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## PERSPECTIVE

## It is high time we monitor the deep ocean

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## 1. Introduction

Seafarers have navigated the ocean for millennia, but the study of the deep ocean is more recent. Global subsurface observations were first recorded 150 years ago, during the Challenger expedition (1872–1876). Deep oceanography and seafloor mapping subsequently benefited from technological developments induced by the world wars, including submarines and sonars to detect them, which led to the need to know vertical profiles of ocean sound speed (hence density). In parallel, oceanographic instruments improved: early hydrographic measurements were collected laboriously using thermometers, buckets, and the like; instruments now automatically and rapidly record conductivity, temperature, and pressure at high precision as they profile the water column, either autonomously or from an electrically-wired winch. The International Geophysical Year 1957–1958 kicked off the effort to systematically measure the deep ocean, including studies of deep water renewal and oceanographic transects throughout the North Atlantic, Arctic, Nordic Seas, and Mediterranean. Observations collected during subsequent international programs, recently the Global Ocean Ship-based Hydrographic Investigations Program (GO-SHIP), have increased our understanding of the deep ocean's value as an anthropogenic carbon and heat sink, with adverse impacts including ocean warming, acidification, and sea level rise.

Human activities have other detrimental effects on the oceans. Fishing is extending ever deeper, with bottom trawlers scarring the sea-floor. Potentially even more damaging to the fragile deep sea environment is the prospect of mining there, which would destroy wide swaths of the sea floor including slow-forming black smokers and unique extremophile ecosystems (Williams *et al* 2022). The deep ocean has also

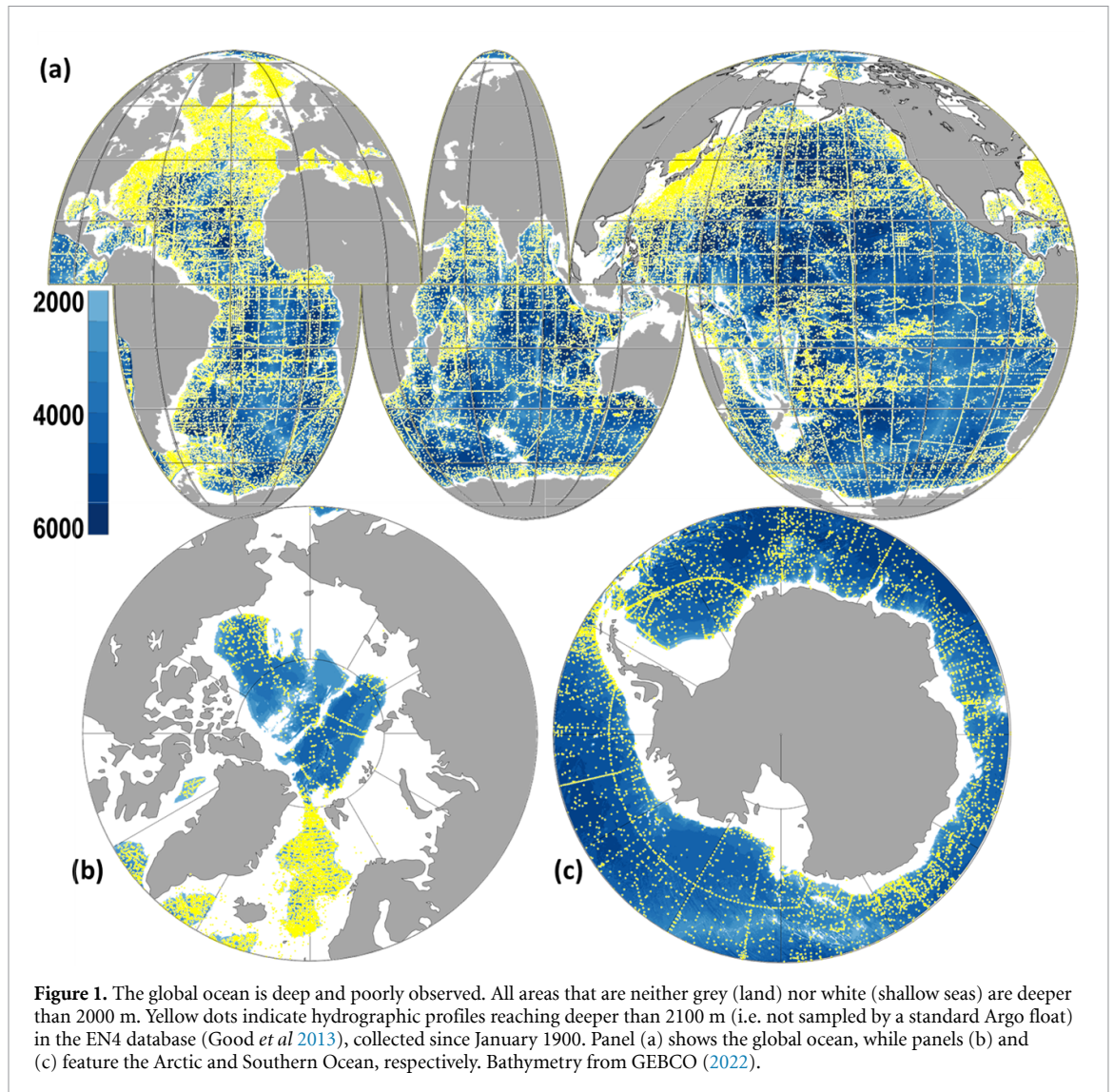
been used for waste disposal: up until the 1990s, nuclear waste was often disposed of in the deep ocean, and plastic waste has been found even at the bottom of the Mariana Trench. Assessing this damage to the deep ocean is difficult as it remains widely under-observed.

Below we review what we know about the roles of the deep ocean in climate science, argue that it is high time we turn our collective attention to this part of the climate system, both in observations and modelling, and suggest practical ways to start doing so now.

## 2. The deep ocean is the largest yet least observed component of the climate system

The deep ocean occupies a large fraction of our climate system. Earth's surface is 71% ocean, of which 79% is deeper than 2000 m (figure 1). Globally, the average depth is  $\sim 4000$  m, twice as deep as traditionally monitored by the Argo program, an array of  $\sim 4000$  autonomous profiling robots that measure the upper ocean's temperature and salinity (Roemmich *et al* 2019). The Arctic Ocean is the anomaly, with a shallow continental shelf occupying half of that ocean, but even there, depths reach 5500 m. Using oceanographic definitions, 'deep' waters such as North Atlantic Deep Water (NADW) and Antarctic Bottom Water (AABW) occupy the majority of the water column globally (figure 2; Johnson 2008).

Yet the deep ocean is extremely poorly observed. Fewer than 200 000 profiles reach deeper than 2100 m depth, only 3% of the 6.5 M profiles that reach at least 500 m. Their spatial distribution is unequal (figure 1): the bulk of the observations are in the North Atlantic, Mediterranean, and North Pacific, while entire regions of the tropics and high latitudes have never been measured. With research funding always tight, monitoring the deep ocean is often given low priority owing to (a) the high cost associated with



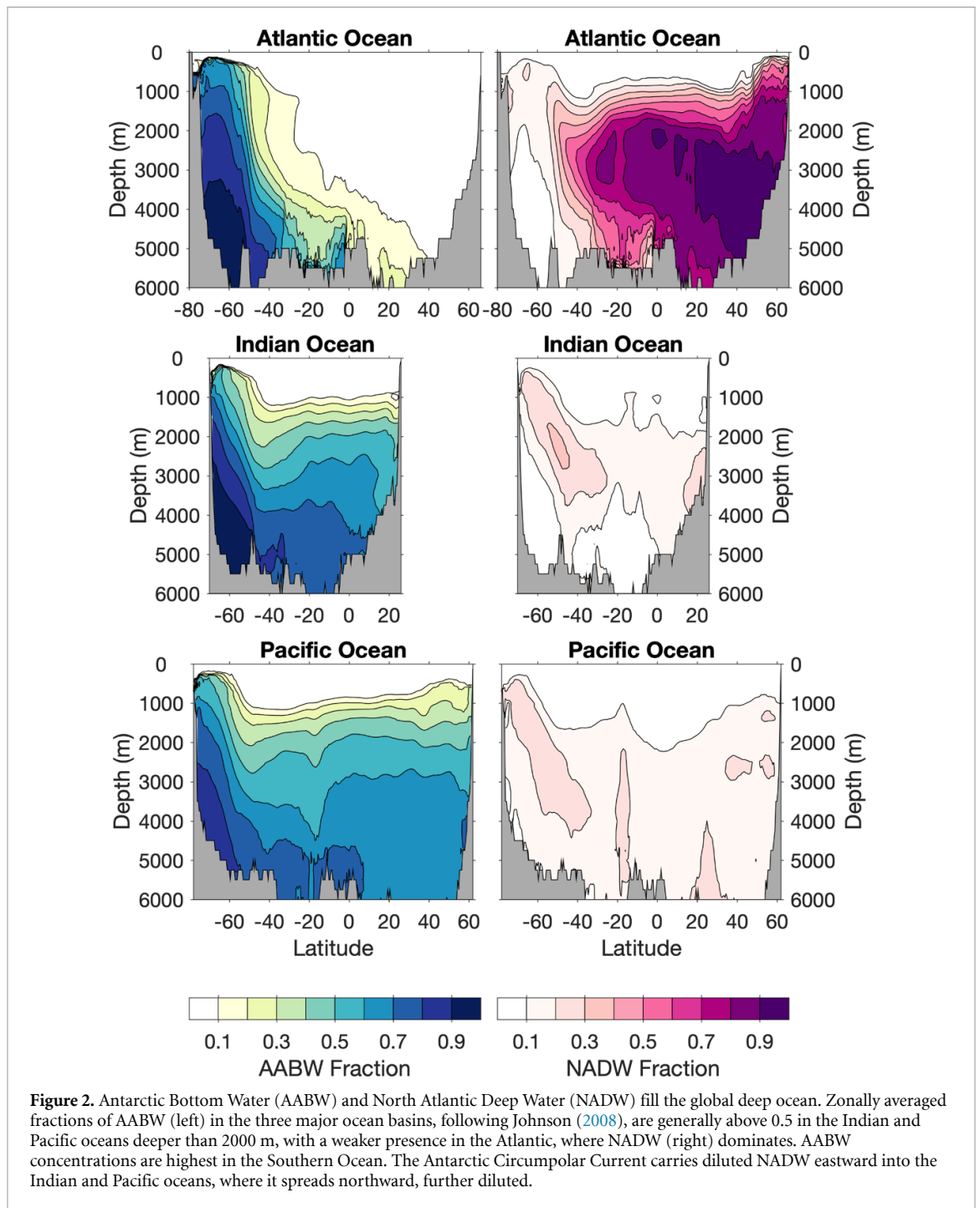
its remoteness and technological challenges of working in extremely high-pressure environments and (b) the historical perspective that the deep ocean is isolated and slow to change, thus needing less frequent observations. Recent studies have, however, shown that the deep ocean is an active part of our climate system capable of changing on short time scales. With deep Argo floats now reaching 6000 m (Roemmich *et al* 2019), it is high time we reconsider our priorities.

### 3. The deep ocean is changing, globally

From simple theoretical frameworks to complex data-driven state estimate models, it is well understood that the conditions at the surface ocean affect the deep ocean. NADW and AABW form as surface water becomes denser, via interaction with the atmosphere and/or ice, and sink to fill much of the global deep and abyssal ocean (figure 2). The Arctic (not shown) is filled from 200 m down by different flavours of

NADW, modified at many timescales from double-diffusive convection to entrainment (e.g. Rudels *et al* 2013). AABW and NADW feed the deep limbs of the meridional overturning circulation (MOC), circulating on time scales of a millennia. The MOC moves heat, freshwater, carbon, oxygen, and nutrients from surface to deep, between ocean basins, and affects weather and climate.

Recent observations are revealing decadal variability in the deep ocean with radical implications for our climate system. Over the past three decades, deep ocean basins around the globe have shown bottom-intensified warming trends, largest in the Southern Ocean, accounting for  $\sim 10\%$  of the total anthropogenic global energy imbalance and  $\sim 4\%$  of the steric sea level rise rate (Purkey and Johnson 2010). Near source regions of AABW in Antarctica, deep Argo and ship-based observations have shown year to year variability in the properties and quantity of AABW produced (e.g. Foppert *et al* 2021, Thomas *et al* 2020)



driven by surface forces on the shelf (Silvano *et al* 2020). A decrease in AABW formation rates can quickly drive deep ocean warming around the globe owing to a slowdown in the renewal of the cold deep waters, consistent with the signal we have recently observed (Purkey and Johnson 2012). Furthermore, an acceleration of deep warming has been observed in the deep Pacific (Johnson *et al* 2019).

In the North Atlantic, the formation and properties of NADW have shown intense interannual variability, with direct implications for Europe's climate. The meridional transport associated with the Atlantic MOC (AMOC) has begun to be monitored in some

locations (see [www.o-snap.org/](http://www.o-snap.org/)). Years with active deep convection see vigorous overturning, bringing oceanic heat north where it is exchanged with the atmosphere, while there have been years of little to no convection, set by local conditions. Paleo observations and models both suggest the AMOC can achieve alternative steady states, and the International Panel on Climate Change (IPCC) most recent assessment shows a highly likely weakening of the AMOC over the coming century due to anthropogenic forcing, although the magnitude is still unknown. Even the bottom of the Arctic Ocean has warmed four times faster than expected from geothermal heating alone



(Rudels *et al* 2013), and the deep Eurasian Arctic has been shown to be far more dynamic than previously believed, with large mesoscale variability and deep eddies (Rabe *et al* 2022).

#### 4. We cannot project future changes accurately

The global climate models currently used to project near- to long-term responses to ongoing climate change, or Climate Model Intercomparison Project phase 6 models (CMIP6, Eyring *et al* 2016), need observations for their design, tuning, and quality checks. The poorly observed deep ocean is therefore poorly represented in those models. For both AABW and NADW, the models exhibit strong and divergent biases in their water mass properties, formation process, transports, and extent (Heuzé 2021). Moreover, there is no strong improvement since CMIP5 (Heuzé 2021), or rather improvement of one aspect tends to lead to a stronger bias in another, because of past cancelling biases. The deep waters of the Arctic are even more poorly represented (Heuzé *et al* 2022). Consequently, very large uncertainties are associated with projections of deep water changes and their impacts on e.g. sea level rise, globally (e.g. Heuzé *et al* 2015).

Model geometry also plays a substantial role in these biases. Deep water formation can take place via two phenomena: deep convection, i.e. intense vertical mixing down to >1000 m, and dense water overflows, usually from a shallow continental shelf to the deep ocean. Deep convection is actively prevented by the models' global mixing scheme, as it is undesirable at all locations except the few high latitude areas where deep waters form. Similarly, overflows are stopped by standard vertical grid types combined with mixing schemes, which do not preserve that thin very dense layer but rather strongly mix it to dissipate it as it travels off-shelf. Besides, standard vertical grid types along with the global coupled models' relatively coarse resolution lead to a poor representation of the bathymetry, crucial for transport representation. In the North Atlantic for example, some models omit the Faroe Islands, others place them in the wrong location, which strongly impacts the poleward transport of heat by the deep Atlantic Water (Heuzé and Årthun 2019).

#### 5. What we need to do

The deep ocean is responding to climate change, delaying or mitigating its effects through heat and carbon sequestration, but consequently warming, expanding, and acidifying. Despite its importance, the deep ocean is not well represented in climate models, thus preventing us from projecting how it will respond in the future. For these reasons and more, the obvious first step is to obtain more data. As a community, we need to implement a global deep ocean

observing network that will adequately monitor the deep ocean's physical, chemical, and biological variability, as suggested by the UN decade for ocean science (e.g. Howell *et al* 2021), and its endorsed Deep Ocean Observing Strategy. From ships, we need to continue collecting high-quality full depth ocean profiles, including water samples of the biogeochemistry and tracer data, with systematic surveys such as those provided by international GO-SHIP ([www.go-ship.org/](http://www.go-ship.org/)), in addition to optimising ship time to allow for opportunistic full-depth casts. Most importantly, as we have learned from the upper ocean, to fully monitor the vast deep ocean and its variability, we must utilise autonomous measurement platforms. Deep Argo is now ready, offering the opportunity, for the first time, to monitor the full-depth ocean temperature and salinity globally and continuously in real time (Roemmich *et al* 2019). A global deep Argo array of 1225 floats, a third of the current traditional Argo fleet, would collect more full-depth temperature and salinity profiles in 5 years than are available now in historical archives. Enhanced data coverage from such an array would shed light on both the variability and mechanisms controlling it, allowing for integration into models, and hence more accurate decadal climate forecasts and longer-term climate projections.

Climate models likewise would benefit from a renewed focus on the deep ocean. Already large efforts are underway to better represent high latitudes, from latitude-dependent schemes to the implementation of interactive ice sheets allowing for more realistic modelling of deep ocean properties. Furthermore, overflow parameterisations (e.g. Danabasoglu *et al* 2010), non-standard vertical grids, and adaptive horizontal grids and nested models that allow for a higher resolution over regions of interest need to be evaluated.

Finally, as a society, we need to care about the deep ocean and the role it plays in our climate and ecosystems. We are obsessed about space exploration, yet we ignore this fascinating, mysterious, and challenging environment that helps to regulate our climate, shelters diverse life, and lies only a few kilometres away from our coastal towns, in the deep dark ocean.

#### Data availability statement

No new data were created or analysed in this study.

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