MARINE CLIMATE CHANGE IMPACTS PARTNERSHIP: SCIENCE REVIEW

*MCCIP Science Review 2013*: 67-70

Submitted June 2013
Published online 28 November 2013
doi:10.14465/2013.arc08.067-070

# Impacts of climate change on shelf sea stratification

Jonathan Sharples [a,b], Jason Holt [b] and Stephen R. Dye [c,d]

[a] *School of Environmental Sciences, University of Liverpool, Liverpool, L69 3GP, UK*
[b] *National Oceanography Centre, Liverpool, L3 5DA, UK*
[c] *Centre for Environment, Fisheries and Aquaculture Science, Lowestoft, NR33 0HT, UK*
[d] *Centre for Ocean and Atmospheric Sciences, School of Environmental Sciences, University of East Anglia, Norwich, NR4 7TJ*

**EXECUTIVE SUMMARY**

Temperature stratification over the NW European shelf seas is showing evidence of beginning slightly earlier in the year, on average. There is some suggestion of strengthening of stratification beyond the normal inter-annual variability. Trends in stratification in regions influenced by fresh water 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 1 week earlier than at present, and end 5 – 10 days later. The strength of the stratification over the whole NW European shelf seas is projected to increase in response to changes in the seasonal heating cycle. Changes to coastal stratification caused by inputs of fresh water cannot yet be predicted.

## INTRODUCTION

A region of the sea is "stratified" when a layer of less dense water sits 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 and erode the stratification (e.g. turbulence caused by tidal currents, wind, and waves). Because the water density is non-linearly related to temperature, increasing the temperature of both surface and near bed waters also increases the density stratification, even if the temperature difference is the same.

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 exchange of water. Any dissolved substance (e.g. nutrients, oxygen) or passive particle (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 impact on vertical exchange.

Over much of the UK shelf seas, away from river sources of fresh water, control of stratification largely resides with the strength of the surface heating by the sun (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 and so surface 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. The structure of this partitioning controls much of the average flows within the shelf seas (Hill *et al.*, 2008).

This shelf sea stratification is a fundamental control on biological growth in shelf seas. When stratification begins in spring the plankton trapped in the upper, well-lit water grow rapidly in the "spring bloom". This bloom is a short-lived feature, as the plankton rapidly consume the available nutrients in the surface water. Many other marine organisms time their breeding cycles to correspond to this sudden arrival of plankton. The timing of this event is controlled by the competition between the solar heating and the tides, 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 this key biological event.

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. Plankton growth continues at the bottom of the surface layer, in response to weak sunlight and a leakage of nutrients upward from the deeper water. Growth rates are low, but added up over the whole summer the total amount of growth is similar to that in the spring bloom (Sharples, 2008) and is believed to be vital in supporting the rest of the marine food chain after the spring bloom (Richardson *et al*., 2000). 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 (Pingree *et al*., 1975; Begg and Reid, 1996; Sims and Quayle, 1998). Stratification has been associated with a reduced oxygen level in bottom waters of open-shelf regions (Greenwood *et al*.; 2010, Queste *et al.,* 2013).

Close to the coast the strength of the tidal currents around much of the UK coast generates sufficient mixing to prevent stratification that would otherwise form due to the inputs of estuarine (low salinity) water. Instead coastal waters tend to be vertically well-mixed, but with salinity 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 (Souza and Simpson, 1996)), 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 many harmful algal blooms (Tett *et al*., 2003). 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.

It is generally appropriate to consider the stratification in these two broad geographical contexts: open shelf seas and near coastal regions of freshwater influence. While model results can provide a more regionalised view there is generally insufficient observations to corroborate this.

## 1. WHAT IS ALREADY HAPPENING?

### Changes in the timing of stratification

In regions away from the coast, which experience thermal stratification there is model based evidence of a recent trend to earlier stratification and blooms (Young and Holt, 2007) largely in response to warming air temperatures (Sharples *et al*., 2006). Spring air temperatures around the UK are now typically 1.5°C higher than they were in the early 1970s, but these changes are constrained by the light climate and the spring equinox. Trends in the timing of stratification in regions influenced by fresh water 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 (based on Sharples *et al*., 2006). There were no clear trends in the strength of the thermal stratification that could be separated from the inter-annual variability. However, recent analysis of temperature data from the ICES data base (Holt *et al.,* 2012a) shows that trends in surface temperatures (from 1985-2004) are significantly greater than trends in near bottom temperatures in the North Sea. This is only indirect evidence for an increase in stratification since the data do not resolve the seasons, but are supported by corresponding model simulations, which do show an increase in seasonal stratification.

Similarly, for the strength of stratification within regions influenced by fresh water; 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.

## 2. WHAT COULD HAPPEN?

The estimates of likely future changes in stratification have been 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 (Holt *et al.,* 2010). Simulations have also been carried out using an alternative climate model for the MEECE FP7 Project (www.meece.eu; Holt *et al.,* 2012b), showing largely similar results for the stratification on-shelf.

### Changes in the timing of stratification

There is a broad projection across the NW European shelf seas of the onset of spring stratification occurring about 1 week earlier. Similarly there is a broad suggestion of the timing of the seasonal breakdown of stratification occurring typically 5 – 10 days later. In both cases the dominant control is the increase in air temperature, which aids stratification. The net impact is for the length of the stratified part of the year to increase, by about 10 – 15 days. 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 forcing becomes more important. Long term regional predictions of wind and rainfall patterns are not yet well developed. For example, 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 fresh water and the need to model horizontal dispersion and mixing away from those sources accurately.

**Changes in the strength of the stratification**

Again, reliable predictions of change are limited to regions where the balance resides mainly with surface heating and mixing by tides. The model projections from UKCP09 and MEECE both suggest that the entire NW European shelf seas become more strongly stratified. This is a result of changes in the seasonal heating cycle and the water temperature being warmer. The MEECE simulations include a fully coupled ecosystem model which demonstrates a reduced nutrient flux across the thermocline in the summer arising from this increased stratification.

In the UKCP09 simulations, there is a marked change in the projection in the open ocean, where much larger increases in stratification result from changes in open ocean salinities. Closer to the coast where fresh water from the estuaries plays a role in determining stratification, knowledge of future rainfall trends is insufficient to allow useful assessments.

## 3. KNOWLEDGE GAPS

The top priority knowledge gaps that need to be addressed in the short term to provide better advice to be given to policy makers are:

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

b. Assessing present changes and trends is hampered by a lack of suitable data: there is a need to maintain the recent efforts in detailed coastal observing in order that (over the next 1 or 2 decades) we reach a position of being able to provide more confident assessments of what is already happening.

c. Model skills in salinity, at the edge of the continental shelf and in coastal regions influenced by river inflows or are intermittently thermally stratified need to be improved. Confidence in the modelling of shelf sea salinity in general is much lower than in temperature, both because of uncertainty in the forcing and in the internal model dynamics.

## 4. SOCIO-ECONOMIC IMPACTS

The socio-economic impacts of changes in shelf sea stratification are most likely to be felt through its role within ecosystem processes that may change the biological productivity of the ocean. This could further impact on society if the changes associated with nutrient cycling were to require alteration of the monitoring and management of inputs to the marine environment or lead to difficulty meeting legislative requirements on ecological or environmental status.

**a. Changes in the timing of stratification**

Some fish species rely on timing their spawning with the spring bloom, in order to provide first-feeding larvae with a supply of food (Platt *et al*., 2003). There are known links between changes in bloom timing and changes in seabird breeding success (Scott *et al*., 2006), mediated by the role of fish larvae and young fish as food for chicks. Intermittent stratification in shelf seas (e.g. by the spring-neap changes in tidal turbulence) can alter the amount of phytoplankton growth (Sharples, 2008). There is large potential for changes in the intermittent nature of coastal stratification (either thermal or due to fresh water) altering primary production.

**b. Changes in the length of time of stratification**

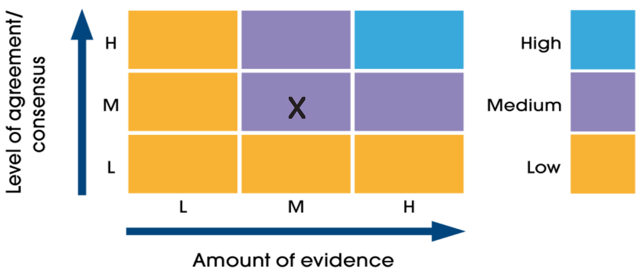
Changes in the amount of time that a region is stratified could have implications for annual primary production budgets and subsequently food availability to fish and seabirds, via the effects on growth of phytoplankton within the thermocline. Increasing the amount of time that a system remains stratified also impacts on conditions in the deep water. Stratification prevents efficient mixing of oxygen between layers. Utilisation of oxygen in the bottom layer (e.g. via the degradation of organic material by bacteria) reduces bottom water oxygen concentrations; increasing the amount of time that the bottom water is isolated from the sea surface will lead to lower oxygen concentrations, with the potential for negative impacts on benthic organisms (including important commercial shellfish); these effects could be pronounced. A recent survey (Queste *et al.,* 2013) shows the stratified regions of the North Sea at 75-80% dissolved oxygen saturation (compared with ~90% in well mixed regions) with some areas as low as 65%. An analysis of historical data from ICES suggests seasonal oxygen depletion has increased over recent decades (Queste *et al.,* 2013).

**c. Changes in the strength of stratification**

Stratification inhibits the transfer of substances between layers of the ocean. Stronger stratification will be more efficient at preventing these vertical transfers. On the shelf this could impact the growth of phytoplankton within the thermocline (by limiting the nutrients mixed into the thermocline), affecting the annual budget of primary production and ultimately the supply of food to the rest of the marine food chain. It will also impact bottom water oxygen concentrations (see point 2 above). This question is amenable to the work ongoing beyond UKCP09, for example the newly funded NERC DEFRA Shelf Seas Biogeochemistry programme. Mixing at the shelf edge has recently been implicated as a driver of key commercial fish stocks via its impact on phytoplankton communities (Sharples *et al*., 2009). Mixing at the shelf edge could be very sensitive to the strength of the stratification (though in this case it is not clear whether stronger stratification will lead to more of less mixing); this is the subject of further investigation in the NERC FASTNet Project (www.sams.ac.uk/fastnet/).

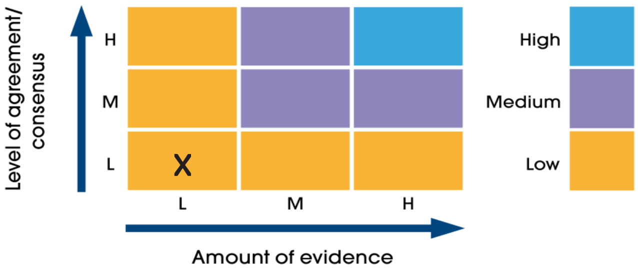
## 5. CONFIDENCE ASSESSMENT

**What is already happening?**




There is good agreement between the observation and modelling studies and good understanding of the basic controls of stratification, but only a moderate amount of evidence being available (there are no long-term time-series of direct observations of stratification).

**What could happen?**




There is broad confidence in the ability of the model to predict changes over the open shelf seas, though with some local uncertainties close to the shelf edge and in regions influenced by estuaries. The lack of confidence in the results arises from predictions, particularly of the strength of stratification, being determined by changes in regional meteorology, which is a challenging aspect of future climate projections. While more simulations are appearing and our understanding of the climatic drivers is increasing, there is not yet a sufficient treatment of the uncertainty to raise confidence levels above those given in the 2010.

## CITATION

Please cite this document as:

Sharples, J., Holt, J. and Dye, S.R. (2013) Impacts of climate change on shelf sea stratification, *MCCIP Science Review 2013*, 67-70, doi:10.14465/2013.arc08.067-070

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