for human development and global environmental changes, barring climate change mitigation beyond what is in place today. Scenarios range from green growth and environmental sustainability (SSP1) to intensive energy and resource development (SSP5)[24]. Some of these scenarios will be used in a framework with the Representative Concentration Pathways to drive climate projections under Phase 6 of the Coupled Model Intercomparison Project for the forthcoming IPCC assessments. None of the baseline SSP CO_2 emissions scenarios reach zero by 2100 CE, so cumulative emissions and the associated committed SLR derived from them are minimum estimates (Supplementary Information). We also consider a hypothetical mitigation scenario by extending the baseline CO_2 emissions down to zero by 2155 CE (see Supplementary Information for details), thus providing a finite and likely minimum value of cumulative carbon emissions for evaluating implications of the baseline SSPs to SLR. The baseline SSP5 scenario with our declining extension has the highest cumulative carbon emissions of the scenarios evaluated here (3,596 GtC, including historic emissions), leading to GMSLR of 3.7 m (2.7 to 4.8 m) by 2300 CE and 41.6 m (37.8 to 45.3 m) by 9000 CE (Fig. 1b and Supplementary Information). Following scenarios that limit warming to 1.5 °C or 2 °C would strongly limit these GMSLR projections, but far from eliminate the risks (Fig. 1a).

The relationship between cumulative carbon emissions and GMSLR developed here is based on a small number of models. Refinements will require more process studies and modelling to better quantify the uncertainties in the relationships that arise from ice-sheet feedbacks on climate, ice-sheet dynamics and long-term carbon cycle changes. Moreover, mitigation scenarios that limit global mean temperature rise to 1.5 °C or 2 °C are often associated with negative emissions in the latter part of the twenty-first century (Supplementary Information)[5]. It is likely that committed SLR for these and similar scenarios would be less if such negative emissions were to continue beyond the twenty-first century[25–28,29], but further work is required to better quantify this response.

As these processes and uncertainties become better constrained, quantitative relationships may provide a basis for assigning responsibility[30]. They may also be incorporated into long-term planning in the coastal zones subject to inundation, and in those areas where vulnerable populations are likely to relocate[9]. Finally, in conjunction with risks posed by increasing global mean temperature[6], our analysis of SLR will further inform policy for identifying an emissions limit that will prevent or mitigate the dangerous, and essentially permanent, anthropogenic interference with the climate system associated with the irreversible loss of the Greenland and Antarctic ice sheets[7]. ❐

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Additional information

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Changing storminess and global capture fisheries

Climate change-driven alterations in storminess pose a significant threat to global capture fisheries. Understanding how storms interact with fishery social-ecological systems can inform adaptive action and help to reduce the vulnerability of those dependent on fisheries for life and livelihood.

Nigel C. Sainsbury, Martin J. Genner, Geoffrey R. Saville, John K. Pinnegar, Clare K. O'Neill, Stephen D. Simpson and Rachel A. Turner

Fisheries are an important source of nutrition, livelihoods and cultural identity on a global scale. Fish provide 3.1 billion people with close to 20% of their animal protein[1], and are relied on for vital micronutrients, which are particularly critical to the health of children and pregnant women[2]. Capture fisheries and aquaculture are estimated to support the livelihoods of 12% of the global population and 38 million fishers regularly risk their lives in one of the most dangerous jobs on Earth[1]. Despite its dangers, fishing is an important source of cultural identity and well-being for fishing communities around the world[3].

In addition to ocean warming and acidification, changing storminess is a climate stressor that affects marine life and habitats (Fig. 1a), with potential negative consequences for fish catch and the well-being of coastal communities. Changing storminess also poses a direct risk to fisheries: storms disrupt fishing effort and pose a physical threat to fishers, their vessels and gear, as well as to fishing communities and their infrastructure. Although ocean warming may alter the potential fish catch over the next 50 to 100 years[4], changing storminess has the potential to cause more immediate and catastrophic impacts. The twenty-first century has already witnessed many tropical, extratropical and thunder storms that have claimed thousands of fishers' lives, destroyed fishery-dependent livelihoods and assets, and disrupted the production of commercial inland and marine capture fisheries (Fig. 1b).

The number of storminess reanalysis and projection studies is growing, as is their geographic scope (Fig. 2). However, uncertainty in past and future storminess from global and regional climate models remains high as a result of widespread variation in analytical methods, poor historic observational data[5] and the challenge of distinguishing externally forced climate changes from natural internal climate variability[6]. The attribution of individual extreme weather events to anthropogenic climate forcing is challenging — particularly for storms[7]. Thus, extreme weather event attribution is an expanding area of research and examples for storm events are beginning to emerge[8].

Despite the difficulties in modelling the location, frequency and intensity of storms, there is sufficient certainty for the IPCC to conclude for the North Atlantic basin (where fisheries productivity is high and historic storm data is particularly rich) that the frequency of the most intense tropical storms has increased since the 1970s[5]. A recent review of future winter storminess studies in Europe, ranging over periods spanning 2020–2190, predicts increases in storm frequency and intensity in Western and Central Europe, and decreasing storminess over the North Atlantic north of 60° N and in Southern Europe[9]. Evidence of changing storminess from studies outside the North Atlantic includes a northward shift in Western North Pacific tropical cyclone exposure towards the East China Sea[10] and increased post-Monsoon storminess in the Arabian Sea[8]. However, substantial uncertainties in storminess projections remain, and represent a real barrier to effective assessment of global fishery vulnerability.

The uncertainties surrounding the changing nature of storm hazards are paralleled by a lack of knowledge about how storm events directly interact with social and economic variables to influence the behaviour of fishers. In addition, the impacts of storms on marine ecosystems, and the linkages by which these cause indirect social and economic perturbations to fisheries, are little understood. An interdisciplinary research effort is now required to clarify the climatic, social and ecological dimensions of changing storminess to support the assessment of fishery vulnerability and inform adaptive action.

Plotting the course ahead

We advocate a roadmap that draws on climate science, environmental social science, psychology, economics and ecology, and is based on four interlinked research areas (Fig. 3): (1) developing climate modelling to better understand changing storm hazards; (2) understanding fishers' behavioural response to storms; (3) examining the effects of storms on coastal marine ecosystems and socio-economic linkages; and (4) assessing fisheries vulnerability and adaptation strategies for changing storminess.

Modelling changing storminess

Identifying the risk to fisheries of changes in storminess requires climate models that provide a reliable spatial and temporal view of the past and future frequency and intensity of tropical, extratropical and thunder storms. To achieve this, improvements are required in the explicit representation of the sub-grid-scale physical processes by which the most intense storms form and develop, such as convection. Advances in ocean–atmosphere coupled models are also necessary to capture the boundary layer processes that drive storms. Progress is being made in these areas, for instance in developing climate models that better represent the coupled ocean–atmosphere processes in tropical cyclones[11].

Improving the characterization of storms in climate models demands finer spatial resolution and a shortening of time steps, which will intensify the trade-off between the resolution and timescale of simulations that results from limited computing resources. Supported by greater computing power, enhanced representation of storms in climate models will improve both reanalysis and predictions of storminess and strengthen our understanding of the influence of climate variability at seasonal to decadal timeframes on storm events.

Fisher behavioural responses

The effect of storms on fisheries is in part a function of fishers' behavioural response to meteorological conditions. The heterogeneity of fisher decisions regarding whether to participate, and where to fish, in adverse weather conditions for different fishery types, vessel characteristics and social and cultural contexts around the world should be explored. Fishers' decisions on where and when to fish are known to be affected by a complex array of socio-economic factors[12]. However, the way in which fishers make weather-related decisions is poorly understood. We do not know how projected weather information is used or if it is accessible to fishers. It will be important to understand fisher decisions to go to sea, or stay at sea, during storms, how weather conditions affect the distribution of fishing activity, the performance of different gears in adverse weather and the interaction of perceptions of physical and economic risk in decision-making.

Explaining the behavioural response of fishers to storms will require the involvement of psychologists, sociologists, anthropologists and economists employing research methods across the epistemological spectrum. Qualitative approaches can unravel the complexity of factors, motivations and processes underpinning decision-making, whereas experimental methods, such as economic choice experiments, offer the potential to reveal how decisions are made where observational data are not readily available, as is the case in many tropical fisheries. The increasing availability of on-board satellite vessel tracking technology and wind and wave hindcast modelled data is creating the potential to model the behavioural response of fishers to weather conditions at unprecedented temporal and spatial resolutions. In addition, the emerging application of agent-based modelling approaches to fisheries could reveal the weather-related behaviour of fleets based on the decisions and interactions of individual fishers.

Ecosystems and socio-economic linkages

Storms have the capacity to cause extensive disturbances to marine ecosystems and habitats that support productive fisheries. Several areas require investigation to improve our knowledge: little is known about the manner in which fish life-cycle events (including spawning migrations,

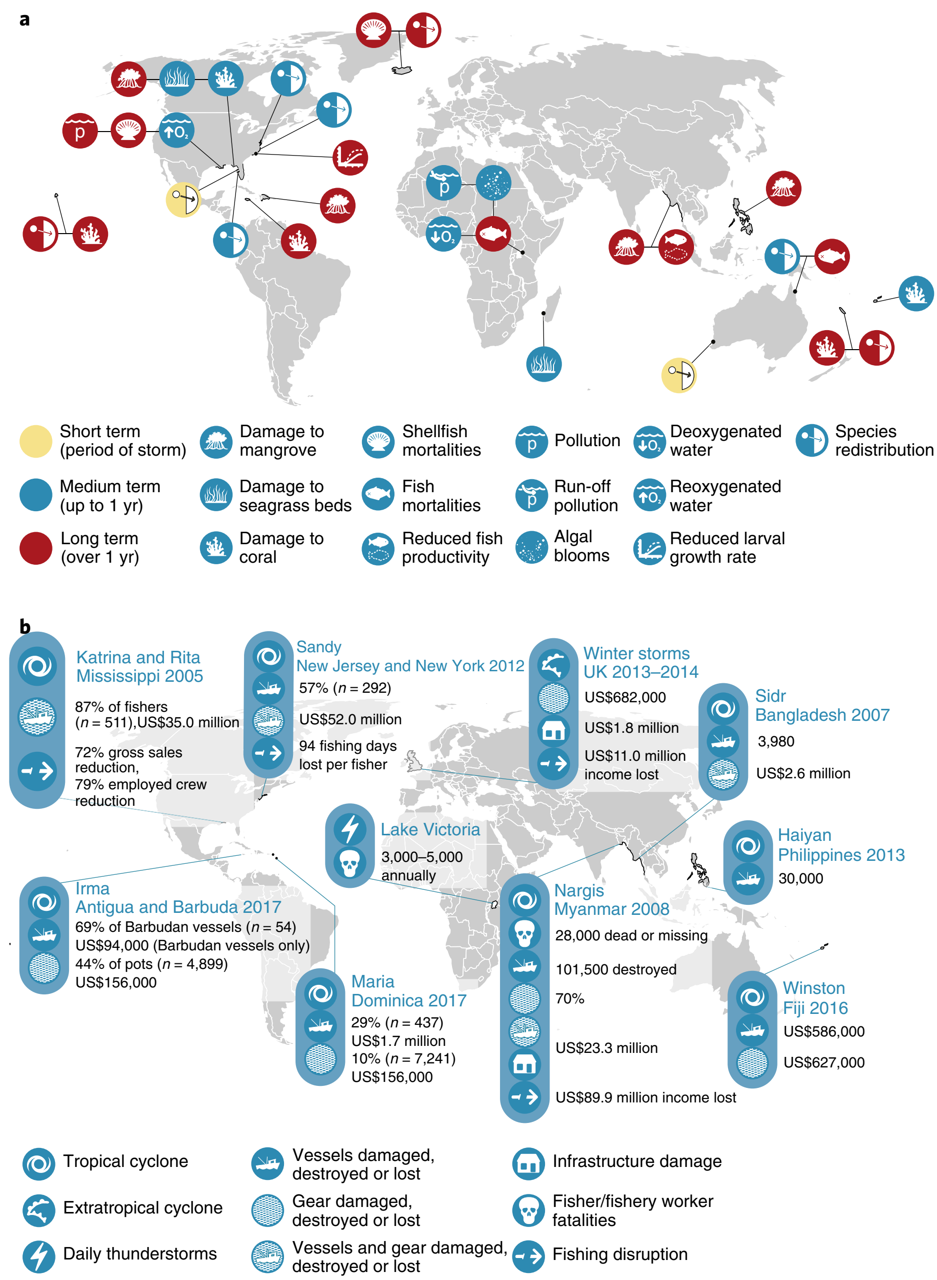

Fig. 1 | Ecological, social and economic impacts of storms on fisheries. a, Examples of storm-induced marine ecosystem disturbances. For further detail see Supplementary Information Section 1a. **b**, Examples of social and economic impact case studies from the twenty-first century. Case studies were selected based on the scale of the impacts, global geographic spread and availability of data. For further detail see Supplementary Information Section 1b.

larval growth and dispersal during the planktonic larval phase) and the use of shallow nursery ground habitats are influenced by storm disturbance. There is some evidence that fish may evacuate storm areas or be redistributed by storm waves and currents (Fig. 1a), but this requires further exploration. Storm-induced fish mortality events, such as the death of 400,000 fish in the Nyanza Gulf of Lake Victoria following post-storm deoxygenation and turbidity in 1984[13], are poorly understood. Finally, the way that changing storminess interacts with other marine impacts of climate change (such as ocean warming, acidification and deoxygenation) to affect marine ecosystems remains unexplored.

Interdisciplinary efforts are required to uncover how direct marine ecosystem impacts are linked with indirect social and economic impacts on fisheries. Although there are examples of storm damage to key habitats, we know little of how this consequently influences the abundance or catchability of targeted fish species. We lack knowledge of how storm-induced changes in fish distribution affect fishery catches, but fishers' logbooks may offer a rich source of data to address this gap.

Vulnerability and adaptation strategies

Assessing the vulnerability of fisheries to changing storminess is essential for prioritizing limited adaptation resources and informing adaptation strategies. The

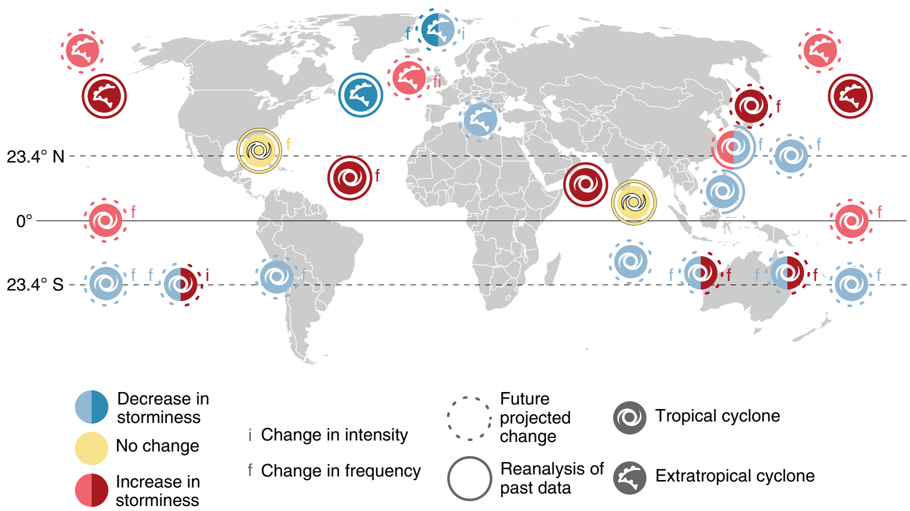

Fig. 2 | The spatially heterogeneous nature of changing global storminess. The selection of reanalysis and projection studies is not systematic, but is designed to reflect a range of studies carried out for the Atlantic, Pacific and Indian oceans, which account for the majority of the global fish catch. Darker colours indicate the most intense storms; for further detail see Supplementary Information Section 2.

exposure of fisheries will vary spatially with projected changes in storm risk, target fish species, the resilience of infrastructure and the extent of natural and man-made storm defences. It is probable that the impact of changing storminess on fisheries will be socially differentiated, with severe impacts more likely to affect small-scale fisheries. The vulnerability of fisheries to changes in storminess is unclear at present. Fishery vulnerability assessments developed over the past decade have acknowledged, but not reflected, changing storminess[14], largely because of the gaps in knowledge outlined here. These assessments can be enhanced by incorporating appropriate measures of exposure, sensitivity and adaptive capacity to storms.

Fishery adaptation measures will require evaluation in local contexts. Possibilities include technological advances, improvements in the accuracy and communication of weather forecasts, and innovative financial solutions. In Kerala, India, a weather forecast service called Radio Monsoon (https://twitter.com/radiomonsoon) provides daily information over loudspeaker in harbours and through social media. Insurance schemes triggered by environmental indices are growing in popularity in terrestrial agriculture[15] and could increase the resilience of fisheries to increased storminess. Modifications of this concept would have to reflect the nature of daily harvesting activity and the dynamic

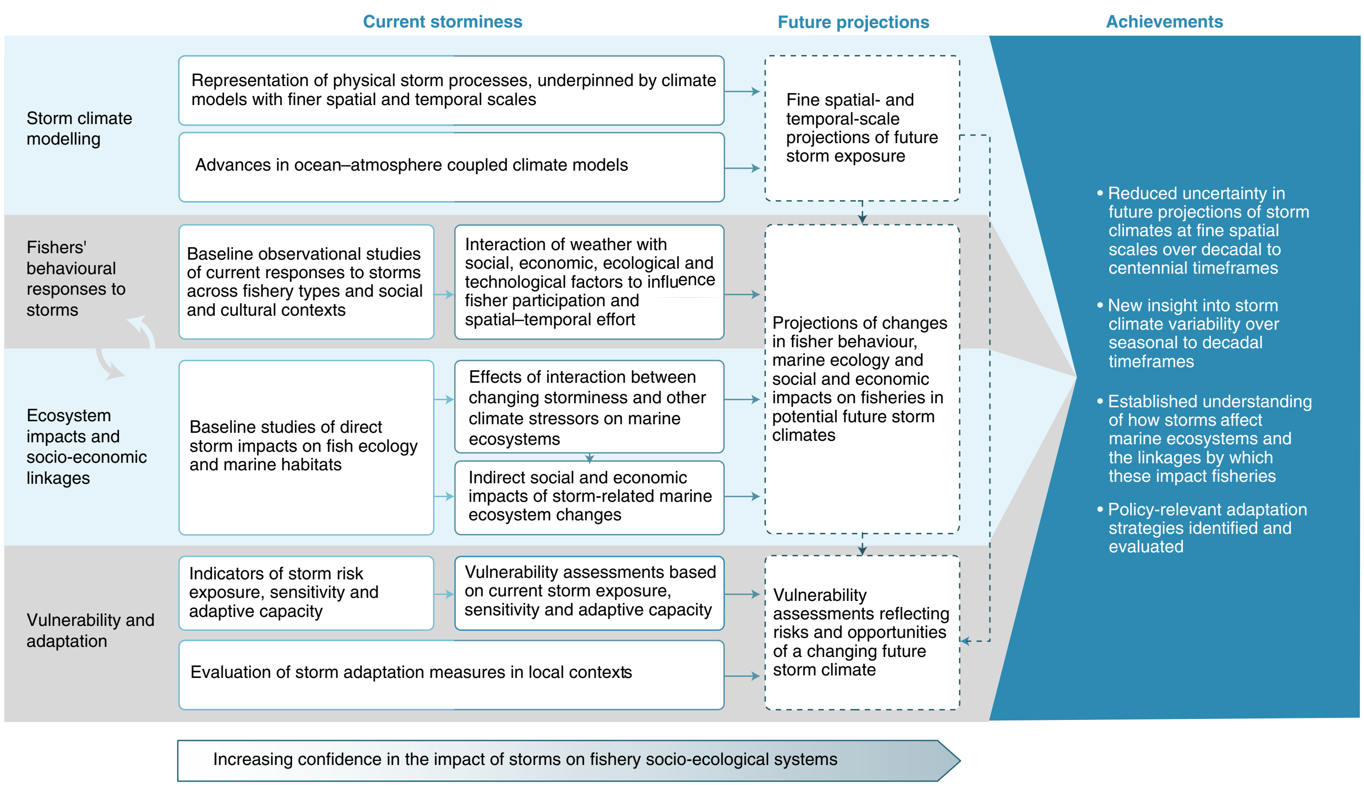

Fig. 3 | Schematic of a research roadmap to understand the impact of changing storminess on fisheries. Straight arrows between boxes demonstrate the dependencies within and between research streams. Curved arrows represent the feedback loop in which changes in fisher behaviour affect the ecosystem and changes to the ecosystem affect fisher behaviour. Collaboration will be required between research streams. Note that the order of research streams does not represent importance or priority.

nature of marine resources. Some fishers may also have opportunities to adapt to take advantage of reduced storminess, which may exacerbate existing challenges to sustainable use of natural resources.

Conclusions

Greater attention to the research priorities outlined here could help inform adaptation and protect the well-being of billions of people worldwide. Although scientists are actively working in some of these areas, research gaps remain, and existing knowledge is yet to be applied to this social-ecological climate issue. The potentially catastrophic impacts of changing storminess for global fisheries over relatively short timescales mean that enhanced integration across disciplines is urgently needed to address this challenge. ❐

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Competing interests

J.K.P. is a co-chair of the 'ICES-PICES Strategic Initiative on Climate Change Impacts on Marine Ecosystems' and will be a Lead Author for the 'Small Islands' chapter in the IPCC's Sixth Assessment Report (WG III).

Additional information

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