COMMENT

CONSERVATION How cold-adapted species respond to climate change **p.302**

ANATOMY Unpacking Renaissance artist Vesalius's drawings of the body **p.304**

RESEARCH PRIZE Controversy over all-male list of awardees **p.307**

OBITUARY Paul Delos Boyer, chemist who discovered tiny molecular motor **p.308**

ALEX MUSTARD/NPL

Fish and other marine life are affected by ocean weather: drastic variations in temperature, pH, oxygen and salinity that are in turn influenced by climate change.

Biologists ignore ocean weather at their peril

Ecologists must understand how marine life responds to changing local conditions, rather than to overall global temperature rise, say **Amanda E. Bates** and 16 colleagues.

The ocean can turn on a dime. Temperature, pH, oxygen levels and salinity can vary drastically — across distances of centimetres and within time frames of minutes[1–3]. That's the latest view being revealed by measurements from thousands of instruments anchored to shores or attached to floats, ocean gliders and ships.

Yet many people think of oceans as a relatively constant environment. That idea might have been hatched when researchers on the HMS *Challenger* expedition of 1872–76 tracked water temperature and currents and lowered weights to gauge depth at thousands of sites across the world's seas[4]. The global picture that emerged after averaging these data was one of stability, in which any variability had been lost. Certainly, that picture was reinforced by twentieth-century images of Earth from space, showing the world's ocean as a uniform deep blue[5].

Most biologists and ecologists trying to understand how ocean biodiversity is affected by climate change focus on large-scale averages across space and time. They try to predict, for instance, how a mean global temperature rise of 2 °C could affect marine ▶

▶ life such as bacteria, phytoplankton, fish and other creatures. To do this, they use projected changes in the mean temperature of the ocean. These are based on estimates from satellites, which measure the temperature of only the top few millimetres of seawater.

But organisms experience and respond to local shifts in 'ocean weather' that occur over weeks, hours and minutes, rather than to changes in climate per se, which unfold over years and decades (although long-term climate changes drive the short-term shifts). A handful of studies that attempt to investigate how local physical conditions affect species (including the numbers of individuals and types of species occurring) are beginning to show the value of a more detailed approach[6].

We call on ecologists to rethink their models and experiments. This would enable them to start linking changes in biodiversity to changes in conditions at the scales of space and time that are relevant to individual organisms.

OCEAN WEATHER

To get the most detailed picture of conditions across the ocean's surface and at depth, physical scientists are starting to combine high-resolution *in situ* measurements of temperature, salinity and so on with satellite data. Remote-sensing and continuous monitoring are revealing a highly dynamic environment, even in the open and deep oceans (see 'Watched waters').

For instance, circular currents, or eddies, occur throughout the ocean. Depending on whether they rotate in the same direction as Earth or counter to it, they can provide conditions that are rich or poor in nutrients — different habitats for different phytoplankton and other organisms[7].

The currents arising from eddies extend down 4,000–6,000 metres to the abyssal ocean, as 'benthic storms'. These resuspend sea-floor sediment, creating nutrient-rich regions at depth[8]. Likewise, tides, storms and strong currents affect mixing and change buoyancy throughout the water column, across scales ranging from centimetres to a few metres. This sets the stage for considerable variation in the amount of photosynthesizing life through space and time. And that affects entire food webs.

Nearer to shore, variability is even more dramatic. The temperature can shift by more than 10 °C in one tidal cycle or as the wind displaces surface water and cold water wells up from below (upwelling). Oxygen levels can swing from 0% to 100%, and pH can shift by more than one unit as microbes use up oxygen and as phytoplankton and plants generate it. Microsensors placed near organisms such as mussels have revealed that oxygen, pH and carbon levels can be highly variable, even on small scales of less than 1 millimetre. Extremes of these variables far exceed the projections made by the Intergovernmental Panel on Climate Change under various scenarios for a warming planet[9].

STORM FORCE

Why do ecologists generally ignore such ocean weather as a force that shapes biodiversity?

In our experience, there is a misperception among researchers that highly localized, rapid changes are irrelevant to understanding or predicting biological changes in marine systems. Spikes in temperature and other variables over hours or minutes are often dismissed as being 'extreme' or 'noise'[10]. A greater barrier, however, is obtaining the relevant data in a format that is accessible to biologists.

Satellite measurements of global temperature have been collected by space agencies such as NASA since the 1980s. And today, data on temperature trends, rainfall, cloud cover and other climate phenomena can be downloaded easily. They are available at gridded scales of tens to hundreds of kilometres, and often at yearly or monthly resolutions (see, for example, https://data.nasa.gov). Averaged ocean-relevant data tailored for ecological questions are also available from initiatives such as Bio-ORACLE, run by a team of marine researchers in Belgium, Portugal and Australia. However, the data generated by high-resolution ocean monitoring are much harder to access.

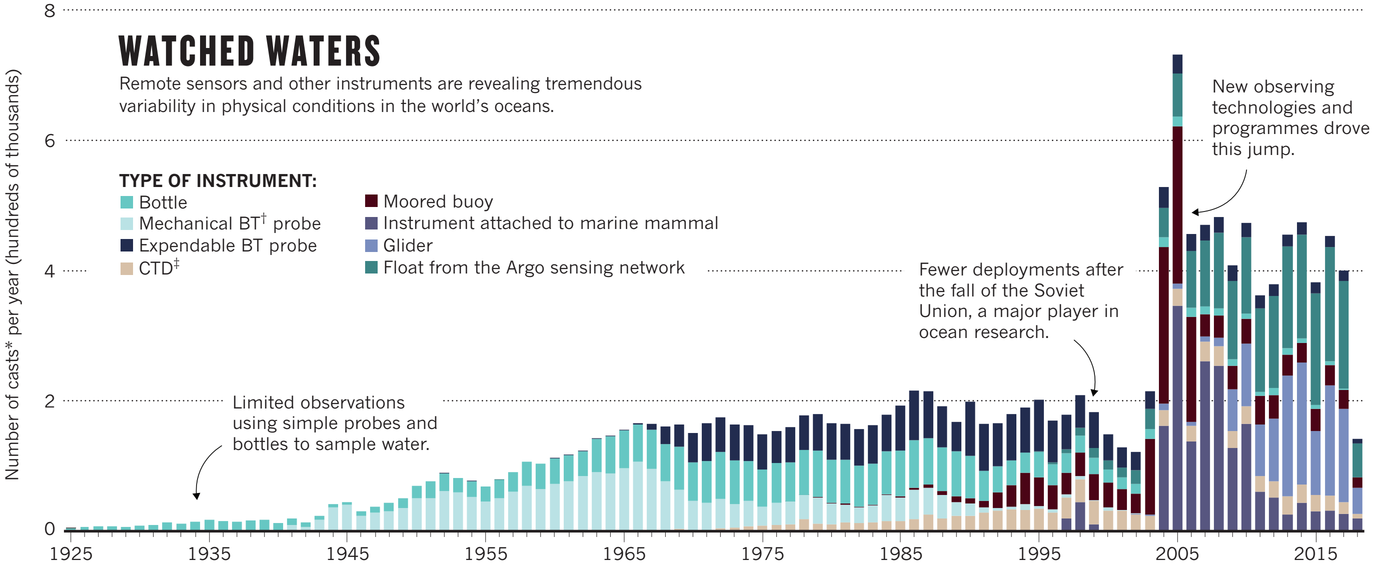
Such monitoring tends to be geographically limited, with the most intensive surveys occurring in waters where nations have economic interests and access. Even when the data have been collected, many ecologists do not have the computational skills or infrastructure to store and manipulate them. When one of us (A.E.B.) recently requested data from a national oceanography institute, for instance, an oceanographer provided a link to many folders. Each folder contained hundreds of files of temperature and other data collected from different time periods — too vast a resource to download on a standard computer.

TURN THE TIDE

This neglect of ocean weather in theory, experimental design and modelling is hampering progress in at least three ways.

Predictions are wrong. When ecologists try to forecast change by running experiments or using macroscale, simulation-based models, physical parameters are generally represented by averages. Such efforts can generate either overly catastrophic projections or excessively optimistic ones.

Ecologists generally agree, for example, that marine species in the tropics and poles will be more vulnerable to the effects of a rise in temperature of 2 °C. Tropical species are already living in the warmest habitats on the planet[11], whereas those at the poles have nowhere else to go[12]. But oceans are not



*A cast is a set of measurements for a single variable such as temperature or salinity at different depths; †BT, bathythermograph; ‡CTD, high-resolution sensor of conductivity, temperature and depth.

SOURCE: NOAA/NCEI WORLD OCEAN DATABASE, HTTPS://GO.NATURE.COM/2OFK8HG

DAN COSTA/UCSC

A Weddell seal equipped with a sensor for measuring ocean conductivity, temperature and depth.

warming evenly across the tropics and poles. Some areas are even cooling[13].

Heterogeneity is overlooked. Overall, Earth is losing species. Yet there are huge differences in the rate of loss at the local scale; biodiversity is even increasing in some places[14]. Certain species, populations and individuals can adapt and adjust, and this will lead to surprises. In 2017, hundreds of surveys on the Great Barrier Reef in Australia before and after a mass bleaching event revealed huge variability in how fish species responded to the extreme heat. Some trophic groups, such as herbivores that scrape algae, became less common on the warmest reefs. For others, such as those that feed on plankton, warmer temperatures seemed to benefit populations[15].

Opportunities are missed. Ignoring the variability in ocean systems could limit conservation and management strategies[6,16]. For instance, the concept of climate refugia, where species can shelter from the effects of climate change, has been considered for cooler terrestrial landscapes such as mountain valleys and rivers. Yet marine spatial planning tends to overlook the possibility of refuge sites arising, say, from the upwelling of cooler waters from depth, or from the shade provided by a coral reef. This is largely because ecologists lack the fine-scale data to establish where potential refugia exist.

THE NEXT WAVE

Each stride forward in the physical sciences should translate to improvements in ecologists' predictions of biodiversity change. Major advances in how atmospheric and climate scientists understand ocean processes are rapidly unfolding as a result of improvements in ocean-monitoring technologies, as well as in climate models[17].

Making equivalent progress in the life sciences — in tandem — will require at least three changes.

Acceptance. Ecologists must embrace the fact that the oceans are variable, and consider more carefully the limitations and biases inherent to physical data. Ocean surface temperatures measured by satellites, for example, shed little light on conditions for organisms that live at depth.

In practical terms, this means incorporating variability into ecological models and experiments. This is starting to happen for terrestrial ecosystems. In 2016, for instance, researchers revealed that daily fluctuations in temperature are just as powerful a predictor of changes in the geographical range of frogs, lizards and other organisms as seasonal variation[18].

High-performance computing. Ecologists urgently need ways to access and analyse high-resolution data on environmental variability. They are used to dealing with megabytes of data, but they need to be able to handle terabytes.

Currently, there are various options for accessing high-performance computing. Researchers can apply for cloud-computing grants offered by Microsoft and Google. And some countries, such as Canada, offer cloud resources and training to enable academic institutions to embrace big-data research. The provision of this type of infrastructure and support should be prioritized more broadly.

Crosstalk and collaboration. Much more dialogue is needed between ecologists, physiologists and climate and ocean scientists to aid understanding of what data are required, and in what formats. For instance, sDiv — the Synthesis Centre of iDiv, the German Centre for Integrative Biodiversity Research in Leipzig — runs workshops to foster crosstalk between researchers and kick-start new approaches. This and hundreds of similar efforts could help to bring the relevant researchers together. Dedicated funding for working groups, and for interdisciplinary science in general, will be key.

Only through global collaboration will ecologists be able to obtain a global perspective on ocean weather. There are already some good models for this. The Global Ocean Acidification Observing Network (GOA-ON), for instance, is an international effort to provide highly resolved biogeochemical data on the scale of metres, to enable researchers to optimize models of ocean acidification.

We predict that when biologists engage with the physical and biogeochemical data now becoming available — at scales matched to those of organisms' lives — major shifts will occur in how we conceptualize and manage biodiversity change in the ocean. ■

Amanda E. Bates *is associate professor of ocean sciences at the Memorial University of Newfoundland, St. John's, Canada, and a Canada Research Chair in marine physiological ecology.* **Brian Helmuth, Michael T. Burrows, Murray I. Duncan, Joaquim Garrabou, Tamar Guy-Haim, Fernando Lima, Ana M. Queiros, Rui Seabra, Robert Marsh, Jonathan Belmaker, Nathaniel Bensoussan, Yunwei Dong, Antonios D. Mazaris, Dan Smale, Martin Wahl, Gil Rilov.**
e-mail: abates@mun.ca

1. Helmuth, B. *et al. Sci. Data* **3**, 160087 (2016).
2. Hofmann, G. E. *et al. PLoS ONE* **6**, e28983 (2011).
3. Naveira Garabato, A. C. *Phil. Trans. R. Soc. A* **370**, 5480–5511 (2012).
4. Tizard, T. H. & Moseley, H. N. *Narrative of the Cruise of HMS* Challenger*: With a General Account of the Scientific Results of the Expedition* (Vol. 2). (HM Stationery Office, 1882).
5. Petsko, G. A. *Genome Biol.* **12**, 112 (2011).
6. Helmuth, B. *et al. Clim. Change Responses* **1**, 10–20 (2014).
7. Condie, S. & Condie, R. *Glob. Ecol. Biogeogr.* **25**, 1264–1277 (2016).
8. Gardner, W. D., Richardson, M. J. & Mishonov, A. V. *Earth Planet. Sci. Lett.* **482**, 126–134 (2018).
9. Hurd, C. L. *et al. Glob. Change Biol.* **17**, 3254–3262 (2011).
10. Dowd, W. W., King, F. A. & Denny, M. W. *J. Exp. Biol.* **218**, 1956–1967 (2015).
11. Comte, L. & Olden, J. D. *Nature Clim. Change* **7**, 218–722 (2017).
12. Flynn, E. E., Bjelde, B. E., Miller, N. A. & Todgham, A. E. *Conserv. Physiol.* **3**, cov033 (2015).
13. Josey, S. A. *et al. Ann. Rev. Mar. Sci.* **10**, 475–501 (2018).
14. Dornelas, M. *et al. Science* **344**, 296–299 (2014).
15. Stuart-Smith, R. D., Brown, C. J., Ceccarelli, D. M., & Edgar, G. J. *Nature* **560**, 92–96 (2018).
16. van Hooidonk, R., Maynard, J. A. & Planes, S. *Nature Clim. Change* **3**, 508–511 (2013).
17. Hewitt, H. T. *et al. Geosci. Model Dev.* **9**, 3655–3670 (2016).
18. Chan, W-P. *et al. Science* **25**, 1437–1439 (2016).

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