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.

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Fisheries are an important source of food, 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 upon 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, extra-tropical 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 particular 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 is 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 storm frequency and severity

Identifying the risk to fisheries of changes in storminess requires climate models that provide a reliable spatial and temporal view of past and future frequency and intensity of tropical, extra-tropical 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 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.

Fishers' behavioural response to storms

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 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.

Coastal marine ecosystems and socio-economic linkages

Storms have the capacity to cause extensive disturbance 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 lifecycle events (including spawning migrations, 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 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 indexes 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 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 natural resource use.

Conclusion

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 across relatively short timescales mean that enhanced integration across disciplines is urgently needed to address this challenge.

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Competing Interests statement

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 within the IPCC 6th Assessment Report (AR6 – WGII).

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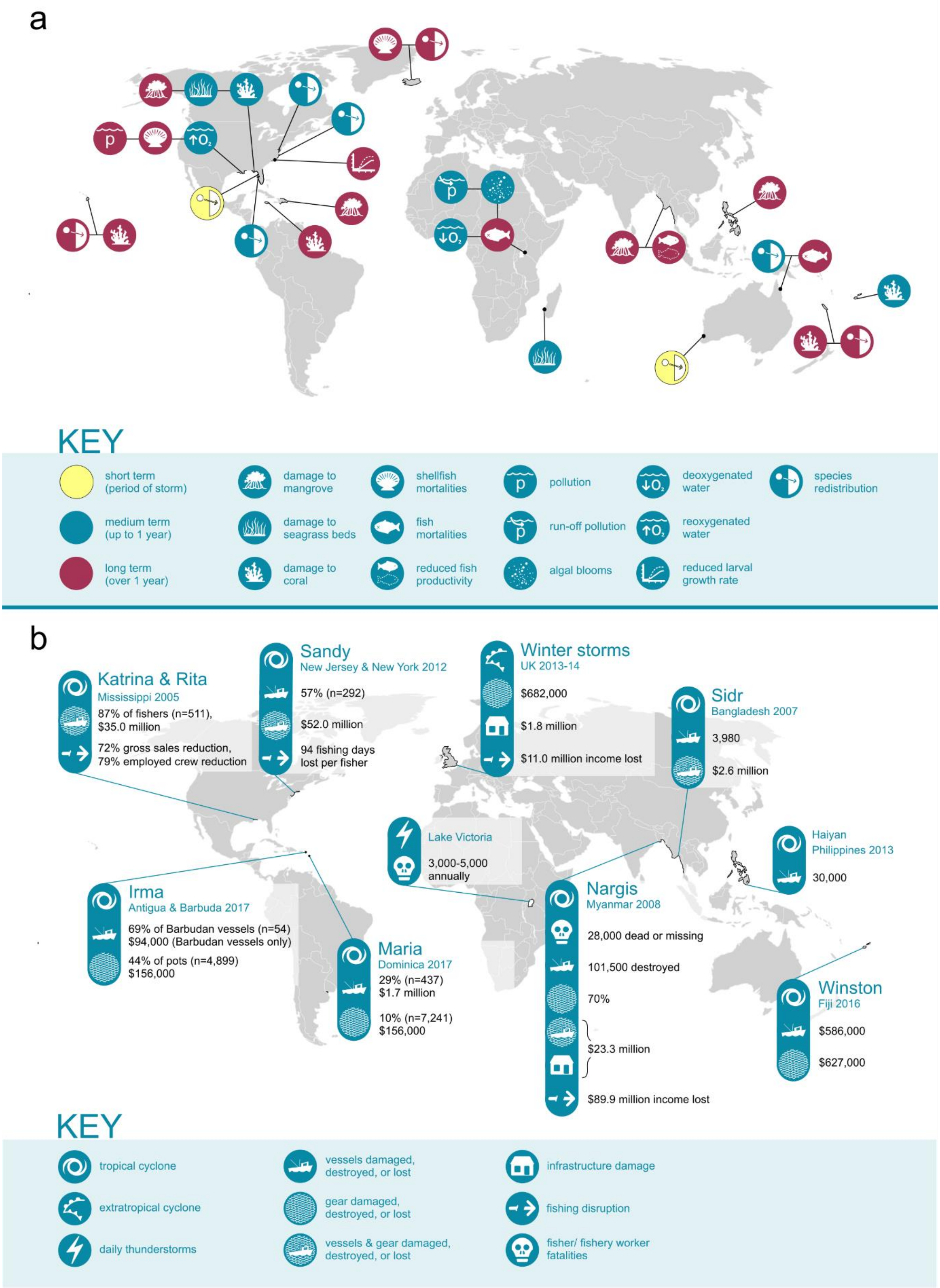

Figure 1. Ecological, social and economic impacts of storms on fisheries. (a) Examples of storm-induced marine ecosystem disturbances. For further detail see

Supplementary Information Section 1a. (b) Examples of social and economic impact case studies from the twenty-first century. Case studies were selected based on scale of the impacts, global geographic spread and availability of data. For further detail see Supplementary Information Section 1b.

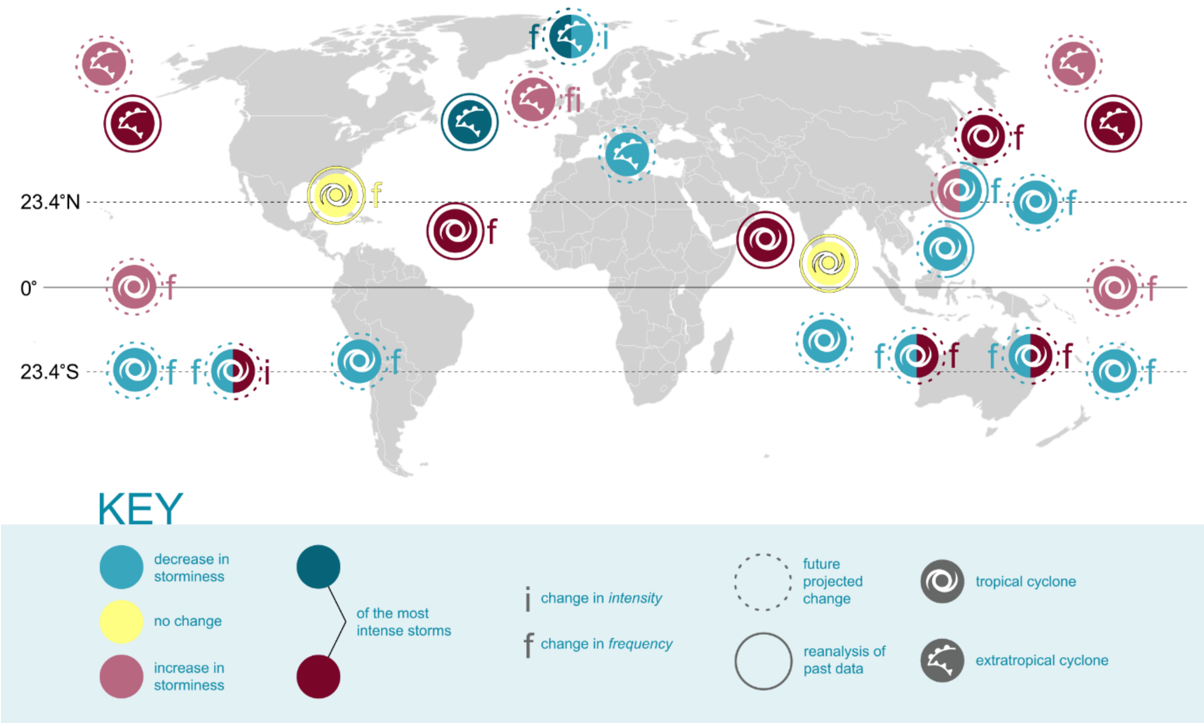

Figure 2. The spatially heterogeneous nature of changing global storminess. The selection of studies is not systematic, but is designed to reflect a range of studies carried out for the Atlantic, Pacific and Indian Oceans, which account for the majority of global fish catch. For further detail see Supplementary Information Section 2.

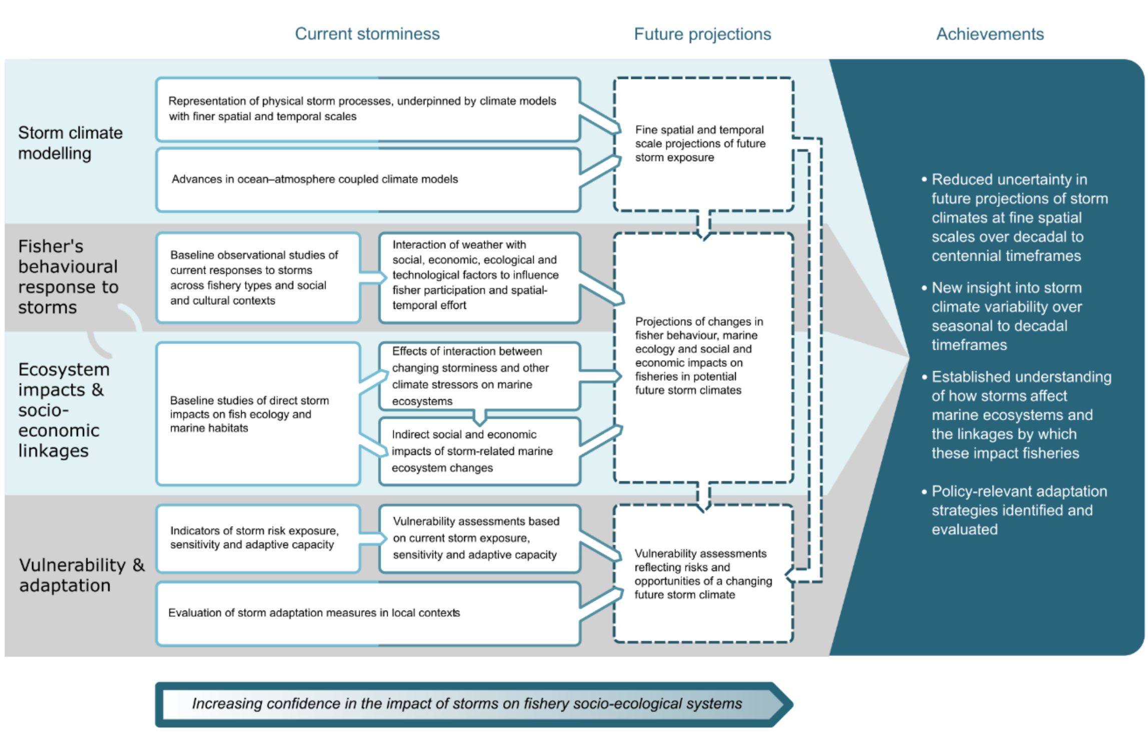

Figure 3. Schematic of a research roadmap to understand the impact of changing storminess on fisheries. Straight arrows between boxes demonstrate the dependencies within and between research streams. Curved arrows represent the feedback loop in which changes in fisher behaviour affect the ecosystem and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

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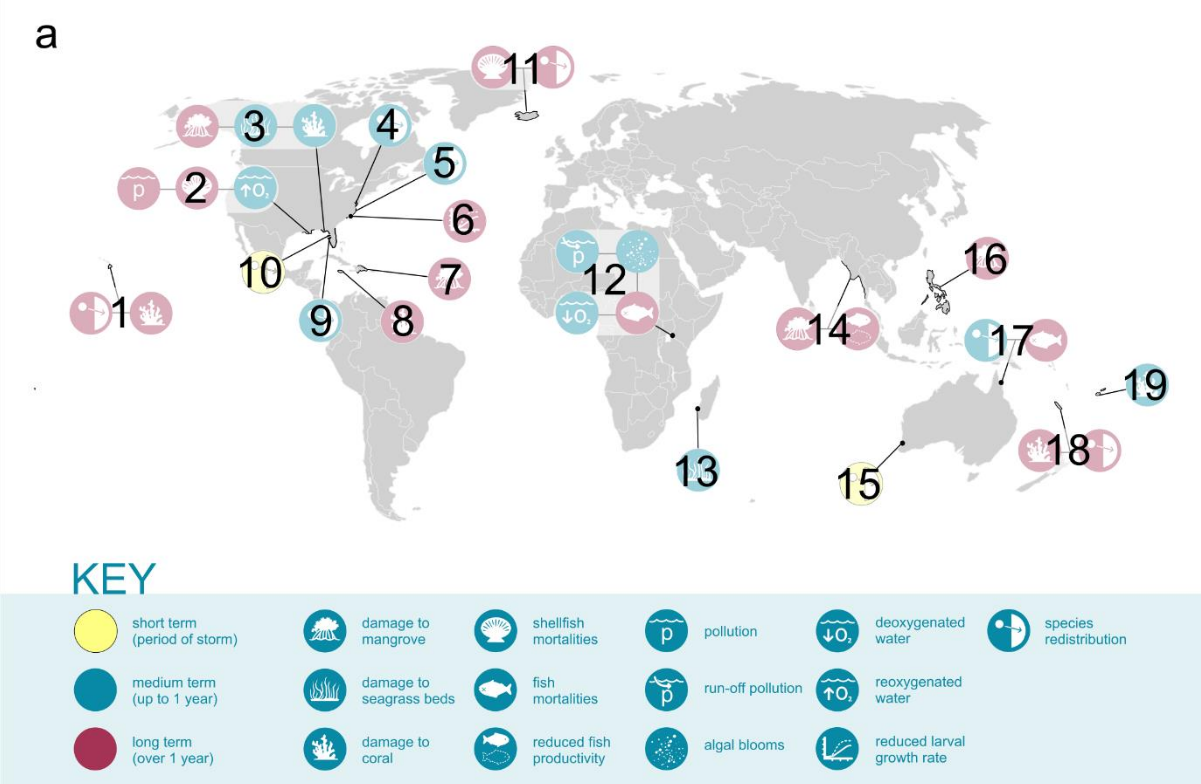
Supplementary Information Section 1a

This section provides references and additional detail for Figure 1a.



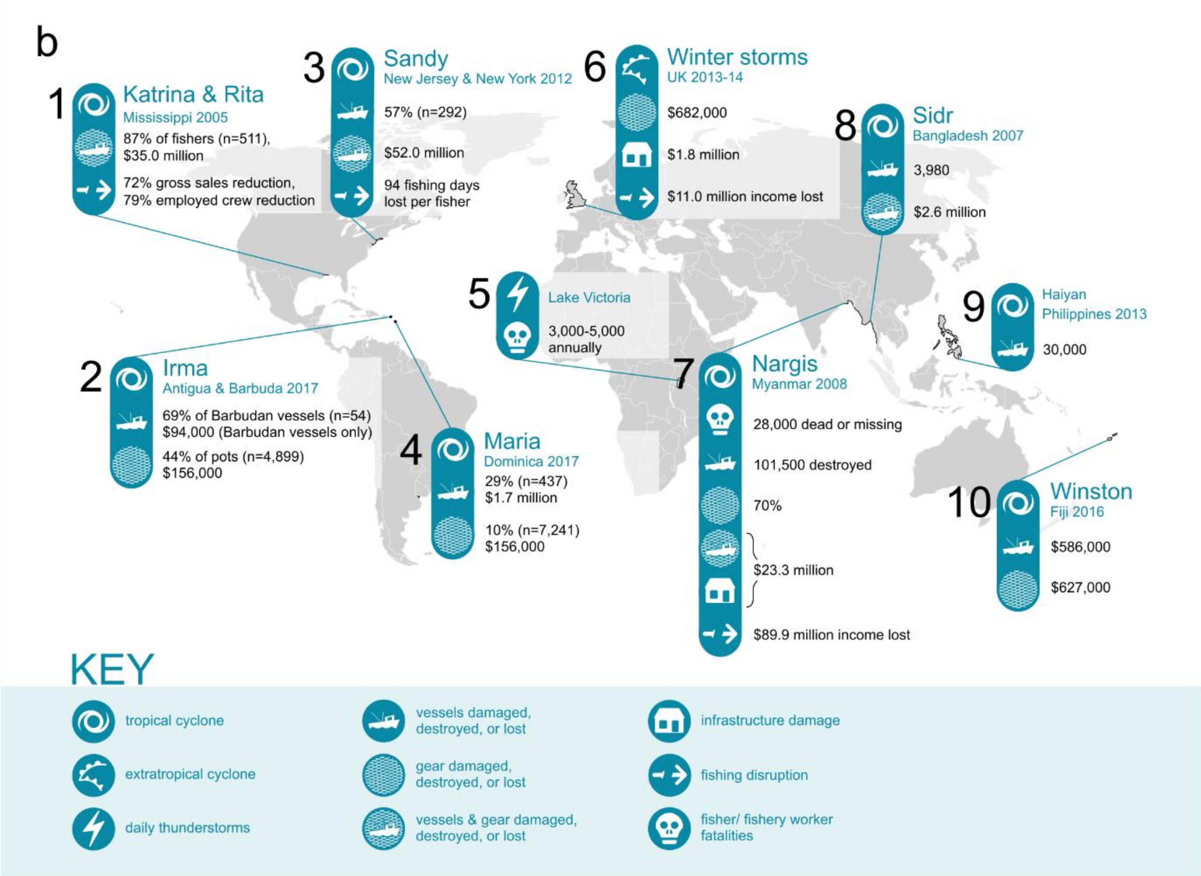
Supplementary Figure 1a. Figure 1a with additional case study reference numbers linking to Supplementary Table 1a.

Supplementary Figure 1a Map Reference	Location	Species	Storm type	Impacts (and source reference)	Time period of impact	Notes
1	Kona, Hawaii	Corals and various reef fish including *Paracirrhites arcatus, Cirrhitops fasciatus* and *Chromis vanderbilti*	Unnamed storm (1980)	Species redistribution; Coral damage[1]	Long term	After 16 months whilst some fish had returned to their pre-storm areas, other remained in shifted locations
2	Mississippi / Louisiana, USA	Shellfish and offshore habitat	Hurricanes Rita, Wilma and Katrina (2005)	Pollution (debris); Shellfish mortalities; Reoxygenated coastal waters[2]	Pollution (long term); shellfish (long term); reoxygenation of water (medium term)	Pollution includes chemical from onshore and offshore industry, organic pollutants and debris from damaged infrastructure
3	Florida, USA	Mangroves	Hurricane Wilma (2005)	Mangrove damage; seagrass bed damage; coral damage[2]	Mangrove damage (long term); seagrass bed damage (medium term); coral damage (medium term)	Timing of damage assessment places seagrass bed and coral damage as medium term impacts. Mangrove damage stated as longer than one year
4	Chesapeake Bay, Washington/Virginia, USA	Pelagic and bentho-pelagic fish species including *Anchoa mitchilli, Ameiurus nebulosus, Lepomis sp., Etheostoma olmstedi* and *Perca flavescens*	Hurricane Isabel (2003)	Species redistribution[3]	Medium term	Fish surveys took places in the months following Hurrricane Isabel
5	North Carolina, USA	Blue crab *Callinectes sapidus*	Hurricanes Dennis and Floyd (1999)	Species redistribution[4]	Medium term	Storm caused river flooding that flushed blue crabs downstream into offshore waters where they were heavily harvested by commercial fisheries
6	Onslow Bay, North Carolina, USA	Atlantic menhaden *Brevoortia tyrannus*	Unnamed storm (1986)	Reduction in larval growth rate[5]	Long term	Data collected within two months of storm. Impact for fish popoulation will be greater than one year
7	Dominican Republic	Mangroves	Hurricane Georges (1998)	Mangrove damage[6]	Long term	Damage surveyed at 7 and 18 months after the storm
8	Jamaica	Corals	Hurricane Allen (1980)	Coral damage[7]	Long term	Post-storm recruitment by the coral, *Acropora* , was nominal. Others were showing signs of recovery over the three years after the storm
9	Charlotte Harbor estuary and Peace River watershed, Florida, USA	Various estuarine fish including *Micropterus salmoides, Lepomis macrochirus, Paralichthys albigutta, Lutjanus griseus, Arius felis, Epinephelus itajara, and Centropomus undecimalis, Hoplosternum littorale and Pterygoplichthys spp.*	Hurricane Charley (2004)	Species redistribution[8]	Medium term	Changes in fish assemblages observed in the two months following the storm. Alterations associated with storm-related hypoxia
10	Terra Ceia Bay, Florida, USA	Blacktip sharks *Carcharhinus limbatus*	Hurricane Gabrielle (2001)	Species redistribution[9]	Short term	Blacktip sharks evacuated the affected area in the period leading up to the storm and returned immediately afterwards
11	Iceland	Ocean quahog *Arctica islandica*	Unnamed strorm (2006)	Shellfish redistribution; Shellfish mortality[10]	Long term	Ocean quahog moved by storm to a hard ocean bottom where, a year later, they were found to have been subject to easy predation
12	Nyanza Gulf of Lake Victoria, Kenya	Fish species *(Lates niloticus* and *Oreochromis niloticus)*	Unnamed storm (1984)	Algal bloom; Run-off pollution; De-oxygenation; Fish mortalities[11]	Algal bloom (medium term); Run-off pollution (medium term); De-oxygenation (medium term); Fish mortalities (long term)	Lower than average lake levels combined with run-off sediment, churned-up lake bottom mud, water hypoxia and algal bloom to cause mass fish mortality event. Whilst the environmental conditions caused by the storm were medium term, the fish mortality event has been classified as long term
13	Andavadoaka, Madagascar	Seagrass	Tropical Cyclone Haruna (2013)	Seagrass bed damage[12]	Medium term	Damage assessed within a month of the storm. Further studies would have been required to establish whether damage lasted more than a year
14	Myanmar	Mangroves and fish species	Cyclone Nargis (2008)	Mangrove damage; Reduced fish productivity[13]	Long term	Cyclone Nargis destroyed 38,000 hectares of mangroves. It has been assumed that the recovery will take morwe than one year. The loss of mangrioves destroyed fish breeding grounds, reducing fish productivity (as with mangrove impacts, this has been assumed to be long term)
15	Warnbro Sound,Western Australia, Australia	Various reef fish including *Austrolabrus maculatus* and *Parma mccullochi*	Four unnamed storms (2013)	Species redistribution[14]	Short term	Study noted variation in the sensitivity of species to storm-related environmental factors during storms.
16	Phillipines	Mangroves	Typhoon Haiyan (2013)	Mangrove damage[15]	Long term	Damage to mangroves remained when study areas were revisited 18 months after the storm
17	Lizard Island (northern Great Barrier Reef), Australia	Reef fish (extensive list of species)	Cyclone Eddie (1981)	Species redistribution; Fish mortality[16]	Species redistribution (medium term); Fish mortality (long term)	High mortality rates of juvenile fish (classified as loing term). Sub-adult fish re-distributed but adult fish did not appear to be affected by the storm. Studies took place regularly in the lead up to, and two days after, the storm
18	New Calidonia	Reef fish and coral	Cyclone Erica (2003)	Coral damage; Species redistribution[17]	Long term	Data collected within a month of the storm and 20 months after the storm. Impact on fish assemplages found to be greater after 20 months than before or just after the storm
19	Fiji	Corals	Cyclone Winston (2016)	Coral damage[18]	Medium term	Damage to coral assessed within a month of the storm. No follow up studies were reported, so impact has been classified as medium term

Supplementary Table 1a. Additional detail and references for Figure 1a.

Supplementary Information Section 1b

This section provides references and additional detail for Figure 1b.



Supplementary Figure 1b. Figure 1b with additional case study reference numbers linking to Supplementary Table 1b.

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Supplementary Figure 1b Map Reference	Location	Event	Impact type	Extent of impact (and source reference)	Notes
1	USA (Mississippi only)	Hurricanes Katrina and Rita 2005	Vessels/gear damaged/lost/destroyed	87% (n = 511)[19]	% of resident licensed Mississippi commercial fishing units damaged estimated based on sample (of 1,030 licensed vessels, 511 returned surveys)
			Vessels/gear damaged/lost/destroyed	$35.0 million[19]	Estimate calculated using average total damages reported by resident licensed Mississippi commercial fishing sample units (n = 511) multiplied by total number of fishing units (n = 1030)
			Fishing disruption	72% gross sales reduction in 2006 compared to 2004[19]	Based on estimates of projected gross sales reduction due to lost market channels from resident licensed Mississippi commercial fishing survey respondents (n = 511)
			Fishing disruption	79% employed crew reduction[19]	Based on reduction in employed crew in 2006 compared to 2004 reported by resident licensed Mississippi commercial fishing survey respondents (n = 511)
2	Antigua and Barbuda	Hurricane Irma 2017	Vessels damaged/lost/destroyed	69% (n = 54) of Barbudan vessels[20]	37 out of 54 active fishing vessels in Barbuda damaged or destroyed
			Vessels damaged/lost/destroyed	$94,000 (Barbudan vessels only)[20]	All vessels affected were Barbudan. XCD to US$ conversion 1:0.37 taken from www.xe.com historic exchange rate database for 01/09/17 (source report published September 2017)
			Gear damaged/lost/destroyed	44% (n = 4,899)[20]	Some losses may be attributable to Hurricanes Jose and Maria. 2,177 of 4,899 fishing pots lost
			Gear damaged/lost/destroyed	$156,000[20]	Some losses may be attributable to Hurricanes Jose and Maria. Losses experiences across Antigua and Barbuda. XCD to US$ conversion 1:0.37 taken from www.xe.com historic exchange rate database for 01/09/17 (source report published September 2017)
3	USA (New Jersey and New York)	Hurricane Sandy 2012	Vessels/gear damaged/lost/destroyed	$52.0 million[21]	Based on surveys conducted with sample of New york and New Jersey commercially licensed fishers (n = 292). Estimate based on average value of damages and losses per vessel multiplied by total number of licensed vessels
			Vessels damaged/lost/destroyed	57% (n = 292)[21]	Based on surveys conducted with sample of New york and New Jersey commercially licensed fishers (n = 292)
			Fishing disruption	94 fishing days per fisher on average[21]	Based on surveys conducted with sample of New york and New Jersey commercially licensed fishers (n = 292)
4	Dominica	Hurricane Maria 2017	Vessels damaged/lost/destroyed	29% (n = 437)[22, 23]	128 out of 437 fishing vessels damaged or destroyed
			Vessels and engine damaged/lost/destroyed	$1.7 million[22]	Estimate
			Gear damaged/lost/destroyed	10% (n = 7,241)[23]	746 out of 7,241 gears affected
			Gear damaged/lost/destroyed	$156,000[23]	Initial estimate. XCD to US$ conversion 1:0.37 taken from www.xe.com historic exchange rate database for 01/10/17 (source report published October 2017)
5	Kenya / Tanzania / Uganda	Daily thunderstorms	Fisher / fishery worker fatalities	3000–5000 annually[24]	Estimate
6	UK	Winter storms 2013–2014	Gear damaged/lost/destroyed	$682,000[25]	Based on the value of claims made by fishers under the UK Government's Gear Replacement Scheme. GB£ to US$ conversion 1:1.710 taken from www.xe.com historic exchange rate database for 30/0/6/14 (date applications closed for the grear replacement scheme)
			Fishing disruption	$11.0 million income lost[26]	Estimate made based on reduced catch at port of Newlyn, Cornwall during January and February 2014. GB£ to US$ conversion 1:1.567 taken from www.xe.com historic exchange rate database for 19/11/14 (date source report published)
			Fishery infrastructure damage	$1.8 million[27]	Level of funding support provided by UK Government to repair damage to fishing ports. GB£ to US$ conversion 1:1.622 taken from www.xe.com historic exchange rate database for 01/10/14 (date source report published)
7	Myanmar	Cyclone Nargis 2009	Fisher / fishery worker fatalities	28,000 dead or missing[28]	Estimate
			Vessels damaged/lost/destroyed	101,500 destroyed[28]	Mostly small inland vessels
			Gear damaged/lost/destroyed	70%[28]	Estimate
			Vessels/gear/facilities/ transport and infrastructure damaged/lost/destroyed	$23.3 million[29]	Estimate. KYAT to US$ conversion 1:0.0009 as used elsewhere within the source document
			Fishing disruption	$89.9 million income lost[29]	Estimate of foregone income. KYAT to US$ conversion 1:0.0009 as used elsewhere within the source document

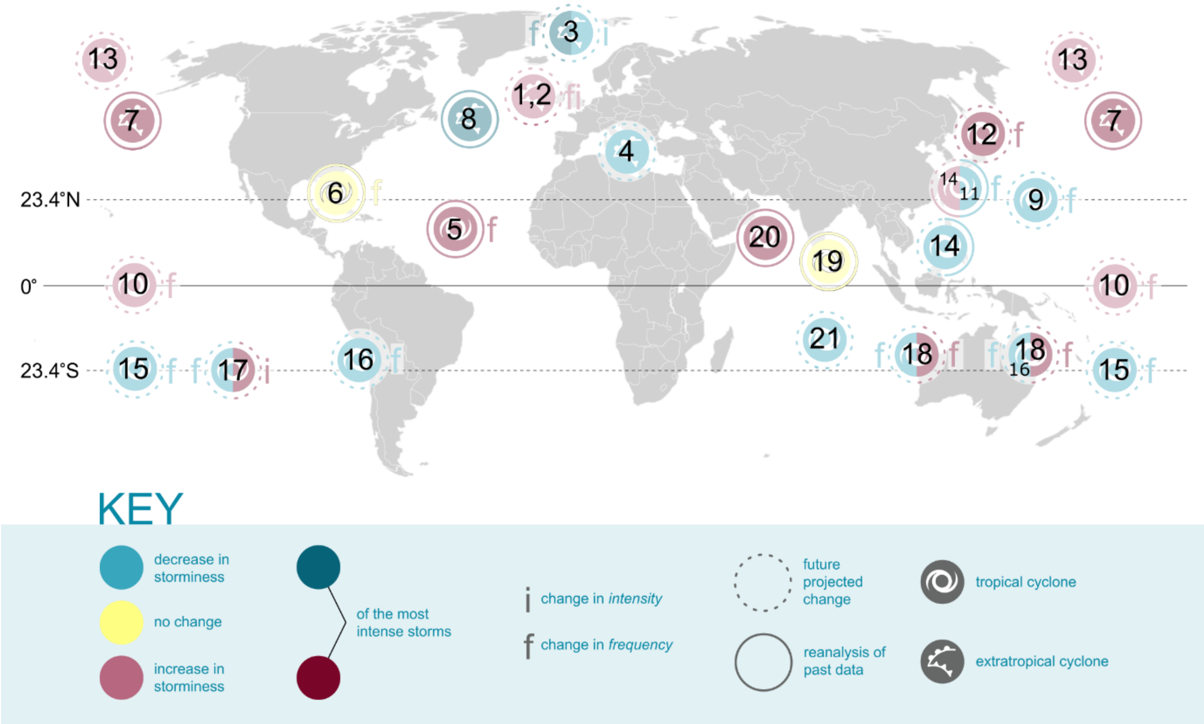
Supplementary Table 1b. Additional detail and references for Figure 1b.

Supplementary Figure 1b Map Reference	Location	Event	Impact type	Extent of impact (and source reference)	Notes
8	Bangladesh	Cyclone Sidr 2007	Vessels damaged/lost/destroyed	3,980[30]	Based on field trips to eight districts and cross checked with damage estimates carried out by Bangladesh Department of Fisheries
			Vessels/gear damage/lost/destroyed	$2.6 million[30]	Damage to boats and gear. Estimates range from US$1.9 million to US$3.3 million. An average of the two has been used. Based on field trips and cross checked with independent estimates
9	Phillippines	Typhoon Haiyan 2013	Vessels damaged/lost/destroyed	30,000[31]	Estimate.
10	Fiji	Cyclone Winston 2016	Vessels and engine damaged/lost/destroyed	$586,000[32]	Total of estimates made by fishers during surveys conducted with across a sample of affected villages (74%, n = 207) within six provinces. Bamboo rafts (bilibili) were not included. FJD to US$ conversion 1:0.485 taken from www.xe.com historic exchange rate database for 01/05/16 (mid-point of survey period)
			Gear damaged/lost/destroyed	$627,000[32]	Total of estimates made by fishers during surveys conducted with across a sample of affected villages (74%, n = 207) within six provinces. Bamboo rafts (bilibili) were not included. FJD to US$ conversion 1:0.485 taken from www.xe.com historic exchange rate database for 01/05/16 (mid-point of survey period)

Supplementary Table 1b (continued). Additional detail and references for Figure 1b.

Supplementary Information Section 2

This section provides references and additional detail for Figure 2.



Supplementary Figure 2. Figure 2 with additional case study reference numbers linking to Supplementary Table 2.

Supplementary Figure 2 Map Reference	Study type	Area	Type of storm	Reanalysis or Projection	Time period	Change described (and source reference)	Time of year
1	Review	Western Europe	Extra-tropical	Projection	Mix spanning 2020–2190 across 33 studies	Increase in frequency and intensity of storms[33]	Mix spanning September–April across 33 studies
2	Review	Eastern North Atlantic south of 60°N	Extra-tropical	Projection	Mix spanning 2020–2190 across 16 studies	Increase in frequency and intensity of storms[33]	Mix spanning September–April across 14 studies, 1 study May–December, 1 study not specified
3	Review	North Atlantic north of 60°N	Extra-tropical	Projection	Mix spanning 2020–2190 across 11 studies	Decrease in frequency of extreme cyclones and decrease in cyclone intensity[33]	Mix spanning September–April across 11 studies
4	Review	Southern Europe	Extra-tropical	Projection	Mix spanning 2020–2190 across 11 studies	Decrease behaviour of storminess over long term[33]	Mix spanning September–April across 9 studies, 2 studies not specified
5	Review	North Atlantic tropics	Tropical	Reanalysis	1970–2013	Most intense tropical cyclones are becoming more frequent since 1970s[34]	Not specified
6	New data	North Atlantic tropics	Tropical	Reanalysis	1900–2000	Hurricanes making landfall in USA have not become more frequent over last century[35]	All year
7	New data	Mid-latitude North Pacific	Extra-tropical	Reanalysis	1958–1977 and 1982–2001	Increasing trend in strong cyclonic activity[36]	January/February/March
8	New data	Mid-latitude North Atlantic	Extra-tropical	Reanalysis	1958–1977 and 1982–2001	Decreasing trend in strong cyclonic activity[36]	January/February/March
9	New data	Western part of Western North Pacific	Tropical	Projection	2075–2099	Decrease in frequency of tropical cyclones[37]	Peak tropical cyclone season in northern hemisphere
10	New data	Central Pacific	Tropical	Projection	2075–2099	Increase in frequency of tropical cyclones[37]	Peak tropical cyclone season in each hemisphere
11	New data	Western North Pacific	Tropical	Projection	2075–2099	Decrease in frequency of tropical cyclones approaching coastal regions[37]	Peak tropical cyclone season in northern hemisphere
12	New data	North-Western Northern Pacific	Tropical	Projection	2075–2099	Increase in frequency of most intense tropical cyclones[37]	Peak tropical cyclone season in northern hemisphere
13	New data	North Pacific near the Aleutian Islands	Extra-tropical	Projection	2081–2100	Enhanced storminess[38]	Not specified
14	New data	Western Northern Pacific	Tropical	Reanalysis and Projection	Reanalysis: 1980–2013; Projection: 2070–2099	Decreased tropical cyclone exposure in the Philippine and South China Sea regions and increased exposure in the East China Sea region[39]	July–November
15	New data	South Pacific	Tropical	Projection	2075–2099	Decrease in frequency of tropical cyclones[37]	Peak tropical cyclone season in southern hemisphere
16	New data	South Pacific	Tropical	Projection	2075–2099	Decrease in frequency of tropical cyclones approaching coastal regions[37]	Peak tropical cyclone season in southern hemisphere
17	Review	South Pacific	Tropical	Projection	Mix from 2061–2200	Tropical cyclone frequency will decrease. The intensity of the most intense storms will likely increase[40]	Not specified
18	New data	Australia	Tropical	Projection	2046–2065 and 2081–2100	Decrease in numbers of tropical cyclones overall, small increase in the most intense tropical cyclones[41]	All year
19	New data	North Indian Ocean	Tropical	Reanalysis	1901–1951 and 1951–2001	No increase in storms despite increase in sea surface temperature in Bay of Bengal and Arabian Sea[42]	Winter/ Pre-Monsoon / Monsoon / Post Monsoon
20	New data	Arabian Sea	Tropical	Reanalysis	Control experiments for 1860 (600 years), 1940 (200 years), 1990 (300 years), 2015 (200 years)	Global warming has increased the probability of post-monsoon extremely severe cyclonic storms over the Arabian Sea[43]	October–December
21	New data	South Indian Ocean	Tropical	Projection	2075–2099	Decrease in number of tropical cyclones[37]	Peak tropical cyclone season in southern hemisphere (November–April)

Supplementary Table 2. Additional detail and references for Figure 2.

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