Climate Change Impacts on Dissolved Oxygen Concentration in Marine and Coastal Waters around the UK and Ireland

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KEY FACTS

What is already happening

- Since the 1960s, the global oceanic oxygen content has declined by more than 2%.
- Sustained observations in the North Sea reveal the recent onset of oxygen deficiency in late summer, partly due to ocean warming. The intensity and extent of oxygen deficiency has also increased over time.
- Short-term measurements for the Celtic Sea also indicate the onset of oxygen deficiency in late summer.

What could happen in the future

- Average Annual mean dissolved oxygen concentration in the global ocean is projected to decline by 1.5 to 4% by 2090 for all RCPs. This decline will be most acute below the thermocline.
- For UK shelf waters, models project that annual mean oxygen concentration will decline most strongly in North Sea regions and the Celtic Sea (5.6 to 5.9% by 2100, RCP 8.5). Deeper regions exposed to exchange with the open ocean (the Irish shelf and Shetland shelf) are expected to be less affected, decreasing by 2.9 to 3.1%.

Citation: Mahaffey, C., Hull, T., Hunter, W., Greenwood, N., Palmer, M., Sharples, J., Wakelin, S. and Williams, C. Climate change impacts on dissolved oxygen concentration in marine and coastal waters around the UK and Ireland. MCCIP Science Review 2023, 31pp.

doi: 10.14465/2023.reu07.oxy

Submitted: 10 2022

- The predicted increase in temperature over this century for UK shelf seas will lead to a decrease in dissolved oxygen through the whole water column because of reduced solubility.
- The risk of oxygen deficiency in summer will increase because of lower oxygen levels experienced during the preceding winter and spring.
- Increased rainfall and runoff would increase the risk of eutrophication and cause oxygen concentrations to locally decrease.
- Continued warming and reduced oxygen availability will affect the metabolism, health, and reproduction of many marine organisms, which could have major impacts on ecosystems and commercial fisheries.

SUPPORTING EVIDENCE

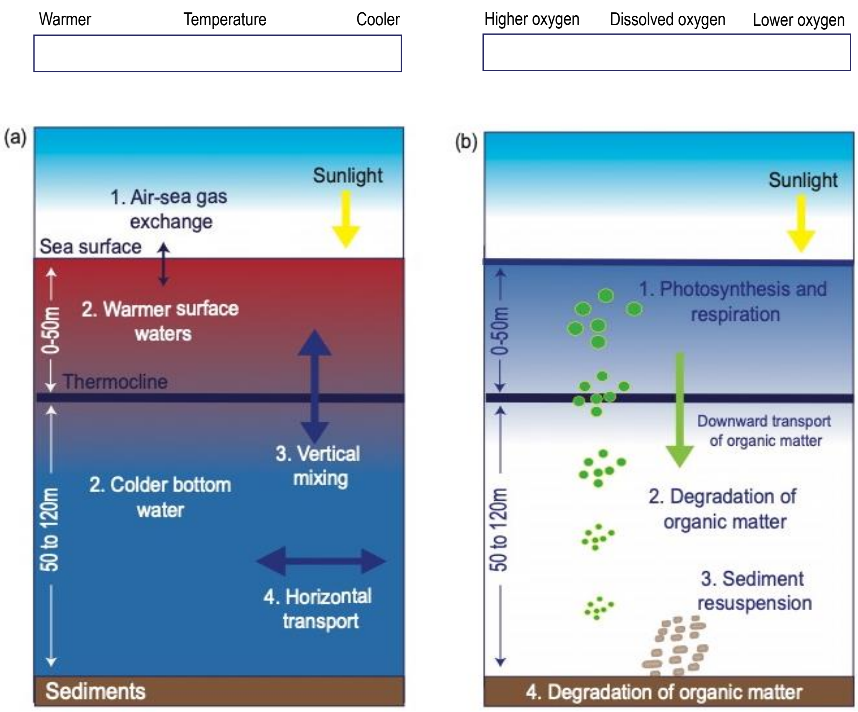
Introduction

Oxygen is the most important gas in the marine environment because it is essential for breathing or 'respiration' by almost all life in the sea. Dissolved oxygen concentrations in the global ocean have declined by 2% since the 1960s (Rhein *et al.*, 2013; Schmidtko *et al.*, 2017; Oschlies *et al.*, 2018). While excessive nutrient loading or 'eutrophication' may be the driver for the decline in dissolved oxygen concentrations in near coastal regions (Diaz and Rosenberg, 2008), the observed global decline in dissolved oxygen has been attributed to ocean warming (Schmidtko *et al.*, 2017). Climate models predict future rates of oxygen decline will increase globally in response to warming (Bopp *et al.*, 2013; Keeling *et al.*, 2010; van der Molen *et al.*, 2013). Depletion of dissolved oxygen can lead to a region being defined as either *oxygen deficient*, when dissolved oxygen concentrations are less than 6 mg/litre (equivalent to ~192 µmol/kg), *hypoxic* when oxygen concentrations are less than 2 mg/litre (equivalent to ~64 –µmol/kg) or *anoxic* when oxygen concentrations are less than 0.5 mg/litre (equivalent to ~30 µmol/kg). The development of oxygen deficiency can have deleterious effects on the marine ecosystem (Vaquer-Sunyer and Duarte, 2008; Breitburg *et al.*, 2018) with the onset of hypoxia or anoxia increasing the severity on the ecosystem response. While the decline in dissolved oxygen in the deep ocean is a global problem, the intensity and impact of dissolved oxygen depletion or 'deoxygenation' is also apparent in the coastal and shelf seas (Diaz and Rossenberg, 2008; Breitburg *et al.*, 2009; Gilbert *et al.*, 2010; Townhill *et al.*, 2017a; Breitburg *et al.*, 2018). The challenge is to better understand the multiple processes that currently control dissolved oxygen to accurately assess the future risk of oxygen deficiency, hypoxia or anoxia in response to climate change (Oschlies *et al*., 2017). Here, we focus on the processes controlling oxygen concentrations in the North-west European shelf seas, which encompasses UK coastal and shelf seas.

What controls oxygen in the marine environment?

Oxygen constitutes 20.95% of our atmosphere and its behaviour is strongly linked to the processes that cycle carbon in the atmosphere and ocean. Over the past 20 years, there has been a small but measurable decrease in the levels of oxygen in the atmosphere due to the burning of fossil fuels (Keeling and Shertz, 1992; Manning and Keeling, 2006). Loss of atmospheric oxygen poses no risk to ecosystems or humans for the foreseeable future. Dissolved oxygen concentrations in the ocean are controlled by a combination of physical and biological processes (Figure 1a and b). Oxygen in the atmosphere readily exchanges with the surface ocean, termed air-sea gas exchange (Figure 1a). Temperature affects the solubility of dissolved oxygen in seawater, with oxygen being more soluble in colder water and less soluble in warmer water (Figure 1a). For example, a 1°C increase in ocean temperature will cause dissolved oxygen concentrations to decrease by approximately 5 µmol/kg or 0.16 mg/litre over typical ranges of salinity (30 to 35) and temperature (10 to 20°C) observed in UK marine waters. *Oxygen saturation* is a common parameter used to describe the ratio of dissolved oxygen in seawater relative to the maximum amount of oxygen that will dissolve in seawater at a given temperature, salinity, and pressure if it were in equilibrium with the atmosphere. Biological activity produces dissolved oxygen via photosynthesis and tends to cause oxygen saturation to be greater than 100%, termed *oversaturation* (Figure 1b). Dissolved oxygen is removed from water via breathing or respiration by marine plants, animals and microorganisms, and by the decay of organic matter back to nutrients; the combination of removal processes is referred to collectively as *biological oxygen consumption* in the present document. These removal processes tend to cause oxygen saturation to be less than 100%, termed *undersaturation* (Figure 1b). Note that in the sunlit surface layer of the ocean, biological oxygen production is typically greater than oxygen consumption resulting in net biological oxygen production, increasing the oxygen concentration above the saturated state. Conversely, in the deeper, dark layers of the ocean, oxygen consumption is typically greater than oxygen production leading to net biological oxygen consumption, decreasing the oxygen concentration below the saturated state (Figure 1b).

There is an important link between nutrients and oxygen in the marine environment. An increase in nutrients will generally increase production of organic matter via photosynthesis, causing an increase in dissolved oxygen production in the surface ocean. However, decay of accumulated organic matter by microbial respiration leads to a decrease in dissolved oxygen. Enhanced nutrient inputs into coastal regions have been shown to cause eutrophication (Painting *et al.*, 2013), one important side effect being a decline in dissolved oxygen. Hence, dissolved oxygen is used as an indicator of the status of ecosystem health within the legislation designed to protect the UK marine environment through the Water Environment Regulations 2017 and the Marine Strategy Regulations 2010 and the Programme of Measures 2015, which are the UK implementation of the EU Water Framework Directive (WFD; Best *et al.*, 2007) and the Marine Strategy Framework Directive (MSFD, Ferreira *et al.*, 2011) respectively. However, in assessments made under this legislation, dissolved oxygen concentrations are used only to identify undesirable disturbance from the indirect effect of nutrient enrichment (OSPAR Common Procedure; Foden *et al.*, 2010) as an indicator within the eutrophication quality descriptor (MSFD Descriptor 5) and an indirect effect of nutrient enrichment (MSFD Criterion 5.3; Ferreira *et al.*, 2011). There is no additional requirement to monitor dissolved oxygen concentration under the legislation despite factors other than eutrophication being responsible for development of oxygen deficiency in coastal and shelf sea waters. Although dissolved oxygen was proposed as an indicator for Seafloor Integrity within the MSFD (Rice *et al.*, 2012), it was not included in the final selection of indicators. As a critical component of several indicators of good environmental status (GES), it is important to develop a thorough understanding of the controls and consequences of oxygen dynamics in UK coastal and shelf water and the potential response of oxygen dynamics to climate change.



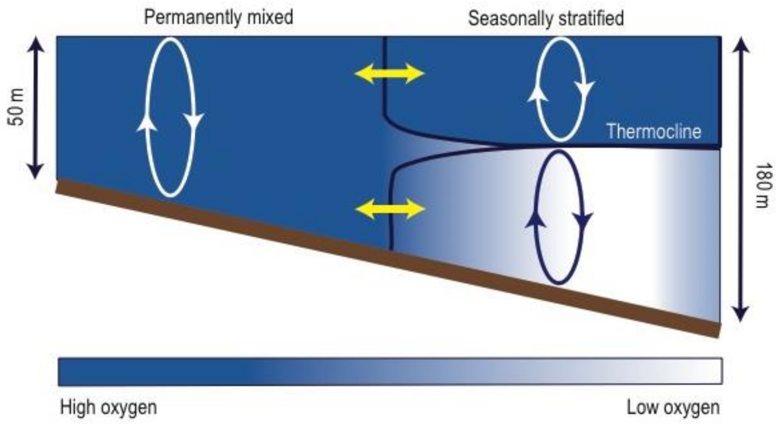
Processes in (a)	Effect on dissolved oxygen		Processes in (b)	Effect on dissolved oxygen
1	Equilibrates oxygen between the atmosphere and ocean		1	Net oxygen production as photosynthesis is greater than respiration in surface waters
2	Oxygen is less soluble in warm water and more soluble in cold water		2	Net oxygen consumption during degradation of organic matter in the water column
3	Mixes oxygenated surface water with less oxygenated bottom waters		3	Oxygen consumption as more organic matter is made available from sediment resuspension
4	Transports water with different oxygen properties		4	Net oxygen consumption during degradation of organic matter in the sediments

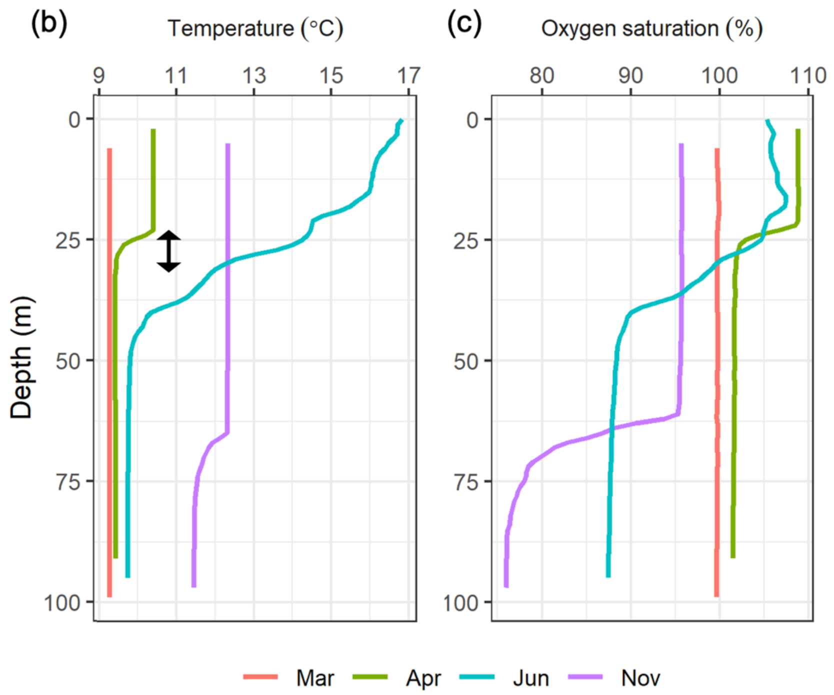
Figure 1: Schematic representation of the vertical structure of (a) temperature and the physical processes that control the distribution of dissolved oxygen and (b) dissolved oxygen and the biological processes that control the distribution of dissolved oxygen in coastal and shelf seas. The underlying tables highlight the principal processes and their effect on dissolved oxygen dynamics. Surface and bottom waters are separated by a thermocline and thus this schematic represents processes in a stratified water column.

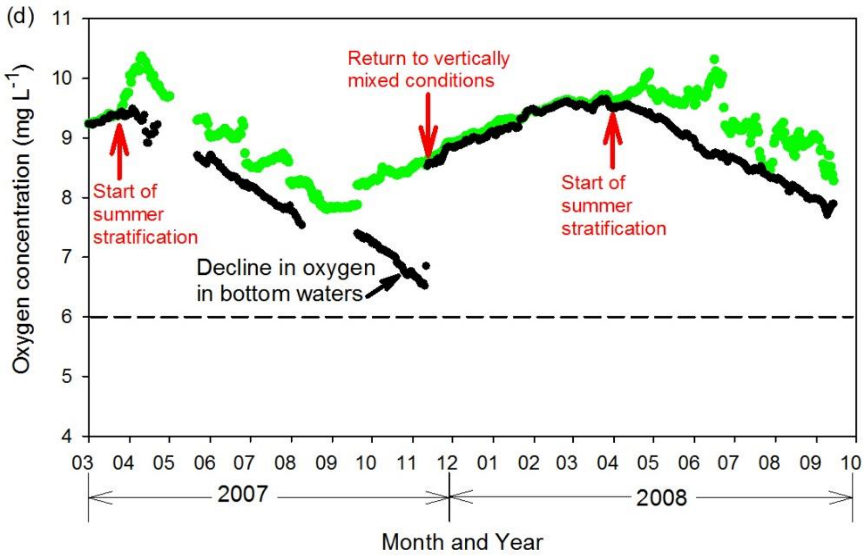
Physical processes, including vertical mixing and horizontal transport, redistribute oxygen vertically and horizontally (Figure 1a). The strength of vertical mixing and the degree of density stratification are key factors controlling the oxygen distribution in coastal and shelf seas (Figure 2a). Stratification occurs when water becomes separated into layers of different density with less-dense water overlaying a layer of denser water. Layers close to the surface may be less dense due to the addition of lower salinity water, for example from freshwater run-off from rivers, or from warming, which typically occurs due to the seasonal solar heating cycle. While salinity-driven stratification is generally restricted to near coastal regions around the UK, there are large areas of UK shelf seas that undergo seasonal thermal stratification when near surface waters and bottom waters are separated by a temperature gradient, or thermocline (Figure 2b, Sharples *et al.*, 2020). Such regions include, but are not limited to, the central and northern North Sea, the Celtic Sea, the western Irish Sea, the Malin Sea and Outer Hebrides region (Sharples *et al.*, 2020). During winter, the shelf seas are mixed by convection (driven by surface water cooling) and wind (Figure 2b) and become well oxygenated as waters mix and are ventilated by air-sea gas and heat exchange (Figure 2c). Winter mixing acts to homogenise surface and bottom water and their associated oxygen concentrations (Figure 2c). Critically, the water temperature in winter places a first-order control on the dissolved oxygen concentration in coastal and shelf seas because of the temperature dependence of oxygen solubility, with warmer winters leading to lower dissolved oxygen concentrations. Seasonal stratification occurs over much of the UK shelf seas when there is sufficient solar heating of surface waters to overcome the combined effects of tidal and wind mixing. This coincides with spring, typically in March or April in UK waters (Figure 2d and 2e) and persists until winter storms and reduced solar heating in autumn months return the water column to winter mixed conditions, typically between October and December, although there is significant spatial variability in both the onset and breakdown of stratification. During this period of seasonal stratification, a thermocline separates the well-mixed near-surface waters and bottom boundary layers. This thermocline significantly reduces mixing between the two layers and results in different oxygen dynamics in each layer (Figure 2c, 2d and 2e). In the surface waters, net biological oxygen production and air-sea gas exchange act to maintain dissolved oxygen concentrations at close to or above 100% saturation (Figure 2c). In contrast, the thermocline restricts mixing of bottom waters with surface waters and prevents direct air-sea gas exchange. There is also net biological oxygen consumption in the bottom waters (Figure 2c, 2d and 2e). If oxygen consumed in the bottom waters is not replenished by episodic mixing events across the thermocline, such as by enhanced mixing from strong tides and storms or by horizontal exchange with oxygenated waters (Hull *et al.*, 2020), then the bottom layer oxygen concentration may decline to levels at risk of oxygen deficiency, hypoxia or anoxia. However, the strong seasonal cycle in the UK temperate coastal and shelf seas means that no regions experience year-round stratification and so any depletion of oxygen during the summer stratified period is temporary, as dissolved oxygen will be replenished during autumn and winter mixing (Figure 2d and 2e). This seasonal pattern is in contrast to many oxygen minimum zones (OMZs) found elsewhere in the marine environment where oxygen deficiency, hypoxia or anoxia can be persistent features over many years (e.g. the Baltic Sea).

In regions of UK coastal and shelf sea waters where there is sufficient energy from tides and currents to permanently mix the water column (left region of Figure 2a), the dissolved oxygen concentration in the entire water column is relatively homogenous, with the absolute concentration changing primarily due to seasonal changes in temperature and therefore solubility. Regions that are classed as permanently mixed include the shallow regions of the central and eastern English Channel, southern North Sea and central Irish Sea. There are also areas that undergo periodic stratification due to the variable nature of the tide, for instance in the eastern Irish Sea influenced by river inputs from North-west England and the far south of the North Sea influenced by the River Rhine. Bottom layers in such regions are typically not at risk of oxygen depletion since stratification is short-lived.

(a)




(b)
Temperature (°C)
9
11
13
15
17
Depth (m)
0
25
50
75
100
(c)
Oxygen saturation (%)
80
90
100
110
Mar
Apr
Jun
Nov


(d)
Oxygen concentration (mg L-1)
Return to vertically mixed conditions
Start of summer stratification
Start of summer stratification
Decline in oxygen in bottom waters
03 04 05 06 07 08 09 10 11 12 01 02 03 04 05 06 07 08 09 10
2007
2008
Month and Year

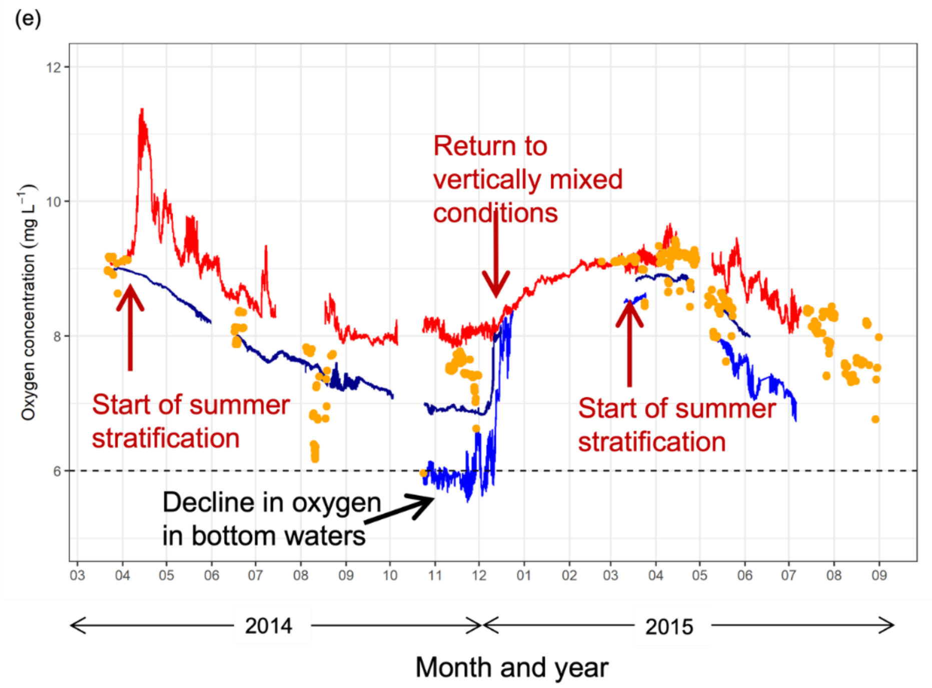


Figure 2: Schematic representation of: (a) the gradient in physical water column structure and dissolved oxygen concentrations from the shallow, permanently mixed regions to deeper, seasonally stratifying regions. Exchange between the two regions is indicated by horizontal transfer (yellow arrows). Seasonal change in (b) water column temperature (°C) and (c) dissolved oxygen saturation (%) in the seasonally stratifying central Celtic Sea at the end of winter (March, red), spring (April, green), summer (June, blue) and autumn (November, purple, data from Hull et al., 2020). (d) seasonal change in dissolved oxygen concentrations (mg/litre) at North Dogger in the North Sea from the Cefas SmartBuoy in surface waters (green) and bottom waters (black) (data from Greenwood et al.*, 2010). (e) Seasonal change in dissolved oxygen concentrations (mg/litre) in the Celtic Sea from the Celtic Deep SmartBuoy (red), Celtic Deep benthic lander (blue) and Haig Fras lander (dark blue), with discrete bottle oxygen concentrations indicated (yellow). (Data is available from https://doi.org/10.14466/CefasDataHub.38 to https://doi.org/10.14466/CefasDataHub.41. Note that the lowest oxygen concentrations in (a) are associated with intermediate rather than the deepest water column in shelf seas due to the rapid depletion of oxygen in a thinner layer which has less total oxygen available.)*

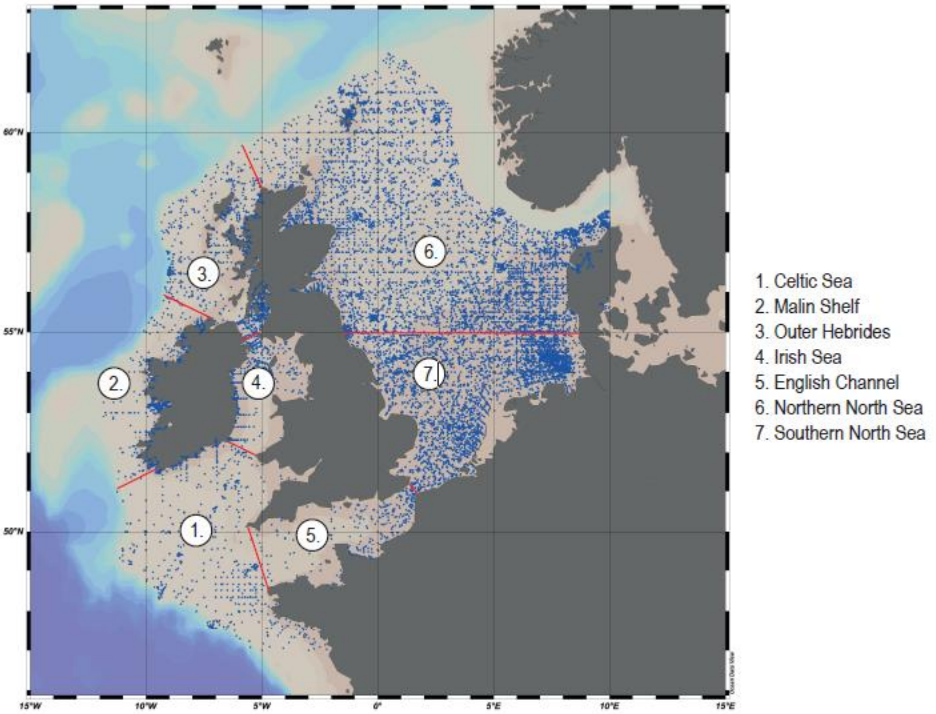
Climate change is likely to affect physical and biological processes that lead to oxygen depletion. As well as reducing the solubility of oxygen, ocean warming is predicted to increase the strength and duration of seasonal stratification over the next 50 years (Lowe *et al.*, 2009; Holt *et al.*, 2010; Sharples *et al.*, 2020). Enhanced stratification increases the isolation of bottom waters from the sea surface thus increasing the risk of oxygen deficiency and hypoxia in seasonally stratifying regions on the European Shelf. Enhanced stratification will also reduce the nutrient supply to the surface ocean, thus reducing biological productivity and the amount of organic material available for microbial respiration. In contrast, ocean warming will increase metabolic processes including biological oxygen consumption (Brewer and Peltzer, 2017). The net effect of a decline in nutrients stunting biological productivity, alongside the direct thermal enhancement of metabolic processes, is currently unknown. Particularly relevant to coastal and shelf seas systems is the change in nutrient inputs from land, which may enhance or reduce the risk of eutrophication with subsequent implications for oxygen dynamics. Changes to shelf sea and deep ocean exchange may also have major impacts on both physical and biogeochemical controls (Holt et al, 2018; Wakelin et al, 2020). Thus, understanding potential causes of oxygen depletion, and the responses of these drivers to climate change, land-use and wastewater inputs is key to predicting the likelihood of oxygen deficiency or hypoxia, and subsequent ecosystem harm, in UK marine waters.

What is already happening?

Detecting climate-driven changes in dissolved oxygen requires observations and understanding of the natural seasonal and interannual variability in surface and bottom water oxygen concentrations so that any long-term deviation from baseline conditions can be accurately assessed. Dissolved oxygen measurements in bottom waters from 1920s to 2017 in the North-west European shelf region are available from the International Council for the Exploration of the Sea (ICES) and the British Oceanographic Data Centre (BODC) databases. Synthesis of these databases reveals that the North Sea is the most intensely studied of UK marine waters for dissolved oxygen, in both space (Figure 3a) and time (Figures 3g and 3h). This level of coverage has not been replicated in other UK shelf sea regions, with a stark disparity between North Sea data coverage and the Celtic Sea (Figure 3b), Malin Shelf (Figure 3c), Outer Hebrides (Figure 3d), Irish Sea (Figure 3e) and English Channel (Figure 3f). Confidence in any results drawn from these poorly resolved regions is therefore inherently low and makes quantitative comparisons between regions, or between observations and models, extremely difficult.

Regional dynamics in dissolved oxygen concentrations

In the North Sea, oxygen concentrations typically vary from ~320 µmol/kg (equivalent to ~ 10 mg/litre or over 100% saturation) in winter to ~192 µmol/kg in summer (equivalent to 6 mg/litre or 70% saturation). A decline in oxygen saturation to 70% or less in bottom waters of the seasonally stratified regions in the UK waters of the North Sea during late summer conditions is well documented (Figure 2d, Weston *et al.*, 2008; Greenwood *et al.*, 2010; Queste *et al.*, 2013; Große *et al.*, 2016; Queste *et al.*, 2016; Topcu and Brockmann, 2015). High temporal resolution data from the Cefas SmartBuoy network has revealed the onset of oxygen deficiency (less than 6 mg/L) in bottom waters during the late summer period in the central and northern North Sea around the Oyster Grounds (5.2 mg/litre, 60% saturation or 167µmol/kg; Greenwood *et al.*, 2010). Re-analysis of dissolved oxygen data over the past 100 years reveals that there has been an increase in the intensity and spatial extent of oxygen deficiency in the North Sea (Queste *et al.*, 2013). This historical period of oxygen depletion coincided with a period of ocean warming observed over the past two decades. Queste *et al.*, (2013) postulate that ocean warming alone explains one third of the change in oxygen, with the remaining two thirds of oxygen depletion being attributed to an increase in biological oxygen consumption.



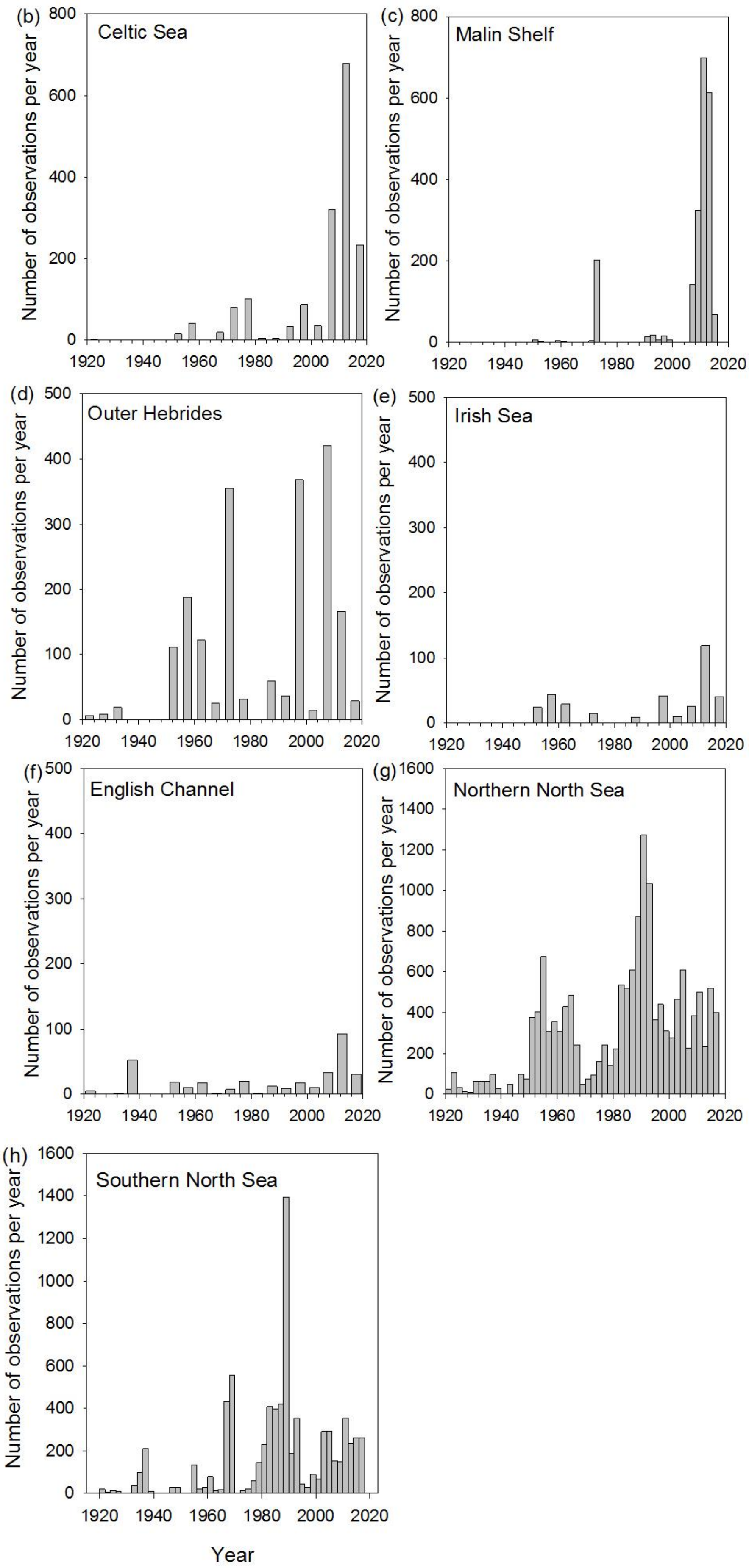

(b)
Celtic Sea
Number of observations per year
0
200
400
600
800
1920
1940
1960
1980
2000
2020
(c)
Malin Shelf
Number of observations per year
0
200
400
600
800
1920
1940
1960
1980
2000
2020
(d)
Outer Hebrides
Number of observations per year
0
100
200
300
400
500
1920
1940
1960
1980
2000
2020
(e)
Irish Sea
Number of observations per year
0
100
200
300
400
500
1920
1940
1960
1980
2000
2020
(f)
English Channel
Number of observations per year
0
100
200
300
400
500
1920
1940
1960
1980
2000
2020
(g)
Northern North Sea
Number of observations per year
0
200
400
600
800
1000
1200
1400
1600
1920
1940
1960
1980
2000
2020
(h)
Southern North Sea
Number of observations per year
0
200
400
600
800
1000
1200
1400
1600
1920
1940
1960
1980
2000
2020
Year

Figure 3: Synthesis of data from ICES and BODC indicating (a) the spatial distribution of measurements of dissolved oxygen below the thermocline or near the seabed from 1920s to 2017, with red lines indicating approximate boundaries between regions, and the temporal distribution of observations per year in the bottom waters from 1920s to 2017 for (b) Celtic Sea, (c) Malin Shelf, (d) Outer Hebrides, (e) Irish Sea, (f) English Channel, (g) Northern North Sea and (h) Southern North Sea. Note that the y-axis scale varies from (b) to (h) with (b) and (c) ranging from 0 to 800, (d), (e) and (f) ranging from 0 to 500 and (g) and (h) ranging from 0 to 1600.

Unlike the well-studied North Sea, the Celtic Sea is poorly sampled in both time and space (Figure 3a and 3d). Data from the recent UK-Shelf Sea Biogeochemistry programme (2011-2017) has significantly improved our understanding of this region. High-resolution data from two benthic landers (Celtic Deep and Haig Fras) equipped with oxygen sensors collected between spring 2014 and autumn 2015 reveals that towards the end of seasonal stratification in late autumn 2014, oxygen concentrations in bottom waters at Haig Fras (Figure 2e, dark blue) decreased below the 6 mg/litre threshold defining oxygen deficiency (5.8 mg/litre or 62% saturation or 186 μmol/kg). Note that oxygen concentrations at the Celtic Deep site remained above 6 mg/litre (Figure 2e, blue), indicating the spatial heterogeneity in oxygen dynamics. These are the first observations indicating the development of oxygen deficiency in the Celtic Sea, albeit with a 10% error of the oxygen sensor data due to lack of geo-located discrete samples for calibration. The lack of observational data in Celtic Sea bottom waters means this important result cannot be set in a historical context and so it is not possible to verify using observational evidence whether this is a recent development or a regularly occurring phenomenon.

There is currently no evidence of oxygen deficiency in the Irish Sea or Malin Sea (O'Boyle and Nolan, 2010), but data is sparse (Figure 3c and e, respectively) and large areas known to undergo seasonal stratification have few or no observations of bottom-layer dissolved oxygen concentration in available databases, and fewer still have data available during late summer or autumn conditions when a seasonal oxygen minimum is most likely to occur.

Looking to the future, a major challenge in detecting the onset of oxygen deficiency in UK coastal and shelf sea regions is making measurements of dissolved oxygen concentrations at the appropriate scales in time and space. Benthic landers (Hull *et al.*, 2020) and autonomous underwater vehicles (Williams *et al.*, 2022, Hull *et al.*, 2021) can provide high-resolution data on dissolved oxygen in shelf sea bottom waters. Coupled physical and biogeochemical models specifically designed to represent the functioning of coastal and shelf seas have been used to predict oxygen dynamics over regional and whole shelf scales (Madec *et al.*, 2012; Butenschön *et al.*, 2016). Model re-analysis by Ciavatta *et al.* (2016) has suggested that large areas (~325,000 km^2) of the North-west European Shelf region are vulnerable to oxygen deficiency. UK regions designated as at risk of deficiency in this study include large areas of the Celtic Sea, Irish Sea and English Channel and small coastal regions around Scotland (Figure 4). A small area of the North Sea in UK waters is also identified, which forms part of a much larger area including Dutch and German waters. There is still some debate on the ability of ocean and climate models to accurately capture the myriad of processes that control seasonal oxygen dynamics. At the global scale, climate models successfully estimate the change in oxygen concentrations within 10% of observed values (IPCC, 2013; Oschlies *et al.*, 2018), but tend to underestimate the variability and decline in oxygen (Bopp *et al.*, 201; Ito *et al.*, 2017). Assessment of model skill of a coupled hydrodynamics-ecosystem model (NEMO-ERSEM) designed to represent shelf sea processes showed that simulations underestimated oxygen by 0.6 mg/litre on average compared to observations (Wakelin *et al.*, 2020).

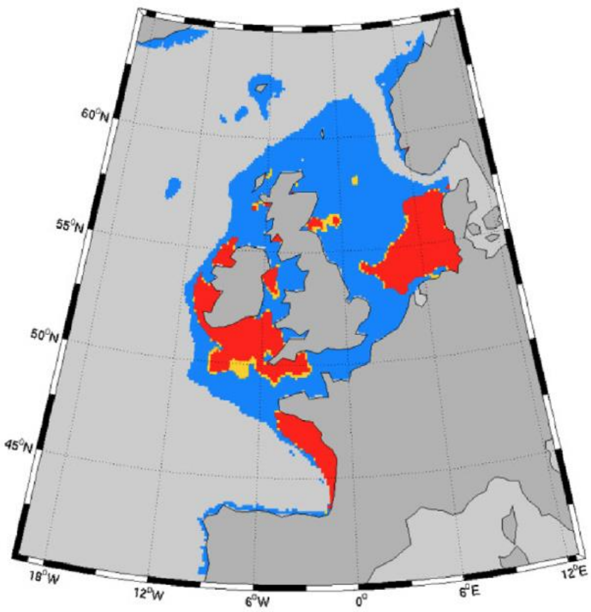


Figure 4: Model output from ERSEM indicating areas vulnerable to oxygen deficiency in bottom waters, defined as at least one daily value in 1998 to 2009 below the threshold of 6 mg/litre. Areas of the shelf where oxygen concentrations are found to be higher than 6 mg/litre at 100% confidence are highlighted in blue. Areas of the shelf where oxygen concentrations are found to be lower than 6 mg/litre at 1% confidence are highlighted in yellow. Areas of the shelf where oxygen concentrations are found to be lower than 6 mg/litre at 100% confidence are highlighted in red. (Reproduced with permission from Ciavatta et al.*, 2016.)*

Causes of oxygen depletion

While the causes for the decline in dissolved oxygen concentrations have been identified, their relative magnitude and net effect on oxygen dynamics are still poorly constrained. For example, the net effect of temperature on oxygen is complex; while warming will unambiguously reduce the solubility of oxygen, the effects of warming on the strength and duration of stratification and on biological oxygen consumption are less well known. Understanding potential drivers of oxygen depletion is key to predicting the likelihood of oxygen deficiency or hypoxia in UK marine waters. In near coastal waters, nutrient enrichment can lead to eutrophication, causing acceleration of phytoplankton growth with undesirable disturbance and potentially harmful effects, including the growth of nuisance or toxic phytoplankton, red tides and dissolved oxygen depletion (Painting *et al.*, 2013). Under EU directives, 21 UK coastal water bodies were assessed as 'Problem Areas' with respect to eutrophication status based on nutrient concentrations (OSPAR 2017; Defra, 2010). In coastal systems, the relatively slow process of dissolved oxygen depletion is frequently interrupted by ventilation of water via physical mixing driven by wind, waves or tides, allowing replenishment of dissolved oxygen by rapid mixing with surface oxygenated waters and equilibration with the atmosphere. However, the nutrient-enhanced organic matter present in these coastal waters does have the potential to be transported away from coastal areas and contribute to biological oxygen consumption elsewhere (Topcu and Brockmann, 2015; Große *et al.*, 2017) and so still may be a problem.

UK marine waters (defined here as areas where local salinity is greater than 30) are considered to be 'Non-Problem Areas' with respect to the risk and impact of nutrient enrichment (OSPAR, 2017). However, eutrophication is not the only driver or precursor of dissolved oxygen depletion. The timing, duration and strength of stratification play critical roles in the seasonal depletion of dissolved oxygen because they dictate the degree of isolation of bottom waters and the potential for mixing. However, there is significant regional disparity between waters that are stratified for long periods of time and the magnitude of oxygen depletion they experience. In the North Sea, areas of prolonged stratification in the central and northern regions generally have a higher bottom-water dissolved oxygen concentration than areas that are stratified for a shorter period of time in the south-central North Sea region (Große *et al.*, 2016; Queste *et al.*, 2016; Topcu and Brockmann, 2015). This disparity indicates that factors other than the strength and duration of stratification play an important role in controlling oxygen depletion. The magnitude of photosynthesis in the sunlit surface layer dictates the amount of organic matter that will eventually sink below the thermocline, with more organic matter leading to greater biological oxygen consumption in deeper, dark waters. In addition, organic matter generated via photosynthesis is a food source for higher trophic levels, such as zooplankton, which graze on phytoplankton and generate sinking faecal material, which contributes to an enhanced downward flux of organic matter which could intensify biological oxygen consumption. The volume of the bottom layer, represented by both the thickness and areal extent of bottom waters, is also a factor controlling the magnitude of oxygen depletion (Große *et al.*, 2016), with dissolved oxygen being more rapidly depleted by both water column and sedimentary processes in areas with a thinner bottom layer than a thicker bottom layer due to the lower total amount of oxygen per unit volume available in a thinner layer. As such, differences in productivity are thought to control the interannual variability in dissolved oxygen conditions in the North Sea, while spatial differences in dissolved oxygen dynamics have been attributed to variations in stratification and water depth or volume alongside tidal energy for mixing (Große *et al.*, 2016).

While stratification is an important prerequisite for bottom water oxygen depletion, other physical processes can contribute to dissolved oxygen dynamics (Queste et al, 2016; Rovelli *et al.*, 2016). Horizontal and vertical advection may transport water into different depths or regions and can lead to the exchange of water with different oxygen properties. In the central North Sea, estimates of horizontal transport or advection are low (Weston *et al.*, 2004; Greenwood *et al.*, 2010) and typically water masses are thought to be transported into areas with similar properties and so have little net effect. In the Celtic Sea, horizontal advection, tidal forcing and vertical mixing control oxygen dynamics in bottom waters at various times over the stratified period (Hull et al 2020). Vertical mixing across the thermocline has the potential to mix well-oxygenated surface waters with oxygen-deplete bottom waters (Rovelli *et al.*, 2016; Queste *et al.*, 2016; Williams *et al.*, 2022). The rate of mixing across the thermocline is highly variable, depending on tides, meteorology and the proximity to banks and slopes, and the contribution from each factor is modified by the strength of local stratification. The combined effect of these processes results in thermocline mixing in shelf seas spanning several orders of magnitude (e.g. Sharples *et al.*, 2009; Rippeth *et al.*, 2014). Extended deployments of autonomous underwater vehicles (AUVs) or ‘gliders’ have recently provided new insight into the importance of mixing of dissolved oxygen across the thermocline in the North Sea (Queste *et al.*, 2016) and the Celtic Sea (Williams *et al.*, 2022). Thermocline mixing is weak when compared to tidal and wind-driven mixing (Williams *et al.*, 2013; Williams *et al.*, 2022). However, these physical processes can drive a steady, albeit small, vertical flux of oxygen into the bottom mixed layer (Williams *et al.*, 2022) or drive cyclic spring-neap changes in oxygen consumption driven by sediment resuspension or ventilation of the seabed (Hull et al 2020). Collectively, physical processes add to the complexity of understanding dissolved oxygen dynamics in shelf seas because they can both enhance oxygen depletion through stratification or act to reduce the potential for oxygen depletion via mixing between layers of the water column. Thus, understanding the role of physical processes now and in the future ocean is vital towards understanding climate change impacts on coastal and shelf sea oxygen dynamics (see Section 2.2).

Below the thermocline, biological processes continuously consume oxygen both in the water column and in the sediment (Figure 1b; Große *et al.*, 2016; Queste *et al.*, 2016; Hicks *et al.*, 2017; Hull *et al.*, 2020). Oxygen consumption in sediments has been found to be dependent on sediment type and season. The highest rates of oxygen consumption occur in cohesive sediments (such as mud) rather than permeable sediments (such as sand and gravel) (Hicks *et al.*, 2017). Increased sedimentary oxygen consumption has been observed during the spring bloom period when more organic matter is immediately available (Hicks *et al.*, 2017). Physical processes continue to play a role as organic matter can aggregate to create 'depocentres' or hot spots of benthic oxygen consumption. In addition, organic matter that is on top of or within surficial sediments can potentially be disturbed by natural mixing (e.g. tides and storms) or by human activities (e.g. trawling), thus making benthic organic matter available for remineralisation in the water column via resuspension, potentially contributing to event-driven oxygen decline (van der Molen *et al.*, 2013; Hull *et al*., 2020). In the Celtic Sea, the spring-neap tidal cycle caused a cyclic change in oxygen consumption due to sediment resuspension enhancing oxygen consumption alongside ventilation introducing oxygen at a muddy-sandy site (Hull *et al*., 2020). Estimates of the role of sediments in driving oxygen consumption on bottom waters span from less than 20% (Rovelli *et al*., 2016; Hull *et al*., 2020) to over 50% (Große *et al.*, 2016). The range likely reflects region specific productivity, remineralisation rates, sediment types or choice of parameters in models.

What could happen in the future?

Results from a regional shelf seas model, the Proudman Oceanographic Laboratory Coastal Ocean Modelling System (POLCOMS), predict an average rise in temperature over the century (in 2069-2089 relative to 1960-1989) of over 3°C for most of the North Sea, English Channel, Irish and Celtic Seas using a medium emissions scenario (Tinker *et al.*, 2016; Hughes *et al.*, 2017). This predicted increase in temperature will lead to a decrease in dissolved oxygen in the whole water column due to a reduction in solubility (Table 1), a decrease in dissolved oxygen in bottom waters due to an increase in the strength and duration of stratification (Table 1: Conley *et al.*, 2007; Keeling *et al.*, 2010; Rabalais *et al.*, 2010; Hofmann *et al.*, 2011; Queste *et al.*, 2013) and impose a greater risk of oxygen deficiency in summer due to lower oxygen in the preceding winter/spring due to warmer waters. Further model projections for the period 2070 to 2098 relative to 1961 to 1990 predict the period of stratification will increase by 10 to 15 days over the entire North-west European shelf region (Lowe *et al.*, 2009; Holt *et al.*, 2010; Sharples *et al.*, 2020).

Table 1. Potential implications of climate change related processes on oxygen dynamics in the coastal and shelf sea environment, including an indication of the timescale over which the process will act and the level of confidence.

Process	Direction	Timescale	Confidence
Decrease in solubility due to ocean warming	**Decrease in oxygen concentration** in surface and bottom waters	Decadal	High
Increase in stratification due to ocean warming	**Decrease in oxygen concentration** in bottom waters due to reduced mixing	Decadal	Medium
Decrease in nutrient supply to the surface mixed layer due to increased stratification	Decrease in phytoplankton growth and amount of organic matter that reaches bottom waters, decrease in oxygen consumption in bottom waters causing a relative **increase in oxygen concentration**	Seasonal	Low
Increase in biological processes due to ocean warming	**Net effect unknown** due to increase in both oxygen production via photosynthesis and oxygen consumption via respiration and other processes. Nutrient availability not considered	Decadal	Low
Increase in frequency and intensity of storms	Localised change in water column stratification and **increase in oxygen concentration** due to water column mixing	Seasonal	Low
Resuspension of sediments due to storms	Increase in organic matter available for oxygen consumption causing a **decrease in oxygen concentration**	Seasonal	Low
Increased precipitation and river runoff	Increase in nutrients will increase the risk of eutrophication and associated **decrease in oxygen concentration**	Annual	Low

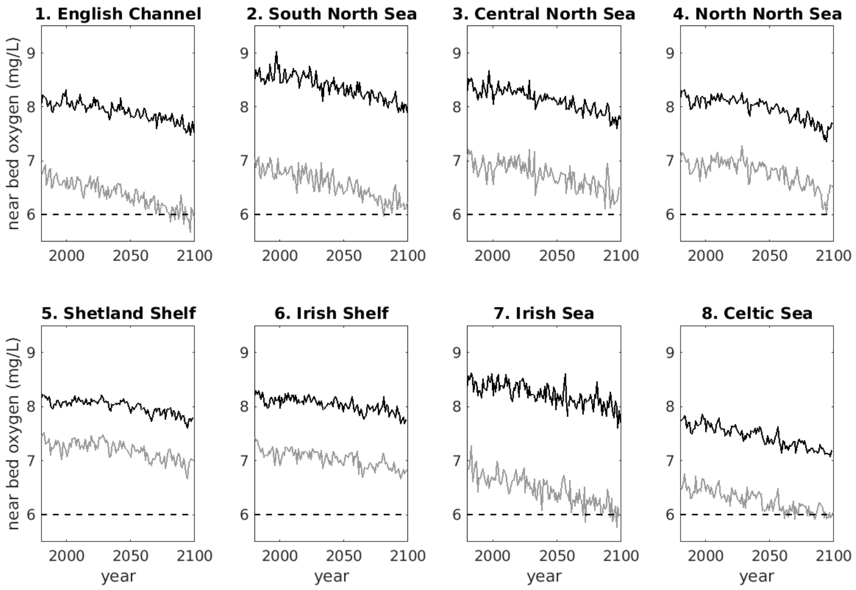
There are additional consequences of climate change that may indirectly impact on the magnitude and even the direction of oxygen dynamics in coastal and shelf seas. For example, while enhanced stratification may reduce mixing between bottom waters and the sea surface, it may also reduce the supply of nutrients to the surface ocean due to reduced mixing across the thermocline. Any reduction in nutrient supply will decrease phytoplankton growth and the amount of organic matter that reaches bottom waters, which will likely decrease the demand for oxygen in the bottom waters. The net effect of these two competing mechanisms is uncertain (Table 1). In contrast, biological processes are thermally sensitive and will likely increase in response to an increase in temperature but their net impact on oxygen dynamics is unknown (Table 1). Increased storm activity driven by a warming atmosphere will enhance ocean mixing. While this will further be modified by a change in stratification from a warmer atmosphere, a likely scenario is an increase in surface layer depth, an increase in energy available to mix bottom waters and a reduction in areal extent of seasonal stratification, and thus a reduction in the risk or extent of oxygen depletion (Table 1). Other contributing processes from this enhanced mixing however may include increased resuspension of sediments, which may increase biological oxygen consumption in bottom waters or reduced light and therefore reduced primary production in upper layers (Capuzzo *et al.*, 2017). Finally, winter precipitation and river flows are expected to increase across northern Europe (EEA, 2015), potentially increasing the input of nutrients to coastal systems and thus enhancing the risk of eutrophication and associated depletion of oxygen (Table 1, Rabalais *et al.*, 2010; Zhang *et al.*, 2010; Ockenden *et al.*, 2017). Alternatively, a reduction in nutrient input via rivers through improved water and land management has the potential to reduce eutrophication and thus reduce the risk of oxygen deficiency (Lenhart *et al.*, 2010; Bussi *et al.*, 2017).

The interaction between these complex processes and their combined effect is difficult to predict, however a suite of global models of varying degrees of complexity agree that dissolved oxygen concentrations in the global ocean will decline by 1.5 to 4% by 2090 or by 6 to 12 μmol/kg by 2100 (Ciais *et al.*, 2013). Model simulations specifically focused on coastal and shelf sea waters estimate that dissolved oxygen concentrations in the North Sea will decline by 5.3 to 9.5 % by 2098 (van der Molen *et al.*, 2013) or as much as 11.5% by 2100 (Meire *et al.*, 2013). Using a coupled hydrodynamics-ecosystem model (NEMO-ERSEM), Wakelin et al (2020) investigated the potential changes in and drivers of oxygen depletion across the North-west European continental shelf seas under a 'business-as-usual' greenhouse gas emissions scenario (RCP 8.5). Model simulations estimate that as the shelf sea waters become warmer and less saline under RCP8.5, the mean near bed oxygen concentration will decrease by 6.3% by 2100, with monthly minimum oxygen decreasing by 7.7%. In regions that currently experience oxygen depletion, such as the central North Sea and Celtic Sea, the model predicts that oxygen depletion will intensify and last longer (see Figure 9 in Wakelin *et al.*, 2020). For UK shelf waters (Figure

5), the mean oxygen concentration is projected to decline most strongly (5.6 to 5.9% by 2100) in North Sea regions and the Celtic Sea while the reduction in the minimum of monthly-mean concentrations is highest (8.8 to 8.9%) in the English Channel, southern North Sea and Irish Sea. Deeper regions exposed to exchange with the open ocean (the Irish shelf and Shetland shelf) are less affected, with annual mean concentrations decreasing by 2.9 to 3.1% and minimum monthly concentrations by ~4%. However, in the western Irish Sea, warming of the sea surface may alter the structure of the gyre system, strengthening stratification and thus increasing the risk of oxygen depletion in bottom waters (Olbert *et al.*, 2012). These model outputs imply that the decline in dissolved oxygen in coastal and shelf seas resulting from climate change would be amplified compared to the effects in the open ocean.

In the open ocean, 15 to 32% of the decline in oxygen is attributed to a decrease in solubility in a warming ocean, with the remaining 58 to 85% of the decline attributed to reduced ventilation due to increased stratification (Helm *et al.*, 2011; Meire *et al.*, 2013) or biological oxygen consumption (Brewer and Peltzer 2017). Observations from the North Sea suggest that one third of the historical oxygen decline is due to warming, whereas two thirds is attributed to increased oxygen consumption (Queste *et al.*, 2013). More recently, model simulations focused on the North-west European Shelf Sea suggest that 73% of the projected decline in oxygen up to 2100 at RCP8.5 is due to solubility changes with the remainder attributed to changes in the ecosystem processes (Wakelin *et al.*, 2020). Thus, it appears that the contribution of reduced solubility in reducing oxygen concentrations will become more important as the ocean warms.

(a)



(b)

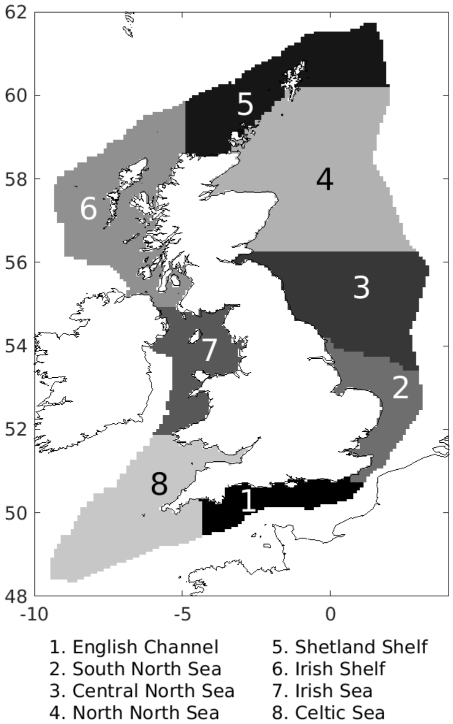


Figure 5: *(a) NEMO-ERSEM projections of near bed oxygen concentrations under a high greenhouse gas emissions scenario (RCP8.5), averaged over (b) the UK shelf regions. The black lines are annual means, the grey lines are the minimum monthly-mean concentrations per year and the dashed lines indicate the 6 mg/litre oxygen deficiency threshold. (Adapted from Wakelin* et al.*, 2020.)*

Consequences of oxygen depletion

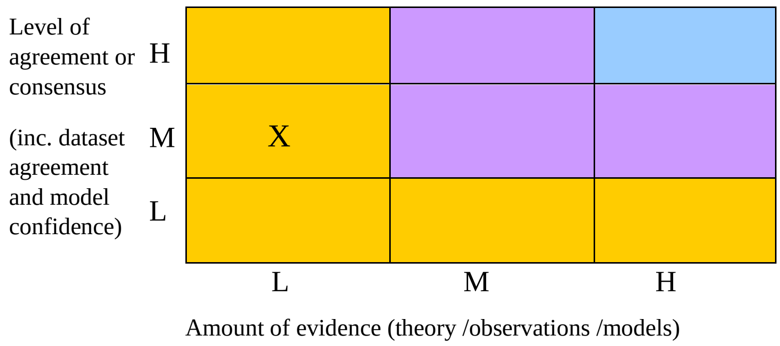
Oxygen is required to sustain vital metabolic processes of marine organisms and is essential for activities such as muscular activity, growth and reproduction (Pörtner and Knust, 2007). Thus, depletion of dissolved oxygen poses a serious threat to marine organisms, with the most-severe responses occurring under hypoxic or anoxic conditions. Most marine organisms have limits or thresholds to the severity of oxygen depletion they can tolerate (Vaquer-Sunyer and Duarte, 2008; Pörtner, 2010). Even a small decrease in oxygen below a threshold can affect oxygen-demanding functions, such as movement and reproduction (Claireaux *et al.*, 2000; Claireaux and Chabot, 2016). Other key factors include exposure time, species, type of organism, respiration mode and physiological requirements. For example, highly active species are generally less tolerant of low oxygen conditions (Stramma *et al.*, 2011). Oxygen depletion can cause a reduction in survival, growth and reproduction, alter behaviour of individual organisms (Baden *et al.*, 1990; Eriksson and Baden 1997; Chabot and Claireaux, 2008; Long *et al*., 2008; Ludsin *et al*., 2009), affect predator-prey relationships and in the most severe case, cause death (Shurmann and Steffensen, 1992; Stramma *et al.*, 2010; Urbina *et al.* 2011; Townhill *et al.*, 2017b). Even brief repeated exposure to oxygen depletion can alter the immune system of macrofauna and thus increase disease and reduce growth (Stierhoff *et al.*, 2009; Keppel *et al.*, 2015). Oxygen depletion can be devastating for commercial fisheries. For example, during a period of oxygen deficiency (oxygen concentration of 3.7 mg/litre, equivalent to a saturation lower than 40% or 116 μmol/kg) in 1982 in German and Danish coastal waters of the North Sea, fish abundance decreased from ~400 kg per 30-minute trawl to less than 5 kg per 30 minute trawl (Westernhagen and Dethlefsen, 1983). While the focus here is on dissolved oxygen, ocean warming will also increase metabolic rates of organisms and thus it is the response to multiple stressors, not just a decline in oxygen, that needs to be understood. To delineate the role of temperature versus oxygen availability on metabolism, Deutsch *et al*. (2015) defined a metabolic index, which compares the ratio of the oxygen supply to an organism's resting oxygen demand. Using this physiological framework, projected ocean warming alongside deoxygenation would reduce the metabolic index as the increase in metabolism increases oxygen demand relative to oxygen supply. This implies that future marine hypoxia will be driven primarily by warming and not a decline in oxygen (Deutsch *et al.*, 2015).

In addition to the ecological risks, oxygen depletion affects ecosystem structure (Levin *et al.*, 2009; Hughes *et al.*, 2009) and the activity of the constituent organisms (Woulds *et al.*, 2007; Hunter *et al.*, 2012). This has consequences for the transfer and storage of organic matter to the sediments (Keil *et al.*, 2016; Cavan *et al.*, 2017), biological removal of nitrate (Neubacher *et al.*, 2011; Neubacher *et al.*, 2013; Kitidis *et al.*, 2017), production of greenhouse gases such as nitrous oxide (Naqvi *et al.* 2010; Freing *et al.*, 2012; Bianchi *et al.*, 2012), and the release of phosphorus and iron from sediments (Scholz *et al.*, 2014; Watson *et al.*, 2018). These biogeochemical responses to oxygen depletion have the potential to affect primary production locally in coastal and shelf seas and lead to feedback loops, which may have both positive and negative effects on ecosystem functioning (Niemeyer *et al.*, 2017).

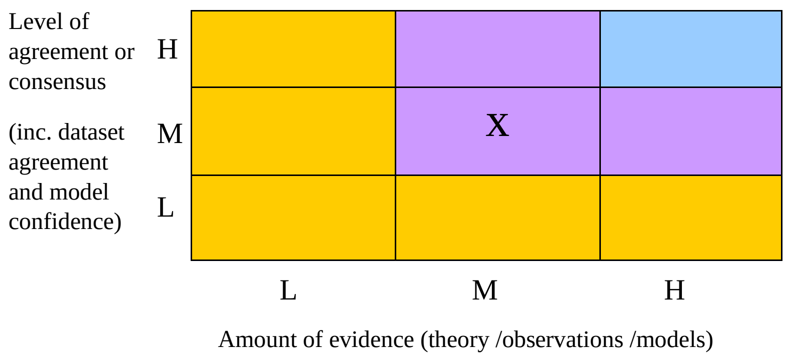
Although hypoxia has not been detected in UK marine waters, it has been detected in the wider North-west European shelf seas including the North Sea (Topcu and Brockmann, 2015) and Baltic Sea (Meier *et al.*, 2019) and thus will affect species that contribute to the ecosystem and perhaps economy of the UK due to connectivity of the marine environment and transfer of migratory species between regions. Periods of oxygen deficiency have been detected in the UK waters of the North Sea and now the Celtic Sea. While the impact of deoxygenation has been documented in non-UK waters of the North Sea (Westernhagen and Dethlefsen, 1983) and globally (Rose *et al.*, 2019) the impacts on the marine ecosystem, specifically commercial fisheries has not yet been documented in UK marine waters.

CONFIDENCE ASSESSMENT

What is already happening?



What could happen in the future?



On a global scale, there is a *high level of confidence* that the oceans are losing oxygen due to ocean warming. In UK coastal waters, there is a high level of understanding of the seasonal and interannual variability in oxygen dynamics in the permanently mixed and seasonally stratifying waters in the North Sea due to the relatively extensive sampling regime for dissolved oxygen concentrations in this region over the past four to five decades. Repeat sampling at specific sites has provided insight into the occurrence and onset of oxygen deficiency but the spatial extent of oxygen deficiency outside of these specific regions within the North Sea is uncertain due to the paucity of direct observations. Approximately one third of the historical seasonally focused depletion of oxygen in the North Sea has been attributed to warming but the remaining two thirds are thought to be due to enhanced oxygen consumption. The relative importance of the processes that drive enhanced oxygen consumption (e.g. more organic matter, decreased ventilation of bottom waters), however, remain poorly understood. Finally, whereas the North Sea is well sampled in time and space, the rest of the

Northwest European Shelf waters, especially the Celtic and Irish seas, are relatively poorly sampled and offer *low levels of confidence* in the occurrence or risk of oxygen depletion. Nevertheless, both observations and models agree that the UK coastal and shelf seas are losing oxygen and thus there is a *medium level of confidence* on the direction of change.

At the global scale, there is a *high level of confidence* that an increase in temperature will continue to reduce the solubility of oxygen and enhance stratification and thus lead to the ongoing decline in dissolved oxygen concentrations, especially below the thermocline. On a regional scale appropriate for coastal and shelf seas, there is a consensus that the ocean will lose oxygen. Model simulations can provide estimates of the magnitude and causes of the decline in dissolved oxygen but there is still uncertainty in how well they represent the coupling between physical and biogeochemical processes, biological processes specifically, strong seasonality in nutrient supply in a shallow water column and interaction with the sediment. Therefore, there is a *medium level of confidence* on the future of dissolved oxygen dynamics on a regional scale relevant to UK marine waters.

KEY CHALLENGES AND EMERGING ISSUES

1. We need to be able to determine the mechanisms driving spatial and temporal trends in dissolved oxygen and confidently identify when and where changes in dissolved oxygen are being driven by human-induced activity such as ocean warming or nutrient enrichment relative to background natural variability.

2. Assessing the occurrence, frequency and spatial extent of oxygen deficiency in UK coastal and shelf waters is hampered by the lack of long-term data in regions outside of the North Sea. The poor resolution of dissolved oxygen data also hampers the ability to confidently test coastal and shelf-sea models. An integrated observing system providing high resolution, continuous time-series data using new technologies such as autonomous ocean gliders or instrumented moorings would provide the means to improve detection of oxygen depletion in the future. Recent and current programmes such as the NERC-Defra Shelf Sea Biogeochemistry programme (Kröger *et al.*, 2018) NERC-Defra WWF AlterEco project (https://altereco.ac.uk) and EU H2020 AtlantOS programme (https://atlantos-h2020.eu) are providing emerging insight into best practices on how to operate autonomous ocean gliders to study dissolved oxygen dynamics in UK marine waters.

3. There is still uncertainty surrounding the ability of models to simulate the individual processes and coupling between processes that control dissolved oxygen dynamics. To accurately predict dissolved oxygen, models need to simulate each contributing process correctly, in isolation but also coupled to other processes. This is an enormous challenge for ocean models since it is not possible to include all physical, chemical and biological processes in any model. Instead, complex processes must be parameterised to produce net effects that are close to that observed, but that may have differing levels of success dependent on local conditions. We do not yet fully understand all processes contributing to the decline in oxygen in the marine environment and thus representing these processes in models is challenging. The lack of understanding is particularly acute within coastal and shelf sea sediments. The lack of long-term time series data for testing coupled physical-ecosystem models, or the variability in functioning between sites with different conditions is also problematic.

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