Restoring or maintaining the vertical mixing of oceanic waters

Aart Heesterman
Retired Senior Lecturer of the University of Birmingham, England
Email: arghees@btinternet.com

DOI: 10.29322/IJSRP.11.06.2021.p114102
http://dx.doi.org/10.29322/IJSRP.11.06.2021.p114102

Abstract: Currents generated by wind and the interaction of the rotation of the earth and the gravitational pull of the sun and moon give rise to horizontal surface movement of sea water. Two basic mechanisms that drive the vertical mixing of ocean waters are reviewed in this article, the action of marine organisms and the regional differences in temperature and salinity. The latter mechanism is called thermohaline circulation. Upwelling of cold water of polar origin helps to prevent further warming of the surface of the tropical ocean areas. In doing so, it is also resulting in containing the development of more and stronger hurricanes. The cold water from the oceans' bottom also supplies minerals. For some areas of the tropical oceans there is no significant amount of mineral supply from other sources. Adequate supply of minerals is essential for life on the surface of the oceans. There was a time when marine animals diving deep into the oceans and returning to the surface made mixing of surface water with water deeper down happen supplies the required minerals to the oceans' surface. However, humanity's large-scale slaughter of marine creatures, led to decimation of the sea life from the second millennium AD onwards. Before that marine life played an important part in the vertical mixing of the oceans.

The focus of this article is, however, on the need to maintain the vertical mixing of ocean water and its relation to the more recent issue of global heating. This is an issue where, it is argued here, a technological remedy is feasible.

Keywords: Oceanic Waters, Vertical Mixing, Marine Organisms, salinity.

Inadequate vertical mixing of the oceans

Waves and animals

Only about 40 metres of the top layer of the oceans is directly mixed by waves. (Wikipedia, 2021, Mixes layer, graph). We tend to think of whales as the prime deep diving sea animals. Indeed, Ponganis and Kooyman (2006) inform us that these can dive hundreds of metres and remain submerged for as long as an hour. Leatherback turtles and seals are also able to dive down to great depths (Macdonald, 2017). It isn't only warm-blooded animals capable of such deep diving feats, for example, the Portuguese dogfish can go down to over 12,057feet (or 3,864 kilometres), see PlanetAndSharkDivers, 2018.

Unfortunately, however, the services of animals in vertical mixing of sea water began in all probability to be compromised by a rapid increase in fishing and associated "efficiency" of humanity's capability to over- exploit marine life as early as the early eleventh century.

> "There is evidence that the capacity of these boats in Northern Europe increased concurrently with the expansion of marine fishing, growing from approximately 18 tonnes displacement around 1000 to 55 tonnes by 1025." (Roberts, 2007, p.29)

There is, in modern times a serious problem in that humanity's technological capability is threatening the sustainability of fish stocks in the ocean.

> "Life on Earth depends heavily on its magnificent and complex ocean ecosystems. But the seas are suffering from overfishing, loss of key habitat—such as coral reefs—and the depletion of important species from sharks to small fish that are the basis for the entire food web." (Pew Trust, 2021)

Modern overfishing is not even efficient in terms of providing fish for human consumption.

> "Abandoned, lost or otherwise discarded fishing gear (ALDFG) is a problem that is increasingly of concern." (FAO, 2009)

The attack on warm-blooded sea animals was, if anything even more ferocious than that on fish:

> "Eighteenth and nineteenth century paintings of northern whale fisheries are often filled with boats stretching from foreground to horizon. Thinking today about the empty desolation of northern seas, such scenes appear contrived more for artistic effect than meant as an accurate representation of reality. But the number of ships involved was extraordinary. In a forty-six period up to 1722, the holland whaling fleet alone numbered 5,886 ships." (Roberts, 2007: 94)

Humanity's attack on warm blooded marine animals was, if anything, even more reckless and wasteful than that on fish. The following quote was drawn from Priceonomics (2015)

> "[..] the majority of the animal's body is left behind on the blood-stained ice. Though channels exist for seal meat and oil, the animal's fur, which is processed, tanned, and fashioned into $4,000 luxury coats, is the sealer's crown jewel.
> Despite the attention it receives, the seal industry is quite small today, though this wasn't always the case. During its golden age, sealing was the second largest source of revenue in Newfoundland's isolated economy; [..]"

As to whales, Roberts (2015; 100) reports as follows:

> "A late nineteenth century map of waling grounds shows half of their total area already abandoned because the whales had already been hunted to the point of commercial extinction."

Thermohaline circulation

In addition to the part played by the natural sea life two other agents of vertical mixing of ocean water, are of major importance. Of these, the action of waves is, unfortunate as that may be for humans, becoming more effective: hurricanes are becoming stronger and more frequent in the greenhouse climate. However, this mechanism of vertical mixing of the oceans is limited to some 40 metres depth, or perhaps a couple of metres more now. As documented in the previous sub-section, mixing of ocean water by animals reached much deeper than this. However, a range of warm-blooded animals lives on fish, which need oxygen as well as minerals in the water to survive

Oxygen is supplied by algae (microscopically small plants) to the very top layer of the water, but not to the deeper parts of the sea. Warm blooded marine animals can derive the oxygen they require from the air above the water, but fish cannot. When animals die after spending their lives in the top layer of the oceans, their bones sink to the bottom, enriching its mineral content.

As there is animal life everywhere in the top layer of the oceans, albeit concentrated on the coastal areas, the balance of the minerals content of the top layer of the oceans requires a corresponding supply from elsewhere. This may be from river runoff in coastal areas, while it could be from wind-blown dust in other regions. However, - it's a reasonable assumption that in other mid ocean areas a major part of the supply of minerals is the result from upwelling from deeper parts of the oceans as part of the thermohaline circulation.

The typical depth of the oceans is some four to eight kilometres. This means that much of the open ocean can only supply the minerals which sustain life if there is another mechanism capable of mixing the surface water with the deeper bottom layers. There are actually two mechanisms which possess this capability under certain circumstances. The first is caused by evaporation in the warmer parts of the earth with the water being transported poleward in form of vapour. The result is that the remaining surface water becomes more saline than the deeper water, where upon this heavier water begins to sink to the bottom. The other relates to the sinking of cold water in in colder parts of the oceans.

Broecker (1981) generally refers to the sinking of cold water whilst Toggweiler and Key (2001) appear to have added the detail that separation of sea water into freshwater ice and a more salty, brine-like remaining water during the winter causes the latter to sink to the bottom. It is doubtful whether cold water on its own actually led to sinking of water. Colder parts of the oceans, and in particular the polar areas have a surplus of precipitation over evaporation. Toggweiler and Key correctly point out that it is the seasonal winter separation between the surface and ice, which causes the remaining brine to sink to the bottom. Open ended loss of salt in the polar parts of the oceans, appears to have been the case during the late Cretaceous, when the Arctic Ocean was a suitable habitat for crocodiles (New Scientist, 2008), but as yet - the poleward flow of water vapour and its associated latent heat does not dominate over the horizontal movement of ocean water as driven by the earth's rotation.

Due to the sinking of cold salt brine the deeper parts of the oceans are very cold and the upward flowing side of the overturning of sea water provides the minerals to the oceans' surface. However, if the surface of the ocean is less saline than the deeper parts a stable configuration arises which acts as a barrier to water mixing. Such a stable configuration impacts the efficiency of vertical exchanges of heat, carbon, oxygen and other constituents. (Li et al, 2020)

The contention that, as Li et al seem to think, sea water is *generally* stratified needs qualifying. Firstly, there is a significant difference between parts of the oceans near the shore, and more specifically those within striking distance of centres of population, and the open ocean well away from coastal areas. Forests underlain by a significant layer of humus or sand, as well as large bodies of water are able to absorb a sudden rain shower locally. This does not, however, apply to cultivated land, and even less to impermeable sealed-off and concreted-over surfaces. Much of the rain falling in populated areas on land during an intense shower will therefore end up in the sea because of river runoff. As a result coastal waters tend to be less saline than mid-ocean areas.

Unfortunately, global heating is leading to a loss of stratification in the Arctic Ocean in particular, even whilst vertical mixing in the tropics is, if anything, increasing. This is because increased evaporation from warmer oceans gives rise to more disturbance increased surface salinity and density because of the salt content.

The general pattern of atmospheric air circulation is that warm air above the tropical ocean rises and flows poleward in the troposphere. The air above the tropical ocean is lighter than that over colder areas. This is the case both because all gases expand and therefore become lighter when warming as well as capable of containing more moisture, because warm air can hold more water vapour than cold air can, while water vapour is much lighter than the dry gasiform components of air, oxygen and nitrogen. A corresponding downward flow of air in colder parts of the earth combined with a low level return towards the tropics is implied. As colder air is unable to hold as much water vapour as warm air, the downward flow of the warm air originating from the tropical ocean is associated with precipitation. The counterpart of this precipitation is a net equatorward flow of water in liquid form, both over land and in the oceans. The resulting profile of salinity and water temperature of the oceans can be quite different, depending on the depth of the equatorward return flow of water. During the Quaternary geological period before humans began to put their stamp on the planet, both in the Arctic and Antarctic oceans the separation of freshwater ice from much saltier remaining brine-like amount of water, which used to sink to the bottom during the winter appears to have been a fact: There is no other plausible explanation of the low temperature of deeper parts of the oceans. The clearest example of this cold water in the deeper parts of the oceans is Antarctic Bottom Water, for which Wikipedia (2021, Antarctic bottom water) indicates that its temperature is at least in some sites lower than the freezing point of fresh water. For a general map see Wikipedia, (2021, Thermohaline circulation). For a relatively recent reference to this mechanism, see Marzocchi and Jansen (2019).

I argue that during the Quaternary, downward sinking of brine, due to the separation between freshwater ice and a remaining layer of much saltier water and a matching equatorward retour flow of water in liquid form used to be over the bottom of the oceans as was the situation during the Quaternary. However, whether the process of brine-like water sinking to the bottom is still taking place, and if so, how long this will last, is another issue. Guarino et al (2020) report that according to their application of the UK Hadley Centre HadGEM3 model, the Arctic Ocean was seasonally ice free during the previous (Eemian) interglacial period. A major reason why the Arctic Ocean is likely to have been seasonally ice-free at the time during would appear to the self-enhancing feedback of the change from sea ice covered in snow which reflected most of the incoming sunshine back into space to open sea water that absorbs it. The summer loss of sea ice implies a significant air temperature increase over the Arctic Ocean. Note also that warmer air can contain more water vapour, and can therefore transport more latent heat from the tropical climate zone to the Arctic climate zone via precipitation. In addition, this implies for a transitional period, a reduced salt content of a top layer of the Arctic Ocean, in particular to a depth of, let us say, a couple of hundred metres. This top layer of reduced salinity may well have resulted, and could result again in a situation where, even if a couple of metres of (freshwater) ice freezes out, the remaining liquid water is still less saline than the deeper parts of the Arctic Ocean, and does *not* sink to the bottom. If so, the collapse of the Northern stretch of the thermohaline circulation is bound to follow.

What can be done

The enhancing feedback of a collapsing Northern arm of the thermohaline circulation can largely be avoided by quite a limited form of climate engineering. There is, we hope, still enough salt in the top layer of the Arctic Ocean to make it possible to largely maintain or restore the Northern arm of the thermohaline circulation by means of breaking any remaining ice in the midst of the Arctic Ocean each year at the onset of the 24 hour winter polar night.

This is likely to imply that poleward transport of water vapour with its latent heat via the atmosphere does not reach to any significant extent that far North: Cold air is also dry air. Restricting this operation to a latitude and time of the year when there is locally no sunshine would not affect the earth's albedo in any direct way, but it would help to contain the carbon dioxide content of the atmosphere. Carbon dioxide is also removed from the atmosphere by plants, but direct absorption by the oceans is at its most effective in the polar climate zone (Ref?:). All gases, including carbon dioxide, are more soluble in cold rather than in warm water. Whilst nature does do that job for free, albeit only to a limited extent, the technology of direct capture of carbon dioxide from the air is expensive because of its energy requirement:

> "The CO_2 in the atmosphere is much more dilute than, for example, the flue gas from a power station or a cement plant. This contributes to the higher energy needs and costs for direct air capture relative to other CO_2 capture technologies and applications." Wikipedia (2021, Direct air capture)

However, clearly, if rapidly reducing the carbon dioxide content of the atmosphere, rather than just containing emissions is what we need to aim for, direct air capture is the only option. Once humanity has failed to contain emissions more timely, spending a significant amount of renewable energy on direct air capture may be the only way to make rapid reduction on the CO_2 count a reality. However, breaking open the central part of the Arctic Ocean would keep the thermohaline circulation going even with the currently elevated level of atmospheric carbon dioxide content.

As to the technical feasibility and economics of braking open a part of the Arctic Ocean, Smith and Stephenson (2013) reckon that the route from Rotterdam to the Bering Street via the north Pole is likely to be navigable by mid-century, i.e. around 2050, in September for moderately strengthened (class 6) ships. However, its year round navigability now is not a technical issue: Russian built nuclear powered ice breakers have no problem with that requirement:

> "During the winter, the ice along the Northern Sea Route varies in thickness from 1.2 to 2.0 metres (3.9 to 6.5 feet). The ice in central parts of the Arctic Ocean is on average 2.5 metres (8.2 ft) thick. Nuclear-powered icebreakers can force through this ice at speeds up to 10 knots (19 km/h, 12 mph). In ice-free waters, the maximum speed of the nuclear-powered icebreakers is as much as 21 knots (39 km/h, 24 mph)." Wikipedia (2021, Russian icebreakers)

As to the availability of icebreakers with a suitable capability, Humpert (2020) informs us that, until the construction of the newly built Arktika, no Russian icebreakers were built in 30 years. In other words, the nuclear icebreakers referred to by Wikipedia above were all Soviet built.

Bringing ice breakers into the centre of the Arctic Ocean would of course require the creation of open water channels in the thinner ice cover nearer to the Atlantic Ocean and/or the Bering Street. The downward flow of cold air over the centre of the Arctic Ocean and the associated equatorward airflow towards warmer parts of the earth would then result in some of the thicker and heavier parts of the broken ice to be pushed into the thinner ice cover further south. There is an obvious way of verifying this: Have a go at it. Note, however, that any braking up of some of the thicker ice nearer to the pole could imply thicker ice floes drifting southward and with that, a need for icebreaker escort at places where the sea was at some stage navigable without icebreaker escort. I would also comment that the inclusion of Iceland in any polar shipping route would have major advantages, even whilst possibly requiring somewhat more fuel and therefore transport cost: It would make Iceland a suitable stop to take in renewable fuel. Synthetic fuel, using carbon dioxide and (geothermal) energy is produced in Iceland (Rapier, 2018). For that reason, including Iceland in the route could be preferable to other routes. A route via Iceland and the Northern coast of Canada might (or might not) imply some additional commercial cost of fuel because it is slightly less bee-line, but is also likely to avoid some of the thickest ice. It might also be attractive as a (summer) cruise route, under 24 hour daylight and views of the mountains and ice filled fjords of Norway and Northern Alaska. Such a holiday cruise modification of the polar shipping route might also prevent missions: Currently, people wishing to see Alaska can do so from Vancouver (Canadian Affair, 2021). But clearly for any Europeans wishing to have that holiday, the (financial and environmental) cost of flying over the Atlantic Ocean comes to it.

Obstacles against taking the required action

A United Nations report (UN news, 2021) warns that the actions and announced CO_2 reduction targets of national governments do not come close to the level of action needed to fight global warming. I have documented earlier (Heesterman, 2020) that replacing the use of fossil fuels by renewable forms of energy is technically straightforward. In addition, avoiding catastrophic climate change almost certainly requires the reduction of the unsustainably high level of the carbon dioxide content of the atmosphere in the long term. Unfortunately, however, the opposite is happening just now. The concentration of atmospheric CO_2 is now in thought to be nearly 50% higher than before the industrial revolution (Galey, 2021).

Senior executives of the oil industry were warned by an insider, a research scientist of Exxon Mobil, James Black, as early as 1977 that continued use of fossil fuels could have catastrophic results (Banerjee et al, 2015). However, instead of planning for an orderly shut-down of the industry, the response was a dis-information campaign (Mann, 2021). There is a well-known technology for removing both sulphur and carbon dioxide from the flue gas stream of fossil fuel burning electric power stations, known as amine scrubbing or amine gas treating. Whilst ammonia (NH_3) has three hydrogen atoms linked to one nitrogen atom, we speak of amines when one or more of the three hydrogen atoms are replaced by a more complicated group of atoms (Clark, 2004). Amines are the chemical compounds that are normally used to separate carbon dioxide from the rest of the flue gas stream of electricity generating plants that burn fossil fuel. They can be used time and again.

> “The resultant "rich" amine is then routed into the regenerator […] to produce regenerated or "lean" amine that is recycled for reuse in the absorber.” (Wikipedia 2021, Amine gas treating).

It is technically quite possible to apply this procedure to the atmosphere, but that is, as documented in Heesterman (2020) not happening on any significant scale. It also requires energy which should be in the form of renewable energy only, if any is going to be spent on direct air capture at all. However, although renewable energy production is increasing in many countries, its share has at 38 percent only barely overtaken that of fossil fuels at 37 percent, even in the area where it is most advanced, the European Union (Reuters correspondent Susanna Twidale, 2021, referring to Ember Energy, 2021).

Bringing back the carbon dioxide content of the atmosphere to a sustainable level is something that cannot be done just now. Currently, about 17 percent of the energy of the incoming sunlight is reflected back upwards by the surface of the earth, including the oceans, and by clouds, whilst due to the greenhouse gas content of the atmosphere, only 12 percent of this energy is radiated back into space as infra-red heat energy (Wikipedia, 2021, Earth’s energy imbalance). To contain further global warming, it is necessary to restore the balance between incoming sunlight and outgoing infra-red radiation. Nevertheless, given the socio-political obstacles against taking effective action on decreasing the existing imbalance between the earth’s incoming and outgoing heat flow mitigating its catastrophic effects should be our immediate task.

There is, besides disinformation (Mann, 2021), a serious socio-political obstacle in that those in power as well as the wider public shy away from admitting that the climate crisis is something that might touch them personally: it is too uncomfortable to acknowledge (Willis, 2020, p.61). In addition it is plausible that the involvement of ruling political parties with fossil fuel companies and their contributions to electioneering clouds their decision making. However, implementing a techno-fix of as suggested below could contain global warming to some extent, while its implementation might not be as politically difficult to realise as more radical measures to contain climate change properly.

ISSN 2250-3153

The partial remedy

Avoiding the low salinity enhancing feedback of global warming could be simple: Break up a large area of Arctic Ocean ice and pump, if necessary, some deeper water towards the surface-while applying a measure of sunshading by injecting a suitable sunlight reflecting substance such as finely ground sulphur into the stratosphere. This will enhance winter freezing out of the top layer of the ocean and would to a significant extent restore the way the ocean water circulates and mixes as modelled by Broecker (1991). The main reasons why this type of action would amount to only a partial containment of the adverse effects of humanity's interference with the natural earth are as follows: As far as the circulation and vertical mixing of the ocean water is concerned, the absence of a large area of relatively thin ice cover that could easily be broken open makes its application in the sea area near Antarctica problematic. In addition, humanity's onslaught on the natural earth is much broader than the physics of ocean circulation.

In any case, there is some tension between this partial remedy of containing further enhancement of global warming and the implied defence of sunshading to in particular the ***tropical*** climate zone that appears to be implied by Vattioni et al (2019). I have no quarrel with their modelling of the effectiveness a particular method of reducing the amount of incoming sunlight, but I question its relation to what they cite as its purpose:

> "Stratospheric sulfate geoengineering (SSG) could contribute to avoiding some of the adverse impacts of climate change [….] sulfur was continuously emitted at an altitude of 50 hPa (≈20 km) ***in the tropics and subtropics***. " (italics added)

Sulfate geoengineering amounts to weakening the incoming sunlight (sunshading) and it may well mitigate some of the symptoms of climate change, but its application to the tropical and subtropical climate zone is less than helpful in relation to the thermohaline circulation. This issue is correctly flagged by Li et al. It also adversely affects plant growth in the (sub)tropical climate zone, and is therefore at the expense of both food production and the storage of carbon dioxide in non-food plant material. In my opinion, researching the effectiveness of sunshading in the polar climate zone would be more relevant.

Direct support of natural carbon absorption and the enforcement problem

I need to make clear that I am entirely in favour of supporting the direct services of nature by activities such as restoring sea grass and kelp meadows in suitable shallow sea areas as well as planting trees. However, I doubt whether this will be sufficient. In addition, a direct attempt to curtail emissions could be backed up by fiscal measures by a "coalition of willing governments": taxing imports from outside countries according to their carbon component including their "embedded" carbon content, i.e. the emissions arising from their production in other countries. We urgently need both approaches.

References

Athropolis (2006): "A couple of tough ships" www.athropolis.com/arctic-facts/fact-icebreakers.htm

Banerjee, Neela; Song, Lisa and Hasekeyer, David; "Exxon's Own Research Confirmed Fossil Fuels' Role in Global Warming Decades Ago" Inside Climate News September 16, 2015 https://insideclimatenews.org/news/16092015/exxons-own-research-confirmed-fossil-fuels-role-in-global-warming/

Bennett, Mia (2019): "The Arctic Shipping Route No One's Talking About" *The Maritime Executive* https://www.maritime-executive.com/editorials/the-arctic-shipping-route-no-one-s-talking-about?__ac_lkid=3e7-cc58-1ee8-9f6d17170d5ecfa

Broecker, W. S.: "The Great Ocean Conveyor" *Oceanography*, 4:79-89, 1991 https:// www.tos.org/oceanography/assets/docs/4-2_broecker.pdf

Canadian Affair (2021): "Cruises to Alaska 2021 and 2022 Sale Now On" https://www.canadianaffair.com/holidays/canada/cruise-holidays?telephone=ppc&msclkid=34660cc6d0101b529c696c715e07a7ba&utm_source=bing&utm_medium=cpc&utm_campaign=CA_Cruises%20Alaska_Top&utm_term=%2Balaska%20%2Bcruises&utm_content=Alaska%20Cruises_BMM

Clark, Jim (2004): "Introducing amines" Chemguide https://www.chemguide.co.uk/organicprops/amines/background.html

Crockett, Zachary (2015): see Priceonomics at https:// priceonomics.com/the-business-of-seal-clubbing/

Ember Energy (2021): "EU leads on wind and solar electricity with double the world average share" https://ember -climate.org/global-electricity-review-2021/g20-profiles/european-union/

FAO (United Nations Food and Agricultural Orginiztion, 2009): FAO FISHERIES AND AQUACULTURE TECHNICAL PAPER No. 523
UNEP REGIONAL SEAS REPORTS AND STUDIES No. 185 Abandoned, lost or otherwise discarded fishing gear www.fao.org/3/i0620e/i0620e00.htm

Galey, Patrick (2021): "CO2 levels this year '50 percent higher than 18th century' " Phys Org 2021 https://phys.org/news/2021-01-co2-year-percent-higher-18th.html

Guarino, Maria-Vittoria; Sime, Louise C.; Schröeder, David; Malmierca-Vallet, Irene; Rosenblum, Erica; Ringer, Mark; Ridley, Jeff; Feltham, Danny; Bitz, Cecilia; Steig, Eric J.; Wolff, Eric; Stroeve, Julienne and Sellar, Alistair: "Sea-ice-free Arctic during the Last Interglacial supports fast future loss" (2020) Nature Climate Change vol 10, pp. 928–932 https://www.repository.cam.ac.uk/bitstream/handle/1810/309133/18887_2_merged_1594159790_asaccepted.pdf?sequence=1&isAllowed=y

Hamitt, Robert (2017): "Ice breakers: an overview" The polar connection https://polarconnection.org

Heesterman, A.R.G. "Containing the risk of catastrophic climate change". Clean Technologies and Environ Policy 22, 1215–1227 (2020). https://doi.org/10.1007/s10098-020-01868-1
https://www.reseachgate.net/publication/342250182_Containing_the_risk_of_catastrophic_climate_change

Humpert, Malte (2020): "Russia's new super icebreaker reaches the North Pole during ice trials" High North News https://www.arctictoday.com/russias-new-super-icebreaker-reaches-the-north-pole-during-ice-trials/

Li, Guancheng; Cheng, Lijing; Zhu, Jiang; Trenbrth, Kevin E.; Mann, Michael E. and Abraham, John P. (2020): "Increasing ocean stratification over the past half-century" *Nature Climate Change* 10 (12):1-8 https://www.researchgate.net/publication/344413534_Increasing_ocean_stratification_over_the_past_half-century

Mann, Michael (2021): "The New Climate War" Scribe, Nelbourne / London ISBN 978925938869

Macdonald, Jessica (2017): "Marine species" https://scubadiverlife.com/top-five-deepest-diving-animals/

Marzocchi, A. and Jansen, M.F. "Global cooling linked to increased glacial carbon storage entry/Mediterranean_Sea#Salinity_and_currentsvia changes in Antarctic sea ice". *Nature. Geoscience.* **12,** 1001–1005 (2019). https://doi.org/10.1038/s41561-019-0466-8

New Scientist 8 June 2008: "When crocodiles roamed the Arctic" httpas://www.newscientis.com/article/mg19826611-200-when-crocodiles-roamed-the-arctic/

Pew Trust (2021): "Ocean Conservation" https:/www.pewtrusts.org/en/topics/oceansPlanet SarkDivers (2018):

Ponganis, Paul J. and Gerald L. Kooyman, Gerald L. (2006): "How do deep-diving sea creatures withstand huge pressure changes?" *Scientific American* https:// www.scientificamerican.com/article/how-do-deep-diving-sea-cr/#:~:text=A%20SPERM%20WHALE%20can%20dive%20down%20more%20thanroutinely%20travel%20from%20the%20surface%20 Ito%20great%20depth.

Pricenomics (2015): "The Business of Seal Clubbing" https:// priceonomics.com/the-business-of-seal-clubbing/

PlanetAndSharkDivers (2018): "PORTUGUESE DOGFISH OR PORTUGUESE SHARK " https:// www.bing.com/search?q=diving+depth+of+potuguese+dogfishshark&cvid=50928c3839a14adc9367a2a2bf131b1c&aqs=edge.0.69i59j69i60j69i57j69i60l2j0l2.20958j0j4&FORM=ANAB01&PC=ASTS

Rapier, Robert (2018): "New Tech From Iceland Can Turn Carbon Dioxide Into Fuel" *Oilprice* https://oilprice.com/Alternative-Energy/Geothermal-Energy/New-Tech-From-Iceland-Can-Turn-Carbon-Dioxide-Into-Fuel.html

Roberts, Callum (Gai a, 2007): "The Unnatural History of the Sea" ISBN 13-978-1-85675-294-31-

Smith, Laurence and Stephenson, Scott R (2013): "New Trans-Arctic shipping routes navigable by mid-century" https://pubmed.ncbi.New Trans-Arctic shipping routes navigable by mid-century; https://pnas.org.content/pnas/early/2013/02/27/1214212110.full.pdf https://researchgate.net/publication/236043799_New_Trans-Arctic_shipping_routes_navigable_y_mid-century

Smithtonian Institute (2021): "Elephant Seals, the Champion Divers of the Deep" https://www.smithsonianmag.com/science-nature/elephant-seals-the-champion-divers-of-the-deep-1-35587919/#:~:text=Elephant%20Seals%2C%20the%20Champion%20Divers%20of%20the%20Deep,work%20to%20discover%20just%20how%20they%20do%20it

Toggweiler, J. R. and Key, R. M. (2001): "Thermohaline Circulation" Encyclopedia of Ocean Sciences, 2001

Twidale, Susanna (Reuters, 2021): "Renewables overtook fossil fuels in EU electricity mix in 2020: Report" https://reuters.com /us-eu-renewables-idUSKBN29T0T8

UN news (2021): "UN climate report a 'red alert' for the planet" https://news.un.org/en/story/2021/02/1085812:

Vattioni, Sandro; Weisenstein, Debra; David, Keith; Feinberg, Aryeh; Thomas, Peter and Stenke, Andrea: "Exploring accumulation-mode H_2SO_4 versus SO_2 stratospheric sulfate geoengineering in a sectional aerosol–chemistry–climate model" *Atmospheric Chemistry and Physics* 19 (2019) pp. Issue 7, Pages 4877-4897 https://hks.harvard.edu/publications/exp loring-accumulation-mode-h2so4-versus-so2-stratospheric-sulfate-geoengineering

Wan, Zheng; Ge, Jiawei and Chen, Jihong (2018): "Energy-Saving Potential and an Economic Feasibility Analysis for an Arctic Route between Shanghai and Rotterdam: Case Study from China's Largest Container Sea Freight Operator" Sustainability March 2018 10(4):921 https://www.researchgate.net/publication/323948532_Energy-Saving_Potential_and_an_Economic_Feasibility_Analysis_for_an_Arctic_Route_between_Shanghai_and_Rotterdam_Case_Study_from_China's_Largest_Container_Sea_Freight_Operator/references

Wikipedia (2021, Russian icebreakers) https://wikipedia.org/wiki/Nuclear-powered_icebreaker#:~:text=Russian%20Arktika%20-class%20icebreakers%20are%20used%20to%2

Wikipedia (2021, Mixed layer): https://en.wikipedia.org/wiki/Mixed_layer

Wikipedia (2021, Antarctic bottom water): https://en.wikipedia.org/wiki/Antarctic_bottom_water

Wikipedia, (2021, Thermohaline circulation): "Thermohaline circulation" https://en.wikipedia.org/wiki/Thermohaline_circulation

Wikipedia (2021, Direct air capture): https://en.wikipedia.org wiki/Direct_air_capture

Wikipedia (2021, Amine gas treating): "Amine gas treating" https://en.wikipedia.org/wiki/Amine_gas_treating#:~:text=Amine%20gas%20treating%2C%20also%20known%20as%20amine%20scrubbing%2C,plants%2C%20natural%20gas%20processing%20plants%20and%20other%20industries.

Wikipedia (2021, Earth's energy imbalance): https://en.wikipedia.org/wiki/Earth%27s_energy_budget

Willis, R. (2020). *Too hot to handle? The democratic Challenge of Climate Change*. Bristol University Press. ISBN: 978-1-5292-0602-9.