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Climate change hotspots and implications for the global subsea telecommunications network

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ABSTRACT

A global network of subsea telecommunications cables underpins our daily lives, enabling >95% of global digital data transfer, $trillions/day in financial trading, and providing critical communications links, particularly to remote, low-income countries. Despite their importance, subsea cables and their landing stations are vulnerable to damage by natural hazards, including storm surges, waves, cyclones, earthquakes, floods, volcanic eruptions, submarine landslides and ice scour. However, the likelihood or recurrence interval of many of these types of events will likely change under future projected climate change scenarios, compounded by sea-level rise; potentially increasing hazard severity, creating previously unanticipated hazards, or hazards may shift to new locations during the 20–30-year operational life of cable systems. To date, no study has assessed the wide-reaching impacts of future climate change on subsea cables and landing stations on a global scale. Here, for the first time we synthesize the current evidence base, based on published peer-reviewed datasets, to fill this crucial knowledge gap, specifically to assess how and where future climate change is likely to impact subsea cables and their shore-based infrastructure. We find that ocean conditions are highly likely to change on a global basis as a result of climate change, but the feedbacks and links between climate change, natural processes and human activities are often complicated, resulting in a high degree of geographic variability. We identify climate change 'hotspots' (regions and locations likely to experience the greatest impacts) but find that not all areas will be affected in the same manner, nor synchronously by the same processes. We conclude that cable routes should carefully consider locally-variable drivers of hazard frequency and magnitude. Consideration should be given both to instantaneous events (e.g. landslides, tropical cyclones) as well as longer-term, sustained impacts (e.g. seabed currents that circulate even in deep water). Multiple factors can combine to increase the risk posed to subsea cables, hence a holistic approach is essential to assess the compounded effects of both natural processes and human activities in the future.

1. Introduction

The global economy relies on uninterrupted use of a seafloor network of >400 fibre-optic cable systems that extend 1.8 million km across the global ocean (Carter et al., 2009; Burnett and Carter, 2017; Fig. 1A&B). Today, more than 95% of all digital data traffic worldwide and $trillions/day in financial transactions are transferred via this vital network (Burnett and Carter, 2017). As a consequence, subsea cables are considered critical infrastructure by many governments. A growing demand for greater bandwidth, shorter latency, and improved remote communications is leading to even greater dependence on subsea cables, which was acutely exposed during the COVID-19 pandemic when internet use surged by 70% (Telegeography, 2020). Yet, despite their importance, subsea cables and their associated shore-based landing stations can be damaged by natural processes and human activities (Carter et al., 2009; Fig. 1C). Repair costs can reach $100s of millions, with further, more financially significant knock on effects as underlined in a UK Policy Exchange Report: *"The effect (of cable breaks) on*

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international finance, military logistics, medicine, commerce and agriculture in a global economy would be profound… When communications networks go down, the financial services sector does not grind to a halt. It snaps to a halt." (Sunak, 2017). To remain resilient, it is crucially important that the cable network is future-proofed to anticipate and withstand environmental and anthropogenic hazards as much as practicable.

1.1. External threats to subsea cables

Human activities, primarily bottom fishing and ship anchoring, account for most of the 200–300 faults that occur on subsea cables annually, while natural hazard events such as storms, earthquakes, submarine landslides and other unknown environmental causes relate to <20% (Carter et al., 2009; Fig. 1C). While fewer in number than those linked to human activities, instances of cable damage arising from natural hazards can be significant as they can synchronously damage multiple cable systems across large areas, isolating whole regions. One example of such an impact was a sediment flow in the deep sea Congo Canyon that was triggered by a 1 in 50 year river flood (Talling et al., 2022). This powerful and long run-out flow (travelling >1000 km) broke cables connecting West and South Africa, and restricted internet connections during the early stages of the first COVID-19 lockdown (Talling et al., 2022). Tropical cyclones severed subsea cable links to Taiwan in 2009 (Carter et al., 2014), and storms caused widespread damage to cables and landing stations across the Caribbean in 2015 (Internet Society, 2018) and knocked out internet connections in New York in 2012 (CNET, 2012). Cable damaging events disproportionately affect remote island states, particularly those with few connections and hence they are more vulnerable. A timely and recent reminder was in January 2022, when the only cable connecting the Kingdom of Tonga to the rest of the world was severed following the eruption of the Hunga Tonga-Hunga Ha'apai volcano, cutting international communications at a critical time for disaster response (National Geographic, 2022).

1.2. A need to address climate change hazards for subsea cables

Subsea cables and their landing stations are designed to operate over 20–30 years. However, the risks facing subsea cables and their landing stations are likely to change on at least decadal timescales, as a result of future climate change and its subsequent effects. These effects are already being felt, and the changing risk profile was acknowledged by the Under-Secretary-General for Legal Affairs and United Nations Legal Counsel: *"Sea-level rise is projected to negatively affect various economic sectors, including by damaging electrical and telecommunication support facilities"* and (as a result of rapid rates of sea level rise) *"low-lying communities, including those in coral reef environments, urban atoll islands and deltas, and Arctic communities, as well as small island developing States and the least developed countries, are particularly vulnerable"* (United Nations, 2021).

Climate change is likely to intensify and/or diversify natural hazards, potentially impacting new locations, and perhaps creating previously-unanticipated hazards. A study of sea-level rise impacts on terrestrial

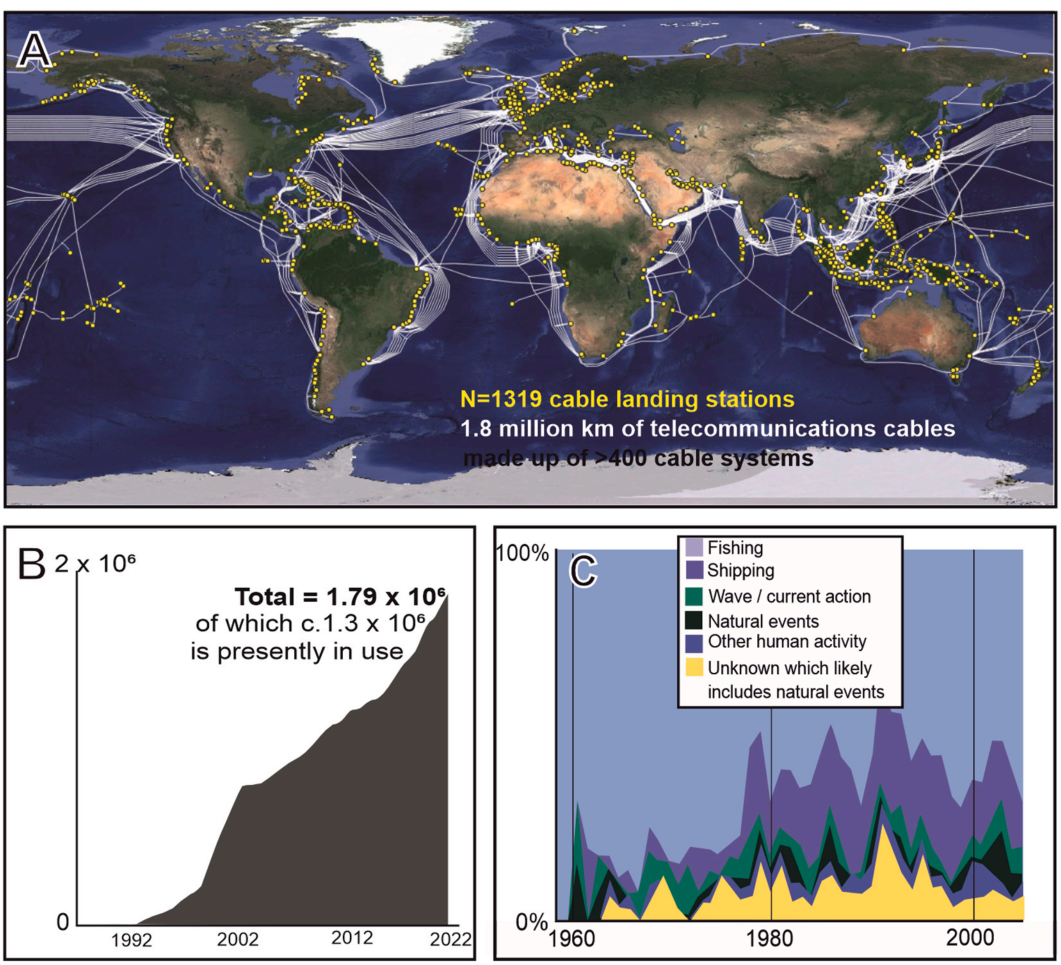

Fig. 1. Overview of the global subsea telecommunications network. (A) General distribution of subsea cables and landing stations based on database of Telegeography (2022). Background topography based on Google Earth. (B) Cumulative length of installed subsea fibre optic cables to date based on Telegeography (2022). (C) External cable faults reported between 1959 and 2000 based on analysis in Carter et al. (2009). Faults caused by fishing and shipping activities are largely in water depths shallower than 200 m.

internet infrastructure in the USA concluded that thousands of km of onshore cable (that is not designed to be immersed in water) may become submerged due to the effects of sea-level rise by 2030 (Durairajan et al., 2018). However, sea-level rise is a "*threat multiplier*" (United Nations, 2021) and Durairajan et al. (2018) did not consider other associated or compounded climate change related impacts, such as: i) inundation by storm surges (whose frequency and impacts will likely increase under sea-level rise); ii) compound effects of other flooding types (e.g. river, coastal and surface water); iii) indirect effects such as enhanced coastal erosion, seafloor mobility and slope instability that may expose/displace buried cables or undermine landing stations; and iv) other hazards, whose frequency, magnitude may increase as a function of future climate change, including human activities. No study has yet assessed the exposure and resilience of subsea cables and landing stations to the wide-reaching impacts of climate change on a global scale, exposing a significant gap in our current understanding.

1.3. Aim and objectives

The Intergovernmental Panel on Climate Change (IPCC) 6th Assessment Report projects a range of scenarios for future climate change, depending on how much fossil fuel emissions are reduced and the extent of other mitigation measures (Intergovernmental Panel on Climate Change, 2021). These future climate scenarios (termed 'Shared Socioeconomic Pathways' by Intergovernmental Panel on Climate Change, 2021) will impact many atmospheric, oceanographic and other natural processes in diverse ways and at different locations; often with complex and extremely geographically variable outcomes. Here, our overall aim is to assess how existing hazards have already changed and may change in future due to climate change and determine whether new hazards may arise. We base our assessments on recently published peer-reviewed datasets (Table 1). First, we address the more direct effects of climate change, focusing on sea-level change and the landing station locations that are prone to the highest rates of rise under two IPCC scenarios. Second, we consider transient sea-level changes that result from storm surges, their potential to inundate shore-based infrastructure, and how their frequency and magnitude may change in response to climate change. Third, we consider less direct climate change impacts that include modified coastal erosion, extra-tropical and tropical cyclones, river flooding, wave conditions, and submarine landslides. Fourth, we discuss observed and potential knock-on effects that may modify human activities with the potential to impact subsea cables, including fishing and shipping. Finally, we discuss mitigation and adaptation strategies to respond to the identified climate change-driven impacts, incorporating inputs from subsea cable practitioners.

It is worth highlighting that the future effects of climate change may lead to fundamental shifts in the behaviour of natural systems, wherein they reorganize and conditions may not return to their initial state, even if the drivers are eased (Intergovernmental Panel on Climate Change, 2021). These switches are often referred to as 'tipping points'; and can result markedly distinct or potentially unexpected responses where climate change exceeds some critical threshold, and the system moves from one stable state to another (Intergovernmental Panel on Climate Change, 2021). We do not explicitly address tipping points in this review; however, we do highlight instances where dramatic changes may occur beyond certain thresholds and where responses may be non-linear.

Table 1
Datasets and models used in this study to project future climate change impacts for subsea cables.

Hazard / Activity Assessed	IPCC or Equivalent Scenario(s)	Reference
Inundation from 1 in 100 year storm surges based on Global Tide and Surge Reanalysis	SSP5–8.5	Muis et al. (2016)
Coastal erosion	SSP5–8.5	Vousdoukas et al. (2020)
Return period for river floods equivalent to 20th century 100 year flood	SSP5–8.5	Hirabayashi et al. (2013)
Tropical and extratropical cyclones	RCP8.5	Dullaart et al. (2021)
Surface wave height	RCP8.5	Morim et al. (2019)
Seafloor currents	RCP8.5	Hu et al. (2020)
Change in maximum fishing catch potential	Emission Scenario A1B	Cheung et al. (2010)
Predicted habitat suitability for commercially important fish in the N Atlantic	RCP8.5	Morato et al. (2020)
Anchor drops from shipping	RCP2.6 and 8.5	Ng et al., 2018

2. Data and methods

2.1. Architecture of subsea cable routes

In the deep ocean (here defined as >2000 m water depth) a modern subsea telecommunications cable is typically a 17–21 mm diameter, polyethylene tube that encases a steel strengthening member, a copper power line and optical glass fibres (Carter et al., 2009) (Fig. 2A). This cable type is laid directly on the seabed surface. In contrast, telecommunications cables in <2000 m water depth may be as large as ~50 mm diameter due to the addition of protective steel wire armour. Additional protection comes from the burial of cables beneath the seabed especially on the continental shelf (0 - ~130 m water depth) where commercial fishing and ship anchoring are pervasive (e.g. Watson et al., 2022). Where a cable comes ashore, it may terminate at a beach manhole (Fig. 2A). This is commonly a concrete structure set into the beach where the subsea cable connects to a terrestrial fibre-optic counterpart that extends further inshore to a cable landing station. In some instances, a beach manhole may not be required and the submarine cable extends directly to the landing station. While stations can vary, they typically contain: (i) Direct Current generators to power repeaters spaced at 70–100 km intervals along a cable route in order to amplify the optical signals; and (ii) line terminal equipment that links the optical traffic to terrestrial networks. Landing stations can be built near or tens of kilometres from the beach manhole depending upon local environmental conditions, land availability, security and other constraints. In this paper, the terminus of a subsea cable system is arbitrarily chosen to be the cable landing station, while recognizing that other submarine systems can terminate at the beach manhole.

2.2. Cable and landing station locations

Analysis of cable faults and assessment of hazard locations relative to cables was performed using a proprietary database provided by Global Marine Ltd. (which was also the basis of two prior cable fault studies focused specifically on tropical cyclones and earthquakes; Pope et al., 2017a&b). As this database is proprietary, it cannot be shared here. Instead, cable route locations and landing stations presented are based on the open-access Telegeography dataset (Telegeography, 2022). The Telegeography database does not reveal the precise real-world locations of cables and landing stations, but is appropriate to provide a visualization of the results of this study, particularly given its global scale.

2.3. Climate change scenarios

In this study we primarily assess climate change-related impacts that relate to the "Shared Socioeconomic Pathways" (SSPs) defined by the IPCC. These SSPs relate to different ways in which the world might evolve in response to different emissions pathways. In our synthesis, we use studies that reference SSPs where possible (specifically SSP1–2.6 and SSP5–8.5; Intergovernmental Panel on Climate Change, 2021; Fox-Kemper et al., 2021); however, due to the relatively recent

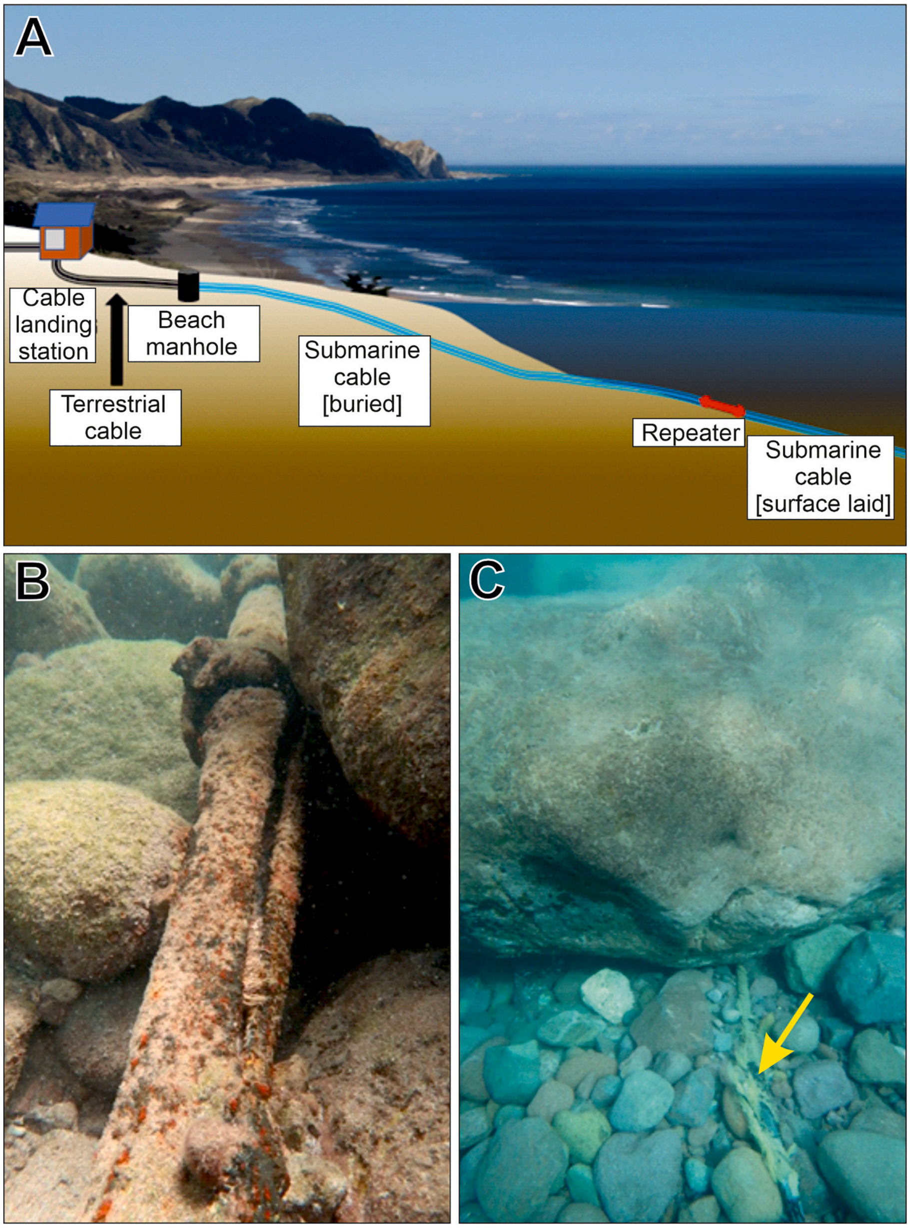

Fig. 2. Cable system architecture and examples of damage. (A) Schematic of a submarine fibre-optic cable system as it transitions from the ocean to the beach manhole and landing station. From there, the cable connects to the terrestrial network. (B) Photograph of cable protection (cast iron casing) damaged by mobilisation of the seafloor substrate. (C) Boulders moved over a cable (labelled with yellow arrow) by Hurricane Irma. Photographs courtesy of J.M. Koppers, Saba, Statia Cable System B.V. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

implementation of SSPs in the IPCC 6th Assessment Report (Intergovernmental Panel on Climate Change, 2021) this is not always possible. As a result, we also make reference to "Representative Concentration Pathways" (RCPs) in this report, which refer to IPCC scenarios that predate the 6th Assessment Report, which describe different levels of greenhouse gas emissions that might occur in the future (including four main pathways: 2.6, 4.5, 6.0, and 8.5 watts per m^2). The two SSPs that we select for our analysis represent differing projected severities of sea level rise, including: (i) SSP1–2.6, wherein global CO_2 emissions are cut substantially but net zero is reached after 2050, with an overall increase in temperature of 1.8 °C by the end of the century; and (ii) SSP5–8.5, in which CO_2 emissions double by 2050, with an average global temperature rise of 4.4 °C by 2100. These and other datasets on which we base our analysis are previously published and come from multiple sources as outlined in Table 1.

2.4. *Sea-level rise*

Regional relative sea-level rise projections were provided using two IPCC scenarios (Fox-Kemper et al., 2021): (i) the less severe SSP1–2.6; and (ii) more severe scenario SSP5–8.5. We use the median value (i.e. 50th percentile) of sea-level rise from the IPCC projections in our calculations. The sea-level projections include thermal expansion, mass loss from glaciers and ice sheets, changes in land-water storage and vertical land movements associated with glacial isostatic adjustment. The projections do not account for localized subsidence which can be very large (several metres) in specific coastal cities and across deltas (Meade, 1996; Syvitski et al., 2009; Nicholls et al., 2021). Note also, that larger sea-level rises are considered possible (up to 2.3 m by 2100), due to a range of possible processes including marine ice sheet instabilities (MISI) or marine ice cliff instabilities (MICI); assessing their likelihood is challenging and should be the subject of future work (Fox-Kemper et al., 2021).

2.5. Hazards other than sea-level rise

We also consider a wider range of natural hazards, based largely on prior evidence of cable damaging events (e.g. Carter et al., 2014; Shapiro et al., 1997). We provide examples of such events and synthesize published models and projections to relate the spatial footprint and temporal aspects of the different hazards, including storm surges, waves and coastal flooding, tropical and extra-tropical cyclones, coastal erosion, ocean currents, offshore weather, river flooding, submarine landslides, ice-related and other high latitude hazards, as well as climate impacts on human activities (Table 1). Where possible, we relate the future projections to the most recent IPCC SSPs and present maps to relate the spatial extent of different hazards to the existing subsea cable network.

3. The Earth System response to climate change and the relevance to subsea cables

We now provide a global view of climate change-related modifications to natural processes and human activities and discuss how they have, and are anticipated to impact subsea cables and landing stations.

3.1. Global variations in sea-level rise at cable landing stations

A global assessment of sea-level rise by 2052 (i.e. over a 30-year operational life of a cable system) shows that the picture is far from geographically uniform (Fig. 3). Relative sea-level rise is projected to be far more pronounced in certain regions, including the Gulf of Mexico, NW Australia, Pacific islands (e.g. Hawai'i, French Polynesia, Samoa, Fiji), SE Asia (e.g. Philippines, Indonesia), Japan and W Caribbean. Other areas will experience lower rates of rise, namely the Mediterranean and Red Sea, much of NW Europe and the majority of N and S American coastlines. Some localized parts of high latitude regions (e.g. Alaska, Norway) are likely to experience relative sea-level fall, rather than rise, as a result of on-going continental rebound following the past removal of ice sheets (Lindsey, 2020).

Projected sea-level was extracted at the locations where cables landfall for each scenario at future 30-year (2052), 50-year (2072) and 100-year (2122) intervals from present, as well as determining the projected time to reach more than 50 cm of sea-level increase (relative to the present day) at each of the cable landfall locations. Within 100 years, >50% of locations where cables landfall are forecast to experience

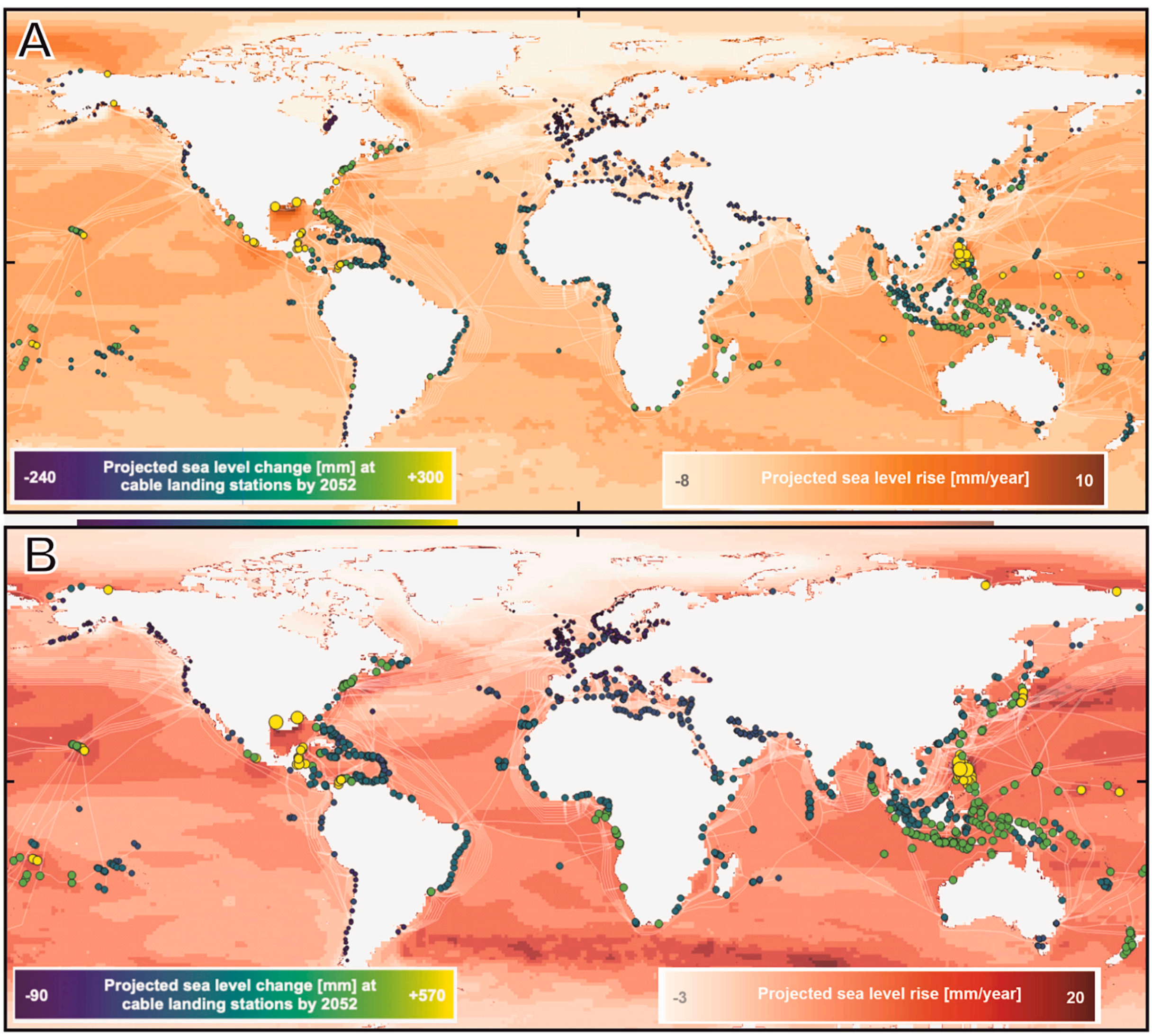

Fig. 3. Projected rates of sea-level rise and elevation change at cable landing stations. Cables shown in white. (A) Sea-level rise under SSP1–2.6 scenario (brown gradational colouring), annotated with projected sea-level rise by 2052 at existing cable landing stations (blue-yellow coloured circles that are also scaled proportionally to sea-level rise). (B) Sea-level rise under SSP5–8.5 scenario (red gradational colouring), annotated with projected sea-level rise at existing cable landing stations (blue-yellow coloured circles that are also scaled proportionally to sea-level rise). Sea level data from Intergovernmental Panel on Climate Change (2021). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

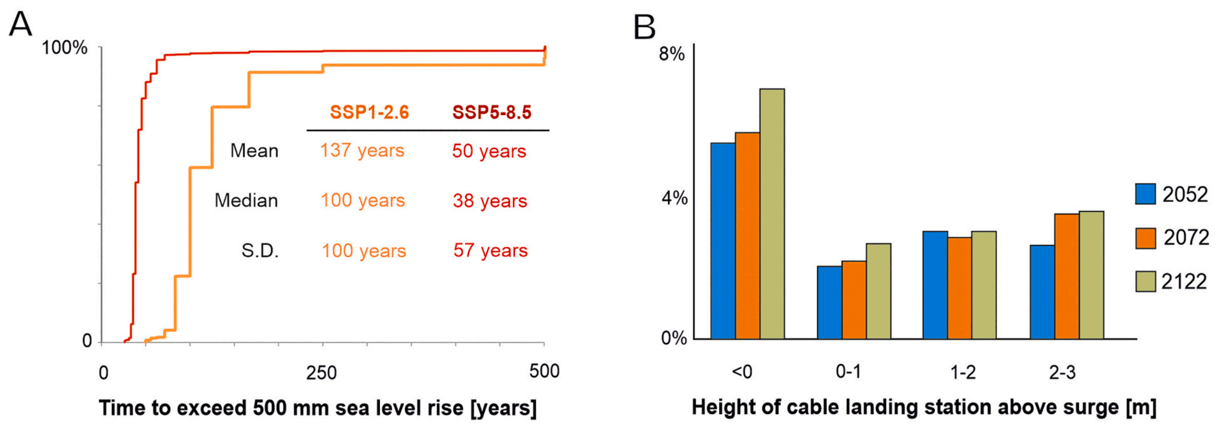

Fig. 4. Projected sea-level at cable landing stations. (A) Proportion of cable landing stations where sea-level rise is projected to reach >500 mm above present day levels within different timeframes under two IPCC sea-level scenarios. (B) Elevation of cable landing stations (expressed as a percentage of cable landing stations globally) above a 1 in 100 storm surge for the IPCC SSP5–8.5 scenario.

>500 mm of sea-level rise under the SSP1–2.6 scenario; whereas for the SSP5–8.5 scenario, this increases significantly to 97% (Fig. 4A). These data were then compared to the height of each cable landing station above present sea-level to identify stations that will lie below, at, or close to mean sea-level in each scenario. It is important to note that the locations selected were for the cable landing stations as presented in the Telegeography database, which do not necessarily represent the absolute location of the landing station; however, given the resolution of global bathymetric and topographic data (15 arc *sec* - equivalent to approximately 450 m; GEBCO Compilation Group, 2021), for the sake of this study this represents a reasonable first approximation. Based on the GEBCO-derived average topography, 37.6% of cable landing stations were found to lie within 10 m of the present mean sea-level, and 4.9% lie within 2 m. The majority of cable stations (80.6%) lie on slopes <4°. Under the SSP1–2.6 scenario only 1% of stations would become submerged by 2122 and 2.5% would be <2 m above mean sea-level. In the SSP5–8.5 scenario, 1.5% of stations are projected to lie beneath mean sea-level by 2052, increasing to 2.6% by 2122, while 4.9% would lie within 2 m of mean sea-level by 2052 and 7.1% by 2122. Cable station exposure to inundation is widely dispersed, controlled primarily by the height of the cable station.

3.2. Exacerbation of coastal inundation due to surge events

Considering IPCC multi-decadal projections of mean sea-level rise alone excludes short term fluctuations in sea-level. In particular this excludes those resulting from storm tides (storm surges, plus astronomical tides), which can be significant events for coastal infrastructure and communities. Storm surges are among the most costly and deadly natural hazards, and can episodically raise coastal water levels by up to 4 m due to extra-tropical weather systems, and over 9 m when caused by tropical systems (i.e. hurricanes, tropical cyclones; Dullaart et al., 2021). Tropical cyclones generally form over warm tropical waters, affecting regions such as SE Asia, South Pacific, the Caribbean and North Australia, while extra-tropical cyclones dominate in South America, Europe and South Australia (Horsburgh et al., 2021; Lugo, 2000). Some regions experience both storm systems, including west and east coasts of Australia, eastern China and the eastern seaboard of the USA.

Several recent studies conclude that storm surges themselves may contribute a bigger threat to coastal flooding than that anticipated by long-term climate change-induced sea-level rise alone. A global study found that existing models of coastal flooding, which exclude storm surges, dramatically underestimate the risk of coastal flooding (Dullaart et al., 2021). Their modelling better represented tropical cyclone risk by simulating 10,000 years of storm data. They predicted that 78 million people are exposed to an extreme flood (a 1000-year return period event) caused by extra tropical cyclones. When tropical cyclones are considered, that number more than doubles (up to 192 million people affected). These new results indicate that previous studies may have underestimated the global exposure to low-probability coastal flooding by a third. A second study, focused on the North Sea, concluded that over the next 10–30 years, the greatest threat from coastal extreme sea-levels is the potential underestimation of natural storm variability (Horsburgh et al., 2021). They simulated storm tides and waves for synthesized ‘grey swan’ events, which are storms expected on the grounds of natural variability but that are not within the observational record. Horsburgh et al. (2021) found that storms in the present-day climate are capable of locally generating additional extreme water levels comparable to the magnitudes of mean sea-level rise predicted by the IPCC under high emissions scenarios by 2100.

Cable-landing stations, beach manholes and their interconnecting cables can be exposed periodically to powerful winds and flooding; the latter reflecting storm surges and land run-off during severe rainstorms as shown by maps of flood-prone areas containing subsea cable infrastructure along the northeast United States coast (Durairajan et al., 2018; Wing et al., 2018). The impacts of Atlantic hurricanes Katrina (2005), Sandy (2012), Maria (2017) and Laura (2020) are particularly relevant as they affected a region with numerous cable landings (Comes and Van de Walle, 2014; Federal Communications Commission, 2020; Kwasinski, 2013; Lasley et al., 2007; Madory, 2012). Coastal flooding, especially by storm surges, may inundate and potentially damage local infrastructure (Vitousek et al., 2017; Vousdoukas, 2018). For example, direct flood damage to a Puerto Rico landing station occurred during Hurricane Maria, resulting from a storm surge of 1.8 to 2.7 m (Madory, 2017). It was necessary to switch off the power supply to the station to prevent further damage to telecommunications equipment by the rising flood waters (Madory, 2017). With respect to the beach manhole, if a subsea cable is jointed to a terrestrial cable, concern has been expressed that the terrestrial component may not be as durable as its submarine counterpart. Datwyler (2014) noted that some terrestrial cables are sheathed in polyethylene that is less robust than the impermeable, high-density polyethylene of subsea cables. Thus, it is suggested that in the long-term, some terrestrial cables may allow water ingress and subsequent downgrading of optical-fibre performance. Another consideration is regional power blackouts that can accompany hurricanes (e.g. Kwasinski, 2013; Ko, 2011). Loss of power to a cable landing station will cease operation of cable repeaters unless the station is supported by emergency back-up generators.

Exposure to storm tides is investigated here using the Global Tide and Surge Reanalysis (GTSR) (Muis et al., 2016), which estimates 1 in 100-year extreme sea-level events based on a hindcast from 1979 to 2014, conducted with the Global Tide and Surge Model (GTSM) and

Finite Element Solution 2012 (FES2012) tide model to simulate astronomical tides (Carrère et al., 2012)(Muis et al., 2016). Surge heights were extracted at each cable landing station and compared to the current height above sea-level at each station and those based on IPCC scenarios 30, 50 and 100 years from present (Fig. 4 & 5). Currently 4.1% of cable landing stations could be submerged by 1 in 100-year events, which rises to 7.0% by 2122 in the SSP5–8.5 scenario (Fig. 4B). The effect of sea-level rise means that a greater number of cable landing stations will more likely be affected by storm tides in the future (Fig. 5B). Again, the exposure to storm surges is not geographically uniform. Instead exposure is focused on certain areas, which include NW Europe, higher latitudes of N and S America and particularly the E coast of USA, E Africa, Bangladesh, Taiwan and NW Australia.

Our analysis does not include projected increases in the magnitude and frequency of storm surges, but these are likely to further increase the percentage of landing stations vulnerable to surge events. Ocean warming is predicted to play a key role in controlling the nature, frequency and location of storm tracks, and hence will also likely modify storm surges (e.g. Marsooli et al., 2019). Storm surges are thus likely to become more frequent as the climate warms. For example, when combining predictions of future storminess on probabilistic projections of sea-level rise along the coast of the United States, it is predicted that a historical 100-year return period event will occur at least every 30 years towards the end of the 21st century in the SE Atlantic and the Gulf of Mexico (Marsooli et al., 2019). Table 2 provides a summary of the regions where cables currently make landfall that are anticipated to experience the greatest impacts from the combinations of sea-level rise and storm tides.

3.3. *Exposure to coastal erosion and drivers of future erosion*

A substantial proportion of the world's coastline is already eroding as a result of ambient shoreline dynamics, and this is likely to be exacerbated by climate change and resultant sea-level rise (e.g. Luijendijk et al., 2018; Vousdoukas et al., 2020). The global median of predicted shoreline change under the previous IPCC RCP 8.5 scenario (broadly equivalent to the SSP5–8.5 scenario) is a retreat of 128 m by 2100 (Vousdoukas et al., 2020). It is estimated that approximately 15% of the world's sandy beaches could face severe (i.e. >100 m) erosion by 2050, rising to 35–50% by 2100 (Vousdoukas et al., 2020). This global erosive trend masks significant spatial and temporal variability, as erosion and accretion can both occur along adjacent coastal sections (particularly being affected by the presence of erodible coastline and the presence of human-built structures), and either during instantaneous events or progressively. Shorelines in some regions of high terrestrial sediment supply are accreting (e.g. Amazon, E and SE Asia and tropical N Pacific); however, the dominant global picture is that of erosion (Vousdoukas et al., 2020). Here, we use the global dataset of Vousdoukas et al. (2020) to visualize geographic variability in future coastal erosion, presenting only beaches where erosion is predicted (i.e. excluding accreting beaches; Fig. 6A). Local trends in erosion can be greater than several metres per year. Hotspots of coastal erosion include central and eastern N America, central America, SE South America, central Europe, E and W Africa, S Asia, N Australia, Pacific and Caribbean, which have median values of >100 m coastal erosion by 2100.

This model does not consider the effects of coastal retreat due to melting of permafrost nor the reduction of coastal fast ice, which will disproportionately affect Arctic regions (Liew et al., 2022). There is considerable uncertainty about such coastal retreat in the Arctic due to the diverse geology along the Arctic coast and the difficulty of site access to make direct observations. Further uncertainty in predictions of retreat along permafrost-affected coasts also stems from the effects of emerging processes associated with Arctic atmospheric warming and exposure of the coast to waves and ocean heat due to sea ice retreat (Irrgang et al., 2022). Nevertheless, field observations at multiple sites, combined with remote sensing data, show that some Arctic coastlines are already experiencing high rates of retreat. Mean multi–decadal rates of 0.5–1 m/year are reported, with measured annual erosion rates peaking up at >20 m/year and a total observed coastal retreat of 50–175 m in localized areas over the last two decades, such as Drew Point in Alaska and Mamontovy Khayata in the Laptev Sea (Rolph et al., 2021). These rates indicate that the total regional Arctic coastal retreat may reach ~1 km by the end of the 2100 and may exceed several kilometres following the 50–500% projected pan-Arctic under SSP1–2.6, SSP2–4.5 and SSP5–8.5 scenarios (retreat rates of 1.5–3 m/year; Nielsen et al., 2022). Other impacts may arise from such pronounced erosion. For example, by the end of 2100, the volume of eroded material entering the Arctic Ocean is projected to reach 681–1400 km^3, loading one third of the Arctic Ocean surface waters with this predominantly terrigenous matter. If all the eroded material accumulates on the Arctic shelf, this could create a

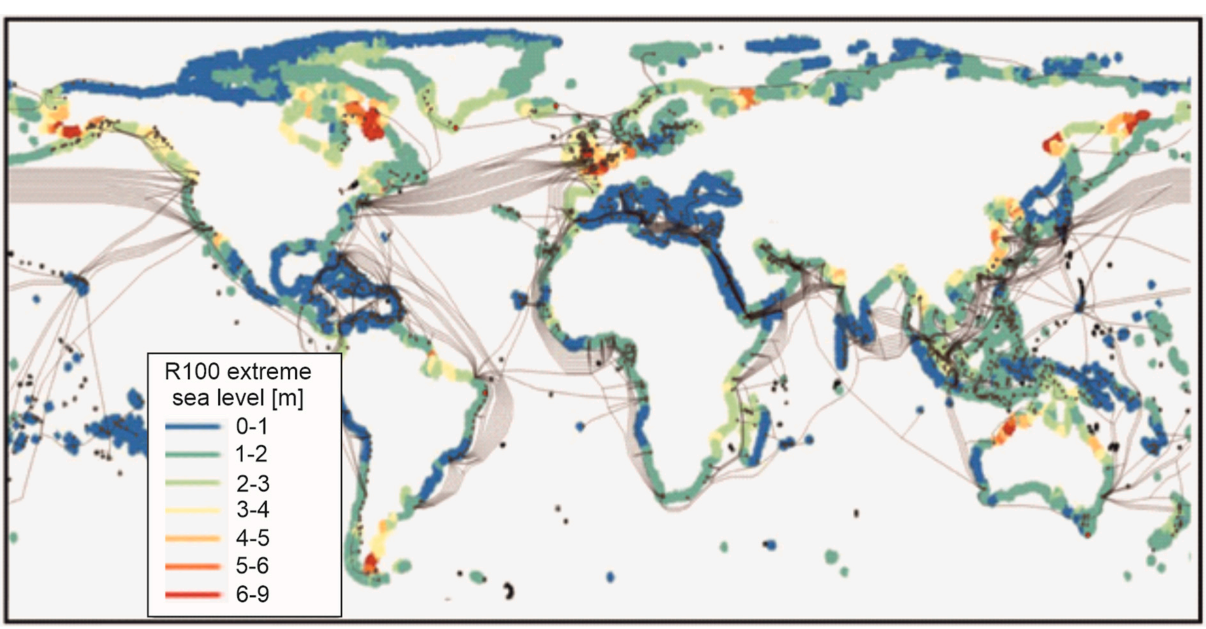

Fig. 5. Future extreme sea-levels relating to surges. Cables shown in black. Shown are projected 1 in 100-year (R100) sea-level surges established by Muis et al. (2016) for coastal regions based on the period 1979–2014.

Table 2
Overview of regions anticipated to experience greatest impacts from sea-level rise and storm levels under future climate change based on results of this study.

		Sea-level Rise		
		Low	Moderate	High
Storm Level	Low	Mediterranean, Red Sea	Southern Caribbean	Hawaii, French Polynesia
	Moderate	Majority of west coasts of North and South America (except N & S extremities)	Brazil, Guyana	Philippines, Indonesia, Japan, Western Caribbean, Samoa, Fiji
	High	NW Europe; Newfoundland; Highest latitude extremities of N and S America	East Africa, Bangladesh, Taiwan, Eastern USA	Gulf of Mexico, NW Australia

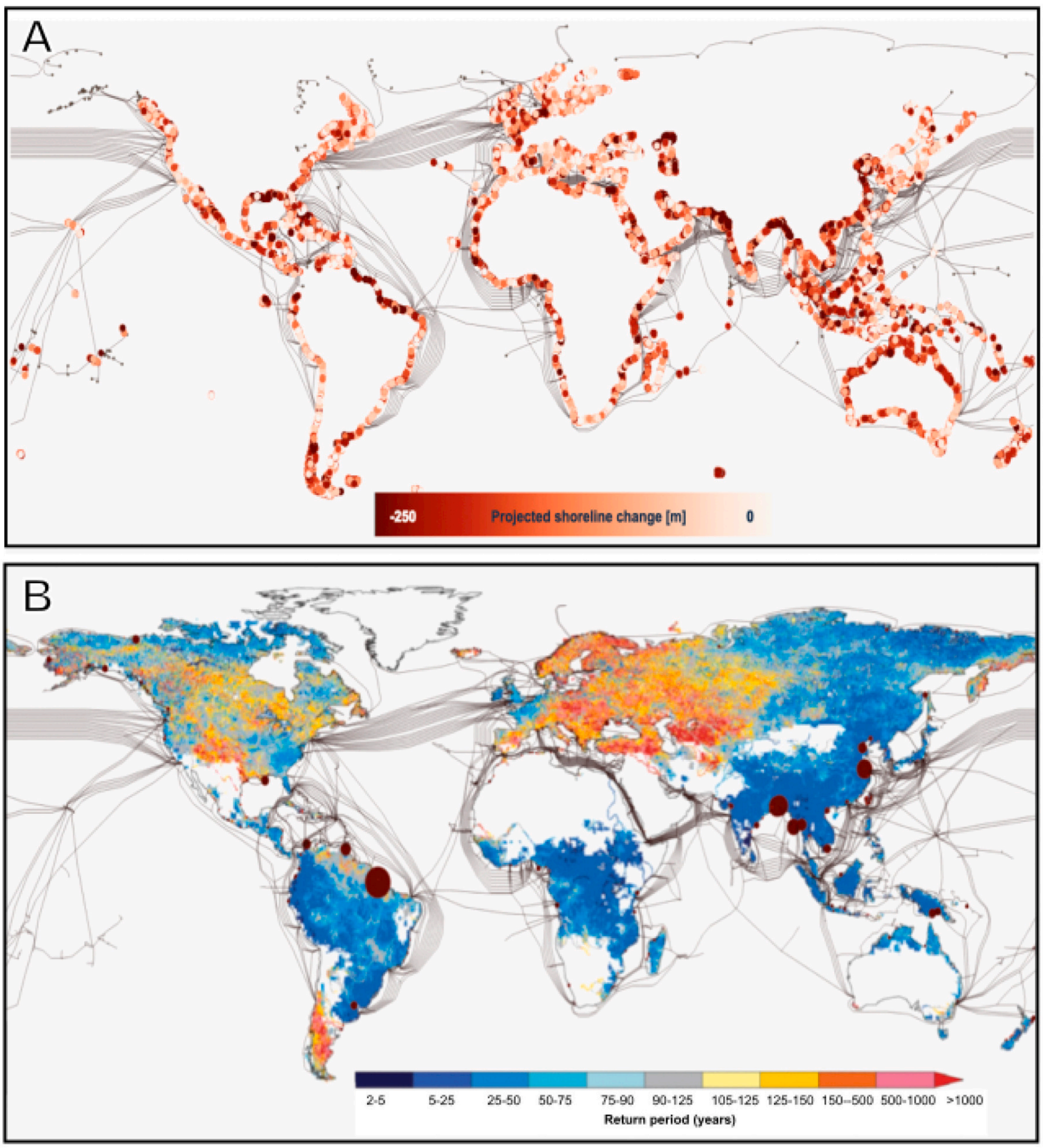

Fig. 6. Climate-driven effects of coastal erosion and river flooding. Cables shown in black. (A) Projected shoreline change at beaches where erosion is predicted to occur by 2100 under SSP5–8.5 scenario, based on median predicted values in Vousdoukas et al. (2020). (B) Return periods for flooding events equivalent to 20th century 100-year flood discharges under future climate change by 2100 (RCP8.5 scenario; modified from Hirabayashi et al., 2013). Filled brown circles are scaled to sediment flux from Syvitski (2011) to illustrate the major rivers that supply sediment offshore. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

seabed rise by 10 m on average in the swath of 3 km around the Arctic coast.

Infrastructure at the coastline related to subsea cables is often at risk from erosion, and is also likely to be exposed to waves; the severity of which depends upon the weather, wave climate, coastal topography, nearshore bathymetry, sediment supply, sea-level rise and the presence/absence of coastal ice (e.g. Durairajan et al., 2018; Schaefer et al., 2013). Low-lying coasts exposed to cyclonic storms are most at risk, as exemplified by the US Atlantic coastline (NOAA, 2019). Hurricane Sandy caused extensive but variable amounts of erosion, while beaches and dunes lost up to 6 m vertical height with the eroded sand redeposited in back-beach areas (Sopkin et al., 2014). This change was driven by a storm surge of up to 2.87 m above predicted tidal levels that allowed wave attack to extend further inland. Despite this major impact, the local subsea cables escaped major damage. Hurricane Sandy made landfall where ~25 subsea cables come ashore (Huston, 2012). Apart from minor damage to a secondary backhaul cable to a landing station, the local subsea cable network proved to be resilient. The loss of internet connectivity was largely due to loss of electrical power supplies and distribution networks (e.g. Gigacom, 2012; Huston, 2012). In the case of subsea cables buried for their protection, storm-forced erosion may reduce or remove the sediment cover. However, cables are typically emplaced 1–2 m beneath the seabed; the actual burial depth depending on the suitability of the substrate for burial and the nature of the perceived hazard (e.g. mobile sand waves, bottom trawl fishing, ship anchors etc.; Burnett and Carter, 2017). In contrast, and acknowledging that shelf erosion will vary with storm intensity/duration and sediment supply (Green et al., 1995), observations for individual storms show that shelf erosion is considerably less than nominal cable burial depth (e.g. 0–14.4 cm of vertical erosion under Cyclone Winifred - Gagan et al., 1990; no widespread erosion on the inner shelf during Hurricane Sandy - Goff et al., 2015; 3–17 cm of vertical erosion during Hurricane Lili - Allison et al., 2005; and < 8 cm by Hurricanes Katrina and Rita combined - Goni et al., 2007). Coastal defences are used in many regions to protect coastal communities from the effects of wave overtopping and excess erosion. However, these structures may also modify the natural sediment budget and influence local erosion rates in complex ways that are not specifically addressed here, but may warrant consideration (e.g. Cowell et al., 2006; Elias et al., 2012).

3.4. Global increases in frequency and magnitude of river flooding

Since the late 19th Century, faults on submarine (telegraphic) cables have been linked to river floods, although the specific mechanism that caused the damage was initially unclear (Benest, 1899). Today, it is well recognized that severe rain storms can cause rivers to discharge large volumes of sediment to the heads of coastal embayments, as well as the open coast bordering the inner continental shelf (0–30 m water depth) and the heads of submarine canyons (e.g. Mulder et al., 2003; Mulder and Syvitski, 1995; Talling, 2014; Talling et al., 2013). Several instances of past cable faults have been linked to river flood-triggered turbidity currents. These include instances offshore SW Taiwan in the linked Gaoping Canyon and Manila Trench, where nine successive cable faults occurred over a distance of several hundred kilometres offshore from the river mouth, following typhoon-related floods in 2009 (Carter et al., 2012), and following major flooding in 2020 of the Congo River when powerful turbidity currents ran out >1000 km from the estuary mouth, breaking multiple cables in the attached deep sea canyon (Talling et al., 2022).

Rivers that enter inlets, such as fjord coastlines of the middle to high latitudes, commonly build deltas that can pose a hazard to cables. On the basis of repair reports for old telegraph cables in Alaskan fjords, Heezen and Johnson (1969) noted at least 23 cable-damaging events between 1906 and 1958. Broken cables were often deeply buried by sediment loosely interpreted as 'submarine landslides' that resulted from failure of local deltas exemplified by that of the Stikine River. A few of these old reports suggest landslides were triggered by earthquakes, such as the 7.8 M_w Lituya Bay earthquake of 1958; a prognosis confirmed by Wilt (2015) who attributed seismic triggering of the Stikine River delta to form a turbidity current/debris flow that broke two subsea cables in 2013. But the triggers for the 'submarine landslides' reported by Heezen and Johnson (1969) remained unresolved. However, instrumented observations from similar Canadian fjords confirm the presence of climate-related sediment density flows - a generic term that includes hyperpynal flows, debris flows and turbidity currents (Talling et al., 2012). For instance, Bute and Knight Inlets in British Columbia receive 25–30 turbidity currents per year that coincide with elevated river discharge associated with seasonally controlled snow and ice melt (Bornhold et al., 1994). River floods can also enhance delta-top sedimentation to a point of failure, which can be exacerbated by tide-driven changes in subsurface pore pressures, as observed for the Squamish Delta, British Columbia (Clare et al., 2016; Talling, 2014). River floods have the greatest potential to impact subsea cables where there is a connection between their entry to the ocean and a seafloor canyon, as such features can funnel and concentrate sediment-laden flood waters to generate an avalanche of sediment characterized by turbidity currents.

A warmer climate is predicted to increase the risk of river floods (Arnell and Gosling, 2016; Syvitski, 2002). However, as with many other processes, the effect is likely to be geographically non-uniform. The global model of Hirabayashi et al. (2013) assessed the impact of future climate change on river flooding based on the outputs of 11 climate models and a global river routing model. Under global warming scenarios that are broadly equivalent to SSP5–8.5, flood frequency is predicted by this model to increase across 42% of the land surface worldwide, primarily due to predicted increases in the frequency of annual precipitation, annual runoff, heavy precipitation, and annual river discharge. Flood frequency is predicted to increase in many regions, particularly across SE Asia, India, E Africa and across much of S America (excluding the extreme south), and also in the UK, Ireland, France, and SW USA, with current 1 in 100-year flooding events anticipated to recur on much shorter timescales in these areas (Fig. 6B). Non-climate-related impacts are not specifically assessed here; however, changes such as human modification of river catchments can have profound impacts on water and sediment discharge to the ocean, driving both increases (e.g. due to deforestation, farming) and decreases in river flow (e.g. due to sand mining, dam installation; Nienhuis et al., 2020). Indeed, it has been suggested that recent instances of cable faults in the Congo Canyon may become more likely due to the influence of both land use and climate changes that affect the catchment of the Congo River (Talling et al., 2022).

3.5. Complex changes in extra-tropical and tropical cyclones paths and intensity

As highlighted previously, cyclonic weather systems can generate storm surges, but also have the potential to damage subsea cables and their landing stations in ways other than flooding. This can include: i) Enhanced coastal erosion that can undermine or adversely impact landing stations and shore-based infrastructure; ii) Wave/current-forced sediment mobility or scour, exposing buried cables, excessively burying cables with mobilized sediment, or leading to abrasion or chafe (Internet Society, 2018; Ogasawara and Natsu, 2019); iii) Destabilization of sediments on the continental slope as a result of cyclic wave action, triggering submarine landslides that can damage cables (Gavey et al., 2016; Pope et al., 2017b); iv) Creating river flooding that transfers large quantities of sediment offshore, potentially triggering powerful turbidity currents particularly where sediment is focused in the head of a submarine canyon (Carter et al., 2012; Hale et al., 2012); and v) Generating high wind speeds that can damage land-based infrastructure.

Tropical and extra-tropical cyclones are projected to become more intense in some regions, although there is considerable disagreement between studies and models due to the short period of accurate observation and large degrees of natural inter-annual variability (Emanuel, 2005; Knutson et al., 2010; Pope et al., 2017b; Tsuboki et al., 2015; Webster et al., 2005; Bloemendaal et al., 2022; Lau and Zhou, 2012). As a consequence, any projections are couched in significant uncertainty. Most climate models indicate an increase in average tropical cyclone intensity and project an average 5% increase in lifetime maximum surface speeds (e.g. Baatsen et al., 2015; Liang et al., 2017; Michaelis et al., 2017; Kossin, 2018; Knutson et al., 2020; Dullaart et al., 2021). The number of slow-moving tropical cyclones is expected to increase, possibly resulting in prolonged coastal flooding (Kossin et al., 2014; Baatsen et al., 2015; Michaelis et al., 2017; Kossin, 2018). Prolonged flooding, creates greater sediment run-off; in turn increasing the likelihood of turbidity currents that are triggered from dense plunging sediment-laden river flood water. This has been suggested as an explanation for the many prior cable faults offshore SW Taiwan (Pope et al., 2017b) and is a likely pattern across the wider NW Pacific, where storm tracks are also migrating poleward as well as slowing (Mei and Xie, 2016; Tu et al., 2009). For extra-tropical cyclones, most climate models show a spatial shift in storm tracks, with a poleward shift in the Southern Hemisphere, but do not indicate a clear change in their intensity (Dullaart et al., 2021).

A global analysis of 35 subsea cable faults related to tropical storms, found that, while some impacts are immediate, cable damage can occur up to several weeks after the passage of a tropical storm as a result of prolonged flooding and sustained sediment transfer to submarine canyons (Pope et al., 2017b). Regions most affected included offshore Taiwan, Philippines, Japan, Indian Ocean, Gulf of Mexico and the Caribbean. The region offshore Taiwan is a particular hotspot because of the compounded hazards that exist there, and its proximity to a concentration of important cable routes, containing at least 17 subsea cables (Carter et al., 2014; Lee et al., 2015). Most cables in the Taiwan region pass along the continental margin and hence intercept multiple canyons. Consequently, cables are exposed to hyperpycnal flows and/or turbidity currents on a regular basis that appear to be largely dictated by the passage of three to four typhoons per year and multiple earthquakes (Liu et al., 2012). To date, the most damaging cyclone is the record-breaking Typhoon Morakot, 2009, which was accompanied by over 2777 mm of rain in three days (Chien and Kuo, 2011; Ge et al., 2010). Off SW Taiwan, about 150 Mt. of sediment were discharged from the swollen Gaoping River to the shelf and head of Gaoping Canyon to form a hyperpycnal flow that broke two cables. Four days later, seven more breaks were recorded. Carter et al. (2012) speculated this second phase of breaks resulted from the failure of quasi-stable flood sediment deposited in the canyon head. This triggered a turbidity current that damaged cables down to 4000 m water depth. At least three other cables broke elsewhere offshore Taiwan during Morakot, but the actual cause of that damage has yet to be determined.

3.6. Changes in surface wave intensity, period and direction

As well as fluvial discharge, the continental shelf is exposed to waves and currents that mobilize, transport and deposit sediment with the potential to abrade cables. In calm weather, cables laid on the inner shelf (0–30 m water depth) are likely subject to abrasion by mobile sand driven by wind waves, ground swell and currents. Calm weather mobility is more pronounced on tide-dominant shelves where sediment mobility can occur at tidal frequencies (Carter and Lewis, 1995; King et al., 2019). Likewise, shelves and continental slopes swept by ocean currents can experience frequent sediment transport, as observed in the Florida Strait where a decommissioned coaxial communications cable is used to monitor the Florida Current (Baringer and Larsen, 2001; Piecuch, 2020), which transports medium-sized sand to in water depths of at least 700 m (Wimbush and Lesht, 1979). The degree of abrasion presumably reflects the frequency, intensity and composition of sediment transport as well as cable placement (i.e. on or under the seabed). Frequent sand transport can abrade a surface-laid cable to the point of failure, as recorded by Kordahi et al. (2016, 2019). Abrasion may also result from cable movement, as observed by Kogan et al. (2006). Breaks resulting from abrasion average around 10% of external aggression faults and occur in all water depths with approximately one third detected on the continental shelf (e.g. Kordahi et al., 2016, 2019).

Changes in ocean surface winds, sea-level, tides, and beach morphology can also have a knock-on effect on the nature of wind-driven waves, modifying their height, period and direction (Hemer et al., 2013; Morim et al., 2019). A reduction of sea-ice can also increase wave fetch and exposure at high-latitudes. Satellite data and model results indicate an upward trend of about 0.14 m/decade in significant wave heights in Arctic shelf seas between 1992 and 2015, although trends between different seas vary and can be positive as well as negative (Liu et al., 2016a; Stopa et al., 2016). These modifications to wave conditions may compound the effects of coastal erosion (including degradation of coastal permafrost as discussed in Section 3.3) and sediment transport on the continental shelf, as well as changing 'typical' offshore conditions that may affect cable installation or maintenance. In cases where wave height is predicted to increase, this may reduce or change the time window for optimal offshore weather conditions for such activities. Wave height and period are projected to change by 5 to 15%, and change direction by 5 to 15^{o} under the RCP8.5 high emission scenario (Morim et al., 2019). However, as with many of the other processes discussed here, the response of waves to future global warming is likely to be geographically variable. Under RCP8.5, annual mean significant wave heights across the N Atlantic and parts of the N Pacific Oceans are actually predicted to decrease, while a similar trend is projected in the E Indian and S Atlantic Ocean in the austral summer (Wolf and Woolf, 2006; Morim et al., 2019; Fig. 7A&B). This reduction in wave height is linked to a projected decrease in wind speeds in these regions.

Polar areas that experience sea ice change and sea ice-wave interactions are likely to significantly alter wave energy, particularly in the coastal zone and close to the sea ice edge (Hošeková et al., 2020, 2021; Stopa et al., 2016). Climate projections run under the Coupled Model Intercomparison Project (i.e. CMIP5/6) do not include coupled sea ice–ocean–wave components and instead artificially force the standalone wind–wave projections (e.g. Morim et al., 2019). It has been argued that sea ice-wave interaction in the Marginal Ice Zone (MIZ) controls most of the wave changes in the Arctic Ocean (Aksenov et al., 2017, 2022; Dobrynin et al., 2012); hence, this approach may underestimate wave height increases. Further model development could therefore assist in reducing uncertainties. Future wave climate will also be controlled by changes in storminess, but climate models project a high degree of uncertainty around future storm track and intensity (e.g. Roberts et al., 2020). Within semi-enclosed and fetch-limited seas, a shift in the position of storm track may also be a controlling factor, as the direction of wave events will likely be more influential than the absolute magnitude. Areas projected to experience the largest increases in significant wave heights include the Arctic, and also the Southern Ocean and tropical E Pacific Ocean, due to increasing Southern Ocean swells that reach the tropics and the poleward shift of the tropical cyclone belt (Morim et al., 2019).

3.7. Changing patterns in ocean currents

Climate change is anticipated to modify global ocean currents, due to changing wind patterns, heat transfer, and freshwater input arising from melting of ice. The precise nature of those changes remains debatable because of complex natural variability (Fig. 8) and interactions between the ocean and atmosphere, and any change is likely to be temporally and spatially variable (Hays, 2017). An overall global increasing trend in the energy of ocean currents has been suggested over the past three decades, primarily driven by a global increase in surface winds, and projects a continuation of that trend under future global warming (Hu et al., 2020); however, there remains much uncertainty and controversy around the precise nature of these changes. For example, Atlantic

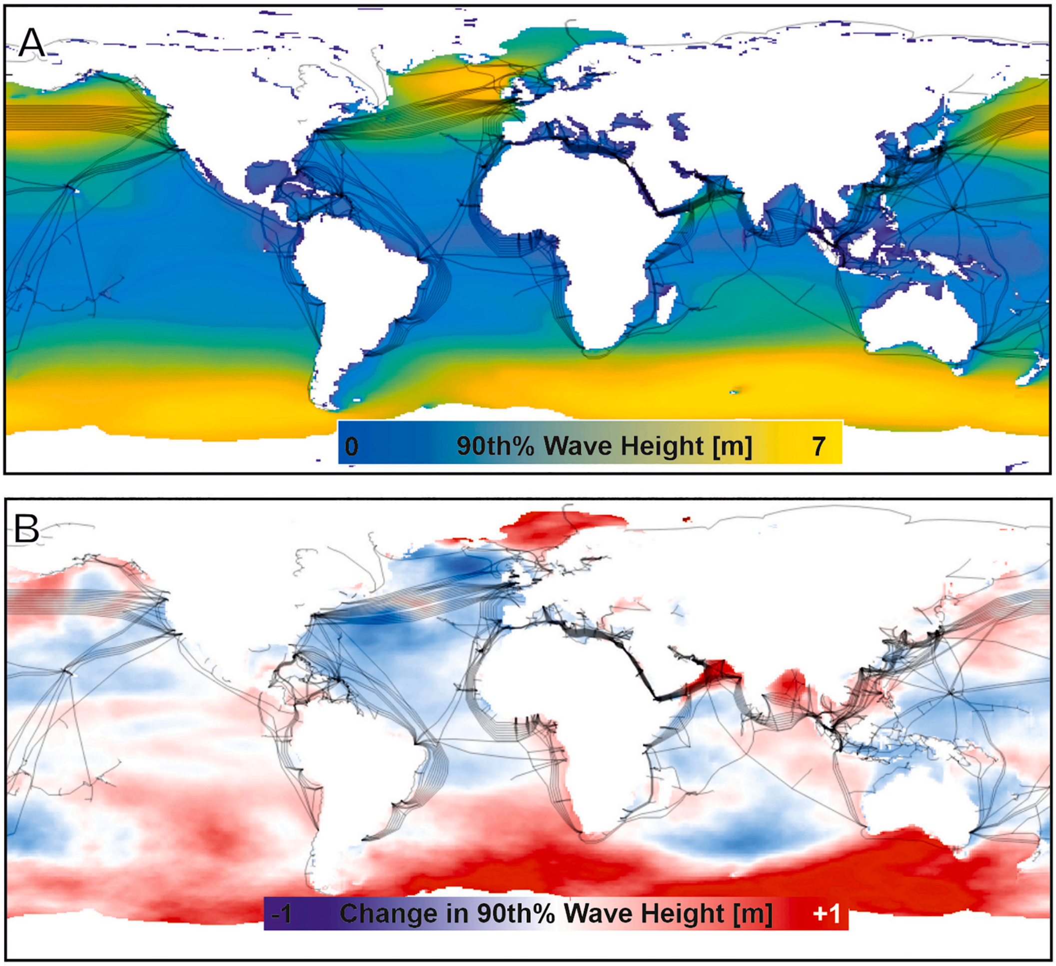

Fig. 7. Future projected changes in wave conditions based on WaveWatch II spectral wave model. (A) Present day 90th percentile of significant wave height and (B) change in 90th percentile of significant wave by 2100 under RCP8.5 emissions scenario.

Meridional Overturning Circulation (AMOC) appears to have slowed since measurements started (likely as a result of freshwater delivered from the Arctic) and it has been suggested that further freshwater influxes could shut down or slow the AMOC, which would have a profound impact on global ocean circulation (Bakker, 2016; Intergovernmental Panel on Climate Change, 2021). While this is an extreme (and some consider to be unlikely) scenario (Intergovernmental Panel on Climate Change, 2021), the fact that such controversies exist in this field is testament to the uncertainties that remain concerning future climate change impacts on ocean conditions.

Acceleration of the mean ocean circulation is generally anticipated in the Pacific, Atlantic and Indian oceans, being particularly prominent in the tropics (particularly the tropical Pacific Ocean; Hu et al., 2020), and in the Arctic Ocean. A notable increase and shifts in ocean currents occur on the continental shelf break, where the depth–uniform (barotropic) ocean flow dominates circulation. This indicates a strong impact on near-seabed ocean flow and benthic sediment transport, resulting in potential impacts for seafloor structures such as subsea cables. Perhaps, the most prominent changes in ocean circulation are projected to occur in the presently sea ice-covered provinces of the Arctic Ocean and sub-Arctic seas, where the reduced sea ice cover allows wind and waves to break up ice floes, thus increasing the momentum transfer from wind to the ocean (Bateson et al., 2020, 2022; Martin et al., 2016).

Southern Ocean currents are also responding to increasing winds but in the case of the Antarctic Circumpolar Current – the world's largest flow – it is unclear if the current is intensifying or becoming more turbulent (Carter et al., 2022). In essence, there is far from scientific consensus on ocean current responses to climate change as feedbacks are dynamic and complicated. For instance, freshening of surface waters in the Atlantic caused by glacial melting limit the formation of deep cold dense waters at high latitudes, and may be responsible for a perceived slowing of the AMOC, which in turn may lead to more stormy conditions in NW Europe and greater instances of drought in W Africa (Holliday et al., 2020). While the impacts of seafloor currents are dominantly felt on the continental shelf, where currents may lead to scour and exposure of buried cables and abrasion of their protective casing, abyssal ocean currents can also have similar impacts in water depths of at least 6000 m (Heezen and Hollister, 1964). One example is the third Canadian Trans-Atlantic (CANTAT-3) cable system that experienced faults offshore Iceland attributed to the effects of deep currents that reached speeds of >0.3 m/s in water depths of 2500–4000 m (Carter et al., 2009).

Climate change can also influence astronomical tides, with small changes in sea-level rise impacting water depth on the continental shelf (Idier et al., 2019). These changes modify the position of amphidromic points (tidal nodes) and resonance, altering the magnitude and timings of high water at the coast, and also change the speed and location of tidal current at the seabed (see Haigh et al., 2020 for a review of tidal changes). Several modelling studies have predicted regional changes in

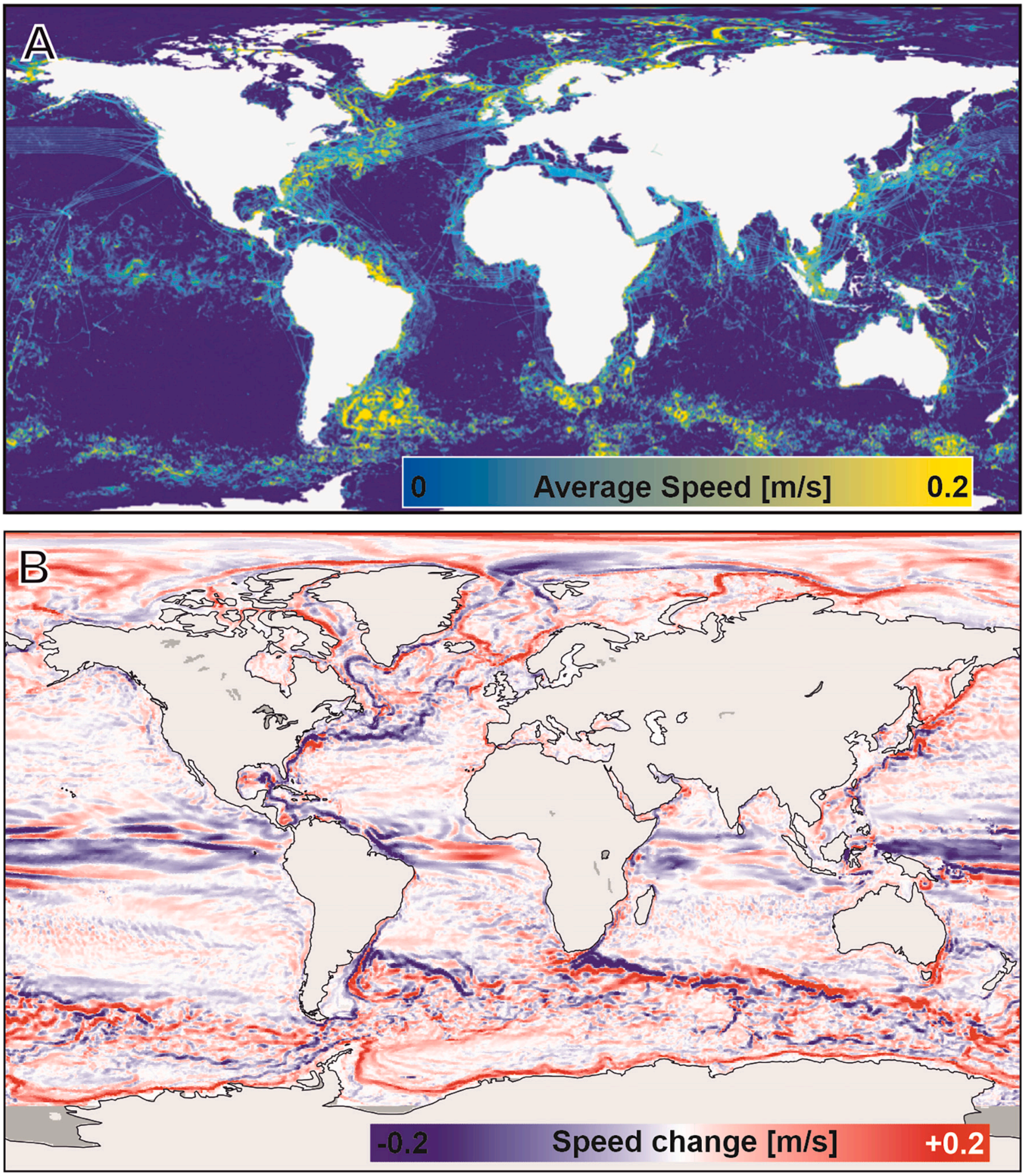

Fig. 8. Variability in seabed currents. (A) Average seabed current speed (m/s) from 1/12th degree Nucleus for European Modelling of the Ocean (NEMO) ocean model shown for January 1993 (Kelly et al., 2020). (B) Projected changes in ocean currents in January from the 2000s to 2090s, based on high-resolution (~10 km) NEMO ocean model with the RCP8.5 IPCC scenario (Aksenov et al., 2017, 2022).

tidal range resulting from future changes in mean sea-level (Haigh et al., 2020). These studies suggest that changes in tidal range will typically be in the order of plus or minus 10% of any changes in mean sea-level, which could slightly enhance or lessen coastal flooding at some locations, but could also alter sediment transport.

3.8. Uncertain influence of climate change on submarine landslide frequency

Instability of sediments on the continental slope can result in submarine landslides that damage cables. Such events can involve transport of up to thousands of km^3 of sediment, which can travel at fast speeds (up to 20 m/s) over long distances (thousands of km; Talling et al., 2014). Submarine landslides can also trigger tsunamis due to the sudden displacement of the overlying seawater, and may initiate a longer runout turbidity current if the slide mass mixes with the ambient sea water. Despite their potentially large volumes and impacts, submarine landslides remain poorly understood due to their relatively rare occurrence. However, evidence from sequential cable breaks and recent direct monitoring has provided key insights into their behaviour (e.g. Carter et al., 2014; Pope et al., 2017a&b; Talling et al., 2022).

Off the east coast of the USA, a number of cables cross former landslide scarps that show evidence of scarp degradation. Larger degradation events may bury and potentially damage cables. While the timescales on which these processes operate is presently unclear (we assume them to be continuous), oceanographic changes in shelf and tidal currents may be sufficient to trigger them; however, there is sparse literature on these events and their drivers (Normandeau et al., 2019).

Whether submarine landslides will become more likely due to climate change is a subject of on-going scientific debate (Brothers et al., 2013; Urlaub et al., 2013). This uncertainty largely results from the limited number of observations of the conditions that result in landslide initiation, which is particularly acute for very large submarine landslides that can involve the collapse of large parts of the continental shelf and slope. The Storegga Slide is one such slide, which occurred offshore Norway approximately 8200 years ago and displaced >3500 km^3 of sediment across an area larger than the size of Scotland (Talling et al., 2014). A repeat event would result in damage to numerous cables and other seafloor infrastructure. It has been hypothesized that the Storegga Slide, and other large landslides like it, may have be controlled by the effects of climate change, such as dissociation of gas hydrates due to a warming ocean, rapid loading by sediment delivered by glacial meltwater, or even changes in crustal loading due to rising sea levels (Talling et al., 2014 and references therein). However, the accuracy of dating such landslides, and the limited number of observations means that no conclusive answer has been reached to date (Urlaub et al., 2013).

Submarine landslides may be triggered by major events, induced by large earthquakes, volcanic eruptions or major storms, and may also be primed by rapid sediment delivery to continental slopes or submarine canyon heads provided by river floods (Cattaneo et al., 2012; Liu et al., 2013; Urlaub et al., 2013; Talling et al., 2014). However, it is increasingly recognized that preconditioning of slopes to failure can happen over long periods of time (potentially hundreds to thousands of years), resulting in a situation where a landslide occurs with no obvious instantaneous trigger (Talling et al., 2014; Bailey et al., 2021). It is plausible that submarine landslides may become more likely in regions where sediment supplies increase and/or where triggering factors are heightened. Such circumstances may include enhanced delivery of sediment offshore from rivers that are more prone to flooding or where tropical cyclones or storm intensity increases, thus causing greater cyclic loading of delta or slope sediments (Piper and Normark, 2009; Puig et al., 2004; Talling, 2014). During Hurricanes Camille, Ivan, Katrina, Rita and likely others, extreme wave conditions drove cyclical loading of sections of the submerged Mississippi Delta and triggered mud flows that caused widespread disruption and destruction of offshore oil/gas infrastructure including a subsea cable network used to monitor hydrocarbon production and drilling operations in the Gulf of Mexico (Chaytor et al., 2020; Kaiser et al., 2009; Hitchcock et al., 2010; Nielsen and Davenport, 2014; Walsh et al., 2006). Another example is Hurricane Iwa (1982), which damaged six coaxial telephone cables laid mainly along the upper continental slope off Oahu, Hawaii, in >900 m water depth (Dengler et al., 1984). At the time, several oceanographic moorings were operating between 90 and 730 m water depth but were later found to have shifted further downslope. It appears that Hurricane Iwa instigated several slope failures that transformed into damaging turbidity currents; however, it was not possible to discount that the turbidity currents may have originated from dense sediment plumes resuspended by storm waves (Normark et al., 1992). It has also been suggested that climate change may have other effects such as dissociation of gas hydrates that can destabilize slopes or lead to calving of icebergs, whose seabed impacts can lead to local slope failures (Ketzer et al., 2020; Phrampus and Hornbach, 2012; Talling et al., 2014; Normandeau et al., 2021).

3.9. Climate change impacts at polar coasts and high latitude oceans

Most subsea cable routes lie in low to mid latitudes. The Arctic is not presently a well-developed region for telecommunication cable routes, and the Southern Ocean currently lacks major cables. However, the loss of ice cover driven by climate change may open up opportunities for new cable routes. There has been a continuing loss of sea ice at 12.7% per decade relative to the 1981–2010 average for September (National Snow and Ice Data Center, 2021; at the time of writing the September 2022 data were not available). As a result, the Arctic Ocean is becoming more accessible to deploy subsea cables to serve remote Arctic communities and provide alternative trans-oceanic routes between the eastern and western hemispheres (e.g. Hardy, 2019; Hernandez, 2019). With this in mind, we now provide a brief overview of relevant changing conditions in the Arctic. To date, only two regional subsea cables operate inside the Arctic Circle (latitude 66°34'N) and include a link between Svalbard and mainland Norway and a recently completed system along the north Alaskan continental margin (Subsea Cable Networks, 2017). However, major trans-Arctic Ocean subsea cables are planned and range from preliminary proposals to fully funded projects scheduled for completion in 2022–2023 (Hernandez, 2019). Plans for the first trans-oceanic cable to Antarctica are also underway, where the focus is on a scientific subsea cable that links McMurdo Sound in the Ross Sea Dependency with either Australia or New Zealand (Neff et al., 2021).

Wilson (2013) provides insights into the effects of observed and potential natural hazards specific to polar environments. Pressure ridges formed by deformation of sea ice can develop a subsurface keel, which can plough the seabed to endanger cables. Coastal ice pile-up occurs where moving sea ice intercepts the coast, and as ice spills onshore it could damage coastal cable infrastructure. Landfast ice (i.e. sea ice that is fixed along the coast) often acts to protect the coast from such ice pile-up and wave inundation; however, the length of the landfast ice period has been decreasing since the 1980s, which may mean coastlines are increasingly exposed in future. This reduction has been linked with a recent increase in nearshore wave energy and the reduced protection of the coast (e.g., Hošeková et al., 2021; Walsh et al., 2022; see Section 3.6). Icebergs, including their smaller counterparts 'bergy bits', can plough (or gouge) the seabed. Keels of large modern icebergs can plough in 500 m water depth and deeper as observed off East Greenland, meaning that cables may need to be buried to significant depths below seafloor (Dowdeswell et al., 1993). As Arctic sea ice continues to decline, coastal erosion may increase as more coastline is exposed to open-ocean conditions for longer periods – a situation exacerbated by global sea-level rise and increased storminess (see Section 4.3). The number of calved icebergs from Greenland substantially varies from year to year. Based on archived daily charts of iceberg observations obtained west of Greenland made by the International Ice Patrol (IIP), the number of icebergs were shown to increase from 1900 to 2015, sourced from west Greenland (Bigg et al., 2014; Marsh et al., 2018). We may therefore anticipate many more icebergs drifting on the shallow shelf, thus increasing the frequency of shelf seabed gouging and risk to subsea cables. Similarly, sea ice keels can be deep enough to cut gouges in soft seabed sediments, which may be up to 5 m deep and ~ 80 m wide.

Other less well-studied Arctic hazards have impacted subsea cables, such as frazil ice that forms in the water column, rather than at the surface. Wilt (2013) documented how a cable was observed floating in the Kvichak River in 2011, which was lifted off the seafloor as a result of the formation of frazil ice. Frazil ice occurs predominantly in near-shore regions, particularly at river mouths, where winds blow ice away from shore and expose large expanses of freezing water to super cold air (Wilt, 2013). Such locations, are also prone to strudel scour – a particular scenario that occurs where fresh river water flows over ocean ice, and upon reaching a hole in the ice, flows downwards in a whirlpool creating bottom scouring that can reach tens of metres deep (Wilt, 2013). Subsea permafrost thaw can result in seabed collapse or soften frozen sediment, which may expose buried cables (e.g. Palmer, 2014).

Ocean current acceleration, both steered by seafloor morphology (as boundary current flow) and across it (flow meandering and eddies), can initiate lee waves behind topographic features and change the bottom mixing and near–seabed flow (Rippeth et al., 2015). Due to weak water column stratification beneath the Arctic halocline, the spin–up of the sub-surface currents is translated in the acceleration of deep flows, creating barotropic flow that more directly connects surface to deep water (Section 3.7). Cascading of waters across the Arctic shelf is likely to become more frequent, creating more vigorous density currents and accelerating seafloor sediment transport (Luneva et al., 2020; Peralta-

Ferriz and Woodgate, 2015; Polyakov et al., 2020). More energetic eddies are found in the open water than under Arctic sea ice, and as sea ice declines, more mesoscale energetic currents are expected to emerge (Manucharyan and Thompson, 2022; von Appen et al., 2022). It is thus clear that the combined effects of waves, sea ice, ocean currents, tides and coast to ocean interactions require consideration and these interactions, and potential for compounded hazards, may be particularly complex in high latitudes (e.g. Aksenov et al., 2017, 2022; Liu et al., 2016b; Peterson et al., 2002; Skliris et al., 2021).

3.10. Modifications to human activities as a result of climate change

The effects of climate change are also likely to have a range of knock-on effects on human activities in the ocean, some of which may result in additional or different interactions with subsea cables. Here we focus specifically on the impacts on fishing and shipping as interaction with bottom gear and anchors has accounted for most cable faults worldwide (Carter et al., 2009).

3.10.1. Climate change impacts on fishing activity

Historically, bottom trawling has been the main type of fishing to interact with subsea cables as it occurs on most continental shelves, and covers large areas of seafloor to water depths of 1500 m or more (Løkkeborg, 2005). The locations and nature of bottom fishing have been changing and are likely to continue to change in future, in part due to climate change (e.g. ocean warming, acidification and changes in storminess, but also in response to a depletion in fishing stocks, driven by overfishing.) It is likely that bottom fishing will continue to expand into deeper water and potentially into areas in which fishing has not previously been so common. Ocean warming is driving the migration of a number of key species towards cooler waters, which in turn will affect the location and type of fisheries (Beare et al., 2004; Cheung et al., 2010; Stenevik and Sundby, 2007; Wilson, 2006; Cheung et al., 2015). Recent modelling of future climate change scenarios in the N Atlantic indicates that deep-sea fish habitats will likely move between two to nine degrees towards higher latitudes (Morato et al., 2020). Implications of this migration are that cables may require protection in areas and jurisdictions that have historically not been fished. Cables are more susceptible to damage in deeper water as it becomes more challenging to bury them. Heavily armoured cable is also harder to deploy in very deep water, so cables in deep water tend to carry less or no armour. In contrast, fishing gear in deeper water tends to be heavier, often using large anchors. It is also more common for fishers to drag grapnels to retrieve fishing gear from fixed locations in deep water (Carter et al., 2009). All of these aspects increase the risk of cable damage where activities coincide. This change has necessarily triggered an increase in the water depths where cables are buried in some locations, such as the NE Atlantic where cables can be buried in water depths up to 2000 m (Benn et al., 2010).

The effects of ocean warming are anticipated to have a marked impact on fishing activities over decadal timescales in many regions (Swartz et al., 2010). One projection of climate change impacts on global fishing catch potential indicated that climate change may lead to large-scale changes in the locations and intensity of fishing (Cheung et al., 2010). Fishing was projected to increase by 30–70% in higher latitudes (particularly the N Atlantic, N Pacific, Bering Sea and poleward tips of S Africa, Argentina and Australia) and reduce by up to 40% in the tropics, semi-enclosed seas and inshore waters by 2055 (Cheung et al., 2010). Effects of changing storminess may result in even shorter-term impacts (Sainsbury et al., 2018). Aside from the impacts on fishing stocks themselves, tropical and extra-tropical cyclones and other storms can endanger fishermen, destroy vessels and disrupt production of commercial inland and marine capture fisheries; as already evidenced by several storms in the 21st century (Sainsbury et al., 2018). The environmental damage caused by deep sea trawling is also of growing concern, as it can damage important seafloor ecosystems, and release large quantities of buried carbon that counteracts climate change mitigation measures (Ferguson et al., 2020; Rijnsdorp et al., 2020; Paradis et al., 2021).

3.10.2. Reduced sea ice cover changes shipping routes and affects maritime operations

Climate change will have wide-reaching impacts on ocean users as well as fishers. One area of particular attention is the Arctic, where the reduction of ice cover and warming in general may provide new opportunities; both for new subsea cable routes but also for other human activities such as shipping (Protection of the Arctic Marine Environment (PAME) Arctic Shipping Status Report (ASSR) #1, 2020; Todorov, 2021). In 2017, a Russian tanker transited through the Arctic without any assistance from an icebreaker for the first time. This has raised the possibility of previously sea-ice-covered regions providing shorter routes for the shipping industry and resulting in marked growth of coastal fish farms, which now produce more fish than wild fisheries (Aksenov et al., 2017; Stroeve et al., 2014; Ng et al., 2018; Stephenson et al., 2011). Such expansion in fishing may pose additional challenges for coastal cables and changes in shipping routes may give rise to new hazards for cables (e.g. due to anchor drops); hence, it is important that route planning assesses how these and other uses (e.g. energy and seabed resource exploitation) may respond to changing ocean conditions. However, the main change in the shipping intensity lies with economics (environmental conditions act as a moderating factor), and shipping transits and cargo volumes can fluctuate substantially from year to year as a result.

Emerging hazards from changing environmental and navigational conditions in the Arctic (for the Polar Code Area definition – PCA see International Maritime Organisation (IMO) Resolution MEPC.265(68), 2022) are multi-faceted and often create compound risks. Increased shipping volumes create a higher possibility for more accidents from maritime code violation, such as accidental anchor drops, grounding, ship-to-ship and ship-to-offshore/shore structures collisions. Consequently, sinking of vessels and debris from structural disintegration, along with rescue and salvage operations may pose a risk for seabed cables. Numbers of ships entering the PCA are increasing (from 784 in 2013 to 977 in 2019) and more ships are present in the PCA (1628 in 2019 compared to 1298 in 2013). Larger vessels (>1000 GT) with larger drafts, and an expansion in regional routes and a 75% increase in distances (from 6.1 to 10.7 $\times$ 10^6 km) may lead to more grounding and accidents, more work on harbours and navigational channels dragging and, in turn potentially increasing the risk for subsea cables. The main increase in the PCA voyages is due to fishing vessels, specifically in the Barents Sea, but also along the Siberian and Alaskan coasts (41% of all ships sailing in PCA in 2019 were fishing vessels), therefore more net catching incidents are expected. Awareness of the new emerging combined hazards, such as sea ice and wave impacts, spray deposition/icing and bergy-bits collisions should all be considered as they have wide relevance to many maritime industries (e.g., Aksenov et al., 2022).

4. Improving future resilience: Needs, priorities and data requirements

Natural hazards involving both climate and earthquake drivers, account for fewer than 20% of all subsea cable faults; however, despite such a low percentage, a major event such as a typhoon or major earthquake can disrupt regional networks by damaging multiple cables, sometimes resulting in a total severance of cable-based communications for a particular area (Renesys Corporation, 2007). Projections of climate drivers known to damage cables are largely on the increase implying that cables will likely be exposed to more hazardous conditions. So, what can be achieved realistically to improve cable resilience at this time of increasing risk? To begin with, the cable industry is accustomed to managing risk as many of subsea cable routes traverse fishing grounds and shipping lanes - fishing and anchoring - the dominant causes of external faults (Drew, 2009; Kordahi et al., 2016, 2019). As a result, the

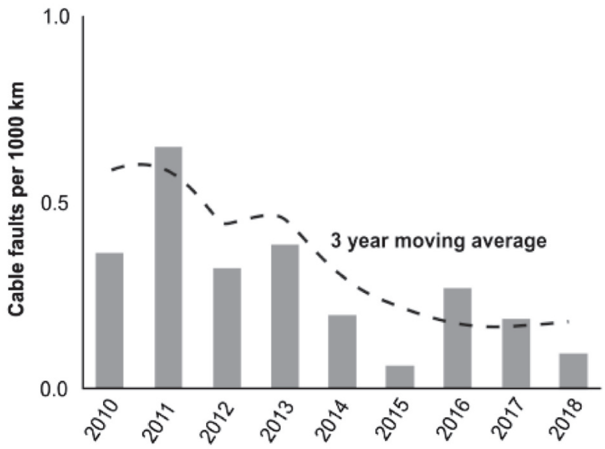

Fig. 9. Cable faults in <1000 m water depth have generally declined into the present mainly in response to improved armouring and cable burial. Based on data from Kordahi et al. (2019).

industry reduces risk by armouring cables and burying them beneath the seabed (Fig. 9). Improved public awareness also plays a role especially by providing information that allows other seabed users to avoid the cables (ICPC, 2021). With regard to natural hazards, these have confronted industry since the first subsea cables were deployed and continues today, as exemplified by resilient cable services to major population centres such as those of the highly seismic circum-Pacific rim. To help prepare for the future challenges of climate change, the following suggestions are made based on this study.

4.1. Cable route planning

Where possible, routes should avoid submarine canyons and channels subject to active turbidity currents and other sediment flows. This particularly applies to tectonically active margins that are also subject to cyclones and earthquakes (Milliman and Syvitski, 1992; Pope et al., 2017a&b). However, canyon avoidance can be difficult especially where numerous cables are forced to pass through a narrow corridor that exists because of its strategic position and commercial viability (e.g. the Strait of Luzon where at least 17 subsea cables link SE Asia with N America but are forced to traverse Gaoping Canyon). New cable routes through the Luzon Strait are now designed to cross the extension of the canyon in Manila Trench where turbidity currents decelerate to a level where they may not damage cables (Carter et al., 2014). This may be appropriate for many other submarine canyon or channel crossings; however, exceptional events can still occur. In the case of the Congo Canyon a so-called 'canyon-flushing' turbidity current was observed to speed up at a distance of 1000 km from the canyon head, causing damage to cables far from shore (Talling et al., 2022). It is therefore important to understand the local drivers and controls on such hazards.

4.2. Determine local conditions

This study illustrates the wide geographically variability in climate-driven changes in ocean and other environmental conditions that can vary globally to locally, depending on the scale of the process(es), and the spatial variation in controls, drivers and vulnerability to impacts. To appropriately assess the impact of climate-driven changes, it is therefore essential to determine site-specific environmental conditions. For instance, between 1970 and 2009 regional sea-level rise off the north-eastern United States was nearly four times the global mean (Sallenger Jr et al., 2012). Even small nations such Taiwan show marked local differences in sediment discharge that reflect the island's topography, typhoon-forced rainfall, geology, earthquakes and human modification of the landscape (Milliman and Kao, 2005). Coastal erosion, in particular, may vary across multiple spatial scales and is controlled not only by ocean and atmospheric conditions, but also local morphology, substrate, and human-built coastal management structures. It is particularly important to determine the rates (which may be non-stationary) at which erosion may occur at cable landing stations and along their shore approaches and assess how that may change over the design life of a cable system.

4.3. Short-term versus long-term damage

Studies of cable damage have typically focused on abrupt breaks because of their frequency and the need to rapidly restore connectivity. From a scientific perspective, breaks provide insights into how the ocean functions. The revelations of the 1929 Newfoundland earthquake highlighted the presence of powerful turbidity currents capable of travelling 100 s of kilometres to transfer nutrients and carbon to the abyssal ocean as well as breaking cables (Heezen and Ewing, 1952). Now, recent monitoring has revealed that multiple turbidity currents per annum may occur in submarine canyons, that are too weak to break cables, but may exert longer-term low-level impacts (Paull et al., 2018; Zhang et al., 2018). This situation, which is well known for current and wave damage in shallow coastal settings, but may also occur where deep western boundary currents move benthic sediment, raises the possibility of long-term cable damage and failure through abrasion and fatigue (Culver et al., 1988; Wu et al., 2012). It is recommended that such sustained, long-term impacts are considered, as well as larger, ephemeral events. This will require integration of short-term observational monitoring datasets with longer-term geological archives to understand the range of magnitudes for different frequencies of event, modelling of different scenarios to assess previously-unobserved but plausible conditions, and analysis of past cable fault case studies to discern the root cause of the damage.

4.4. The need for a holistic approach to assessing natural hazards

While this study has focused on climate, active tectonism also plays a role that can amplify the climatic forcing. Milliman and Syvitski (1992) and Syvitski and Milliman (2007) drew attention to tectonically active areas, where small "dirty" rivers collectively deliver up to 40% of the fluvial sediment discharge to the global ocean. That contribution reflects the combined effects of earthquakes, steep slopes and strong climatic signals. On Taiwan, for example, earthquakes and associated landsliding make landscapes more prone to erosion, especially during typhoons, to increase fluvial discharge and the risk of creating hyperpycnal plumes (Chen et al., 2012; Dadson et al., 2004; Kao et al., 2010; Dzhamalov et al., 2012). That discharge also contributes to shelf and canyon deposits, which because of their rapid accumulation accompanied by interstitial gas, are triggered by earthquakes of $\sim >$ M5.0 to form various sediment density flows (Hsu et al., 2008; Gavey et al., 2016; Soh et al., 2004). In a similar vein, human modification of the landscape has markedly contributed to the sediment discharge to the ocean although this input has been alleviated by entrapment of fluvial load within terrestrial reservoirs (Lin et al., 2008; Syvitski et al., 2005). There is no simple solution to tackling this issue, other than ensuring that multiple datasets are integrated and that geological, oceanographic, atmospheric and social components are considered on a case by case basis for future cable routes, with the underlying recognition that the Earth System is formed of a complex connection of processes that operate on multiple scales.

4.5. Indirect climate-change effects on cables

Climate change also affects the activities of other ocean users, which in turn can positively or negatively influence cable resilience. However,

Table 3
Climate change risk register outlining the anticipated effects of processes modified by future climate change, the potential impacts of subsea cables and landing stations, and identifying locations that are likely to experience the greatest impacts.

Process/ Activity	Effects of climate change	Potential impacts for subsea cables or landing stations	Anticipated locations of greatest impacts (Hotspots)
Sea-level rise	General pattern of sea-level rise (up to 20 mm/ year) worldwide in response to melting ice cover and warming ocean.	Inundation of data centres, power stations, landing stations and terrestrial cables.	Areas of greatest sea-level rise in Central and S Pacific islands, Philippines, Indonesia, Japan, W Caribbean, Gulf of Mexico, NW Australia.
Storm tides	The effect of sea-level rise means storm tide heights will be greater in future. Climate change and sea-level rise likely to increase frequency and magnitude of extreme sea-level events.	Direct impacts of storms on built infrastructure, including scour and abrasion of cables, undermining of landing stations and beach manhole covers. Storm surges may reach up to 9 m above normal.	NW Europe, high latitude N and S America, E USA, E Africa, Bangladesh, Taiwan, Gulf of Mexico, NW Australia.
Tropical and extra-tropical cyclones	Global increase in average cyclone intensity and surface speeds, but the pattern is geographically variable. General poleward shift of cyclone tracks. Coastal flooding via rainfall and/or storm surge.	Enhanced scour and abrasion. Also cause slopes to fail to form turbidity currents that can damage cables. Increased storminess and wave height reduce working windows for offshore survey, installation & repairs, adding to project delivery times and costs.	Complex global pattern. Increased extra-tropical storminess anticipated in NE Atlantic and N Pacific. Increased tropical cyclone activity expected in NW and S Pacific, central Atlantic and Indian Oceans.
Coastal erosion and seafloor sediment transport regime	Global trend of shoreline retreat due to ambient shoreline dynamics and sea-level rise. General increase in near-bed currents and sediment mobility due to overall global changes in in storm frequency, duration, wind speed, and wave height.	Expose, suspend and abrade previously buried cables, undermining of shore-based infrastructure including shore-end, beach manhole cover and front haul route.	Geographically widespread but hotspots include central and eastern N America, Central America, SE South America, central Europe, E and W Africa, S Asia, N Australia, Pacific and Caribbean, which have median values of >100 m of coastal retreat by 2100.
Ocean currents	Intensity, location, direction and timing of ocean currents may shift due to sea-level rise and changes in ocean temperature, salinity and wind-forced circulation.	Impact on survey, cable laying and maintenance. Enhanced sediment mobility or scour around cables causing abrasion and suspension-based fatigue	Acceleration of ocean circulation most prominent in tropical oceans, particularly tropical Pacific Ocean. Increase and modification of currents in the Southern Ocean.
Offshore weather	Changing storminess – becoming more intense in some regions. Wave height and period is projected to change by 5–15%, and change direction by 5-15° under high emissions scenarios.	Impact on survey, cable laying and maintenance. Decrease in previous optimal weather windows.	Largest increases in significant wave heights in the Southern Ocean and tropical E Pacific Ocean, due to increasing Southern Ocean swells that reach the tropics and the poleward shift of the tropical cyclone belt.
River flooding	Warming climate generally increases risk of floods, wherein 1:100 year events may recur on much shorter timescales.	Flooding of land-based facilities. Triggering of slope failures and offshore sediment flows that can break multiple cables (most likely where rivers flow into submarine canyons).	Flood frequency is predicted to increase significantly in many regions, particularly across SE Asia, India, E &W Africa and across much of S America (excluding the extreme south), and also including UK, Ireland, France, and SW USA.
Submarine landslides	Submarine landslides may become more likely in regions where sediment supplies increase and/or where triggering factors are heightened.	Cyclic loading of shelf and slope sediments triggering slope failures and offshore sediment flows that can break multiple cables.	Offshore from rivers where sediment supply is increased (e.g. E Africa, Congo River, SE Asia) or where storm triggering is likely (e.g. Caribbean, SE Asia, S Pacific).
Arctic sea ice and icebergs	Pressure ridges and coastal ice pile up. Coastal erosion. Calved icebergs. Enhanced river discharge.	Underwater iceberg keels scour seabed to damage cables. Reduced ice cover and increased storms expose coast to erosion, while pile-up may affect coastal infrastructure. Scoring of shelf and upper slope. Increased river discharge into Arctic Ocean may raise risk of turbidity currents.	For 1979–2018 sea ice has very likely declined for all months - this trend projected to continue. Record for 1900–2008 shows highly variable discharge of east Greenland icebergs with highest rates in 1990s.
Relocate fishing grounds due to changing ocean	Global warming, ocean acidification and overfishing push stocks into newer habitats that are often cooler due to higher latitude and/or increased depth.	Fish stock relocation may create new conflicts between seabed users, and damage to unarmoured & unburied cables by fishing gear.	Fishing projected to increase by 30–70% in higher latitudes (particularly the N Atlantic, N Pacific, Bering Sea and poleward tips of S Africa, Argentina and Australia) and reduce by up to 40% in the tropics, semi-enclosed seas and inshore waters by 2055
New shipping routes due to changing conditions	Warming oceans and melting ice opens up previously ice-covered ocean routes.	New shipping routes intersect existing cable corridors, increasing risk of damage to seafloor cables by anchoring. Other activities (e.g. resource extraction may need to be considered.	Previously ice-covered parts of the Arctic.

in the absence of systematic recording of indirect climate effects and resultant cable faults, our knowledge is limited. Thus, we are restricted to simply identifying the potential hazard. Climate is contributing to changes in the distribution and abundance of commercial and non-commercial fish species (Perry et al., 2005). Such migrations can change the style and intensity of fishing that may either endanger or benefit cables due to, for example, increased or reduced bottom trawling. The effect of cyclones on shipping can also pose a risk to subsea cables. Roughly 13% to 40% of ships that that attempt to “ride out” typhoons off major ports have been estimated to drag their anchors (Bell, 1980). As such they plough the seabed, endangering cables in the vessels’ path. For example, in 1979, anchor dragging during Typhoon Hope damaged five subsea cables in Hong Kong Harbour (Hong Kong Observatory, 2020; Post, 2020). In the absence of systematic recording of cable faults caused in this manner, our knowledge is limited. Therefore, the gathering and wider sharing of such data is an important starting point to better understand this issue.

5. Climate change hotspots and mitigation strategies

This study aimed to synthesize the current state of knowledge concerning the potential future effects of climate change on hazards that may impact subsea cables and landing stations. In doing so, we now highlight the areas where the greatest impacts are anticipated, which are summarized in Table 3.

5.1. SE Asia and S Pacific: landslides, earthquakes and tropical cyclones

Across SE Asia and the S Pacific greater sediment discharge is anticipated due to more frequent and larger river floods, that may trigger turbidity currents, particularly where rivers connect to submarine canyons or pile sediment offshore that can later be triggered as a submarine landslide. The compound effects of high rates of sea-level rise, more intense (and/or slower moving) tropical cyclones and greater wave heights, enhanced seabed current velocities, compounded by the background activity of earthquakes, are also anticipated to lead to a greater hazard for cables. Offshore Taiwan is a particular hotspot because of the compounded hazards, and their proximity to a major cable corridor through the Luzon Strait.

We exclude volcanic eruptions from this review, as they typically operate independently to climate change; although there are some suggestions of potential links between climate change and volcanic activity (Aubry et al., 2022). Active and dormant seamounts and other volcanic terrain create a rough seabed topography, however. Such conditions prevail in many parts of the S Pacific, particularly along the Tonga-Tofua-Kermadec Arc, where two subsea cables were recently broken following the explosive Hunga Tonga-Hunga Ha'apai eruption in January 2022 (Cassidy and Mani, 2022). While these breaks were closely linked to the eruption itself, similar rough terrain can exacerbate abrasion and suspension fatigue, especially in an energetic ocean. Major eruptions may also have other implications, in that they can trigger landslides and turbidity currents, but may also directly affect climate that may then have subsequent effects for cables (Marshall et al., 2022).

5.2. N Atlantic: storms, seafloor currents and abrasion

Climate change is projected to create more challenging weather conditions and greater storminess in the N Atlantic that may aggravate coastal and beach erosion and inundation of shore-based facilities whose effects may be more significant than that of sea-level rise. Changes in ocean conditions (varying wind forcing, temperature, salinity and acidity) and fishing practices are anticipated to see a move in commercial bottom fishing towards cooler, higher latitude and deeper waters. With regard to ocean circulation, subsea cables intercept deep western boundary currents and other flows intensified by zones of steep bathymetry, in particular that of continental margins. This is well shown in the N Atlantic where at least 20 cables link N America and Europe and, in so doing, cross the Gulf Stream, the Atlantic Deep Western Boundary Undercurrent and a series of southward currents steered by the Mid-Atlantic Ridge and associated fracture zones (Lozier, 2010; McCartney, 1992). As a result, cables may encounter zones of active sediment transport and rough topography (Culver et al., 1988; Heezen and Hollister, 1964; Hollister and McCave, 1984). A similar but less congested trans-Pacific route, linking Asia and North America, intercepts the Kuroshio Current, locally intensified currents of the Hawaiian Seamount Chain (e.g. Qiu et al., 1997) and the southward California and northward Davidson currents that pass along the California continental margin (Hickey, 1979; Strub et al., 1987). The presence of mobile sediment, even at depths exceeding 4000 m, is likely to heighten the risk of abrasion and suspension fatigue.

5.3. Gulf of Mexico and Caribbean: sea-level rise, storm surges and sediment density flows

Local hotspots of sea-level rise and enhanced surges due to more frequent and more intense tropical storms and hurricanes are anticipated in parts of the Gulf of Mexico and Caribbean Sea. Such storms will likely contribute to locally higher river discharges and formation of sediment density flows facilitated by earthquake triggers (Lugo, 2000; Heezen, 1956; Lewsey et al., 2004; Naranjo-Vesga et al., 2022); hence cable-damaging flows related to such events may be experienced from shallow into deep waters.

5.4. E Africa and wider Indian Ocean: cyclones and river flooding

Storm surges driven by cyclones and enhanced coastal erosion are anticipated in E Africa and parts of the Indian Ocean. An increased frequency of river flooding is projected in many parts of this region, but also offshore from major rivers and potentially from presently ephemeral rivers (that may episodically flood following cyclones) where they connect to offshore submarine canyons.

5.5. Polar coasts and oceans: ice-related hazards and future human activities

While the Arctic is not presently a well-developed region for telecommunication cable routes, the loss of ice cover driven by climate change may open new opportunities. At the same time, other human activities may change in that region (e.g. fishing, shipping, resource exploitation). New hazards are likely to be complex in high latitude regions, including the direct impacts of sea ice and icebergs, as well as combined impacts from waves, ocean currents and land-coastal processes. The coastal zone is liable to become more vulnerable due to increased exposure to open-ocean storms, which may become more frequent/intense (Parkinson and Comiso, 2013; Simmonds and Keay, 2009). It is unclear if cables on the continental shelf and slope will be exposed to more seabed scouring by icebergs, although the number of observed icebergs in the polar oceans appears to have been increasing since the 1990s. A century of observations of icebergs from west Greenland reveal strong interannual and decadal variability but with a period of pronounced discharge of 659 km^3/year in 1990–1999 that was two to three times more than in previous decades back to 1900 (Bigg et al., 2014). At the same time, other human activities may change in that region (e.g. fishing, shipping, resource exploitation, construction of shore terminals and other structures). New hazards are likely to emerge in high latitude regions, including the direct impacts of climate change on sea ice decline, wave climate, ocean and shelf seas and the coast (Stephenson et al., 2011; Aksenov et al., 2017), which should be considered at the earliest stages of planning for new cable systems (Wopschall and Michels, 2013).

5.6. Adaptation and mitigation strategies

While this is the first published global review of climate change related hazards for subsea cables, it is an issue that is already firmly on the radar of the subsea cable industry. Indeed, the International Cable Protection Committee, a global organization that comprises cable designers, operators, and installers, published a Position Paper on climate change that states *"the global climate has been and will likely continue warming at an unprecedented rate as a result of human-induced greenhouse gas emissions"* (ICPC, 2020). This was further emphasized at a consultative meeting of the United Nations on sea-level rise and its impacts, where the ICPC commented: "*It is critical that sea-level rise and climate change be considered in future route and landing station planning, as well as assessing the risk posed to existing systems*" (United Nations, 2021). The industry is therefore adopting various mitigation and adaptation measures to adapt to or protect against adverse impacts of climate change. Some of the examples provided by ICPC members include: i) Increased armouring and/or cable burial protection at shore-ends where erosion is worsening; ii) Mitigation against threats related to deep sea fishing, including liaison with fishers, desk study, route clearance of discarded fishing gear, and use of more resistant cable; iii) Avoidance of low lying areas for landing points, beach manhole cover and cable landing stations; iv) Local knowledge ascertained from site visits regarding environmental conditions and historical events; and v) Geographical Information System (GIS) analysis using various geospatial datasets that are incorporated into desktop studies to identify the optimal routes and landing points (ICPC, 2020).

6. Conclusions

The critical role played by subsea cables in global communications means it is important that they remain as resilient as possible over their design lives. This study provides the first global review of how hazards to subsea cables are anticipated to change in response to future climate change scenarios. Our overarching conclusion is that ocean conditions are highly likely to change on a global basis as a result of projected climate change, but the feedbacks and links between climate change, natural processes and human activities can be extremely complicated, resulting in pronounced spatial and temporal variability. Not all regions will be affected in the same way (nor at the same time) by the same processes, and in many cases, there is anticipated to be local variability. Therefore, future cable routes should be carefully selected based on local conditions. In particular, submarine canyons and channels prone to active sediment gravity flows should be avoided where possible. Consideration should be given both to short-term (e.g. one-off events) as well as longer-term impacts, such as the sustained impacts of seabed currents that circulate even in deep water. As new environments are entered, the potential for previously unencountered hazards should be anticipated, particularly as routes move into higher latitudes. Multiple factors can combine to increase the risk posed to submarine cables, hence a holistic approach across engineering, socio-economics and natural sciences is required, to assess the compounded effects of both natural processes and human activities, all of which are projected to change under future climate change. We identified regions and locations that are anticipated to experience the greatest impacts. Future targeted collaborative industry and academic research could improve the wider understanding of the hazards and the most appropriate methods for adaptation or mitigation.

Author contributions

MAC led in the conception of the study in collaboration with LB, IY, JB, TW and JC. All authors contributed to the development, writing and editing of the paper, with specific contributions involving analysis and discussion on the following topics: sea-level change at landing stations (MAC, IY, LB, IH), coastal erosion (JB, CS, YA), storm tides (TW, IH), tropical cyclones (IH, JH), river flooding (MAC), wave climate (LB, JB, YA, LC), submarine landslides (MAC, JC, LC), Arctic conditions (YA, LC), shipping (YA) and fishing (BB).

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Data availability

The authors do not have permission to share data.

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