A well-designed sectoral club involving those countries early on could provide a much-needed foundation for global cooperation and serve as a role model for other GHG-intensive and trade-exposed sectors, and may ultimately result in an overarching cross-sectoral club arrangement. □

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The small scales of the ocean may hold the key to surprises

Sharp fronts and eddies that are ubiquitous in the world ocean, as well as features such as shelf seas and under-ice-shelf cavities, are not captured in climate projections. Such small-scale processes can play a key role in how the large-scale ocean and cryosphere evolve under climate change, posing a challenge to climate models.

Helene Hewitt, Baylor Fox-Kemper, Brodie Pearson, Malcolm Roberts and Daniel Klocke

There is much debate about what scales of motion need to be represented explicitly ('resolved') in models in order to produce robust climate projections. By contrast to atmospheric jet streams, mid-latitude weather systems and squall lines, the oceanic equivalents (boundary currents such as the Gulf Stream, mesoscale eddies and submesoscale eddies) are roughly ten times smaller in scale. The ocean also has boundaries (coastlines) and sub-surface orography (bathymetry) that constrain the circulation pathways, and shallower shelf regions where tides become more important. Determining the scales that need to be explicitly resolved in the ocean is challenging as small-scale processes can have a substantial impact on high-impact, low-likelihood events.

Critical regions
The IPCC *Sixth Assessment Report* (AR6)[1] has made new assessments of future changes in the ocean. The agreement between multiple lines of evidence led to increasing confidence in large-scale changes such as warming of the global ocean and sea-level rise due to thermal expansion. However, there is less confidence in future projections linked to the large-scale circulation associated with the Atlantic Meridional Overturning Circulation (AMOC) and the Southern Ocean[2], sometimes described as the oceanic conveyor belt. The North Atlantic and Southern Ocean are both associated with high mesoscale activity

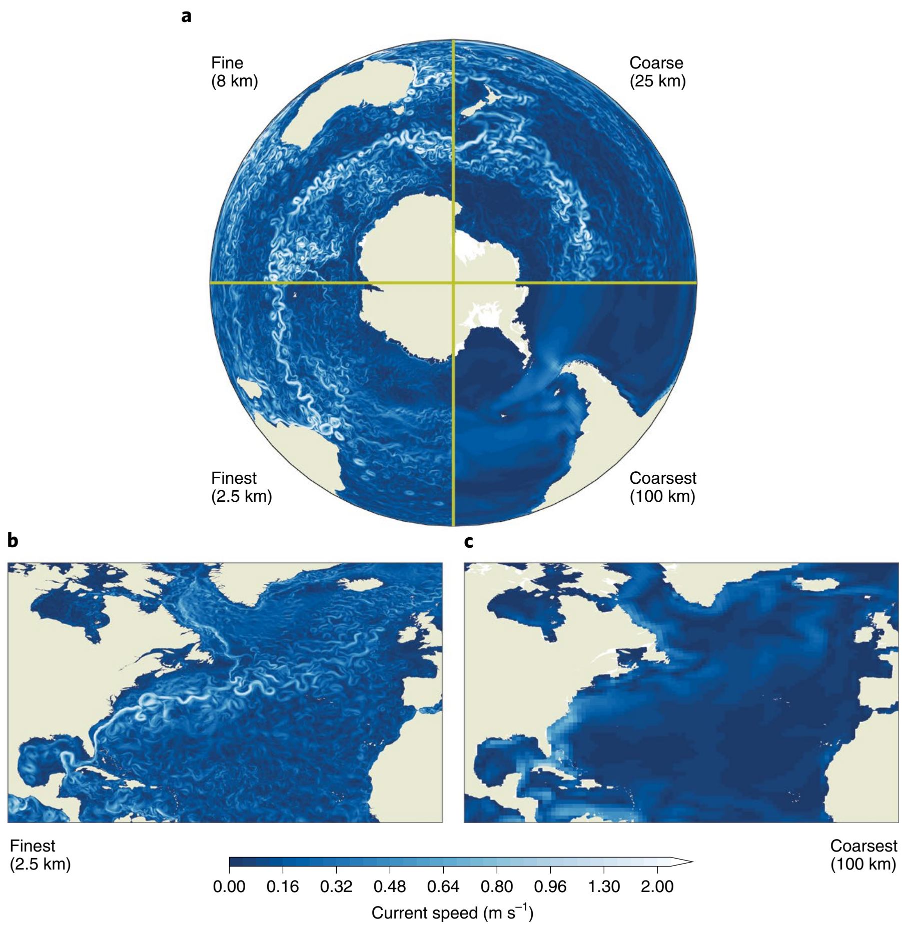

Fig. 1 | Surface currents at a range of model resolutions. a–c, Representation of the surface ocean currents at different resolutions for the Southern Ocean (**a**) and North Atlantic (**b**,**c**). Data are from the ICON 2.5 km coupled simulation from the European Union's NextGEMS project (https://code.mpimet.mpg.de/projects/iconpublic and https://nextgems-h2020.eu). Lower-resolution models are from the Coupled Model Intercomparison Project Phase 6 (CMIP6) HighResMIP simulations using the HadGEM3-GC3.1 model (100 km, http://doi.org/10.22033/ESGF/CMIP6.1901; 25 km, http://doi.org/10.22033/ESGF/CMIP6.446; 8 km, http://doi.org/10.22033/ESGF/CMIP6.445).

and complex geography (Fig. 1). In both of these basins, ocean circulation in small regions is strongly linked to the possibility of high-impact, low-likelihood events.

As the climate warms, the AMOC is expected to affect global climate change by weakening[1,2]. It is unclear how much weakening should be expected, although an abrupt collapse of the circulation is not expected this century[1]; however, it is still physically possible and would have large impacts. Uncertainty in the future response of the AMOC in the IPCC AR6 is related to the inability of models to capture its complexity and the challenges of estimating its historical strength from geological proxies. The complexity of the AMOC includes the narrow Gulf Stream and how it is steered by the bathymetry, as well as the formation of deep water that makes up the return branch of the AMOC. The position of the Gulf Stream also dominates model errors in Atlantic air–sea fluxes that affect large-scale climate and influence weather systems over Western Europe. The deep water that constitutes the subsurface AMOC is formed in convective areas and can be transported down steep slopes. A collapse or strong reduction of the AMOC (and associated changes in European and global climate) would be linked to these small-scale processes in the North Atlantic, which are not well-represented in current climate models.

The Southern Ocean links all the other major ocean basins via the Antarctic Circumpolar Current. It is not only one of the least observed parts of the global ocean, but also one of the most complex, with small-scale fronts, eddies, sea ice, shelf regions and ice-shelf cavities all playing a role in the ocean circulation. There is already evidence of surprises occurring in the Southern Ocean; unlike in the Arctic, sea ice around Antarctica has not shown a coherent pattern of decline. Experiments with high-resolution ocean models better capture regional and seasonal patterns of sea-ice growth and decline[3], and suggest that mesoscale eddies have delayed the response of the sea ice to a warming atmosphere[4]. If we were to rely solely on projections from coarse-resolution models, we may miss surprises such as these. Further surprises related to small-scale processes are expected; changing mesoscale eddies will allow the Antarctic Circumpolar Current to maintain its strength in a warming climate, even as winds are projected to increase[5]. Critically, unexpected loss from the Antarctic ice sheet would lead to very high rates of global mean sea-level rise. Heat transported across the Antarctic shelf to melt ice shelves from below[6,7] will be one of the major factors in determining the amount of loss from the Antarctic ice sheet leading to sea-level rise[1]. While mesoscale eddies, heat transport onto the Antarctic shelves and flow under ice shelves are key to the Southern Ocean's influence on climate, these processes are not directly represented in current global climate models.

Small-scale ocean processes will also play a role in the response to mitigation efforts and possible overshoots of global temperature, given their role in heat and carbon uptake by the ocean. This uptake is particularly critical in the Southern Ocean, where high- and low-resolution models differ in uptake processes and sensitivity[1]. Mesoscale and submesoscale fronts and eddies, as well as boundary-layer processes in the atmosphere and ocean, all impact the ocean boundary layer and the exchange of heat and carbon through both physical and biological processes.

Kilometre-scale modelling

Many of the processes described above originate at scales that are smaller than those currently resolved in climate models (Fig. 2). One way to address this is to simply keep increasing the model resolution to explicitly represent key processes[8,9]. This is a common approach to represent mesoscale eddies over the global ocean; although ocean models used in climate projections generally do not resolve mesoscale eddies, there were some shorter simulations in the IPCC AR6 with ocean resolutions of approximately 8 km where eddies were resolved over the mid- (but not high-) latitudes[8]. Increasing resolution to sufficiently capture not just mesoscale eddies but all the critical small-scale processes is challenging as

Box 1 | CMIP6 and scales of ocean processes

CMIP6 models ran with ocean components with a median resolution near 1° (Fig. 2). At this resolution, gyres are resolved but western boundary currents are slow moving (Fig. 1). At this coarse resolution, there is a large spread between models presumably due to differing parameterizations, particularly in vertical distributions of salinity and temperature, sea-ice concentration, and the profile of the AMOC.

The ocean mesoscale is defined to be near the Rossby radius, which is related to the Earth's rotation and the depth and stratification of the ocean. At mid-latitudes, this means that a resolution of 25 km (or approximately 0.25°) will start to allow the representation of mesoscale processes, particularly western boundary currents such as the Gulf Stream. However, to fully represent mesoscale eddies, a resolution of 10 km (or ~0.1°) is needed at mid-latitudes[12], as used in some HighResMIP and Ocean Model Intercomparison Project simulations. At high latitudes even finer resolution is required, as the Rossby radius decreases towards the poles[12]. The submesoscale is linked to processes such as restratifying eddies, which have been shown to be important in the representation of sea ice and the AMOC[15]; resolutions between 500 m and 2 km accurately represent submesoscale fronts and eddies — summer eddies require finer resolution than winter ones due to thinner surface boundary layers[13]. In the shallow shelf seas, the ocean depth becomes a controlling factor in the physics, with tides being the dominant process and resolutions of ~1–2 km required to accurately resolve[14].

The oceanic horizontal resolution in CMIP models is being refined over time (Fig. 2), but the resolution needed to resolve process scales is still some time away (estimated ranges for between half and most grid cells to resolve the process scale[12] are shown in Fig. 2). The median CMIP resolution is refining slowly (~6 years for the finest models to halve grid dimension and 10 years for the median model), suggesting that complexity such as biogeochemistry is being prioritized rather than resolution in the typical ocean model. This highlights the ongoing importance of parameterization to represent unresolved ocean processes. However, parameterizations are not designed to capture all effects of a particular scale. For example, mesoscale eddy parameterizations do not improve (mesoscale) western boundary currents, and submesoscale parameterizations[15] neglect coastal features, internal gravity waves and tides. Some CMIP6/HighResMIP models may be able to explicitly represent the ocean mesoscale but typically only near the Equator. This so-called 'grey zone' is a challenge to modelling: parameterization may taint the resolved dynamics where resolution is sufficient, while failure to parameterize may lead to processes not being represented at all.

Prototype global ocean models resolve all oceanic mesoscales and even some submesoscales[11], but their cost allows only short simulations. If resolution is refined further, improved sea-ice rheology and non-hydrostatic ocean dynamics will be required. However, directly resolving the submesoscale and boundary-layer processes in Earth system models lies decades away, based on present computing trends.

computational cost increases rapidly with resolution; reducing the ocean horizontal grid size by a factor of 10 in each direction is approximately 1,000 times more costly. The increasing cost of high-resolution models is challenging when faced with the need to provide probabilistic information on long timescales for different emissions scenarios, and some models are already being rewritten to use computer chips more effectively[10]. Prototype global simulations[11] with very high resolution (~2 km) are becoming available (Figs. 1 and 2). These kilometre-scale global ocean models can resolve mesoscale eddies at all latitudes and better represent ice cavities and shelf regions, but can currently simulate climate for only years, not the decades needed for projections.

Alternative approaches

As explicitly representing the full ocean mesoscale (and perhaps submesoscale) uniformly over the whole globe with standard multi-centennial simulations of current climate models is some years away (Fig. 2), we ask if there are other ways to address the need for improved simulation of key processes. Representing the effects of small-scale ocean processes such as mesoscale eddies on the larger scale (parameterization) has been heavily relied on in climate simulations (Box 1).

For mesoscale and submesoscale processes, improved parameterization (Box 1) will remain important. In the future, idealized simulations of the small-scale ocean processes will be needed to glean parameterizations for lower-resolution models, and could include novel and improved schemes based on machine learning and emulation. However, some small-scale processes in climatically sensitive regions — cavities under ice shelves, deep convection regions, key deep ocean overflows, submesoscale eddies carrying warming waters across the Antarctic shelf, or Agulhas rings carrying Indian Ocean waters into the Atlantic — may only be captured by ocean models at the kilometre scale. Focussing model resolution in critical regions is a possible approach. This can be achieved either via nested regional patches of enhanced resolution (for example, in sensitive areas such as North Atlantic convection zones or under ice shelves) or unstructured mesh models where, for example, resolution can be made a function of ocean variability to represent frontal regions[4]. Novel experimental designs for climate simulation, much shorter than the current standard (which often require thousands of years in total), could allow kilometre-scale ocean models to be used to address specific science questions, and provide increased confidence in projections and climate surprises.

Summary

There are many small-scale ocean processes that contribute to the large-scale response of the climate system and may lead to climate surprises. Here, we particularly highlight small-scale processes in the North Atlantic and the Southern Ocean that can be linked to the possibility of a collapse of the AMOC or sea-level rise much higher than the expected range. The climate modelling community urgently needs to accelerate efforts to investigate the role of small-scale ocean processes on large-scale climate. In the first instance, kilometre-scale global ocean models are needed as a tool to understand the impact of small-scale processes on large-scale climate. Although such models are on the horizon, the community needs to mirror present efforts on kilometre-scale atmospheric modelling to develop these models. Challenges include improving the computational efficiency of such models so that the full climate system can be modelled at the kilometre scale.

If we want to capture uncertainty in future climate projections, this may not be feasible at the kilometre scale using

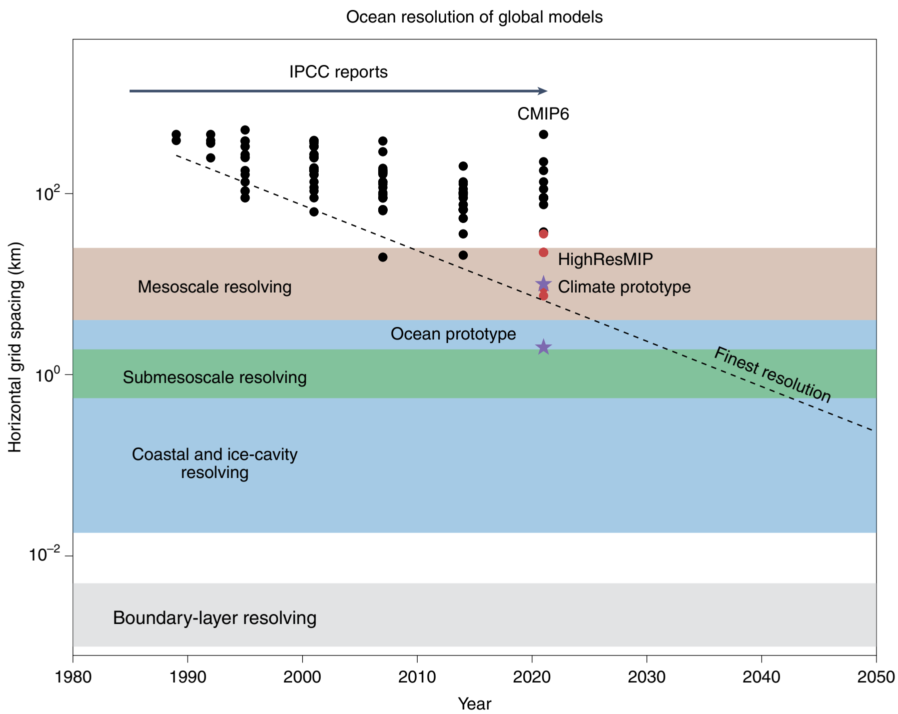

Fig. 2 | The evolution of global ocean model resolution by publication year. Shown are models from the CMIPs (black circles) and HighResMIP (red circles), and prototype submesoscale-permitting global simulations of the ocean or the coupled climate system (purple stars). Estimated ranges to resolve processes are shown from observations (mesoscale and submesoscale ranges reflect latitudinal variations in Coriolis parameter and regional/seasonal variations in stratification) and studies of coastal, ice cavity and boundary-layer process simulations[1,6–8,11–14].

current experimental designs. Exploring new experimental designs as a climate modelling community would be one approach to address this. In parallel, kilometre-scale global models have the potential to further facilitate the development of improved parameterization and allow evaluation of regionally enhanced resolution. Ultimately, the community needs future climate projections that do not overlook high-impact, low-likelihood outcomes. Ensemble projections are needed that encompass (climate) uncertainties from a large number of (low-resolution) models together with a small number of kilometre-scale models in which mesoscale processes and their associated uncertainties and impacts are explicitly represented. ❐

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Competing interests
The authors declare no competing interests.

Ambitious partnership needed for reliable climate prediction

Current global climate models struggle to represent precipitation and related extreme events, with serious implications for the physical evidence base to support climate actions. A leap to kilometre-scale models could overcome this shortcoming but requires collaboration on an unprecedented scale.

Julia Slingo, Paul Bates, Peter Bauer, Stephen Belcher, Tim Palmer, Graeme Stephens, Bjorn Stevens, Thomas Stocker and Georg Teutsch

Water is Earth's life blood and fundamental to our future. Hydro-meteorological extremes (storms, floods and droughts) are among the costliest impacts of climate change, and changes in the seasonality and natural variability of precipitation can have profound effects on many living systems, in turn threatening our food security, water security, health and infrastructure investments. Yet the current generation of global climate models struggles to