Atlantification of the Arctic Ocean

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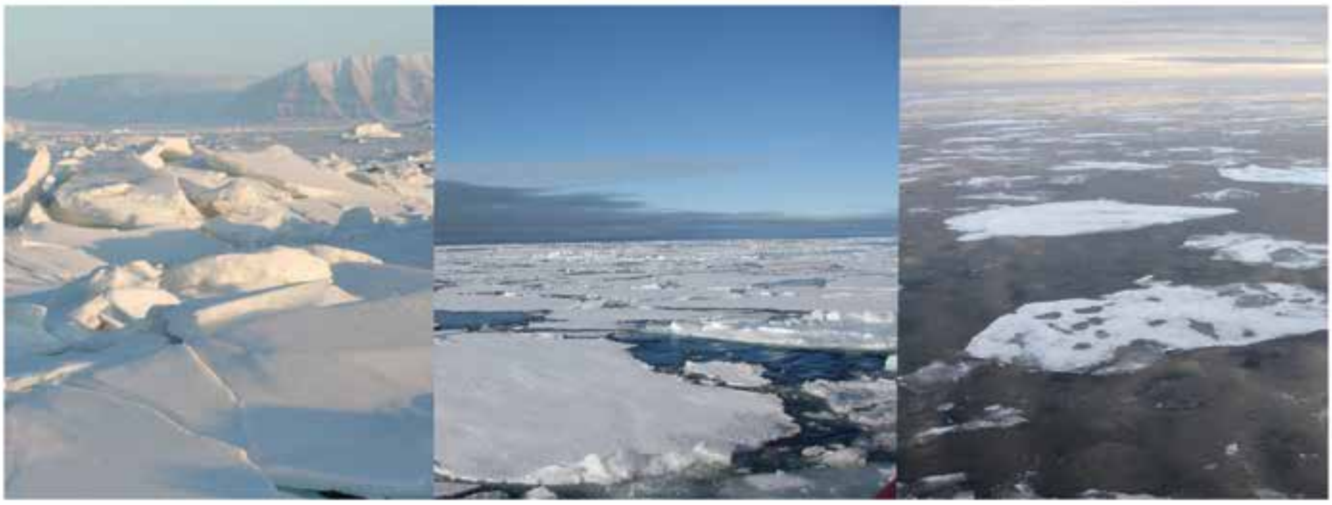
Atlantification of the Arctic



Tom Rippeth

The Arctic Ocean may be the planet's smallest ocean – its surface area is only 4.3% of the total for the global ocean – and it is situated many miles from the heavily populated mid latitudes of the Northern Hemisphere, but over the past decade and a half it has become a focus of interest on account of its rapidly changing climate. Air temperatures in the Arctic are increasing at twice the rate of the rest of the planet through a phenomenon known as Arctic amplification. Consequences include unprecedented heatwaves and wildfires over northern Europe and Siberia, declining sea-ice cover in the summer facilitating the opening up of new shipping routes, and the potential for new opportunities for hydrocarbon extraction across the far north. It is also possible that Arctic warming could affect weather in mid latitudes.

The Arctic Ocean's abyssal depths (Figure 1) are surrounded by shallow continental shelf seas, which occupy over 40% of its total area. Its main link to the global ocean system is to the Atlantic Ocean via the Fram Strait and the Barents Sea, with limited connections through the Canadian Arctic Archipelago, whilst the shallow Bering Strait provides a link to the Pacific Ocean. In oceanographic terms the Arctic Ocean is in some respects unique: the upper ocean density structure is dominated by changes in salinity (which increases with depth), and the ocean as a whole is relatively fresh compared with the other oceans because of the large river inflows. It also has very low levels of mixing in comparison with the oceans further to the south, not least because sea ice isolates the surface ocean from the turbulent atmosphere above.

Figure 1 *A map of the Arctic Ocean showing the locations referred to in the text together with the pathway of Atlantic water (red arrows) which enters via the Fram Strait and the Barents Sea; the change in colour from red to blue indicates the transformation of the Atlantic water as it is cooled and freshened as it flows around of the Arctic Ocean. Increasing widths of the current arrows indicate entrainment of Arctic water. Cooler, fresher Pacific water (mauve arrow) flows in via the much shallower Bering Strait.*
(From Lenn, 2009)

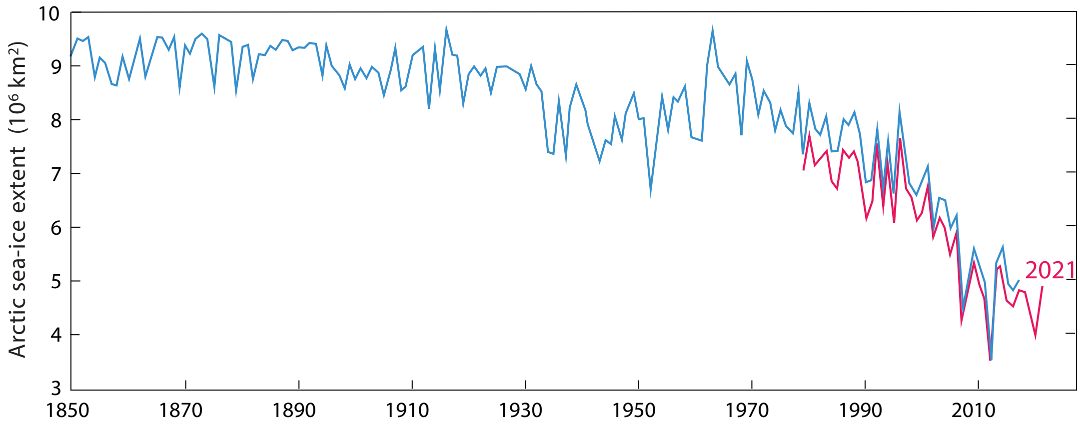


Figure 2 ***Blue plot*** *The variation in the average Arctic sea-ice extent for September (the annual sea-ice minimum area) since 1850, as estimated by Walsh* et al. *(2019) (see Further Reading).* ***Red plot*** *The variation recorded by satellite, from 1979 to 2021. (By courtesy of the National Snow and Ice Data Centre) (Combined plot based on a graphic by Zack Labe)*

Arctic sea-ice extent follows a strong seasonal cycle in response to the extreme seasonal cooling and heating cycle. In the cold of the perpetual darkness of winter, seasonal sea ice grows to cover much of the Arctic Ocean, and it then shrinks back in the 'midnight sun' of summer, reaching its minimum extent every September. The ice that survives the summer, referred to as multi-year ice, gradually gets thicker as a result of ridging and rafting, and seawater freezing on its underside. A conspicuous consequence of the warming of the Arctic in recent decades has been a decline in the extent of sea ice in the summer (Figures 1 and 2). Because less ice is surviving from year to year, the old multi-year ice is gradually being replaced by thinner seasonal ice.

Figure 2 shows how the September (i.e. seasonal minimum) sea-ice extent has changed since 1850. Satellite records over the past 42 years (red plot) have revealed an overall decline in the seasonal sea-ice minimum; it currently decreases by an average of 83 700 km^2 per year, which means that each year sea-ice coverage in September is on average smaller than the year before by an area equivalent to four times the size of Wales. This equates to a rate of loss of sea-ice coverage of 13.1% per decade, relative to the 1981 to 2010 average (National Snow and Ice Data Centre, 2021).

In September 2007 a new record was set with a particularly dramatic reduction in the area of summer sea-ice which hit the headlines globally. The *Independent* newspaper declared: 'Meltdown: Massive loss of Arctic ice means global warming now past point of no return', and there was much speculation in both the scientific community and the media as to whether the dramatic decline was due to a 'perfect storm' of environmental conditions, or to the system reaching a tipping point. Moreover, the seasonal minimum sea-ice extents for the subsequent 15 years were the lowest 15 on record.

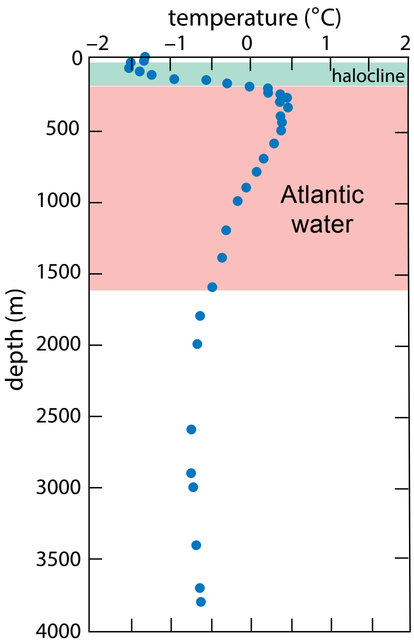
The declining summer sea-ice extent is thought to be a major contributor to Arctic amplification of global warming through an ice–ocean albedo feedback mechanism. The declining sea-ice coverage is facilitating increased ocean warming because dark open water (low albedo) is replacing highly reflective (high albedo) snow and ice, resulting in further ice retreat. This mechanism leads to increased open water areas in summer, with the warmer surface ocean leading to a later return of sea ice, impacting on both the thickness and extent of winter sea ice.

Whilst this feedback mechanism is forced by atmospheric warming, over the past decade or so interest has started to focus on the potential of the intruding warm Atlantic water to impact sea-ice thickness. The Atlantic water flows into the Arctic Ocean through Fram Strait and the Barents Sea as shown in Figure 1. This warm current was first observed by the Arctic explorer and oceanographer Fridtjof Nansen during the 1893–96 *Fram* expedition. He reported the observation in his record of the expedition, *Farthest North*:

> *'The hydrographic observations made during the expedition furnished some surprising data. Thus, for instance, it was customary to look upon the polar basin as being filled with cold water, the temperature of which stood somewhere about –1.5 °C. Consequently our observations showing that under the cold surface there was warmer water, sometimes a temperature as high as +1 °C, were surprising. Again this water was more briny than the water of the polar basin has been assumed to be. This warmer and more strongly saline water must clearly originate from the warmer current of the Atlantic Ocean (the Gulf Stream), flowing in the north and north-easterly direction off Novaya Zemlya and along the west coast of Spitzbergen, then diving under the colder, but lighter and less briny, water of the Polar Sea, and filling up the depths of the basin.'*

A profile of temperature taken by Nansen and his team is shown in Figure 3 (p. 19). The profile illustrates the laborious nature of the measurements made at that time, with 34 discrete water bottle samples, which took four days to collect. The profile was made in a water depth of 3850 m, north of the Laptev Sea (cf. Figure 1) and revealed the layer of intruding Atlantic water extending down to 1600 m, below a colder, fresher halocline layer.

Figure 3 *Profile of seawater temperature reported by Nansen (1897). It was taken over 4 days during 13–17 August 1894 at 81°5' N, 127°28'E through sea ice of thickness 3.17 m. The surface mixed layer below the ice is white. The region of the water column occupied by the halocline, in which salinity increases with depth, is shown in aqua, and that occupied by warmer, more saline Atlantic water is shown in pink.*



It is estimated that the heat associated with the intruding Atlantic water is sufficient to melt the sea ice covering the Arctic Ocean several times over. However, mixing across the halocline layer is weak, so it acts as a barrier to significant heat fluxes. Later high-resolution profile measurements revealed that across much of the Arctic the temperature and salinity structure across the lower halocline/uppermost Atlantic water shows sharp changes in temperature and salinity occurring every few metres depth. This is a consequence of the development of double diffusive convection leading to the formation of stepped temperature and salinity profiles or 'staircases' (see Lenn (2009) in Further Reading, and Figure 6 overleaf). These features are associated with cooler, less saline water overlying warmer, more saline water and can only exist in regions with low levels of turbulence. Furthermore, their presence implies only a weak leakage of heat from the Atlantic water towards the surface (< 1 W m^{-2}). A notable exception to this situation is the shelf-break region to the north of the Barents Sea and Svalbard, where strong tidal mixing prevents the formation of double diffusive convective staircases and greatly weakens the halocline barrier, leading to upward heat fluxes as large as 50 W m^{-2}.

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In recent years there has been growing evidence of the increasing impact of heat associated with the inflowing Atlantic water in melting sea ice from below and preventing its regrowth in winter. Warming of the inflowing Atlantic water by ~ 1 °C around 2005 has resulted in a retreat of winter sea ice out of the southern Barents Sea, with the southerly extent of the winter sea-ice coverage restricted to around 76° N, as shown in Figure 4.

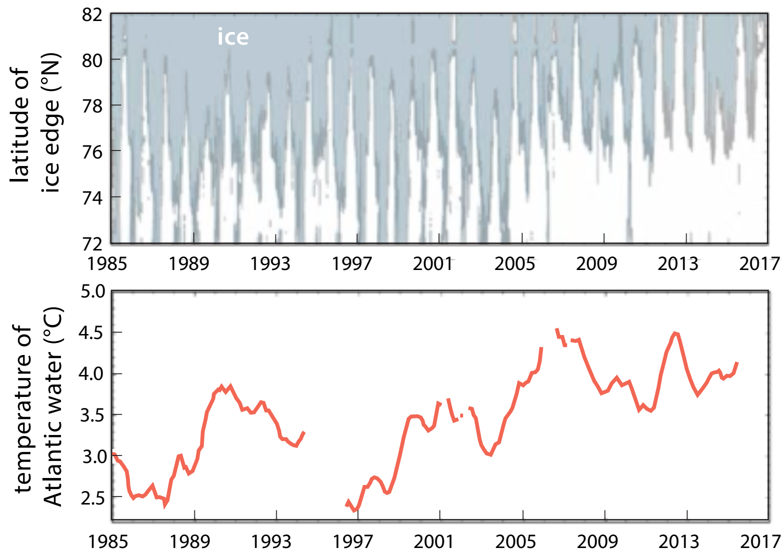

Figure 4 Upper *Variation in the latitudinal extent of sea ice in the Barents Sea between 1985 and 2017, together with* ***(lower)*** *the corresponding temperature of inflowing Atlantic water. (Redrawn from Barton* et al. *(2018) in Further Reading)*

Further to the east, annual CTD surveys to the north of the Laptev Sea, around the 125°E meridian, by the NABOS team led by Igor Polyakov at the University of Alaska, have revealed a warming and a shoaling of the Atlantic water coupled with a weakening of the halocline stratification in recent years. For example, a CTD profile taken in a water depth of 4000 m on 1 September 2018, approximately 40 km to the west of that reported by Nansen (Figure 5), shows that the Atlantic water temperature maximum has increased by over a degree, to > 1.5 °C, and occurs at a shallower depth, in comparison with that reported by Nansen.

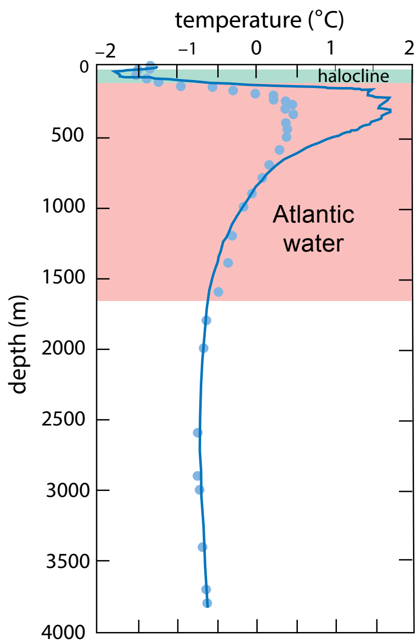

Figure 5 *Temperature profile taken in Sept. 2018, about 40 km to the west of that reported by Nansen, shown alongside in pale blue. Note that in 2018 Atlantic water was found at a shallower depth, below a thinner halocline layer, and its maximum temperature had increased from 0.4 °C to >1.5 °C.*

Further, the upward oceanic heat flux associated with the Atlantic water is estimated to have increased from 3–4 W m^{-2} (2007–2008) to > 10 W m^{-2} (2016–2018). As a result, over that time, the thickness of sea ice formed in winter in that region has decreased by more than half. Furthermore, mooring observations in the upper 50 m of the water column indicate that current speeds and associated shear have increased over this period, pointing to greater coupling between wind, sea ice and the upper ocean. The coincidence of the increasing upper ocean currents and weakening stratification suggests more turbulent mixing and a new positive feedback mechanism in which reduced sea-ice extent facilitates more energetic inertial currents, leading to enhanced mixing up of Atlantic water heat towards the surface, melting back ice further.

The changes documented in the eastern Arctic Ocean are summarised in Figure 6; today there is more open water, and thinner and more mobile ice, leading to increased wind-driven currents, which in turn drive turbulent mixing, which replaces the double diffusive fluxes. This, together with a resultant warming of the surface mixed layer, a weakening of halocline stratification, and a warming and shoaling of the Atlantic water, are resulting in increased Atlantic water heat fluxes. The net result could ultimately be a shift in ocean state in this region, towards that found further to the west, where strong turbulent mixing dominates the ventilation of the Atlantic water which in turn greatly restricts or prevents sea-ice growth. The changes in the eastern Arctic also highlight the key role of lower latitude processes (which set the temperature of the inflowing Atlantic water) in determining the future evolution of the Arctic Ocean.

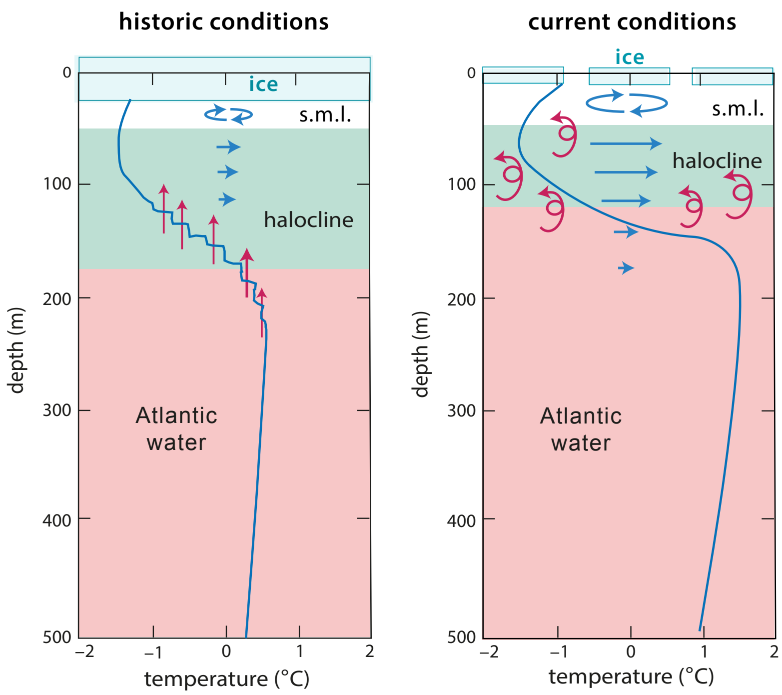

Figure 6 *Schematic diagrams of the uppermost 500 m in the eastern Arctic Ocean demonstrating the shift in recent years. Prevously, ice cover was extensive, the halocline layer was thicker, upward movement of heat was limited and was associated with thermohaline 'staircases' across the boundary between the halocline layer and the Atlantic water. Today the ice is thinner and more mobile, and there are stronger inertial currents in a warmer surface mixed layer (s.m.l.) with a thinner halocline, together with warming and shoaling of the Atlantic water and increased vertical mixing caused by stronger wind-driven currents, all conspiring to increase upward heat fluxes from the Atlantic water layer. (Redrawn from Polyakov* et al.*, 2020, in Further Reading)*

These new insights into the changing Arctic Ocean further highlight the complex relationship between stratification and mixing in the Arctic Ocean, where small perturbations in heat fluxes determine whether or not sea ice is able to form. The processes determining the water properties on the wide expanse of continental shelves around the Arctic Ocean are key to setting halocline stratification and yet are potentially most affected by sea-ice retreat. The high latitude, and hence marked Coriolis effect, imposes dynamical constrains on the rate of conversion of tidal energy to mixing, and also on the propagation of wind energy into the ocean through the generation of inertial waves. Identification of the energy pathways from both tides and the wind through the Arctic Ocean is therefore vital to the accurate parameterisation of the oceanic mixing processes which ventilate the Atlantic water.

The past decade or so has seen the increasing influence on Arctic sea ice of heat exported from the Atlantic Ocean into the Arctic Ocean. Within the eastern Arctic increased melting has triggered a new feedback mechanism whereby decreasing sea-ice extent is allowing an increased coupling between the atmosphere and ocean, which in turn is resulting in more relatively warm Atlantic water being stirred up towards the surface, reducing sea-ice extent further. The pernicious influence of the Atlantic water in this region is leading to a change in water column structure which could be viewed as a tipping point.

Further reading

The early measurements

Griffiths, G. (2004). Measuring ocean temperature. What can we learn from Nansen's experience on the *Fram* from a century ago? *Ocean Challenge* **14** (1), 24–8.

Lenn, Y.-D. (2009) How Atlantic Water is cooled in the Arctic Refrigerator. *Ocean Challenge* **16** (3), 28–31.

Lenn, Y.-D., PJ. Wiles and 13 others (2009) Vertical mixing at intermediate depths in the Arctic boundary current. *Geophysical Research Letters* **36** (5), L05601. doi:10.1029/2008GL036792

Nansen, F. (1897) Fram *over Polhavet. Den Norske Polarfærd 1893–1896.* Aschehoug and Co., Kristiania; published in English as: Nansen, F. (1898) *Farthest North*, George Newnes Ltd, London.

Polyakov, I.V., L. Padman, Y.-D. Lenn, A. Pnyushkov, R. Rember and V.V. Ivanov (2019) Eastern Arctic Ocean diapycnal heat fluxes through large double-diffusive steps. *Journal of Physical Oceanography* **49** (1), 227–46. doi: 10.1175/JPO-D-18-0080.1

Determination of past sea-ice extent

Walsh, J.E., J.S. Stewart and F. Fetterer (2019) Benchmark seasonal prediction skill estimates based on regional indices. *The Cryosphere* **13**, 1073–88. doi: 10.5194/tc-13-1073-2019

Atlantification

Barton, B., Y.-D. Lenn and C. Lique (2018) Observed Atlantification of the Barents Sea causes the Polar Front to limit the expansion of winter sea ice. *Journal of Physical Oceanography* **48** (8) 1849–66 doi: 10.1175/JPO-D-18-0003.1

Polyakov, I.V., A.V. Pnyushkov and 15 others (2017) Greater role for Atlantic inflows on sea-ice loss in the Eurasian Basin of the Arctic Ocean, Science **356** (6335), 285–91.

Polyakov, I.V., T.P. Rippeth and 9 others (2020) Weakening of cold halocline layer exposes sea ice to oceanic heat in the eastern Arctic Ocean. *Journal of Climate* **33** (18), 8107–23.

Polyakov, I.V., T.P. Rippeth and 8 others (2020) Intensification of near-surface currents and shear in the Eastern Arctic Ocean: A more dynamic Eastern Arctic Ocean. *Geophysical Research Letters* **47** (16), e2020GL089469. doi: 10.1029/2020GL089469

Schulz, K., M.A. Janout and 9 others (2021) On the along-slope heat loss of the boundary current in the Eastern Arctic Ocean. *Journal of Geophysical Research: Oceans* **126** (2), e2020JC016375.

Arctic Ocean turbulent mixing

Rippeth, T.P. and E.C. Fines (2022) Turbulent mixing in a changing Arctic Ocean. *Oceanography* (Special Issue on the New Arctic Ocean) **35** (2). doi.: 10.5670/oceanog.2022.103

Impact of Arctic sea-ice decline on weather

Screen, J. (2021) An ice-free Arctic: What could it mean for European weather? *Weather* **76** (10), 327–8.

Polar bears are not alone in facing challenging changes in the Arctic

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Tom Rippeth is the established Chair of Physical Oceanography at the Bangor University School of Ocean Sciences. He is an observational oceanographer who specialises in using measurements of turbulence in the ocean to identify the key processes driving oceanic mixing. His interest in the Arctic was initially encouraged by Sheldon Bacon and the late Seymore Laxon through involvement in the International Polar Year Arctic Synoptic Basin-wide Oceanography programme. t.p.rippeth@bangor.ac.uk

Fish can modify ecosystems too

An article in the last *Ocean Challenge* described how whales may engineer their ecosystem by using their huge bulk to mix the upper ocean. A recent study led by researchers from the University of Southampton has shown that fish may do something similar, though on smaller length scales.

The researchers were working in an area of upwelling off the north-west coast of the Iberian Peninsula, and were intending to study how vertical mixing affects marine life, using a microstructure profiler, which measures variations in current speed and temperature over vertical distances as small as a millimetre. Measurements were taken for two weeks, 24 hours a day.

It was a surprise when at night the microstructure profiler showed that in an area close to the vessel there was a 10–100-fold increase in turbulence and mixing similar to what might be caused by a major storm, although the weather was calm.

Further investigations, including studying signals from the ship's echo-sounder and deploying small fishing nets to sample the water, revealed the answer. The nets came up full of recently spawned eggs of the European anchovy, *Engraulis encrascicolus* – it was the energetic behaviour of large numbers of anchovies coming together for night-time spawning that was causing the turbulence.

It had previously been thought that only turbulence and mixing caused by tides and waves would be significant in the ocean; it was assumed that turbulence caused by fish would produce minimal mixing because the eddies that fish generate while swimming are too small. While true in the open ocean, where seawater properties are more homogeneous, closer to land, where waters are more stratified, mixing by fish could be important in redistributing seawater constituents, e.g. stirring up nutrients, so promoting phytoplankton growth, and reoxygenating layers that had become depleted in oxygen.

Ed.

This study formed part of the REMEDIOS project and the results are described in Fernández Castro, B., *et al.* (2022) Intense upper ocean mixing due to large aggregations of spawning fish. *Nature Geoscience* **15**, 287–92. doi: 10.1038/s41561-022-00916-3