinking, but also shield the plastic surface from UV light, reducing the rate of photodegradation.

4.2.2 Hydrolysis

Hydrolysis is the process where the polymer material reacts with water and results in a physical change of the polymer chains by splitting them into two. Hydrolysis is catalysed by acid, base or enzymes, and is not limited to the plastic surface as the water can penetrate the bulk material. For the acid-base catalysed reaction, the mechanism involves a nucleophilic attack (of water or hydroxyl ion) on the carbon of the carbonyl group in for example esters or amides (Figure 6)[119]. In aqueous base solutions, the hydroxyl ion will be a better nucleophile than water, and the carbonyl group will be protonated to promote attack at the carbon. The product will in both cases be a compound with a carboxylic acid group.

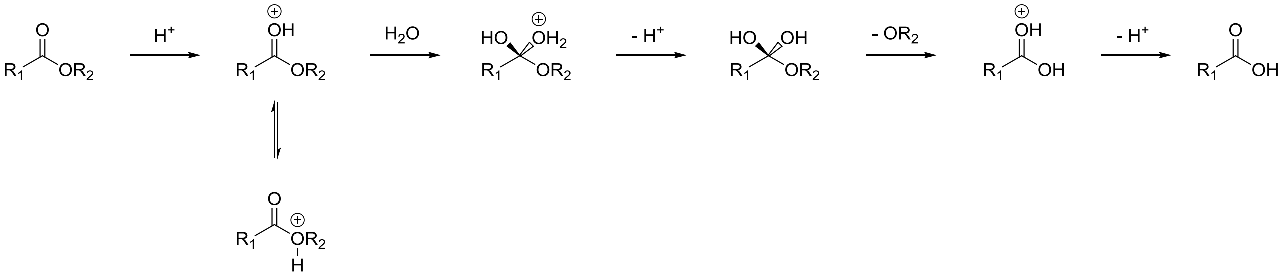


Figure 6. Mechanism of acid-catalysed hydrolysis of an ester.

There are many factors that affect hydrolysis, with bond stability being one of the most important. The more labile (i.e. more likely to undergo change or breakdown) the bonds, the faster the hydrolysis process proceeds. If there is a possibility for different resonance stabilised intermediate structures, the hydrolysis rate would decrease. Hydrolysis typically decreases with increasing hydrophobicity or increasing molecular weight of the polymer. In general, the more crystalline the structure is, the slower the hydrolysis, and the opposite for a more porous structure where the water can more easily penetrate in to the material. In addition, the hydrolysis will decrease when the mobility decreases, for example at the point the glass transition temperature (T_g) is reached. Polymers such as PE and PP are not susceptible to degradation by hydrolysis, while those containing an ester or amine group (PET, PU) are. However, the hydrolysis of PET is slow due to the stabilising effect of the aromatic ring, where electrons from the ring make the carbonyl carbon less attractive for nucleophilic attack. Hydrolysis is autocatalytic, but the relative rate is much slower than for photodegradation. As seawater pH is generally considered neutral (pH 7.5 - 8.4), no strong acidic or alkaline conditions are present and so any hydrolysis is slow. However, the further the degradation process proceeds, and the more polymer chains that are cleaved, the more carboxylic acid groups are formed. This decreases the pH locally within the material and increases the hydrolysis rate[119].

4.2.3 Mechanical degradation and abrasion

When plastic materials enter the marine environment, they can undergo mechanical fragmentation by external forces as well as abrasion from sand and stones due to wave and tidal forces. This mechanical fragmentation leads to the formation of smaller pieces of plastic. Unlike many other degradation mechanisms, no specific chemical bonds are broken during mechanical degradation. Importantly, oxidative and hydrolytic degradation processes lead to a reduction in the molecular weight of the polymer chains, causing the mechanical properties of the material to change and become brittle. This embrittlement then promotes the fragmentation of the material by mechanical forces, ultimately leading to the formation of microplastic and nanoplastic fragments[1]. Factors influencing this process include the length of the polymer chain, intermolecular forces between polymer chains, and polymer crystallinity. In addition, the impact of mechanical forces is also effected by the mechanical stability and weight of the plastic items. Styrofoam items, for example, will, though lightweight, fall apart rather quickly due to their low mechanical stability, whereas fibres and microplastic particles will be less effected due to their flexibility and very low weight.

4.2.4 Thermal degradation

Thermal degradation of plastics generally occurs at elevated temperatures (i.e. >100 °C), usually close to the melting point of the specific polymer type, and is therefore important during manufacturing. In general, plastics contain antioxidants to prevent thermal oxidation. At moderate temperatures, thermal degradation proceeds via a very slow oxidative breakdown process. Under typical global environmental conditions, and especially the cold-temperate marine environments found along the Norwegian coast, the role of thermal degradation is considered negligible.

4.2.5 Biodegradation

Biodegradation is the disintegration of materials by the action of living organisms, mainly microorganisms, such as microbes and fungi.[120] The biodegradation of plastics in the environment has recently been comprehensively reviewed by Kruger et al, 2015[121], and this text builds on the information considered relevant to plastic pollution in Norwegian marine areas from that review. Plastics that enter the marine environment are quickly colonised by native microorganisms, giving rise to biofouling and possibly biodegradation of the material. Biofouling usually happens within the first few weeks after the plastic has entered the marine environment and this process also influences degradation pathways. Photooxidation rapidly declines with biofouling, since the biofilm formed shields the material from UV light. Furthermore, mechanical degradation may be influenced by biofouling, e.g. through organisms grazing on the surface of the plastic material and/or excreting chemicals influencing the stability of the material, thereby making it more brittle. The buoyancy of the material will also change, generally decreasing with biofouling, which may cause the material to sink rather than float in sea water.

Plastics could potentially be considered as good carbon sources, and in some cases nitrogen sources, for microorganisms. However, the most commonly manufactured plastics, i.e. PE, PP, PS, PVC and PET, are regarded as persistent (non-biodegradable) in nature[8, 12]. They proved to be especially resistant against microbial attack, since during their short time of presence in nature evolution could not design new enzyme structures capable to degrade synthetic polymers[122]. It has even been suggested that all plastic that enters the marine environment remains unmineralised[123, 124]. As biodegradation of PP, PE, PS, PVC and PET polymers, which compromise the bulk of the current marine plastic pollution, is exceedingly slow, biodegradation can be considered almost negligible in the short-term (over decades), but plays a role in the terminal fate of plastic in the marine environment (over centuries). The main reasons for the slow biodegradation of plastic are the solid nature of the substrate and inertness of very long polymer chains. These features lead to very low bioavailability of plastic, i.e. microorganisms can only access the surface of the plastic and long polymers normally cannot traverse cell membranes and enter cells, were the main metabolism takes place. The slow biodegradation makes it very difficult to measure biodegradation rates and measuring complete mineralisation (metabolic conversion to CO_2, water and biomass by aerobic microorganisms) of plastic in the environment is very challenging. Therefore, most methods focus on analysing disintegration and/or "disappearance" of plastic in samples by measuring endpoints such as mass loss of plastic or indirectly by analysing the activity of microorganisms through determination of microbial growth. It should be kept in mind that reports on biodegradation in the environment, using such indirect measurements, are to be considered only as estimates. PE and PP are the most abundant plastic types manufactured and the most common environmental plastic pollutants. Several bacteria and fungi have been shown to be capable of degrading PE and PP (reviewed in Restrepo-Flórez et al. 2014 and Arutchelvi et al. 2008)[125, 126]. However, very few studies have reported on the biodegradation of PE and PP in natural marine environments.

4.3 Factors influencing degradation processes

4.3.1 Environmental conditions

The environmental and climatic conditions in the global marine environment can vary significantly with respect to temperature, light, oxygen, and biota (microbial communities). Consequently, the potential for degradation of plastic also varies significantly, depending on which environmental compartment and geographical location it is present. In general, lower temperatures, less oxygen, less light and less biota (microbes) will slow down the overall process of degradation. The following environmental parameters relevant to the marine environment will be reviewed:

- Temperature
- Amount of sunlight
- Oxygen levels
- Water (hydrolysis)

The influence of each of these parameters are discussed below. In many cases, individual parameters often influence the degradation of plastic materials in conjunction with one or more environmental parameters. For example, UV degradation is dependent upon on the presence of both sunlight and oxygen, and can be influenced by temperature. The relative importance of each parameters will then be assessed for key environmental compartments presented in Section 4.2.

Temperature

Temperature is of relevance as it affects all chemical reactions, with abiotic degradation rates typically faster with increasing temperature. Therefore, latitudinal differences and seasonal (winter vs. summer) differences will influence abiotic degradation rates globally. Generally, every 10°C increase in ambient temperature will result in a doubling of the chemical reaction rate. Temperature also influences polymer chain mobility, which in turn influences enzyme activity during biodegradation. With increasing temperature, the chains become more mobile and thus it becomes easier for an enzyme to find and attach to the right chemical group on the polymer chain. Furthermore, the diffusion rates of oxygen, radicals, and water are influenced by temperature, which subsequently influences the reaction rates of oxidative and hydrolytic degradation. The diffusion rate increases at higher temperatures, leading to a corresponding increase in reaction rates due to (i) oxygen and water diffusing deeper into the material, and (ii) radicals diffusing further into the material before they react. These processes ultimately increase the volume of material that is effected by degradation. Temperature also has a significant impact on biodegradation rates (within the range tolerated by microorganisms), with biodegradation typically proceeding more rapidly at higher temperatures.

Amount of sunlight (UV)

The amount of sunlight is another key factor for degradation and influences photodegradation, one of the main degradation mechanisms. When other factors, such as oxygen, are not limiting, photodegradation is solely limited by the availability and exposure to UV radiation from the sun. The higher the intensity and the longer the exposure, the faster the photodegradation proceeds. The intensity of UV radiation depends mainly on the geographical position, the weather, and the seasons. Close to the equator the intensity is strongest and the amount of sunlight is high and relatively constant over the course of a year. However, in Norway and closer to the Pole the intensity of sunlight is lower and varies significantly during the seasons, being high during summer and low during winter, but never as high at the maximum at the equator. Thus, the photodegradation rates in the Norwegian environment will vary significantly over one year. Combined with the seasonal temperature changes, this results in very low degradation rates during the winter months (low temperature, low UV), especially when the sea surface or shoreline is covered with ice and snow that block the sunlight.

Oxygen levels

The availability of oxygen will affect the degradation rate of all processes that depend on oxygen being present e.g. photodegradation, which proceeds via photo-initiated oxidative degradation. Higher concentrations of oxygen typically result in faster degradation of plastic materials until another parameter becomes a rate limiting factor. The availability of oxygen also significantly influences the biodegradation rate and controls the composition of the microbial community in each environmental matrix. The Norwegian Sea and Greenland Seas are highly oxygenated, with very little vertical variation, and on intermediate depth oxygen minimum. The North Sea can have lower dissolve oxygen concentrations at the bottom compared to the surface[127].

Water

Water is an essential component for degradative processes such as hydrolysis and biodegradation. In the marine environment, water is rarely a limiting parameter, but may play a more prominent role in influencing the rate of degradation on shorelines. Water also reduces the intensity of UV light, which means photodegradation can only occur in the upper region of the water column. At the sea surface, moisture and high humidity promote light-induced degradation since soluble photo-stabilisers might leach out of the plastic matrix under high humidity, reducing the effectiveness of the light stabilisers and leading to degradation.

4.3.2 Material properties

Crystallinity

Most plastics are semi-crystalline, which means they have regions where the polymer chains are highly ordered and oriented (i.e. crystalline) and regions where the polymer chains are randomly oriented (i.e. amorphous) (Figure 7). The degree of crystallinity typically ranges from 10% to 80%[128]. The higher the degree of crystallinity of a plastic material the stronger it is, but also the more brittle it is. The amorphous regions give flexibility to a material. The crystallinity of a plastic will also influence its degradation rate. Polymers exhibiting a more rigid and compact crystalline structure will reduce the amount of oxygen and water that can penetrate and initiate the degradation process. In contrast, an amorphous structure will allow oxygen and water to enter much more readily, penetrate deeper and in larger amounts compared to a crystalline structure. Amorphous regions in the polymer are reported to be more labile to thermal oxidation compared to crystalline areas, owing to their high permeability to molecular oxygen[129]. As a result, the amorphous regions of the plastics will degrade first and more rapidly than crystalline domains.

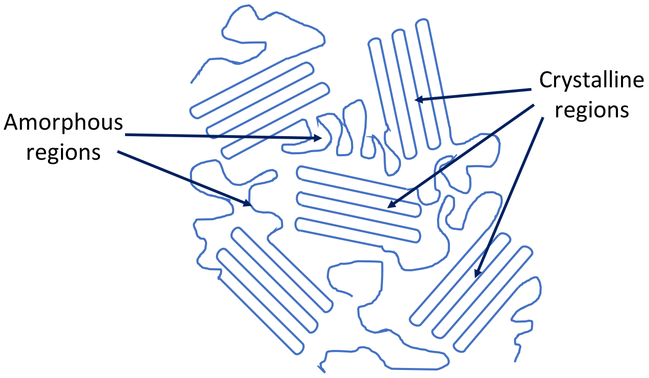


Figure 7. Crystalline and amorphous regions of a polymer.

Chemical composition

The chemical composition of the polymer plays a key role in its degradation. The influence of polymer composition will partially be discussed in the following Section (4.3.3), where there are clear differences in the susceptibility of different polymers depending on whether they contain heteroatoms in the main chain (e.g. polyamide; nylon) or have a C-C backbone. Long carbon chains, characteristic of thermoplastic polyolefins such as PE, make polymers non-susceptible to degradation by microorganisms, while incorporation of heteroatoms such as oxygen in the polymer chain (e.g. polyester) makes it labile for thermal degradation and biodegradation[109]. The presence of heteroatoms in the polymer chain affects the strength of neighbouring C-H bonds and promotes carbanion formation (i.e. anion of carbon) in the presence of a base. Linear saturated polyolefins (e.g. PE, PP) are resistant to oxidative degradation, while the presence of unsaturated C-C double bonds in the polymer chain makes them susceptible to oxidation. The oxidation rates depend on the reactivity of the peroxy radical that is formed, and on the dissociation energies of available C-H bonds in the polymer matrix. Polymers without hydrogen atoms or with unreactive groups such as methyl or phenyl show resistance to oxidation processes.

Molecular weight

The molecular weight of a polymer will also affect its degradation rate. Larger polymers typically undergo slower degradation, as they have a lower relative surface area available for degradation. Most degradation processes will occur at the surface rather than the interior of a plastic. As degradation increases with decreasing size of the molecules in a polymeric material[109], it is expected that degradation will proceed more rapidly once the process is ongoing and generates shorter fragments of polymer and small molecules.

Hydrophobicity and morphology

The hydrophobicity of the polymer influences the potential for degradation, with degradation typically decreasing with increasing hydrophobicity. Owing to the low affinity of polymers to water, the hydrolysis rate, which depends on the diffusion of water, is highly reduced. Furthermore, the hydrophobicity of plastics, such as PE, has been shown to interfere with the formation of microbial biofilms, which decreases the level of biodegradation. Photo-oxidation leads to the introduction of oxygen into the surface, reducing the hydrophobicity over time and facilitating biofilm formation. Items of plastic exhibiting rough surfaces will also provide microbes a better opportunity to attach and colonize plastic litter, which will influence the potential for biodegradation to occur.

Functionalisation

The type of chemical functionalisation exhibited by a polymer will affect the rate of degradation. For example, carbonyl groups will increase the rate of photodegradation in polyolefins as they contain chromophores (causing a colouring of the molecules).[109] The presence of higher numbers of chromophores results in more sites being available to adsorb a photon and initiate photodegradation. The presence of any metal-metal bonds in the polymer backbone will also induce photodegradability since the metal-metal bond is cleaved homolytically upon irradiation[130].

Production method

The method of production has also been shown to affect polymer stability. For example, PS formed by anionic polymerisation is more stable towards photodegradation than the PS made by free radical polymerisation. This is due to the presence of peroxide residue in the latter, which is labile for photodegradation[131]. PP made by bulk polymerisation or by Ziegler-Natta catalyst is more susceptible towards photodegradation compared to co-polymerised PP.[132]

Additives

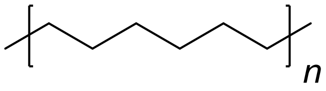
A vast number of organic and metal-based compounds are used as additives for different plastics to provide the material with specific physical or chemical properties. Theoretically, each additive can be added to modify a single parameter of a plastic, tailoring the overall material properties. Additives can be used to modify the material aesthetics (design, colour etc.), mechanical, thermal, electrical and optical performances, as well as the processability during moulding, extrusion etc.[116] They are also used to specifically modify the long-term behaviour, such as ageing (heat, sunlight, weathering, wet environment), creep, relaxation and fatigue. Since they are usually inexpensive and simple, additives are widely used and fillers are also added to reduce the overall cost of plastic materials.

Crucially, these additives are often overlooked as an important parameter in the degradation of plastic materials in the environment, and they have the potential to significantly influence plastic degradation. Many additives are added to plastics to prevent specific degradation process from occurring or to slow their progress over time to ensure a maximum service life. Typically referred to by the generic term 'stabilisers', such additives include antioxidants, UV stabilisers and antimicrobial agents which are specifically designed for their purpose. UV stabilisers absorb/capture the photon (preventing the radical being formed) and convert it to heat, preventing the initiating step in photodegradation. Examples of UV stabilisers are benzophenones, typically used in sunscreen. Antioxidants, such as the aniline group of compounds, terminate the reaction due to absorption of UV light from sunlight. As a result, these additive chemicals will delay or slow the degradation processes of plastics and contribute to their persistence when entering the marine environment. Only once the stabilisers are consumed, which may take decades, will the plastic material will start to degrade more rapidly. In contrast, pro-oxidants used in the production of oxo-degradable plastics act to decompose the material in shorter timeframes.

4.3.3 Polymer type

When considering degradation of plastic polymers, it is useful to divide them into two categories; polymers with a carbon-carbon backbone and polymers with heteroatoms in the main chain[4]. For polymers with a C-C backbone, degradation occurs mainly through photo-initiated oxidative degradation (UV radiation and oxygen) and they are resistant to hydrolysis and biodegradation. Such polymers include PE, PP, PS and PVC. In contrast, degradation of polymers containing heteroatoms in the main chain can proceed by photo-oxidation, hydrolysis and biodegradation, with all three potentially occurring simultaneously[4]. Polymers with heteroatoms in the main chain (e.g. PET, PU, and PA) have an increased stability compared to polymers with a C-C backbone. Degradation of a polymer can lead to fragments with lower molecular weight, e.g. monomers and oligomers, and new end groups such as carboxylic acids can be formed. In the following, the six most common, i.e. highest industrial volume, commodity plastics in Europe are presented with their main applications, properties, and degradation pathways.

Polyethylene (PE)



Polyethylene (PE)

PE is one of the most common polymers and about 80 million tonnes are produced globally each year. In 2015, PE (all forms) represented ~29.4% (~14.4 million tonnes) of a total annual plastics demand of 49 million tonnes in Europe[133]. High and medium density PE (HD-PE and MD-PE) are commonly used in toys, milk bottles/cartons, shampoo bottles, pipes, and general houseware products. Low density and liner low density PE (LD-PE and LLD-PE) is mostly used as packaging, reusable bags, trays and containers, agricultural film (LD-PE), disposable bags and packaging film (LLD-PE). The mechanical properties of PE include low strength, but high flexibility. Its density is between 0.88 g/cm^3 (LD-PE) and 0.97 g/cm^3 (HD-PE) and so most PE items will float at sea until their weight increases (e.g. due to biofouling). As a result of its low density, LD-PE will most likely float for an extended amount of time, which results in a longer exposure to sunlight (UV) and thus higher rates of photo-oxidation. PE has a high chemical resistance and is not readily affected by strong acids or bases, oxidising or reducing agents. PE is transparent or opaque depending on the quality and does not absorb water. The temperature resistance depends on the PE quality, with HD-PE melting at approximately 120-180°C and LD-PE melting at approximately 105-115 °C. PE degrades mainly by photo-initiated oxidative degradation. The degradation is initiated by UV radiation, which is the rate-determining step. Auto-oxidation in the propagation step forms low molecular weight fragments such as aliphatic carboxylic acids, alcohols, aldehydes and ketones (Figure 8). The process of UV degradation leads to a more brittle material, which is more easily fragmented. Microorganisms can attack PE at any terminal methyl group and biodegradation is found to be faster when the molecular weight is smaller than 500 Da[4].

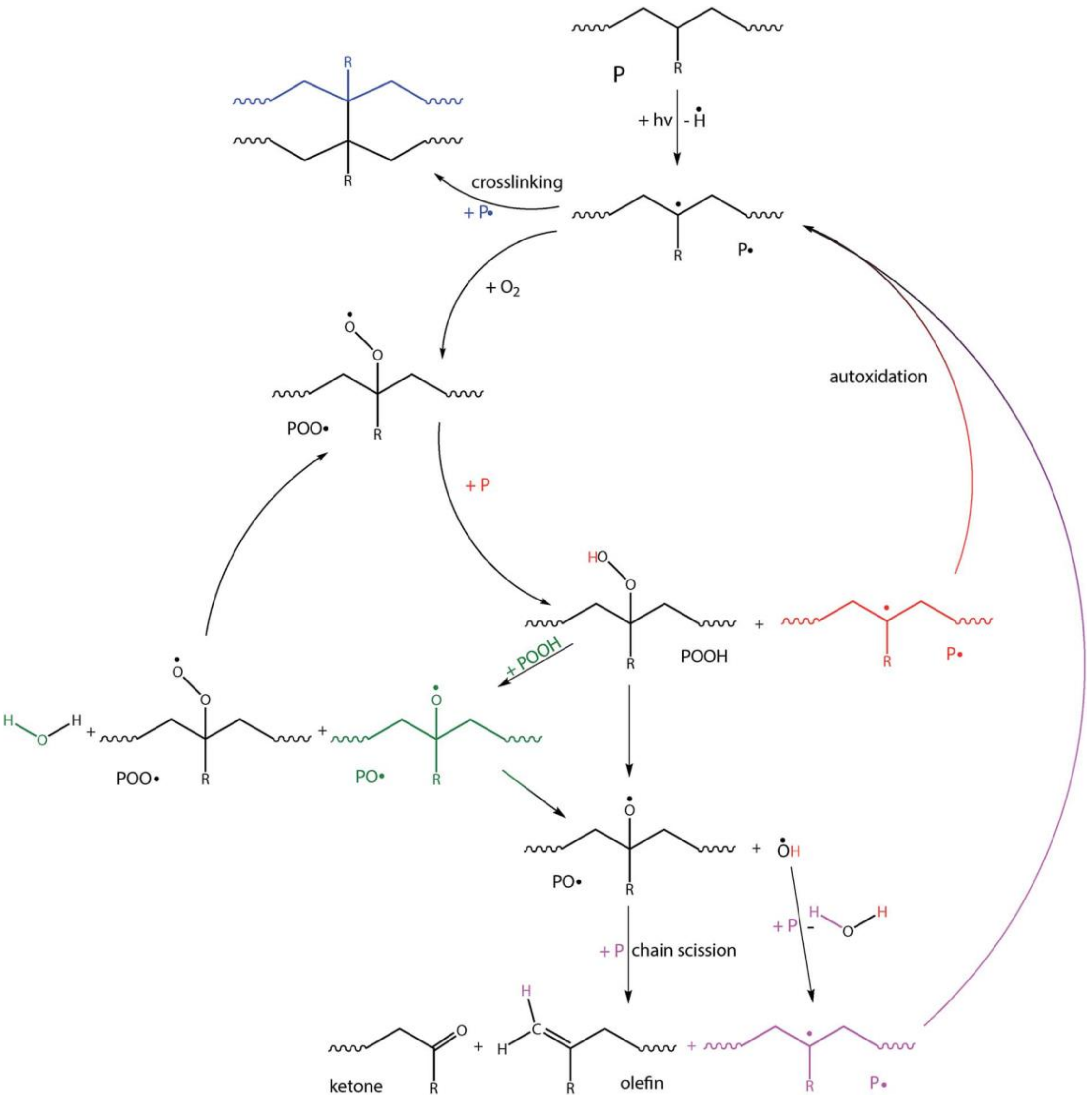
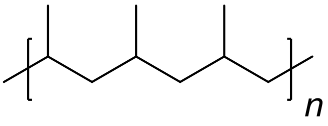


Figure 8. Abiotic degradation pathways for PE (R = H), PP (R = CH_3) and PS (R = aromatic ring); after initiation by photolytic cleavage of a C–H bond on the polymer backbone (P = polymer backbone). [Reproduced from Gewert et al.][4]

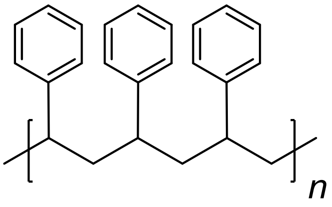
Polypropylene (PP)



Polypropylene (PP)

In 2015, PP represented ~19.1% (~9.4 million tonnes) of a total annual plastics demand of 49 million tonnes in Europe.[133] PP is a thermoplastic like PE, but has some improved mechanical properties due to the additional methyl group in the chemical structure. PP is tougher than PE, but still flexible. PP is used in packaging and labelling, textiles, ropes, pipes, automotive parts, and reusable plastic containers. The density of PP is 0.90-0.92 g/cm^3. Like PE, PP will float at sea until its weight increases due to biofouling. PP also exhibits a high chemical resistance and is therefore frequently used in laboratory equipment. The melting point of PP varies due to the degree of crystallinity, but is most commonly around 160-170°C. PP is less transparent than PE and has a slightly lower thermal expansion. Degradation of PP is also by photo-initiated oxidative degradation, via a comparable radical mechanism to that of PE (Figure 8). Radical formation in PP yields a tertiary radical (connected to three other carbon atoms), making it more stable than the secondary radical formed in PE degradation. This makes PP less stable and more susceptible to photo-initiated degradation. Formation of smaller molecular weight fragments by chain scission is predominant, which also increases the resistance to aerobic biodegradation. PP is therefore less susceptible to microbial degradation than PE.

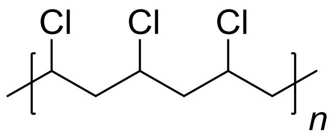
Polystyrene (PS)



Polystyrene (PS)

In 2015, PS and expanded PS (EPS) represented ~6.9% (~3.4 million tonnes) of a total annual plastics demand of 49 million tonnes in Europe[133]. PS can be made as both a solid and a foam (EPS), the latter being most commonly known by the trademarked brand Styrofoam. PS is mostly used as single use plastic cutlery, plates and cups, egg trays, whilst EPS is commonly used in packaging and building insulation. PS has a density of about 1.05 g/cm^3, which is slightly higher than sea water (~1.03 g/cm^3) and therefore will sink. Owing to its foam structure, EPS has a much lower density (~0.05 g/cm^3), which gives it a high buoyancy in water. As a result, it will float for a long time, meaning a much higher exposure to sunlight (UV) and thus higher rates of photo-oxidation. PS is more susceptible to outdoor weathering and thermo-oxidation is the main degradation pathway. Thermo-oxidation proceeds via the same steps as photo-oxidation, and differs only in the initiation step. In PS, a phenyl radical is formed by irradiation with UV-light. Cross-linking and chain scission is the result, with the formation of ketones and olefins (Figure 8). End-chain scission is known to be predominant, making styrene monomers the main volatile degradation product. PS has a much lower rate of biodegradation compared to PE and PP, and PS is considered the most resistant thermoplastic polymers towards biodegradation. As with most plastics, PS often contains UV stabilisers and anti-oxidants as additives, reducing its rate of degradation even further.

Poly(vinyl chloride) (PVC)



Poly(vinyl chloride) (PVC)

In 2015, PVC represented ~10.1% (~5 million tonnes) of a total annual plastics demand of 49 million tonnes in Europe[133]. PVC is commonly used in window frames, floor and wall covering, pipes, cable insulation and garden hoses. The density of PVC is around 1.4 g/cm^3, however hollow parts may float in the sea. PVC is significantly more susceptible to UV radiation than PE, PP and PS, meaning that photodegradation is therefore the main degradation mechanism. As PVC contains only saturated chemical bonds, impurities are required to kick-start the photo-initiation.[134] De-chlorination is the first step in the degradation process, and takes place when PVC is exposed to sunlight. The de-chlorination step leads to conjugated C-C double bonds in the polymer and the generation of hydrochloric acid (HCl) (Figure 9). Photo-induced de-chlorination occurs more quickly under aerobic conditions, when HCl is present, and for lower molecular weight polymers. De-chlorination of PVC is autocatalyzed, implying that chlorine atoms are cleaved off the macropolymer. However, the formation of C-C double bonds makes the polymer more readily photodegradable. The presence of halogens increases the resistance of PVC to aerobic biodegradation, and de-chlorination of the polymer will precede any biodegradation. PVC is often used with plasticisers, thermal stabilisers and UV stabilisers to reduce the rate of degradation.

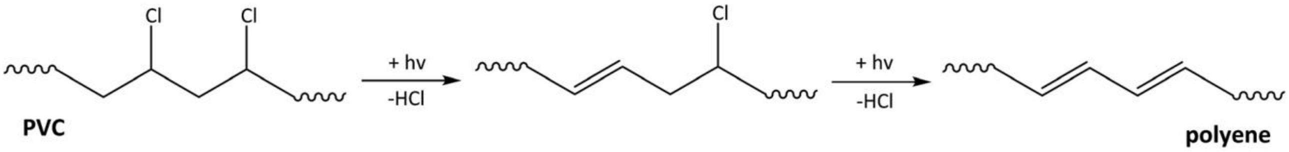
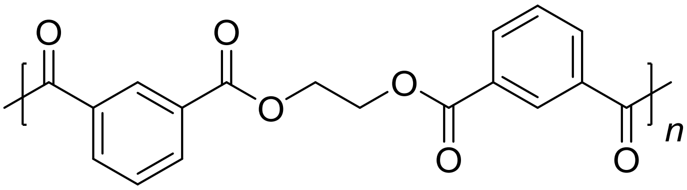


Figure 9. Dechlorination of PVC and formation of polyene. [Reproduced from Gewert et al.][4]

Poly(ethylene terephthalate (PET)



Poly(ethylene terephtalate) (PET)

In 2015, PET represented ~7.1% (~3.5 million tonnes) of a total annual plastics demand of 49 million tonnes in Europe[133]. PET is commonly used in bottles for water, soft drinks, juices and cleaners. PET has a density of about 1.4 g/cm^3, but bottles and other hollow parts made of it may float in the sea until they fracture. PET degrades mainly by photo-oxidative and hydrolytic degradation process under marine environmental conditions. The ester bond is cleaved during photodegradation, directly forming a carboxylic acid end group and a vinyl end group, or forming radicals which ultimately proceed to the formation of carboxylic end groups (Figure 10). PET can undergo photo-induced autoxidation via radical reactions, comparable to those observed for polymers containing a C-C backbone (PE, PP, PS, PVC) described above. Photo-oxidation results mainly in chain scission and formation of carboxylic end groups, which promote thermo-oxidative degradation and therefore also photo-oxidative degradation. PET is susceptible to hydrolytic degradation in water. Although hydrolysis at room temperature is extremely slow, it is still the most important low temperature degradation mechanism of PET. The rate of degradation increases under acidic and basic conditions, and is autocatalytic when carboxylic acids are present (as end groups for example). Abiotic weathering of PET in the marine environment is likely to occur predominantly by photo-induced oxidation and hydrolytic degradation processes and it is characterized by a yellowing of the material.

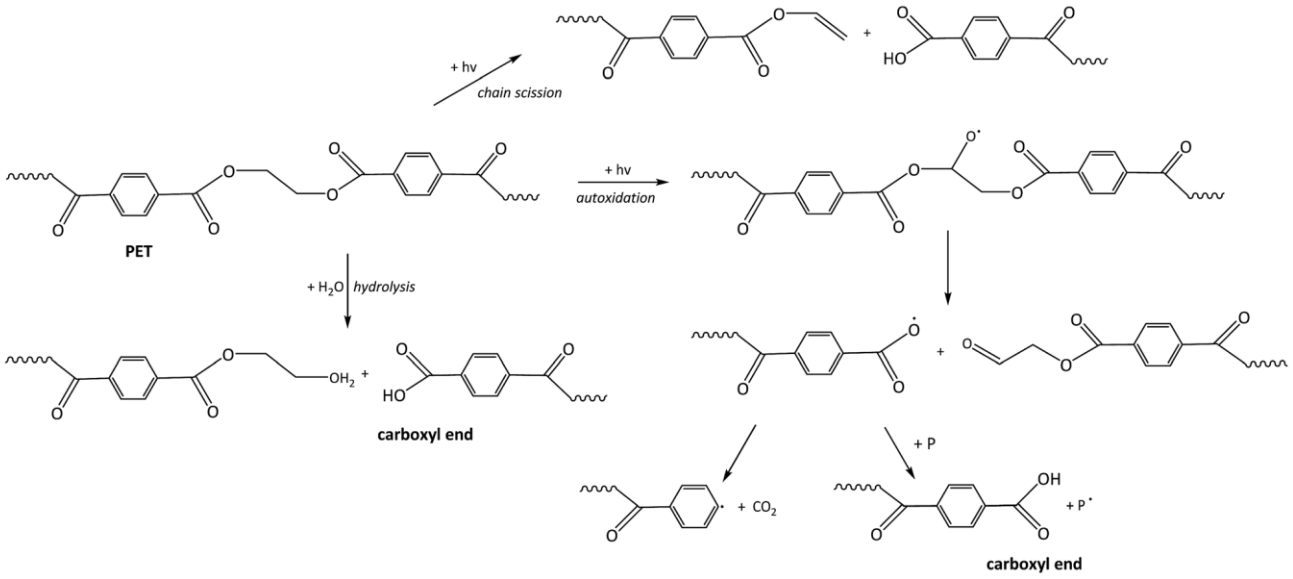
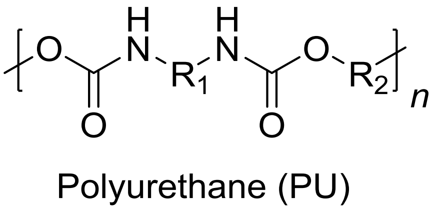


Figure 10. Abiotic degradation of PET: chain scission induced by radiation (cleavages that lead to radical formation are not shown), photo-induced autoxidation (the initiation and some propagation reactions of the photo-oxidation, which follow the same pattern as for PE, are left out to simplify the mechanism) and hydrolytic degradation. [Reproduced from B. Gewert et al.][4]

Polyurethane (PU)



In 2015, PU represented ~7.5% (~3.7 million tonnes) of a total annual plastics demand of 49 million tonnes in Europe[133]. PU is commonly used in building insulation, pillows and mattresses, and insulating foams for fridges. PU foams have very low densities (~0.05-0.1 g/cm^3) and will therefore float at sea, which leads to a much higher exposure to sunlight (UV), and thus higher rates of photo-oxidation. PU has a more complex polymer structure than other polymers, having both carbon, oxygen and nitrogen in the main chain. The ester bonds in PU are the most susceptible to degradation, with photo-oxidation, hydrolysis and biodegradation the most important degradation processes in the marine environment[4]. The photo-induced oxidation occurs at the α-methylene position, and after this photoinitiation, the radical reactions lead to hydroperoxides, and follows a similar process as for the C-C backbone polymers (Figure 8). The most prevalent hydrolytic degradation reaction is hydrolysis of the ester bond, but urea and urethane bonds can also degrade by hydrolysis but at slower rates (Figure 11)[135, 136]. The hydrolysis is accelerated by acidic conditions and this process is autocatalytic since carboxylic acids are formed. PU is well known to be susceptible to fungal biodegradation, although bacterial or enzymatic degradation are also possible, with urethane bonds or polyol segments the regions degraded/cleaved.[137-139] Microorganisms are known to degrade polyester segments more easily than polyether segments in PU. Enzymes cleave the polymer chain, but since they are unlikely to diffuse into the bulk polymer due to their size, the degradation occurs mainly on the surface, resulting in cracks.

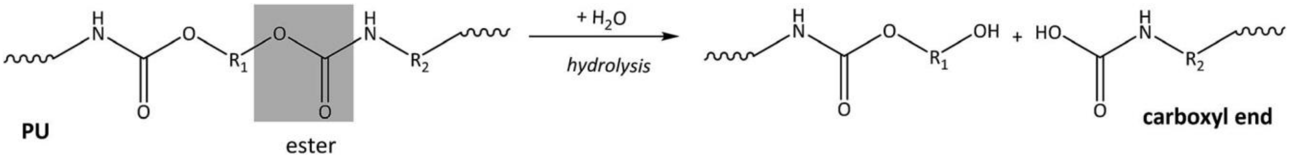


Figure 11. Hydrolytic degradation of the ester bond of PU. [Reproduced from Gewert et al.][4]

4.4 Degradation rates in the Norwegian marine environment

As illustrated in the previous sections, the degradation of plastics in the environment is extremely complex and depends on a multitude of different parameters. In addition, the degradation rate will change during the degradation process[118]. Attempts to simulate and accelerate these degradation processes in the laboratory have been made for several decades. This has helped gain an understanding of the basic mechanisms of polymer degradation, but the results are not always relevant for environmental degradation. In many cases, available studies include only a few parameters and therefore do not represent the natural environment. In contrast, field tests present relevant environmental conditions, but have several serious disadvantages. As degradation processes are very slow, fields tests require a long time and the process cannot be accelerated. In addition, parameters, such as temperature, oxygen level or UV intensity cannot be controlled, and the analytical opportunities to monitor the degradation process are limited. In most cases, it is only possible to evaluate visible changes on the plastic specimen, or perhaps to determine disintegration by measuring weight loss. However, the latter approach is problematic if the material breaks into small fragments (e.g. microplastic) that must be quantitatively recovered from the soil or water. The analysis of residues and intermediates is complicated by the complex and undefined environment[140]. For practical reasons, most studies have been conducted with macroplastic and the results cannot be easily translated to microplastic. In general, the degradation of microplastic will proceed faster than that of macroplastic, due to the higher surface to volume ratio (Figure 12). Therefore, it is almost impossible to give precise numbers for how long it will take until a certain material is fully degraded in a specific environment. However, based on field tests, rough estimates can be made and different materials as well as environmental compartments can be compared relative to each other (Figure 13).

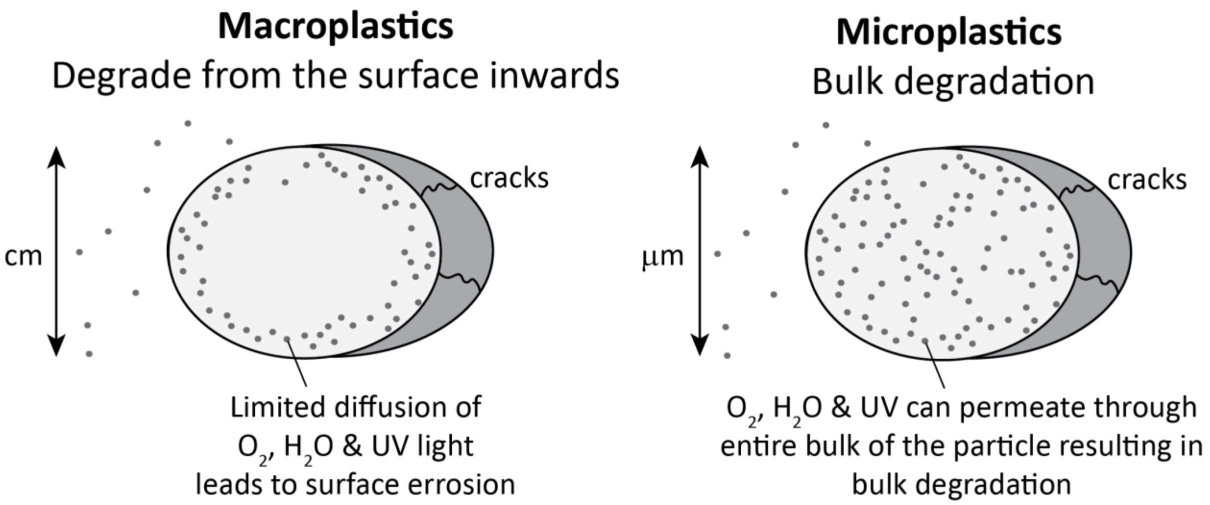


Figure 12. Influence of surface to volume ratio on the degradation of macroplastic and microplastic litter in the marine environment.

Figure 13. Estimated decomposition rates of common marine debris items (source: National Oceanic and Atmospheric Administration, U.S.).

No field studies concerning degradation rates of plastic and microplastic performed in the Norwegian marine environment could be found. However, studies in other parts of the world, such as the Baltic Sea, the Mediterranean Sea, the Indian Ocean, are available. Based on these published studies from around the world we have attempted to estimate the degradation rates of common plastics in three different marine environments under typical Norwegian environmental conditions.

Shoreline and beach

At the shoreline and beach, photodegradation, which is the main degradation process for all common plastics, will be the rate defining process, as there is plenty of sunlight and oxygen available. In addition, there is mechanical degradation due to waves and birds ripping and tearing the plastics apart as well as abrasion from sand covering and moving the plastics, causing fragmentation and cracks. Furthermore, the presence of microorganisms in the sand along the shoreline and beach will facilitate biodegradation. The temperature at the beach can be relatively high compared to the seawater, but it will also fluctuate more than the seawater. Plastics at the beach or shoreline will degrade much faster than plastics floating in the sea[141]. A study over 12 months performed in Biscayne Bay (Florida) showed a reduction of tensile strength of PP samples by about 90% when exposed in air (i.e. at the beach) compared to about 20% when floating in sea water[50]. The reduction of the degradation rate at sea is due to lower temperature and oxygen level in the water and the formation of a biofilm on the floating items, which blocks the sunlight. Both temperature and the amount of sunlight along the Norwegian coast are much lower than in Florida and will differ significantly during the year and from south to north. Hence, degradation rates will be much lower than in Florida, though higher in the south of Norway than in the north where sunlight intensity is higher.

Shallow water

Many plastic types float and will therefore be exposed to significant amounts of sunlight. For dense plastic materials that sink, photodegradation will still be one of the dominant degradation processes in very shallow waters, as the UV is able to penetrate a small distance. However, the low water temperature and the lower amount of oxygen in Norwegian coastal water, compared to the shoreline, will slow down the degradation[142]. The formation of a biofilm on the plastics surface will reduce the rate of photodegradation, but may facilitate biodegradation. Furthermore, the presence of sediments or algae in the water will act as a sunlight filter, reducing the intensity and therefore slowing photodegradation. Currents, turbulences and wave action in shallow waters may also promote mechanical degradation of plastic items (especially in conjunction with increasing brittleness due to photodegradation), making them smaller and thus increase the degradation rate.

In a recent study performed in Greece, PET bottles were collected from the seafloor of the Saronikos Gulf and Aegean Sea (East Mediterranean) from depths of 150-350 meters[143]. The collected bottles were up to 20 years old and were compared with a reference sample purchased from a supermarket (2015). Analysis revealed a change in the chemical structure of PET that was related to degradation. However, PET appears to remain largely undegraded for about 15 years in the marine environment, before the first significant signs of degradation were observed. Environmental degradation, including biodegradation, is typically reported as a gravimetric weight loss of the plastic over time. The weight loss of low density PE, high density PE, and PP has been reported to be 1.9%, 1.6% and 0.65%, respectively, after 12 months in the Bay of Bengal at a depth of about three meters[144]. A second study, also from the Bay of Bengal, looked at the same materials at a depth of three meters over a period of six month. The reported maximum weight losses were 1.5-2.5% (LD-PE), 0.5-0.8% (HD-PE), and 0.5-0.6% (PP)[145]. These two reports highlight the degree of variation in the limited amount of data, even for the same geographical area. Rutkowska et al. (2002) reported that there were no visible signs of weight loss in PE after 20 months in the Baltic Sea (Polish coast) at a depth of two meters[146]. However, a reduction in tensile strength of ~30% was reported, which may be attributed to degradation.

This small number of example studies provide an indication that the degradation rates of plastics in shallow waters are very low even at relatively high temperatures and UV intensities found in the Indian Ocean. Extrapolating from these results to the degradation rates for the Norwegian marine environment is very difficult. Due to lower temperatures and lower intensity of the sunlight the degradation rates will be much lower than the reported ones. Considering that reaction rates typically double for every 10°C temperature increase, a rough estimation for the gravimetric weight loss due to degradation of plastic in the Norwegian marine environment is proposed to be less than 0.5% per year. It is highly likely that this value is an overestimation, especially in the northern and Arctic regions of the Norwegian coastline.

Deepsea

At the deep seafloor, the temperature is considerably lower than on the surface and in coastal regions. As we have discussed above, lower temperatures typically reduce the rate of most degradation processes. Furthermore, there is no sunlight, so photodegradation can be considered negligible. Microorganisms present in this environmental compartment may be limited by the low levels of oxygen, and significant degradation of macroplastic and microplastic items is unlikely. Finally, mechanical degradation processes are also likely to be negligible in the deepsea. As a result, plastic polymer materials lying at the bottom of deepsea areas will undergo much slower degradation rates than those present at the sea surface or in coastal and shoreline environments. With no obvious degradation mechanisms operating in deepsea areas, it is hard to estimate the lifetime of plastic materials in this environmental compartment.

4.5 Biodegradable plastics

There have been significant efforts in recent decades towards developing and industrialising so-called 'biodegradable' plastics that might have shorter residence times in the environment[147]. The challenges and misconceptions associated with biodegradable plastics have recently been reported and are summarised below[148, 149].

4.5.1 Oxo-degradable plastics

Oxo-degradable plastics are a class of plastic materials that are commonly promoted as biodegradable. In reality, these are conventional plastics (e.g. PE, PP, PET) containing additives that accelerate the oxidation process, including so-called prodegradants[150]. The major issue with oxo-degradable plastics is that they rapidly fragment into huge quantities of microplastic when exposed to a combination of sunlight and oxygen. While this speeds-up the first step of the degradation process, making large plastic items 'disappear' relatively quickly compared to conventional plastics, the generated microplastic is no different to any other type of microplastic. Under natural environmental conditions, microplastic fragments resulting from oxo-degradable plastics still take a long time to completely biodegrade and continue to pose a threat to the environment[151]. New knowledge has subsequently led to a move away from oxo-degradable materials, which are designed to rapidly fragment without considering the formation of microplastic[113], towards truly biodegradable plastics and so-called multiple use products made from conventional, recyclable materials.

4.5.2 Biodegradable plastics

For those plastics that are considered truly biodegradable (e.g. polylactic acid, polycaprolactone, polybutyrate adipate terephthalate), the biodegradability of the final product is not solely determined by the properties of its polymer. It is also determined by additives that are incorporated in final consumer products, as well as the environmental conditions in which the material ends up[152]. Although individual polymers and plastics can be classified as biodegradable according to test methods designed to assess biodegradability under optimised industrial composting conditions, there is limited control or regulation over how the data is utilised. In recent years, the term 'biodegradable' has become an appealing marketing term that is very misleading; in most cases, the biodegradability was tested only under very specific conditions and does not represent the generic property of the material[148]. In the natural environment, these same materials will take much longer to fully biodegrade (often taking decades), and the degradation process still generates large quantities of potentially-harmful small particles[153]. The available evidence suggests that the residence time of biodegradable plastics in the natural environment is less than that of conventional plastics, but degradation is highly dependent upon environmental conditions and they still undergo processes that generate microplastic[113, 141]. Biodegradable plastics are also challenging to recycle and they are currently difficult to isolate from mixed plastic waste streams that contain recyclable (PE, PP, PET) and non-recyclable plastics. Technologies for isolating biodegradable plastics could be implemented, but the volume of biodegradable plastic needs to be sufficiently high to make this economically viable. Ultimately, many of the same challenges appear to exist for biodegradable plastics as for conventional plastics. They need to be contained in existing waste streams to prevent release to the environment and they need to be separated from all other waste materials (including plastics). Importantly, when they are mineralised in industrial composting facilities this represents the loss of a potentially useful resource that fails to meet societal goals for a circular economy.

4.6 Estimating the degradation of macroplastic into microplastic

One of the goals of this report is to try and estimate the contribution of macroplastic degradation in the marine environment to the total load of microplastic. The complexity of macroplastic degradation has been discussed above, which highlights how variable plastic degradation rates are, and the large number of factors that influence these rates (e.g. polymer type, environmental conditions, presence of additive chemicals). It is therefore not possible to estimate a single degradation rate that is representative of all plastics and all environmental compartments and conditions. However, we are certain that macroplastic degradation is slow, even under natural marine environmental conditions at shorelines and on beaches, which are considered to provide the highest rates of degradation (high UV exposure, high energy). As macroplastic litter in the marine environment has increased over recent decades, we can also be certain that input rates are currently much higher than any degradation rates.

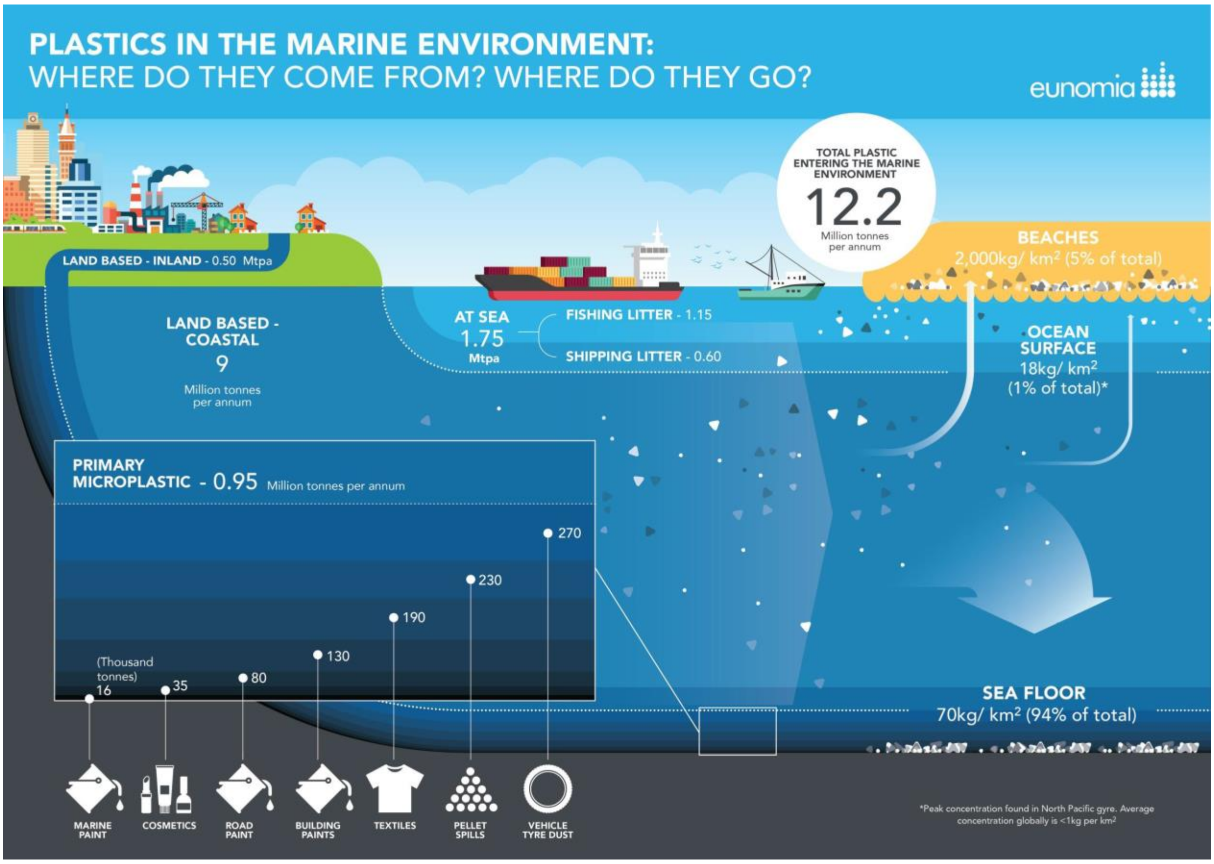


Figure 14. Infographic produced by Eunomia Research & Consulting Ltd summarising the principal sources of macroplastic and microplastic in the world's oceans, and where this material is deposited.[154]

A 2016 report from Eunomia Research & Consulting Ltd[154] estimated 94% of macroplastic is on the seafloor (Figure 14). Values estimated in the current project also suggest that sediments contain 90% of the microplastic that is present in the world's oceans. This microplastic has either been formed through macroplastic degradation in the marine environment, or it has been formed on land and transported to the marine environment. As we have shown, most global sediment environments represent low energy zones, with little or no UV radiation present. Only in the nearshore coastal environment, where there are shallow waters and higher energy, would conditions promoting degradation occur. We also know that there are higher concentrations of macroplastic on beaches and near shore sediments (2000 kg km^{-2}) than on the seafloor (70 kg km^{-2}; Figure 14).

The Eunomia report estimates that there is somewhere in the region of 25 - 65 million tonnes of macroplastic currently on the seafloor globally. We assumed the macroplastic items in the marine environment lose approximately 0.5% of their mass annually due to degradation, and that all of this mass is converted into microplastic. This represents an upper limit, as we know in reality not all of the lost mass will be in the form of microplastic. However, from this we can estimate that 0.13 - 0.33 million tonnes (average 0.23 million tonnes) of microplastic is formed annually from degradation of macroplastic litter already present in the marine environment. The Eunomia report also suggests that 0.95 million tonnes of microplastic enters the marine environment every year from terrestrial sources. This means a total of 1.19 million tonnes of microplastic are either being formed or entering the marine environment each year. Of this total amount, microplastic formed by degradation of macroplastic already in the marine environment represents 20%. This suggests that the most significant source of microplastic pollution in the marine environment is coming from the transport of terrestrial microplastic.

Note that the estimated loss of 0.5% is very uncertain and may well be an overestimation. Furthermore, this value will vary considerably depending on the size, type, and location of the plastic item in the marine environment. However, a yearly loss of 0.5% of the mass of an item of macroplastic in the marine environment corresponds to a half-life of approximately 140 years, (i.e. after this time, half of the mass of the original macroplastic item is gone). When the proposed degradation rates provided by NOAA for different plastic items in the marine environment are considered (Figure 13), we see that this ranges from decades to centuries. Therefore, our estimated degradation half-life of 140 years appears to be consistent with macroplastic litter degradation rates proposed by NOAA.

4.7 Knowledge gaps

There remain several key knowledge gaps that prevent a true understanding of the persistence of plastic in the marine environment being determined. All the established degradation mechanisms for plastic in the marine environment share a common issue: they are extremely slow processes. This is the primary reason underlying our limited knowledge as it severely limits what is achievable at the laboratory scale, even when we are able to accelerate the processes by manipulating conditions. The specific degradation rate of a plastic item depends on many factors, including polymer type, the presence of additive chemicals, environmental conditions, seasonal differences etc. As a result, the overall complexity of degradation processes in the environment makes it difficult to design relevant and reliable experimental setups at the laboratory scale. Improved experimental design is needed to be able to gain a better understanding of plastic degradation.

From a Norwegian perspective, there is a lack of studies conducted under conditions that represent relevant Norwegian environmental and climatic conditions. We suggest our understanding of plastic degradation in the Norwegian environment would be significantly improved by the establishment of well-designed, long-term field studies (e.g. a minimum of 10-20 years in duration). This would present the opportunity to study degradation under natural conditions over more relevant time scales. Such studies should seek to include field locations that represent key marine environments for Norway (e.g. fjord systems, arctic, temperate coast). Computer simulations of environmental degradation mechanisms have the potential to help predict the lifetime of plastics and their degradation products. Such models could also be used as a predictive tool alongside monitoring of environmental plastic pollution. However, it is likely that more environmentally relevant empirical data will be needed before such models can be developed.

There is also very little information regarding the influence of degradation process on the impacts of plastic in the marine environment. It has also been proposed that the aging of microplastic particles, whereby a biofilm is formed on the surface, may influence their ingestion. For example, a recent study has indicated that such aging processes promote ingestion in zooplankton and may result from the aging process causing the microplastic to resemble food items more closely[155]. Further studies could clarify the importance of the biofouling processes for a broader range of species. There is also a poor understanding of whether the chemical changes driven by degradation processes have the potential to make plastic more harmful to marine organisms. Furthermore, there is currently virtually no knowledge regarding the type, fate and effects of products that are formed as part of these degradation processes.

The plastic degradation process will result in the formation of smaller and smaller particles on the way to complete mineralisation. The environmental fate and effects of very small microplastic (<50 µm) and nanoplastic particles is an emerging field of research. At this small size microplastic particles are likely to remain in the water column for longer periods of time, meaning they are more mobile. Also, at this scale, particles begin to interact with organisms and biological processes in a different way to larger particles potentially being more likely to undergo true uptake and possible accumulation by organisms. Understanding the degradation processes that produce small microplastic and nanoplastic will be key to studying their environmental risk.

Another major knowledge gap is the current lack of understanding regarding the role that plastic additive chemicals really have in their degradation in the marine environment. There is increasing interest and study into the possible fate and effects of these chemicals when they leach out of plastics into the marine environment. However, their influence of plastic degradation has received little attention to date. As many of these additive chemicals are incorporated into plastic products to prolong their life and protect plastics against specific degradation mechanisms, it would appear crucial to have a clearer understanding on their influence regarding the environmental fate and behaviour of plastic. In particular, the role of UV stabilisers requires further study, as this is one of the most effective degradation mechanisms for many polymer types and the presence of such additives may mean that we are significantly underestimating the life of plastic materials in the marine environment. A study of the most common polymer additive components and their effect on the fate of plastic materials in a marine environment would provide valuable information that can be used in the design of plastic materials in the future.

The currently available ASTM and ISO standard tests for measuring and defining 'biodegradability' and 'degradability' are not suitable for describing the persistence of marine litter. Standards are often misused and can lead to consumer misconception about materials being safe to dispose in the environment. A rigorous application of specially developed materials standards would be a driver for improved materials and product design. We also suggest that biodegradable plastics require further study from an environmental perspective. Although the residence time of such materials in the marine environment appears to be shorter than conventional polymer materials, they still undergo a slow degradation under natural environmental conditions as their degradation is optimised for industrial compositing conditions. Furthermore, biodegradable plastics will most likely produce large quantities of microplastic, as this fragmentation is a critical part of the overall degradation process. Further study is needed into whether such materials offer a genuine long-term benefit over conventional plastics, which are currently easier to collect and recycle into new products if they are not released into the environment.

5 Marine transport and accumulation zones of plastic and microplastic

5.1 Introduction

The distribution of microplastic between biota, the sea bed, and the different ocean compartments in the Norwegian marine environment depends on (i) the origin and circulation of water off the Norwegian coast, (ii) large-scale and local winds, and (iii) the local ecology. Floating plastic of different densities and sizes will drift differently owing to the specific combination of currents and winds, usually modelled as a combination of surface currents and the local winds[a] scaled by "windage" factor. The more buoyant and the larger cross section an individual object has available to the wind, the more the wind can potentially direct the object. Therefore, macro- and microplastic of the same material can have very different trajectories. For similar sized objects with different

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[a] Note that land breezes and seabreezes are important in determining beach collection of surface debris, but very few numerical models simulate these processes.

densities, those with lower densities (e.g. more buoyant) will be more influenced by the wind. A recent study in the Seto Inland Sea showed that winds influenced the collection of macroplastic along the coast, and the degradation of the macroplastic to microplastic led to the coast being proposed as a source of microplastic[156]. Surveys repeated over time are important for monitoring levels of marine debris and extracting trends.

A key factor in the transport and accumulation of plastic and microplastic litter is the rate at which it is transferred to the seafloor through sedimentation or to the shore (primarily by wind). Dense microplastic (e.g. PET, polyamine and polystyrene) is expected to sink rapidly in coastal waters, only floating if it contains trapped air (e.g. polystyrene in the form of Styrofoam). In contrast, high production volume plastics such as polyethylene and polypropylene are buoyant and have the potential to disperse over long distances from source areas[157]. However, the sedimentation of buoyant plastic and microplastic litter does occur over time, driven by three main processes: biofouling, heteroaggregation and incorporation into faecal material.

Biofouling by bacteria, algae and other organisms colonising the surface increases the overall density of a plastic item to the point at which it begins to sink[158, 159]. Buoyancy is related to item volume, whereas fouling is related to surface area. Small items such as microplastic, which have high surface area to volume ratios, should start to sink sooner than large items[157]. Estimates of the time taken for biofouling to change the relative density of buoyant plastic litter is on the order of 30 days[158]. Potential colonisation with exotic species represents an additional concern; for example, *Vibrio spp.* (Cholera) of bacteria have been found on microplastic[20]. Water quality changes are possible based on such microplastic "hitchhikers", and some baseline data exists for the Atlantic Ocean at high latitudes, e.g. Svalbard[24].

Heteroaggregation of microplastic particles with higher-density naturally occurring particulates in the water column such as zooplankton and inorganic particles promotes sinking and sedimentation[36, 160]. The availability of transparent exopolymers particles (TEP) is likely to be important in this process, as TEP provides a "glue" to create aggregates that sink readily[161-163]. TEPs are defined as >0.4 µm transparent particles consisting of acidic polysaccharides, and are known to be generated by many marine organisms[161, 164]. TEP levels in the world's oceans are highly variable, suggesting their influence may vary from region to region. We are unaware of any studies investigating the influence of TEP on microplastic aggregation and sedimentation processes.

Zooplankton and other marine organisms have been shown to act as a vector for microplastic sedimentation. Microplastic and other particulates are ingested and then excreted as part of a dense faecal pellet that sediments[165-167]. However, incorporation of microplastic in faecal pellets changes their overall density (and thus the sinking rate). Although microplastic flux to the sea floor is increased, a 2.25 times reduction of faecal pellet sinking rate was found in laboratory testing with ingestion of 20.6 µm polystyrene[168]. Furthermore, the presence of microplastic has been shown to increase the potential for the faecal pellet to fragment higher in the water column than normal biodegradation and consumption processes would cause breakup[165].

Numerical modelling of microplastic transport makes use of ocean and atmospheric circulation model output, and is a fundamental tool for identifying microplastic sources, distribution paths, and potential sinks[169, 170]. Traditional trajectory modelling is an established tool for studying the transport and fate of microplastic[156, 171-173], and examples for microplastic are included in this report. New methodologies applying chaos theory have resulted in approaches that calculate trajectories over an entire environmental domain at once, and preliminary results are shown later in this section. These methodologies have previously been applied to a variety of key societal questions[174-176]. Barriers to, and collection areas of, Lagrangian transport can be calculated directly from environmental data (winds and currents[174]) at the ocean surface and in 3D[177]. [b] A key need for synthesis and prediction of microplastic transport and fate is coherent observational data freely available in Network Common Data Format with community agreed metadata under the Climate and Forecast conventions (netCDF CF), e.g. Asplem et al[178].

5.2 Area of interest in Norwegian waters: Circulation, drift modelling and transport barriers in Norwegian waters

The area of interest for this study is the Norwegian exclusive economic zone (EEZ) shown below (Figure 15). This includes the regions of the North Sea, Norwegian Sea and Barents Sea, along with major fjords along the Norwegian Coast. The Norwegian EEZ receives Arctic water from the Greenland Sea. The Norwegian Sea receives surface water from the Baltic Sea and deeper waters from the North Sea.

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[b] See example pictures at http://www.rsmas.miami.edu/personal/tamay/index2.html

Figure 15. Norwegian exclusive economic zone (EEZ). Source: United Nations.

5.2.1 Circulation in Norwegian waters and surrounding seas

The ocean circulation in the Norwegian EEZ determines the transport and fate of microplastic in Norwegian waters. The Norwegian coastal circulation receives water from the Baltic Sea, Arctic Ocean, and North Atlantic Ocean, and any drifting materials will also be transported. In the Northern Hemisphere, major garbage patches are found in gyres with clockwise rotation (e.g. North Pacific and North Atlantic Oceans)[169] due to geostrophic balance leading to surface convergence. The overall North Sea circulation (Figure 16) is anti-cyclonic (anti-clockwise) meaning there is surface divergence, so we would not expect a surface garbage patch to form in the North Sea. The Norwegian Coastal Current has a significant input of brackish water from the Baltic Sea and the fjords of Coast Norway. This brackish water will remain along the coast due to geostrophic balance, transporting coastal microplastic northwards. The surface and deep flow out of the North Sea follows the Norwegian Trench along the Norwegian border of the North Sea. In the Barents, Greenland and Norwegian Seas, there is some cyclonic (clockwise) circulation in the deeper area well offshore of the Lofoten area (Figure 17). A modelling study based on historical drift data showed the potential for a garbage patch to form in the eastern Barents Sea, as well as a smaller degree of retention of particles in the Norwegian sea[169]. This is supported by relatively high observations of macroplastic and microplastic west of Novaya Zemlya[179]. In the same study, increased observations of plastic were also made west of Svalbard, and both sites were suggested to be endpoints for plastic arriving from the North Atlantic branch of the thermohaline circulation[179]. This indicates that for Norwegian waters, the eastern Barents Sea and the Greenland sea might represent accumulation areas for macroplastic and microplastic, both in the water column and in the sediments. We show in the section on Lagrangian Coherent Structures, that permanent surface Garbage Patches are not likely to form in the Norwegian or Greenland Seas due to the summer circulation structure.

Figure 16. Surface circulation of the North Sea based on Holt and Proctor, 2008[180]. The northern portion of the North Sea is a mixture of North Sea water and Atlantic water that is bounded to the south by the Dooley Current. Within the main portion of the North Sea is Central North Sea Water. The inflow of relatively freshwater from the Baltic Sea remains along the Norwegian coastline.

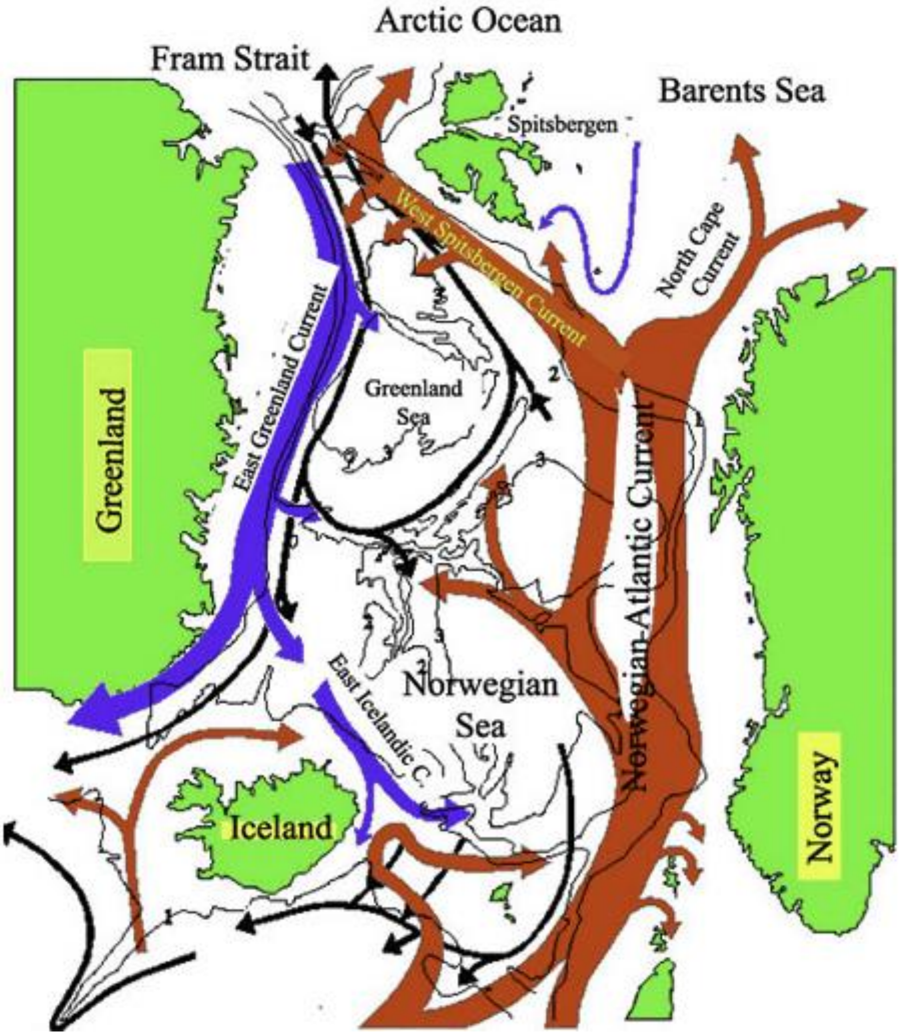

Figure 17. Surface and Deep Circulation in the Norwegian and Greenland Seas west of Norway[c]. Colours indicate "warm" vs "cold currents". The inflow of any microplastic from North America would arrive along the Norwegian coast, while inflow of any microplastic from the Arctic would travel first along the coasts of Greenland and, in places, Iceland.

5.2.2 Ocean circulation modelling domain

Selection of the circulation models to be used is a key step in obtaining quality results. Having a domain that is larger than the area of interest is important, particularly in areas of smaller gyres or recirculation areas. We use the Nordic4km model, whose area of coverage is shown in Figure 18 below. This area includes the major inflows from the North Atlantic Ocean, Arctic Ocean, and the Baltic Sea, and the circulation in the Greenland Sea, North Sea, Norwegian Sea, and Barents Sea. Only one year of data is available, so we cannot determine the influences in inter-annual and inter-

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[c] From University of San Diego (California, USA) "Earthguide" series. http://earthguide.ucsd.edu/virtualmuseum/climatechange1/10_2.shtml

decadal changes in ocean circulation, such as that of the North Atlantic Oscillation and the Arctic Oscillation[181-183].

Figure 18. Domain of the Nordic4km ocean circulation model. We have used the Nordic4km model to investigate Lagrangian Coherent Structures and microplastic particle transport. Within the model area, ocean currents are resolved to a spatial resolution of 4 km, and the model data is available on a 1 hour resolution.

5.3 Application of Lagrangian modelling approaches to Norwegian coastal environments

Here, we provide two types of Lagrangian modelling: Lagrangian Coherent Structures (LCS) and particle modelling. The LCS calculations give an overall view of Lagrangian transport in the Norwegian EEZ, while the particle modelling shows microplastic trajectories from specific starting points and times. Classical particle release modelling is conducted using the SINTEF Marine Environmental Modelling Workbench (MEMW). In the particle models, densities and particle sizes are based on available microplastic information. In the LCS calculations, small particle trajectories are calculated throughout the modelling domain, and rules are used to group them into "structures". These structures include "transport barriers", which are lines that Lagrangian particles will not cross. The LCS calculations are discussed below, and the MEMW modelling is discussed in Section 5.4.

Other studies have attempted to model the fate and transport of microplastic. Of particular interest, was the modelling of benthic microplastic in the Nazaré Canyon, Portugal, using the MOHID particle model. The output of the model indicated that benthic microplastic would be transported up and down the canyon through tidal action, with little net downward transport until winter cooling events led to water densification[171]. In coastal Norway, this suggests fjord sills could block flushing of benthic microplastic, but otherwise the channels and slopes on the Norwegian Shelf would lead to a net transport of microplastic toward deeper waters, primarily in late fall and winter. Analysis of colder winter periods, when coastal deep water formation occurs (through densification of the water mass), could lead to insight in the frequency, transport path and endpoints of these potential "microplastic deepening" events.

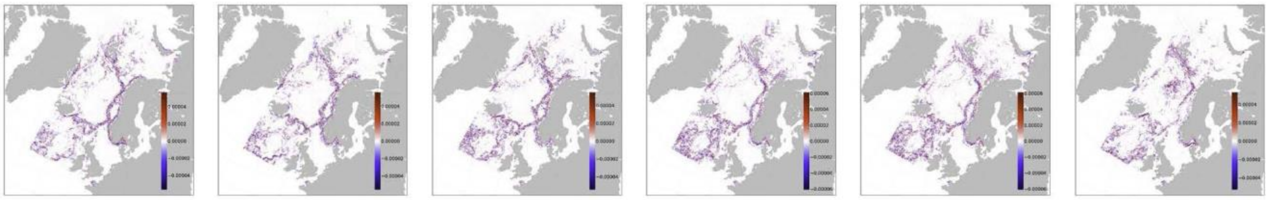
5.3.1 Lagrangian coherent structures

Lagrangian Coherent Structures are an aspect of chaos theory, which is a branch of dynamical systems theory. These are the skeleton of fluid circulation, for example in the ocean, showing how the overall currents are arranged and change[176]. Exploiting this understanding has merit in Decision Support, for example, during the Deepwater Horizon oil spill, the location of the initiation of the "Tiger's Tail" event, when the surface spill suddenly expanded toward the Loop Current, could be identified two days earlier than trajectory models showed the change[184]. Rather than considering individual trajectories (as in modelling a spill), the idea is that an analysis of the entire flow field is conducted, taking a small trajectory at each grid point, to determine if barriers exist that will prevent transport between certain areas. Calculation of surface Lagrangian Transport Barriers over areas within Norwegian (and nearby) waters identifies coherent/connected areas for aggregating observations.

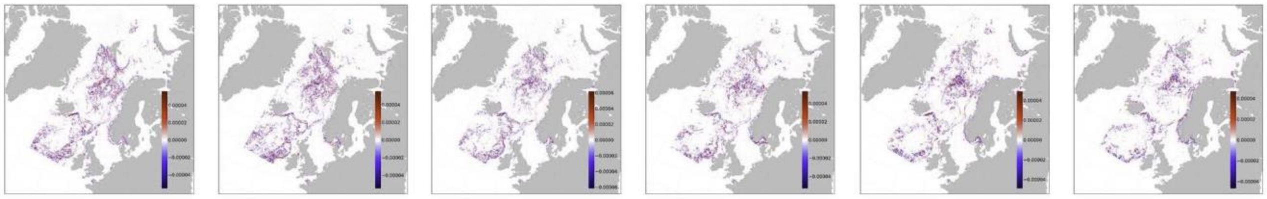
The quantity calculated is known as the Finite Time Lyapunov Exponent (FTLE). Positive values indicate that the distance between nearby trajectories will tend to increase exponentially with time, and negative values indicate that the distance will decrease exponentially. As the name suggests, the FTLEs are only valid for a finite time, but any features that consistently show up when the analysis is repeated for different time points, can be considered persistent features. In some cases, these will vary seasonally, in other cases they may be dictated by bathymetry or large-scale circulation patterns, and therefore persist throughout the year.

To represent the ocean currents, we have used a one-year dataset for 2016-2017 from the Nordic 4km model domain produced by the Norwegian Meteorological Institute (MET). According to

NOAA, the North Atlantic Oscillation[185] (NAO)[d] in the winter of 2016-2017 oscillated between positive in summer (wet) and negative in winter (dry). Other years when the NAO is in a single pattern for the full year may show different results. This dataset provides a grid of vectors to describe the velocity of the currents, using 4 km by 4 km horizontal resolution, and a timestep of 1 hour. In the analysis presented here, we used the surface currents. Approximately 500 000 trajectories were calculated, one for each grid cell in the dataset. In some areas, neighbouring trajectories tend to move apart, and in other areas they tend to move closer together. By analysing the relative distance between trajectories that start out close together, it is possible to identify attracting and repelling areas. This analysis will typically be done for a transport time of one or a few days, or in some cases up to a few weeks. In our case, we have used a transport time of 24 hours, and repeated the analysis for each day in the year for which we have data. Results for the first day (Month Day 1 calculations over 24 hours) of each month are shown in Figure 19. The months are arranged to represent the periods of oceanographic winter (top row) and oceanographic summer) bottom row.



October 2016 November 2016 December 2016 January 2017 February 2017 March 2017



April 2017 May 2017 June 2017 July2017 August 2017 September 2017

Figure 19. Finite time Lyapunov exponent (FTLE) calculations using the Nordic 4km model. These calculations use the first day (24 hours) of each month as example calculations. These show oceanographic winter (top row) and oceanographic summer (bottom row). We have included larger individual images in Appendix C.

The key continental shelf areas show the strongest coherent signal of transport barriers, particularly in winter (Figure 19). At the high latitude of Norwegian waters, conservation of potential vorticity[186] constraints indicate that the water on the continental shelves would behaves as stiff fluid columns. This keeps oceanic shelf water from easily moving over the deep basins of the Norwegian

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[d] Generally, the difference in sea level pressure between the Icelandic Low and the Azores High, which alters the storm tracks of the North Atlantic, changing the amount of rain in Norway.

and Greenland Seas. More formally, this is the balance between the rotation of the Earth (planetary vorticity) and rotation in the fluid flow (local vorticity) to the water depth. For example, the Gulf Stream current flowing northward along the U.S. east coast separates from the coast at the latitude of Cape Hattaras, North Carolina, because the water is closer the Earth's axis of rotation, and like an ice skater spinning and bringing their arms closer to their body, water coming from the south is spinning faster. Changing water depth changes the diameter of the fluid column, and thus rotation, similar to the ice skater. Our 2D calculations showed organised LCS only in the continental shelf areas (Appendix C); therefore, due to this fluid "stiffness" on the continental shelf where the transport barriers were located, 2D calculations are sufficient, and we did not consider the need to conduct 3D calculations for this analysis.

As microplastic at the surface and descending through the water column will be transported by horizontal currents, we can use the calculation of LCS transport barriers as flow boundaries to discuss different groupings and their movement along the coast. In Figure 19, the shelf breaks are clearly identified by the LCS calculation in the winter, but these break down over the summer months. We interpret this to mean that in winter, coastal waters from the coastal Atlantic Ocean along the UK and the North Sea would be brought directly along the Norwegian continental shelf into the Norwegian and Barents Seas. This suggests that (i) microplastic on the continental shelf will stay on the continental shelf in winter and (ii) microplastic present in waters coming from the North Sea would not be able to leave the shallower continental shelf regions of Norway while the transport barrier at the shelf break was present (primarily oceanographic winter).

In the deeper waters, note how in summer, the more northern area is filled with attracting and repelling lines. Our hypothesis is that these summer conditions prevent the area from becoming a perennial collection zone. As discussed earlier in the chapter, other references have shown that materials moves through this area or collects for a limited time at the surface. Further analysis is needed to understand the mechanisms that cause the shift of between water moving along the continental shelf in winter to more of the water moving offshore in summer, and the stability of these transitions.

Freshwater from the Baltic Sea and Norwegian river inflows is coastally trapped, moving coherently along the coast, and is clearly defined in the LCS calculations. During winter, when there is more freshwater input from rain and snow, this circulation is broader and more clearly defined along the coast. Microplastic present in these water sources would also be trapped close to the coast for extended periods. This may mean a higher potential for sedimentation of microplastic from these sources to coastal regions during winter months. This coastal and continental shelf trapping reduces slightly in summer, likely due to decreases in freshwater outflow. This reduction in trapping suggests that it would be easier for microplastic to move in and out of Norwegian coastal regions. Therefore, floating and suspended material such as microplastic originating from the North Sea are also more likely to be able to move offshore into the Barents Sea during summer.

5.4 Simulation of microplastic arrival to Norwegian waters from discharges in European countries

The water along the Norwegian coast originates from the Baltic, the North Sea, the Atlantic (Figure 16) and from river runoff in Norway. Given the potential for microplastic to sink to the sediments, it may be expected that the contribution of microplastic from the Atlantic branch is smaller than from the other sources containing microplastic more recently discharged to the sea. Therefore, we consider that the largest potential source for microplastic in Norwegian coastal waters are from discharges in Norway itself and discharges from its neighbouring countries that enter into the Norwegian coastal current. Off-coast water is of more Atlantic origin, although some of this water passes by the Irish and Scottish coasts (Figure 16). To answer the question of how much microplastic there is in the Norwegian marine environment, we used a numerical particle tracking model to simulate the ocean transport of microplastic released from Western and Northern European countries. Particle modelling is an established method of investigating the fate of marine litter and is suited to understanding how microplastic disperses in the ocean[158, 187]. The main sources of microplastic into the European environment are estimated to be wear from tyres and microfibres that originate from synthetic textiles[188]. Here, we focus specifically on the release and transport of microfibres, which is often the dominant category of microplastic observed in samples collected from the water column, sediments, and on shorelines[25, 158, 189]. Although much is uncertain about their transport from land into the marine environment[190], microfibres are well characterised in terms of size-ranges, densities, and behaviour in the water column[158, 191]. In contrast, less is known about the characteristics and environmental presence of particles derived from tyres, partially due to the small sizes of these particles[192]. Our main aim is to use the best available data to deliver an estimate about the total amount of microfibres present in the Norwegian marine environment today and ten years into the future. Our secondary aim is to demonstrate the suitability of this modelling approach for any group of microplastics by using microfibres as a case study.

5.4.1 Methods

As input to the model, we obtained data from Jambeck et al.[8], who estimated the amount of plastic released into the ocean from coastal areas in different countries. Using the same approach as Jambeck et al., we represented the total amount of plastic released along the country's coastline as a fraction of the local population density. Figure 20 shows the geographic placement of the release locations. The local population density was obtained from GPWv4 [193]. In their study, Jambeck et al. estimated the total release of plastic to the sea, both macroplastic and microplastic[8] (supplementary materials), however they do not distinguish the relative mass fractions of microplastic and macroplastic. To estimate the mass fraction of microplastic, we have used a previous report showing that the median fraction of microplastic by mass is 60% based on observations of plastics in rivers[194], which are major sources of plastic discharge to the sea[195]. We further assumed that all the microplastic is microfibre. This is in line with the suggestion that microfibres originating from synthetic textiles represent the second most common form of microplastic generated in Europe after tyres[196], and that the mass discharge data does not consider tyre particles[8]. The resulting total yearly mass release for each country is given in Table 5. The releases are limited to the specified countries and do not consider microfibre inflow from the Baltic or Atlantic oceans.

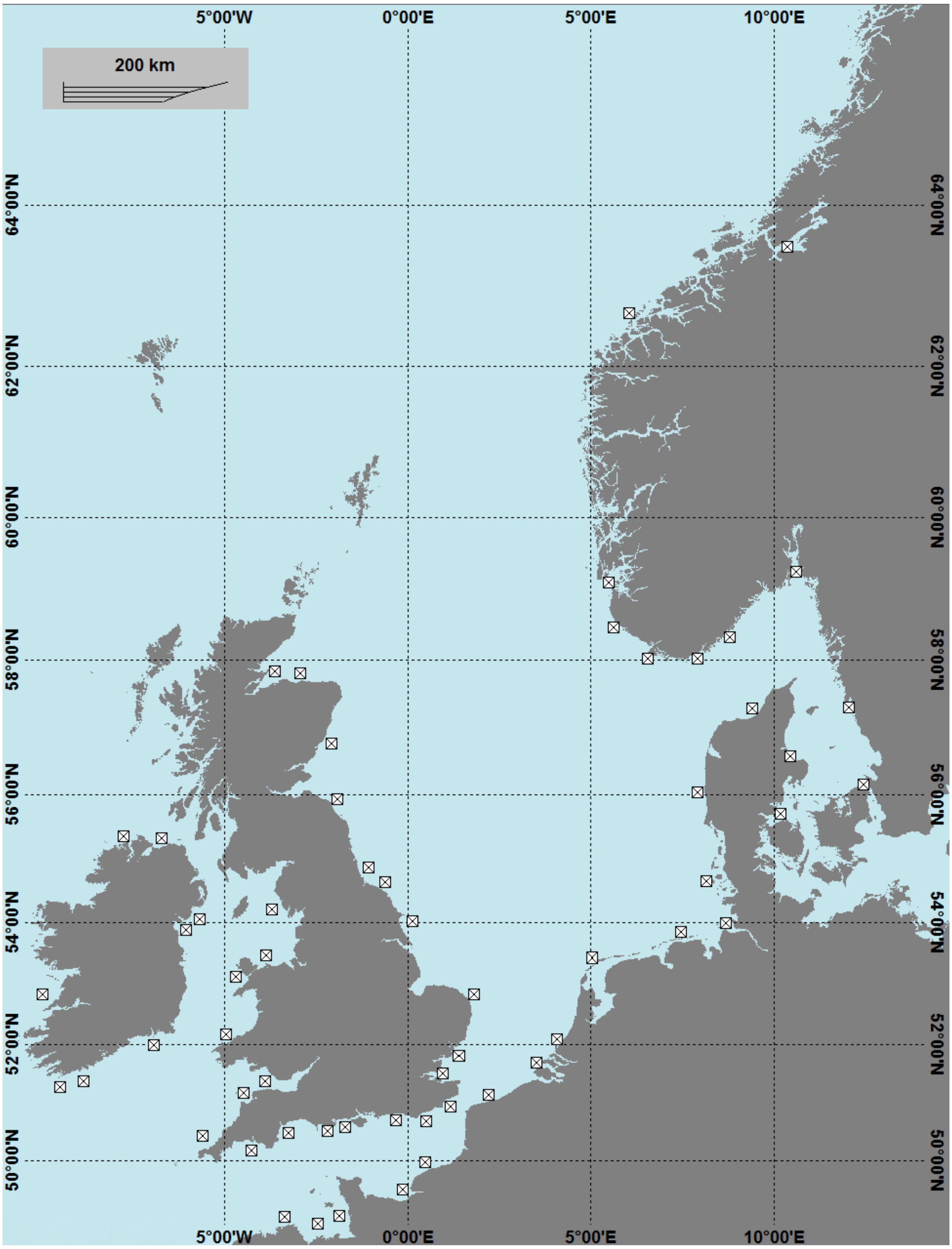

Figure 20. Microfibre release sites. The density of size and the amount of microfibre per site is proportional to the local population density.

Table 5. Yearly discharge of microfibres for each country in 2010 for low, medium, and high fractions of releases to the ocean. The numbers were obtained from published values of total plastic release (Jambeck et al.)[8], and adjusted for the assumption that 60% of released plastic mass is microplastic (see text). Values are given in metric tonnes. The values for Germany and Sweden were reduced by 50 % since their Baltic-facing coastlines are not included in the simulation.

Country	Low	Medium	High
Belgium	230	411	658
Germany	1308	2336	3737
Denmark	133	238	381
France	2025	3616	5786
UK	5616	10029	16048
Ireland	954	1703	2725
Netherlands	2326	4155	6648
Norway	597	1066	1706
Sweden	90	161	158

The release locations were imported to the DREAM ocean pollution model[197]. Model ocean currents spanning one year from October 2016 to October 2017 were downloaded for the Nordic4 model from a server provided by the Norwegian Meteorological office[e]. The Nordic4 model has a model timestep of one hour and a spatial resolution of 4 km. The DREAM model was run with a timestep of 30 minutes and the output was summarised in a grid at 4 km resolution. The DREAM model was run with continuous microfibre releases to the ocean, until reaching a steady state of accumulation of microfibres in the Norwegian environment. Model results are reported in terms of mass of microfibre in the sediment and in the water column in the Norwegian exclusive economic zone (EEZ) and in coastal areas. Coastal areas are defined as all model grid-cells adjacent to Norwegian shorelines, therefore generally extending 4 km from the coastline. Reported numbers for the EEZ includes coastal areas.

The key parameter for modelling the transport of microplastic is the settling velocity of microplastic particles. We represent the settling velocity of microfibres with a model that was fitted to experimental data of sinking fishing line and calculated a sinking velocity based on fibre length, diameter, and density[191]. Microfibre diameter is reported to generally vary between 10 and 30 µm[158]. In our simulations, we assume a diameter of 15 µm. The length of microfibres is determined by the fibre length during manufacturing and degree of subsequent fragmentation. One study found that when washing synthetic clothing, fibres in the size range of 20 to 2000 µm were produced[198]. Microfibres observed in the environment, although limited by sampling net size meshes, are generally reported to have lengths between 50 to 5000 µm[158]. Owing to the lack of a consensus size distribution for microfibre lengths when they arrive to the marine environment, we have assumed a

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[e] https://thredds.met.no/thredds/fou-hi/nordic4km.html

flat mass distribution from 50 to 5000 µm. As microfibre diameter is kept constant, fibre volume increases only with length. The uniform mass distribution used here therefore corresponds to a linear number distribution, where the number of fibres doubles for every halving of the fibre length.

For microfibres in the size range we are considering, it is density that determines the vertical fate in the water column. The density of microfibres depends on the fibre origin, varying in specific gravity from around 0.9 to more than 1.4 [199], making them either negatively or positively buoyant in seawater. The most commonly found microfibre types in shorelines and in sediments tend to be polyester and acrylic, which are negatively buoyant [200]. Here, we assume four different classes of densities (in tonnes m^{-3}), 1.05, 1.10, 1.20., 1.30, 1.40, covering most of the reported microfibre density range. The smallest density category represents microplastic that is close to buoyant and will have a prolonged lifetime in the water column after release.

5.4.2 Results

The simulation was run for 5 months, which was the time needed for the change in concentration in sediments and the water column in the Norwegian environment to reach a steady state. A geographic view of the simulation state at this point is given in Figure 21, and the mass of microfibre in the sediment is given in Figure 22. The steady-state increase in the last three months of the simulation were used to estimate an increase in mass to the sediment of 381 tonnes/year in Norwegian coastal areas and 1188 tonnes/year in the Norwegian EEZ for the year 2010. The mass of microfibres in the water column reached a steady state at around 20 tonnes (Figure 23). At the end of the simulation 92% of all released microfibre was in the sediment while 8% was still suspended in the water column. This shows that for the microfibre size and density ranges considered here, rapid sedimentation occurred even without additional processes such as agglomeration and incorporation into faecal pellets.

To estimate past and future arrival of microfibres, we assumed that the annual European microfibre release to the ocean is proportional to the amount of synthetic textiles produced globally. Based on reported historical values of synthetic fibre production, we found an annual growth of 5.7% from the years 1992 to 2010, and an annual growth of 3.5% from 2007 to 2010 [196]. For the years from 1950 to 2010 we assumed the faster 5.7 % growth trend and from 2010 to 2030 we assumed the slower 3.5% growth trend. Extrapolating the 2010 annual increase in sediment mass with these values gave a projected past and future accumulation of microfibres in the Norwegian environment (Figure 24). From this graph, we extracted the estimated total mass of microfibre in the Norwegian environment today and in 10 years (Table 6).

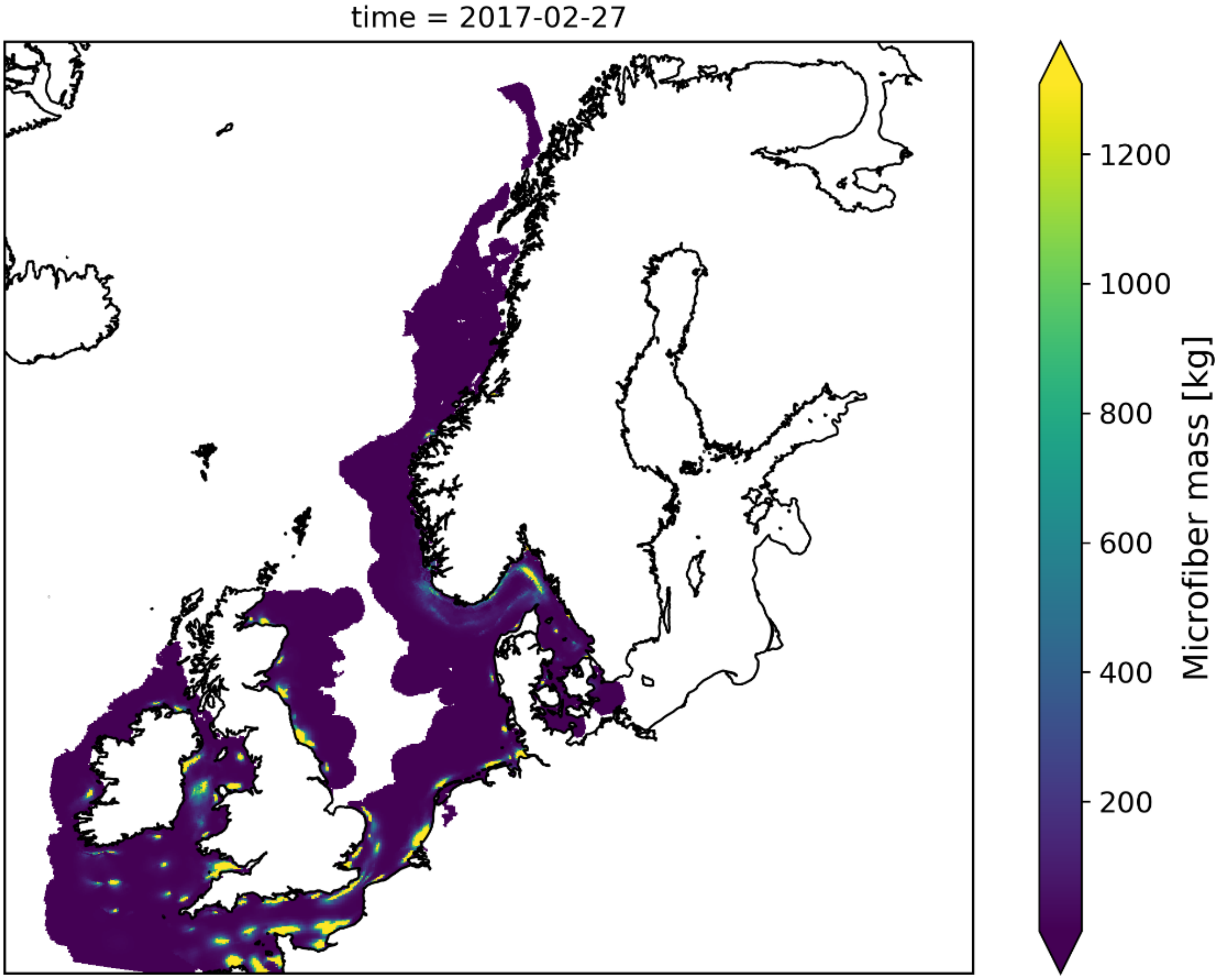

Figure 21. Sedimentation state of microfibre after five months of releases. Most microfibres settled close to their coastal dischage locations.

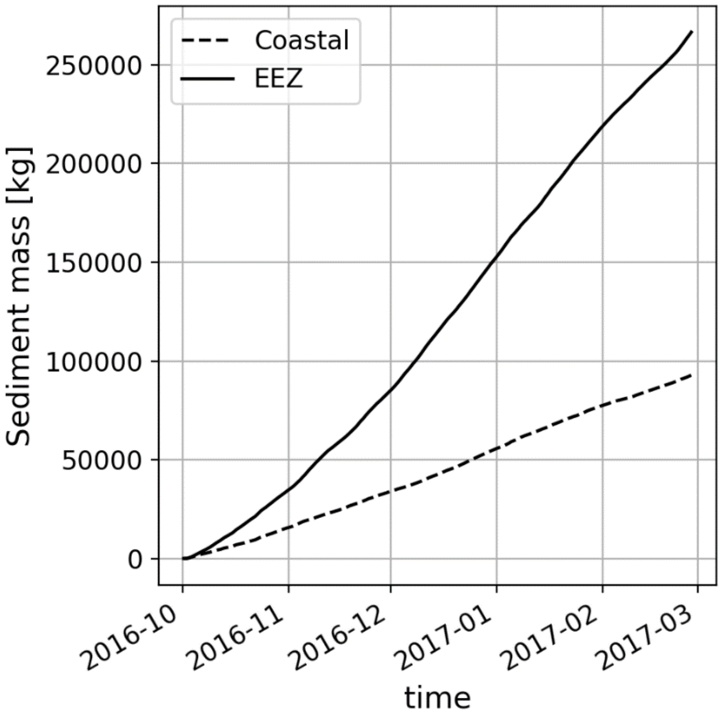

Figure 22. Timeseries of microfibre sedimentation in the Norwegian EEZ and coastal areas during the model simulation duration.

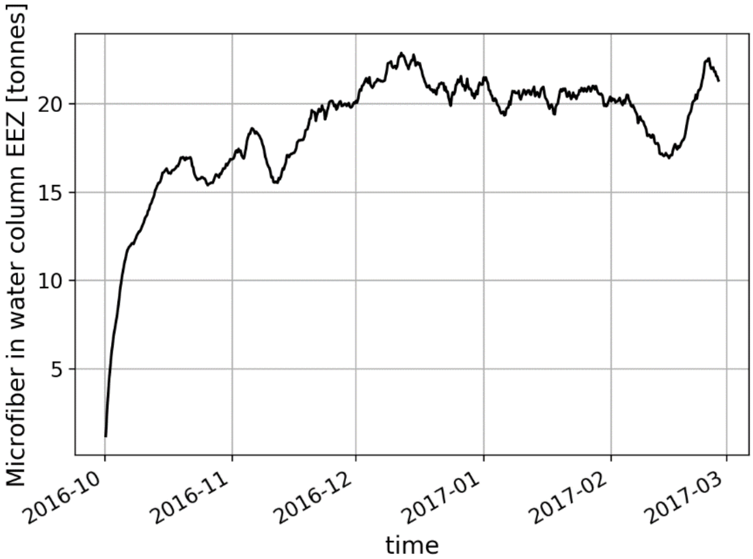

Figure 23. Timeseries of mass of microfibre suspended in the water column in the Norwegian EEZ during the model simulation period.

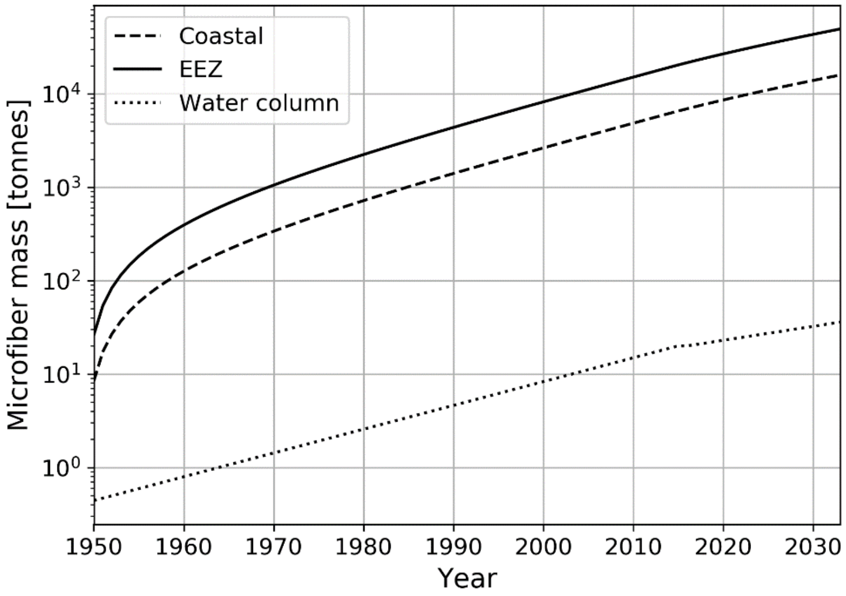

Figure 24. Extrapolated amount of microfibre mass in Norwegian EEZ and coastal sediments and in the EEZ water column from 1950 to 2032.

Table 6. Estimated mass of microfibre in the Norwegian environment today and in 2027 [tonnes] for three different estimates of plastic discharge to the ocean (see methods for source of low, medium, and high discharge rates).

Environment	Low	Medium	High
Coastal sediment today	4105	7330	11728
Coastal sediment 2027	6789	12124	19398
EEZ sediment today	12784	22828	36525
EEZ sediment 2027	21145	37759	60414
EEZ water column today	11	20	32
EEZ water column 2027	16	29	46

5.4.3 Discussion and conclusion

Using microfibres as a case study, we simulated continuous releases of microfibres from coastal areas in Northern and Western Europe in order to estimate the amount that reaches the Norwegian marine environment. Our primary finding is that most of the released microfibre settles close to the discharge locations (Figure 21), and 92 % of fibres were located in the sediments at the end of a simulation. Considering that the microfibre textile industry is growing, we found that the quantity of microfibres reaching the marine environment annually will increase in the near future (Figure 24). For the medium release scenario, we estimated that 1188 tonnes of microfibre will settle each year in the Norwegian EEZ, including coastal areas. When compared to annual microfibre release estimated to come from Norwegian sources (1066 tonnes), it appears that most of the microfibre originates from local releases in Norway rather than being transported from neighbouring countries. The amount of microfibre present in the water column was estimated to be much lower than that in the coastal sediments (Figure 23 and Figure 24). Considering the large volume of the water column compared to the sediment surface, our results are in agreement with the finding that volume-concentrations of microplastic are generally much higher in sediments than the water column[10] (see also Section 3 of this report).

The results presented must be considered in light of the uncertainties associated with the input data and in the modelling methods. In terms of input, the total mass of plastic reported for each country was used, but since the original study did not specify the fraction of macro- versus microplastic we determined this with a factor of 60%. It is likely that more accurate estimates and measurements of the total amount of microplastic and microfibre released from different countries will be determined in future studies. Furthermore, uniform distributions of microfibre length and microfibre density are assumed in the current work. In reality, these distributions are rarely uniform[10, 26, 200], but it is not currently clear what the relevant discharge distributions would be. In terms of model processes, we consider that the largest uncertainty is resuspension of microfibres from the sediment. In our simulations, the microfibres settle permanently when they encounter sediments. However, microfibres are light with a large surface area and will be prone to resuspension, potentially transporting them further from their initial site of settling. This is expected to be an important factor in a shallow sea such as the North Sea investigated here. Although resuspension is a well-studied phenomenon for mineral particles, experimental research into the resuspension behaviour of microplastic is needed to build accurate models[201]. A challenge with modelling resuspension is that it requires high-resolution currents and bathymetry [171]. Another factor that has not been considered in the current modelling approach is the process of biofouling and flocculation between microfibres and other marine particles, which can contribute to sinking rates[202]. Microfibres are too small to be colonised by larger biota, which are known to cause sinking of larger plastic[203], but may well be incorporated into flocs with phytoplankton[160, 204]. Estimating vertical transport from flocculation would involve coupling microplastic transport simulations to plankton concentration fields from biogeochemical ocean models to calculate the contribution from flocculation processes.

This current work has considered the transport and fate of microfibres in the Norwegian marine environment as a case study. However, the main source microplastic in the Norwegian end European marine environments may be from other sources (e.g. fragments of car tyres)[196, 205]. Tyre fragments are less studied in the marine environment, and their transport and dispersive modes of action are not well identified[192]. The much smaller size of tyre-derived microplastic compared to microfibres suggests they will enter the sediment to a smaller degree, and rather be transported passively with ocean circulation systems. Although estimates regarding the amount of tyre particle releases from European countries has not yet been assembled, this has been done for individual countries[192], which suggests that it is possible to produce modelled estimates of fate and transport similar to that which is presented here for microfibres. By developing such datasets for other types and sources of microplastic, and combining this with estimates of size distributions and densities, it should be possible to model the transport of fate of tyre and other types of microplastic particles from sources in Europe.

Using available knowledge about the likely abundance and physical characteristics of microfibres, combined with a numerical model for ocean particle transport, we have estimated the amount of microfibre that is continuously arriving in the Norwegian marine environment. Based on current usage patterns and the slow degradation of plastic, the amount of microfibre arriving to the Norwegian environment is predicted to increase in the coming years. A reduction in synthetic fibre production and consumption, or the development of improved systems for preventing their release to the marine environment, would contribute to reducing the expected concentrations in the future.

5.5 Ultimate fate of microplastic on the seafloor

As microplastic ages and sinks to the seafloor, bioturbation and other mechanisms are expected to promote downgradient (downhill) transport. Once on the seafloor, movement will cease as sufficient sediment accumulates over the particle. Although transport in the sediment was not included in the microfibre particle tracking study, it is known that the steeper the bathymetry, e.g. the continental slope, the higher the potential for more downgradient transport compared to flatter areas on the continental shelf or in the deeper basins of the Norwegian Sea. The bathymetry of the Norwegian EEZ exhibits some very steep areas (Figure 25 and Figure 26). There is a particularly deep area offshore of Oslofjorden, which extends below 500m (detailed in Figure 27). Owing to the relatively high population density in the surrounding the area, and the influx from the Baltic and North Seas, this area is likely to contain a large concentration of plastic particles. This area may also be close enough to collect denser microplastic from the vicinity of Oslo and the outlet of Baltic Sea. This is also a location where deepwater corals are found (Figure 27). Although the resolution in the particle modelling study (4 km) was too coarse to meaningfully compare coral areas (Figure 27) with areas of microfibre sedimentation (Figure 21), this could be investigated with the same modelling approach using currents and bathymetry from a higher resolution ocean model. Literature on the consumption and effects of microplastic on corals is very limited, but preferential ingestion of microplastic based on "taste" (chemoreception) in an experiment with scleractinian hard corals raises a concern[206]. Experiments with scleractinian corals[207] from the Great Barrier Reefs show that they can consume up to 50 µg of plastic per cm^2 per hour. Scleractinian corals are found in many areas of Norway[208], where fjords in particular may have high populations, e.g. Trondheimsfjorden and Oslofjorden.

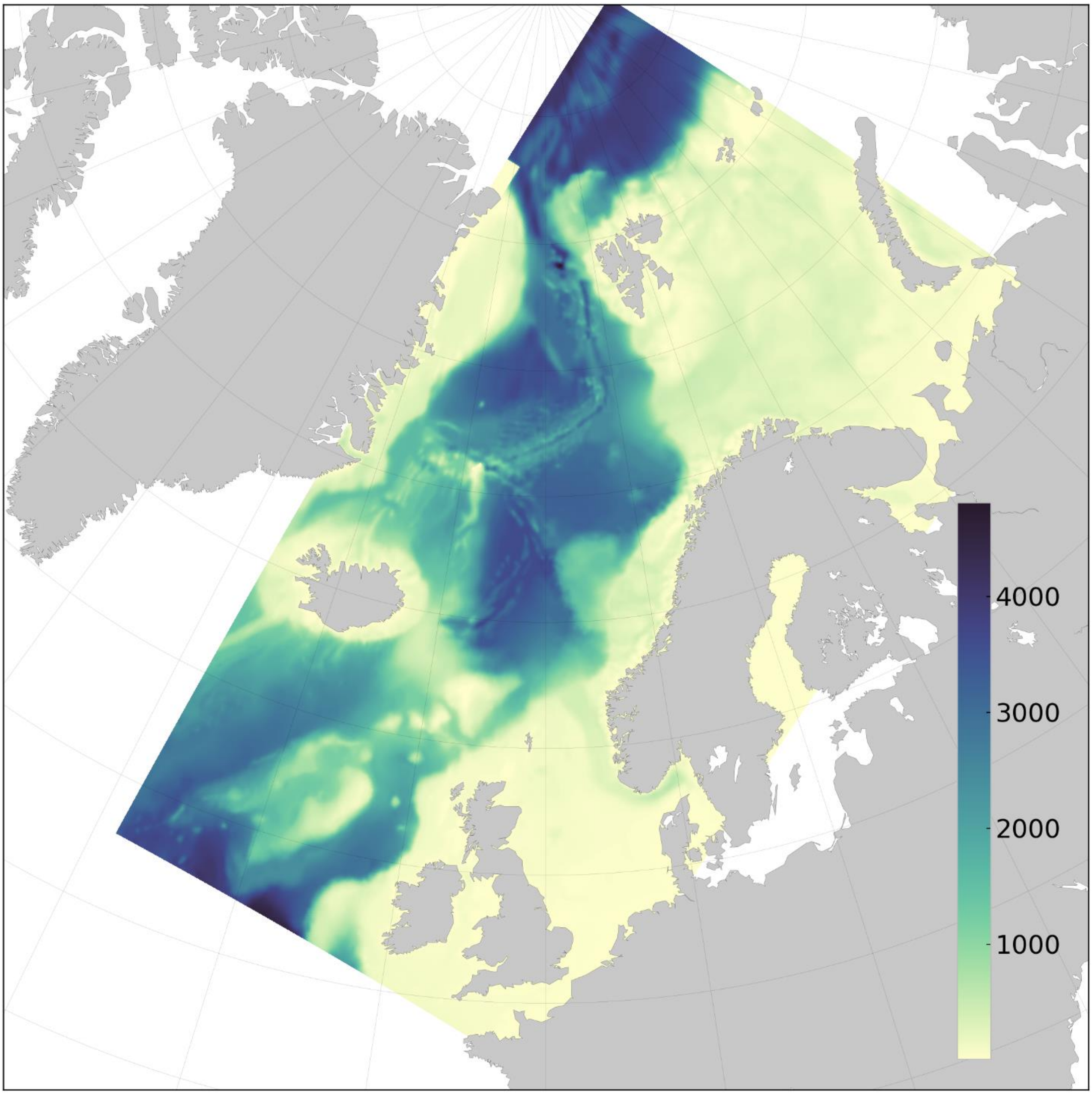

Figure 25. Bathymetry to full depth. This shows the deeper areas in the Norwegian EEZ, which will be the ultimate sink for sedimented microplastic over time. Note that there is a particularly deep area of the Norwegian Trench offshore of Oslofjorden. This area is expected to the ultimate repository of microplastic from the eastern North Sea, some of the surface microplastic from the Baltic Sea, and urban development near the city of Oslo. See Figure 26 for detail of the continental shelf.

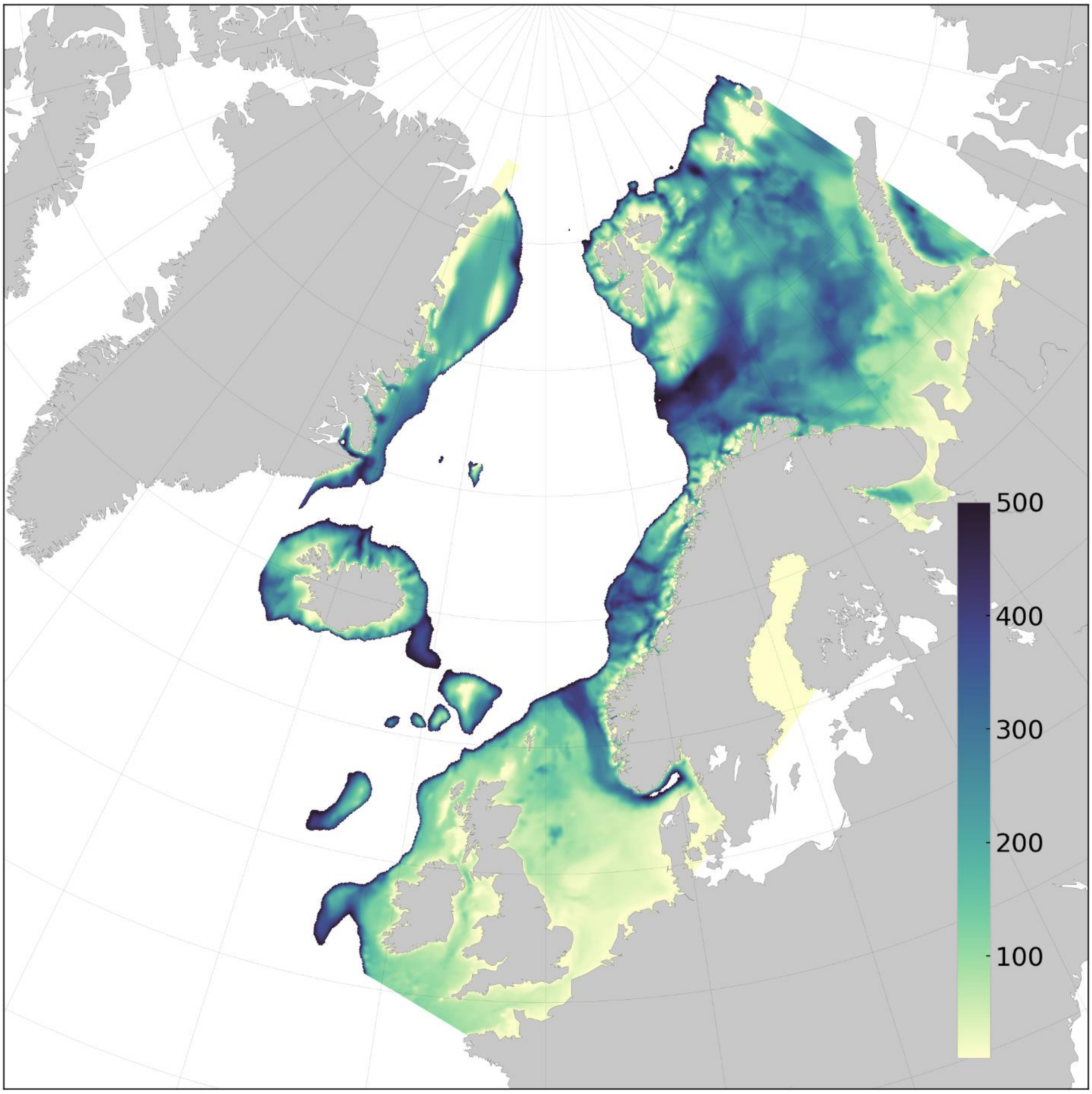

Figure 26. Bathymetry to 500 m. This diagram shows only the detail of the Nordic4km model domain between 0-500 meters, to show the continental shelf. This picture shows more clearly the drainage from Svalbard, the Barents Sea, coastal Norway, and the North Sea. Note the "hole" in the bathymetry graphic south of Oslo where the bathymetry is deeper than 500m.

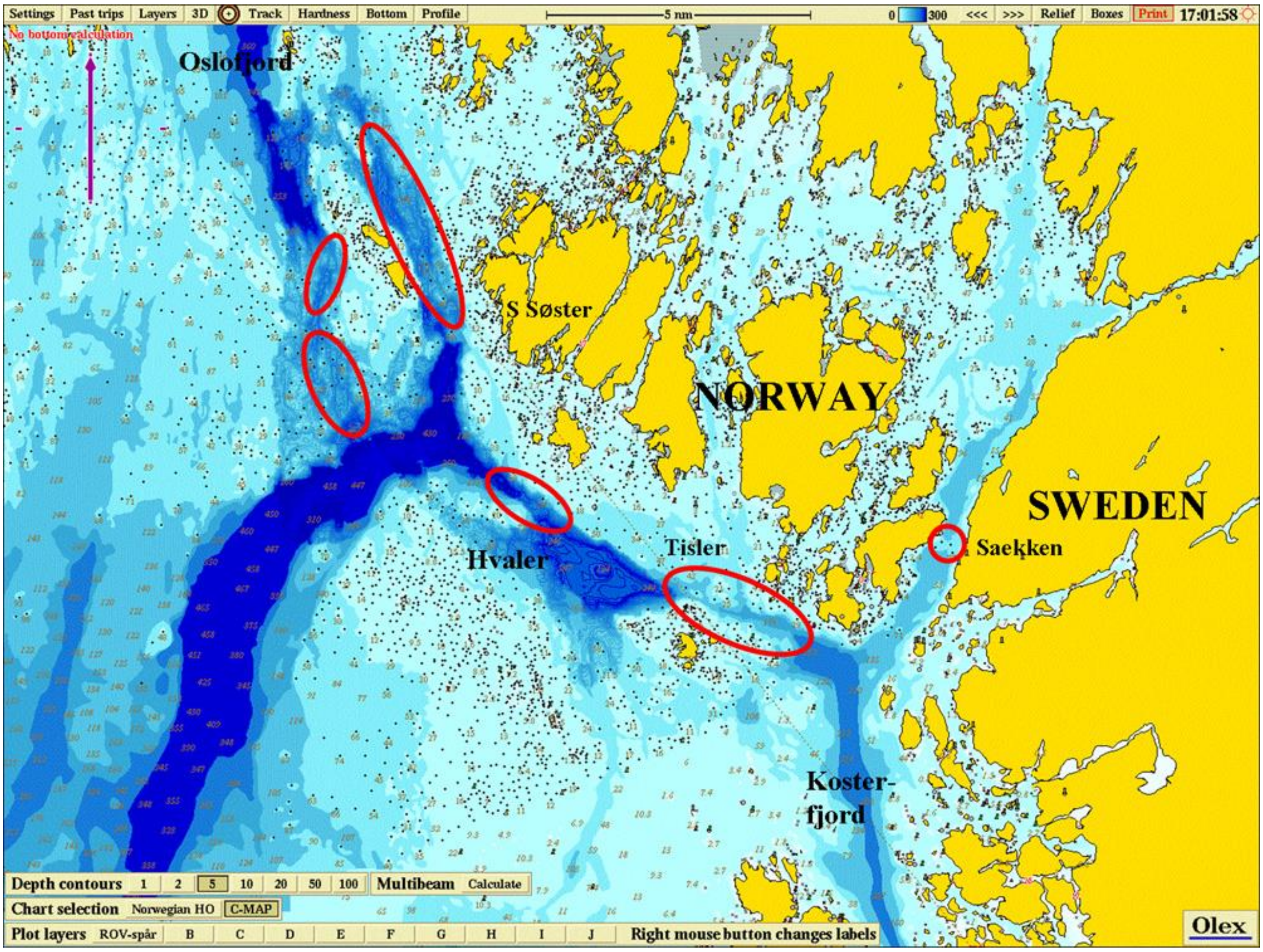

Figure 27. Detailed Bathymetry offshore of Oslofjorden and the border between Norway and Sweden. Red circles are known areas where deepwater corals live.
http://www.stroembergiensis.se/coral_occurrences.html

5.6 Knowledge gaps

Based on our research, we have identified several key knowledge gaps. The chronic lack of data regarding the concentration and physical characteristics of microplastic in different marine environmental compartments (sediments, surface waters, water column) is currently preventing both the development and validation of transport and accumulation models. This is particularly the case in Norway, where very little data currently exists. There is a need to generate more microplastic concentration and distribution data that can be used in the further development of models such as those presented in this report. Atmospheric modelling studies are also needed to estimate the contribution of atmospheric transport to input of microplastic particles to the marine environment[192]. Furthermore, laboratory experiments are needed to determine the fate of specific microplastic types in the marine environment in terms of settling velocity and potential for flocculation with other marine particles. The models developed have already been able to indicate areas around the Norwegian coast where microplastic may accumulate. It would therefore be important to utilise data from models in selecting appropriate sampling locations (high accumulation zones and low accumulation zones) for future research studies and for monitoring activities. Collected samples from such areas would not only provide the opportunity to generate new data that can be used to improve the models, but it would also help during model calibration and validation. The modelling work conducted in this report has highlighted several potential accumulation zones around the Norwegian coast, including those which may be home to deepwater corals. Research is needed to determine the exposure, uptake and impacts of microplastic on deepsea corals as well as other marine organisms which are important within Norwegian marine ecosystems. Development of standard sampling and nomenclature that supports the key Decision Support questions related to microplastics is an important step.

This report has used microfibres as a case study for investigating the transport and fate of microplastic in the Norwegian marine environment. However, microfibres represent just one type and source of microplastic, and more detailed knowledge of the types, sources, quantities and properties of other types of microplastic are urgently needed so that similar modelling studies can be conducted. At smaller sizes, microplastic remains in the water column for a longer period as friction and drag forces begin to dominate over density. These two parameters are highly interdependent at the microscale and future modelling work would benefit from utilising a full summary of the range of densities for common plastics and access to relevant microplastic particle size distributions (especially at the Norwegian level). Car tyres have been identified as potentially one of the main sources of microplastic to the Norwegian marine environment, but their transport and dispersive modes of action are not currently well identified. Other types of microplastic will also be industry-specific and sampling in relevant locations (e.g. offshore oil, marine terminals, shipyards, wastewater treatment plant outlets etc) followed by detailed characterisation of microplastic physical and chemical properties is necessary. It is therefore suggested that generation of such data for key sources of microplastic is a focus in the near future. Furthermore, improved methods for separation, detection and identification of different microplastic particle types are needed[209]. This will facilitate estimation of *in situ* concentrations and environmental abundance and allow, in some cases, source identification.

There is a need for more information on the aging and degradation of plastic and microplastic in the ocean. With sufficient empirical data, modelling approaches be could developed to predict these processes under different marine environmental conditions (e.g. temperature, ice, wave action, biodegradation). This would also provide data that could later be used in modelling the fate and transport of microplastic more accurately. There is currently limited knowledge regarding the role of TEP on the heteroaggregation of microplastic with other naturally occurring particulate materials in the water column. These naturally produced chemicals promote particulate aggregation processes, but as their concentration can vary significantly from region to region, and seasonally, knowledge of their influence in the sedimentation of microplastic is needed. Furthermore, it would be important to study in more detail the role of plastic and microplastic as vectors for transporting human and animal pathogens to Norwegian waters. Modelling of plastic and microplastic transport into Norwegian waters has the potential to provide critical information in understanding this process and how viable such transport might be.

6 Discussion and conclusions

6.1 Are sediments the main environmental sink for plastic and microplastic?

The available information and the work conducted in this report support the suggestion that marine sediments act as global sinks and accumulation zones for plastic and microplastic pollution. The concentration of microplastic in sediment compartments is orders of magnitude higher than other environmental compartments. The high concentration of microplastic in marine sediments appears to be reflected in the higher concentrations of microplastic in benthic organisms compared to pelagic species. This indicates the general pathways to the sediments are either through direct transfer or through incorporation into marine snow and faecal material from marine organisms. Crude estimates of the distribution of the total number of microplastic particles in the marine environment indicated approximately 90% could be in global sediments. This is support by the modelling studies conducted as part of this report. These also indicate that approximately 90% of microplastic particles are likely to be transferred to the sediment compartment. The models suggest that this sedimentation processes occurs quite quickly meaning highest concentrations would be expected closest to the source.

The degradation of plastic items in the marine environment is very slow. This means that plastic and microplastic in the marine environment has a long time to undergo transport and sedimentation processes. Furthermore, many of the degradation processes (e.g. UV degradation, hydrolysis) change the physical and chemical properties of plastic in a way that might promote sedimentation. It is also important to note that once plastic has reached many sediment environments, the main degradation processes are slowed down (mechanical and biodegradation) or stopped completely (UV degradation).

There is insufficient data to be able to comment on the role of sedimentation for nanoplastic, and this requires further research. We currently have no data on the concentrations of nanoplastic in global sediments. At the nanoscale, particles may remain in the water column for much longer periods of time as they sediment more slowly. The process of heteroaggregation with other larger, denser particles and incorporation into marine snow could play a significant role in driving nanoplastic sedimentation.

6.2 Macroplastic litter as a source of microplastic in the marine environment

We know that both macroplastic and microplastic litter are ubiquitous across all marine environmental compartments. What remains unclear, is whether degradation of macroplastic items already in the environment represents the main source of microplastic or whether it is microplastic formed in the terrestrial environment and transported to the marine environment. The crude estimate that we have provided in this report suggests that 20% of the microplastic currently present in the world's oceans was formed through degradation of macroplastic litter already present in the marine environment. Correspondingly, it is estimated that the remaining 80% is formed as microplastic on land and subsequently transported to the marine environment.

The formation of microplastic from macroplastic items typically requires a combination of degradation mechanisms, most of which are very slow processes in the marine environment. This is especially the case in environmental compartments such as the water column below the photic zone and sediments where there is little or no UV and little turbulent energy. For microplastic that is formed through degradative processes in the marine environment, specific compartments are likely to be the main sources of microplastic formation. For example, coastal zones could be considered as the most likely regions for microplastic formation. In addition to higher exposure to UV, wave energy interacts more directly with shoreline and bottom sediments, which is likely to result in higher microplastic generation than open ocean areas with the same wave energy. However, there is currently insufficient laboratory research on the combination of UV light intensity and wave action intensity in breaking down microplastic to geographically identify higher intensity breakdown areas from lower intensity areas.

The terrestrial environment appears to be the larger source of microplastic to the marine environment. All plastic is produced on land, and the vast majority of plastic products are used, disposed of and processed on land. Marine environmental compartments most closely located to human activities are likely to be the main recipients of microplastic from terrestrial sources. In addition to the plastic materials manufactured at the micrometre-scale, there are a vast number of scenarios where anthropogenic activity is directly forming microplastic that is emitted into the environment. A small number of examples include (i) the generation of microplastic (and nanoplastic) particles from vehicle tyres whilst driving, (ii) generation of polymer paint particles during painting and renovation work, (iii) the generation of microfibres during the manufacture, use and washing of synthetic textiles and (iv) generation of microplastic during waste handling, processing and recycling processes. There are many processes that could contribute to the formation of microplastic on land, with potential formation at all lifecycle stages (production, use, disposal and waste processing). Once at the micrometre scale, plastic particles are very light and mobile meaning that they can easily be transported to the marine environment.

The degradation of plastic and the subsequent formation of microplastic in the marine environment has been demonstrated and certainly contributes the total microplastic load observed in the marine environment. However, the available literature indicates that terrestrial inputs must represent a sizeable proportion of the total load of microplastic currently in the marine environment. The estimates of microplastic sources produced for this report are based on high degree of uncertainty, but suggest that the terrestrial environment is currently the largest source of microplastic to the marine environment. However, further research is needed to fully understand which of these two microplastic sources is the main contributor to microplastic in the marine environment, and how this might change over time.

6.3 Estimated total load of microplastic in Norwegian marine environment today

One of the goals of this report is to estimate the load of microplastic in the Norwegian marine environment today. Most of the available studies investigating the occurrence and distribution of microplastic in the global environment report concentrations in terms of the number of particles. Therefore, we attempt to provide estimates of the microplastic load in the Norwegian marine environment in terms of particle number. Using estimated seawater surface areas, seawater volumes, sediment surface areas and biomass (fish) values, we utilise the data from the previous sections to estimate the current load of microplastic in the Norwegian marine environment. In addition, we have performed a modelling study of microfibers released from several European countries to quantify the mass of microfibres in the Norwegian marine environment. A summary of the global microplastic concentrations, estimated average total number of microplastic particles, and their estimated percentage distribution in key global marine environmental compartments was derived in Section 3 of the report and is summarised in Table 7.

Table 7. Summary of the estimated average global microplastic concentrations, estimated average total number of microplastic particles, and their estimated percentage in key global environmental compartments

Environmental compartment	Average global concentration (kg^{-1})	Estimated number of microplastic particles	Percentage distribution
Surface waters	0.79	1.42×10^{18}	0.21
Water column	4.2×10^{-2}	5.61×10^{19}	8.16
Sediments (all sediment compartments combined)	349.79	6.30×10^{20}	91.63
Fish species	1.46	2.04×10^{12}	3×10^{-7}
Total	**-**	**6.87×10^{20}**	**100.00**

We have used the same approach to estimate the average total number of microplastic particles and their estimated percentage distribution in Norwegian marine environmental compartments. We have again generated estimates for (i) surface waters, (ii) water column, (iii) total sediments, and (iv) fish biomass. Whilst global-level values for the size, volume or mass of these environmental compartments are available in the literature, we have had to estimate equivalent values for the Norwegian marine environment (defined as the Norwegian EEZ). We estimated that the sea surface area of the Norwegian EEZ is approximately 988 000 km^2. If we apply in reverse the approach we have used previously to convert the number of particles per km^{-2} to the number of particles kg^{-1} of seawater (see Section 3), we can use the microplastic concentrations estimated for Norwegian surface waters to estimate that the total amount of microplastic in Norwegian surface waters ranges from 1.68 x 10^{12} – 1.58 x 10^{13} particles, with an estimated average of 8.89 x 10^{12} particles (Table 8).

Table 8. Summary of the estimated average Norwegian microplastic concentrations, estimated total number of microplastic particles, and their estimated percentage in key Norwegian environmental compartments (based on estimated values from Norway)

Environmental compartment	Average Norwegian concentration (kg^{-1})	Estimated number of microplastic particles	Percentage distribution
Surface waters	1.8 x 10^{-3}	8.89 x10^{12}	1.6 x 10^{-3}
Water column	2.7 x 10^{-3}	2.35 x10^{15}	0.42
Sediments (all sediment compartments combined)	112.05	5.54 x10^{17}	99.58
Fish species	1.14	2.71 x10^{9}	4.9 x 10^{-7}
Total	**-**	**5.56 x10^{17}**	**100.00**

We have estimated that the Norwegian EEZ has a seawater volume of approximately 870 000 cubic kilometres (8.70 x 10^{14} m^3), which corresponds to approximately 8.70 x 10^{17} kg. For this we have assumed that 1 L of seawater weighs 1 kg, and we have not applied a factor to correct for seawater density, which ranges from 1020 to 1029 kg m^{-3}. If we apply in reverse the approach we have used previously to convert the number of particles m^{-3} to kg^{-1} (see Section 3), then can use the microplastic concentrations estimated for the Norwegian water column to estimate that the total amount of microplastic in the Norwegian water column is 2.33 x 10^{15} particles (Table 8). As there is only a single Norwegian water column concentration value available in the literature, we are not able to present a range estimate. Note that a sizeable proportion of the Norwegian EEZ can be considered deepsea, with only a very small proportion being considered shallow coastal zones. Based on the modelling work conducted in Section 5, we would expect the majority of microplastic to be present in the coastal water column, including the continental shelf.

We have already estimated that the Norwegian EEZ has a surface area of approximately 988 000 km^2. If we assume that the total area of marine sediments is similar, and apply in reverse the approach we have used previously to convert the number of particles km^{-2} to kg^{-1} (see Section 3), then we can use the microplastic concentrations estimated for Norwegian sediments to estimate that the total amount of microplastic in the Norwegian sediment compartment (beaches, shorelines, coastal sediments and deepsea sediments combined) ranges between 3.11 x 10^{16} and 1.48 x 10^{18} particles. The average number of microplastic particles in Norwegian sediments is estimated as 5.54 x 10^{17}, based on combining available data from all sediment compartments (Table 8). Note, this approach assumes a flat, even sediment surface and neglects the real seafloor topography. The true sediment surface area will be higher than 988 00 km^2.

The particle modelling work conducted in Section 5 did not store information about the size and density of sedimented particles, which means it is not straight forward to go from mass to number of fibres. However, an estimate can be built using the mass averaged fibre length (2750 µm) and the average fibre density (1200 kg/m^3). A single fibre would then have a mass of 5.832 x 10^{-10} kg. Using the average estimate for sediment mass in the Norwegian EEZ, 22828 tonnes (Table 6), this corresponds to 3.91 x 10^{16} fibres in the sediment (~200 fibres kg^{-1}), which is roughly an order of magnitude less than the estimate using average observed quantities (Table 8). Considering the uncertainties involved in both methods, and the fact that the modelling study only considered microfibres, the numbers can be considered a close match. This estimation has factored in sediment deposition rates for the North Sea (average ~0.1 cm/m^2/year)[210], and continuous mixing of the upper sediment layers through bioturbation (up to 10 kg m^{-2})[211]. Due to increased sedimentation rates over time, this will result in a concentration gradient of microfibers in the sediments, where the deep sediments have lower concentrations and upper sediment layers higher concentrations. In contrast to the sediment, the estimated mass of microfibre in the water column is only 20 tonnes, which corresponds ~3.9 x 10^{-5} fibres kg^{-1}. These data again show that the sediments represent the major accumulation zone globally and in the Norwegian marine environment.

Although there is a global estimate available for the total biomass of fish in the world's oceans[88], comparable data for the biomass of fish (and other marine organisms) in the Norwegian marine environment is not available. Therefore, we have estimated this value by calculating the percentage contribution of Norwegian surface water area and the Norwegian water column volume to the global values in the literature. Norwegian surface water (defined as the Norwegian EEZ) represents approximately 0.27% of the global marine surface waters, whereas the Norwegian water column represents approximately 0.065% of the global water column volume. We have then taken the average of these two values (0.17%) and utilised this as a conversion factor for estimating the biomass of fish in the Norwegian EEZ from the global value (1.4 billion tonnes).

This approach provides a very rudimentary estimate of Norwegian fish biomass of 2.4 million tonnes. If we simply convert the microplastic concentrations determined for fish in Norwegian waters from the number of particles kg^{-1} to the number of particles tonne^{-1}, and multiply by 2.4 million, we can estimate that the total amount of microplastic in Norwegian fish ranges from 1.19 x 10^9 and 5.94 x 10^9 particles, with an estimated average of 2.71 x 10^9 particles (Table 8). We acknowledge that our approach for estimating the biomass of fish in the Norwegian EEZ represents a significant source of uncertainty. The Norwegian EEZ represents a region of high productivity, whereas the global fish biomass estimate the average of all marine waters representing a broad range of productivities.

The estimated total microplastic load in each of the selected Norwegian environmental compartments is summarised in Table 8. By adding the values for the different environmental compartments together, we generate a total microplastic load in the Norwegian marine environment of 5.56 x 10^{17} particles. When the relative distribution of the amounts of microplastic in the marine environment is calculated, we see that >99% is estimated to be in the sediment compartment (Table 8, Figure 3). Less than 1% is estimated to be in the water column and an extremely small percentage is estimated to be in surface waters and fish.

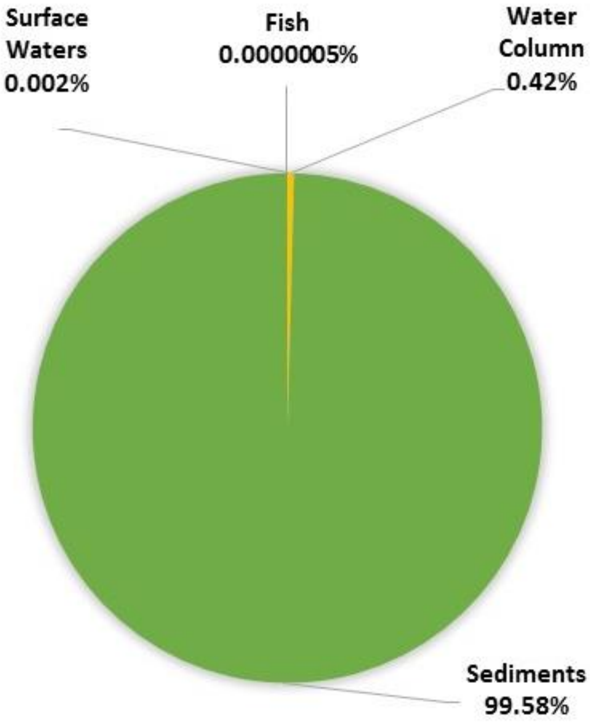

Figure 28. Percentage distribution of microplastic in Norwegian environmental compartments, estimated using calculated average Norwegian microplastic concentrations.

The estimated average concentrations for the different environmental compartments in the Norwegian EEZ are based on a very small number of data points. As a comparison, we have also estimated the total number and distribution of microplastic particles in Norwegian marine environmental compartments using the global average concentration values instead of Norwegian-only values. We have combined these with the Norwegian EEZ estimates for surface water area, water column volume, sediment area and fish biomass as a basis (Table 2). The total amount of microplastic in Norwegian surface waters is estimated to range from 4.20×10^9 – 7.90×10^{16} particles, with an average of 3.90×10^{15} particles. The total amount of microplastic the Norwegian water column is estimated to range from 1.48×10^{13} – 2.44×10^{17} particles, with an average of 3.65×10^{16} particles. The total amount of microplastic in Norwegian sediments is estimated to range from 7.41×10^{13} – 2.14×10^{19} particles, with an estimated average of 1.73×10^{18} particles. The total amount of microplastic in Norwegian fish is estimated to range from 7.13×10^7 – 1.71×10^{10} particles, with an estimated average of 3.47×10^9 particles.

By adding the total microplastic values for the different environmental compartments together (Table 2), we estimated a total microplastic load in the Norwegian marine environment of 1.77 x 10^{18} particles. When the relative distribution of the amounts of microplastic in the marine environment is calculated, we see that >97% is estimated to be in the sediment compartment (Figure 29). Approximately 2% is estimated to be in the water column, approximately 0.2% is estimated to be in fish and an extremely small percentage is estimated to be in surface waters.

Table 9. Summary of the estimated average global microplastic concentrations, estimated total number of microplastic particles, and their estimated percentage in key Norwegian environmental compartments (based on estimated global values)

Environmental compartment	Average global concentration (kg^{-1})	Estimated number of microplastic particles	Percentage distribution
Surface waters	0.79	3.90 x10^{15}	0.22
Water column	4.2 x 10^{-2}	3.65 x10^{16}	2.07
Sediments (all sediment compartments combined)	349.79	1.73 x10^{18}	97.71
Fish species	1.46	3.47 x10^{9}	2 x 10^{-7}
Total	**-**	**1.77 x10^{18}**	**100.00**

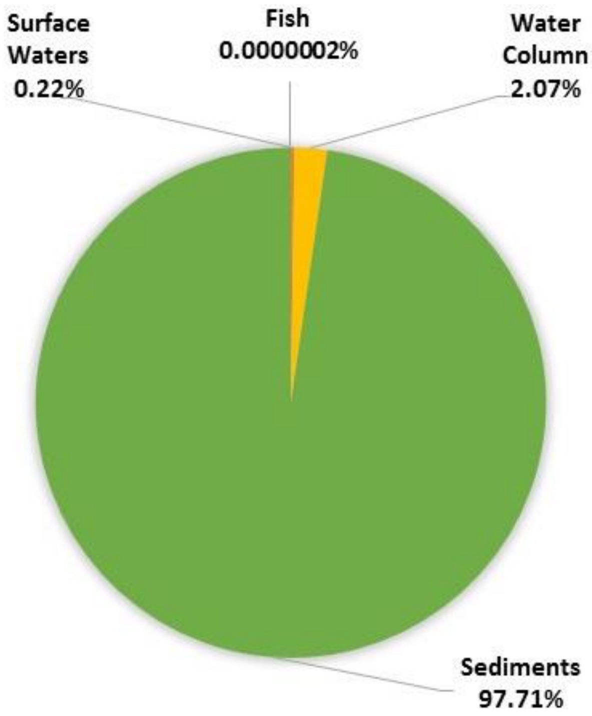

Figure 29. Percentage distribution of microplastic in Norwegian environmental compartments, estimated using calculated average global microplastic concentrations.

The percentage distribution of microplastic across the different environmental compartments is largely similar when this is estimated using either Norwegian (Figure 3) or global (Figure 29) microplastic concentrations. Importantly, the estimated distributions both suggest that over 90% of microplastic currently present in the Norwegian marine environment will be in the sediment compartment. A small percentage is expected to be in the water column and a very small proportion is suggested to be in surface waters and the biomass. At the global level, the sediments are estimated to contain over 90% of microplastic in the marine environment (Table 7). This is in agreement with the microfibre transport modelling in Section 5, which showed that more than 90% of released microfibre by mass ended up in the sediments. The distributions estimated for the global and Norwegian levels are generally very similar, supporting the suggestion that sediments are the major sink and accumulation zone for microplastic. Interestingly, the total microplastic loads estimated for the Norwegian marine environment using the Norwegian average concentration values (5.56×10^{17}, Table 8) are reasonably similar to the values estimated when using global average concentration values (1.77×10^{18}, Table 9), being less than an order of magnitude in difference.

Although we have presented estimate values for the total load of microplastic in the Norwegian marine environment, there are two key issues to consider. Firstly, these numbers are based a high level of uncertainty arising from the need to make multiple assumptions during the calculations. As a result, they should be interpreted and used with this in mid. Secondly, these numbers are based on reported microplastic concentrations in Norwegian and global marine environments. These data are limited in scope, especially for the Norwegian marine environment, and would be significantly improved if larger data sets were available. Perhaps more important, is the fact that most studies at the global and Norwegian scale report microplastic concentrations in the marine environment where there were limitations in the size of particles that could be measured. In many cases only larger microplastic items (>300 µm) are identified and counted in such studies, with smaller particles typically not included. We expect there to be proportionally higher amounts of microplastic particles in the lower size range (e.g. <100 µm) and even more at the nano-scale[6, 9-11]. As a result, the estimated load of microplastic in Norwegian environmental compartments (Table 8, Table 9) is likely to underestimate the real load of microplastic particles in the Norwegian marine environment.

6.4 Estimated total load of microplastic in the Norwegian marine environment in 10 years

Using estimates for the current load of microplastic in combination with estimated plastic production volumes since 1950 and values predicted until 2027, we attempt to estimate the total load of microplastic in the Norwegian marine environment in 10 years' time. The estimates assume that the proportion of produced plastic that is released into the environment up until today will remain constant over the next 10 years. We do not factor in any implementation of measures designed to reduce the emissions of plastic litter to the marine environment that may come into force within the next decade.

Though plastic production is increasing worldwide[133, 212], long-term sampling studies indicate that the concentration of microplastic at the ocean surface in the major gyres areas is at steady state (Table 10)[29, 213]. A recent, detailed global simulation of macro- and micro-plastic also indicates that once all the sources are stopped, the ocean surface layer would be free of plastic in 3 years[214]. However, in other regions (e.g. coastal and polar) studies suggest that the concentration of macro- and microplastic litter is currently increasing in both marine waters and sediments over time (Table 10)[87, 124, 215]. Litter concentrations have increased (3635 to 7710 items km^{-2}) on the deep-sea floor over time in the Arctic between 2002-2011[215] and 2002-2014[87]. However, the number of plastic litter items at HAUSGARTEN did not increase gradually, indicating either a large variability in sampling or burial of plastics in the sediments[215]. Another study has shown that microplastic debris in the North Pacific has increased by two orders of magnitude between 1972–1987 and 1999–2010 in both numerical and mass concentrations[216]. These results indicate that overall concentrations in the major gyres is not increasing, while coastal amounts are increasing. This suggests that microplastic fibres and particles are removed from the sea surface rather rapidly (e.g. sinking due to biofouling, packaging into faecal pellets) close to the source of entry into the ocean.

Table 10. Summary of selected long-term microplastic sampling and modelling studies.

Study area	Reference	Length of study	Results
Global ocean	Koelmans et al (2017)[214]	Model scenarios between 1950 - 2100	Steady state
Baltic Sea	Beer et al (2017)[213]	Sampling from 1987 - 2015	Steady state
North Atlantic Ocean and Caribbean Sea	Law et al (2010)[29]	Sampling from 1986 - 2008	Steady State
North Atlantic near Iceland; UK to Iceland	Thompson (2004)[124]	Sampling from archival beach samples from beaches	Significant increase over time.
North Atlantic near Iceland; UK to Iceland	Thompson (2004)[124]	Sampling from plankton tows since 1960s – 1990s	Significant increase over time from 1960s/1970s to 1980s/1990s
Arctic deep-sea HAUSGARTEN observatory	Bergmann et al., (2012)[215]; Tekman et al., (2017)[87]	Seafloor floor analysis of plastic litter (79°N, 2500 m depth)	Significant increase from 2002-2014

Based on the available data, it is difficult to ascertain a rate of increase of microplastic in the marine environment. To estimate the change in number of particles from 2017 to 2027, we have therefore used the increase in total global plastic production. The global production of plastic increased by 8.8% from 1950 to 2010, and by 3.6% from 2010 to 2015[133, 212]. Note that these numbers do not include production of synthetic fibres; but the corresponding growth factors for fibres are comparable, see section 5.4. Assuming that plastic production increased with 3.6% from 2015 to 2017, and assuming no further increase in annual plastic production volumes from 2017-2027, the accumulated global plastic production is estimated to be 5018 million tonnes in 2017 and 8173 million tonnes in 2027, representing an increase of 63%. If the number of plastic items in the ocean is proportional to global production, we can estimate an increase from the 2017 numbers by the increase in total produced plastic. Furthermore, a proportion of the macroplastic and microplastic litter present in the environment in 2017 will have undergone degradation processes to form 'new' microplastic. Given the uncertainties regarding macroplastic and microplastic degradation at scale, it is not straight forward to estimate the contribution from degradation. However, given that most particles reside in the sediments where degradation is slow, we believe that the contribution is small relative to the continuous contribution from terrestrial inputs. Given these assumptions, the estimated number of microplastic particles present in the Norwegian marine environment in 2027 (and individual marine environmental compartments) is estimated in Table 11. We can see that the total load microplastic in the Norwegian marine environment is expected to increase from 1.77 $x10^{18}$ particles today, to 2.91×10^{18} particles in 2027. This corresponds to an increase of approximately 64% over the next decade.

Table 11: Projected number of microplastic particles present in the Norwegian marine environment in 2027.

Environmental compartment	Estimated number of microplastic particles in 2027
Surface waters	6.41×10^{15}
Water column	6.00×10^{16}
Sediments (all sediment compartments combined)	2.84×10^{18}
Fish species	5.70×10^{9}
Total	**2.91×10^{18}**

The particle modelling work conducted in Section 5 allowed us to estimate the number (3.91×10^{16} fibres) and concentration (~200 fibres kg^{-1}) of microfibres currently present in Norwegian EEZ sediments. Similarly, we estimated the number (3.43×10^{13} fibres) and concentration (~3.9×10^{-5} fibres kg^{-1}) of microfibres present in the Norwegian EEZ water column. Extrapolating our numbers based on estimated increase in synthetic fibre production, we estimate that up to 38000 tonnes of microfibre will be present in the Norwegian EEZ sediment (~330 fibres kg^{-1}) and 29 tonnes in the water column (~5.7×10^{-5} fibres kg^{-1}) 10 years from now.

6.5 Further research needs

6.5.1 Microplastic distribution

Here we provide a summary of the knowledge gaps that we believe are currently preventing an accurate assessment of microplastic distributions in the global and Norwegian marine environment.

- The most critical knowledge gap is the lack of data concerning the concentration of microplastic in different marine environmental compartments at the global scale.
- There remains an urgent need for more information about microplastic concentrations in all environmental matrices along the Norwegian coast as currently data is very limited or simply not available for some compartments and regions.
- Recurrent sampling of locations is necessary so that the concentration of microplastic in key environmental compartments can be monitored over time.
- There needs to be a system for compiling the existing and new data so that it can be archived and utilised more readily in the future.
- To improve reliability and comparability of data, standardised methods and approaches are needed for collection and processing of environmental samples, and for the identification and quantification of microplastic.
- Future studies need to include more detailed physical (e.g. particles, fragments, fibres) and chemical (polymer type and additive chemical content) characterisation which utilise diagnostic approaches for their unequivocal identification as microplastic (e.g. ATR-FTIR, µFTIR and pyrolysis GC-MS techniques).
- More focus on the relative importance of less studied groups of microplastic that have been proposed as major sources to the marine environment (e.g. microfibres from clothing and particles from car tyres).
- There is a need to develop methods to separate, recover, characterise and quantify small microplastic (<100 µm) and nanoplastic in order to study their distribution in marine environmental compartments.
- Investigation into the potential for using larger microplastic (>300 µm) concentrations as a proxy for accurately estimating the concentration of smaller microplastic (<100 µm) and nanoplastic.
- There is a need to study the importance of plastic additive chemicals and their potential to leach from macro- and microplastic into environmental matrices (waters, sediments and biota).

6.5.2 Plastic and microplastic degradation

There remain several key knowledge gaps that prevent a true understanding of the persistence of plastic in the marine environment being determined. Here we provide a summary of the knowledge gaps that we believe are currently preventing an accurate assessment of microplastic degradation in the global and Norwegian marine environment.

- All degradation mechanisms of plastic in the marine environment are extremely slow processes, and there is a need to develop accelerated, but environmentally relevant, test methods at the laboratory scale.
- As the specific degradation rate of a plastic item depends on many factors, there is a need to have a clearer understanding of plastic degradation mechanisms and rates under different environmental conditions and in different environmental compartments.
- There is a specific lack of studies conducted under conditions that represent relevant Norwegian environmental and climatic conditions, which needs to be addressed in future studies.
- We suggest our understanding of plastic degradation in the Norwegian environment would be significantly improved by the establishment of well-designed, long-term field studies (e.g. a minimum of 10-20 years in duration, with sampling in different seasons), that are comparable to existing monitoring studies.
- There is a need to understand more clearly the products and intermediates formed during plastic degradation.
- The development and implementation of computer simulations for environmental degradation mechanisms should be considered to predict the lifetime of plastics and their degradation products.
- There needs to be further research into the role of plastic degradation and aging (e.g. biofilm formation, chemical alteration) on the potential impacts of micro- and nanoplastic in the marine environment.
- There also needs to be a focus on understanding the role plastic additive chemicals have in the degradation of plastic items in the marine environment, especially as many additives are included to prolong the lifetime of plastic materials (e.g. stabilisers).
- The role of plastic degradation processes on the release/leaching of plastic additive chemicals needs to be studied, including the degradation of the additive chemicals and formation of chemical intermediates and products.
- Oxo-degradable and biodegradable plastic materials need to be urgently studied and compared to conventional plastics in terms of their true and environmental fate, persistence and potential for impacts.
- Further study is needed into whether oxo-degradable and biodegradable materials offer a genuine long-term benefit over conventional plastics, which are currently easier to collect and recycle into new products.

6.5.3 Microplastic transport

Here we provide a summary of the knowledge gaps that we believe are currently preventing an accurate assessment of microplastic distributions in the Norwegian marine environment.

- It is necessary to determine the settling velocities for microplastic particles originating from car tyres and other specific sources. Relevant size classes and densities of these particles should be obtained from environmental samples, both in the water column and in the sediments.

- To determine long-term fate, there is a need to investigate the potential for flocculation with other marine particles, such as sinking detritus after algae blooms. Also in need of study for long term fate is the potential for biodegradation and particle breakup under relevant environmental conditions. The focus should be on the most prevalent particles, such as those from fibres, tyres, and paint.
- Atmospheric modelling studies are needed to estimate the contribution of atmospheric transport to input of microfibers to the marine environment. This work requires samples from the atmosphere from multiple stations at multiple heights to determine relevant microplastic types and size spectra.
- When additional information is available about settling velocities, size distribution, and atmospheric transport, further transport modelling studies of specific microplastic classes is needed to estimate the fate of different particle types in the marine environment.
- Descriptions of local microplastic types, particle size distribution and degradation needs standardised methodologies and reporting of these data such that spatial databases should be constructed. This effort would improve larger scale modelling of the Norwegian EEZ and in general.
- Insufficient data exists on microplastic from melting Arctic Sea Ice to quantify this potential source.
- More studies are needed to investigate the potential for Lagrangian Coherent Structure modelling to provide guidance on the location, transport and overall mass balance of microplastic.
- Spatial data from Australia indicates that the offshore oil industry could be a source of microplastic comparable in volumes to urban sources, but which may have distinctive characteristics. Comparable studies for the Norwegian offshore oil industry should be conducted.

7 References

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Appendices

Appendix A: Summary of global microplastic concentration data for different environmental compartments.

Table A1. Reported concentrations of microplastics in global marine surface waters

Environmental Compartment	Concentration of plastic particles	No. Particles kg^{-1}	Sampling method	Comments	Reference
Surface Water	334271 particles km^{-2} 5114 g km^{-2}	0.00223	Manta net	North Pacific central gyre	Moore et al., 2001[217]
Surface Water	0.2-1.0 particles m^{-3} 0.02-0.04 mg m^{-3}	0.0006	Manta net	Santa Monica Bay, California (offshore); range represents before and after storm conditions	Lattin et al., 2004[56]
Surface Water	0.5-18.5 particles m^{-3} 0.002-2.4 mg m^{-3}	0.0095	Manta net	Santa Monica Bay, California (nearshore); range represents before and after storm conditions	Lattin et al., 2004[56]
Surface Water	7.25 m^{-3}	0.00725		Southern California coast	Moore et al., 2002[218]
Surface Water	Average of 0.65 particles L^{-1}	0.65	Rotating drum sampler	Singapore; mostly polyethylene	Ng and Obbard, 2006[219]
Surface water	0.12 particles m^{-3}	0.00012		North Pacific Subtropical Gyre	Goldstein et al., 2012[216]
Surface Water	0.004–0.19 m^{-3} 0.000097 L^{-1}	0.000097	Sameota sampler/ manta net	Bering Sea, North East Pacific Ocean coast	Doyle et al., 2011[220]
Surface Water	85,184 km^{-2}	0.000017	Manta net	North Pacific central gyre	Carson et al. 2013[221]
Surface Water	0.011–0.033 m^{-3}	0.000022	Manta net	South Californian current system	Gilfillan et al., 2009[222]
Surface Water	0.02–0.45 m^{-2}	0.0000466	Manta net	North Pacific subtropical gyre	Goldstein et al., 2013[11]
Surface Water	174,000 (±467,000) km^{-2}	0.000034	Neuston net	North Pacific Kuroshio current system	Yamashita and Tanimura, 2007[223]
Surface Water	4137.3 (±8.2 × 104) m^{-3}	4.1373	Neuston net	North Pacific, Yangtze estuary system, East China Sea	Zhao et al., 2014[224]
Surface Water	16000 (±14 × 103) m^{-3}	16	Bulk sampling, hand-net, manta net	North Pacific, Geoje Island, South Korea	Song et al., 2014[54]

Surface Water	26898 (±60818) km^{-2}	0.0000054	Manta net	South Pacific subtropical gyre	Eriksen et al., 2013[225]
Surface Water	4256.3 (±757.8) km^{-2}	0.00000085	Manta net & Neuston net	South Pacific, Australian coast	Reisser et al., 2013[51]
Surface Water	800-66300 km^{-2}	0.00000658	Neuston net	Western Pacific Ocean	Uchida et al., 2016[226]
Surface Water	150–2400 m^{-3}	1.275	Manta net (80 µm)	West Coast of Sweden	Norén, 2007[72]
Surface Water	0.01–0.14 m^{-3}	0.000075	Manta net (450 µm)	West Coast of Sweden	Norén, 2007[72]
Surface Water	1.33 m^{-2}	0.00027	Manta net	Northwest Mediterranean	Collignon et al., 2012[227]
Surface Water	0.062 m^{-2}	0.000012	WP-2 type net	Bay of Calvi, Corsica, France	Collignon et al., 2014[228]
Surface Water	0.15 m^{-3}	0.00015	Manta net	Gulf of Oristano, Sardinia, Italy	de Lucia et al., 2014[229]
Surface Water	0–0.74 m^{-3}	0.00037	Manta net	North Sea, Finland	Magnusson, 2014[230]
Surface Water	1720000 km^{-2}	0.000344	Neuston net	East Asian seas around Japan	Isobe et al., 2015[231]
Surface Water	100000 km^{-2}	0.000042	Neuston net	Southern Ocean (Polar)	Isobe et al., 2017[78]
Surface Water	0.31 m^{-3}	0.00031	Neuston net	Pelagos Sanctuary, Mediterranean Sea	Fossi et al., 2016[232]
Surface Water	0.49 m^{-3}	0.00049	Neuston net	Ligurian Sea, Mediterranean	Fossi et al., 2016[232]
Surface Water	0.16 m^{-3}	0.00016	Neuston net	Sardinian Sea, Mediterranean	Fossi et al., 2016[232]
Surface Water	0.00 - 0.14 m^{-3}	0.00007	Neuston net	Sea of Cortez (La Paz Bay), Gulf of California	Fossi et al., 2016[232]
Surface Water	257.9 - 1215 m^{-3}	0.73645	WP-2 type net	South-eastern coastline of South Africa	Nel and Froneman, 2015[233]
Surface Water	>1000 particles m^{-2}	n/a	Plankton net	North Pacific subtropical gyre	Law et al., 2014[53]

If the concentration of microplastic particles were not reported in m^{-3}, the values have been converted as follows[52]:

(1) km^{-2} to m^{-2} calculated by division by 1,000,000 followed by multiplication by 0.2 m

(2) m^{-2} to m^{-3} calculated by 0.2 multiplication

Table A2. Reported concentrations of microplastics in global marine water columns

Environmental Compartment	**Concentration of plastic particles**	**No. Particles kg^{-1}**	**Sampling method**	**Comments**	**Reference**

Water column	0.017 particles m^{-3}	0.000017	Bongo net	North Pacific central gyre, sampling at 10-30 m	Moore et al., 2005[58]
Water column	0.2-0.4 particles m^{-3} 0.01-0.02 mg m^{-3}	0.0003	Bongo net	Santa Monica Bay, California (offshore); range represents before and after storm conditions	Lattin et al., 2004[56]
Water column	1-11 particles m^{-3} 0.01-0.13 mg m^{-3}	0.006	Bongo net	Santa Monica Bay, California (nearshore); range represents before and after storm conditions	Lattin et al., 2004[56]
Epibenthic (near bottom)	1.5-6 particles m^{-3} 0.12- 0.25 mg m^{-3}	0.00375	Epibenthic sled	Santa Monica Bay, California (offshore); range represents before and after storm conditions	Lattin et al., 2004[56]
Water column	8-9180 particles m^{-3}, Ave 279	0.279		Sub-surface seawaters (4.5 m below surface) of the northeastern Pacific Ocean and coastal British Columbia. Over 75% were fibres.	Desforges et al., 2014[37]
Water Column	1.69 m^{-3}	0.00169	Multi-level trawl	North Atlantic subtropical gyre to a depth of 5 m	Reisser et al., 2015[55]
Water Column	2.46 m^{-3}	0.00246	Pumped on to boat	North Atlantic, Celtic Sea to a depth of 3 m	Lusher et al., 2014[57]

Table A3. Reported concentrations of microplastics on global shorelines and beaches

Environmental Compartment	Concentration of microplastic	Concentration of microplastic (kg^{-1})	Plastics observed	Comments	Reference
Shoreline	8-124 particles L^{-1} of sediment	16	polyester (56%), acrylic (23%), polypropylene (7%), polyethylene (6%), and polyamide fibres (3%). High proportion of fibres.	Study of 18 shorelines from 6 continents	Browne et al., 2011[25]
Shoreline	10 L^{-1}	10	Fragments and fibres	Beach UK site	Thompson et al., 2004[124]
Shoreline	90 particles L^{-1} of sediment	90		Chagos Archipelago, Indian Ocean	Readman et al., 2013[234]

Shoreline	Average of 95 particles kg^{-1} dry sediment	95	Fibres, granules, films	Beach locations in Belgium	Claessens et al., 2011[189]
Shoreline	Average of 1 particles kg^{-1} dry sediment	1		Singapore; polymers polyethylene and polypropylene, as well as other such as polyvinyl alcohol, acrylonitrile butadiene styrene, polystyrene and nylon	Ng and Obbard, 2006[219]
Shoreline	28.6-392.8 particles m^{-2} Ave 185.1 particles m^{-2}	1.851	Pellets and fragments	Portuguese coastline	Martins and Sobral, 2011[235]
Shoreline	0.7-167 m^{-2}	0.8385	Pellets	Maltese coast, Mediterranean	Turner and Holmes 2011[236]
Shoreline	0-62100 particles kg^{-1} d.w. 3800 kg^{-1} d.w.	3800	Fibres and granules	Beaches of the East Frisian Islands	Liebezeit and Dubaish, 2012[32]
Shoreline	37.8 kg^{-1}	37.8	Fragments 1–15 mm	North Pacific, 9 beaches, Hawaiian islands	McDermid and McMullen, 2004[237]
Shoreline	4.9 kg^{-1}	4.9	Pellets 1–15 mm	North Pacific, 9 beaches, Hawaiian islands	McDermid and McMullen, 2004[237]
Shoreline	29 m^{-2}	0.29	Fragments and pellets	Coastal beaches, Russia	Kusui and Noda, 2003[69]
Shoreline	>1,000 m^{-2}	n/a	Pellets	Tokyo, Japan	Kuriyama et al., 2002[238]
Shoreline	1.52 m^{-2}	0.0152	Pellets and Fragments	North Pacific, Coastal beaches, Japan	Kusui and Noda, 2003[69]
Shoreline	PS spheres 874 (±377) m^{-2} Fragments 25 (±10) m^{-2} Pellets 41 (±19) m^{-2}	9.4		North Pacific, Heugnam Beach, South Korea	Heo et al., 2013[67]
Shoreline	30 m^{-2}	0.3	Fragments and pellets 1–10 mm	Pacific, Coastal beaches, Chile	Hidalgo-Riz and Thiel, 2013[239]

Shoreline	1-805 m^{-2}	4.03	Fragments and pellets 1–10 mm	Pacific, Easter Island, Chile	Hidalgo-Riz and Thiel, 2013[239]
Shoreline	200–800 fibres kg^{-1}	500	Fibres	Atlantic, Nova Scotia, Canada	Mathalon and Hill, 2014[85]
Shoreline	1289 m^{-2}	12.89	Pellets 3–6 mm	Atlantic, Portuguese coast	Antunes et al., 2013[240]
Shoreline	<1 g kg^{-1} – >40 g kg^{-1}	n/a	Pellets and fragments <5 mm	Atlantic, Canary Islands, Spain	Baztan et al., 2014[241]
Shoreline	3.5 kg^{-1} (Pellets 23 %) 9.63 kg^{-1} (Fragments 65 %) 0.73 kg^{-1} (Nylon monofilament 5 %)	13.86	Pellets, fragments and fibres	Atlantic, Fernando de Noronha, Brazil	Ivar do Sul et al., 2009[68]
Shoreline	300,000 m^{-3}	300	Pellets (3.3 %) and fragments (96.7 %)	Atlantic, Recife, Brazil	Costa et al., 2010[242]
Shoreline	59 m^{-3}	0.059	Fragments 1–10 mm	Atlantic, Northeast Brazil	Costa et al., 2011[243]
Shoreline	0–2500 m^{-3}	1.25	Pellets	Atlantic, Santos Bay, Brazil	Turra et al., 2014[244]
Shoreline	152 kg^{-1}	152	Fibres and granules	Jade System, Germany	Dubaish and Liebezeit, 2013[245]
Shoreline	1.3-2.3 kg^{-1} d.w.	1.8	Fragments	Norderney, Germany	Dekiff et al., 2014[246]
Shoreline	17 kg^{-1}	17	Pellets and fragments	Beach, Belgium	Van Cauwenberghe et al., 2013[247]
Shoreline	672–2175 kg^{-1} d.w.	1423.5	Fragments and fibres	Venice lagoon, Italy	Vianello et al., 2013[248]
Shoreline	10-575 m^{-2}	2.925	Pellets	Kea Island, Greece	Kaberi et al., 2013[249]
Shoreline	81.4 mg kg^{-1}	n/a	Fragments	India Ship-breaking yard	Reddy et al., 2006[250]
Shoreline	5000–7000 m^{-3}	6		Germany, Urban beach	Ballent et al., 2012[171]
Shoreline	150–700 m^{-3}	0.425		Germany, Rural beach	Ballent et al., 2012[171]
Shoreline	36.8 kg^{-1}	36.8	Fibres, grains, fragments	Coastline, Singapore	Nor and Obbard, 2014[251]

Shoreline	<18 m^{-2}	n/a	Pellets	Selangor, Malaysia	Ismail et al., 2009[252]
Shoreline	10-180 m^{-2}	0.95		India, Beach in Mumbai	Jayasiri et al., 2013[253]
Shoreline	Dry season 8205 m^{-2}	82.05		South Korea Beach	Lee et al., 2013[70]
Shoreline	Rainy season 27606 m^{-2}	276.06		South Korea Beach	Lee et al., 2013[70]
Shoreline	56-285673 m^{-2}	1428.645		South Korea Beach	Kim et al., 2015[254]
Shoreline	177.8 kg^{-1} d.w.	177.8		Slovenia beach, Mediterranean Sea	Laglbauer et al., 2014[255]
Shoreline	12–1300 m^{-2}	6.56	Fibres, fragments, styrofoam, pellets	Beaches of Guanabara Bay, Southeast Brazil	Carvalho and Baptista Neto, 2016[256]
Shoreline	63–201 kg^{-1}	132		Chinese Bohai Sea	Yu et al., 2016[257]
Shoreline	3120-5560 kg^{-1} w.w.	4340	Beads and pellets	Burrard Inlet, British Columbia, Canada	Boucher et al., 2016[63]
Shoreline	30,900 m^{-3}	30.9		Milnerton beach in Table Bay, South Africa	MSc thesis cited by Nel and Froneman, 2015[233]
Shoreline	688.9-3308 m^{-2}	19.9845		South-eastern coastline of South Africa	Nel and Froneman, 2015[233]

Table A4. Reported concentrations of microplastics in global sediments

Environmental Compartment	Concentration of microplastic	Concentration of microplastic (kg^{-1})	Plastics observed	Comments	Reference
Sediment	0.1-0.9 particles g^{-1} sediment	500	High levels of fibres	Mediterranean Sea, coastal shallow sediments	Alomar et al., 2016[49]
Sediment	120 L^{-1} 86 kg^{-1}	86	Fragments and fibres	Subtidal UK site	Thompson et al., 2004[124]
Sediment	80 L^{-1} 31 kg^{-1}	31	Fragments and fibres	Estuary UK site	Thompson et al., 2004[124]
Sediment	Average of 167 particles kg^{-1} dry sediment	167	Fibres, granules, films, spheres	Harbour locations in Belgium	Claessens et al., 2011[189]
Sediment	Average of 126 particles kg^{-1} dry sediment	126	Fibres, granules, films	Continental shelf of Belgium	Claessens et al., 2011[189]

Sediment	105 kg^{-1}	105	Pellets and fragments	Atlantic, Maine, USA	Graham and Thompson, 2009[258]
Sediment	214 kg^{-1}	214	Pellets and fragments	Atlantic, Florida, USA	Graham and Thompson, 2009[258]
Sediment	20 kg^{-1}	20	Fragments	Harbor sediment, Sweden	Norén, 2007[72]
Sediment	50 kg^{-1}	50	Fragments	Harbor sediment, Sweden	Norén, 2007[72]
Sediment	3320 kg^{-1}	3320	Pellets	Industrial harbour sediment, Sweden	Norén, 2007[72]
Sediment	340 kg^{-1}	340	Pellets	Industrial coastal sediment, Sweden	Norén, 2007[72]
Sediment	16-766 m^{-2}	3.91	Fragments and fibres	Mackellar Inlet, South Shetland Islands, Southern Ocean	Waller et al., 2017[71]
Sediment	170.4 kg^{-1} d.w.	170.4		Slovenia infralittoral, Mediterranean Sea	Laglbauer et al., 2014[255]
Sediment	1491 L^{-1}	1491		Durban harbour, South Africa	MSc thesis cited by Nel and Froneman, 2015[233]

Table A5. Reported concentrations of microplastics in deepsea sediments

Environmental Compartment	**Concentration of microplastic**	**Concentration of microplastic (kg^{-1})**	**Plastics observed**	**Comments**	**Reference**
Deepsea sediment	1.4-40 particles L^{-1} of sediment Average 268 particles L^{-1} of sediment	268	All fibres 2-3 mm in length	Data from 12 locations including subpolar North Atlantic, North East Atlantic, Mediterranean, South West Indian oceans collected from 300-3500 m depth. Dominated by polyester fibres.	Woodall et al., 2014[35]
Deepsea sediment	60-2000 particles m^{-2}	10.3	Over 75% were fibres.	Samples collected from 4869-5766 m along the Kuril-Kamchatka Trench (NW Pacific).	Fischer et al., 2015[73]
Deepsea sediment	40 m^{-2}	0.4	Fragments	Atlantic, Porcupine abyssal plain	Van Cauwenberghe et al., 2013[36]

Deepsea sediment	40 m^{-2}	0.4	Fragments	Southern Atlantic	Van Cauwenberghe et al., 2013[36]

Table A6. Reported concentrations of microplastics polar environments

Environmental Compartment	Concentration of plastic particles	No. Particles kg^{-1}	Comments	Reference
Sea Ice				
Arctic Sea Ice	38 to 234 particles m^{-3} of ice	0.136	Sea ice cores from Arctic Ocean	Obbard et al., 2014[75]
Arctic Sea Ice	2x10^{-6} particles m^{-3} in pack ice	0.000000002	Ice cores from the western and eastern Fram Strait	Bergmann et al., 2017[76]
Arctic Sea Ice	6x10^{-5} particles m^{-3} in land-locked ice	0.00000006	Ice cores from the western and eastern Fram Strait	Bergmann et al., 2017[76]
Polar waters				
Arctic surface Water	0-1.31 particles m^{-3} Average 0.34 particles m^{-3}	0.00034	Barents Sea. Collected in the top 16 cm of seawater using a manta net. 95 % fibres. single sample which was free from microplastics was found furthest offshore.	Lusher et al., 2015[34]
Arctic water Column	0-11.5 particles m^{-3} Average 2.68 particles m^{-3}	0.00268	Collected at a depth of 6 m.	Lusher et al., 2015[34]
Antarctic surface water	0.100–0.514 g km^{-2}	n/a	South of the Polar Front	Cózar et al., 2014[60]
Antarctic surface water	0.55–56.58 g km^{-2}	n/a	Southern Ocean	Eriksen et al., 2014[6]
Antarctic surface water	22 particles L^{-1}	22	Southern Ocean	AdventureScience.org, 2016[77]
Antarctic surface water	46,000–99,000 particles km^{-2}	0.0000145	Southern Ocean (south of 60°S)	Isobe et al., 2016[78]
Polar sediments				
Antarctic sediment	16 and 766 synthetic particles m^{-2}	3.91	Inlet, South Shetland Islands, Southern Ocean	Waller et al., 2017[71]
Arctic sediment	42–6595 microplastics kg^{-1}	33.19	Nine sediment samples taken at the HAUSGARTEN observatory in the Arctic at 2340–5570 m depth	Bergmann et al., 2017[79]

Table A7. Reported concentrations of microplastics in marine fish species

Species	**Order**	**Reported Concentration of microplastic**	**Concentration of microplastic (kg^{-1})**	**Plastics observed**	**Comments**	**Reference**
Pacific saury (*Cololabis saira*)	Fish	3.2 (±3.05) per individual	3.2	1–2.79 mm	North Pacific	Boerger et al., 2010[82]
Atlantic herring (*Clupea harengus*)	Fish	1–4 per individual	2.5	0.5–3	North Sea	Foekema et al., 2013[99]
Whiting (*Merlangius merlangus*)	Fish	1–3 per individual	2	1.7 (±1.5)	North Sea	Foekema et al., 2013[99]
Merlangius merlangus	Fish	1.75 (±1.4) per individual	1.75	2.2 (±2.3)	English Channel	Lusher et al., 2013[259]
Haddock (*Melanogrammus aeglefinus*)	Fish	1.0 per individual	1	0.7 (±0.3)	North Sea	Foekema et al., 2013[99]
Cod (*Gadus morhua*)	Fish	1–2 per individual	1.5	1.2 (±1.2)	North Sea	Foekema et al., 2013[99]
Blue whiting (*Micromesistius poutassou*)	Fish	2.07 (±0.9) per individual	2.07	2.0 (±2.4)	English Channel	Lusher et al., 2013[259]
Poor cod (*Trisopterus minutus*)	Fish	1.95 (±1.2) per individual	1.95	2.2 (±2.2)	English Channel	Lusher et al., 2013[259]
Lampris sp. (*big eye*)	Fish	2.3 (±1.6) per individual	2.3	49.1 (±71.1)	North Pacific	Choy and Drazen, 2013[260]
Lampris sp. (*small eye*)	Fish	5.8 (±3.9) per individual	5.8	48.8 (±34.5)	North Pacific	Choy and Drazen, 2013[260]
Reinhardt's lantern fish (*Hygophum reinhardtii*)	Fish	1.3 (±0.71) per individual	1.3	1–2.79	North Pacific	Boerger et al., 2010[82]
Lantern fish (*Loweina interrupta*)	Fish	1.0 per individual	1	1–2.79	North Pacific	Boerger et al., 2010[82]
Lantern fish (*Myctophum aurolaternatum*)	Fish	6.0 (±8.99) per individual	6	1–2.79	North Pacific	Boerger et al., 2010[82]

Lantern fish (*Symbolophorus californiensis*)	Fish	7.2 (±8.39) per individual	7.2	1–2.79	North Pacific	Boerger et al., 2010[82]
Anderson's lanternfish (*Diaphus anderseni*)	Fish	1 per individual	1	n/a	North Pacific	Davison and Asch, 2011[261]
Lanternfish (*Diaphus fulgens*)	Fish	1 per individual	1	n/a	North Pacific	Davison and Asch, 2011[261]
Boluin's lanternfish (*Diaphus phillipsi*)	Fish	1	1	Longest dimension 0.5	North Pacific	Davison and Asch, 2011[261]
Coco's lanternfish (*Lobianchia gemellarii*)	Fish	1 per individual	1	n/a	North Pacific	Davison and Asch, 2011[261]
Pearly lanternfish (*Myctophum nitidulum*)	Fish	1.5	1.5	Longest dimension 5.46	North Pacific	Davison and Asch, 2011[261]
Drums (*Stellifer brasiliensis*)	Fish	0.33–0.83	0.58	<1	Goiana estuary, Brazil	Dantas et al., 2012[262]
Drums (*Stellifer stellifer*)	Fish	0.33–0.83	0.58	<1	Goiana estuary, Brazil	Dantas et al., 2012[262]
Mojarra (*Eugerres brasilianus*)	Fish	1–5	3	1–5	Goiana estuary, Brazil	Ramos et al., 2012[263]
Flagfin mojarra (*Eucinostomus melanopterus*)	Fish	1–5	3	1–5	Goiana estuary, Brazil	Ramos et al., 2012[263]
Caitipa mojarra (*Diapterus rhombeus*)	Fish	1–5	3	1–5	Goiana estuary, Brazil	Ramos et al., 2012[263]
Horse mackerel (*Trachurus trachurus*)	Fish	1.0	1	1.52	North Sea	Foekema et al., 2013[99]
Trachurus trachurus	Fish	1.5 (±0.7)	1.5	2.2 (±2.2)	English Channel	Lusher et al., 2013[259]
Yellowtail amberjack (*Seriola lalandi*)	Fish	1	1	0.5–10	North Pacific	Gassel et al., 2013[264]
Dragonet (*Callionymus lyra*)	Fish	1.79 (±0.9)	1.79	2.2 (±2.2)	English Channel	Lusher et al., 2013[259]
Red band fish (*Cepola macrophthalma*)	Fish	2.15 (±2.0)	2.15	2.0 (±1.9)	English Channel	Lusher et al., 2013[259]

Solenette (*Buglossidium luteum*)	Fish	1.23 (±0.4)	1.23	1.9 (±1.8)	English Channel	Lusher et al., 2013[259]
Thickback sole (*Microchirus variegatus*)	Fish	1.58 (±0.8)	1.58	2.2 (±2.2)	English Channel	Lusher et al., 2013[259]
Red gurnard (*Chelidonichthys cuculus*)	Fish	1.94 (±1.3)	1.94	2.1 (±2.1)	English Channel	Lusher et al., 2013[259]
Madamago sea catfish (*Cathorops spixii*)	Fish	0.47	0.47	1–4	Goiana estuary, Brazil	Possatto et al., 2011[265]
Catfish (*Cathorops spp.*)	Fish	0.55	0.55	1–4	Goiana estuary, Brazil	Possatto et al., 2011[265]
Pemecoe catfish (*Sciades herzbergii*)	Fish	0.25	0.25	1–4	Goiana estuary, Brazil	Possatto et al., 2011[265]
Indo-Pacific snaggletooth (*Astronesthes indopacificus*)	Fish	1.0	1	1–2.79	North Pacific	Boerger et al., 2010[82]
Hatchetfish (*Sternoptyx diaphana*)	Fish	1	1	Longest dimension 1.58 mm	North Pacific	Davison and Asch, 2011[261]
Highlight hatchetfish (*Sternoptyx pseudobscura*)	Fish	1	1	Longest dimension 4.75 mm	North Pacific	Davison and Asch, 2011[261]
Pacific black dragon (*Idiacanthus antrostomus*)	Fish	1	1	Longest dimension 0.5 mm	North Pacific	Davison and Asch, 2011[261]
John Dory (*Zeus faber*)	Fish	2.65 (±2.5)	2.65	2.2 (±2.2)	English Channel	Lusher et al., 2013[259]
Striped red mullet (*Mullus surmuletus*)	Fish	0.04-1.07 per individual	0.555		Balearic Islands, western Mediterranean	Alomar et al., 2017[266]
Alosa fallax	Fish	1 per individual	1	Particles	Portuguese coast	Neves et al., 2015[81]
Argyrosomus regius	Fish	0.80 ± 0.8 per individual	0.8	Fibres & Particles	Portuguese coast	Neves et al., 2015[81]
Boops boops	Fish	0.09 ± 0.3 per individual	0.09	Fibres & Particles	Portuguese coast	Neves et al., 2015[81]
Brama brama	Fish	0.67 ± 1.2 per individual	0.67	Fibres	Portuguese coast	Neves et al., 2015[81]
Dentex macrophthalmus	Fish	1 per individual	1	Fibres	Portuguese coast	Neves et al., 2015[81]

Lophius piscatorius	Fish	0.5 per individual	0.5	Fibres	Portuguese coast	Neves et al., 2015[81]
Merluccius merluccius	Fish	0.29 ± 0.49 per individual	0.29	Fibres	Portuguese coast	Neves et al., 2015[81]
Merluccius merluccius	Fish	0.40 ± 0.89 per individual	0.4	Fibres	Portuguese coast	Neves et al., 2015[81]
Mullus surmuletus	Fish	2 per individual	2	Fibres	Portuguese coast	Neves et al., 2015[81]
Mullus surmuletus	Fish	1.66 ± 0.57 per individual	1.66	Fibres	Portuguese coast	Neves et al., 2015[81]
Pagellus acarne	Fish	1 per individual	1	Fibres	Portuguese coast	Neves et al., 2015[81]
Raja asterias	Fish	0.57 ± 0.79 per individual	0.57	Fibres	Portuguese coast	Neves et al., 2015[81]
Scomber japonicus	Fish	0.57 ± 1.04 per individual	0.57	Fibres & Particles	Portuguese coast	Neves et al., 2015[81]
Scomber scombrus	Fish	0.46 ± 0.78 per individual	0.46	Fibres & Particles	Portuguese coast	Neves et al., 2015[81]
Scyliorhinus canicula	Fish	0.12 ± 0.33 per individual	0.12	Fibres & Particles	Portuguese coast	Neves et al., 2015[81]
Scyliorhinus canicula	Fish	0.67 ± 0.58 per individual	0.67	Fibres	Portuguese coast	Neves et al., 2015[81]
Trachurus picturatus	Fish	0.03 ± 0.18 per individual	0.03	Fibres	Portuguese coast	Neves et al., 2015[81]
Trachurus trachurus	Fish	0.07 ± 0.25 per individual	0.07	Fibres & Particles	Portuguese coast	Neves et al., 2015[81]
Trigla lyra	Fish	0.26 ± 0.57 per individual	0.26	Fibres & Particles	Portuguese coast	Neves et al., 2015[81]
Zeus faber	Fish	1 per individual	1	Fibres	Portuguese coast	Neves et al., 2015[81]

Table A8. Reported concentrations of microplastics in pelagic marine organisms

Species	**Order**	**Reported Concentration of microplastic**	**Concentration of microplastic (kg^{-1})**	**Plastics observed**	**Comments**	**Reference**
Humbolt squid (*Dosidicus gigas*)	Mollusc	Maximum: 11 particles per individual	0.44	Nurdles: 3–5 mm	British Columbia, Canada	Braid et al., 2012[84]
Harbor seal (*Phoca vitulina*)	Mammal	Max: 7-8 items	0.113636364	>0.1 mm	Stomachs and intestines. Samples from The Netherlands	Bravo Rebolledo et al. 2013[267]
Fur seal (*Arctocephalus* spp.)	Mammal	1–4 particles per item of faeces	n/a	4.1 mm	Samples of faeces. Macquarie Island, Australia	Eriksen and

						Burton, 2003[268]
True's beaked whale (*Mesoplodon mirus*)	Mammal	88 particles per organism	0.073333333	2.16 mm	Stranded whales from Irish coast. Majority of microplastics were fibres	Lusher et al., 2015[269]
Green turtle (*Chelonia mydas*)	Reptiles	Total: 11 pellets 0.32 pellets per individual	0.00248062	<5 mm	Rio Grande do Sul, Brazil. Pellets assumed to be <5 mm. Other plastic items found but no size information provided.	Tourinho et al., 2010[83]

Table A9. Reported concentrations of microplastics in benthic marine organisms

Species	**Order**	**Concentration of microplastic**	**Concentration of microplastic particles (kg^{-1})**	**Plastics observed**	**Comments**	**Reference**
Blue mussel (*Mytilus edulis*)	Mollusc	3.7 particles 10 g^{-1} mussel	370	Fibres 300–1,000 µm	Samples from Belgium, The Netherlands	De Witte et al. 2014[270]
Mytilus edulis	Mollusc	0.36 (±0.07) g^{-1}	360	5–25 µm	Samples from North Sea, Germany	Van Cauwenberghe and Janssen, 2014[271]
Pacific oyster (*Crassostrea gigas*)	Mollusc	0.47 (±0.16) g^{-1}	23.5	5–25 µm	Samples from Atlantic Ocean	Van Cauwenberghe and Janssen, 2014[271]
Mytilus edulis	Mollusc	0.2 particles g^{-1} w.w.	200		French–Belgian–Dutch coastline	Van Cauwenberghe et al., 2015[61]
Mytilus edulis	Mollusc	34-178 individual^{-1}	10600		Halifax Harbor, Nova Scotia, Canada	Mathalon and Hill, 2014[85]
Goosneck barnacle (*Lepas* spp.)	Crustacean	1–30 per individual	1550	1.41 mm	Samples from North Pacific	Goldstein and Goodwin, 2013[272]

Brown shrimp (*Crangon crangon*)	Crustacean	1.23 ± 0.99 particles per individual 0.68 ± 0.55 g^{-1} wet weight of shrimp	680	95 % fibres, 5 % films 200–1000 µm	Samples from Belgium	Devriese et al., 2015[39]
Lugworm (*Arenicola marina)*	Polychaete	1.2 particles g^{-1} w.w.	12		French–Belgian–Dutch coastline	Van Cauwenberghe et al., 2015[61]

Appendix B: Summary of Norwegian microplastic concentration data for different environmental compartments.

Table B1. Reported concentrations of microplastics in Norwegian marine surface waters and water column

Environmental Compartment	Concentration of plastic particles	No. Particles kg^{-1}	Sampling method	Comments	Reference
Surface water	0-14 particles per m^{-3} Average 3.2 particles per m^{-3}	0.0032		Samples collected from Norwegian coast very close to Norwegian boarder. Water pumped through a 300 µm filter	Magnusson and Norén, 2011[90]
Surface Water	0-1.31 particles m^{-3} Average 0.34 particles m^{-3}	0.00034		Barents Sea. Collected in the top 16 cm of seawater using a manta net. 95 % fibres. Single sample, which was free from microplastics was found furthest offshore.	Lusher et al., 2015[34]
Water column	0-11.5 particles m^{-3} Average 2.68 particles m^{-3}	0.00268		Collected at a depth of 6 m.	Lusher et al., 2015[34]

Table B2. Reported concentrations of microplastics in Norwegian sediments from shorelines and beaches, coastal zones and the deepsea

Environmental Compartment	Concentration of microplastic	Concentration of microplastic (kg^{-1})	Plastics observed	Comments	Reference
Shoreline	6.3 kg^{-1}	6.3	Fibres and particles	Collected from the shoreline near Longyearbyen, Svalbard	Sundet et al., 2015[91]
Coastal sediment	9.2 kg^{-1}	9.2	Fibres	Collected from the Greenland Sea in Adventfjorden off the coast of Svalbard coast	Sundet et al., 2015[91]
Coastal sediment	1-25 kg^{-1}	13		West coast of Norway	NGU Preliminary Data[92]
Coastal sediment	26-50 kg^{-1}	38		West coast of Norway	NGU Preliminary Data[92]
Coastal sediment	26-50 kg^{-1}	38		West coast of Norway	NGU Preliminary Data[92]

Coastal sediment	51-100 kg^{-1}	75.5		West coast of Norway	NGU Preliminary Data[92]
Coastal sediment	51-100 kg^{-1}	75.5		West coast of Norway	NGU Preliminary Data[92]
Coastal sediment	51-100 kg^{-1}	75.5		West coast of Norway	NGU Preliminary Data[92]
Coastal sediment	201-400 kg^{-1}	300.5		West coast of Norway	NGU Preliminary Data[92]
Coastal sediment	201-400 kg^{-1}	300.5		West coast of Norway	NGU Preliminary Data[92]
Coastal sediment	201-400 kg^{-1}	300.5		West coast of Norway	NGU Preliminary Data[92]

Table B3. Reported concentrations of microplastics in fish species from Norwegian waters

Species	**Order**	**Concentration of microplastic**	**Concentration of microplastic particles (kg^{-1})**	**Plastics observed**	**Comments**	**Reference**
Fish species						
Atlantic Cod (*Gadus morhua*)	Fish	0.5 per individual	0.5		Northern part of the North Sea	Bråte et al., 2016[97]
Atlantic cod (*Gadus morhua*)	Fish	0–2 per individual	1		Northern part of the North Sea	Foekema et al., 2013[99]
Atlantic herring (*Clupea harengus*)	Fish	0–4 per individual	2		Northern part of the North Sea	Foekema et al., 2013[99]
Atlantic mackerel (*Scomber scombrus*)	Fish	0 per individual	0		Northern part of the North Sea	Foekema et al., 2013[99]
Whiting (*Merlangius merlangus*)	Fish	0–3 per individual	1.5		Northern part of the North Sea	Foekema et al., 2013[99]
Gray gurnard (*Eutrigla gurnardus*)	Fish	0 per individual	0		Northern part of the North Sea	Foekema et al., 2013[99]
Haddock (*Melanogrammus aeglefinus*)	Fish	0-1 per individual	0.5		Northern part of the North Sea	Foekema et al., 2013[99]

Horse mackerel (*Trachurus trachurus*)	Fish	0-1 per individual	0.5		Northern part of the North Sea	Foekema et al., 2013[99]
Atlantic cod (*Gadus morhua*)	Fish	0–5 per individual	2.5		North Sea	Lenz et al., 2015[102]
Atlantic cod (*Gadus morhua*)	Fish	0–4 per individual	2		Skagerrak	Lenz et al., 2015[102]
Atlantic herring (*Clupea harengus*)	Fish	0–4 per individual	2		Skagerrak	Lenz et al., 2015[102]
Benthic species						
Blue mussel (*Mytilus edulis*	Mollusc	9.5 per organism	0	none	Greenland Sea, Adventfjorden off the coast of Svalbard coast	Sundet et al., 2015[91]
Iceland Cockle (*Clinocardium ciliatum*)	Mollusc	0 per organism	950	fibres	Greenland Sea, Adventfjorden off the coast of Svalbard coast	Sundet et al., 2015[91]
Lugworm (*Arenicola marina*)	Polychaete	5 per organism	500	Mostly fibres	Byfjorden, North Sea, Bergen	Haave et al., 2016[104]

Appendix C: Large-scale versions of the LCS analysis pictures.

Below are all twelve of the LCS pictures in a larger format.

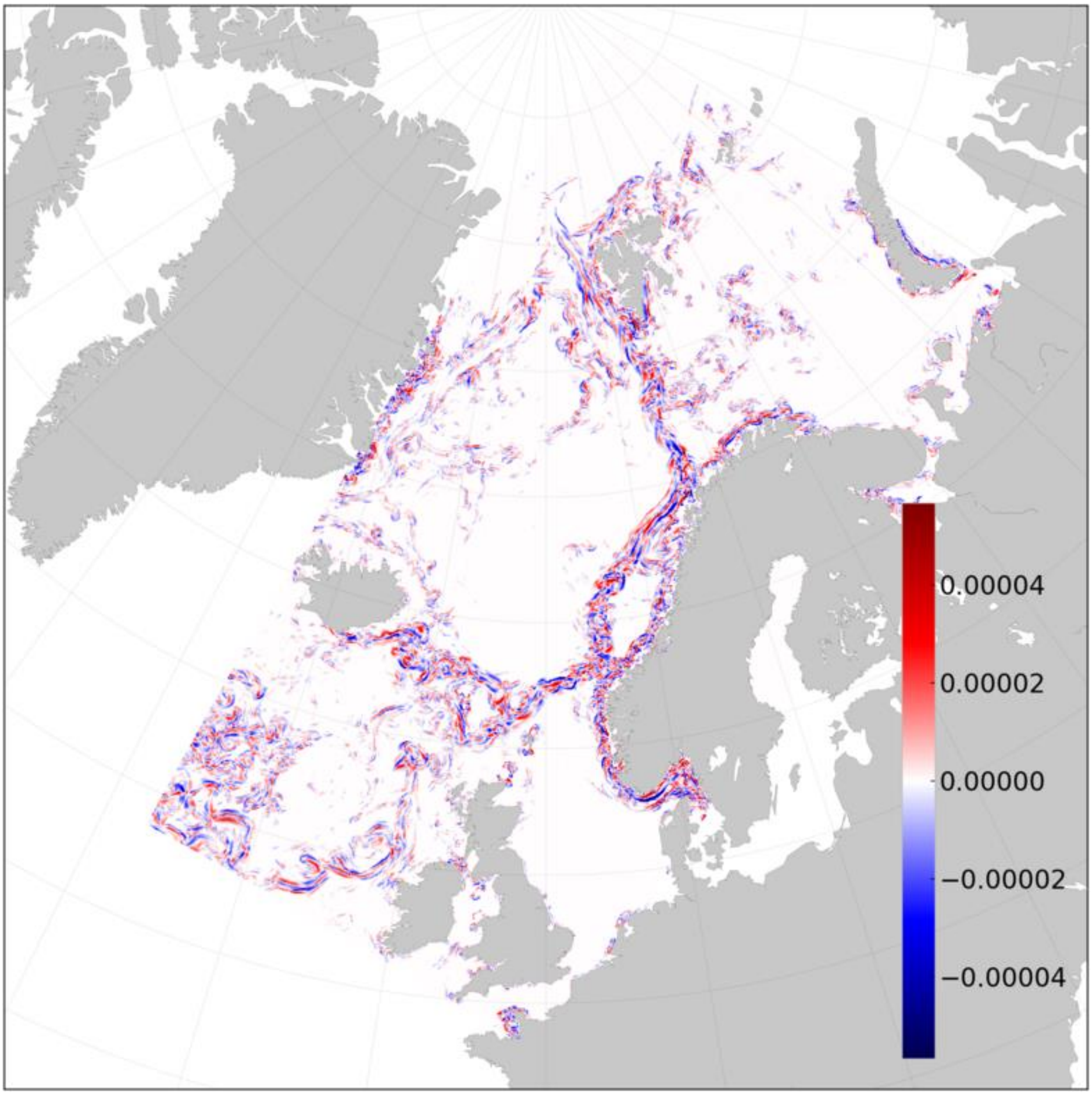

Figure C1: FTLE calculation for 1st of October 2016.

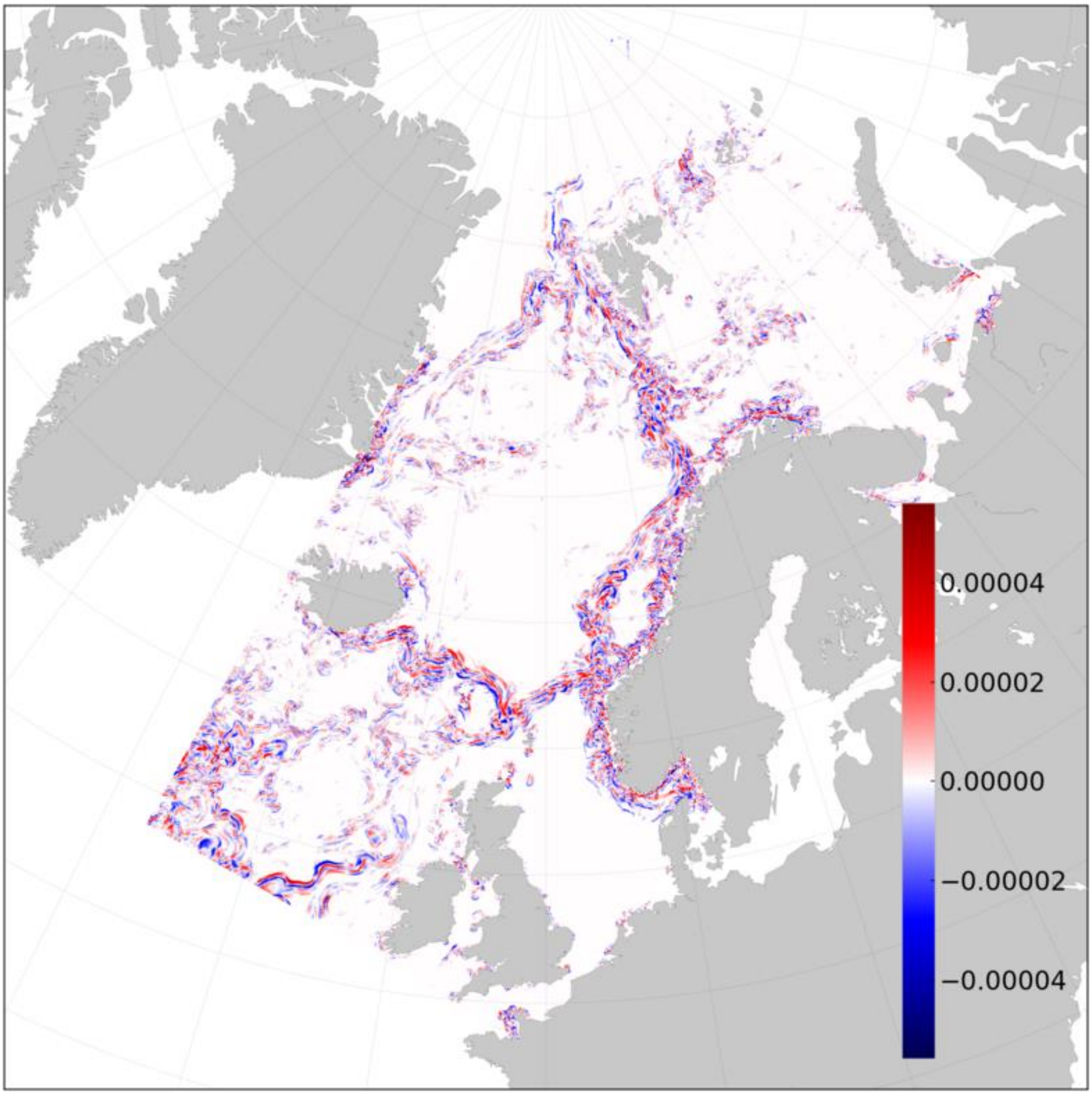

Figure C2: FTLE calculation for 1st of November 2016

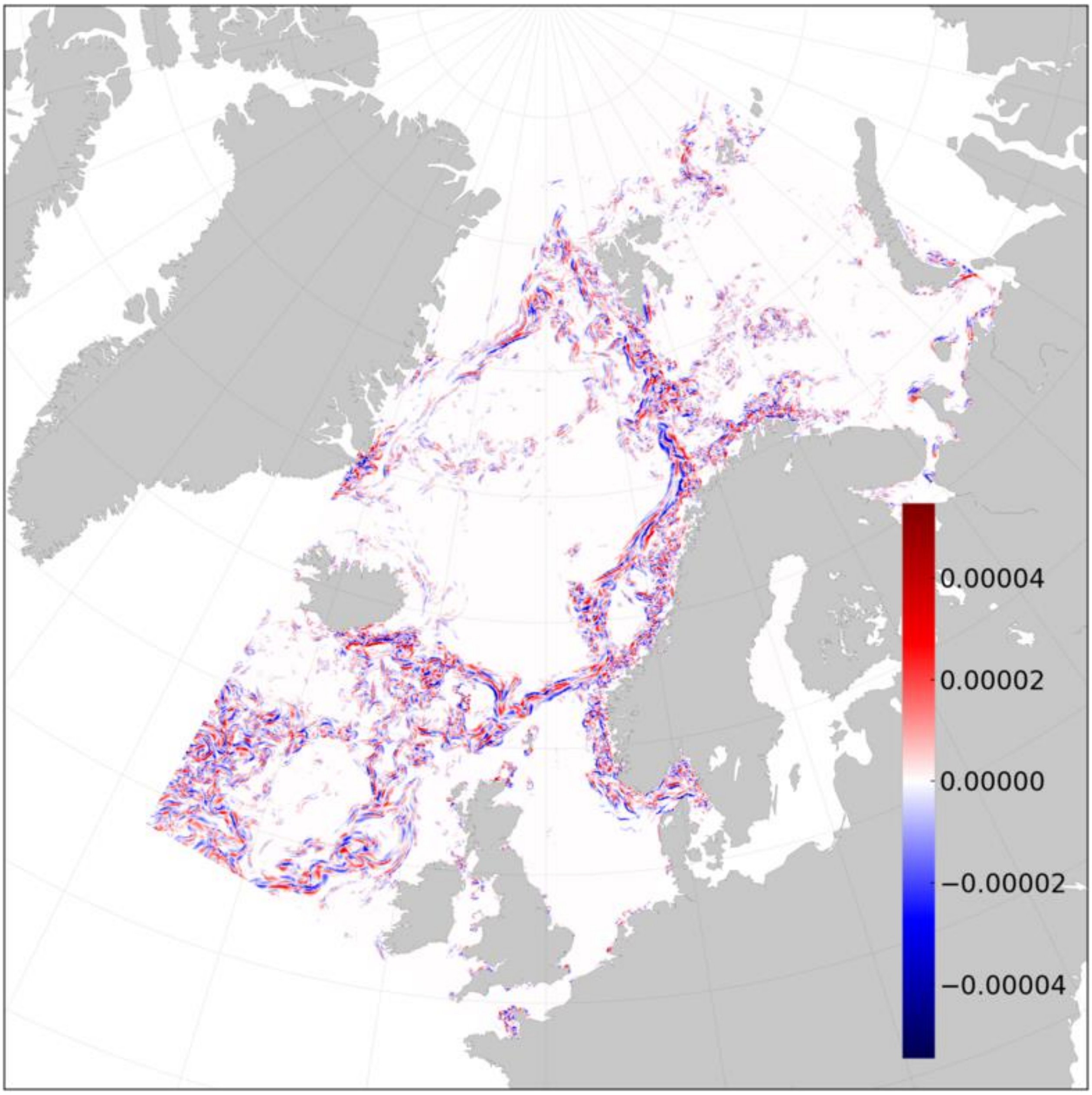

Figure C3: FTLE calculation for 1st of December 2016

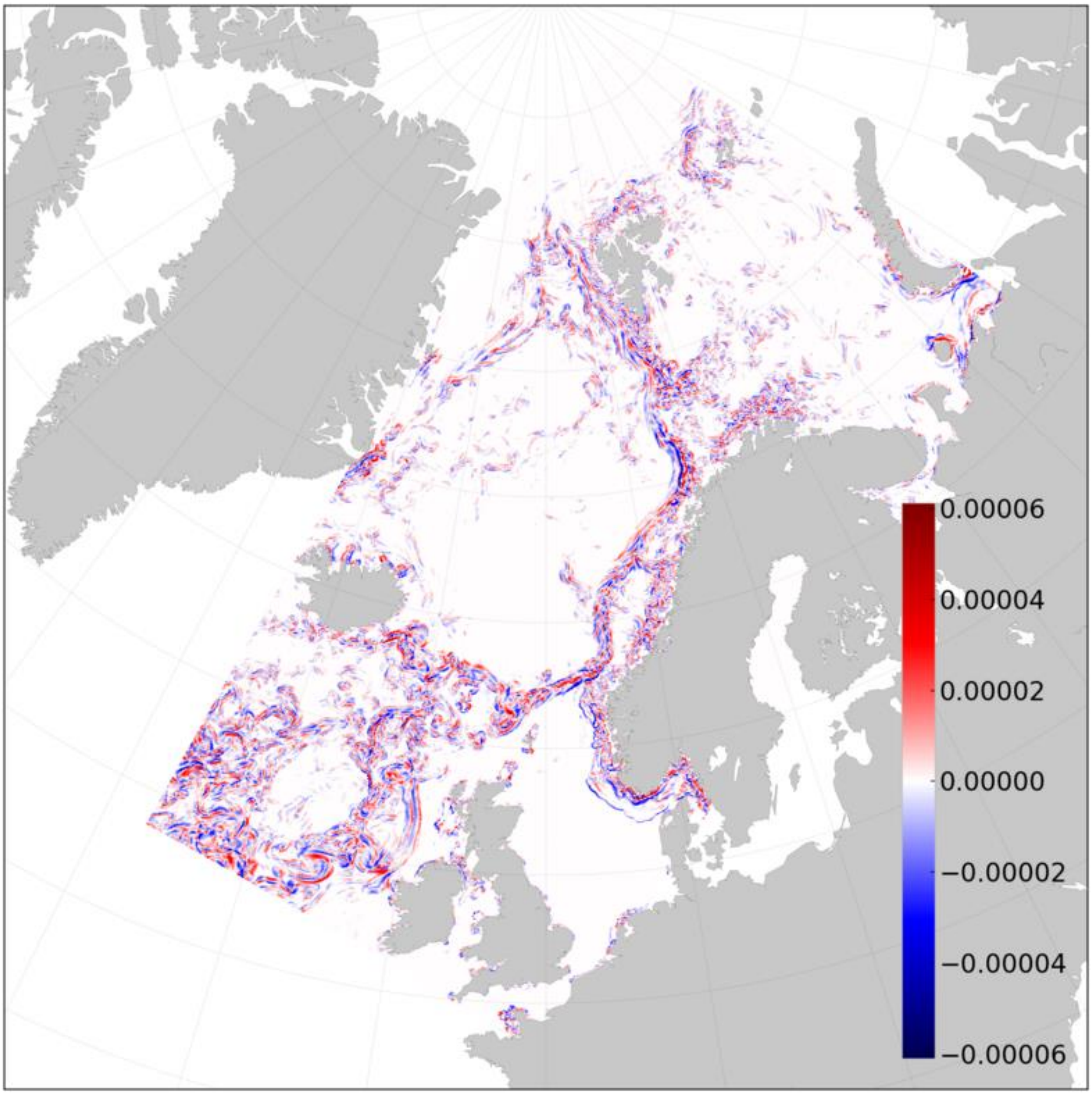

Figure C4: FTLE calculation for 1st of January 2017.

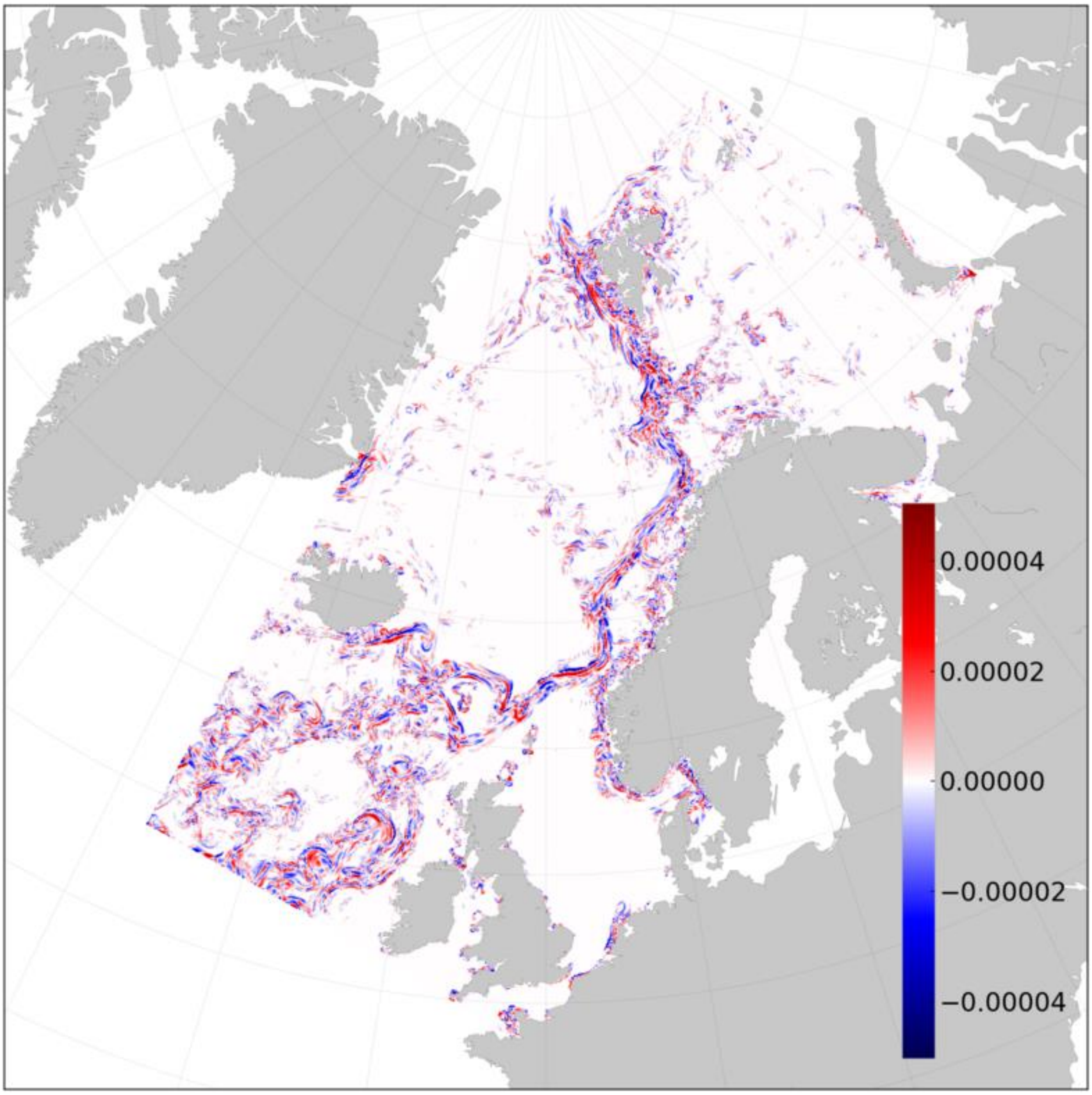

Figure C5: FTLE calculation for 1st of February 2017.

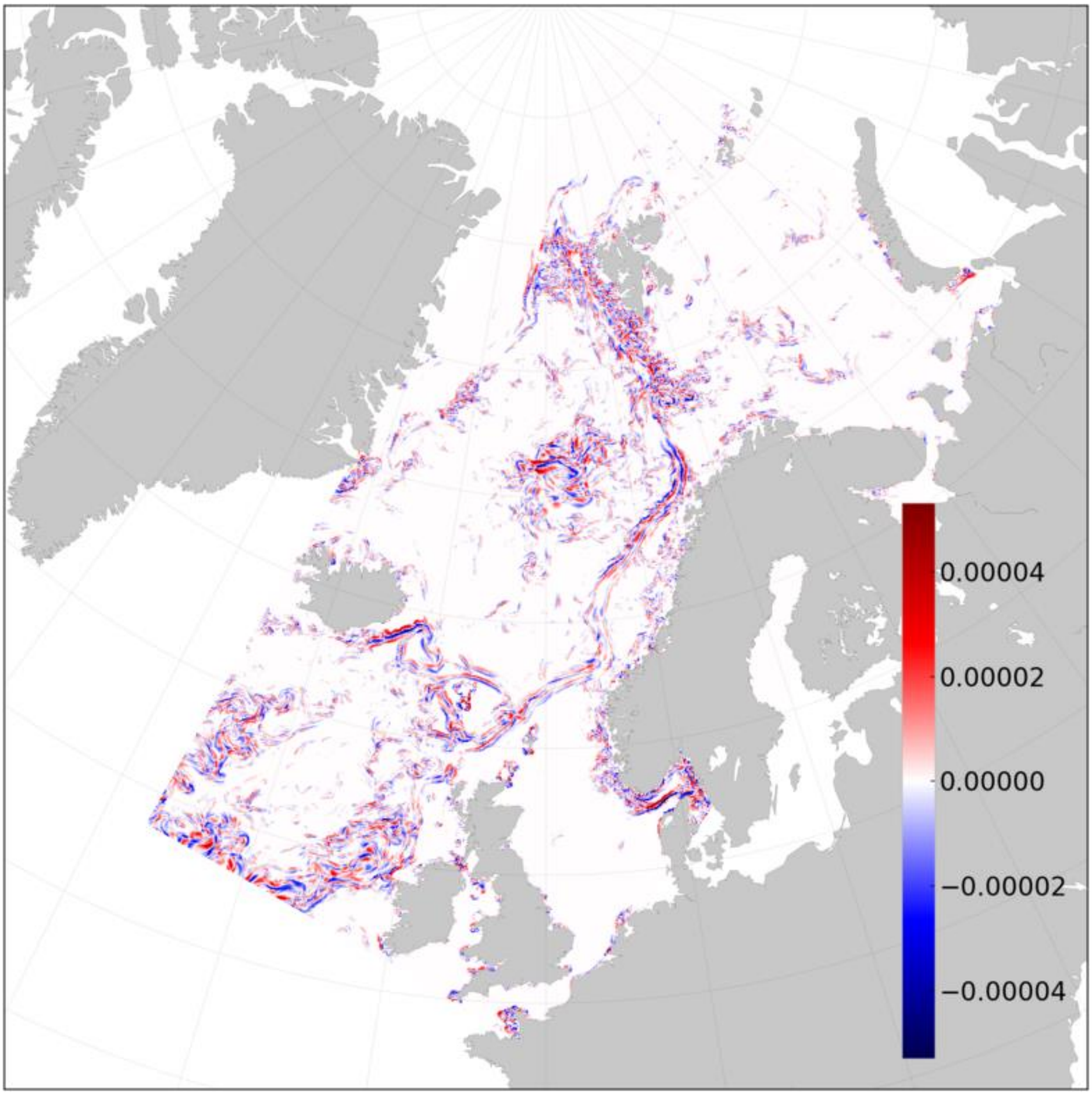

Figure C6: FTLE calculation for 1st of March 2017.

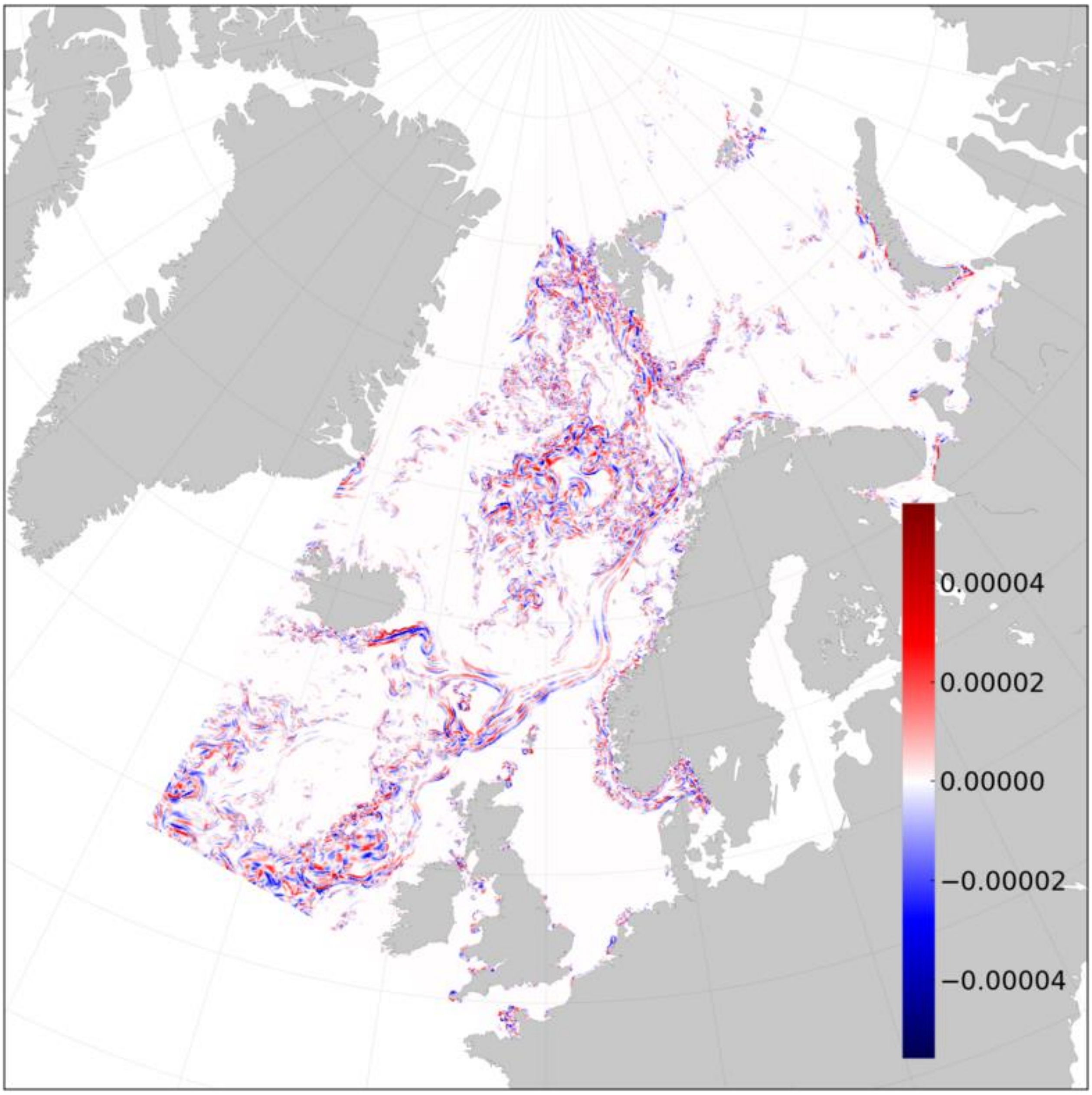

Figure C7: FTLE calculation for 1st of April 2017.

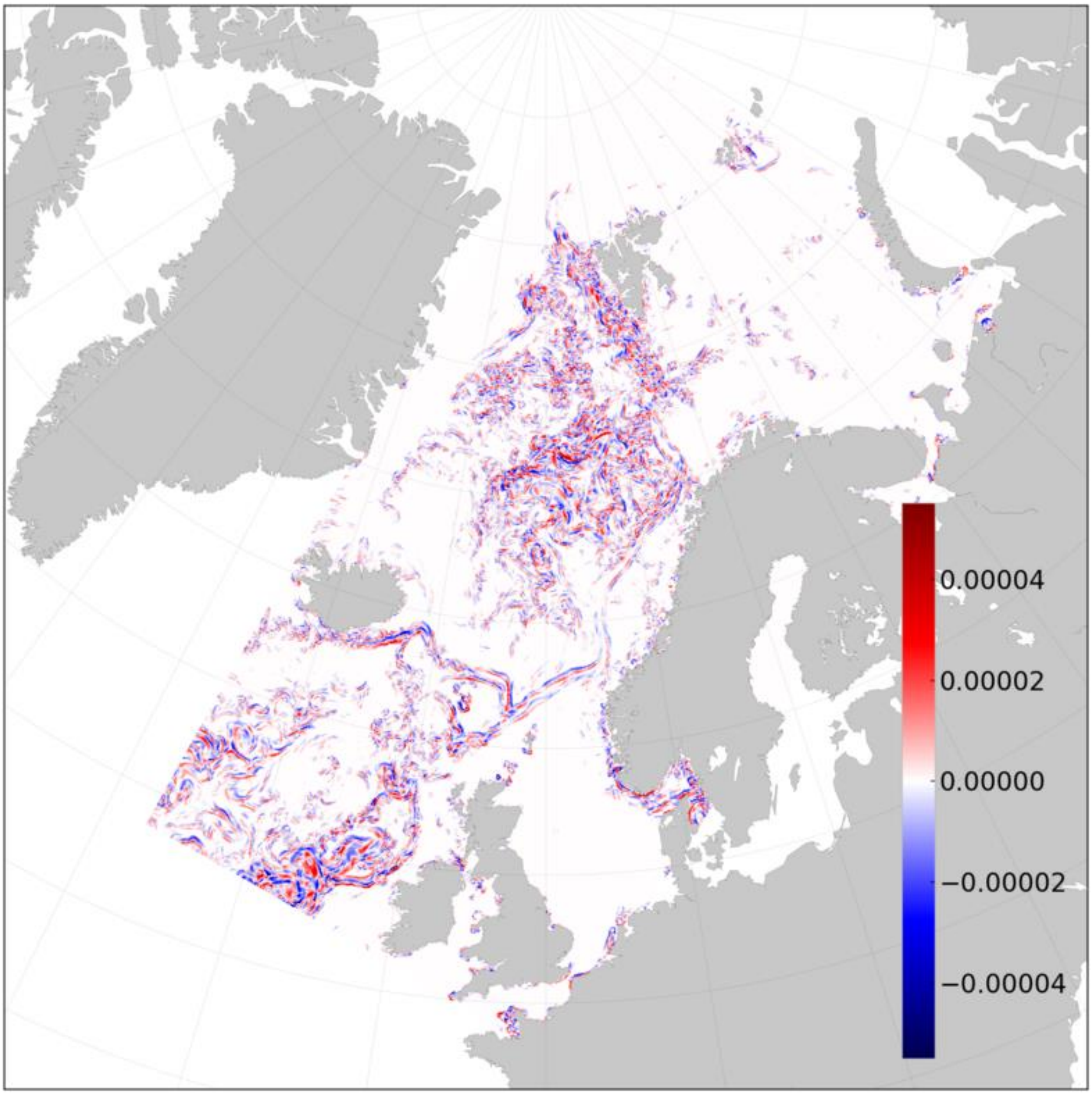

Figure C8: FTLE calculation for 1st of May 2017.

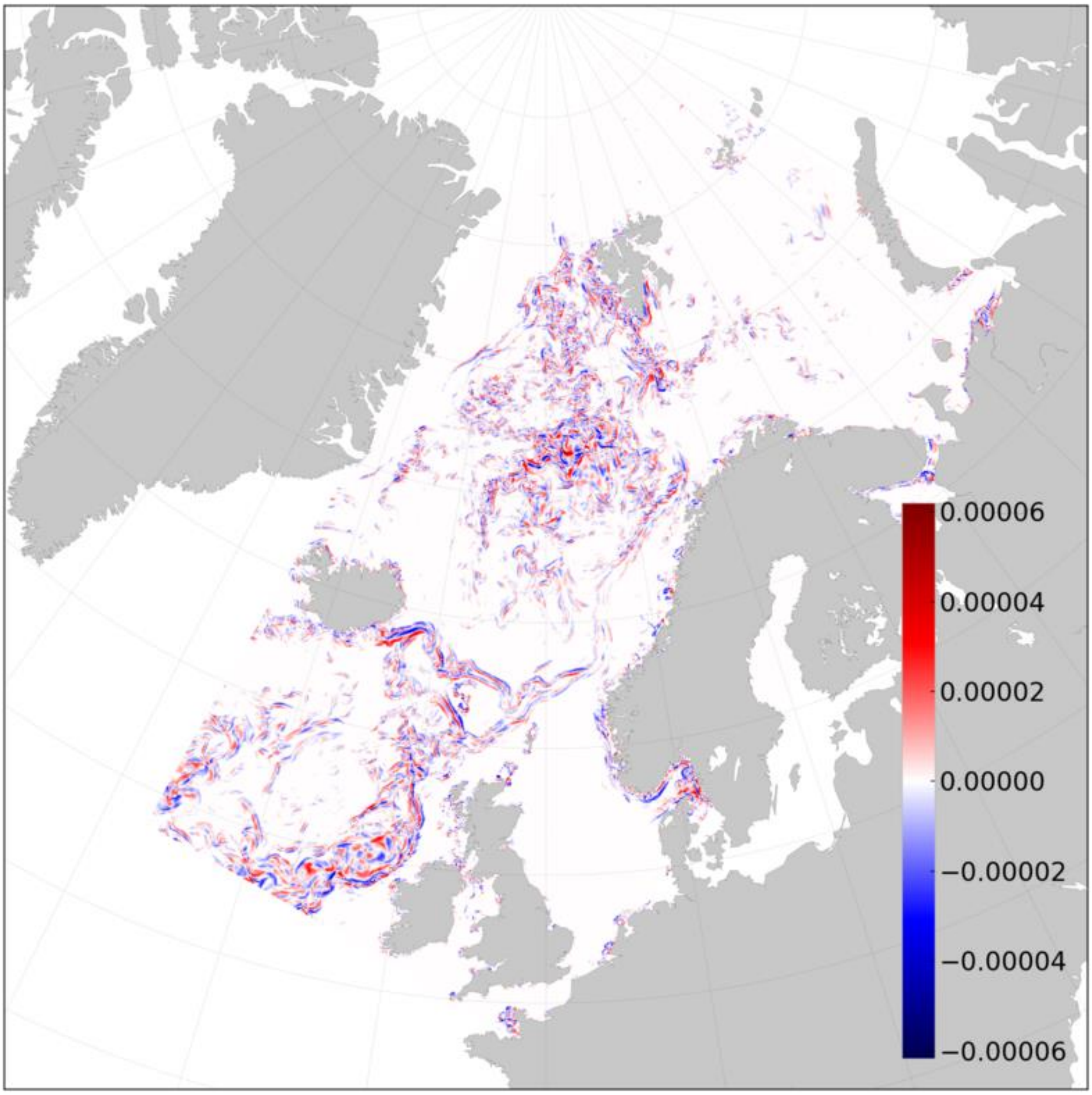

Figure C9: FTLE calculation for 1st of June 2017.

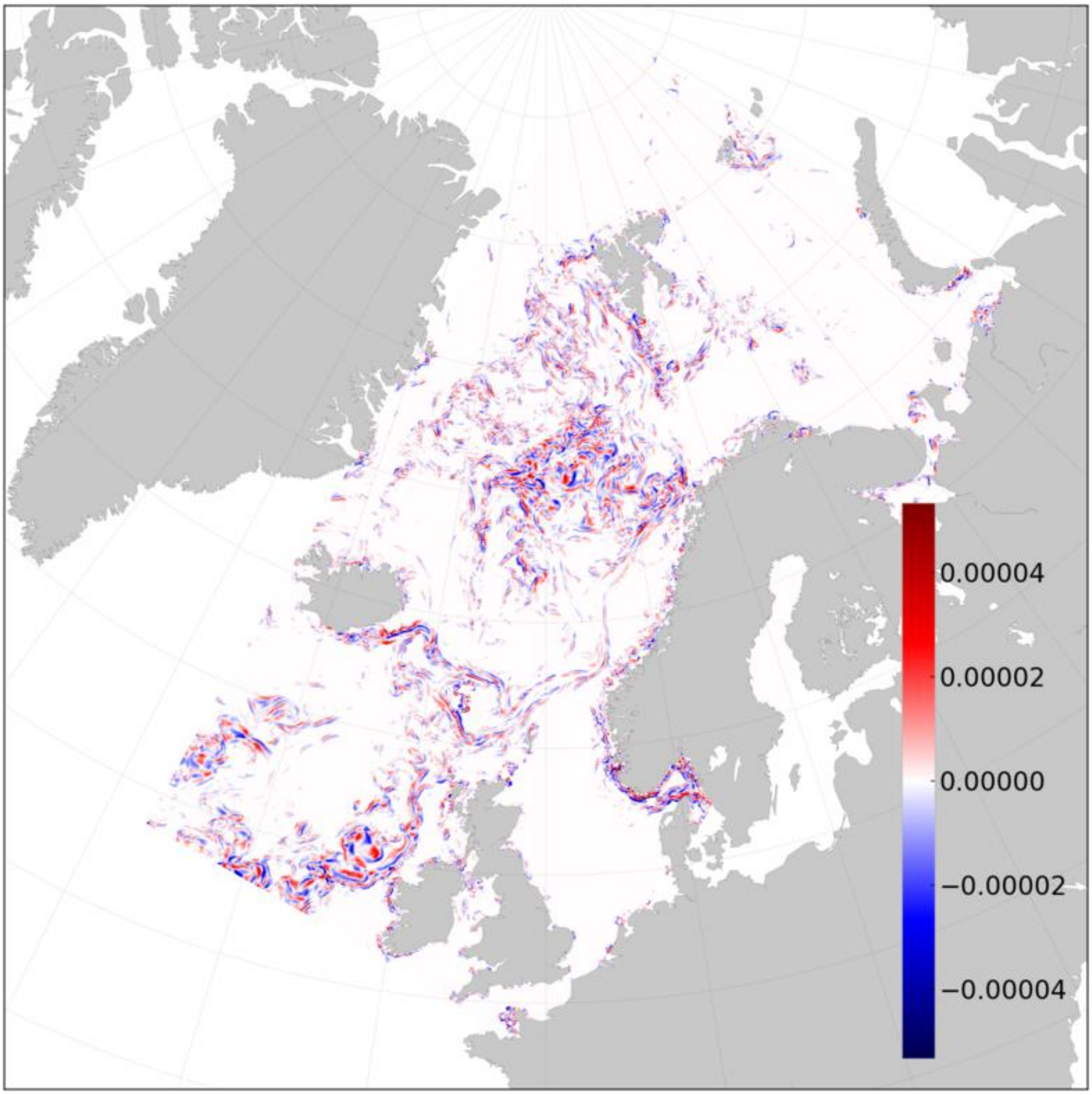

Figure C10: FTLE calculation for 1st of July 2017.

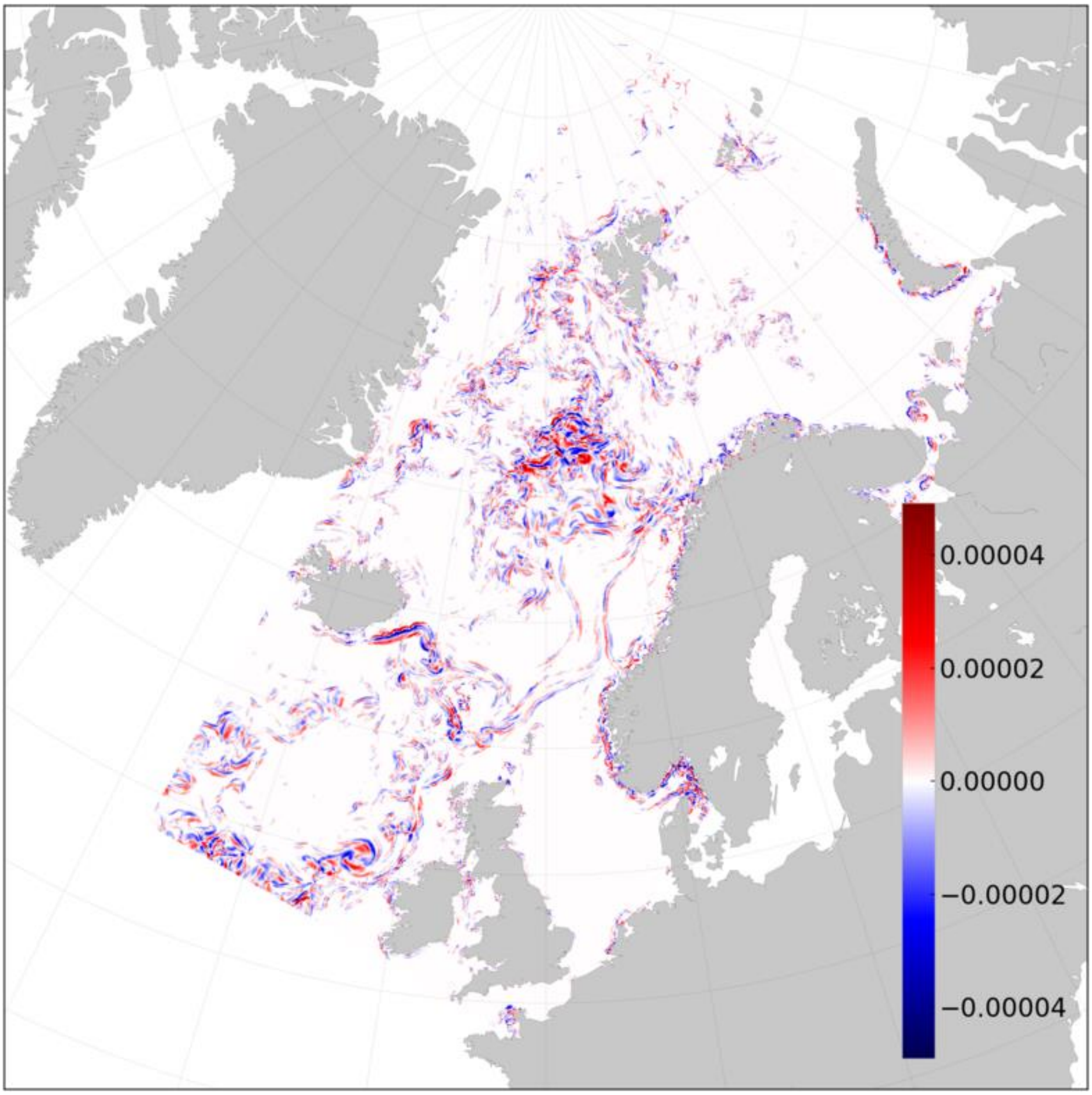

Figure C11: FTLE calculation for 1st of August 2017.

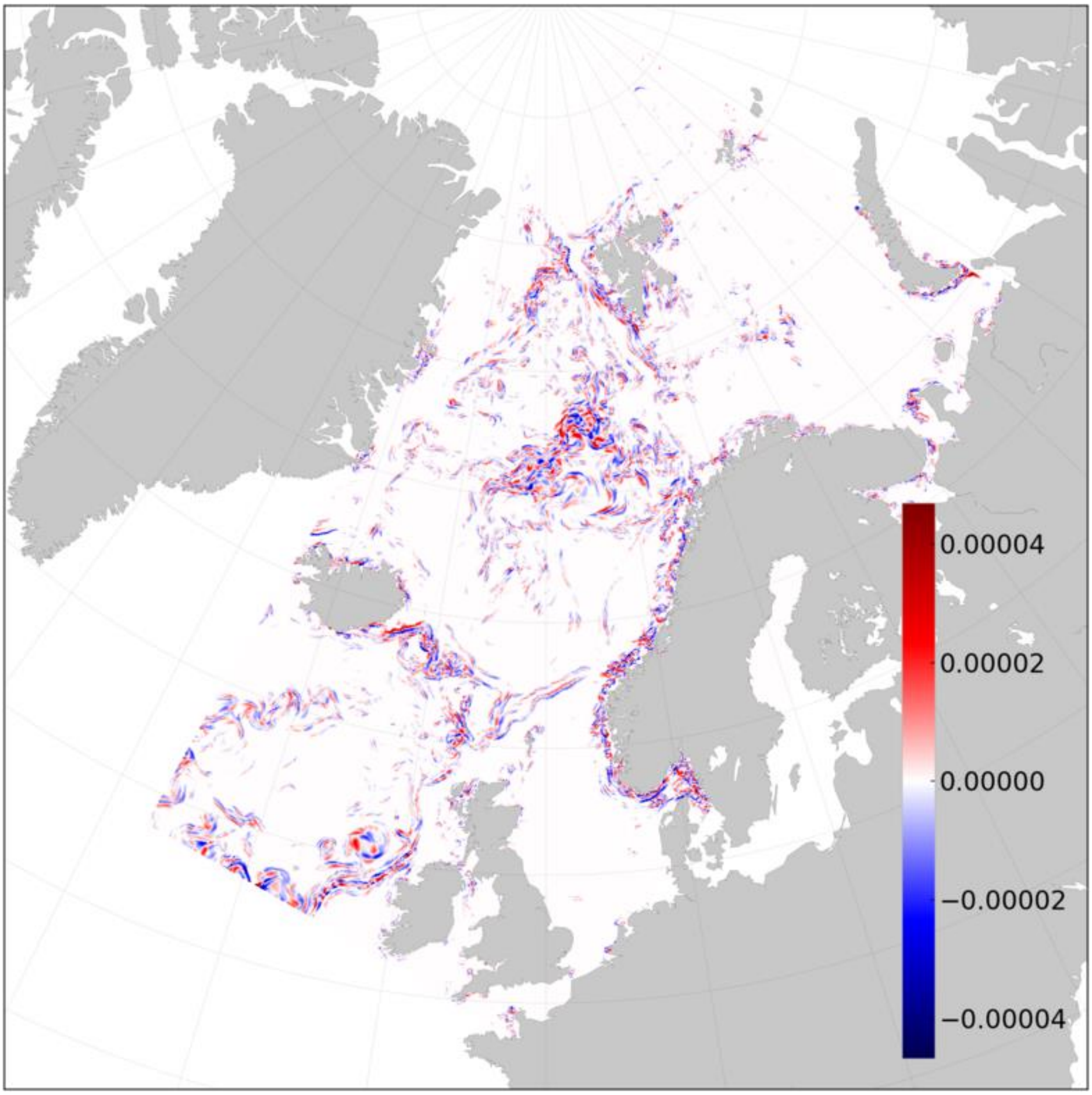

Figure C12: FTLE calculation for 1st of September 2017.

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