Climate change impacts on stratification relevant to the UK and Ireland

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KEY FACTS

What is already happening

- There is a suggestion of earlier onset of seasonal stratification in UK shelf seas and tentative evidence of long-term trends in the strengthening of stratification.
- Stratification in coastal regions influenced by freshwater inputs shows no discernible long-term trends against the background of natural variability.

What could happen in the future

- Projections suggest that by 2100, thermal stratification in UK shelf seas will extend in duration by around 2 weeks (with both earlier onset and later breakdown), and increase in strength, due to changes in air temperature.
- The timing of stratification will respond to changes in winds (which can drive or prevent stratification) and rainfall.
- Future large-scale deployments of floating offshore wind turbines in deeper, seasonally stratifying waters have the potential to disrupt stratification.
- Projected changes to shelf-sea stratification may lead to less upward mixing of nutrients, possible reductions in primary productivity and changed in bottom water dissolved oxygen.
- More rainfall and run-off from the land could increase coastal stratification and exacerbate eutrophication.

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SUPPORTING EVIDENCE

Introduction

Stratification and its importance in the ocean

A region of the sea is 'stratified' when a layer of less-dense water is situated above denser water. The surface layer could be less dense because it is less salty than the deeper water (e.g. because of an input of fresher water from an estuary), or because it is warmer than the deeper water (i.e. because the surface has been warmed by heating by sunlight and the overlying atmosphere), or because of a combination of heating and contrasts in salinity.

Stratification is important because it inhibits vertical mixing of water properties, such as heat, salt, nutrients, phytoplankton and oxygen. Much of the biogeochemistry and ecology of the ocean is tightly linked to cycles of stratification.

Seasonal temperature stratification

Over much of the UK shelf seas, away from the influence of river sources of freshwater, control of stratification largely resides with the strength of the surface heating by the Sun (an effect which is strongly seasonal) and the strength of the tides in driving mixing (Simpson and Bowers, 1984). Strong tides, and/or shallow water, leads to vertically mixed conditions being maintained all year. Weaker tides, and/or deeper water, lead to a reduction in the strength of mixing, so that heating can warm the surface water and generate stratification that can be sustained for several months until autumn/winter.

The timing of spring stratification is mainly controlled by the competition between the solar heating and the tides (Simpson and Bowers, 1984), with a smaller, but still important, contribution from mixing caused by winds (e.g. spring stratification and the phytoplankton bloom tend to be delayed in windier springs) and some further control by freshwater inputs (e.g. from rainfall). A changing climate, both in terms of warming and shifts in meteorological conditions, is likely to alter the timing of spring stratification, and subsequently the timing and success of phytoplankton primary production because the onset of stratification is a key physical control on the formation of the spring bloom (Holt *et al*., 2010). Climate driven changes to the duration of stratification will likely impact shelf sea carbon cycling and ocean health, via changes to remineralisation processes that are dependent on seasonally sustained stratification (Holt *et al*., 2016). However, modification of the available light (e.g. via clouds and/or changes in ambient sunlight associated with the date of stratification) could also provide additional constraints on the biological processes that underpin shelf sea biogeochemistry.

The timing of the onset of seasonal stratification and the resulting spring phytoplankton bloom is important for the success of many marine animal populations that regulate their own reproduction cycle with the new supply of food to the system (e.g. Platt *et al*., 2003). The timing and strength of stratification has also been implicated in the breeding success of seabirds (Carroll *et al*., 2015; Scott *et al*., 2006).

Stratification restricts exchange between layers, limiting the exchange of water masses, nutrients, phytoplankton and dissolved gases. Stratification limits the ventilation of waters beneath the surface mixed layer, with a gradual decrease of oxygen in bottom waters throughout summer months until winter remixing of the entire water column allows replenishment of the oxygen deficit from the atmosphere. Changes to the duration and strength of stratification, or changes to mixing that allows limited exchange across stratified interfaces, will therefore have implications for regional ocean health and productivity.

Stratification caused by freshwater inputs

The development of stratification in coastal areas can cause an increase in the transport rates of estuarine water and its constituents (including sediments, nutrients, anthropogenic contaminants) away from the coast at the sea surface, but at the same time increased onshore transports of material in the bottom waters (Palmer and Polton, 2011). As stratification by fresher water at the coast is dependent on the balance between the rate of supply of the estuarine water and the strength of the mixing processes, changes in the climate (i.e. changes in winds and rainfall) will modify this balance.

The combined effects of estuaries on coastal waters leads to a weak salinity gradient across the whole shelf, with gradually increasing salinity towards the shelf edge and open ocean (Ruiz-Castillo *et al*., 2019). Recent work has suggested that initial spring stratification can be triggered by wind-driven transport of surface water towards the shelf edge (Ruiz-Castillo *et al*., 2019). In addition, rainfall has been seen to provide a source of initial spring stratification by directly supplying freshwater to the sea surface (Jardine, 2020).

WHAT IS ALREADY HAPPENING?

Changes in the timing of stratification

In regions away from the coast that experience seasonal thermal stratification, there is some evidence of a recent trend to earlier stratification. In a model-based study, Young and Holt (2007) have indicated earlier stratification by about 5–8 days in the western Irish Sea between 1960 and 1999, with much of the trend to earlier dates occurring through the mid-1980s and 1990s. A similar trend has been reported for the north-western North Sea, in an analysis over the period 1974–2003 (Sharples *et al*., 2006), again with the trend to earlier dates occurring only from the late 1980s at an average rate of about 0.5 days earlier per year.

However, these observed trends are weak, and there is currently no reliable indication that they are sustained (Jardine *et al*., 2022). Note that typical natural inter-annual variability in the timing of stratification in the North Sea was found to be about ±7 days (1 standard deviation about the mean) (Sharples *et al*., 2006). Long-term trends in the timing of stratification in regions influenced by freshwater inputs are so far not seen, largely because the natural variability in the rate of supply of fresh water combined with cycles in mixing caused by the tides (e.g. the spring-neap tidal cycle) dominate the variability.

Numerical model results confirm that the timing of the onset of seasonal stratification is linked in part to the occurrence and intensity of spring storm events, with wind-driven cross-shelf transport of surface water and direct rainfall providing early triggers for short-lived stratification that can be prolonged by subsequent thermal stratification (Ruiz-Castillo *et al*., 2019; Jardine *et al.,* 2023). Such storm events are linked to climate cycles, and research shows a close relationship between the timing of the onset of spring stratification and the North Atlantic Oscillation. Coupled physics-ecosystem models demonstrate links between climate changes in winds and rainfall in spring and the biological responses, evident in the timing and productivity of phytoplankton spring blooms (Jardine *et al*., 2022).

Changes in the strength of stratification

Numerical modelling in the north-western North Sea (1973–2003) indicates marked inter-annual variability in the strength of thermal stratification with a periodicity of about 7–8 years (Sharples *et al*., 2006). There were no clear trends in the observed strength of the thermal stratification that could be separated from the inter-annual variability within the time period 1974–2003. However, model results from 1985-2004 (Holt *et al*., 2012) show a trend in the difference between surface and near-bed temperatures during July to September across the North-West European Shelf, indicating an increase in stratification over this 20-year period. Holt *et al*., 2012, corroborate this using a trend analysis of ICES data (Hughes *et al*., 2012) which shows sea surface temperatures (SST) warming more quickly than near-bed temperatures (NBT), e.g. 0.066 ± 0.030ºC yr^{-1} for SST and 0.038 ± 0.030ºC yr^{-1} for NBT in the southern/ Central North Sea. The increases in stratification strength in the North Sea are supported by Chen and Staneva (2024) for 1993-2012 using a model reanalysis. However, from 2013-2022, although the positive trend continues in the northwestern North Sea, the model shows a decline in stratification strength in the eastern North Sea. The same model (Chen and Staneva, 2024) also shows a reduction in stratification in the western Celtic Sea over the period 1993-2022. In the western Irish Sea, where a gyre circulation is set up by the seasonal thermal stratification, there is some indication of strengthening stratification over recent decades (Olbert *et al*., 2011). This gyre is critical to the sustainability of a commercially important *Nephrops norvegicus* population, and the ability of the gyre in maintaining *Nephrops* larvae may reduce as stratification increases (Olbert *et al*., 2012).

Marine heatwaves (MHWs) have been observed to shallow the surface layer and significantly strengthen stratification over wide areas of ocean on the European shelf (Berthou *et al*., 2024). These episodic events can be driven by meteorological conditions (e.g., low cloud cover, low winds, the introduction of warm tropical air), lasting from a few days up to 2 weeks. Increased stratification due to MHWs could limit mixing, reducing upward mixing of deep-water nutrients and the exchange of gases, including oxygen, both at the surface and internally. Work on timing and ecosystem impacts of MHWs is expanding (e.g. Giménez *et al*., 2024). More monitoring and research is needed to understand the frequency and impacts of MHWs for the wider marine ecosystem (Jacobs *et al*., 2024; Cornes *et al.,* 2025).

WHAT COULD HAPPEN IN THE FUTURE?

Changes in the timing of stratification

Over much of the North-West European Shelf seas the onset of spring stratification is projected to occur earlier by the end of the century (Figure 1a) caused by changes in surface heating. There is also a suggestion that the seasonal breakdown of stratification will occur later than present (Figure 1b). In both cases, the dominant control is the increase in air temperature, which aids stratification. There is uncertainty in how changes in winds might affect stratification timing. There is an overall weak trend over the past 30 years of stronger average winds in the North Atlantic (Young and Ribal, 2019), as expected with warmer SSTs, though the limited length of that time–series is insufficient to determine reliably a link to a warming climate. Stronger wind events in spring could feasibly prevent earlier stratification by increasing mixing. However, wind (depending on direction and wind speed) and rainfall can also act as potential triggers of stratification. There are considerable uncertainties in how storm strength, frequency and tracks might alter in a warmer climate. Nevertheless, the most recent model predictions suggest that the net impact is for the length of the stratified part of the year to increase by about 20 days (Figure 1c). Most of this is associated with later timing of winter re-mixing (~ 19 days) with a smaller contribution from earlier dates for the onset of spring stratification (~ 4 days). These results are consistent with those presented in previous studies, however the change in duration is greater than previously suggested (10-15 days; Holt *et al*., 2010).

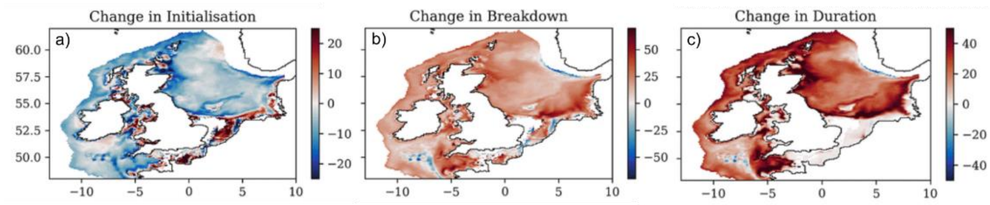


Figure 1: Comparison between present-day (2000-2019) and future (2079-2098) timing of stratification. Future projections are based on the high greenhouse gas emissions scenario RCP8.5.

(a) Change in timing (days) of the initialisation of seasonal stratification.

(b) Change in timing (days) of the autumn/winter breakdown of stratification.

(c) Change in the total number of days for duration of stratification during one year. (From Tinker et al., 2024).

Changes in the strength of the stratification

Again, reliable predictions of changes are limited to regions where the balance resides mainly with surface heating and mixing by tides. Model projections suggest that the entire North-West European Shelf seas develop greater surface-bottom temperature differences (Figure 2 and Tinker *et al*., 2016; 2024). This is a result of changes in the seasonal heating cycle, with greater SST warming suggested during June-December (Tinker *et al*., 2024). The largest difference is seen in Autumn, leading to the later breakdown in stratification. Alongside the strengthening stratification there will be small shifts in the position of the weak, transitional stratification (e.g. the tidal mixing fronts, Simpson, 1981) that separate seasonally stratifying and mixed waters as thermal stratification pushes into shallower and/or stronger tidal regions. However, Tinker *et al*. (2024) projected little change in the spatial extent of stratification on the North-West European Shelf.

Warming in winter is important for setting the pre-spring conditions that control subsequent heat flux and stratification. Temperatures immediately before the onset of stratification are also pivotal in setting the seasonal behaviour of bottom water oxygen with warmer winters leading to lower bottom water oxygen concentrations later in summer (Mahaffey et al., 2025). Summer stratification will also depend on the mixing and changes in net heat flux caused by storms. Currently there is a trend of increasing numbers of storms over UK coastal seas, though it is unclear if this is driven by climate warming or is part of longer climate cycles (Bricheno *et al*., 2025.

There is a marked change in the projection for the strength of stratification in the open ocean, where much larger increases in stratification result from changes in open ocean salinities rather than surface heating. Closer to the coast where freshwater from the estuaries plays a more important role in determining stratification, knowledge of future rainfall trends is insufficient to allow confident assessments.

Climate warming is expected to lead to greater incidence of MHWs (Smale *et al*., 2019). MHWs will impact stratification, however increasing stratification could also increase the risk for more intense heating in the surface ocean, as observed in 2023 (Berthou *et al*., 2024). The full implications of the resulting warmer waters and stronger stratification, for instance on ecological impacts and post-heatwave effects on shelf sea conditions (e.g. heat storage and stratification), have yet to be determined.

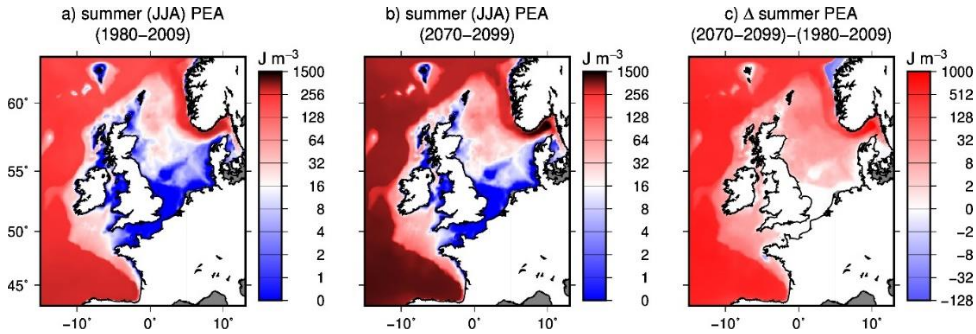


Figure 2: Present day and predicted strength of stratification. The unit used to measure stratification is 'potential energy anomaly' (PEA) which is equivalent to the amount of energy required to completely mix the water column. Adapted from Wakelin et al*. (2020). Future projections are based on the high greenhouse gas emissions scenario RCP8.5.*

(a) Present day average strength of stratification.
(b) Predicted strength of stratification towards the end of the century
(c) Predicted change in stratification towards the end of the century (the difference between (b) and (a)).

Note in (a) and (b) that the blue areas (zero PEA) are the regions with strong tidal flows that do not stratify (see also Fig. 1).

Detailed changes at selected locations

Climate-driven trends are apparent when considering the more-detailed behaviour at representative points across the North-West European Shelf (Figure 3). Three seasonally stratifying regions (central Celtic Sea, Malin shelf and northern North Sea) show the typical behaviour of thermal stratification, with surface waters warming relative to near-bed waters from early April, and re-mixing of the water column occurring in early or mid-December. The future predictions of earlier April stratification, and particularly of the delayed winter re-mixing, are also clear (Figure 3, compare left and right panels).

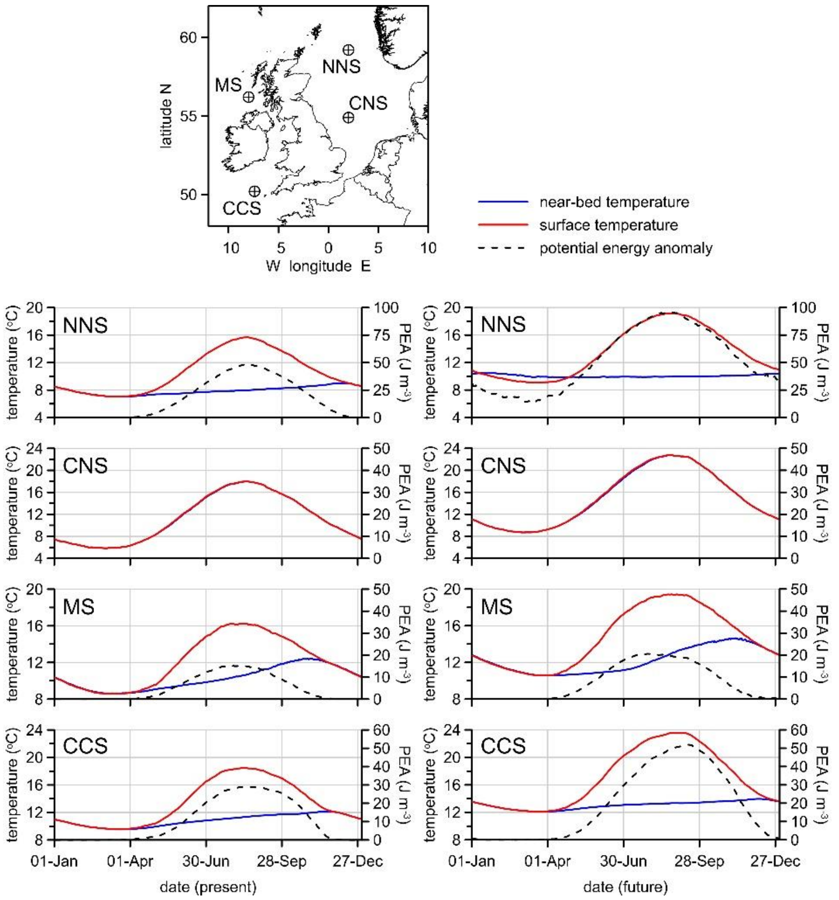


Figure 3: Examples of changes in stratification at four sites on the NW European shelf: northern North Sea (NNS), Malin shelf (MS), central North Sea (CNS) and central Celtic Sea (CCS) [Wakelin et al., 2020]. The map illustrates the site positions; the plots show the annual changes in temperature and the potential energy anomaly, with the left column for the present day (average for 1980-2009), and the right column for the end of this century (average for 2070-2099, based on scenario RCP8.5). Note that CNS remains vertically homogeneous throughout the year, so surface and near-bed temperatures are the same and the potential energy anomaly is zero.

Three other aspects of climate-driven changes are highlighted in Figure 3.

(1) There is clear overall warming at all locations, with summer surface temperatures typically warmer by about 4°C (though nearly 6°C in the central Celtic Sea). This is also true for the central North Sea which, while remaining vertically mixed throughout the year in both present day and the future scenario, continues to warm and also has a stronger seasonal variation in the future. At all locations the coldest temperature reached in late winter increases by about 2°C in the future.

(2) The strength of the stratification (contrast between surface and near-bed temperatures) is significantly greater in the future predictions for the three locations that stratify in the summer (northern North Sea, Malin shelf and central Celtic Sea), though significant regional differences are apparent.

(3) There is apparently anomalous behaviour in the prediction for the future northern North Sea, with winter near-bed temperatures warmer than the surface water. This inversion in the temperature is more than compensated for by lower salinity water at the surface which, in these model predictions,

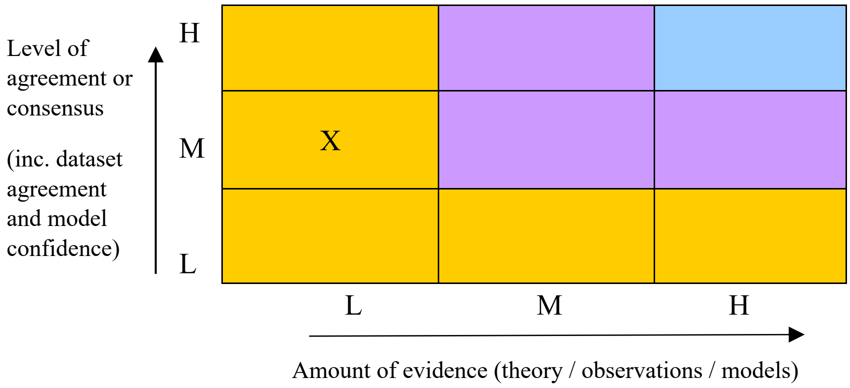
arises from a reduction in the exchange between the North Sea and the North Atlantic, and spreading of lower salinity water westward from the Norwegian coast (Holt *et al*., 2018). The model prediction for this region suggests that stratification becomes permanent, caused by strong vertical gradients of temperature (in summer) and of salinity (in winter).

There is a current consensus that strengthening stratification will reduce the upward mixing of nutrients and so lead to a reduction in primary production (Chust *et al*., 2014). Increased coastal stratification caused by higher rainfall and river run-off is generally expected to worsen any problems of eutrophication (Laurent *et al*., 2018), though around the UK coasts the strength of the tidal mixing may act to offset some of this (OSPAR, 2017). Extending the period of stratification will likely result in further reduction of oxygen concentrations at depth (see MCCIP review on dissolved oxygen), which will be exacerbated by lower initial oxygen concentrations in winter arising from a warming sea.

Future large-scale developments of floating offshore wind farms (FLOW) could significantly alter mixing in shelf seas. Current offshore wind farms tend to be in shallow, well-mixed coastal regions. Plans include deployments of large, floating structures covering significant areas of deeper, seasonally stratifying waters. Tidal flows interacting with these large floating structures may drive a local increase in mixing within the seasonal thermocline (Dorrell *et al*., 2022). Modelling suggests a wind deficit downwind of large wind farms may reduce wind mixing over 10s or possibly 100s km (Akhtar et al, 2021), though observational support for this effect is needed. Work to assess the potential impacts of additional mixing caused by tidal flows interacting with deep-water wind farms is planned in recently funded UK projects.

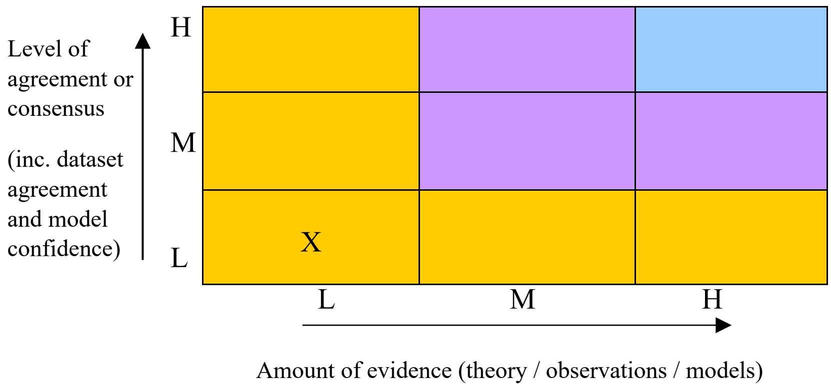
CONFIDENCE ASSESSMENT

What is already happening?



There is good agreement between the observation and modelling studies and good understanding of the basic controls of stratification caused by surface heating. However, long-term observational data is limited in scope and less is known about the roles of salinity and freshwater in coastal and shelf stratification. Models have less reliability in depicting salinity fields. There is a need for better long-term data on stratification, to capture the onset/breakdown, the strength, and the relative contributions of heating and salt/freshwater. Observations require both long-term sustained moored instrumentation and regular ship-based and autonomous vehicle sampling of key sites. Stratification caused by freshwater inputs (from estuaries and via rainfall) is particularly difficult to assess because of a lack of consistent long-term salinity observations.

What could happen in the future?



The UKCP09 predictions were the first attempt at regional-scale assessment of changes in the marine climate over the next century and were extended using a model ensemble by Tinker *et al.* (2016), and more recently Tinker *et al*. (2024). There is broad confidence of the ability of the model to predict changes over the open-shelf seas where surface heating/cooling is the dominant control. There are some uncertainties locally close to the shelf edge and in regions influenced by estuaries; more confidence is also required in how changes in salinity, both in the shelf interior and in the open ocean, will contribute to future stratification. The overall lack of confidence arises from (1) predictions of both the timing and strength of stratification are determined by changes in regional meteorology, which is a challenging aspect of future climate projections, and (2) stratification caused by salinity changes is much more difficult to model than that caused by surface heating/cooling.

KEY CHALLENGES AND EMERGING ISSUES

1. Increasing the range of observations, including temporally and spatially well-resolved temperature and salinity, and better data and understanding of deep-water oxygen concentrations.
2. Model developments are now beginning to address the physics of the shelf edge and other small-scale processes. There remain modelling challenges in simulating salinity, riverine inputs, intermittent coastal stratification, and the role of stratification in controlling vertical mixing.
3. Continuing research into emerging issues, including the role of rainfall in stratification, climate-driven changes in rainfall and wind patterns, marine heatwaves, and the impacts of large-scale deployment of offshore wind turbines in seasonally stratifying shelf seas.

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