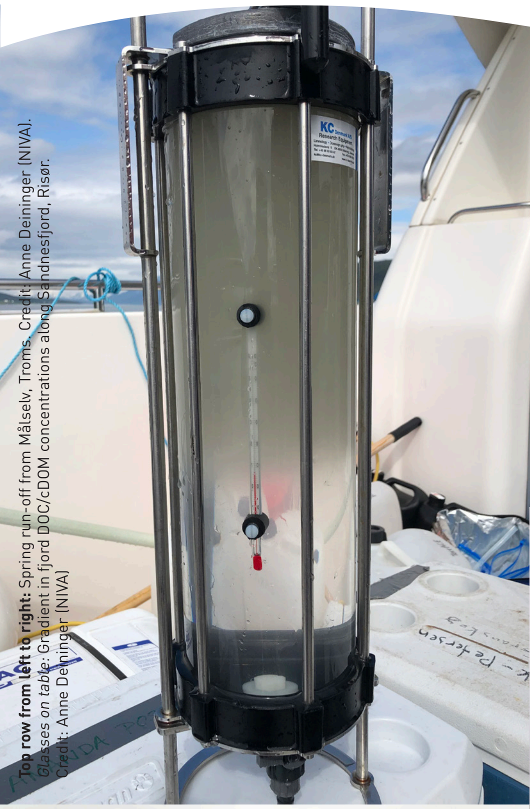
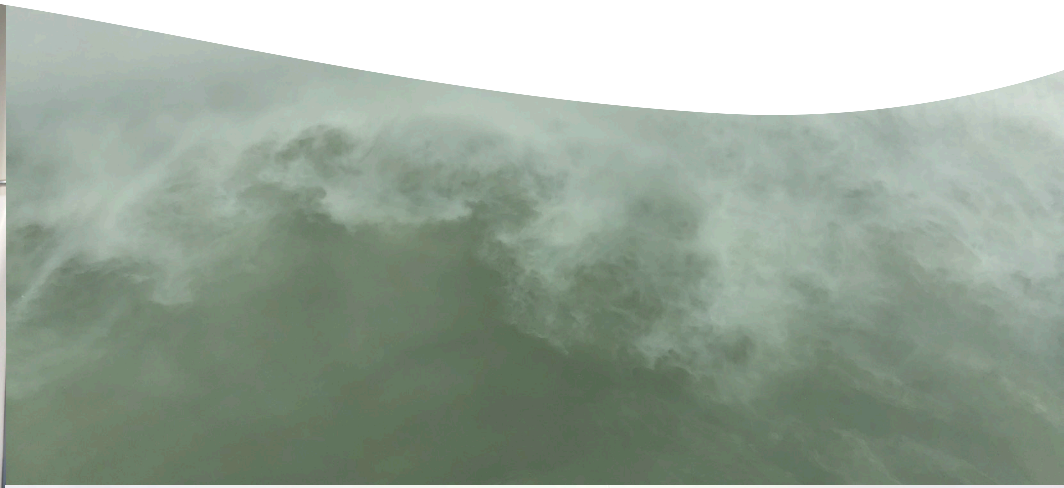
REPORT SNO. 7551-2020

Increased light attenuation in Norwegian coastal waters

- A literature review


Top row from left to right: Spring run-off from Målselv, Troms. Credit: Anne Deininger (NIVA). *Glasses on table:* Gradient in fjord DOC/cDOM concentrations along Sandnesfjord, Risør. Credit: Anne Deininger (NIVA)



Bottom row from left to right: Scientists taking river samples in Svalbard. Credit: Anne Deininger (NIVA). Aerial view from run-off in Svalbard. Credit: Anne Deininger (NIVA). Sentinel-2 RGB-image of lake Øyeren 20170811, processed by Anna Birgitta Ledang (NIVA).

Norwegian Institute for Water Research

REPORT

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Summary

This report describes the results of a literature review on increased light attenuation and biological effects in Norwegian waters and comparable global coastal regions. An overview of research projects on increased light attenuation is given.

Four keywords	Fire emneord
1. Coastal darkening	1. Kystformørkning
2. Light	2. Lys
3. Biological effects	3. Biologiske effekter
4. Management measures	4. Forvaltningstiltak

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Preface

This project was performed by NIVA on behalf of the Norwegian Environment Agency in the period July to November 2020.

We thank Trine Bekkby (NIVA) for contributing the text and figures on the models of the light attenuation coefficient, K_d(PAR) from EMODnet, which are described in the Chapter 1.

We thank Piotr Kowalczuk (IOPAN, Poland), Alexey Pavlov (Akvaplan-Niva), Dag Aksnes and Anders Opdal (University of Bergen) and Dag Hessen (University of Oslo) for providing information to the overview of relevant research projects in Norway (incl. Svalbard) in Chapter 4.

Grimstad, 16 November 2020

Helene Frigstad
(project leader)

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Summary

In Norway, there has been a documented increase over the last 30 years in river discharge and transport of dissolved organic matter (DOM) from land to coastal waters. This has been attributed to climate change, in addition to other human impacts, and is expected to increase in the future. For Norwegian coastal waters, Aksnes et al. (2009) showed that there had been a long-term reduction in water clarity, termed "coastal darkening", which was connected to a freshening of the Norwegian coastal current. The aim of this report is to provide an updated knowledge status by performing a literature review of recent publications (since 2009) on increased light attenuation and reported biological effects in Norwegian coastal waters (including Svalbard) and in global coastal systems comparable to Norway. In addition, we provide an overview of research projects (since 2005) related to changes in coastal light attenuation.

Light attenuation is a measure of how quickly the light availability decreases from surface waters and down through the water column. There are several different optical variables that impact light attenuation in the water column by absorption (*a*) and scattering (*b*) of light, such as Chlorophyll *a*, colored dissolved organic matter (cDOM) and total suspended matter (TSM; inorganic and organic material).

We found several studies that show a long-term decrease in Secchi depth and increased light attenuation in the North Sea and Norwegian coastal waters over the 20th century. Most of these studies link these changes to increases in riverine DOM (and in particular cDOM). Locally, an increase in TSM, either organic or inorganic, can also be a driver for increased light attenuation. Future predictions indicate an increase in precipitation which will most likely further increase the transport of DOM, cDOM and TSM to the coastal zones. Fjords, the Skagerrak/North Sea and Svalbard are areas that may be particularly likely to experience changes in light attenuation, either due to the physical characteristics of fjords with low sills restricting the water exchange, the Skagerrak due to high levels of cDOM, and Svalbard as the glaciers are bringing high loads of terrestrial material to the coastal zones.

The depth of the euphotic zone is affected by changes in light attenuation, and increased light attenuation will affect all organisms that are dependent on light for photosynthesis, such as phytoplankton, benthic macroalgae and seagrasses and visual predators. For phytoplankton, delays in the onset of the spring bloom in the North Sea has been attributed to increased light attenuation. The largest number of articles were found in relation to mass occurrences of jellyfish in western fjords, where a long-term increase in light attenuation is believed to have increased the competitive advantage of jelly fish (tactile predators) over fish (visual predators). For several macroalgae species, a reduction in the lower growth depth has been observed in the Skagerrak, which has been partly attributed to increased light attenuation.

Our global literature review showed that drivers and effects of reduced light availability have been reported across comparable global coastal systems to Norway (Baltic, North Sea, Canada, South America and New Zealand). Negative effects were mostly reported for light-dependent organisms, such as macroalgae and seagrasses and phytoplankton. Positive effects have been described for bacterial production, as well as filter feeders such as mussels. Mitigations have been reported to be most effective on catchment levels to reduce the increased input of terrestrial material and by advancing nature-based solutions to coastal protection.

Our compilation of recently completed and ongoing relevant research project highlights a broad range of research related to changes in coastal light attenuation, as well as the broader impacts of riverine and glacial inputs on Norway's coastal ecosystems, including Svalbard. While these studies will result in new relevant knowledge on this theme, this work also points to a need for more detailed process oriented research focusing on drivers, trends, and ecosystem impacts of coastal darkening, as

well as predictions for how climate change is likely to impact light conditions in Norwegian coastal waters (including Svalbard) in the future.

An inclusion of cDOM, DOC and TSM, as an additional parameter to K_d(PAR), Secchi depth, Chlorophyll *a* and turbidity within monitoring programs will make it possible to study and follow possible changes in the parameters contributing to the changes in the light attenuation. Sensors for spectrally-resolved light measurements and other related optical parameters should be used to provide a more detailed understanding of light attenuation and its drivers. In addition, use of remote sensing data and more autonomous monitoring systems allow for a larger spatial and temporal coverage.

The reports summarize some key research needs, especially related to differentiating between key drivers of light conditions in coastal regions, the relevant processes involved in transforming organic material along the salinity gradient and potential mitigation measures for improving coastal light conditions.

Sammendrag

Tittel: Økt lysvekking i norske kystvann – en litteraturstudie
År: 2020
Forfatter(e): Helene Frigstad, Therese Harvey, Anne Deininger and Amanda Poste
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Det har vært en dokumentert økning i vannføring og tilførsler av løst organisk materiale (DOM) fra land til kysten i Norge over de siste 30 årene. Dette har vært forårsaket av klimaendringer, og andre menneskelige påvirkninger, og er ventet å øke ytterligere i fremtiden. For norske kystvann, har Aksnes et al. (2009) vist at det var vært en «formørkning» av kystvannet over tid, som er koplet til at den norske kyststrømmen har blitt ferskere. Formålet med denne rapporten er å gi en oppdatert kunnskapsstatus gjennom en litteraturstudie på økt lysvekking og biologiske effekter i Norge siden 2009. I tillegg har vi laget en oversikt over forskningsprosjekter (siden 2005) knyttet til endringer i lysforholdene i kystvannet.

Lysvekking er et mål på hvor fort lystilgjengeligheten minker fra overflaten og nedover i vannsøylen. Det er flere optiske variabler som påvirker lysvekkingen i vannsøylen gjennom absorbsjon (a) og spredning (b) av lys, slik som klorofyll a, farget løst organisk materiale (cDOM) og totalt suspendert materiale (TSM, både organisk og uorganisk materiale).

Gjennomgangen av litteraturen avdekket flere studier som viste en nedgang i siktedyp og økt lysvekking i Nordsjøen og det norske kystvannet over det 20. århundre. De fleste av disse studiene kopler denne endringen til økt elvetilførsler av DOM (spesielt cDOM). På mer lokal skala, så kan en økning i TSM (enten organisk eller uorganisk) også være en årsak til økt lysvekking. Klimaframskrivninger viser en økning i nedbør, som mest sannsynlig ytterligere vil øke transporten av DOM, cDOM og TSM med elvene til kystsonen. Områder som er spesielt sårbare for endringer i lysvekking er fjorder, Skagerrak/Nordsjøen og Svalbard.

Endringer i lysvekkingen påvirker dybden på den eufotiske sonen og vil ha en effekt på alle dyr som er avhengige av lys for å drive fotosyntese, slik som planteplankton, bentiske makroalger, sjøgress og visuelle predatorer. For plateplankton, så har man funnet at økt lysvekking har forsinket våroppblomstringen i Nordsjøen. Flest artikler ble funnet på biologiske effekter av økt lysvekking på masseoppblomstringer av glassmaneter i fjorder på Vestlandet, hvor mindre tilgjengelig lys i vannsøylen kan bidra til å øke fortrinnet til glassmaneter (taktile predatorer) over fisk (visuelle predatorer). Det er observert en reduksjon i nedre voksedyp for flere arter av makroalger i Skagerrak, som er delvis tilskrevet endringer i lysforholdene.

Det globale litteratursøket avdekket at redusert lystilgjengelighet har blitt beskrevet for flere kystsystemer som er sammenlignbare med Norge (Østersjøen, Nordsjøen, Canada, Sør-Amerika, New Zealand). Negative effekter ble funnet for lys-avhengige organismer, slik som makroalger, sjøgress og plateplankton. Positive effekter ble beskrevet for produksjon av bakterier og filtrerende organismer, slik som blåskjell. Avbøtende tiltak ble beskrevet som mest effektive gjennom å redusere tilførsler av organisk materiale på nedbørsfeltnivå og gjennom å fremme naturbaserte løsninger for beskyttelse av kystlinjen.

Sammenstillingen av pågående og nylig avsluttede forskningsprosjekt viser at det er omfattende forskningsvirksomhet på effekter av lysvekking i kystvannet, i tillegg til de bredere påvirkningene av tilførsler fra elver og isbreer på norske kystøkosystemer. Disse studiene vil gi økt kunnskap om dette temaet i nær fremtid, men sammenstillingen avdekket også behov for mer detaljerte prosess-baserte studier på drivere, trender og økosystemeffekter av kystformørkning. I tillegg, er det behov for mer kunnskap om hvordan lysforholdene i norske kystvann (inkludert Svalbard) vil bli påvirket av klimaendringer i fremtiden.

I overvåkingsprogrammer, så vil det være en fordel å inkludere cDOM, DOC og TSM, som støtteparametere til K_d(PAR), siktedyp, klorofyll og turbiditetsmålinger. Disse optiske variablene sammen med spektrale lysmålinger gir en mer helhetlig forståelse av lysforholdene, og gjør det mulig å studere og følge mulige endringer som fører til lysvekkingen i kystvannet over tid. I tillegg, så vil økt bruk av satellittdata og automatiske overvåkingssystemer gi mulighet for en bredere dekning i tid og rom enn standard overvåkning.

Denne rapporten oppsummerer noen sentrale forskningsbehov, slik som spesielt økt forståelse av hva som driver endringer i lysforholdene, relevante prosesser i endringer i organisk materiale langs saltholdighetsgradienter og mulig avbøtende tiltak for å forbedre lysforholdene langs kysten.

1 Background

In Norway, there has been a documented increase over the last 30 years in river discharge and transport of **dissolved organic matter (DOM;** see definitions of terms in **bold** in Fact Box 1) from land to coastal waters (Gundersen et al., 2019). This has been attributed to effects of climate change, in addition to other human impacts, and is expected to increase in the future (Larsen et al., 2011; de Wit et al., 2016). For Norwegian coastal waters, Aksnes et al. (2009) showed that there had been a long-term reduction in water clarity, termed "**coastal darkening**", which was connected to a freshening of the Norwegian coastal current. Further, recent analyses of river and coastal monitoring data from the last 30-years for Skagerrak has revealed considerable changes in water chemistry and soft- and hard-bottom benthic communities and identified runoff from land as an important explanatory variable in driving these changes (Frigstad et al., 2018).

Based on these findings, the Norwegian Environment Agency has requested a literature review on factors contributing to **increased light attenuation** in Norwegian coastal waters, and the implications of these changes for Norway's coastal ecosystems. This is needed to implement necessary measures to ensure good ecological status and ecosystem-based management for Norway's coastal waters.

The aim of this report is to provide an updated knowledge status by performing a literature review of recent publications (since 2009) on increased light attenuation along the Norwegian coast and Svalbard (Question 1) and reported biological effects (Question 2). In addition, we have performed a literature review on effects on increased light attenuation in global coastal systems comparable to Norway (Question 3). In Chapter 4, we provide an overview of research projects (since 2015) on increased light attenuation in Norway and Svalbard.

Brief introduction to optical oceanography

Light attenuation is a measure of how quickly the light availability decreases from surface waters and down through the water column. This indicates how much light is available for photosynthesis by primary producers, including **phytoplankton**, **macroalgae** and marine plants (e.g. seagrasses). Primary producers need both nutrients and light to grow and are therefore directly impacted by changes in light availability. Light attenuation in water is strongly correlated with Secchi depth and has been shown to impact the depth-distribution and production of macroalgae, seagrasses and phytoplankton (Middelboe & Markager, 1997; Krause-Jensen et al., 2009; Opdal et al., 2019). There are several different **optical variables** that impact light attenuation in the water column by **absorption** (*a*) and **scattering** (*b*) of light (see Figure 1, terms in *Italics* are shown in the figure):

1) **Phytoplankton** (algae and cyanobacteria) both absorb and scatter light (*a + b phyto*);
2) Dissolved organic matter (DOM) is a complex mixture of organic compounds derived from land and from marine primary production, including smaller molecules created when larger organic matter (OM) fractions are broken down. Dissolved organic matter, and especially DOM from land, includes a strongly light absorbing fraction, often called **colored dissolved organic matter (cDOM)** or humic substances (*a cDOM*).
3) **Particulate organic matter (POM)** and inorganic material contribute to **total suspended material (TSM)** which both absorbs and scatters light. The inorganic fraction is responsible for most of the scattering (typically includes clay, silt and mineral particles), but POM can also contribute to scattering of light (*a + b TSM*);
4) Water molecules themselves can both absorb and scatter light (*a + b w*)

Vegetation and the seafloor can also absorb light and to some degree also contribute to scattering of light.

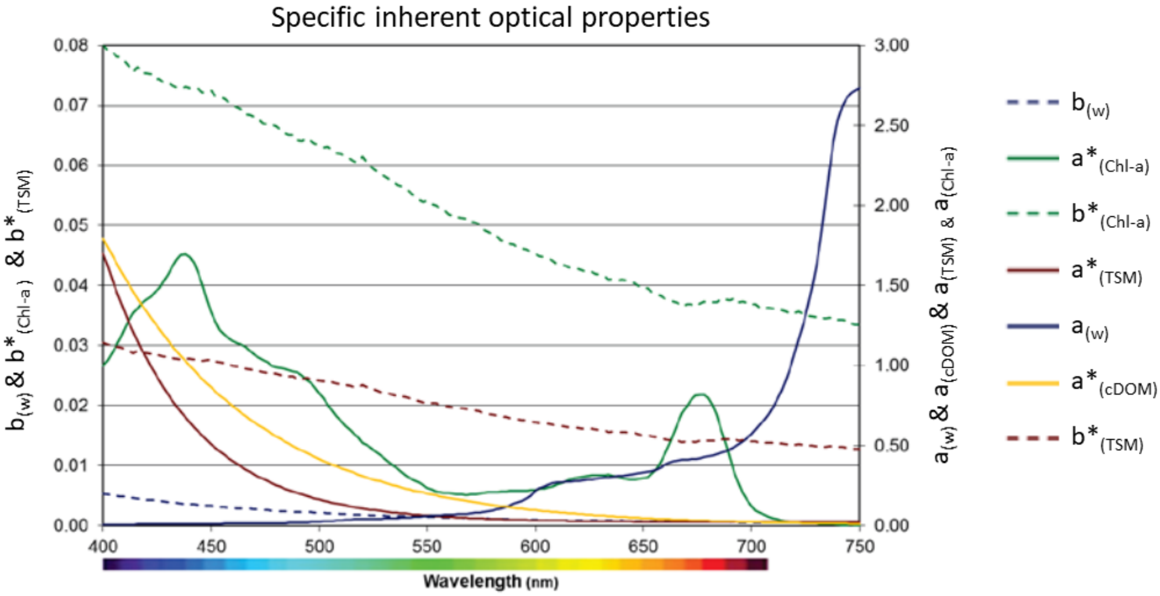

Figure 1. Specific absorption (*a*) and scattering (b) by water (*w*), phytoplankton (Chlorophyll *a*), particulate organic and inorganic material (TSM) and colored dissolved organic matter (cDOM). The left y-axis and the dashed lines indicate scattering of light, and the right y-axis and the solid lines indicate absorption. The x-axis shows wavelength of light in nanometers.

Both absorption and scattering of light by the different optical variables depend on the wavelength of light, meaning that the degree of absorption and/or scattering changes with changing wavelength (see variation along **x-axis** in Figure 1). It is the combination of the concentration and composition of the optical variables that determine how quickly light decreases as it moves down through the water column (Kirk 2011), and thereby how strong the light attenuation is (i.e. the sum of all lines in Figure 1). All optical variables can impact light attenuation, and they can also be independent or vary with each other (Harvey et al., 2019), for example riverine inputs will often have high concentrations of both cDOM and TSM. Therefore, it is challenging to identify one single reason for changes in light conditions, if there is not sufficient information available. However, with monitoring of DOC, cDOM, POM, TSM, chlorophyll *a*, as well as carrying out light profiles (i.e. measuring light and changes in light throughout the water column), it is possible to determine how these different optical variables contribute to light attenuation.

From an optical perspective, water is often divided into two main categories (Figure 2): Case-1 and Case-2 waters. The light conditions in Case-1 waters are defined by changes in phytoplankton and the optical characteristics of water itself (or waters where phytoplankton is the main cause for changes in cDOM or TSM). This typically includes the open ocean, nutrient-poor (oligotrophic) waters or clear lakes. In Case-2 waters the light conditions are impacted by two or all three of the optical variables (phytoplankton, cDOM and TSM) at the same time, and the concentration of these can vary independently from each other. This is typical of coastal waters and fjords with runoff from land, including Norwegian coastal waters.

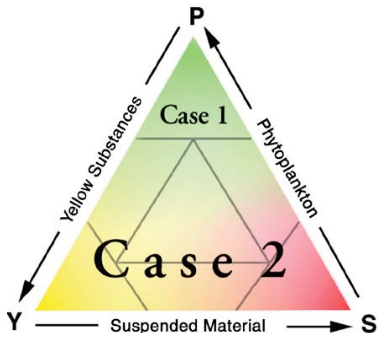

Figure 2. Classification of Case-1 and Case-2 waters, where coastal waters and fjords, including Norwegian coastal waters, are typical Case-2 waters. Yellow substances is another word for cDOM (Figure from (IOCCG, 2006).

Climate change and potential impacts on light in Norway's coastal ecosystems

We have made a conceptual diagram illustrating how the different optical variables impact light attenuation in coastal ecosystems in an 'undisturbed' system (Figure 3a). With climate change at Norway's latitudes, there is an ongoing and expected future increase in precipitation and frequency/magnitude of extreme rainfall events, resulting in increased runoff from land to coastal waters (Larsen et al., 2011; de Wit et al., 2016; Gundersen et al., 2019), which is illustrated in Figure 3b. From an optical perspective, this means that there will be increased light attenuation in coastal waters, because of increased light absorption due to cDOM and light scattering and absorption due to TSM, and thereby less light reaches the deeper parts of the water column. Increased runoff from land could also transport more nutrients from land to coastal waters, which could stimulate an increase in phytoplankton production, which could further increase light attenuation (because of the absorption and scattering of phytoplankton cells).

In summary, climate change is expected to result in increased precipitation as well as more frequent extreme rainfall events, larger floods, landslides, reduced amount and duration of snow cover, an increase in freeze-thaw events, longer summer drought periods, as well as sea level rise and increased storm-surges. Taken together, these changes have the potential to increase light attenuation by **1**) increased absorption of light through increased inputs of cDOM to coastal waters, and/or **2)** increased scattering and absorption of light due to increased particle inputs (TSM) from land, or from coastal erosion/sediment resuspension.

Reduced light availability (due to increased light attenuation) can have a negative impact on phytoplankton and the depth-distribution of macroalgae and eelgrass (Middelboe & Markager, 1997; Krause-Jensen et al., 2009; Opdal et al., 2019), in addition to having a potential negative impact on visual predators that are dependent on sight to find prey (Aksnes et al., 2009, see further descriptions in Chapter 2 Question 2).

Figure 3 a) Optical variables that impact light conditions in coastal ecosystems

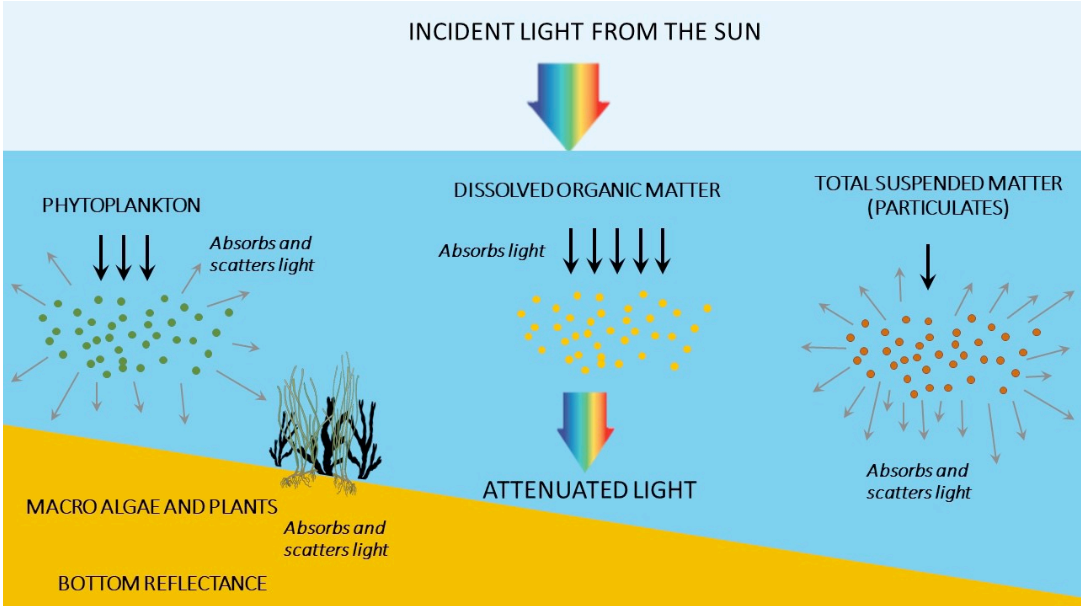

Figure 3 b) Changes in light conditions in coastal ecosystems related to climate change

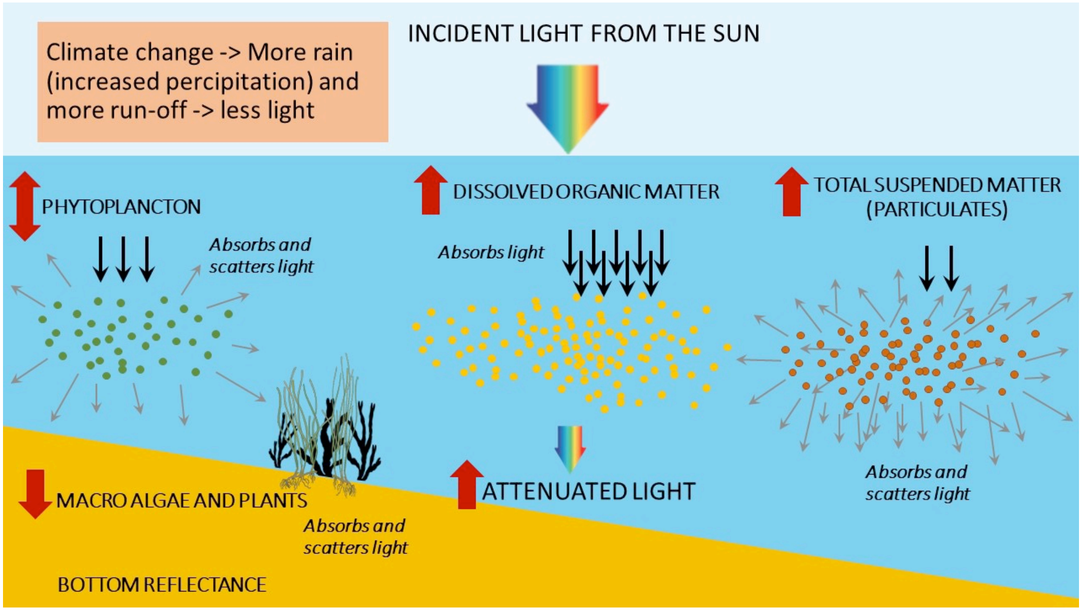

Figure 3. Conceptual diagram illustrating the impact of different optical variables on light conditions in coastal ecosystems; **a)** in an 'undisturbed' system, and **b)** under increased runoff from land to coastal waters.

Models for light attenuation in European and Norwegian coastal waters

EMODnet Seabed habitats (www.emodnet.eu) is a project aiming to map and delineate marine nature types in the EU (based on the EUNIS-system). As a part of this work there has been a need to model environmental conditions that drive the distribution of marine habitats. EMODnet Seabed habitats has therefore modelled several optical variables, including the light attenuation coefficient, K_d(PAR); ("svekningskoeffisient"), which is the degree to which attenuation decreases with depth, here estimated from satellite data. More details on the models can be found in the technical report (*EUSeaMap Technical Appendix No. 1*) and in a Norwegian application of the model for Søre Sunnmøre (Bekkby et al., 2018).

Figure 4 shows how the **estimated light attenuation coefficient for K_d(PAR**) varies in European coastal seas, where, for example, light attenuation is higher in the North Sea and Norwegian coastal waters compared to the Mediterranean Sea. Figure 5 shows estimated light attenuation for mainland Norway and Svalbard. Here we see that the light attenuation is generally higher in nearshore areas and inner fjords, compared to more open coastal regions and further off-shore. Light attenuation also tends to increase towards the south of Norway and is much higher in coastal Skagerrak than in any of the other coastal regions. This is likely related to the generally higher riverine discharge and transports of nutrients and organic matter into Skagerrak and the advection from the North Sea and Baltic (Frigstad et al., 2020).

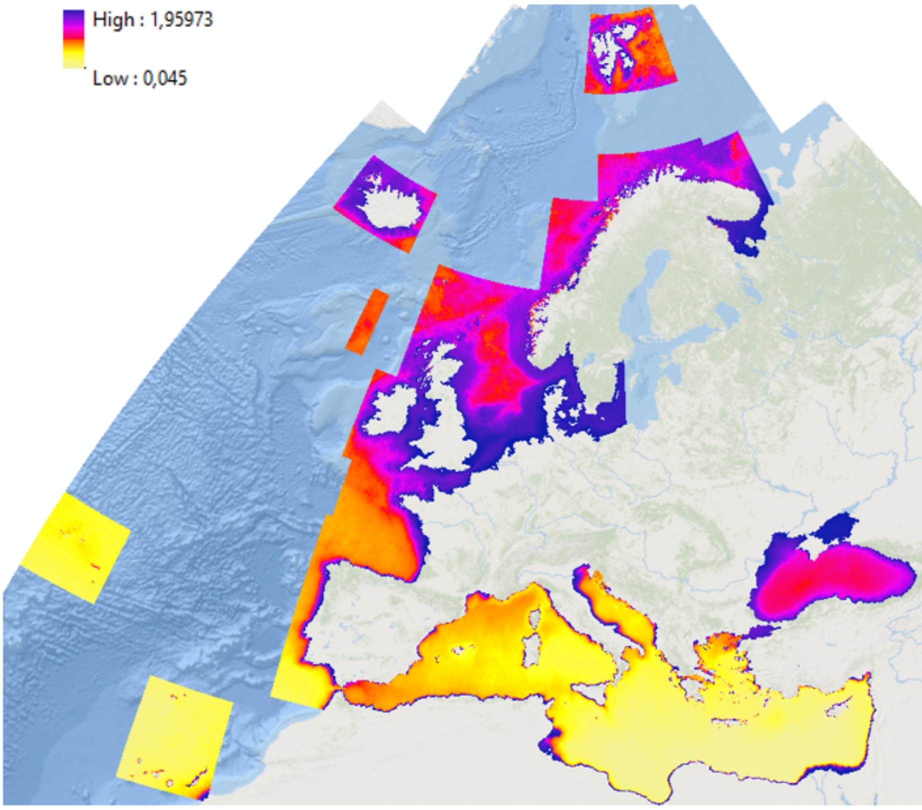

Figure 4. Estimated light attenuation coefficient K_d(PAR) for European waters, as modelled using EMODnet Seabed Habitats with 100m resolution. The darker the colours, the higher the light attenuation. Unpublished © Trine Bekkby (NIVA)

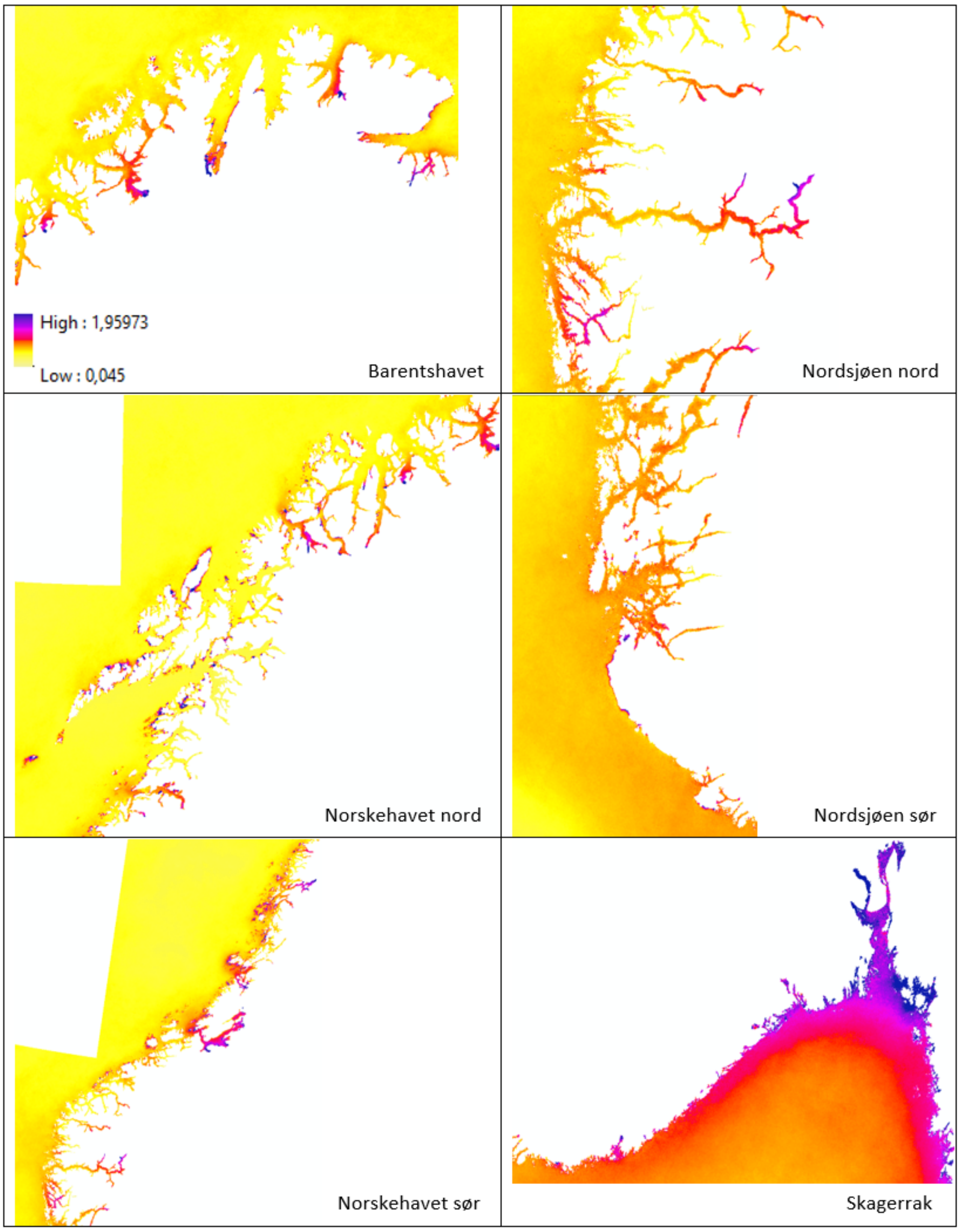

Figure 5. Estimated light attenuation coefficient K_d(PAR) for mainland Norway, displayed to better show contrasts (i.e. with stretch = standard deviation in ArcGIS), as modelled using EMODnet Seabed Habitats with 100m resolution. The darker the colour, the higher the light attenuation. Unpublished © Trine Bekkby (NIVA)

Fact box 1 Definitions of terms used in this report	
Term	**Explanation/Definition**
Absorption	Measure of how much light that is being absorbed by particulate or dissolved components within the water and by water itself, (m^{-1}).
Autotroph	An organism that uses sunlight as energy source to produce complex organic compounds from carbon dioxide trough **photosynthesis**, such as **phytoplankton** and **macroalgae**. Synonym primary producer.
cDOM	The colored fraction of **DOM**, which is strongly light absorbing. Also referred to as humic matter or yellow substances (German: gelbstoff).
Coastal darkening	Here defined as a long-term *increase in light attenuation* in coastal waters. Equivalent to the Norwegian term: "formørkning av kystvannet".
Dissolved Organic Matter (DOM)	The organic matter that is dissolved in seawater and is operationally defined as the organic fraction that passes through a filter (with pore size ranging from 0.22 to 0.7 micrometers). Dissolved organic carbon (DOC) is the carbon fraction of the dissolved organic matter. DOM also includes other dissolved organic elements such as nitrogen and phosphorous.
Euphotic zone	The part of the water column (close to the surface) where there is enough light for photosynthesis to occur. See **phytoplankton.**
Eutrophication	Increased supply of nutrients from land causing excessive growth of **phytoplankton** and reduced water quality.
Flocculation	Here, a process where dissolved matter aggregates and forms larger particles in an estuarine environment.
Heterotroph	An organism that is not able to use sunlight as an energy source (in contrast to e.g. **phytoplankton** that are **autotrophs**). They receive their nutrition from consuming other sources of organic carbon, e.g. from DOC, macroalgae, phytoplankton, or dead animal material.
K_d(PAR)	Light attenuation coefficient for the PAR spectra (m^{-1}). **K_d(PAR)** is the linear slope of the log-transformed PAR value as a function of depth from the surface, it is an indication of how much light energy that is available for photosynthesis.
$K_d(\lambda)$	Light attenuation coefficient for any wavelength, λ (m^{-1}).
Light attenuation	Refers to the reduction in light intensity as it travels through the water due to **absorption** and/or **scattering** of photons.
Macroalgae	Large marine algae attached to the bottom, such as different species of kelp and rockweed. Dependent on light for growth.
Optical variables	Components that absorbs and scatters light, e.g. **Phytoplankton**, **DOM, cDOM**, **TSM** and **POM.**
PAR	Photosynthetic Active Radiation, which is the range of the solar radiation that photosynthetic organisms use of for energy production during photosynthesis. It is solar radiation between 400 and 700 nm.

Particulate Organic Matter (POM)	The organic matter that is present in seawater in the form of particles and is operationally defined as the organic fraction that is retained on a filter (with pore size ranging from 0.22 to 0.7 micrometers). Particulate organic carbon (POC) is the carbon fraction of the particulate organic matter, but POM also includes other particulate organic elements, such as nitrogen and phosphorous.
Photosynthesis	Process by which algae and some other organisms use sunlight to synthesize nutrients from carbon dioxide and water, generally involves the green pigment Chlorophyll *a* and generates oxygen as a by-product.
Phytoplankton	Free-floating microscopic marine organisms that can utilize sunlight to create chemical energy through photosynthesis. Derived from the Greek words phyto (plant) and plankton (made to wander or drift).
Remote Sensing	When something is observed from a distance, here referred to satellite observations.
Scattering	Measure of how much light that is being spread by particles within the water and water itself, (m^{-1}).
Secchi disc	An opaque disc, typically white, used to gauge the transparency of water by measuring the depth—known as the Secchi depth —at which the disc ceases to be visible by the human eye from the surface.
Total suspended matter (TSM)	The organic and inorganic particles suspended (i.e. not dissolved) in the water column and operationally defined as the weight of the particles retained on a filter (with pore size ranging from 0.22 to 0.7 micrometers). The inorganic fraction typically includes clay, silt and mineral particles.

2 Methods

General Approach: A literature study was performed to get an overview of the relevant literature on increased light attenuation for the following three research questions:

Q1	Are there studies showing increased light attenuation in Norway published after 2009?
Q2	Are there studies showing biological effects of increased light attenuation in Norway published after 2009?
Q3	Are there studies showing increased light attenuation in comparable global coastal regions to Norway?

Relevant studies were identified on Google Scholar (GS; https://scholar.google.com/)) using the search terms described below for each research question. The software Zotero (https://www.zotero.org/) was used in to collect and organize the first 500 results of the GS search for Q1 and Q2 and the first 600 or 100 results for Q3 (see details below). The title and abstract of the papers were scanned, and the reference was imported into Zotero and organized into the different sub-sections.

The following checklists were used for the respective sections

Q1. Are findings relevant for factors controlling light attenuation in Norwegian coastal waters (cDOM, POM, TSM, Chlorophyll *a*)? (Yes: -> Q1; No: exclude)

Q2. Are biological effects of changes in light attenuation in Norway assessed? (Yes: -> Q2; No: exclude)

Q3. Are findings relevant for factors controlling light attenuation (Yes: -> Q3; No: exclude)

- in comparable coastal ecosystem to Norway?
- In other coastal ecosystems, but with important, transferable insights for Norwegian ecosystems
- Are management solutions or societal relevance presented

In addition, all articles citing Aksnes et al. (2009) were scanned (total 90), and relevant articles were categorized according to criteria above.

Searches for Q1-2: For the research questions on increased light attenuation and biological effects in Norway (Q1 and Q2), the following search terms were used and the first 500 appearing articles scanned. Search terms:

- (coast) AND (light) AND (attenuation) AND (Norway) AND (Since 2009).
- (Coastal) AND (darkening) AND (Since 2009).

Search for Q3: For the research question on increased light attenuation in comparable global coastal ecosystems to Norway (Q3.A) we focused on specifically selected areas in similar climatic zones (i.e. Baltic Sea, Nordic Seas, Canada, Arctic), as well as comparable ecosystems (New Zealand, Chile, Argentina, Antarctica). However, as many insights regarding the drivers and effects of increased light attenuation on coastal zones may be derived from studies and reviews from other global regions not similar to Norway (e.g. drivers such as increased storm runoff, or ecosystem effects such as on kelp reduction), we decided to include results from other global regions that might of relevance for Norwegian coastal zones. Lastly, to highlight management solutions and the societal relevance of our research questions, we also included papers that focused on solutions and management to increased light attenuation.

The following three steps were performed in our literature search for Q3:
Step 1. The selection process followed the procedure outlined above, using the following search words:

- (coast) AND (light) AND (attenuation) AND (Since 2009). *[The first 600 articles were scanned for a broad overview]*
- (coast) AND (light) AND (attenuation) AND (effect) AND (Since 2009). *[The first 100 articles were scanned]*
- (coast) AND (light) AND (attenuation) AND [(New Zealand) OR (Argentina) OR (Chile) OR (Baltic) OR (Nordic Seas) OR (Canada)] AND (Since 2009). [*The first 100 appearing articles were scanned for each specific region]*

Step 2. Cross-check was performed with references previously known by the authors of this report and relevant articles were added.
Step 3. Articles were grouped into the categories presented above, which were:

- A) comparable global coastal regions to Norway
- B) other global regions with study outcome of relevance for Norway
- C) focus on solutions, management, societal relevance

For the searches for Q1 – Q3, additional literature was assessed by checking the references cited by the identified articles (i.e., backward scanning) and the articles that cite the identified articles (i.e., forward scanning) for selected papers for additional missing studies.

3 Literature review

This study is based on the literature searches described in the Methods section above and is limited to articles published after 2009 that were identified as most relevant according to the literature search. Key publications from before 2009 were identified through backtracking references cited, and these are also addressed in the study.

Question 1: Are there studies published after 2009 showing increased light attenuation in Norwegian coastal waters?

In total, the search for articles for changes in the light attenuation in Norway after 2009 (Q1) resulted in 50 papers and reports, of which 25 papers were directly relevant to Q1 and included below.

Question 1 was broken down in 4 specific questions, which are answered in separate sections below;
A) Are there long-terms studies published after 2009 showing increased light attenuation in coastal waters in Norway?
B) In the available literature, are any coastal regions in Norway considered particularly vulnerable to changes in light attenuation? If so, which are these and why are they vulnerable?
C) In the available literature, are there indications/predictions on how light attenuation in coastal waters will develop in the future? Are the findings unanimous or are there contradicting findings?
D) In the available literature, are there any recommendations for methods to discover changes in light attenuation in coastal waters for monitoring purposes and/or assessing environmental status in terms of the WFD?

General findings on factors controlling light attenuation in Norwegian coastal waters
In general, there are many studies that covers the optical characteristics (absorption and scattering) for cDOM, TSM and Chlorophyll *a* as well as their seasonal differences for Norwegian coastal and fjord areas and parametrization of the total absorption and/or the effects of the optical variables on the underwater light field (Mascarenhas et al., 2017; Mascarenhas & Zielinski, 2018, 2017; Pavlov et al., 2019; Sagan & Darecki, 2018; Thewes et al., 2020; Urtizberea et al., 2013).

The drivers for changes in light attenuation are phytoplankton, cDOM and TSM (inorganic and organic) as they affect the absorption, scattering and attenuation of light (described in Chapter 1). The relationship between these are complex and can be difficult to study and understand as the changes often are linked. However, the Norwegian waters have been fairly well documented showing that the total absorption was dominated by cDOM (contributing 59% to the total absorption) in the Røst coastal areas at 440 nm, followed by non-algal TSM (23%) and Chlorophyll *a* (18%) (Nima et al., 2016). It has been shown that there is a large inflow from terrestrial sources to arctic fjords with and without glaciers, including both TSM and DOM (Białogrodzka et al., 2018; McGovern et al., 2020). Strong relationships have been documented between the attenuation of light by cDOM and TSM for Sognefjord and Trondheimsfjord (Białogrodzka et al., 2018; V. J. Mascarenhas et al., 2017; Veloisa J. Mascarenhas & Zielinski, 2018). In Skagerrak, the contribution of cDOM to the Secchi depth was 71 %, followed by Chlorophyll *a*, while the contribution by inorganic TSM was insignificant, which indicates that cDOM is one of the main drivers for the light attenuation in the southern Norwegian waters (Harvey et al., 2019).

The seasonal or spatial patterns for TSM or particulate aggregations for Norwegian fjords were found to be important for understanding more local changes (Białogrodzka et al., 2018; Nima et al., 2016) and glacial inflows (Sagan & Darecki, 2018; Trudnowska et al., 2020). In Sagan & Darecki (2018) the cDOM absorption, particle backscattering and particle concentrations were studied along two Arctic fjords from the vicinity of the glaciers towards more open waters. In general, there was a decrease for all optical variables when moving from the glaciers towards the open water, but the particle concentration was specifically high in Kongsfjorden. The effects and concentrations of particles from glaciers seems to be most pronounced close to the front, as there seems to be a strong settling of the particles and aggregates as you move away from the glacier (Trudnowska et al., 2020).

When there is an increase in light attenuation in the water column, it means that there is a decrease in light over all wavelengths but especially in the deeper waters where there is less of the total light (see Figure 6). The change in the light spectra is affected by both the absorption and the scattering. Figure 6 shows a schematic of conditions in open ocean waters compared to coastal water. The main difference is in the light depth (higher light attenuation in the coastal site means less light in deeper waters) and in the shape of the spectrum where the peak is shifted towards the red in coastal waters due to absorption by Chlorophyll *a* and cDOM in the blue and green wavelengths. Increased particles also leads to more turbid water and higher light attenuation.

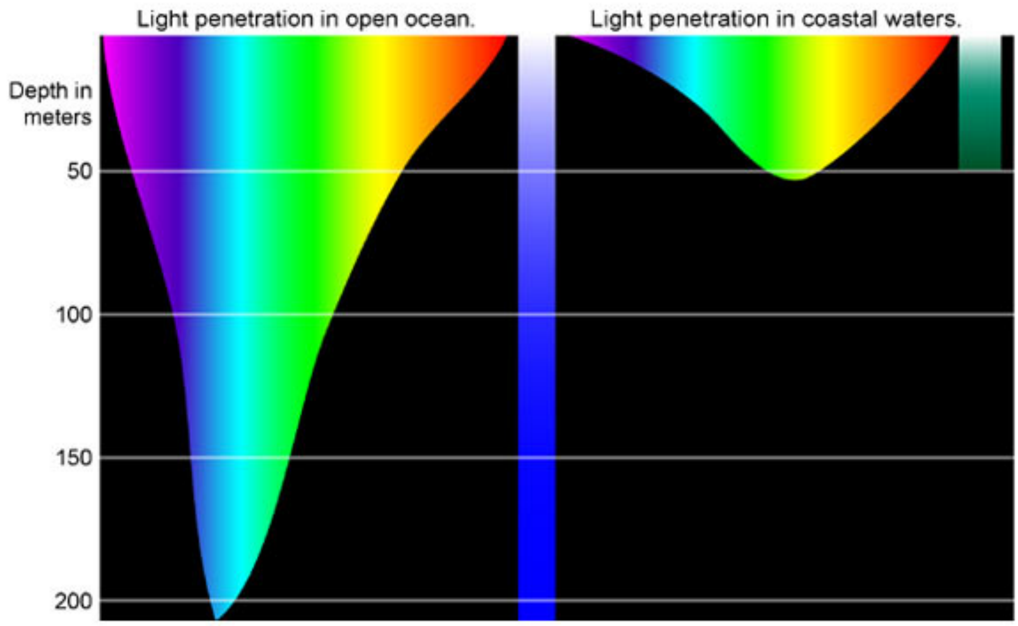

Figure 6. Image courtesy of Kyle Carothers, NOAA-OE (https://oceanexplorer.noaa.gov/explorations/04deepscope/background/deeplight/media/diagram3.html)

A) Are there long-term studies published after 2009 showing increased light attenuation in coastal waters in Norway?

Yes, there are long-term studies that have showed increased light attenuation in Norwegian coastal waters, which are described more detailed below.

In general, all Norwegian coastal waters are influenced by riverine inputs, and upstream changes in river catchments will impact the coastal zone (Deininger et al., 2020; Frigstad et al., 2020 and references therein). At Svalbard, coastal waters also receive substantial inputs of freshwater and particles from glacial rivers and marine terminating glaciers (McGovern et al., 2020; Pavlov et al., 2019; Sagan & Darecki, 2018). The riverine or glacial inputs transport freshwater, nutrient, organic matter and particles to the coastal waters have effects on seasonal and spatial dynamics of the ecosystems, such as the spring blooms and the underwater light conditions (see e.g. Frigstad et al., 2020; Harvey et al., 2019; Kratzer et al., 2020; McGovern, Pavlov, et al., 2020; Opdal et al., 2019). Although eutrophication has been and still is a large problem within the coastal zones, changes in coastal light attenuation is today assumed to be driven largely by the changes in the terrestrial inputs (Harvey et al., 2019; Opdal et al., 2019), but to some extent still by Chlorophyll *a* (Lundsør et al., 2020).

Studies on long-term changes in Secchi depth

The term darkening is used in (Aksnes et al., 2009) to describe a long-term increase in light attenuation connected with decreased salinity in the Norwegian Coastal Current. The study makes use of historical measurements of salinity and dissolved oxygen levels between 1935-2007 from six Norwegian coastal fjords. The salinity and oxygen data are combined into empirical relationships between a) the total absorption and the light attenuation coefficient at 500 nm, $K_d(500)$ and b) between total absorption and salinity, dissolved oxygen and Chlorophyll *a* based on data from two Norwegian western fjords (Lurefjorden and Masfjorden). The results from the study showed that there has been an increased in total absorption in Lurefjorden over 75 years, however less evident in Masfjorden. The increased absorption in Lurefjorden corresponded with an almost 2-times increase in light attenuation in the deep waters in 2007 compared to 1935. The same change was not seen in Masfjorden as the sill is deeper with a higher input of high salinity marine waters to the bottom basin, but it is suggested that there has been a darkening (increased light attenuation) in the upper part of the water column. However, their results implicate that other fjords may be affected in the same way, specifically fjords on the western Norwegian coast, coupled with increased levels of organic matter from Norwegian lakes and an increase input of freshwater to the coast.

The changes in Secchi depth in the North Sea (including the Skagerrak and Kattegat) were studied over almost a century (1903-1998) by Dupont and Aksnes (2013). They found that the Secchi depth has decreased by 3.4 ± 0.2 (-26%) m for the deep waters and by 3.6 ± 0.25 (-36%) for the shallow areas within the North Sea. The pronounced and significant changes are corrected for distance to land, bottom depth and seasonality. The Secchi depth has increased again after the 1970`s but have not reach the previous depths. In the same study the cDOM effects on light are addressed theoretically and they use the well-known relationship between salinity and cDOM for marine waters (increased salinity is correlated with a decrease in cDOM absorption) for assuming that the changed light regime may have been driven by increased cDOM absorption, causing the state and regime shift of the Secchi depth in the North Sea in the 1980`s.

Another long-term study between 1973-2017 in the inner Oslofjord showed that a decrease in Chlorophyll *a* concentration was mainly driven by decreases in nutrients followed by an increase of the Secchi depth until 1980, after that an increase in the Secchi depth was not noticeable and does not follow the phytoplankton patterns (Lundsør et al., 2020). We therefore assume that the changes in Secchi depth are caused by factors (e.g., cDOM and/or TSM) other than Chlorophyll *a* responses to nutrient changes as eutrophication in the Oslofjord has decreased without the same response in the Secchi depth.

Studies on effects of cDOM and TSM on light attenuation

A recently published model study by Opdal et al. (2019), based on the same Secchi depth dataset in the North Sea as in Dupont & Aksnes (2013) and Capuzzo et al. (2015), found an increase in the light attenuation based on historical Secchi depth data and Chlorophyll *a* data over the 20th century (1903-1998). The new model specifically addressed the non-phytoplankton light attenuation caused by mainly DOM in the deeper regions of the North Sea (but resuspension of particles/suspended matter could also be important in the shallower regions). Figure 7 is taken from this publication and clearly shows the increase in light attenuation caused by DOM over the 20th century.

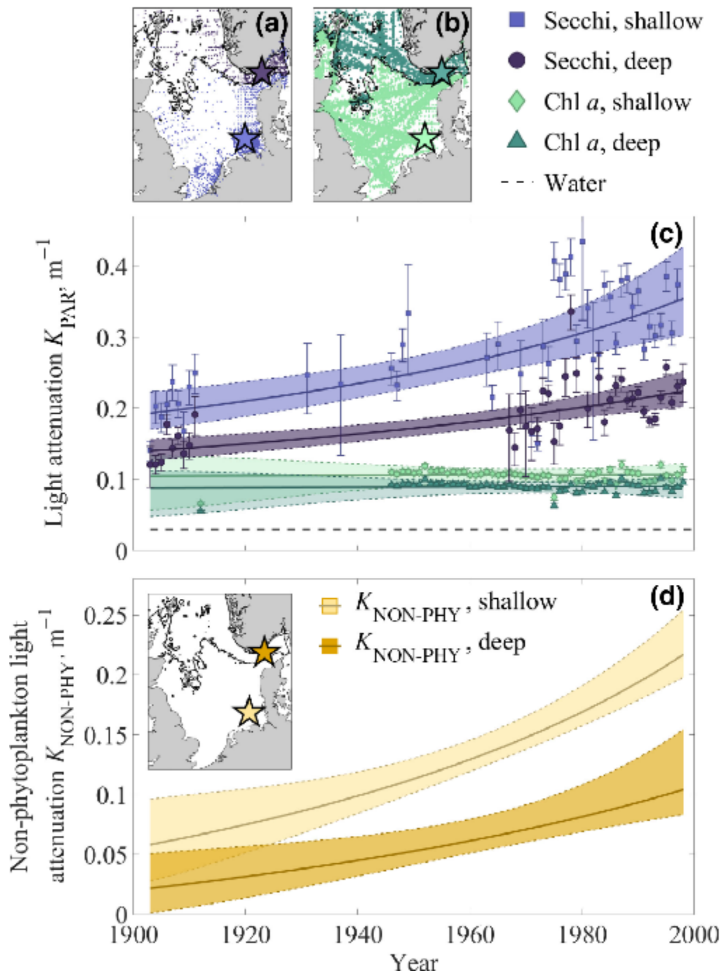

Figure 7 from Opdal et al. (2019), showing an increased light attenuation in panel c, estimated from Secchi disk depth (purple) and chlorophyll a concentrations (green). The attenuation from water itself is show as the water as a black dotted line. Panel d is showing the non-phytoplankton light attenuation for same the deep (dark brown) and shallow (light brown) locations (shown in map insert). Please see figure 1 in Opdal et al. (2019) for a full explanation.

There has also been an increase in the TSM concentrations in the North Sea from 1988 to 2011, with a significant increase seen during all seasons, except summer (Capuzzo et al., 2015). The increase is explained to be driven mostly by the inorganic fraction of TSM as the same increase was not seen in the Chlorophyll *a* concentration, which were decreasing in the summer during the same period. Several causes, like increased bottom trawling, changes in weather patterns and in the benthic communities as well as coastal erosion may have contributed to the changes in TSM (Capuzzo et al., 2015).

An long-term increase in POM in Skagerrak coastal waters was reported by Frigstad et al. (2013) where a 20-year time series between 1991-2010 was studied. An increase in the concentrations of suspended particulate organic matter (POM), dissolved organic nitrogen and the estimated fraction of non-autotrophic material (including dead phytoplankton, small heterotrophs, and detritus of both marine terrestrial origin) within the POM have increased between 1998 and 2000, and have remained at those levels since then. The observed increase in POM is hypothesized to be caused by flocculation, causing the river DOM to coagulate into larger particles and thereby be defined into the marine POM pool. This "salinity-induced flocculation" is a phenomenon known to occur when terrestrial freshwater meets the saline waters, as in coastal areas (Asmala et al., 2013). In Frigstad et al. (2018) this increasing trend in POM was confirmed and found to be significantly connected to the increase to riverine discharge and total riverine organic carbon concentrations.

B) In the available literature, are any coastal regions in Norway considered particularly vulnerable to changes in light attenuation? If so, which are these and why are they vulnerable?

The coastal zone is strongly influenced by changes in the environment and is affected by several different human pressures (McGovern et al., 2019). Substances that both absorb and scatter light (Chlorophyll *a*, cDOM and TSM) in the coastal zones are highly variable and can reach high concentrations. Norwegian coastal areas with shallow euphotic zones are described in Aas et al. (2013), where the coastal waters are categorized as Oceanic water type III or Coastal water type 1 or 3, with characteristically high K_d, shallow depth of the euphotic zone and high content of cDOM and TSM.

Fjords

Fjords are particularly vulnerable to changes in light attenuation due to their pronounced sills and therefore longer retention times. They are more stratified due to differences in the salinity between the more saline deeper waters and the freshwater influenced surface waters. This halocline in combination with a thermocline (temperature difference) during the summer months prevents the surface and the bottom waters to mix. This high degree of stratification means that fjords can be more sensitive to an increase of freshwater with high cDOM/DOC and TSM content since mixing and dilution are restricted, and coastal darkening can be more pronounced (see e.g. Aksnes et al., 2009; Białogrodzka et al., 2018; Brattegard et al., 2011; Frigstad et al., 2020; Mascarenhas et al., 2017; McGovern, Pavlov, et al., 2020).

Skagerrak/North Sea:

The Skagerrak/Southern North Sea areas are typically higher in light attenuation with relatively large and increasing terrestrial DOM loads (browning) (Larsen et al., 2011; McGovern et al., 2019), showing increasing DOM and DOC with increased climate-induced precipitation in boreal regions. Also shown from the model results of the light attenuation in coastal waters (see Background, Figure 5), Skagerrak has the regionally highest light attenuation of all the Norwegian coastal regions. Frigstad et al. (2020) also found the Skagerrak to be the region with the most persistent influence of riverine organic matter, corresponding to high cDOM concentrations in surface waters, compared to western and northern Norwegian fjords. There has been a decrease in the Secchi depth over the 20th century in the Skagerrak area (Capuzzo et al., 2015).

The Oslofjord and Southern Norway have higher background DOC and cDOM fluorescence levels arising from both river inflow and mixing with both Baltic Sea cDOM/DOC rich waters and waters from the southern/central North Sea (Frigstad et al., 2013, 2020). Light attenuation is already relatively high in the southern Norwegian coastal waters and any increase in cDOM input from rivers or the Baltic Sea would further attenuate light with several possible biological effects, described under Question 2.

Svalbard (and glacier-influenced mainland Norwegian fjords):

On Svalbard, glacier-fed rivers and marine terminating glaciers deliver high loads of inorganic particulate matter to adjacent coastal waters, leading to highly turbid waters and high light attenuation. This strong influence of glacial run-off on coastal light attenuation has been documented in several fjord systems on Svalbard, including Kongsfjorden (Pavlov et al., 2019; Sagan & Darecki, 2018), Isfjorden (McGovern et al., 2020), and Hornsund (Sagan & Darecki, 2018).

Rapid climate change is leading to melting glaciers, permafrost thaw, changes in precipitation patterns and increased freshwater runoff. These changes can be expected to lead to increased inputs of terrestrial particles and DOM, with important implications for light attenuation in Svalbard's coastal waters (Pavlov et al., 2019; McGovern et al., 2020). Reductions in the extent of land-fast sea ice and thawing of coastal permafrost may also lead to increased coastal erosion, which can also lead to turbid waters with high light attenuation.

It is important to note that several western and northern Norwegian fjords are also impacted by inputs of freshwater and inorganic particles from glacier-fed rivers. As outlined for Svalbard, climate change driven increases in melting of glaciers could also be expected to lead to increased TSM concentrations (and light attenuation) in impacted mainland Norwegian waters. However, from a long-term perspective, reduced extent (and potential loss) of mainland Norwegian alpine glaciers could eventually also lead to reduced particle transport to the coast, thus increasing light availability in these systems that are no longer strongly impacted by inputs from glaciers.

C) In the available literature, are there indications/predictions on how light attenuation in coastal waters will develop in the future? Are the findings unanimous or are there contradicting findings?

Not many papers have modelled the future changes in light conditions for the Norwegian coastal waters. However, there are papers that discuss potential future changes in light conditions based on observed trends in DOM and particles (e.g.Frigstad et al., 2013, 2020; McGovern et al., 2020). There is a predicted further increase in light attenuation due to the strong link with increasing input of terrestrial DOM and TSM (Harvey et al., 2019; Mascarenhas et al., 2017; Urtizberea et al., 2013).

In the Baltic Sea, future projections of ecosystem effects was modelled with decreases in salinity in all areas, but with the most pronounced effects in the Kattegat which most likely will experience increased light attenuation (Andersson et al., 2015). There are studies with future projections for how climate change is expected to increase precipitation and temperatures with effects on freshwater systems, which also will lead to a higher inflow of freshwater and terrestrial material (de Wit et al., 2016; Larsen et al., 2011; Monteith et al., 2007). Those studies are therefore also relevant to the Norwegian coastal zones and fjords.

In the future scenario by de Wit et al. (2016) they estimate that a 10% increase in precipitation would increase the mobilization of organic carbon from soils to freshwaters by at least 30%. This would mean that the current browning of the freshwater would continue and that it also will increase the input of carbon (and thus cDOM) to the coastal zones. This reasoning is also supported by e.g. Dupont & Aksnes (2013) and Opdal et al. (2019). Therefore, the increased light attenuation in coastal waters that have already been seen during the 20th century can be expected to continue.

There are no contradicting findings in the literature, instead they are supporting each other. There is a consensus that the terrestrial inflows will increase with a warmer and wetter climate, which from empirical studies will, and has shown to already have, a strong effect on increasing light attenuation, making the waters darker and more turbid. However, dedicated studies where the projected effect of these riverine changes on coastal light attenuation were modelled were not found.

D) In the available literature, are there any recommendations for methods to discover changes in light attenuation in coastal waters for monitoring purposes and/or assessing environmental status in terms of the WFD?

In two recent studies based on the ØKOKYST monitoring programs and the parameters collected that are connected to climate change (Frigstad et al., 2017, 2018), a main conclusion and recommendation is to include measurements of DOC, cDOM and light profiles (including spectral composition) in the future monitoring programs of coastal waters. Over the last years, it has increasingly been recognized that more optical measurements, including cDOM and TSM (organic and inorganic fraction), are important for understanding changes in light attenuation and it has now started to be included in the Swedish national monitoring program for the same reasons (personal comment by T. Harvey).

The depth of euphotic zone is critical for many biological and ecological processes (see Question 2) and K_d(PAR) or Secchi depth are often measured as indicators of water transparency and light availability within the monitoring programs. These are integrated parameters that give a sum of the light available for photosynthesis (ie. between 350-700 nm; K_d(PAR)) or an indication of the total light penetration within the waters (Secchi depth), which gives information of the total changes in the light environment but not about the drivers of the changes. Chlorophyll *a* is routinely measured and is often one of the drivers of the changes, but in coastal waters TSM (both organic and inorganic fractions) and cDOM also contribute. Measurements of cDOM and TSM have not been common in Norwegian waters, and it has been argued to be included within the regular programs or to consider in further studies (Aas et al., 2014; Capuzzo et al., 2015; N. Dupont & Aksnes, 2013; Fleming-Lehtinen & Laamanen, 2012; Harvey, Kratzer, & Andersson, 2015; Harvey et al., 2019; Kratzer et al., 2014). Salinity and dissolved oxygen has been used for absorption and light attenuation models in Norwegian fjords (Dupont & Aksnes, 2013).

Turbidity measurements are highly correlated to TSM, as it measures the scattering in the water column. There are robust, easy-to use bench instruments that easily can be implemented within monitoring programs in a cost effective way (Kari et al., 2017).

Since the light attenuation is wavelength dependent, in situ spectrally-resolved measurements of light attenuation at different wavelengths by a radiometer would be an additional valuable parameter to measure to be able to follow changes in the specific wavelengths as e.g. cDOM absorbs highly in the blue and Chlorophyll *a* in the blue and orange/red spectra. While Secchi depth has been historically, and still is, an important metric that has been used by many studies as a proxy for changes in K_d, Chlorophyll *a*, TSM and cDOM and for developing empirical relationships and models that can be applied historically or locally (e.g. Aas et al., 2013, 2014; Capuzzo et al., 2018; N. Dupont & Aksnes, 2013; Fleming-Lehtinen & Laamanen, 2012; Harvey et al., 2019; Lundsør et al., 2020; Opdal et al., 2019; Urtizberea et al., 2013; Wollschläger et al., 2020). However, Secchi depth is less precise and provides less information than spectrally-resolved radiometer measurements.

Parametrization of the absorption and scattering effects on the total attenuation of light requires in situ radiometric data and optical measurements. By collection of these types of data, absorption budgets of the available light can be made and changes can be monitored, which would make it possible to describe the contribution from cDOM, Chlorophyll *a*, TSM (inorganic and organic) to the total light attenuation. Based on these data it would be possible to understand and develop indices on the effects of the different drivers for changes in coastal light attenuation.

Remote sensing data from satellites

Other ways to study long-term changes could be to use remote sensing satellite data, that can be merged and reprocessed into coherent products, which also can be integrated with in situ data and models (Arabi et al., 2020; Kratzer et al., 2016, 2019; Saulquin et al., 2013). The use of remote sensing for aquatic applications are becoming standard for products such as TSM, turbidity, Chlorophyll *a*, K_d and Secchi depth. In the Baltic Sea, Alikas et al., (2015) and Alikas & Kratzer (2017) have developed robust algorithms for K_d and Secchi depth retrieval in lake and coastal waters. The use of remote sensing data for implementation within the water Framework Directive (WFD) are shown by Alikas et al., (2015), Harvey et al. (2015) and for Norwegian lakes as well by Ledang et al. (2019).

Remote sensing of different DOM parameters (such as TOC, DOC and cDOM) have shown to be retrieved successfully from Swedish lakes (Al-Kharusi et al., 2020) and rivers in Norway (Fagernes, 2020). Studies in coastal waters, however, are rare as the algorithm needs to be locally adjusted.

Remote sensing of TSM usually works very good in coastal waters and can be retrieved with 60 m resolution from e.g. the satellite Sentinel-2 or 300 m resolution from the MERIS or OLCI sensor (Kari et al., 2017; Kratzer et al., 2019, 2020; Kyryliuk & Kratzer, 2019). TSM, Chlorophyll *a* and Secchi depth has also shown to be working good also in Norwegian lakes (Ledang et al., 2019), which can to some extent be applied to coastal areas as well.

McGovern et al. (2020) state that a possible way to capture the high spatial and temporal dynamics is by the use of satellite remote sensing data and airborne platforms as the nutrient, DOM and TSM input were strongly related to turbidity (which is a parameter that is robust and accurate to measure by satellite remote sensing).

Techniques to monitor changes in the light attenuation

- <u>In situ sensors:</u> hyperspectral radiometers, LISST (and related sensors), PSICAM (phytoplankton, cDOM), AC9/ACS sensor (measures the absorption attenuation in several spectral bands), backscattering sensors, turbidity sensors
- <u>Above water sensors (where surface observations can adequately predict mixed layer conditions):</u> hyperspectral radiometers, multispectral cameras, LIDAR from fixed platforms, such as planes, ships, drones, satellites

Methods to study long term changes in light attenuation and the drivers of change

- Monitoring programs with Secchi depth, Chlorophyll *a*, cDOM, TSM (both inorganic and organic fraction) and spectral K_d included (observations)
- Detailed optical studies of the parametrization of the factors contribution to the light changes in order to establish empirical relationships that can be applied on historical data or in models (observations)
- FerryBox systems (autonomous observations)
- Buoys (autonomous observations)
- Remote sensing data (observations)
- Model hindcasts (estimations)
- Empirical models like Aksnes (2009, 2013 & 2019) (estimations)

Question 2: Are there studies published after 2009 showing biological effects of increased light attenuation in Norway?

In total the search for articles for biological effects of reduced light attenuation in Norway after 2009 (Q3) resulted in 102 papers and reports, of which 27 papers were directly relevant to Q2 and described below. There were most relevant papers on jellyfish blooms (11), followed by macroalgae and hard-bottom communities (9) and phytoplankton (7).

Euphotic zone

In general, light availability is fundamental for life in the oceans. It is the main energy source for autotrophs (through photosynthesis) and therefore supports the primary production that the oceanic food web is built upon. In coastal systems, primary production is primarily carried out by phytoplankton and benthic vegetation (macroalgae and seagrasses). The euphotic zone is the layer in the oceans closest to the surface, where there is enough light for photosynthesis to occur. The depth of the euphotic zone varies with the intensity of the incoming solar radiation, which is determined by the latitude and season, in addition to the water clarity. As described in the Background section, phytoplankton cells will absorb and scatter light, and can in high concentrations significantly attenuate light and result in light limitation of primary production. In addition, light-attenuating substances (e.g. cDOM and TSM) from land can significantly reduce the depth of the euphotic zone in coastal regions. In Aksnes (2015) it was calculated that the euphotic zone (defined as where 1% of surface PAR penetrates) was around 14m deep in the Norwegian coastal water, compared to around 112m deep in the North Atlantic Ocean water, in a water column without Chlorophyll *a* (i.e. without phytoplankton). This difference of 98m in euphotic depth between the marine and coastal water masses was caused by the non-phytoplankton attenuation of light, and salinity was found to be the most important explaining factor for difference in light conditions. Thereby the light attenuating substances in the freshwater sources has a large influence on how deep the euphotic zone is (and thereby how deep the phytoplankton grow) along the Norwegian coast. This is also reflected in the depth of the nitracline (i.e. the depth separating low surface values from the higher deeper values of nitrate) which is also shallower in the coastal waters due to the shoaling of the euphotic zone (Aksnes et al., 2007). However, Aksnes (2015) does not explicitly separate between effects of the riverine cDOM and TSM on the light conditions, just stating that cDOM is known to be an important light absorber in the Baltic, Kattegat, Skagerrak waters, and that generally the non-phytoplankton attenuation was found to be highest in the south and decrease northward along the Norwegian coast.

Phytoplankton

<u>Bloom timing</u>

In high-latitude regions, the spring phytoplankton bloom is traditionally described to occur when the incoming light intensity increases during spring (penetrating deeper into the water column), and simultaneously increasing temperature and reduced winds stabilize the water column (decreasing the mixed layer depth), which leads to an exponential increase in the phytoplankton concentrations (Sverdrup, 1953). With climate change and ocean warming, there will be earlier stratification of the water column, which should in theory lead to an earlier spring bloom, if the optical conditions remain unchanged. In a recent paper, Opdal et al. (2019) analyzed long-term Secchi disk data and Chlorophyll *a* concentration estimates, and found that there has been an increase in light attenuation in the North Sea over the last 100 years, caused by increased terrestrial DOM load, with contribution from resuspension of particles in shallower coastal regions (see Q1 above). This increase in light attenuation was found to have caused a 3 week delay in the onset of the spring bloom in the North Sea over the last 100 years (see Figure 8).

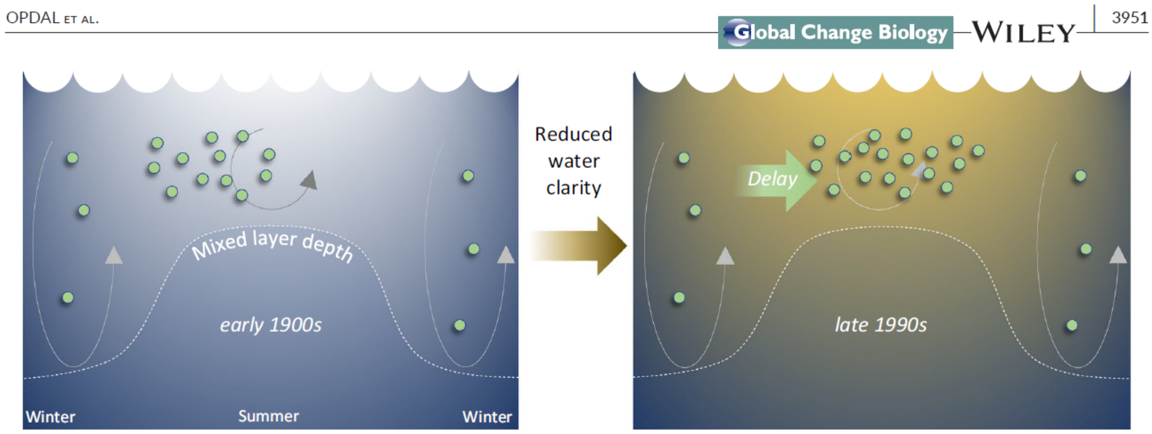

Figure 8. Illustration from Opdal et al. (2019) showing the predicted changes in phytoplankton responses to increased light attenuation (= reduced water clarity).

<u>Chlorophyll a and Secchi depth</u>
In the inner Oslofjord, the Chlorophyll *a* concentrations were found to decrease by 70% from 1980-1990, returning to good ecological status (as defined by the Water Framework Directive) following a reduction in inorganic nutrient concentrations (Lundsør et al., 2020). There was also an increase in Secchi depth (i.e. reduced light attenuation in the water column) following the reduction in Chlorophyll *a* however the light in the water column did not increase as much as the reduction in Chlorophyll *a* would imply. Lundsør et al. (2020) suggested the increase in DOM from rivers in the region as a possible explanation for this discrepancy, and state that more knowledge is needed on the combined effects on salinity, temperature and coastal darkening on the highly dynamic inner Oslofjord system.

<u>Interactions between eutrophication and cDOM</u>
The recent and projected increase in cDOM supply to coastal waters result in effects that resemble the responses to high nutrient loads and eutrophication in coastal systems. The increased light attenuation caused by cDOM causes a shoaling of the euphotic zone (as described above) and a model study shows that this "lifts" the phytoplankton higher in the water column, and thereby could result in eutrophication symptoms in the upper water column, such as increased Chlorophyll *a* and nutrient concentrations (Urtizberea et al., 2013). In a review of the effects of increased terrestrial DOM supply on coastal eutrophication, Deininger & Frigstad (2019) discuss that that the predicted response would be an overall reduction in phytoplankton production (due to shading effect) and increase in bacterial production (by stimulating the microbial loop). These effects will depend on the properties of the riverine DOM, such as the optical variables (cDOM and TSM) and the bioavailability of the riverine organic matter. Increased riverine input of DOM and increased light attenuation (reduced Secchi depth) could therefore potentially hinder a coastal system to recover from eutrophication, even though there has been a decrease in the inorganic nutrient supply.

<u>Arctic coastal waters</u>
In Svalbard coastal waters, light conditions will be affected by both decreasing sea-ice (causing increased light) and glacial and permafrost melting and increased riverine run-off that increase the turbidity and reduce the light available for photosynthesis (both pelagic and benthic) (Pavlov et al., 2019). Substantial inputs of inorganic particles from glacier-fed rivers and marine-terminating glaciers can have strong impacts on the euphotic zone in coastal waters. For example, in a recent study in Isfjorden (McGovern et al., 2020) observed euphotic zones that were often less than 2 m deep in river

estuaries and nearshore coastal waters, and although inorganic particles from land tended to sediment out quite quickly in river estuaries, the authors still observed increased light attenuation linked to high TSM even several km out into the fjord system. It has been suggested in several studies that strong reductions in light availability in Svalbard's coastal waters during the summer melt season are likely to lead to reduced phytoplankton and benthic algal production (Pavlov et al., 2019; McGovern et al., 2020). On the other hand, McGovern et al. (2020) also note that inputs of freshwater and particles from land are also associated with substantial inputs of nutrients, which could in fact support increased phytoplankton production where light is sufficient for photosynthesis (e.g. further out in the fjord). Climate change is expected to impact both the timing and magnitude of snowmelt, glacial runoff, and rainfall on Svalbard. As outlined in McGovern et al. (2020), a shift toward an earlier melt season could lead to increased likelihood of the spring phytoplankton bloom coinciding with the onset of the melt season and runoff from land, with important implications for light and nutrient availability for primary producers.

Kelp and hard-bottom communities

The shoaling of the euphotic depth due to increased light attenuation in Norwegian coastal waters (Dupont & Aksnes, 2013; Aksnes, 2015) will have implications for the maximum depth that benthic organisms dependent on photosynthesis can grow (due to light limitation).

There has been a documented long-term decrease in the lower depth growth limit of several macroalgae species in Skagerrak (Moy et al., 2008; Frigstad et al., 2018; Fagerli et al., 2020; Naustvoll, 2020). This is caused by multiple interacting stressors, however has been connected with both increased loads of terrestrial material (increasing light attenuation) and increasing temperatures over the last 30 years in Skagerrak (Moy & Christie, 2012; Norderhaug et al., 2015; Frigstad et al., 2018; Andersen et al., 2019). Rueness & Fredriksen (1991) showed that the lower depth limit of several algal species had become shallower between 1950 and 1989, with the lower depth limit of sugar kelp (*Saccharina latissima*) decreasing from 25 to 15m. Sogn Andersen et al. (2019) describes the sugar kelp to be in a ”vertical squeeze” where the deeper depths where the kelp is not being overgrown by turf algae is close to the lower depth limit of kelp, and this ”window” is narrowing due to the shoaling of the euphotic zone in the Skagerrak. Christie et al. (2019) describe the shifts between kelp and turf algae and conclude that reductions in eutrophication and improved light conditions are likely to be the most important mitigating efforts for improving conditions for kelp forests in Norwegian coastal waters.

A shift in the species composition in hard-bottom communities has also been observed in Skagerrak over the last 30 years, with a reduction in the macroalgae species (especially red algae) and increase in animals, especially filter feeders (Frigstad et al., 2018). This was found to be connected to increasing temperature and increased suspended particles (POM and TSM).

Zooplankton

The vertical distribution of zooplankton in the water column is dependent on light, and the depth at which *Calanus* species overwinter has been shown to be dependent on the optical properties of the water column (Dupont & Aksnes, 2012). However, a potential consequence of long-term increases in coastal light attenuation is not discussed.

Jellyfish vs. fish

Underwater light is not only important for algae and plants to perform photosynthesis, but also for animals that require light for feeding. There has been a number of publications that discuss the relationship between increased light attenuation in coastal waters and the increased abundances of jelly fish (mainly *Aurelia aurita*) along the Norwegian coast (Aksnes et al., 2009; Bozman et al., 2017; Dupont et al., 2009; Geoffroy et al., 2018; Haraldsson et al., 2012; Purcell, 2012; Tiller et al., 2017; Ugland et al., 2014). The mechanism behind this shift is that water clarity has a large influence on organisms that use vision to search for prey, therefore increased light attenuation will provide a competitive advantage for tactile predators (jellyfish) versus visual predators (fish). This shift has been particularly described for western Norwegian fjords, where there has been mass occurrences in jelly fish linked to increased coastal darkening (Aksnes et al., 2009).

Water clarity can also affect the vertical distribution of fish and zooplankton in the water column (acoustic scattering layer) (Aksnes, 2007; Aksnes et al., 2004, 2017; Røstad et al., 2016).

Soft-bottom communities
The soft-bottom communities are animals (ie. not dependent on light for photosynthesis) and only indirectly affected by changes in light-attenuation and increased riverine discharge of terrestrial organic material, through changes in the pelagic food web and changes in particle sedimentation on the seafloor.

Long-term monitoring data from soft-bottom stations in Skagerrak shows an improvement in ecological status, believed to be caused by a reduction in eutrophication (Trannum et al., 2018). This improvement in ecological status of deep soft-bottom communities was also found for the outer/deep station outside Arendal in Frigstad et al. (2018), however at the more coast-near and shallow station, a worsening trend in the ecological condition was found, which was connected with an increase in suspended particle concentrations in the water column and ultimately settling on the seafloor. Both stations showed an increase in the species feeding on suspended material in the water column or on the sediment surface, which could be a response to the change in food supply for the benthic community.

A study on the benthic community composition in northern Norway (McGovern, Poste, et al., 2020) found that high riverine input lead to decreased species and functional diversity in the impacted fjord, due to the changes in sediment grain size and high rates of sediment deposition. However, the species able to persistent in this environment (including mobile deposit feeders) with high terrestrial carbon and nutrient inflow, were important for the incorporation of terrestrial carbon into the coastal food web.

Impacts on contamination of coastal food webs
One recent 'viewpoint' article (McGovern et al. 2019) provided a conceptual overview of how coastal darkening could potentially impact contaminant cycling and food web accumulation in northern coastal ecosystems. In this paper, the authors suggest three main potential impacts: 1) increased inputs of particle and DOM-associated contaminants from land to coastal waters, 2) changes in uptake of contaminants at the base of the food web due to changes in bioavailability (since reduced uptake of contaminants can occur when they are strongly bound to particles or DOM), and 3) change in food web transfer of contaminants due to potential shifts in food web structure in response to reduced light availability (e.g. from more phytoplankton-based food webs to more bacteria-based food webs, or impacts on visual predators).

Question 3: Are there studies showing effects of increased light attenuation in comparable global coastal systems to Norway?

The literature search conducted in this report confirms the overall outcome of a global meta-analysis of light reduction experimental findings presented below (Striebel et al., submitted). For question 3, we did not focus on autotrophic producers in general, but also on effects on other ecosystem components and overall functioning. We start with a review of Striebel et al. (submitted), and then follow with results found for each region and finish with an overall summary of the main effects, drivers, and identified knowledge gaps at the end of this section (Citations see **Table 1**).

A highly relevant global synthesis paper is currently in review (*Striebel et al. submitted*), which is led by the University of Oldenburg, Germany (a co-author of the report A. Deininger is part of the paper). In this paper a global meta-analysis was performed on light reduction experiments, to summarize the response of marine pelagic and benthic photoautotrophs (i.e. seagrasses, macroalgae, microphytobenthos ad phytoplankton) (*Striebel et al. submitted*). The article is currently under revision (and therefore not included in Table1), however the results of this study (weighted meta-analysis on 207 published light reduction experiments) suggest that light reduction will strongly affect ecosystems and especially photosynthetic (i.e. light dependent) organisms from pelagic phytoplankton to benthic macrophytes. "Across all studies, reduced light led to an average 29% reduction in biomass-related performance and 19% reduction in physiological performance. Effect sizes were strongly associated to remaining light intensity (stronger reduction yielding stronger negative responses) and time (reflecting acclimation potential), but surprisingly consistent across habitats and organism groups" (Striebel et al. *submitted*).

Findings for the different regions (see region-specific references in Table 1):
Baltic: In the Baltic, effects of increased light attenuation, effects have originally been attributed to "eutrophication" and the effects on water quality, such as Secchi depth. However, over the past decade the role of terrestrial material entering via river discharge has gained increased attention for explaining the ecosystem state of the Baltic Sea. In the Baltic, increased river runoff, and increased input of terrestrial material has been attributed to climate change and specifically increased precipitation, as well as historic land-use and forestry. Also, interaction effects of eutrophication and terrestrial material have been investigated and emphasized for this area. Overall, we found that in the assessed literature, Baltic studies have focused on effects on basal food webs, and especially on bacterial pathways. As the increasingly available terrestrial material will not only affect light levels, but also act as additional resource for basal producers that do not require light for their growth, such as bacteria. Also, some studies have looked at effects on macrophytes, where declines have been reported across the Baltic. Lastly, the accumulation of mercury, as well as of organic pollutants in aquatic food webs in relationship to the increased input of terrestrial material has been of concern for this area.

North Sea: In the North Sea, effects of terrestrial organic matter on light have been detected, both on light intensity, as well as light quality. Also, the importance of TSM has been investigated because there have been particles entering the water column following by large-scale dredging in the area. As for the Baltic, effects have been detected on macrophytes where also an increase in epiphytic "turf" algae have been described. Additionally, also alterations and declines in phytoplankton communities have been described, as well as changes in nutrient stoichiometry with potential large effect on zooplankton such as copepods. Further, as for Norway, also in the North Sea increases in jellyfish have been observed. Lastly, studies indicate that terrestrial organic matter effects might potentially interact with the carbonate system of the North Sea, and further increase the risk of hypoxia in ocean sediments.

Especially the last point is of major concern for coastal managers as large efforts have focus on abating eutrophication. However, if terrestrial organic matter continues to increase to the North Sea, managers need to reduce the inorganic nutrient inputs to coastal systems even more to compensate for effects of terrestrial organic matter on coastal systems.

Canada: The same drivers and effects of increased light attenuation on coastal ecosystems are described for Canada as for Norway. Namely the increased riverine discharge of terrestrial organic matter (e.g. from the Mackenzie River to the Beaufort Sea) with effects on turbidity and light conditions. In addition, the increase in episodic storm events and attributed increased riverine runoff have been described. Ecosystem effects have been described on seagrasses (decline), plankton ecosystems, the timing of the spring-bloom, as well as for the increased risk of anoxic bottom-water zones. Lastly, shellfish farming is of economic importance in Canada, and the importance of sustainable management approaches has been discussed as shellfish farms might both increase the input of nutrients to adjacent coastal zones, as well as act as filters for the increasing particles brought in by the rivers.

South America: Compared to the other areas, fewer studies have been reported for South America. However, studies from Chile and especially Argentina have reported increased freshwater discharge for some areas, and several articles discussed the effects of changed coastal light conditions on the distribution and abundance on coastal primary producers (phytoplankton to kelp), but also fate of increased runoff of organic material in fjords.

New Zealand: For New Zealand, alterations in coastal optics have been observed due to increased riverine discharge attributed to climate change and also to runoff from agriculture and urban landcover, as well as dredging of coastal waters. Effects have been described to include the decline in macrophytes, kelp forests and microphytobenthos but also phytoplankton, and especially the increase in nuisance macroalgae. Interestingly, mangroves have been observed to increase in area where especially particle runoff has been increasing. Negative effects have been described for coral reefs, both due to the direct decrease in light, as well as due to the sedimentation of particles onto the benthic organisms.

Other globally relevant drivers and effects: Extreme weather events resulting in episodic increased inflow of organic material from land to coastal zones have been described across the globe, with most detailed studies conducted especially in Australia, as well as the United States. An additional important driver is dredging, and the resulting resuspension of sediments as well as destruction of e.g. macrophyte coverage and habitat. Further, eutrophication is still an important driver for the light climate in coastal regions (Hartill et al., 2020). Lastly, all activities in the catchment that may increase the mobility of terrestrial material to be transported downstream may be a potential driver increasing land-ocean interactions with effects on costal optics, as well as biogeochemistry.

Table 1. Summary of results found for relevant studies investigating the effects of increased light attenuation on coastal zones. Presented are region/area, discussed drivers, ecological or economic impacts, and potential management solutions. Ter-OM = terrestrial organic matter.

Regions	Discussed Drivers	Observed direct and indirect Environmental/Ecological/Economic Impacts	Management / Discussed Solutions
Baltic Sea	• **Increased precipitation with climate change** (Agneta Andersson et al., 2015; Meier et al., 2012; Wikner & Andersson, 2012) • **Increased riverine discharge of ter-OM** (Fleming-Lehtinen et al., 2015; Fleming-Lehtinen & Laamanen, 2012; Harvey, Kratzer, & Andersson, 2015; Hoikkala et al., 2015; Kyryliuk & Kratzer, 2019; L. Lund-Hansen & Christiansen, 2008; Meier et al., 2012; Stramska & Świrgoń, 2014) • **Increase in coloured DOM in general** (Harvey, Kratzer, & Andersson, 2015; Kratzer et al., 2014, 2020; Kratzer & Moore, 2018; Kyryliuk & Kratzer, 2019; Stedmon et al., 2010; Traving et al., 2017) • **Importance of (increased) SPM especially in coastal zones (**Kratzer et al., 2020) • **Land management** (e.g.-Land use (e.g. forestry; Kritzberg, 2017; Kritzberg et al., 2020) • **Nutrient runoff** (stimulating eutrophication) (Carstensen et al., 2020; Hoikkala et al., 2015; Kritzberg et al., 2014)	• **Decline and alteration in macrophyte coverage** (Krause-Jensen et al., 2009; Lappalainen et al., 2019; Luhtala et al., 2016; Sahla et al., 2020) • **Alteration and stimulation of bacterial food webs** (Lindh et al., 2016; Meunier et al., 2017; Rowe et al., 2018; Traving et al., 2017), **verus phytoplankton based food webs** (A. Andersson et al., 2018; Asmala et al., 2013; Dahlgren et al., 2010; Hoikkala et al., 2015; Lefébure et al., 2013; Sandberg et al., 2004; Wikner & Andersson, 2012)- Alteration in phytoplankton community composition • **Alteration phytoplankton community composition** (A. Andersson et al., 2018; Paczkowska et al., 2016, 2020) • **Increase in ter-OM associated pollutants and effects on microbial communities** (Rodríguez et al., 2018) • **Bottom up effect on fish** (Lefébure et al., 2013) • **Indirect effects on water temperature** (Löptien & Meier, 2011) • **Interaction with eutrophication** (Agneta Andersson et al., 2013; Fleming-Lehtinen & Laamanen, 2012; Harvey et al., 2019; Hoikkala et al., 2015) • **Anoxic sediments / bottom waters due to flocculation of DOM** (Deutsch et al., 2012; Hoikkala et al., 2015; Kuliński et al., 2016) • **Effecting light transfer through drift ice** (Kari et al., 2020)	• **Reduction in nutrient runoff** (Agneta Andersson et al., 2013, 2015; Carstensen et al., 2020; Kritzberg et al., 2020; Meier et al., 2012) • **Sustainable catchment** management (Kritzberg et al., 2020) • **Mussel farms as filters for ter-OM** (Schröder et al., 2014)
North Sea	• **Ter-OM effects on light** (Fooken & Liebezeit, 2000) • **Trends in declining light availability** (Astoreca et al., 2012; Capuzzo et al., 2015, 2018; N. Dupont & Aksnes, 2013; Opdal et al., 2019) • **Recent trends in optical quality changes (cDOM and FDOM)** (Aas et al., 2013; Kristiansen & Aas, 2015; Makarewicz et al., 2018; Poryvkina et al., 1992; Stedmon et al., 2010) • **Increased SPM, importance of SPM for light attenuation** (Astoreca et al., 2012; L. C. Lund-Hansen, 2004; L. Lund-Hansen & Christiansen, 2008; van Raaphorst et al., 1998) • **Dredging** (Carstensen et al., 2013; Forsberg et al., 2019)	• **Decline in macrophytes cover** • **Increase in epiphytic "turf"algae on kelp** (Andersen et al., 2019; Christie et al., 2019; Sogn Andersen et al., 2019) • **Increase in particulate organic matter** (Frigstad et al., 2013) • **Declining phytoplankton and alteration in phytoplankton community composition** (Alvarez-Fernandez & Riegman, 2014; Desmit et al., 2020; Hamizah et al., 2020; Mustaffa et al., 2020; Nohe et al., 2020) • **Bottom up effects on zooplankton (copepod) community** (Boersma et al., 2015) • **Risk of favoured conditions for invasive jellyfish species** (Hosia et al., 2011) • **Potential interaction with carbonate system** (Artioli et al., 2012) • **Interaction with "oligotrophication"** (Lenhart et al., 2010) • **Risk of hypoxia** (Meire et al., 2013)	

Canada	• **Increased riverine discharge of particles (e.g. Mackenzie River to Beaufort Sea)** (Doxaran et al., 2015) • **Turbidity alterations due to river-runoff** (Le Fouest et al., 2010) • **Importance of suspended particles and particle size distribution** (Jackson et al., 2010; Xi et al., 2014) • **Episodic storm events** (Rabinovich et al., 2013) • **Importance of OM for light climate** (Loos & Costa, 2010)	• **Pressure on seagrasses** (Filbee-Dexter et al., 2019; Murphy et al., 2019; O'Neill et al., 2011) • **Plankton ecosystem response to turbidity changes** (Le Fouest et al., 2010) • **Potential effect on spring bloom timing** (Mei et al., 2010) • **Improved environmental conditions for invasive phytoplankton species** (RoySuzanne et al., 2012) • **Sinking of organic materials** (Lapoussière et al., 2009) • **Potential effects on corals** (Hartill et al., 2020) • **Multiple stressor interactions** (Sullivan et al., 2019)	• **Sustainable shellfish farming management and shellfish as filters** (Geonet et al., 2015; Ibarra et al., 2012)
Argentina, Chile	• **Increased riverine** runoff due to melting glaciers, episodic storm events (Cuevas et al., 2019; González et al., 2010; Vargas et al., 2011) • **Increased TSM** (Gurinder et al., 2009; Marín Brian et al., 2013)	• **Macrophytes (e.g. kelp)** (Gómez & Huovinen, 2011) • **Phytoplankton** (Cuevas et al., 2019; González et al., 2010; Guinder et al., 2009; Vargas et al., 2011) • **Loss in fish habitat (as early life stages kelp habitat might be affected)** (Bruno et al., 2018)	• **Reduced / Sustainable kelp Management** (Buschmann et al., 2014)
New Zealand	• **Increased riverine discharge of ter-OM, runoff from agricultural and urban land cover** (Dudley et al., 2020) • **Dredging** (Cussioli et al., 2019)	• **Decline in macrophytes, kelp forests, microphytobenthos** (Cussioli et al., 2019; Desmond et al., 2015; Mangan, Bryan, et al., 2020; Mangan, Lohrer, et al., 2020; Pritchard et al., 2013; Zabarte-Maeztu et al., 2020) • **Light limitation of benthic ecosystems function** (Mangan, Bryan, et al., 2020) • **Phytoplankton** (Gall & Zeldis, 2011) • **Increase in nuisance macroalgae** (Nelson et al., 2015) • **Mangrove expansion** (Horstman et al., 2018) • **Decline in coral reefs** (Schiel, 2011; Zabarte-Maeztu et al., 2020)	• **Shellfish farming** (Ren et al., 2010) • **Management of mangroves "terrestrial" filters, versus competition for habitat** (Horstman et al., 2018, 2018) • **Visual clarity and light penetration as index for water quality measures in NZ** (Cussioli et al., 2020; Gall et al., 2019)
Climate Change – Storm events (extreme rain events, hurricanes etc.)	• **Mediterranean** (A. Deininger et al., 2016; Liess et al., 2015) • **Summary of global cases see:** (Anne Deininger & Frigstad, 2019)	• **Macrophytes (kelp)** • **Phytoplankton** • **Corals** (Edmunds et al., 2019)	• **Compensational measures such as restoration of benthic vegetation** (Barbier et al., 2011; Bouma et al., 2014; Carr et al., 2010; Christianen et al., 2013, 2013; Greening et al., 2011; Hansen & Reidenbach, 2012; Ondiviela et al., 2014) • **Preventing coastal erosion by using ecosystems** (Gracia et al., 2018)
Human impacts such as Dredging, river management, land use	• **E.g. Australia** (Chartrand et al., 2016; Pineda et al., 2016; Strydom et al., 2017) • **Summary of global cases see** (Anne Deininger & Frigstad, 2019)	• **Macrophytes (e.g. Kelp)** • **Phytoplankton** • **Corals** (Chow et al., 2019)	• **Dredging management** (Chartrand et al., 2016; Cussioli et al., 2019; Forsberg et al., 2019; Pineda et al., 2016) • **Catchment management** (Kritzberg et al., 2020) • **Reduction in nutrient runoff** (Carstensen et al., 2013, 2020) • **Restoration of benthic vegetation e.g. to prevent particle resuspension** (Ondiviela et al., 2014; Orth et al., 2010; Orth & McGlathery, 2012)

4 Overview of current and completed (since 2015) research projects on increased light attenuation in Norway (incl. Svalbard).

Relevant research projects were identified in three ways: 1) a search of NFR's prosjektbanken for relevant key words, 2) a search of the 'Research in Svalbard' database for relevant key words, 3) checking references to projects in acknowledgments of relevant papers, and 4) compilation of projects that we were aware of through our networks. We identified 24 current and completed research projects (since 2015) either directly related to, or highly relevant for, increased light attenuation in Norway, including Svalbard (Tables 2, 3). Four of these projects were supported through internal funding from NIVA (Table 3), including the 4-year Strategic Institute Programme for Land-Ocean Interactions (which included several sub-projects) and NIVA's three infrastructure sites for research related to land-ocean interactions. Of these projects, 14 include research on mainland Norway, including projects in Skagerrak/Outer Oslofjord, Adger, Vestlandet, Troms og Finnmark, as well as projects with a broader Norwegian coastal focus. Meanwhile, 12 of these projects include research on Svalbard, pointing to a high level of research activity related to this theme in Svalbard's coastal waters.

Of the projects identified, only a few had a primary focus on documenting changes in coastal light attenuation or on direct impacts of reduced light availability in Norwegian coastal waters (Tables 2, 3). However, while the remaining projects had a less direct focus on light attenuation, they nearly all include reduced light availability as a key potential impact (e.g. of changing inputs from land), or as a potential key driver of coastal ecosystem change. These projects take a broad range of approaches (Tables 2, 3), including field observations and experimental approaches, remote sensing and *in situ* sensor-based approaches (including method development work), modelling approaches, and review/synthesis of existing data.

While several of the papers included in this review are outputs from some of the listed projects, 16 of the 24 projects identified are ongoing, suggesting that research results will become available in the coming years that will provide new knowledge related to drivers and impacts of increased light attenuation in coastal waters as well as more broadly related to impacts of terrestrial organic matter and particles on coastal ecosystems. There is a growing interest in research on these themes, and several of these projects take a broad approach, where increased light attenuation is just one of several ongoing changes in the coastal environment in Norway and on Svalbard. However, there remains a need for more detailed process-oriented research focusing directly on drivers and ecosystem impacts of coastal light attenuation in these systems, as well as a need for research tools and models that could provide insight into ongoing and potential future changes in light conditions in Norwegian coastal waters, and in particular the role that climate change could play in future coastal darkening.

Table 2. Overview of current and completed (since 2015) research projects related to increased light attenuation in Norway (including Svalbard).

Project name	Funding source	Timeline	Project lead	Geographic area (s)	Main research questions/approaches	Research focus*			Methods used**			
						A	B	C	A	B	C	D
EcoSense	NFR	2020-2024	UiB	Vestlandet	Using remote sensing to estimate optical properties in coastal waters.	X				x		
A blue-green link made browner	NFR	2019-2023	UiB	Norwegian coastal waters	Identifying links between reduced coastal light (and DOM drivers) and cod ecology.	X	x				x	
MARTINI	NFR	2018–2021	MET/ NIVA	Skagerrak, Outer Oslofjord	High-resolution physical-biogeochemical model of Skagerrak and outer Oslofjord	x					x	
MARTINI – particle model	MDir	2020-2021	NIVA	Skagerrak, Outer Oslofjord	Add-on project to MARTINI, developing an inorganic sediment module for the model	x					x	
Coastal Ocean Darkening	Lower Saxony Ministry of Science and Culture	2016–2020	Univ. Oldenburg	Global	Identifying past and potential future coastal ocean darkening on a global scale.	x	x		x	x	x	x
State of Svalbard's Coasts report	SSF (NFR)	2020	UNIS	Svalbard	Synthesis report with a focus on coastal change on Svalbard, including light	x	x	x				x
CoastDark	Polish NCN	2019-2022	IOPAS (Poland)	Svalbard	Impacts of glacier/river runoff on marine pelagic food webs		x	x	x	x		
FreshFate	Framsenter	2019-2021	NIVA	Svalbard	Effects of terrestrial inputs on DOM, light conditions, and microbial ecology.		x	x	x	x		
ACESS	ERA-Net	2019-2021	UNIS	Svalbard and pan-Arctic	Includes using remote sensing to estimate trends in coastal light attenuation.	x	x	x	x	x		x
DOM Season	UiA (CCR)	2020	NIVA	Adger	DOM seasonality along a river-fjord gradient.	x		x	x			
TerrACE	NFR	2017-2021	NIVA	Svalbard	Effects of terrestrial inputs on coastal physical, chemical and ecological conditions.		x	x	x			
Klima-overblikk	MDir	2017-2018	NIVA	Skagerrak/ Oslofjord	Synthesis of climate-relevant results from monitoring programmes. Includes trends in river inputs, and coastal Secchi depth.	x	x	x				x
Sediment flux from source to sink	NFR	2016-2018	UNIS	Svalbard	The role of the coastal zone for sediment transfer to fjord basins on Svalbard.	x			x			
DOMCON	Framsenter	2015-2016	NIVA	Troms and Finnmark	Effects of inputs of terrestrial DOM on coastal food webs and mercury cycling.			x	x			
NorSOOP	NFR	2018-2023	NIVA	Norway/Svalbard	Observing environmental change in Norwegian oceans using ships of opportunity		x	x	x	x		
JERICO-S3	EU H2020	2020-2024	IFREMER	European coastal seas	Multi-platform observations of coastal European seas	x	x	x	x	x	x	x
INTAROS	EU H2020	2016-2021	NERSC	Arctic (including Svalbard)	Integrated Arctic observing system to assess changes and interaction between land, cryosphere, and ocean	x			x	x		

SIOS Svalbard	NFR	2019-2021	SIOS Svalbard	Svalbard	Integrated observing system for climate change effects near Svalbard	x	x	x	x	x		
cDOM-HEAT	Polish NCN	2013–2016	IOPAS/ NPI	Svalbard/ Fram Strait	Source and transformation of cDOM and its role in surface ocean heating and C-cycling	x	x		x	x	x	
DarkFjords	Svalbard Miljøvernfond	2019-2020	IOPAS	Svalbard	Estimating long-term variability of optical properties in Svalbard fjords using remote sensing	x				x		

*Research focus indicated as follows: A) direct focus on drivers and/or trends in light attenuation, B) focus on direct impacts of increased light attenuation, or C) focus on other impacts of increased inputs of DOM and SPM from land to coast.

**Main methods indicated as follows: A) field observations/experiments, B) remote sensing/in situ sensors/method development C) modeling, D) synthesis/review.

Table 3. Overview of current and completed (since 2015) relevant NIVA-funded internal projects, and NIVA-operated infrastructure related to reduced light attenuation in Norway (including Svalbard).

Project name	**Funding source**	**Timeline**	**Geographic area(s)**	**Main research questions/approaches**	**Research focus***			**Main methods****			
					A	**B**	**C**	**A**	**B**	**C**	**D**
Land-ocean research infrastructure	KLD, NIVA, NFR	2017-ongoing	Adger, Troms and Finnmark, Svalbard	In situ sensor-based infrastructure focusing on land-ocean interactions in three river-fjord systems along a gradient from southern norway to Svalbard	x	x	x	x	x		
VårFlom	KLD, NIVA	2020-ongoing	Oslofjord, Troms and Finnmark	Impacts of spring flood on river chemistry and coastal physicochemical conditions.	x		x	x	x		
Global change at northern latitudes (NoLa)	NIVA	2020-2023	Norwegian coast, Troms and Finnmark	Includes a work package focusing on controls on fluxes of DOM and particles from land to sea as well as identifying places/times where coastal cDOM is particularly high.	x	x	x	x	x	x	
Strategic Institute Programme on Land-Ocean Interactions	NIVA/KLD	2015-2018	Norway	This 4-year research programme at NIVA included a large number of sub-projects with relevance for coastal light attenuation, including studies on drivers and variability of DOM in rivers and coastal waters, and on how inputs from land impact physical and chemical conditions as well as ecology in coastal ecosystems.	x	x	x	x	x	x	x

*Research focus indicated as follows: A) direct focus on drivers and/or trends in light attenuation, B) focus on direct impacts of changing light attenuation, or C) focus on impacts of increased inputs of DOM and SPM from land to coast.

**Main methods indicated as follows: A) field observations/experiments, B) remote sensing/in situ sensors/method development C) modeling, D) synthesis/review.

5 Conclusions and outlook

In this report, we have performed a literature review of recent publications (since 2009) on increased light attenuation along the Norwegian coast and Svalbard (Question 1) and reported biological effects related to these changes (Question 2). In addition, we have performed a literature review on effects of increased light attenuation in global coastal systems comparable to Norway (Question 3). In Chapter 4, we provide an overview of research projects (since 2015) related to increased light attenuation in Norway and on Svalbard.

Increased light attenuation in Norwegian coastal waters
A decrease in Secchi depth and increased light attenuation in the North Sea and Norwegian coastal waters have been observed in several studies that include data from the 20th century (Aksnes et al., 2009; Dupont & Aksnes, 2013; Capuzzo et al., 2015; Opdal et al., 2019). The long-term increase in light attenuation is unlikely to be caused by reductions in Chlorophyll *a* (e.g. Opdal et al., 2019), instead the papers point to documented increase in riverine DOM (Larsen et al., 2011; de Wit al., 2016) and state the drivers are likely to be terrestrial inputs of cDOM (Aksnes et al., 2009; Dupont & Aksnes, 2013; Capuzzo et al., 2015; Opdal et al., 2019). Both organic and inorganic TSM have also been identified as potential contributors to the long-term increase in light attenuation (Capuzzo et al., 2015), especially in shallow regions of the North Sea (Opdal et al., 2019). However, the lack of historical and continuous *in situ* data makes it hard to study the direct impact of cDOM on light attenuation. Most papers point to the strong relationship between cDOM and decreased salinity, and for example Aksnes et al. (2009) make use of this to build empirical models of light attenuation based on salinity and oxygen.

One complicating factor is that riverine DOM will flocculate into particles and thereby enter into the marine POM pool when freshwaters mixes with marine waters in coastal areas (Asmala et al., 2013). Therefore, it is difficult to separate the increase in particles in coastal waters from freshwater DOM flocculated into marine POM, and inorganic and organic TSM originating from land. This process is believed to have caused the long-term increase in POM concentration in coastal Skagerrak (Frigstad et al., 2013, 2018). A way forward would be to conduct in depth studies of flocculation processes across the salinity gradient and measure the inorganic and organic TSM fractions.

Future predictions all indicate that an increase in precipitation caused by a warmer and wetter climate will increase DOM transport from catchments to rivers and lakes, and will most likely lead to an increased transport of DOM, cDOM and TSM from land to the coastal zone, driving a potential increase in light attenuation. Previous studies have shown that there has already been a decrease in the Secchi depth in Norwegian coastal waters, which, given these ongoing changes, can be expected to continue.

Fjords, Skagerrak/North Sea and Svalbard are areas that may be particularly likely to experience changes in light attenuation, either due to the physical characteristics of fjords with low sills restricting the water exchange, the Skagerrak are due to its already high levels of cDOM, and Svalbard as the glaciers are bringing loads of terrestrial material to the coastal zones. Changes due to climate change is also more pronounced on Svalbard.

The main conclusion is that the increased light attenuation observed is primarily due to a higher cDOM absorption in coastal waters, driven by an increase in terrestrial run-off linked to a warmer and wetter (more precipitation) climate. Locally, increased particles (TSM, either organic or inorganic), can be the main driver for the increased light attenuation.

Norwegian biological effects
Changes in light attenuation affect the depth of the euphotic zone, and therefore all organisms that are dependent on light for photosynthesis, such as phytoplankton, benthic macroalgae, seagrasses and visual predators. For phytoplankton a 3-week delay in the onset of the spring bloom has been shown for the North Sea, which was directly connected to the long-term increase in light attenuation (Opdal et al., 2019). The largest number of articles were found in relation to mass occurrences of jellyfish in western fjords, where a long-term increase in light attenuation is believed to have increased the competitive advantage of jelly fish (tactile predators) over fish (visual predators) (e.g. Aksnes et al., 2009). For several macroalgae species, a reduction in the lower growth depth has been observed in the Skagerrak, which has been partly attributed to increased light attenuation (Frigstad et al., 2018; Sogn Andersen et al., 2019). While some studies have identified other (related) effects of changing inputs from land on Norwegian coastal ecosystems, very few studies have directly quantified ecological impacts of increased coastal light attenuation.

Global cases
Our literature review showed that drivers and effects of reduced light availability have been reported across comparable global coastal systems to Norway (i.e. the Baltic, the North Sea, Canada, South America (Chile, Argentina), and New Zealand. In sum, especially organisms requiring light for growth, reproduction and survival were strongly affected by alterations in coastal light availability. These are especially macrophytes and seagrasses, as well as phytoplankton. Positive effects have been described for bacterial, and bacteria-dominated food webs, as well as filter feeders such as mussels. Further, sedimentation might strongly reduce the suitable habitat not only for macrophytes such as kelp, but also corals. We did not find any information in our search on how corals in the boreal or arctic zone might be affected by increased terrestrial organic matter runoff and effects on light and sedimentation. Effects might be transferred higher up the food web to zooplankton, as well as fish. Effects of jellyfish have been reported, however mechanisms remain mostly unclear. Interactions with eutrophication, but also other multiple stressors have been reported and deserve increased attention. Mitigations have been reported to be most effective on catchment levels to reduce the increased input of terrestrial material (both organic matter and nutrients; Deininger et al., 2020; Kritzberg et al., 2020), and by linking social, ecological, and physical science to advance nature-based solutions to coastal protection (Arkema et al., 2017; Barbier et al., 2011; Bouma et al., 2014).

Overview of research projects
Our compilation of recently completed and ongoing relevant research projects on this theme highlights a broad range of ongoing research related to changes in coastal light attenuation, as well as the broader impacts of riverine and glacial inputs on Norway's coastal ecosystems, including several projects focusing on Svalbard. While this highlights increasing interest and will result in new relevant knowledge on this theme, this work also pointed to a need for more detailed process oriented work focusing on drivers, trends, and ecosystem impacts of coastal darkening, as well as predictions for how climate change is likely to impact light conditions in Norwegian coastal waters (including Svalbard) in the future.

Monitoring recommendations
An inclusion of cDOM, DOC and TSM (differentiating between organic and inorganic fractions), as an additional parameter to K_d(PAR), Secchi depth, Chlorophyll *a* and turbidity, within monitoring programs will make it possible to study and follow possible changes in the parameters contributing to the changes in the light attenuation. Sensors for spectrally-resolved light measurements and other related optical parameters should be used to provide a more detailed understanding of light attenuation and its drivers.

The use of remote sensing data should be incorporated into operational monitoring to a larger extent- so that both the spatial and temporal dynamics can be followed in a consistent and objective way. The European Commission Copernicus program will continue to provide remote sensing data of high quality for at least 30 years to come. FerryBox and autonomous buoy systems can provide in situ data to be used both for monitoring spatial and temporal coastal ocean variability, as well as for remote sensing validation.

Key research needs:

1) Long-term studies of differentiating between the various optical variables driving the increase light attenuation observed in the Norwegian coastal waters, the North Sea and the Baltic Sea, i.e. how much is caused by increased input of terrestrial DOM/cDOM, Chlorophyll *a* and TSM
2) Field studies examining how much and where along the salinity gradient the riverine DOM is flocculating to POC and determining the inorganic/organic fractions of TSM
3) Experiments on the heterotrophic and autotrophic response to increased terrestrial organic matter and the net effect on the metabolic balance (i.e. if the system is a net source or sink of atmospheric CO_2)
4) Field studies on potentially mitigation measures, such as catchment management to reduce runoff of terrestrial organic material and nature-based solutions to improve coastal light conditions (e.g. mussel farms)

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