Impacts of climate change on shelf-sea stratification, relevant to the coastal and marine environment around the UK

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EXECUTIVE SUMMARY

- Temperature stratification over the North-West European Shelf seas is showing evidence of beginning slightly earlier in the year, on average.
- There is no suggestion of strengthening of stratification beyond the normal inter-annual variability.
- Trends in stratification in regions influenced by freshwater inputs are also not apparent against the background of natural variability.
- Predictions for the end of this century suggest that thermal stratification will begin typically one week earlier than at present, and end 5–10 days later.
- The strength of the stratification over the whole North-West European Shelf seas is projected to increase in response to changes in the seasonal heating cycle.
- Changes to coastal stratification caused by inputs of freshwater cannot yet be predicted.

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1. 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 sunlight). Whether or not a region becomes stratified depends on the balance between the inputs of fresher water and/or heat, and the effects of turbulence that act to mix the water vertically and erode the stratification (e.g. turbulence caused by tidal currents, wind, and waves). The interface between the upper and lower layers is called the *pycnocline* (a region where water density changes steeply), *thermocline* (a region of rapidly changing temperature), or *halocline* (a region of sharply changing salt concentration).

Stratification is a key control on shelf-sea marine ecosystems. The interface between the surface and deeper layers acts as an efficient barrier to the vertical mixing and exchange of water. Any dissolved substance (e.g. nutrients, oxygen) or passive particles (e.g. phytoplankton, sediments) in the water will be affected by this reduced capacity for transfer between the surface and deeper waters. Stronger stratification has a correspondingly greater effect on inhibiting vertical exchange.

Seasonal temperature stratification

Over much of the UK shelf seas, away from 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. 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 is able to warm the surface water and generate stratification. These processes lead to a partitioning of shelf seas into regions that are permanently mixed and regions that stratify in spring and summer (Figure 1; Simpson and Sharples, 2012). The boundaries between these mixed and stratified regions cause much of the average flows within the shelf seas during the summer months (Hill *et al.*, 2008).

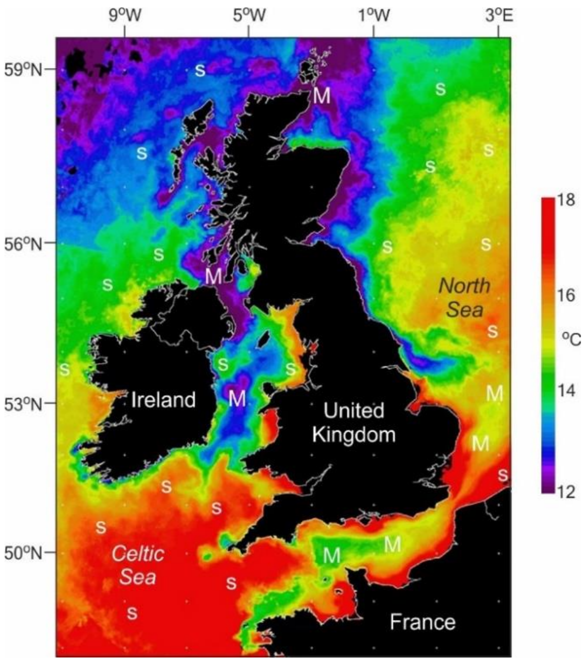


Figure 1: Sea-surface temperatures in summer around the UK and Ireland, measured by satellite (data courtesy NEODAAS). Warmer surface waters generally indicate areas that stratify in summer, colder waters are regions that stay vertically mixed all year. The 'S' and 'M' indicate stratified and mixed areas respectively.

The annual development of this shelf-sea stratification is a fundamental control on biological growth in shelf seas. When stratification begins in spring, the phytoplankton (single-celled aquatic plants) trapped in the upper, well-lit waters grow rapidly in the 'spring bloom'. This bloom is a short-lived feature, as the phytoplankton rapidly consume the available nutrients in the surface water. Some marine organisms time their breeding cycles to correspond to this sudden arrival of phytoplankton; overall the spring bloom is a key event in the supply of food into the base of marine food chains. The timing of spring stratification is 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. stratification and the bloom tend to be delayed in windier springs). A changing climate, both in terms of warming and shifts in wind patterns, is likely to alter the timing of spring stratification and as a key physical control on the formation of the spring bloom the timing of stratification will be important for bloom timing. 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 phytoplankton growth.

During summer in the stratified regions there is little biological growth in the surface water, as the stratification prevents the re-supply of deeper nutrients. Phytoplankton growth continues at the base of the surface layer, seen as a layer of chlorophyll in the thermocline, in response to weak sunlight and a leakage of nutrients upward from the deeper water. Growth rates are slow, but added up over the whole summer the total amount of growth is similar to that in the spring bloom (Fernand *et al*., 2013; Hickman *et al*., 2012; Richardson *et al*., 2000). The primary production within the thermocline is also thought to 'pulse' with the changes in tidal currents over the spring-neap tidal cycle (Sharples, 2008). Short-duration gales or storms can briefly weaken the stratification, driving new nutrients into the thermocline which can cause significant extra primary production (Williams *et al*., 2013).

Stratification and the primary biological production associated with it are vitally important components of the ocean system that support marine animals. The timing of the stratification and the spring bloom is thought to be important for the success of many marine animals that need to time their own reproduction with the new supply of food to the system (e.g. Platt *et al*., 2003). The timing and strength of stratification has been implicated in the breeding success of seabirds (Carroll *et al*., 2015; Scott *et al*., 2006). The boundaries between the mixed and stratified regions are also important regions for biological growth and the distribution of marine animals that depend on the plankton for their food (Cox *et al*., 2018).

The organic material generated by the phytoplankton of the spring bloom, and later in the layer inside the thermocline, slowly sinks into the deeper water during the summer. Here bacterial action recycles the organic material back to inorganic carbon and nutrients. This recycling removes oxygen from the bottom waters. The stratification prevents replenishment of this oxygen from the surface layer (and the atmosphere), and it is frequently observed that bottom-water oxygen concentrations gradually decrease through the summer until winter remixing of the entire water column allows replenishment of the oxygen deficit from the atmosphere. An important aspect of this is the total length of time that the water remains stratified (e.g. Greenwood *et al*., 2010). A longer stratified period will result in lower bottom water oxygen concentrations because of the extra time that the bottom water is kept isolated from the surface water and atmosphere by the stratification. The details and implications of reduced oxygen in shelf seas are discussed in the accompanying MCCIP Report Card on dissolved oxygen concentrations (Mahaffey *et al*., 2020).

Stratification caused by river/estuary outflows to the coast

Close to the coast, the strength of the tidal currents around much of the UK generates sufficient mixing to prevent stratification that would otherwise form due to the inputs of estuarine (low salt) water. Instead coastal waters tend to be vertically well-mixed, but with salt content gradually increasing offshore away from the estuaries. Two notable exceptions to this are the eastern Irish Sea (Liverpool Bay, influenced by the estuaries of the Dee, Mersey, Ribble, Wyre and Lune (Sharples and Simpson, 1995) and the Southern North Sea (influenced by the Rhine; Simpson *et al.*, 1993), where a fresher surface layer can form during weaker tidal flows (neap tides) but is then eroded when the tidal currents increase (spring tides). The development of stratification in these coastal areas can be associated with an increase in the transport rates of estuarine water and its constituents (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. Coastal stratification is also implicated in harmful algal blooms (Davidson *et al.*, 2014), and the development of reduced oxygen in the bottom waters (Greenwood *et al.*, 2010). 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.

2. WHAT IS ALREADY HAPPENING

Changes in the timing of stratification

In regions away from the coast that experience 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 occuring only from the late 1980s at an average rate of about 0.5 days earlier per year. These trends are weak, and there is currently no reliable indication that they are sustained. 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). 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.

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, in the western Irish Sea there is some suggestion of stronger stratification in the mid-1990s compared to the early 1980s (Young and Holt, 2007), though a 15-year period is too short a timescale to link this change to a climate warming mechanism. For the strength of stratification within regions influenced by freshwater; increased rainfall particularly in the summer, as in 2007–2009, does influence the strength of coastal stratification, but the evidence available does not indicate any clear trend visible against the background of strong inter-annual variability.

3. WHAT COULD HAPPEN IN THE FUTURE?

The first estimates of likely future changes in stratification were produced under UK Climate Projections 2009 (UKCP09, Lowe *et al*., 2009). Using weather scenarios provided by the UK Met Office, projections of the state of the UK coastal and shelf seas have been predicted for 2070–2098 and compared with the mean for the period 1961–1990. Further estimates were obtained from a 1980–2099 model simulation for the Regional Ocean Acidification Modelling (ROAM) project, part of the UK Ocean Acidification (UKOA) programme (Holt *et al*., 2018).

Changes in the timing of stratification

There is a broad projection across the North-West European Shelf seas of the onset of spring stratification occurring about one week earlier by the end of the century (Figure 2a). Similarly, there is a broad suggestion of the timing of the seasonal breakdown of stratification occurring typically 5–10 days later than at present (Figure 2b). 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), consistent with what would be expected in a world with warmer sea surface, though the length of that time–series is not viewed as sufficient to determine reliably whether the link is to a warming climate. Stronger wind events in spring could feasibly counter earlier stratification, but there are considerable uncertainties in how storm strength, frequency and tracks might alter in a warmer climate. The present best model predictions suggest that the net impact is for the length of the stratified part of the year to increase by about 10–15 days (Figure 2c), with later timing of winter re-mixing having a bigger influence that earlier dates for the onset of spring stratification. Long-term predictions are thought to be fairly robust as long as the dominant balance is between heating of the sea surface and tidal mixing. In shallower water, and closer to the coasts, meteorological and river-flow forcing become more important. Long-term regional predictions of wind and rainfall patterns are not yet well developed. For instance, changes in rainfall may alter the balance of stratification and mixing outside the estuaries, but predictive capability of climate-induced changes in rainfall patterns is as yet too weak to allow any reasonable assessment. There are also challenges in any modelling of freshwater-driven stratification. This is inherently more difficult to simulate correctly compared to stratification by heating because of the localised nature of the sources of freshwater and the need to model horizontal dispersion and mixing away from those sources accurately.

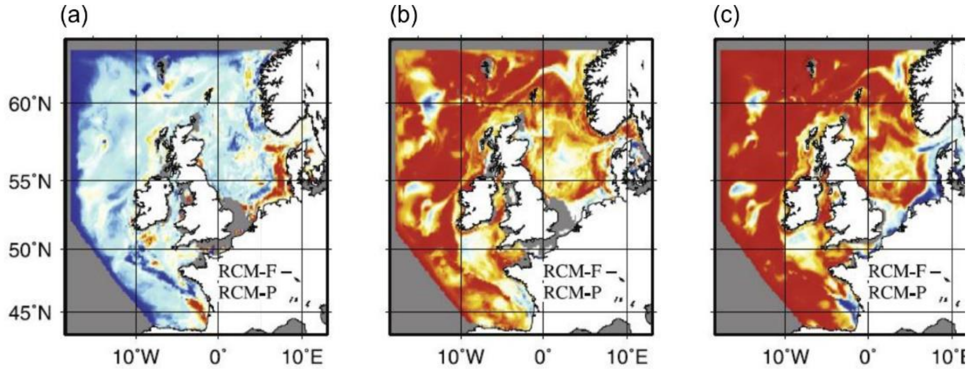


Figure 2: Comparison between present-day (1961–1990) and future (2070–2098) timing of stratification. The future prediction was based on a 'business as usual' climate projection (scenario SRES A1B). (a) Change in timing (days) of the onset of seasonal stratification. (b) Change in timing (days) of the autumn/winter breakdown of stratification., (c) Change in the total number of days of stratification during one year. (From Holt et al., *2010.)*

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 become more strongly stratified (Figure 3). This is a result of changes in the seasonal heating cycle. The strength of stratification is here quantified in terms of the Potential Energy Anomaly (PEA), which is a useful measure of the amount of mechanical mixing energy required to completely mix a stratified water column. Over the shelf seas this prediction is for an increase in the potential energy anomaly of typically about 5 J m^{-3}, compared to values currently of about 30 J m^{-3}. This additional stratification can be understood perhaps by considering that removing 5 J m^{-3} would require an increase in average winds over three months of about 4.5 m s^{-1} (9 knots).

Note that the criterion for stratification used in Figure 2 is for a surface-depth temperature difference of >0.5 °C (equivalent to a PEA of about 8 J m^{-3}) sustained for longer than 10 days. This results in the central Irish Sea appearing stratified in the future (in particular see Figures 2c and 3b); this stratification is very weak but can persist for several weeks, though it does not occur every year. 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 role in determining stratification, knowledge of future rainfall trends is insufficient to allow useful assessments.

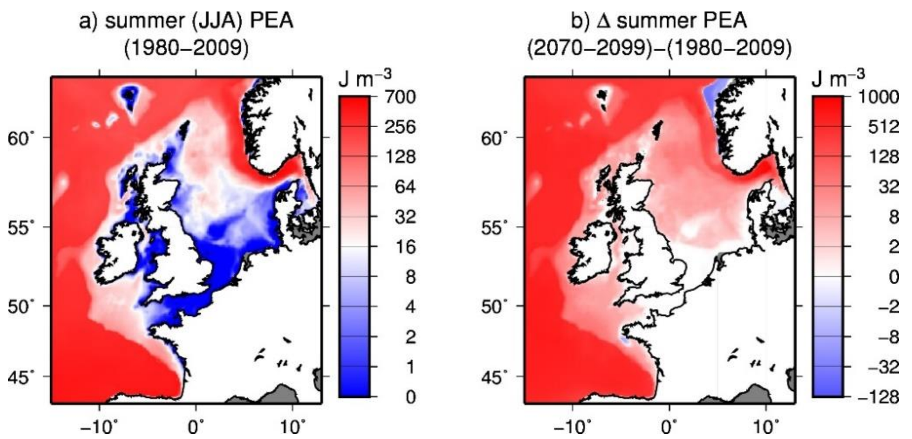


Figure 3: Present day and predicted strength of stratification. The unit used to measure stratification is 'Potential Energy Anomaly' (PEA) which is equivalent to the amount of energy required to completely mix the water column. (a) Present-day average strength of stratification. Note that the blue areas (zero PEA) are the regions with strong tidal flows that do not stratify (see also Figure 1). (b) Predicted change in stratification towards the end of the century. (Wakelin et al.*, in prep.). Future projections are based on the high greenhouse gas emissions scenario RCP8.5.*

Detailed changes at selected locations

Further climate-driven trends are also apparent when considering the more-detailed behaviour at representative points across the North-West European Shelf (Figure 4). The 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 winter re-mixing are also clear (Figure 4, compare left and right panels).

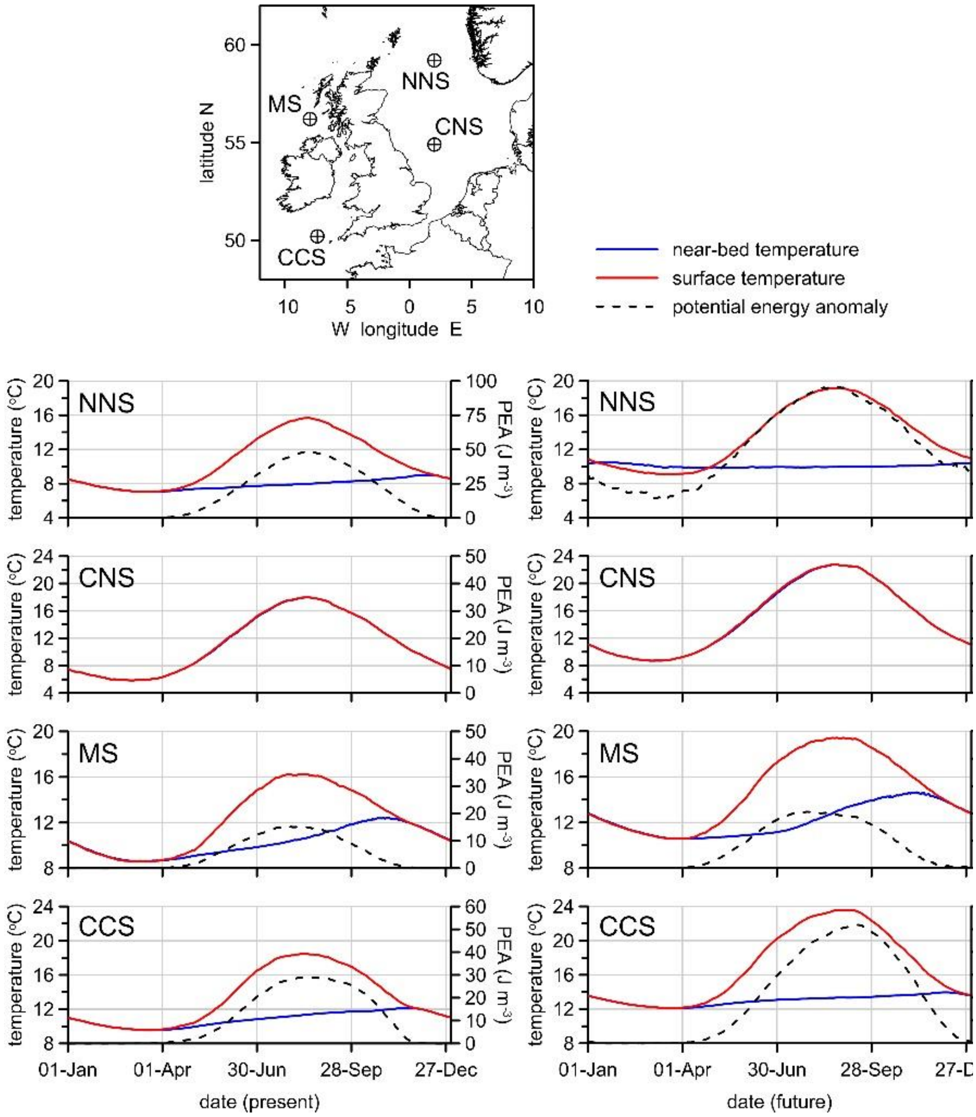


Figure 4: Examples of changes in stratification at four sites on the NW European shelf: northern North Sea (NNS), Malin shelf (MS), central North Sea (CNS) and central Celtic Sea (CCS). The map illustrates the sites positions; the plots show the annual changes in temperature and the potential energy 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).

Three other aspects of climate-driven changes are highlighted in Figure 4:

(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, warms 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.

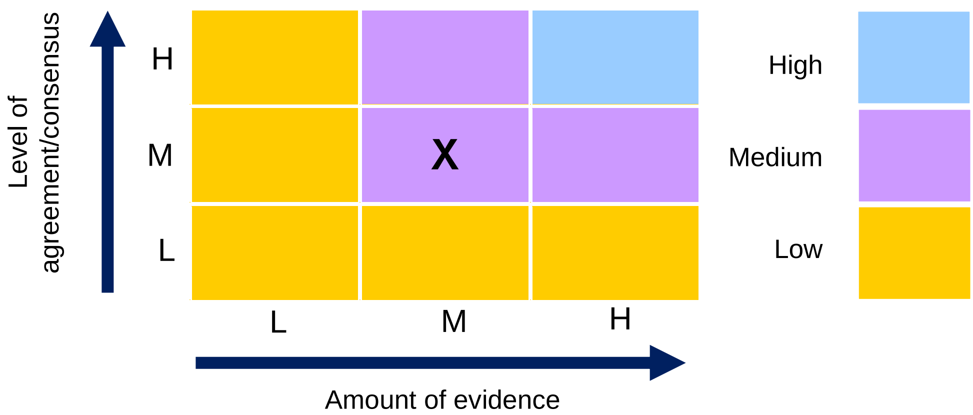
(2) The strength of the stratification is significantly greater in the future predictions for the three locations that stratify in the summer, though significant regional differences are apparent. Again, using the potential energy anomaly as a measure of stratification strength, the central Celtic Sea peak stratification increases from about 30 to 50 J m^{-3}, the Malin shelf from 15 to 20 J m^{-3} and the northern North Sea from 50 to 90 J m^{-3}.

(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 temperature differences in summer and salinity differences in winter.

There is 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 help to offset this. Extending the period of stratification will likely result in further reduction of bottom water oxygen concentrations (see accompanying MCCIP Report Card on dissolved oxygen, Mahaffey *et al.*, 2020), which will be exacerbated by lower initial oxygen concentrations in winter arising from a warming sea.

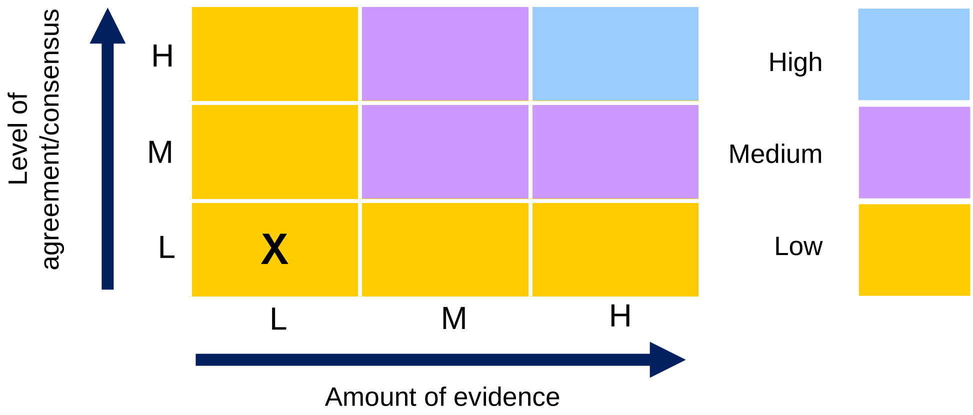
3. CONFIDENCE ASSESSMENT

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. There is a need for better long-term data on stratification, both to capture the onset/breakdown, the strength, and the relative contributions of heating and salt. Observations require both long-term sustained moored instrumentation and regular ship-based sampling of key sites. Coastal stratification caused by freshwater inputs is particularly difficult to assess because of a lack of consistent long-term 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. Updates to these predictions are currently in progress. 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 in the predictions arise from (1) these are the first predictions available, and (2) predictions particularly of the strength of stratification are determined by changes in regional meteorology, which is a challenging aspect of future climate projections, and (3) stratification caused by salinity changes is much more difficult to model than that caused by surface heating/cooling.

4. KEY CHALLENGES AND EMERGING ISSUES

Knowledge challenges

1. We need to improve knowledge of how regional patterns in rainfall and winds will change over the next century.

2. Assessing present changes and trends is hampered by a lack of suitable data: there is a need to rejuvenate efforts in detailed coastal observing in order that (over the next one or two decades) we reach a position of being able to provide more confident assessments of what is already happening.
3. Model skills in simulating salinity, processes at the edge of the continental shelf and in coastal regions influenced by river inflows or are intermittently thermally stratified need to be improved. Predicted changes in stratification in the central North Sea and in the central Irish Sea could have important chemical and biological consequences, so better confidence is vital. Recent model developments following on from NERC strategic research programmes are beginning to address the issue of the shelf edge. Confidence in the modelling of shelf sea salinity is in general is much lower than in temperature.

Emerging issues

1. Stratification, both its strength and its duration, is now recognised as key to understanding changes in bottom-water dissolved oxygen concentrations (see MCCIP accompanying paper on oxygen by Mahaffey *et al*., 2020).
2. Mixing of water properties across the pycnocline, i.e. between the sea surface and the deeper water in a stratified water column, still presents major challenges for numerical models. Shelf sea biology and physics are very sensitive to this mixing.
3. Work is currently ongoing to assess new insights into the role of rainfall and of horizontal changes in salinity across a shelf sea in triggering spring stratification (arising from recent NERC-Defra strategic research programmes): this has major implications for the timing of stratification and for model predictions of stratification (because models are less skilful at describing salt distributions than they are at describing heating).

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