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ADVANCED REVIEW

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Implications of climate change for railway infrastructure

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Abstract

Weather phenomena can result in severe impacts on railway infrastructure. In future, projected changes to the frequency and/or intensity of extreme weather events could change weather–infrastructure risk profiles. Infrastructure owners and operators need to manage current weather impacts and put in place adequate plans to anticipate and adapt to changes in future weather risks, or mitigate the impacts arising from those risks. The assessment of the risk posed to railway infrastructure from current and future weather is dependent on a good understanding of the constituent components of risk: *hazard*, *vulnerability*, and *exposure*. A good understanding of the baseline and projected future risk is needed in order to understand the potential benefits of various climate change adaptation actions. Traditional risk assessment methods need some modification in order to be applied to climate change timescales, for which decisions need to be made under deep uncertainty. This review paper highlights some key challenges for assessing the risk, including: managing uncertainties; understanding weather-impact relationships and how they could change with climate change; assessing the costs of current and future weather impacts and the potential cost versus benefit of adaptation; and understanding practices and tools for adapting railway infrastructure. The literature reveals examples of progress and good practice in all these areas, providing scope for effective knowledge-sharing—across the railway infrastructure and other sectors—in support of infrastructure resilience and adaptation.

This article is categorized under:

Assessing Impacts of Climate Change > Evaluating Future Impacts of Climate Change

KEYWORDS

climate change, climate change adaptation, exposure, extreme weather, hazards, infrastructure, railway, risk assessment, vulnerability

1 | INTRODUCTION

Railways represent a significant global asset, with more than 228,000 km of rail lines in the EU alone (EUROSTAT, 2016). Many of the individual structures along these railways including bridges (Casas & Wisniewski, 2011), tunnels (Skaric Palic et al., 2018), and earthworks (Potts et al., 1997) are more than 150 years old and in some cases are heritage objects. As such structures were constructed before the advent of modern design and construction standards and many have far exceeded typical design lifetimes, their weather resilience could potentially be lower than modern infrastructure and is undoubtedly more uncertain.

The impacts of extreme weather events can be particularly severe on rail infrastructure because of the highly integrated nature of the rail system and the need to maintain safe operations. Historical failure of rail infrastructure due to weather related effects is well documented, with examples even from the early days of modern railways; as early as 1842, snowmelt caused Brunel's Great Western Railway line to flood just outside Exeter, UK (Brierley, 1964), and in 1846 other sections of the same line were damaged by sea flooding (Woolmer's Exeter and Plymouth Gazette, 1846). This same line was most recently—and infamously—destroyed by the sea at Dawlish in February 2014 (e.g., Dawson, Shaw, & Gehrels, 2016). The impact of flooding, landslides, windstorms, and heatwaves in the 20th century is described widely in the literature (Brierley, 1964; Burnham, 1922; Canovan, 1971; Champion, 1947; Changnon, 2006; Dromain et al., 1985; Harris, 1982; Hay, 1957; Ward, 1931; Wintle, 1960).

Failure of a single asset can result in potential fatalities, large replacement costs, loss of service (sometimes for extended periods), and reputational damage. Replacement costs for civil engineering infrastructure items such as bridges and tunnels are sometimes prohibitive, leading to long-term closure. Consequently, global rail management is moving towards risk assessment methods as part of holistic asset management, in compliance with international standards such as ISO 31000:2018 (ISO, 2018). With multiple uncertainties, such as the characteristics of the weather event and the condition of the infrastructure assets, and in many cases where the composition of the asset(s) and the deterioration rate of the components are either unknown, or are intrinsically linked to the magnitude of the weather event, a risk assessment approach is also preferable.

The importance of understanding transport infrastructure and the effects of weather and/or climate change upon it has given rise to multiple national and trans-national research studies, including Koetse and Rietveld (2009); ARISCC (Nolte et al., 2011); FP7 EWENT (e.g., Leviäkangas et al., 2011; VTT, 2011); FP7 WEATHER (e.g., Doll et al., 2012); FP7 SMART RAIL (Gavin et al., 2012); Nemry & Demirel (2012); Stipanovic Oslakovic et al. (2012); MOWE-IT (e.g., Jaroszweski, Quinn, et al., 2014); FUTURENET (e.g., Dijkstra et al., 2014); H2020 Destination RAIL (Gavin, 2016); and FP7 RAIN (Nogal et al., 2018). Table A1 gives more information about the aforementioned research projects.

Research at country level has also been conducted in the UK, United States, Canada, the Netherlands, Finland, Australia, South Africa, and Germany (Dawson, Thompson, et al., 2018, and references therein), and in Sweden (Lindgren et al., 2009). In Spain, a government initiative explored infrastructure vulnerability to weather and climate

BOX 1 Tomorrow's Railway and Climate Change Adaptation (TRaCCA)

From 2010 to 2016, the railway in Great Britain (GB[1]) undertook a comprehensive assessment of its climate change knowledge and response, through the TRaCCA program. Initial RSSB-funded research (Dora, 2011; Palin et al., 2013) explored projected impacts of climate change on the GB railway, including preliminary indications of projected risk. Further research was then commissioned (RSSB, n.d.-a):

- Phase 1 (2013–2015) delivered a compendium of current research shared with the industry, and a series of recommendations prioritized by the industry. Some of these recommendations were taken forward by Phase 2.
- Phase 2 (2014–2016) built upon Phase 1 by delivering a step change in climate change understanding within the GB railway, identifying potential cost-effective and timely actions, and outlining decision-making tools and information to aid resilience and climate change adaptation. These include methods for financially evaluating climate adaptation investments; geospatially-based methods to integrate metrics currently captured by the industry; and systems tools to provide insight into critical interfaces and dependencies, within and outside the railway system. In the spirit of learning from other countries, an analogue study (Sanderson et al., 2016) was also undertaken, combining climate analogues (countries/regions with current climates like those projected for GB) with railway analogues (countries/regions whose railways share characteristics with GB's).

Key findings (RSSB, n.d.-b) included:

- Climate change will impact railway asset lifetimes, requiring changes to railway standards and asset management policies.
- Infrastructure systems are interdependent, requiring a multi-agency response to climate change.
- GB's railway is ahead of other national railways in managing climate risk and understanding asset vulnerability.
- Regions with both climate and railway analogues are France, the Netherlands, Belgium, Germany, and Denmark (Sanderson et al., 2016).
- Prototype metrics have been proposed, for use in assessing railway resilience as part of the wider transport system. New asset vulnerability tools have also been demonstrated.
- Economic appraisal of rail investment schemes should include the consideration of socioeconomic benefits.

All TRaCCA reports can be accessed online at http://www.sparkrail.org.

change, in the context of understanding adaptation needs (CEDEX, 2013). In the UK, key railway stakeholders commissioned the "Tomorrow's Railway and Climate Change Adaptation" (TRaCCA) project (Box 1), which captured current understanding of railway weather hazards; how these could change in future; current resilience and adaptation actions; opportunities for further resilience and adaptation actions; and requirements for further frameworks and tools to support cost-effective action (Arup TRaCCA Phase 2 Consortium, 2016a).

In addition to characterizing weather and climate impacts, prior research has included exploring how climate change could be managed—either in terms of adapting to its effects or in terms of reducing its impacts—and estimating the economic costs of such options. This paper therefore brings together these elements in the railway context, with an overview of the impacts of severe weather on the infrastructure considered, and how climate change could affect this (Section 2), a discussion of assessing climate change risk to infrastructure (Section 3), and key challenges to undertaking such assessments (Section 4), before drawing these themes together and reflecting on the future in Section 5.

As well as weather resilience and climate change adaptation, it should be noted that the transport sector has a major role to play in the climate change mitigation agenda, in terms of reducing its contributions to global greenhouse gas (GHG) emissions. While we acknowledge the role that railways could take in this, climate change mitigation is outside the scope of this review.

2 | HOW DOES WEATHER AFFECT RAILWAY INFRASTRUCTURE, AND HOW MIGHT THIS CHANGE IN A CHANGING CLIMATE?

2.1 | Weather events affecting railway infrastructure

Table 1 summarizes the ways in which weather can affect railway infrastructure. Meteorological phenomena such as temperature and precipitation are not necessarily hazardous themselves: hazards arise when a weather phenomenon manifests itself in a way that could cause harm—for example, the occurrence of temperatures below freezing, excess precipitation, or sustained gales. The complex nature of meteorological phenomena means that there are also hazards such as snow and convective storms that arise from particular meteorological situations and can have severe additional impacts on railway infrastructure and operations. Equally there are some railway impacts, for example, wildfires, that can arise from a variety of hazards, both meteorological and non-meteorological. TRaCCA provided a detailed presentation of weather impacts on railways (Arup TRaCCA Phase 1 Consortium, 2014b).

As Table 1 implies, the complexity and connectedness of railway infrastructure means that its true weather response is rarely "linear." Figure 1 shows that weather hazards can have multiple impacts and consequences, including on railway elements other than infrastructure (and indeed, more widely than that). While the direct effects of extreme weather are often short-lived, the longer-term impacts on railway infrastructure can be safety- and performance-critical, and thus form part of holistic asset management.

Consequences of infrastructure failure are mainly governed by the type of failure—whether requiring routine repair, or major replacement—and the impact that failure has on the people and services depending on it. The consequences

TABLE 1 Examples of the physical relationships between weather phenomena, associated hazards, and their possible adverse effects on railway infrastructure

Phenomenon	Associated weather hazard	Secondary associated hazard(s)/impact(s)	Possible adverse effect on railway infrastructure
Temperature	High temperatures	Heatwaves; wildfire	Buckling of rails; thermal expansion in structures
	Large seasonal temperature range	Permafrost thaw	Differential thaw settlement of track bed in permafrost regions
	Low temperatures	Snow; ice; frost; freeze–thaw action	Damage to overhead lines and signaling equipment; rock falls; freezing of points[a]; tunnel icing; cracking/breakage of rails
Precipitation	Excess precipitation	Flooding (surface water, fluvial, groundwater); infiltration; landslide	Infrastructure slope failure; bridge scour; flooding of track, depots, buildings; water damage to electronic equipment
	Precipitation deficit	Drought; drying of soil; shrinkage cracking; landslide	Infrastructure slope failure; track misalignment; misalignment of poles supporting overhead lines
Wind	Windstorms/gales	Tree fall; wind-blown objects	Downed power lines; structural damage and/or track misalignment by fallen trees/wind-blown objects
Sea level, wind, atmospheric pressure	Short- and long-term changes to extreme coastal water levels	Coastal flooding; wave overtopping; tidal river floods	Scour; structural damage; tunnel and track flooding

Note: Adapted from Arup TRaCCA Phase 1 Consortium (2014b).
[a]"Points" is the UK English term; elsewhere this infrastructure is known as switches or turnouts.

can be direct, including loss of asset value and lives; and indirect, including consequential revenue losses (Faber, 2008). Delays following an event are an example of indirect consequences, which are country- and even route-specific, because factors such as existing alternative routes, increased network congestion, or the provision of alternative transport (via another transport mode) may need to be quantified in understanding the true extent of the influence of infrastructure failure. Such quantification may or may not be monetized (Arup TRaCCA Phase 2 Consortium, 2016b).

2.2 | Examples of impacts on railway infrastructure arising from weather

The following sections give examples of weather impacting particular infrastructure classes. Examples have been chosen from the authors' local experiences and are intended to be illustrative of impacts that occur in many other parts of the world. As noted above, the impact on the infrastructure itself (e.g., damage requiring repair or replacement) can in turn lead to an adverse effect on the capacity for safe and efficient service operation.

Local weather impacts on railway infrastructure should be considered in the decision-making process for maintenance and renewal programs, as part of asset management strategies, to help minimize the risk or severity of impacts. However, given the strong local geographical effect, and—for existing infrastructure—previous design and maintenance decisions, detailed asset information is required, including condition and exposure. In addition, within a railway network system such assessments should be made consistently across the network, to avoid conflicting standards of reliability.

2.2.1 | Whole-system impacts

Some weather events result in very widespread impacts. Synoptic-scale storms can cause network-wide impacts, causing failure of multiple elements of infrastructure and sometimes cascading effects. For example, severe flooding of central Europe in June 2013 closed a major rail bridge in Germany for 4 months, closed the Brenner Crossing in Austria for over a week (EEA, 2014), and caused widespread damage to earthworks and tracks across the region (Jaroszweski,

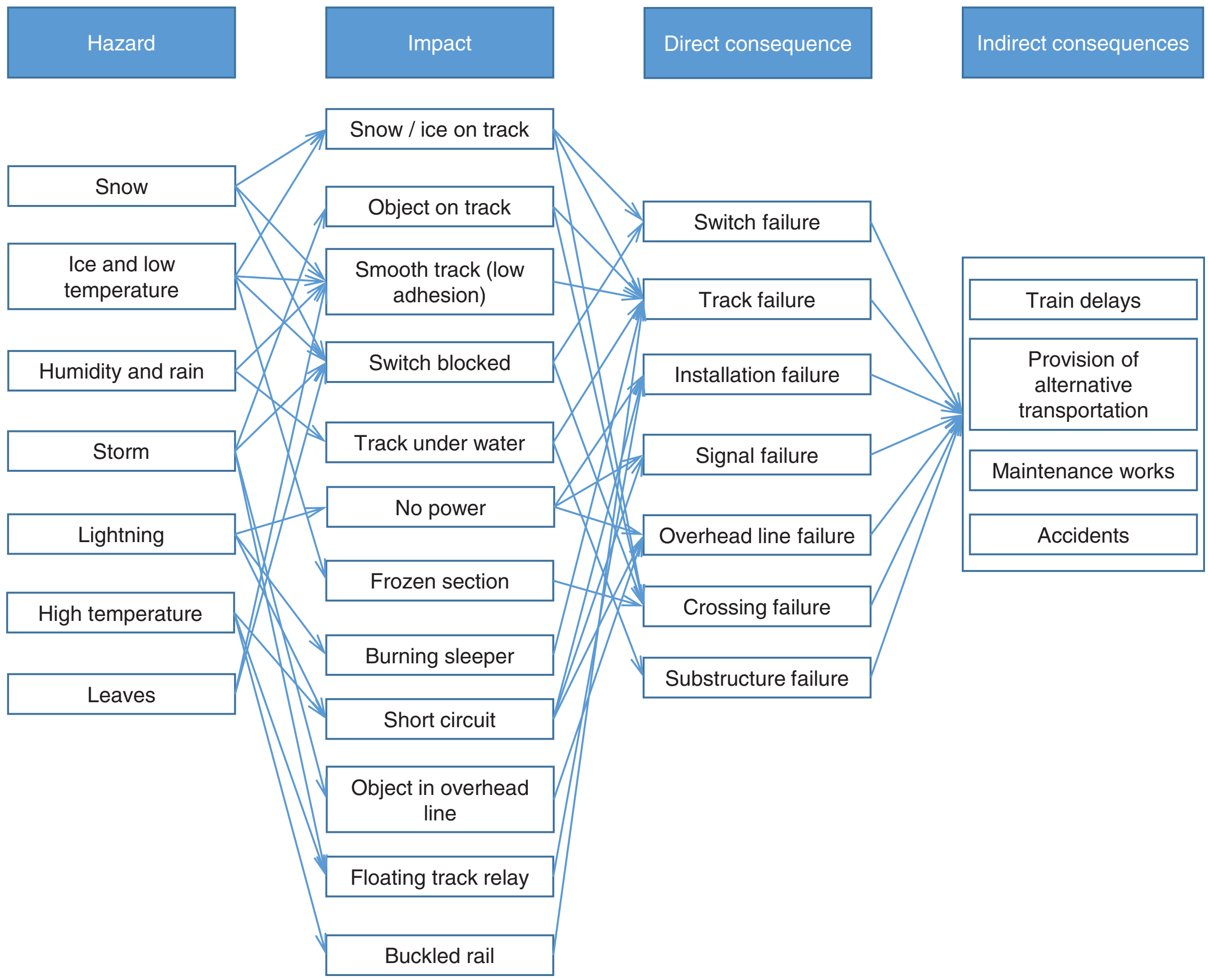

FIGURE 1 Examples of the relationships between weather (or related) hazards, railway infrastructure impacts, and direct/indirect consequences, showing the complexity of the railway system

Quinn, et al., 2014). A severe windstorm on January 18, 2018 led to widespread closure of the Dutch rail network, and delays and service suspension on the German and UK rail networks (Henley, 2018). In 2019, Typhoon Hagibis caused widespread destruction in Japan; a yard housing high-speed trains was flooded, leading to service disruption and cancellations at the time, and the subsequent scrapping of the trains due to the damage sustained (Kageyama, 2019), and landslides closed the tracks (Japan Times, 2019). A bridge on the route of a railway line which connects to the high-speed network also collapsed during the flood event (BBC News, 2019a).

2.2.2 | Slopes

Many slopes along railway networks were built more than 100 years ago, before modern design standards existed. The average angle of these slopes is usually much higher than would typically be permitted for modern transport infrastructure. Common problems affecting slopes are *shallow translational landslides* caused by high rainfall; *deep-seated rotational failures* caused by weak subsoils which are triggered by increased loading and/or changes in location of the water table or slope geometry; and *rock falls* caused by freeze–thaw effects.

Shallow translational failures

Shallow translational landslides typically occur after periods of high rainfall on high-angle slopes where there is poor soil cohesion or distinct shallow horizons have formed. Examples of shallow landslides on the Slovenian and Croatian rail lines are shown in Figure 2. Both occurred near the entrance to tunnels where slope angles are usually at their highest.

FIGURE 2 (a) Shallow landslide on the Ljubljana-Kamnik line, Slovenia. (b) Failure at the Zaluka Tunnel, Croatia, on the Karlovac-Kamanje line. After Gavin (2016)

Because of the relatively small volume of soil involved, the consequences of shallow translational slides that occur on embankments (when the track is above the failure) are usually low. In cuttings, where the track is below the slope, the impact is closely related to the clearance between the slope edge and the track. In cases where the failed material covers the track, derailment is possible if suitable detection monitoring is not in place. Repeated failures along stretches of cuttings are also a feature of this type of failure.

Deep rotational failures

Deep rotational slope failures typically involve large volumes of material. For example, the 2013 failure near Hatfield Colliery, South Yorkshire, UK resulted in major deformation to the rail track. The movements were caused by progressive failure triggered by instability in the nearby waste heap. The railway slope suffered a large rotational landslip (Figure 3) and the track repairs took 6 months to complete (Network Rail, 2013), involving the relocation of approximately 1 million cubic meters of material and the reinstatement of four tracks (Network Rail, 2014a).

Rock falls

Rock falls occur primarily because of water filling natural joints in the rock mass. The failure mechanism develops when freeze–thaw action gradually results in expansion of the joints. As a result, there is a strong correlation between rock falls, intense rainfall, and low temperature. The impact of a recent rock fall on the Zaprešić–Čakovec line in Slovenia is shown in Figure 4.

2.2.3 | Retaining walls

Most modern retaining walls are flexible embedded structures that mobilize the soil strength to provide stability. However, given the age of some railway networks, a large proportion of the retaining structures are gravity structures, relying on a combination of the self-weight of the structure and the retained soil for stability. These walls are not homogeneous (e.g., they are constructed from discrete blocks) and it is not easy to assess the structural integrity, condition of the drainage system, or to determine the condition at the wall-soil interface, which is critical. Given their low safety margins, these structures are particularly sensitive to any change in loading. Two recent examples of failure are shown in Figure 5—collapse of a wall on the Croatian rail network in Figure 5a, and in Figure 5b, severe damage caused to a section of the mainline railway at Dawlish, in Devon, UK, by coastal flooding in February 2014. The flood caused a 30 m-long stretch of the sea wall to collapse and resulted in severe scour of the rail track and damage to

FIGURE 3 Landslip near Hatfield Colliery, UK, February 2013. Image © Network Rail

FIGURE 4 Rock fall at Krušljevac, Podrute, on the Zaprešić-Čakovec line, Slovenia; after Gavin (2016)

adjacent houses. This important section of track was repaired quickly, reopening 2 months later. The repair costs were estimated at £40–45 million (Network Rail, 2014b).

2.2.4 | Tunnels

Weather impacts on tunnels include flooding and drainage problems, which lead to increased stress, and seepage/ice formation (Figure 6). Ice formation leads to ice hitting passing trains (either by falling or by encroaching on the line

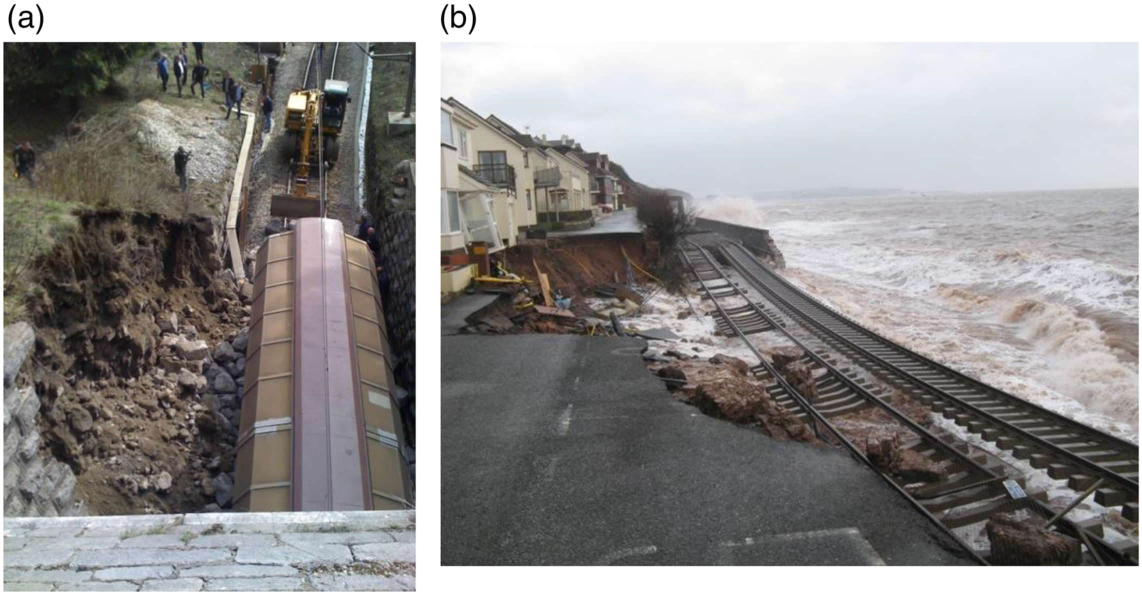

FIGURE 5 (a) Retaining wall collapse at Kupjak Tunnel, Croatia (Gavin, 2016). (b) Sea wall failure at Dawlish, Devon, UK; image © Network Rail

FIGURE 6 Ice formation in rail tunnel, Slovenia; after Gavin (2016)

gauge)—particularly a safety risk for drivers and/or a potential derailment risk if it falls on the track. Heavy rainfall can cause flooding and temporary closure. A more serious problem is coastal flooding of tunnels, which can result in the requirement to re-route sections of track. In 2012, the storm surge associated with Hurricane Sandy caused flooding of several subway tunnels in New York (e.g., Strachan & Camp, 2013); the cost of reconstructing one of the affected tunnels was estimated at $1 billion, with other tunnels each costing tens to hundreds of millions of dollars to return to service (Sneider, 2016).

2.2.5 | Track

Extreme heat causes steel rail track to expand, leading to a risk of buckling (Figure 7a). For example, extreme heat caused disruptive rail buckling in Melbourne, Australia in 2009 (Nguyen et al., 2012). In July 2019, there was widespread

FIGURE 7 (a) Lateral buckling of the track due to high temperatures, Slovenia. (b) Embankment scour at Krušljevac, Podrute on the Zaprešić-Čakovec line (Gavin, 2016)

disruption in the UK when trains were subject to speed restrictions (BBC News, 2019b) and in the Netherlands, extra track inspections were conducted (ProRail, 2019b)—in both cases, these actions were taken to reduce the buckling risk and thus the potential for derailments.

Track flooding is also a serious problem that can lead to derailments. When the track is located close to a flood-prone watercourse, embankment scour can occur, whereby the supporting soil may be washed away (Figure 7b). For example, a US freight train derailment in 2009 was attributed to track washout after heavy rain (National Transportation Safety Board, 2012).

Strong winds may also cause objects, such as fallen trees, to block the line. During the period 2012–2015, of the top 14 events causing at least 20 tree falls on Czech railways, 11 of these were windstorm-related (Bil et al., 2017).

Trackside points (movable sections of track, allowing trains to move from one line to another) can easily fail during flooding, high temperatures (excessive expansion of the switching mechanism), or low temperatures (clogging by ice or snow), thereby giving rise to service disruptions.

The presence of leaves on the track during autumn can also give rise to adhesion issues—that is, moist leaf matter on the rails is crushed by the passage of trains into a smooth layer that reduces wheel grip (RSSB, 2004). In these conditions trains must travel more slowly to reduce the risk of "station overruns," where the train cannot brake efficiently enough to stop fully alongside the platform.

2.2.6 | Bridges

During flood events material can be removed from around foundations in water—a process known as scour (Figure 8). The loss of material causes—at a minimum—a loss of stiffness and may lead to collapse. Scour of foundations has been identified as the leading cause of bridge failure worldwide (Gavin et al., 2018; Prendergast et al., 2013), and has led to the failure of many important rail bridges. Bridges founded on shallow foundations are most at risk. In the UK, the Lamington Viaduct was closed for over 7 weeks for emergency repairs in 2015–2016, when scour was found to have damaged one of the piers supporting the bridge (RAIB, 2016). In Ireland, a 20 m section of the Malahide viaduct carrying the main Dublin–Belfast rail line collapsed due to scour erosion of one pier in August 2009 (RAIU, 2010).

2.2.7 | Electrical systems

Overhead power line integrity can be affected by heat (excessive sag) or cold (icing, Figure 9). Strong winds can also bring down power lines or their supporting structures. Third-rail traction—where traction power is provided by a third

FIGURE 8 Scour of foundation at Plaznica bridge on the line between Ljubljana and Jesenice (Gavin, 2016)

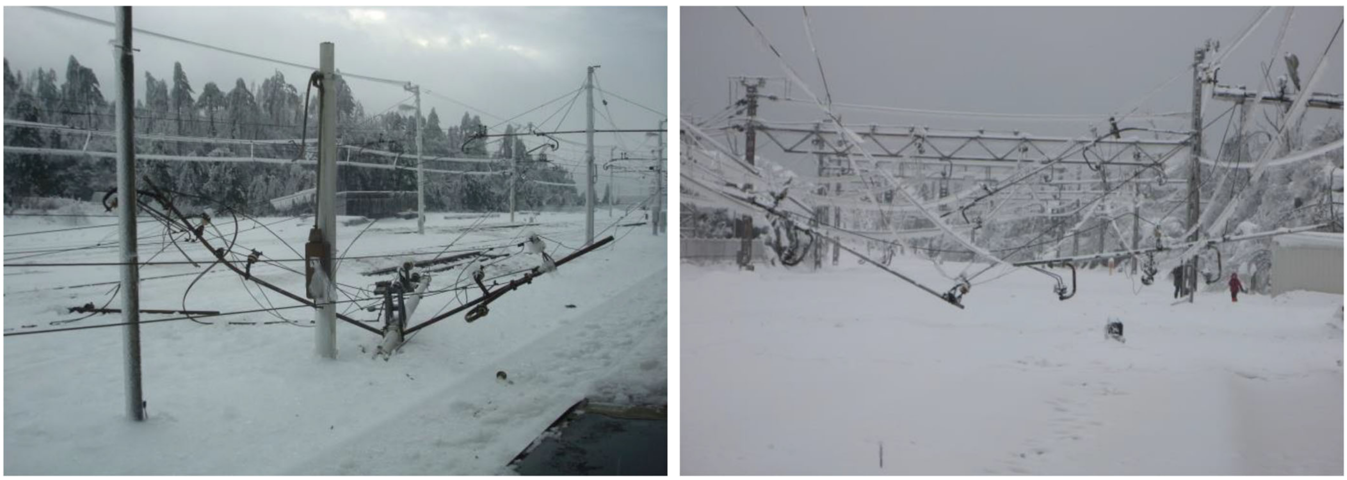

FIGURE 9 Damaged overhead lines and equipment during heavy icing in 2014, Slovenia (Gavin, 2016)

(conductor) rail parallel to the running rails—can be affected by flooding, and by icing (ice disrupts the traction power supply between the rail and the contact "shoes" on the trains).

Freezing rain can lead to rapid ice build-up on wires and supporting structures (e.g., Degelia et al., 2016). This significant extra load can form, during high winds, into aerodynamic shapes that then cause excessive movement of cables leading to failure of cables or junctions.

Sensitive electronic signaling equipment can overheat in hot weather, especially if housed in poorly ventilated casings; and—where trackside—can be prone to flooding. Signaling systems that use electric currents in the track to detect trains can also be disrupted by leaf material on the tracks, as such material interferes with the wheel-rail contact (Rail Delivery Group, 2018).

2.3 | Potential impacts of climate change on weather hazards

The infrastructure sector's interest in climate change stems partly from the wide range of working lifespans of different infrastructure assets, some of which are over 100 years old already, and/or are planned to function for centuries.

Additionally, the weather disruption of basic infrastructure function such as rail transport is often cause for considerable public and political concern. It is therefore important to understand how climate change could affect the weather hazards already known to impact railway infrastructure.

Climate change is studied using climate models—mathematical representations of the climate system in which the world (or a region thereof) is represented by a grid of interacting points. Equations for key climate system processes are solved by discretizing these processes onto the grid. Some sub-gridscale processes are represented conceptually, by parameterizations (Flato et al., 2013). Models may be global (GCMs) or regional (RCMs) in spatial scope, with GCMs covering the whole globe, but typically at low spatial resolution, and RCMs covering limited areas at higher resolution, but driven by boundary conditions usually from a GCM. The process of taking global, low-resolution information and using it in an RCM is one example of *dynamical downscaling* (Tapiador et al., 2020 and references therein). Higher resolution can better represent features such as topography, but the quality of downscaled information is always limited by that of the driving GCM's information.

A complementary approach is *statistical downscaling*, which uses statistical relationships between large-scale atmospheric variables and local or regional climate variables (IPCC, 2013). Weather generators, a common statistical downscaling tool (Wilks, 2010, 2012) can be used to create synthetic future weather timeseries, consistent with climate change projections for longer temporal (e.g., seasonal) averaging periods. Statistical downscaling assumes present-day statistical relationships will hold in future, which may not be true; this is especially relevant for extremes, where future extremes may not be represented by current weather.

Climate models are run under several future GHG scenarios representing different futures that account for the different possible evolution of factors such as population, technological development, and energy use. Two "standard" sets of scenarios have been used: the SRES (Special Report on Emissions Scenarios; Nakicenovic & Swart, 2000), and more recently the RCPs (Representative Concentration Pathways; van Vuuren et al., 2011). Although there are many structural differences between the SRES and RCPs, the point is to provide—and use in climate modeling—scenarios spanning futures representing a range of human actions, from maintaining past behavior through to aggressive climate change mitigation. Comparing projections under these scenarios demonstrates possible outcomes under different futures.

Climate change assessments are undertaken periodically by the IPCC. These assessments usually apply globally or to "large regions" (e.g., Western North America, South East Asia) which are typically larger than the geographic scope of many infrastructure studies. Global mean surface temperature (GMST) is commonly used as a summary metric of climate change; however, projected changes to regional temperature (or other regional parameters) are not uniform globally (Collins et al., 2013) and hazards associated with these parameters will also vary.

Conventionally, climate statistics are often quoted as 30-year averages (Arguez & Vose, 2011) but the use of long-term averages masks how a changing climate could affect weather extremes—which are often the most impactful phenomena for infrastructure. Ideally, then, for conducting an infrastructure risk assessment, climate data at high spatial and often temporal resolution, and describing extremes, are desired.

Recent IPCC syntheses have explored climate change effects on weather extremes (Collins et al., 2013; IPCC, 2018; Seneviratne et al., 2012) as summarized in Table A2. IPCC regional assessments of climate change have also been provided by Christensen et al. (2013), framed in terms of changes to major climate drivers such as monsoons and cyclones; and by Hewitson et al. (2014), including a regional synthesis of projected changes in extremes related to temperature and precipitation. A key result is that climate change can lead to changes in frequency, intensity, spatial extent, duration, and timing of weather and climate extremes, and can result in unprecedented extremes (Seneviratne et al., 2012). Even in a "1.5°C world" (i.e., one in which the GMST increase since pre-industrial times is limited to 1.5°C—IPCC, 2018), impacts are still projected to occur, supporting the need for both climate change adaptation and mitigation, as will be discussed below.

To facilitate more local evaluation of climate change impacts, some countries have developed their own official projections using downscaling methods—for example, Australia ("CCIA"; CSIRO and Bureau of Meteorology, 2019), the Netherlands ("KNMI'14"; KNMI, 2019), Sweden (SMHI, 2019), Switzerland ("CH2018"; NCCS, 2019), and the UK ("UKCP18"; Met Office, 2019). Note that higher spatial (and/or temporal) resolution projections may not always offer improved understanding of the hazards associated with climate change; the fidelity of the higher-resolution information is influenced by that of the lower-resolution information. In addition, high-resolution GCMs are now being developed and evaluated (e.g., Roberts et al., 2018), taking advantage of increases in computer power to study the globe at resolutions typically associated with RCMs; it has been suggested (Tapiador et al., 2020) that such GCMs may now supersede RCMs for some applications.

There is a balance to be struck between good representation of processes at different scales, depending on which of those processes are important for particular hazards and extremes. For example, in the midlatitudes, moderately extreme rainfall over a large area can arise from the passage of synoptic-scale low-pressure systems, which may be captured adequately by lower-resolution models; however, localized, extremely heavy rainfall can arise from small-scale convective storms, which can only be resolved explicitly by higher-resolution models (Kendon et al., 2019).

3 | RISK ASSESSMENT

3.1 | Introduction

Risk assessment is a process to determine the probability of losses "by analysing potential hazards and evaluating existing conditions of vulnerability that could pose a threat or harm to property, people, livelihoods and the environment on which they depend" (UNISDR, 2009). It is a key element of the risk management process.

Since risk cannot largely be eliminated, managers of transport systems must, implicitly or explicitly, accept some level of risk associated with operations. Risk assessment thus attempts to answer the fundamental questions: (a) what can happen and why (risk identification), (b) what are the consequences of any identified risks being realized, (c) what is the probability of their future occurrence, and (d) are there any factors that could mitigate the consequence or reduce the probability?

Dealing with climate change impacts means developing long-term investment planning, which includes adaptation and mitigation measures. Therefore, an iterative risk management approach is recommended (Jones et al., 2014) to support the decision-making process to inform practices that reduce the probabilities of failures, thereby preventing the consequences and achieving safe and reliable infrastructure performance.

Numerous research studies have already tried to reveal the influence and/or cost of weather and climate change on infrastructure networks (e.g., Baker et al., 2010; Chinowsky et al., 2011; Dobney et al., 2009, 2010; Enei et al., 2011; FHWA, 2011; Koetse & Rietveld, 2009; Leviäkangas et al., 2011; Papanikolaou et al., 2011). These studies suggest that climate change will modify the risk of weather-induced impacts on infrastructure, challenging current design rules and procedures for transport infrastructure operation and maintenance, given that many are implicitly or explicitly based on an assumption that past conditions are representative of future weather. A limitation of these studies is their focus on a global or national level of analysis. This makes the results less directly applicable for local infrastructure management, since climate impacts are expected to vary at a finer spatial scale. In order to develop effective adaptation strategies, a detailed analysis of local infrastructure assets is ideally required, with a methodology to combine these consistently across an entire railway network.

3.2 | Risk assessment framework

A wide array of risk assessment framework reviews exists in the literature (Aleotti & Chowdhury, 1999; Dai et al., 2002; Fell et al., 2005; Sánchez-Silva & Gómez, 2013). Most frameworks follow a universal overall layout as part of the risk management process, as defined in ISO 31000:2018 (ISO, 2018) and ISO 31010:2019 (ISO, 2019b), and shown in Figure 10, which also shows a possible application to climate change risk. The output of such risk assessment is an input to the decision-making processes of the entity undertaking the assessment.

Risk *analysis*, which is the detailed examination of risks identified, involves consideration of the causes and sources of risk while accounting for the presence and the effectiveness of any existing controls.

We begin with a consideration of risk in these "classical" terms—that is, as a function of the likelihood of a future weather event under a climate change scenario, and its impacts. This framework allows the consideration of the different management of low-likelihood, high-impact events, and more frequent, low-impact events. In particular, very extreme events require special attention in terms of warning and community preparedness as it may not be possible to systematically protect against them. Where possible a climate change risk assessment should consider a full range of loadings, impacts, and possible responses; it should also consider the potential for opportunities as well as risks (Dawson, Thompson, et al., 2016).

In this framework, a climate change risk assessment of railway infrastructure involves a number of stages: identifying and characterizing relevant hazards (currently and under future scenarios); assessing vulnerability; assessing

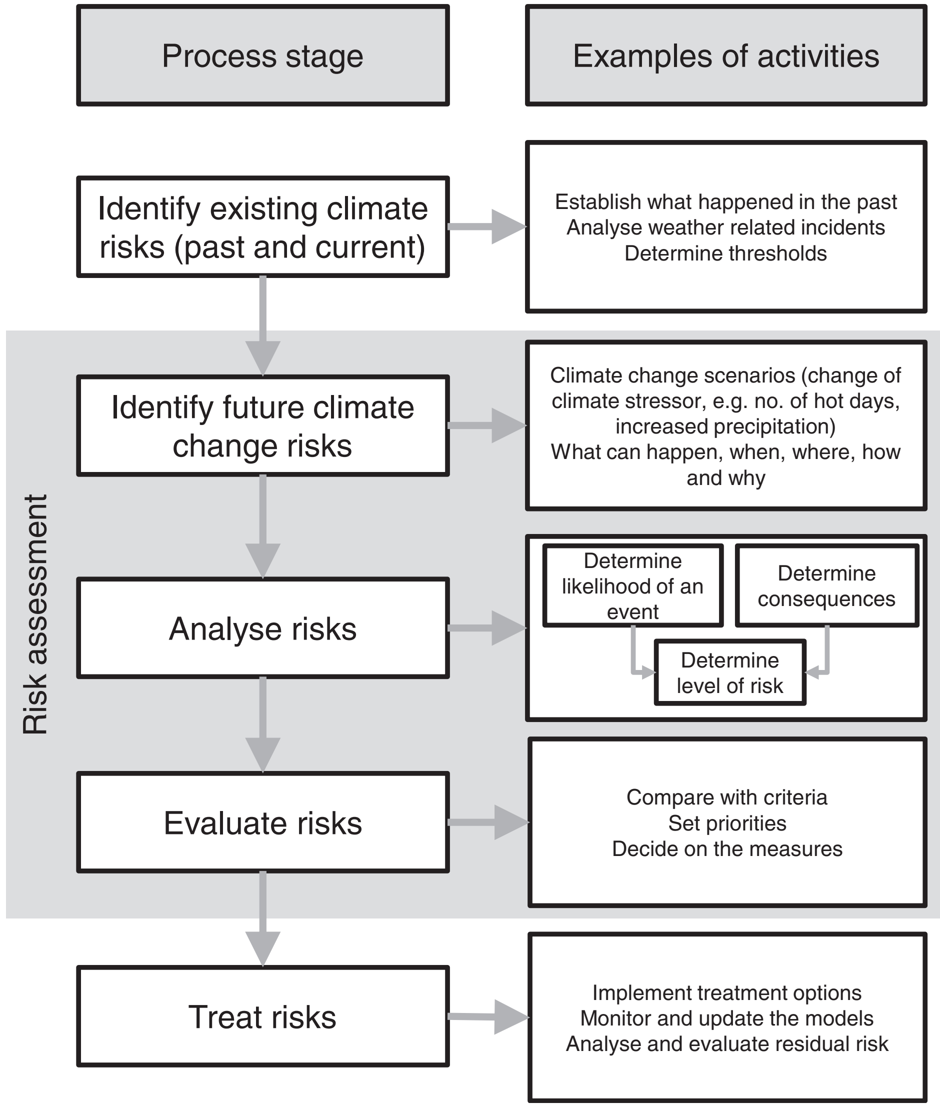

FIGURE 10 Risk *management* process (left; based on ISO 31000:2018 and ISO 31010:2019) and a possible application to climate change risk (right). The shaded area represents the risk *assessment* component

consequences, including network-wide effects, interactions, and interdependencies; assessing systemic risks related to infrastructure service loss; and identifying and developing adaptation strategies (Dawson, Thompson, et al., 2016).

Referring back to Figure 10, in situations where the likelihood of occurrence of a hazard of a certain intensity can be quantified, we refer to the term probability of occurrence (P). When the extent of the impacts, namely consequences (C) are independent of the probability of occurrence of the hazard, which is often the case for purely natural hazards, risk can be expressed algebraically as:

$$\text{Risk} = f(\text{P}, \text{C}) = \text{P} \times \text{C}.$$

This "classical" definition of risk can be applied in a stationary climate but is difficult to apply in practice in a climate change context. Indeed, in the ISO risk assessment standards, the language stays rather more in the "likelihood" realm, though referencing the possibility of defining this mathematically. Extreme weather event probabilities can be estimated (Makkonen, 2006; Meehl et al., 2000; Vajda et al., 2011) but establishing the direct link with consequences is more difficult. In order to address this, risk has instead been connected to the concepts of "vulnerability" (although this has been noted to have multiple meanings; Molarius et al., 2014), and "exposure."

The IPCC uses this complementary framing of climate risk and provides useful definitions of "risk" and related terms ("hazard," "vulnerability," "sensitivity," "impacts," and "exposure": IPCC, 2012; IPCC, 2014), see Appendix C; risk "results from the interaction of vulnerability, exposure, and hazard." This framing removes the need to define a hazard's probability, though this can still be done if possible. We will show below that the vulnerability, exposure, and hazard concepts are quite interrelated.

In this framework, risk can be reduced via either (a) reducing the hazard (which, for climate hazards, is possible only by climate change mitigation), or (b) reducing the exposure and/or vulnerability, by climate change adaptation. It should be noted that there is much variation in the use of the terminology in the literature; references cited here may not be using the terms in the same way as in this paper. In the following sections we explore vulnerability, exposure, and hazard analysis.

3.2.1 | Vulnerability and exposure analysis

Vulnerability and *exposure* are closely related in the IPCC framework. Essentially, vulnerability encompasses the inherent characteristics of a system that make it more or less sensitive to potential impact (whether adverse or beneficial), and exposure sets out the factors that determine that sensitivity.

Quantitative analysis of weather-impact relationships can reveal threshold values for particular hazards, above or below which there are "unacceptable" (by some definition) impacts. The applicability of such thresholds may range from the whole network to a specific asset type, or even specific asset. Attempts have been made to specify widely applicable thresholds for European transport impacts (Vajda et al., 2011), although this is difficult due to the diversity of regional European climates, and hence the different probabilities and intensities of weather phenomena (e.g., rain, snow, wind) across Europe. Whole-network thresholds for the Austrian railway are published (Kellermann, Bubeck, et al., 2016), and the Dutch railway operator ProRail also has some thresholds for weather management (ProRail, 2019a, 2019c). Asset-type specific thresholds are defined for the GB railway, such as those for track buckling (Dobney et al., 2009, 2010), which depend on both track condition and antecedent daily weather conditions. Some relevant thresholds in both operational and design standards for the GB railway were captured in TRaCCA (Arup TRaCCA Phase 1 Consortium, 2014a).

Vulnerability assessment can be challenging, however, and studies use the term in different ways. An example of vulnerability analysis applied to specific assets can be found in Martinović et al. (2018), which proposes a methodology for developing fragility curves for rainfall-induced landslides on railway networks. Fragility curves are a common concept in this type of analysis; they provide the probability of exceedance of different limit states for a given hazard considering a range of magnitudes. The vulnerability of slopes, as expressed by a loss of performance, is quantified for rainfall events of various intensities and duration. The approach expands upon probabilistic slope stability analysis and provides a rational logical framework for considering how vulnerable a slope is to rainfall-induced failure.

Pant et al. (2016) also used the fragility curves concept in an assessment of the GB railway infrastructure network and later expanded their method to consider interdependent sectors and identify critical infrastructure "hotspots" (Thacker et al., 2017). Their studies required the compilation of vulnerability and exposure datasets from several different sources; though their methodology is transferable, similar datasets might not always be easily available in other countries. Lamb et al. (2019) devised a probabilistic model of the economic risk to the GB railway from bridge scour during flooding, also incorporating fragility curves. Schloegl and Matulla (2018) used a rainfall-related climate index as a proxy for landslide activity, together with mapping of present-day exposure elements (e.g., geology, soil type, landcover), to explore possible future landslide risk in a region of central Europe, stating explicitly that all of these data sources are publicly available.

Some information needed to assess vulnerability and exposure is not public (e.g., Surminski et al., 2018), with many infrastructure organizations considering such information confidential, typically for commercial or security reasons (Thacker et al., 2017). For assessments with scope beyond a single organization, transport mode or country (i.e., not just being conducted by, or specific to, the organization holding the information), it can be difficult to assess how widely particular thresholds (or indeed other vulnerability principles) could be applied. Related to this, even if such information is not actively kept confidential, it can be siloed within organizations or sectors, limiting information-sharing about possible risk-reducing actions. Finally, where relevant information does exist, it is rarely collected with the purpose of weather impact analysis in mind. For instance, a person logging a weather-related railway incident in a fault management system will likely be concerned about fixing the problem and restoring normal service, rather than what type of weather caused the problem. As such, incidents may be ambiguously recorded, or attributed incorrectly, for example, if weather were not the obvious cause of the problem (Ferranti et al., 2016).

Although we have noted above that climate change adaptation actions can intentionally reduce vulnerability and/or exposure, a further element of complexity in this area is that there will be developments in society (e.g., economic, demographic, cultural) and technology—including within the railway sector—that could also result in changes to the vulnerability and/or exposure of railway infrastructure.

3.2.2 | Hazard analysis

In practice, hazard analysis should consider the following parameters:

- Geographical analysis (location, extent)—for example, areal extent of flooding of a given depth.
- Temporal analysis (frequency, duration, etc.)—for example, temperatures exceeding a particular threshold for some number of consecutive days.
- Dimensional analysis (scale, intensity)—for example, hurricane intensity on the Saffir-Simpson scale (Saffir-Simpson Team, 2019)

In order to understand the hazard occurrence and (where possible) determine the probability, it is necessary to understand the underlying causes and processes, as already seen in Section 2 (and Figure 1 specifically).

The aim of the hazard analysis is to understand how the hazard evolves over time in terms of intensity, duration, or frequency, for a given region, time horizon and future climate change scenario. Ideally, we need to know which hazard is associated with a particular impact (e.g., high temperature and track buckling), and how often the hazard occurs. This in turn brings in elements of the exposure: defining the important events could be interpreted as identifying the elements defining the sensitivity in the first place.

Detailed information on the hazard behavior is advantageous—for example, whether it exhibits threshold behavior (e.g., more track buckles above a certain value of daily maximum temperature). Good-quality data for the impacts of the hazard are also beneficial (e.g., for the number of track buckles observed, or the number of days when mitigating actions were taken). Exploring the weather-impact relationship involves blending the physical sensitivity (of the infrastructure, to impacts of the hazard) with the societal susceptibility to these impacts. The future hazard can be estimated using information from climate modeling or downscaling studies, as outlined in Section 2.3. Section 4.2 discusses the literature around weather-impact relationship elicitation for railway infrastructure.

3.3 | New standards for climate change risk assessment

The above discussion began with a generic risk assessment framework, and considered how one can move from the generic towards the specific case of climate change. A new family of ISO standards is now being developed, about climate change vulnerability, impacts, and risk assessment (ISO 14091—in development; ISO, n.d.); climate change adaptation (ISO 14090—published; Quinn et al., 2017; ISO, 2019a); and investments/financing activities relating to climate change (ISO 14097—in development). These standards provide guidance on how organizations can frame some of the concepts in a climate change risk assessment. When published, ISO 14097 will be relevant in the context of the emerging need for organizations to report on their climate resilience to their capital providers (Sanderson et al., 2019), colloquially known as "TCFD" after the Task-force on Climate-related Financial Disclosures, who recommended that such reporting be implemented (TCFD, 2017).

At the time of writing, a preview of ISO 14091 (ISO, n.d.) is available. The standard introduces climate change risk assessment, including key components: hazard, exposure to hazard, sensitivity to hazard, and risk with and without adaptation. This latter point is important; climate change risk could involve changes to vulnerability and exposure both from adaptation and from other causes, so consideration will be needed of how to partition these into the different risk settings. The standard also provides guidance on preparing, implementing, and reporting and communicating the results of such an assessment, including potentially useful examples of tools, approaches, and guidance.

ISO 14090 (Quinn et al., 2017; ISO, 2019a) provides a flexible and modular approach to climate change adaptation, designed to be relevant to any organization, regardless of its stage along the adaptation journey. It uses definitions of key concepts that are largely adapted from the IPCC's glossary, and it outlines an approach which can include stages involving scoping, assessing impacts (and opportunities); adaptation planning; implementation; monitoring and evaluation; and reporting and communication.

The approach does not prescribe such factors as the choice of climate projections to be considered, nor the decision-making approaches to be used (e.g., risk assessment is mentioned as *a* method for understanding climate change impacts, rather than *the* method). Importantly, the use of "systems thinking" (Beckford, 2013) is encouraged—that is, the recognition and consideration of one's own organization (or department, asset class, or other such element) as an element of a wider system. For instance, points are part of the track system; a railway infrastructure organization is part of the wider railway system; a country's railway infrastructure is part of its wider critical infrastructure; and so on. This is important in the sense that risk assessment increasingly needs to account for interdependencies between the system being considered and other, related systems (here, the railway infrastructure's interdependencies with sectors such as energy, water, and digital infrastructure). Although interdependency is becoming more widely recognized as a concept (e.g., Beckford, 2015; Dawson, Thompson, et al., 2016; Markolf et al., 2019), approaches for this aspect of risk assessment are relatively novel (e.g., Dawson, 2015), and infrastructure interdependencies are seen as a knowledge gap (Committee on Climate Change, 2019).

For most entities, climate change risk will be only one element of their risk assessment portfolio. It is therefore important that an entity's risk assessment considers how their climate change risk interfaces with their other risks, which in turn will require the consideration of more general future scenarios exploring how the world may evolve in a wider sense. The Shared Socioeconomic Pathways (Riahi et al., 2017) are one such set of scenarios, based on five narratives describing plausible alternative global pathways for future society (Hausfather, 2018).

3.4 | Alternatives to the risk approach

It is noted above that a critique of the "classical" risk assessment framework is that it requires the assessment of probabilities in a system where their quantification is difficult or impossible, or where there is little agreement between studies (Kunreuther et al., 2013); the somewhat different IPCC framing of risk attempts to address this. A remaining issue is that a poor understanding of the probabilities could lead to an underestimation of the possible importance of low-probability, high-impact events: the "fat tails" problem (Weitzman, 2009, 2011), so labeled to reflect the fact that if the relevant probability distribution is poorly characterized, its tails may be "fatter" than assumed, meaning that the tail events become more important in determining expected damage: "fatter tails on probability distributions of climate outcomes increase the importance in understanding and quantifying the impacts and economic value associated with tail events" (Kolstad et al., 2014).

As such, considering low-probability, high-impact events can be used to "stress-test" adaptation strategies. In the UK, the "H++" scenarios are available for this purpose. The first of these was for sea level rise for use in the TE2100 project (Lowe et al., 2009), but more recently this has been expanded to cover other hazards: heat waves, cold snaps, droughts, floods, and windstorms (Wade et al., 2015). The approach combines different strands of information (observations, projections, physical limits, and expert judgment) to create the scenarios.

As noted above, ISO 14090 is not prescriptive about risk assessment, though it is mentioned therein in both the "classical" and IPCC framing. The standard lists a range of decision-making approaches that permit one to address the uncertainties in climate predictions in undertaking adaptation planning (ISO, 2019a): adaptation pathways (Quinn et al., 2018); decision mapping (Bouchart et al., 2002); dynamic adaptive policy pathways (Haasnoot et al., 2013); robust decision-making (Kunreuther et al., 2013 and references therein); and adaptive policy making (IISD, 2007). Other potentially useful decision-making approaches are also listed: cost–benefit analysis and cost-effectiveness analysis (Kunreuther et al., 2014); multi-criteria analysis (Jones et al., 2014); real options analysis (Buurman & Babovic, 2016; Wreford et al., 2020); expert judgment (Oppenheimer et al., 2016; Thompson et al., 2016); systems approaches (Keller, 2015); and planning scenarios (Galy, 2019). Though not explicitly mentioned in ISO 14090, the use of storylines (Shepherd et al., 2018) is a further option, having some commonality with scenarios. The intention is that the user has at their disposal a range of possible methods from which to choose in addressing their adaptation needs.

4 | CHALLENGES IN ASSESSING CLIMATE CHANGE RISKS FOR RAILWAY INFRASTRUCTURE

The literature regarding weather, climate change, and railways presents several challenges for those wishing to assess infrastructure climate change risks. These are discussed below and highlight some gaps between the theoretical description of risks and their actual characterization in practice. Adger et al. (2018) identify similar challenges.

4.1 | Managing uncertainties

The concept of uncertainty is key in any risk assessment. The IPCC defines it as "a state of incomplete knowledge that can result from a lack of information or from disagreement about what is known or even knowable. It may have many types of sources, from imprecision in the data to ambiguously defined concepts or terminology, or uncertain projections of human behaviour. Uncertainty can therefore be represented by quantitative measures (e.g., a probability density function) or by qualitative statements (e.g., reflecting the judgment of a team of experts)" (IPCC, 2014).

The process of evaluating climate change risk or its components can be described in terms of multiple steps, with uncertainties at each step. Wilby and Dessai (2010) described a "cascade of uncertainty," from future society through to adaptation responses, with the "envelope of uncertainty" expanding at every step. Dikanski et al. (2017, 2018) focused on the specific case of the climate change–bridge scour risk relationship, in which they identified six steps, with some discussion of the uncertainties involved therein. They distinguished aleatory uncertainty (an irreducible component of uncertainty arising from intrinsic statistical variations of the system being modeled) from epistemic uncertainty (uncertainty which can be reduced by gathering more information), noting that both limit the prediction of climate change impacts on scour risk, but that uncertainties in basic asset data could be larger than the climate change uncertainty, and are potentially reducible even if the climate change uncertainties are not. Chinowsky et al. (2017) discussed a three-step modeling process for modeling climate change impacts on US railway network operation: essentially, modeling the railway asset system and traffic volumes; creating climate scenarios spanning several future outcomes; and estimating baseline and future risks in terms of delay minutes and costs, and potential savings that could be achieved with new technologies. Armstrong et al. (2017) proposed a seven-step framework for assessing and improving the resilience of the UK railway network to weather and climate, themselves acknowledging that "given the uncertainties surrounding climate change [...] effects on the railway's infrastructure, this is inevitably an inexact exercise." These examples reflect the complexity of multi-step processes used in impact and risk assessment at several scales, and their uncertainties.

4.1.1 | Key uncertainties in climate modeling

Like most simulation techniques, climate modeling itself is subject to uncertainties (Flato et al., 2013). Climate model simulations are simply the best estimates that can be made based on current scientific knowledge and modeling capability.

The key uncertainties in climate modeling are (a) uncertainty due to randomness (*aleatory uncertainty*, already mentioned above); (b) uncertainty in the future evolution of GHG emissions (*scenario uncertainty* or *forcing uncertainty*); (c) *modeling uncertainty*, arising from our incomplete knowledge about the climate system, and hence our ability to represent its components and processes in models (*structural uncertainty*), including incomplete knowledge about the values of key parameters in the models (*parameter uncertainty*); (d) the fact that the climate varies naturally on all timescales (*natural variability*). The ways in which these are addressed scientifically are discussed below, with illustrative examples. The relative importance of the different sources of uncertainty in climate projections depends on the variable of interest; the spatial and temporal scales of the projections; and the lead time of the projections (Kirtman et al., 2013 and references therein).

Scenario uncertainty

Scenario uncertainty is handled by driving climate models with different future GHG scenarios to evaluate different possible futures (Figure 11a). Many of the quantitative studies mentioned above (and discussed in Section 4.2) consider two or more such scenarios. However, scenarios (whether of GHG emissions or otherwise) are typically not associated with any probability of occurrence, and therefore it is up to the decision-maker to decide which scenario(s) is/are most appropriate for their purposes. Yet even at this early step in the assessment process, the possible outcomes may be very different. For example, the GMST projections for 2100 in Figure 11a span a range of increases between about 2 and 6°C with respect to pre-industrial (1861–1890) values, depending on the GHG scenario used. In turn, these temperatures are global averages: the associated regional temperature changes will vary, as will the associated impacts. Decision-makers should ideally consider different possibilities to highlight what could occur in different futures.

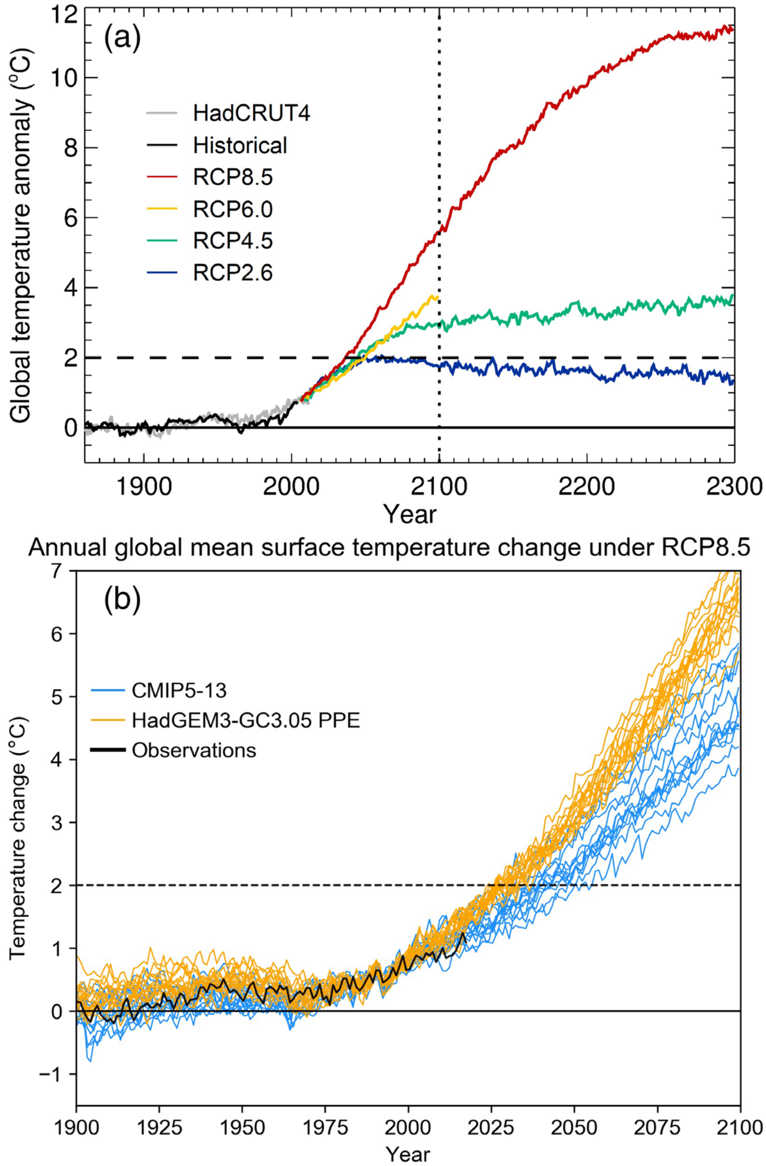

FIGURE 11 Examples of uncertainties in climate model simulation outcomes. (a) The same model is run under four different RCPs, sampling scenario uncertainty. (b) Two different sets of climate models, run under RCP8.5 only, are compared: one set (orange) in which the same model is run with slightly different input parameters (sampling parameter uncertainty), and one set (blue) comprising results from many different centers' climate models (sampling structural uncertainty). Temperature anomalies (y-axis) are plotted with respect to the same pre-industrial baseline, 1861–1890. A dashed line is plotted at a temperature anomaly of 2°C. (a) Adapted from Figure 1 of Caesar et al. (2013); (b) adapted from Figure 2.13 of Lowe et al. (2018)

Structural uncertainty and parameter uncertainty

It will never be possible to create a perfect model of the climate system, given its complexity. However, as scientific understanding increases, it is possible to model more and more of the system's components and interactions in some way. Although all models represent the same real system, different climate modeling centers around the world have developed their models in slightly different ways, which means that no two models will ever produce identical outcomes, even when driven by the same input.

Instead of seeing this as a drawback, the scientific community uses these different models as a *multi-model ensemble* (MME), looking across the models at the range of responses, instead of focusing on the output from just one. The IPCC's reports use MMEs, and these have become more sophisticated as time goes on, with similar protocols being used for experimental design in order to create models which may be systematically intercompared. Nonetheless, there remain criticisms of MMEs—for instance, models are tuned to match observational data, so they may not sample the full range of uncertainty; and there are often co-developed model components where more than one modeling center collaborates on a given piece of computer code, thereby effectively reducing model independence (Pennell & Reichler, 2011; Tebaldi & Knutti, 2007).

Parameter uncertainty is a further dimension of modeling uncertainty—the importance of a given climate process may be known, and it may be possible to represent it by an equation, but the values of parameters in that equation may not be known. This can be addressed by allowing these parameters to vary systematically across different runs of the same climate model, using expert judgment to determine which parameters may (co-)vary and what values they may take, thereby creating a *perturbed parameter ensemble* (PPE). PPEs sample parameter uncertainty but not structural uncertainty, as the same climate model is used for all runs. UKCP18, for example, includes regional projections from a PPE, alongside global projections that contain information from a PPE and an MME (a subset of the IPCC models). Some projections from UKCP18 are shown in Figure 11b, which demonstrates sampling of structural uncertainty and parameter uncertainty—but not scenario uncertainty, as the models were run under RCP8.5 only. The blue lines represent different members of the MME underlying the IPCC Fifth Assessment report, and the orange lines represent a PPE of runs of a Met Office Hadley Centre model. Note that the PPE projects outcomes which are generally warmer than those from the MME, meaning the PPE member projections typically reach a given value of GMST increase (say, 2°C as plotted in Figure 11) earlier than the MME members.

Natural variability

The uncertainty due to natural variability is a more significant fraction of the total uncertainty in climate projections at the relatively near term (e.g., earlier in the 21st century) than at longer lead times; it is also more important for some parameters (e.g., precipitation) than others (e.g., temperature; Kirtman et al., 2013 and references therein). It is useful to ascertain the relative size of any projected trend in a variable for a given region and/or time horizon, compared to the relative size of the year-to-year variability in that variable. For example, the trend in projections of winter mean wind speed over the UK from UKCP18 is known to be very small compared with the year-to-year variability, making it more useful to consider the latter, even on climate change timescales, if one were interested in mean wind speeds (Fung et al., 2019).

As noted in Section 2.3, climate projections are often quoted as anomaly (trend) values for a future 30-year period (or periods) with respect to a baseline 30-year period, but for some applications it is the projected variability which is of interest. UKCP18 includes projections for shorter averaging periods, which give a wider spread of outcomes for a given future time horizon than do the projections with longer averaging periods (Lowe et al., 2018). Users of climate projections may use different baselines and multiple future periods to explore the underlying variability at these different time horizons.

4.1.2 | "Downstream" use of climate model output

As noted in Wilby and Dessai's (2010) "cascade of uncertainty," climate model output is often an onward input for some other kind of impact modeling (e.g., hydrological modeling). An additional challenge is therefore providing climate information in an appropriate format for these "downstream" uses. Temporal and spatial resolution is often a major factor (e.g., Jaroszweski, Hooper, & Chapman, 2014); approaches to obtaining higher-resolution information from lower-resolution information were briefly described in Section 2.3. Nonetheless, it is not always possible to provide, using climate models, some of the parameters desired by decision-makers (Jacobs et al., 2013).

As well as the use of climate model ensembles, there is increasing use of impact model ensembles, to represent uncertainties in impacts for a given projection of climate. AgMIP (Rosenzweig et al., 2013), for agriculture, and ISI-MIP (Warszawski et al., 2014), for a range of sectors, are examples of such approaches.

4.2 | Understanding the weather-impact relationship, and the climate change effect on it

Generally, to understand present-day weather-impact relationships and thus to extend this to climate change timescales, quantitative information is preferred. However, the extent to which quantitative assessments have been made in the literature is variable.

Some studies focus solely on a *qualitative* commentary, typically discussing the ways in which weather can affect infrastructure, outlining how a changing climate may change the future weather, and thereby noting the possible effect of climate change on a given infrastructure impact (Al-Alawi, 2010; Delgado & Aktas, 2016; Rossetti, 2002; Sa'adin et al., 2016). In simplistic terms, this may be based on the expected direction of change in the impact with climate change. Further studies are *semi-quantitative*, typically either (i) studying present-day weather impacts in detail, but future climate impacts only in overview (Dindar et al., 2016; Ferranti et al., 2016, 2018; Geertsema et al., 2009; Liu et al., 2018); (ii) discussing quantitative climate projections, but with only qualitative (or no) relation of these to future infrastructure impacts (Arkell & Darch, 2006; Baker et al., 2010; Cochran, 2009; Hooper & Chapman, 2012; Koetse & Rietveld, 2009; Love et al., 2010; Loveridge et al., 2010; Nasr et al., 2019; Peterson et al., 2008; Tang et al., 2018); (iii) performing experiments on purpose-built infrastructure in testing environments designed to reproduce future weather conditions anticipated with climate change (Hughes et al., 2009; Kaewunruen & Tang, 2019; Toll et al., 2012), or (iv) a combination of these (Kilsby et al., 2009).

Some studies make *quantitative* estimates of climate change impacts on the railway generally, or for its infrastructure specifically (Dawson, Shaw, & Gehrels, 2016; Dawson, Thompson, et al., 2016; Dobney et al., 2009, 2010; Doll et al., 2014; Leviäkangas & Michaelides, 2014; Nemry & Demirel, 2012; Palin et al., 2013; Princz-Jakovics & Bachmann, 2018; Roca et al., 2016; Stipanovic Oslakovic et al., 2012; Thornes et al., 2012; Villalba Sanchis et al., 2020). Such studies aim to provide more useful and actionable information to decision-makers. Dobney et al. (2009, 2010) studied UK track buckling risk, using meteorological observations and a weather generator to construct relationships between current weather/projected future climate and buckling-related delays. Stipanovic Oslakovic et al. (2012) explored the climate change effect on summer and winter Dutch rail incidents, deriving simple weather-impact relationships and applying change factors for climate change to observations, generating plausible future weather timeseries to explore how the relationships could change under different scenarios. Palin et al. (2013) worked with GB railway stakeholders, using industry understanding to translate RCM data into projected changes in railway-specific hazards like track buckling and excessive overhead line sag. Leviäkangas and Michaelides (2014) and Doll et al. (2014) compared the costs of weather extremes on transport now and in future, noting discrepancies between the costs calculated by research in two different EU-funded projects using different methods (see Section 4.3 for further discussion of costs).

Quantitative estimates of "days with line restrictions" under different future climate change scenarios were made by Dawson, Shaw, and Gehrels (2016) for the railway at Dawlish, UK. A further study of Dawlish estimated overtopping rates using future scenarios of sea level rise, storm surge probability, and river flow change (Roca et al., 2016). Melvin et al. (2017) estimated costs to infrastructure (including railways) from climate change in Alaska under two different future GHG pathways. Chinowsky et al. (2017) estimated climate change-related delay costs on the US rail network arising from projected future temperature increases. Princz-Jakovics and Bachmann (2018) applied a classical (likelihood-impact) risk assessment process to a new stretch of the Hungarian railway, assigning categorical risk levels associated with various weather impacts for the case study location. Villalba Sanchis et al. (2020) used climate change projections and Monte Carlo simulation to project the number of track buckling events on the Spanish high-speed rail network, finding a significant increase in buckling events in future, assuming current maintenance standards and procedures.

The gradual evolution from qualitative to quantitative assessment is facilitated by advances in the availability and/or quality of information for the contributing factors to risk. The availability of more relevant and more usable data from climate models, and longer observational data records, can support better hazard characterization. Vulnerability and exposure information are slowly developing as the recording of weather impacts gradually improves, the information captured in asset databases becomes more detailed, and the length of records increases, leading to a better understanding of what exactly happens following severe weather; the effects on both railway infrastructure and interdependent systems; and how any issues are remediated. In addition, recording this kind of information will allow the evaluation of how any risk management and/or adaptation actions subsequently affect vulnerability and exposure. Nonetheless, the openness of this information and its usefulness for weather/climate impacts studies (by anyone outside the organization holding the information) is still limited.

4.3 | Understanding the cost implications of climate change

There are three main elements to the economic cost of weather and climate change to railway infrastructure: (a) the cost of direct impacts on infrastructure assets, (b) the cost of transport delays and cancellation arising from weather, and (c) the cost of adaptation actions. Studies (Table 2) have attempted to characterize impacts in terms of economic cost for the present day and/or the future, based either on direct costs from damages or indirect costs through remediation.

Comparing these studies is challenging: different climate models, GHG scenarios, and future time periods were used; different economic assessment approaches were used; and the scope of the studies varies geographically (regions, countries, EU) and systemically (specific weather impacts vs. a range thereof; railway infrastructure vs. transport infrastructure vs. transport system). What is clear, then, is that estimating the costs and/or benefits—whether of existing impacts, future impacts, or adaptation actions—is a further area of uncertainty in risk assessment. Additionally, the

TABLE 2 Summary of studies exploring the costs of weather impacts and climate change adaptation on transport

Study	Topic	Geographic scope	Data/ scenario(s)	Time period (s)	Costs		
Dobney et al. (2009)	Track buckling risk management	Southeast England	UKCIP02/ medium-high emissions	2020s (2011–2040); 2050s (2041–2070); 2080s (2071–2100)	£53.7 million (2080s)		
Dobney et al. (2010)	Track buckling risk management	Great Britain	UKCIP02/low and high emissions	As above	£23 million for an extreme summer in the 2080s (high emissions)		
Nemry and Demirel (2012)	Track buckling risk management	EU-27	Several models, run under A1B, RCP8.5 and E1 scenarios	Present day	€33.7 million/year		
				2040–2100	RCP8.5: €61.3 million/ year	A1B: €54 million/ year	E1: €54.7 million/year
				2070–2100	RCP8.5: €163.4 million/ year	A1B: €68.7 million/ year, reduced to €49 million/ year with adaptation	E1: €60 million/year
Nemry and Demirel (2012)	Bridge scour risk management (assumed 80% road and 20% rail bridges)	EU-27	KNMI model/ A1B scenario	2040–2070	€541.3 million/year adaptation cost to reduce scour risk		
				2070–2100	€382.7 million/year adaptation cost to reduce scour risk		
Leviäkangas and Michaelides (2014)	Costs to transport due to extreme weather events	Europe (EU-27)	Not stated	Present: 1998–2010	€15 billion/year, with c.€10 billion/year from road accidents		
Doll et al. (2014)	Comparison of costs across European transport as computed in FP7 EWENT and WEATHER projects	Europe (EU-27)	Not stated	Present: 1998–2010	Damage cost of €2.5 billion/year		
Dawson, Shaw, and Gehrels (2016)	Order of magnitude analysis of various costs in coastal flooding management of railway	Dawlish, UK	UKCP09/low, medium, high, H++ scenarios	Out to 2100	Increased maintenance/line restriction costs: £millions Damage from extreme events: £10s of millions Diversion of the railway: £100s of millions to billions		

(Continues)

TABLE 2 (Continued)

Study	Topic	Geographic scope	Data/ scenario(s)	Time period (s)	Costs
Kellermann, Schönberger, and Thieken (2016)	Flood damage to Austrian railway	Mur River catchment, Austria	30, 100 and 300-year floods	Present day	Expected annual flood damage: €8,878,000 for railway in Mur catchment Resulting repair costs also estimated, including with varying level of risk aversion Climate change impact not quantified but costs expected to rise due to increased flood hazard
Melvin et al. (2017)	Climate change damage to public infrastructure	Alaska, USA	Five CMIP5 global climate models run under RCP8.5	2015–2099	Cumulative totals: $5.5 billion (no adaptation) $2.9 billion (with proactive adaptation)
			Five CMIP5 global climate models run under RCP4.5	2015–2099	Cumulative totals: $4.2 billion (no adaptation) $2.3 billion (with proactive adaptation)
Chinowsky et al. (2017)	Delay costs on rail network	USA	Five CMIP5 global climate models run under RCP8.5	Until 2100	Cumulative increase in delay-minute costs of $35–60 billion
			Five CMIP5 global climate models run under RCP4.5	Until 2100	Cumulative increase in delay-minute costs of $25–45 billion
Bachner (2017)	Economy-wide effects of adaptation options on Austrian road and rail transport	Austria	Not stated	"Climate impacts of 2050 in today's economy"	Direct impact costs more than double due to macroeconomic linkages Indirect costs are larger than direct costs by a factor of 2.2 Benefit–cost ratios imply a clear benefit of adaptation for the rail sector in both the case where only direct effects are considered, and when indirect effects via sectoral interlinkages are also captured
Dawson, Hunt, et al. (2018)	"Real options analysis" (ROA) approach to estimate value of using up-to-date sea level rise (SLR) information for two adaptation options.	Dawlish, UK	UKCIP02 and UKCP09/low and high scenarios	2002 and 2010	"Real option" being tested is to delay adaptation investment relating to the main railway line through Dawlish until improved knowledge results in the partial resolution of uncertainties in SLR projections Three adaptation actions explored: (i) "do minimum" option (maintaining current defenses) (ii) improvement of current defenses. Capital cost £528 million. (iii) a retreat of the line further inland. Capital cost £2.182 billion. Value gained by delaying decision, and therefore giving decision-maker the opportunity to re-evaluate adaptation measures in light of new SLR projections, is ~6%–20% of capital cost of railway line adaptations

TABLE 2 (Continued)

Study	Topic	Geographic scope	Data/ scenario(s)	Time period (s)	Costs
Bubeck et al. (2019)	Railway flood risk	Europe	Seven GCM-RCM pairs from EURO-CORDEX, run under RCP8.5	1976–2005 (baseline) For future, time periods not used—rather, global warming levels of 1.5, 2, and 3°C (with variable time periods at which these are reached in models)	Expected annual damages (EAD) of €581 million/year in baseline (range €403–801 million/year) 255% increase under 1.5°C global warming 281% increase under 2°C global warming 310% increase under 3°C global warming Avoided losses of €317 million/year at 1.5°C global warming cf. 3°C global warming Avoided losses of €164 million/year at 2°C global warming cf. 3°C global warming
Koks et al. (2019)	Multi-hazard risk analysis of road and railway infrastructure assets	Global	Various hazard datasets (not climate modeling)	Present day	Expected annual damages (EAD) due to direct damage to road and railway assets: US$3.1–22 billion Global EAD are small (c. 0.02%) cf. global GDP, but in some countries EAD reach 0.5 to 1% of GDP annually—same order of magnitude as national transport infrastructure budgets

wider socio-economic costs of disruption—such as reduced capacity for transporting goods, or reduced tourism demand in affected areas—are discussed even more rarely.

In a review of the economics of adaptation, Watkiss (2015) identified the challenge of appraising adaptation options under deep uncertainty, and described the strengths, challenges, applicability, and potential use of a range of decision-support methods for this, many of which are listed in Section 3.3 above; those which involve monetization (e.g., cost–benefit analysis and real options analysis) have been used in various studies in Table 2.

Ideally, economic estimates for the future should be made under multiple scenarios—at least with and without adaptation, and ideally with different adaptation options considered. Wider socioeconomic costs should also be included (RSSB, n.d.-b), as disruptions already experienced have shown that these can be large and desirable to avoid. We note that such costs can be assessed using the "computable general equilibrium" (CGE) modeling approach (Bachner, 2017). Finally, interdependent entities should preferably use the same modeling methods, to allow comparable outcomes, or even work together to consider the economics of their climate change interdependencies.

4.4 | What does "climate change adaptation of railway infrastructure" actually involve?

4.4.1 | Progress, barriers, and bottlenecks

The IPCC notes that "despite many successful examples around the world, progress in adaptation is, in many regions, in its infancy and unevenly distributed globally" (de Coninck et al., 2018). Others have also commented on the scarce details of what rail infrastructure adaptation involves (Armstrong et al., 2017; Eisenack et al., 2012), and on some barriers to adaptation with quite deep-seated causes, rooted in politics (e.g., political decisions resulting in changes to organizational funding models), organizational values (e.g., different perspectives on the relative importance of adaptation cf. other tasks), and competition between actors (Rotter et al., 2016). On organizational values, the difference between public and private adaptation is important for railways: there may be a different degree of focus on adaptation, and different perceptions around the importance of decisions realized on short versus long timescales, depending on whether the railway is publicly or privately-owned.

EEA (2014) reported on European transport system adaptation, noting that incremental changes for reducing transport system vulnerability worked well in many cases, but that "a more fundamental and comprehensive change" could be needed in the event of disruptive or fundamental changes in climate, society or the economy. Better links between adaptation and mitigation policies in the transport sector were also recommended.

Stamos et al. (2015) created "roadmaps" for adaptation measures for transport, including railways. Their measures were classified into those about organizational decision-making processes; technical, procedural, and operational; information flow and ICT support; decision and risk models; and legislative options. Generally the technical measures, which were the most numerous for railways (19 of 35 proposed measures), had the longest implementation timescales and the highest implementation costs; lower-cost measures with shorter implementation timescales included those around mapping vulnerabilities (and critical locations), emergency planning, better maintenance and monitoring, and better data management.

Hendel-Blackford et al. (2017) explored adaptation knowledge in several sectors, noting three key gaps for transport: a need for fuller integration of climate change considerations into existing procedures; poor understanding of current and future vulnerabilities across different transport modes, including inter-modal vulnerability assessments and the potential for integrated adaptive solutions across and beyond the transport sector; and a lack of coordinated action plans to assess, prioritize and implement adaptation actions across different transport modes, agencies, and governance levels.

Depoues (2017) identified three quite similar "bottlenecks" in the adaptation of the French railway: (i) the lack of a consistent institutional framework (even though a national adaptation policy exists); (ii) poor engagement of infrastructure managers with climate scientists; and (iii) the fact that processes and procedures are not aligned with incorporating an uncertain dynamic phenomenon such as climate change. The literature discussed above for the other challenges gives examples of good practice which could support progress towards overcoming such gaps and bottlenecks.

4.4.2 | Characterizing and classifying adaptation measures

Railway system adaptation to extreme weather and climate change should be considered an extension of the established railway safety culture, which has long sought to manage risk through changes in infrastructure design, operating practices and staff training. As described previously (Section 3), the assessment of any risk includes consideration of hazards, vulnerability and exposure, and impacts. Since climate change mitigation is the only way to reduce the hazard itself, adaptation must focus on the other elements; adaptation approaches can first be categorized into those that seek risk reduction through reducing:

- The exposure to the hazard—for example, providing a flood diversion channel for routing excess water flow away from the infrastructure location.
- The vulnerability of the asset—for example, improving the performance of components across a wider range of weather conditions.
- The effect of a failure—for example, providing an alternative service route that does not depend on the at-risk asset.

This is useful when the risk to be reduced is characterized by a particularly high value in one term of the risk calculation as then an appropriate adaptation approach which potentially deals directly with that term can be formulated, rather than, for example, investing in enhancing asset components which may still be overwhelmed by a flood hazard.

Adaptation approaches are typically also characterized by the *goal* of the risk alleviation. Therefore, approaches may be considered that seek to:

- Increase robustness—that is, the adaptation reduces risk by enhancing protection from the hazard(s) involved, thus reducing asset vulnerability to the hazards, and thereby allowing continued operation in a wider range of conditions. For example, raising electrical systems above predicted flood water levels either temporarily or permanently.
- Provide redundancy within the system—that is, additional or alternative capacity exists to enable services to continue even if the infrastructure asset is unable to operate.
- Enable rapid recovery—that is, the infrastructure manager has capacity available to deliver a timely and effective response to reinstate the infrastructure and thus services. This may include temporary interventions such as portable flood barriers to control and limit infrastructure damage and hasten recovery.

A further approach is to consider the "system level" at which measures apply. A TRaCCA compendium of weather resilience and climate change adaptation measures used in other countries (Arup TRaCCA Phase 2 Consortium, 2016-c) comprised measures at four such levels: socio-political (e.g., consideration, when planning for future resilience, of the future transport system's structure and use), strategic (e.g., consideration of infrastructure interdependencies within and outside the railway), operational (e.g., development of severe weather event plans, plus review/update thereof in response to incidents) and local/specific (e.g., site-specific evaluation of applicability of proposed measures at particular locations). An example applicable to strategic, operational and local/specific levels is the partnership, since 2005, between ÖBB (Austrian national rail service) and the weather service provider UBIMET. The key element of this partnership has been the jointly-developed bespoke weather information system, "infra:wetter," providing 24/7 severe weather alerts and forecasts for the Austrian rail network and also permitting local rail staff to input observations to enhance modeling and decision-making. Wider stakeholder engagement as part of the adaptation process is also valuable. To protect their railway infrastructure from Alpine hazards, ÖBB engages partners to jointly plan and implement adaptation. The core of these partnerships lies in information exchange and cost-sharing. It includes formal, standardized processes fixed in regulations, as well as informal elements and ad hoc negotiations (Kellermann et al., 2015).

As this example shows, infrastructure adaptation interventions need not be direct engineering or technological ("gray" or "hard") interventions on infrastructure assets. Regulatory and/or policy-based ("soft") adaptation that improves management, communication and response to extreme events within and between organizations is extremely valuable and is a step towards "transformational" adaptation. This concept "refers to actions aiming at adapting to climate change resulting in significant changes in structure or function that go beyond adjusting existing practices" (de Coninck et al., 2018). It can be more challenging to implement than localized interventions such as flood protection measures, as it will be larger-scale, and involve more actors. Klein et al. (2014) cited generic examples of transformational adaptation but noted a lack of clarity about the extent to which it could be operationalized. Lonsdale et al. (2015) noted confusion over what transformational adaptation is, and a dearth of examples, but felt that enhancing knowledge exchange and shared learning could start to address this.

Soft adaptation options may also be "lower-regret" than hard interventions, or even "no-regret"—that is, they may offer a positive cost–benefit balance regardless of the climate change that is realized. SNCF's adaptation strategy is based on a series of such measures (EEA, 2014; Jourdan et al., 2013).

4.4.3 | Flexibility in adaptation measures

The long lifespans of many infrastructure assets make maladaptation ("actions that may lead to increased risk of adverse climate-related outcomes, increased vulnerability to climate change, or diminished welfare, now or in the future"; IPCC, 2014) a very real possibility for infrastructure. Approaches are needed which allow for decisions to be made despite uncertainty (see Sections 3.3 and 3.4, and Watkiss (2015), for descriptions thereof)—for example, which facilitate staged adaptation actions and decisions that are flexible to the possibility of needing to do something different in the future, thereby avoiding the "lock-in" of irreversible (or costly to reverse) decisions made in the shorter term that later turn out to be inappropriate in the longer term.

The managed adaptive pathways approach (Chapter 7, Lowe et al., 2009) is one such method, which allows for incremental decision-making based on regular re-evaluation of risk profiles and has been used to define the future climate risk management plan for London's Thames Barrier (Environment Agency, 2012), which protects billions of pounds' worth of assets from flooding. Incremental implementation of risk management solutions means that costs are also incremental, allowing for decisions to be changed in light of a changing risk profile, and for consideration of different adaptation options when particular levels of future change are reached. The challenge is then to ensure that previous decisions have not excluded options now considered desirable, thereby requiring either accepting a suboptimal solution based on existing provision or undoing the existing provision to enable the new optimal solution. Quinn et al. (2018) recommend the use of the adaptive pathways approach in their two-part iterative framework for climate-change-ready transport infrastructure, which comprises the development of an adaptation strategy (objectives to be achieved and priority risks to be addressed), and an implementation plan, which considers options for each risk within the constraints of an organization's situation, yielding practical adaptation measures for the stakeholder in question.

TABLE 3 Examples of measures to adapt railway infrastructure to climate change

Impact	Adaptation example	Characteristics
Slope failures	Re-engineering of slopes to change grade, improve drainage or provide stabilization; local monitoring (e.g., Smethurst et al., 2017)	Reducing vulnerability through robustness
Slope failures—rock falls	Detection of events by local monitoring of slopes with sensors (e.g., Collins et al., 2014)	Enabling safe operation and rapid recovery with reduced impacts
Slope failures—shallow failures	Detailed slope risk evaluation model for Japan Railway Group (e.g., Quinn et al., 2017; Railway Technical Research Institute, 2010)	Enabling prediction of when and where debris flow is most likely to occur, thus enabling better vulnerability assessment to be factored into warnings
Slope failures—shallow failures	Vegetation management to enhance slope stability (e.g., Coppin & Richards, 2007; Mickovski & Van Beek, 2006)	Reducing vulnerability
Slope failures—deep rotational failures	Vulnerability mapping by geo-hazard organizations (e.g., British Geological Survey, n.d.)	Enabling improvements in risk assessment
Failure of retaining walls	Upgrading drainage, rock bolting/anchoring, regrouting (McCombie et al., 2012; O'Reilly & Perry, 2008) Soil pinning (e.g., Payne et al., 2018) to strengthen unconsolidated material, particularly when wet	Reducing vulnerability by managing pressure on retaining wall structures
Flooding and icing in tunnels	Pressure relief duct and ventilation shaft shields inside the tunnel; applying hydrophobic coatings in tunnel structures (Synavax, n.d.)	Diverting water and ice build-up outside gauge of tunnel thus reducing impacts
Track buckling	Maintenance of track to ensure pre-stressing of rail and ballast strength is maintained (e.g., Palin et al., 2013)	Pre-stressing enables expansion to occur safely and ballast prevents lateral motions, reducing both vulnerability and impacts
	Use of slab track as an alternative to ballasted track—slab track is less able to buckle (e.g., Leykauf, 2005)	Reducing vulnerability
	Painting rails white at particular buckle-prone locations, to reduce solar gain (see Figure 12)	Reducing vulnerability
Flooding of track, points and crossings	Maintenance and upgrade of drainage, including outfalls, for higher capacities predicted by higher precipitation intensities (e.g., Jaroszweski, Quinn, et al., 2014)	Enhancing redundancy through increased capacity, reducing vulnerability
	Elevation of the track and/or other assets (e.g., Rail Technology Magazine, 2016)	Reduced vulnerability
Bridge scour	Risk-informed inspection of assets, both routinely and after flood events (e.g., McKibbins et al., 2006; Prendergast & Gavin, 2014)	Enabling improvements in risk assessment both in short-term forecasting and long-term
Bridge scour	Foundation countermeasures or replacement (Wang, Yu, & Liang, 2017)	Reducing vulnerability of asset
Low-temperature issues at points and crossings	Enhanced heating units (e.g., Bardstu et al., 2014), predictive failure maintenance and changing materials used for low-temperature tolerance	Reducing vulnerability and/or impacts
Windblown debris	Vegetation management; engagement with adjoining landowners to control vegetation and land use; fencing (e.g., Network Rail, n.d.)	Reducing secondary hazard and impacts
Permafrost-related track deformation	Insulation of embankments; sun sheds; high-albedo surfacing materials; air ducts in embankments; heat drains; thermosyphons (Doré et al., 2016)	Reducing vulnerability and impacts

FIGURE 12 Italian railway, with rails painted white to reduce buckling risk. Image courtesy of Peter van der Linden—used with permission

4.4.4 | Examples of specific adaptation measures

For new railway infrastructure, the most obvious adaptation measure is to ensure that climate change is proactively accounted for in the design, construction and operation of the new assets—in design, for example, by including "uplift" factors which attempt to incorporate any changes to relevant environmental parameters arising from climate change (e.g., High Speed Two Ltd., 2013, 2017). Analogously, weather-related standards for existing infrastructure should also be reviewed and updated for continued relevance in a changing climate (Quinn et al., 2017).

Vincent (2017) identified examples, from delta regions, of adaptation that were deemed "transformational," including several for infrastructure: staged and managed retreat of infrastructure from the coast (Mekong); incorporating wetland protection into infrastructure planning (Mississippi); incorporating climate change and sea level rise impacts into infrastructure planning (Mississippi); mixing "green" infrastructure with "gray" infrastructure (Mississippi); and municipal regulations for modified infrastructure in urban areas (Rhine).

Table 3 presents some examples of adaptation measures and the associated impacts which they seek to reduce. The choice of adaptation measure(s) taken by a given actor will depend on many factors such as overarching policy and/or legislation; exposure to particular hazards; degree of interaction with other adaptation actors; appetite to risk (climate-related and otherwise); desired adaptation expenditure; and infrastructure lifetime.

5 | DISCUSSION AND CONCLUSIONS

Weather has affected railway infrastructure throughout its history, and climate change could exacerbate some of those impacts in future. The links between weather and adverse railway impacts are generally quite well known (at least qualitatively), and management thereof is usually undertaken through standard risk assessment approaches. Extending this to the climate change timescale requires subtly different methods that allow for decision-making under uncertainty, in a non-stationary climate; new ISO standards are being developed that support this.

Challenges in undertaking risk assessments for railway infrastructure have been outlined above, and current research directions are allowing for some gaps to be addressed. TRaCCA compiled research needs (Arup TRaCCA

Phase 2 Consortium, 2016d), which can broadly be categorized thus: (a) better characterization of weather-impact relationships; (b) better characterization and mapping of asset vulnerabilities; (c) better communication, collaboration and mutual learning, both within the railway sector and between it and interdependent sectors; (d) adoption of new technologies, including use of national and international datasets, and implementing data analytics in decision-making; (e) better weather management plans and better climate management strategies, including consideration of the possible nature of the future transport system; and (f) consideration of wider social costs/impacts in economic evaluations. Encouragingly, the literature shows examples in all these areas.

Remote condition monitoring is a particular current area of research; the use of smart infrastructure for fault prediction and the guidance of preventive maintenance can contribute to increasing capacity and network availability, by reducing track access requirements for maintenance/renewals, and could improve performance (Armstrong & Preston, 2019). Recent advances in sensor technologies are allowing infrastructure managers to adopt risk-based approaches to many of their assets. The further roll-out of this technology provides the following benefits. First, insight into the response of assets during operation: for example, the response of a slope can be quantified during a rainfall event rather than back-analyzing after failure. Second, advanced geophysical techniques (e.g., Ahlmer et al., 2018; Ciampoli et al., 2020; Wang, Zhang, et al., 2017) and the use of UAVs (e.g., Banic et al., 2019 and references therein) allow a detailed, periodic, or real-time assessment of assets. Finally, these technologies typically produce large quantities of digital data, some of which can be useful in developing data-driven approaches for risk assessment.

The construction of new railways requires careful attention to climate resilience, as these new assets will have lifespans far into the future and thus potentially experience large future changes from both current climate and current transport system. However, they also provide a "clean slate," design- and construction-wise, for which learning from experience of managing existing, aging infrastructure can bring maximal benefits.

Whatever the future holds, some degree of climate change adaptation will be needed, even if the most drastic climate change mitigation goals are to be achieved. Transport will have a role to play in both adaptation and mitigation, and activities in these two areas should ideally be linked (EEA, 2014). Examples of adaptation approaches and measures for railways are also starting to appear in the literature. Adaptation actions which change current management practices—such as changing maintenance or inspection regimes—represent a different kind of adaptation measure from ambitious or complex engineering solutions, which may protect only one locality.

It can be difficult for organizations to take their first steps in adaptation, especially in the absence of policies driving such action, or a lack of knowledge about what adaptation entails. However, sharing knowledge and good practice enables learning from the experiences of others, and facilitates collaborative approaches. Finally, it is now being recognized that the interdependency of railways with other infrastructure leads to benefits from closer or more focused engagement with other railway and/or infrastructure stakeholders, in terms of both supporting effective adaptation and facilitating better weather management (e.g., the management of cascading failures). There is also an opportunity to develop and use a multi-hazard approach to climate risk assessment, of which understanding is currently limited, but interest high (Green & Chmutina, 2019). Burnham (1922) wrote that "fate has decreed the battle of the railroads with nature a perpetual one"; nearly a century on, there are ever better means with which that battle can be waged.

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CONFLICT OF INTEREST

The authors have declared no conflicts of interest for this article.

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Data sharing is not applicable to this article as no new data were created or analyzed in this study.

AUTHOR CONTRIBUTIONS

Erika J. Palin: Conceptualization; methodology; writing-original draft; writing-review & editing. **Irina Stipanovic Oslakovic:** Conceptualization; methodology; writing-original draft; writing-review & editing. **Kenneth Gavin:** Conceptualization; methodology; writing-original draft; writing-review & editing. **Andrew Quinn:** Conceptualization; methodology; writing-original draft; writing-review & editing.

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ENDNOTE

[1] The railway of Great Britain (England, Scotland, Wales) is owned and operated by a different company from that in Northern Ireland—hence the term "GB," not "UK," is used here.

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APPENDIX A: KEY RESEARCH PROJECTS

TABLE A1 Summaries of key research projects referenced in Section 1

Project name	Project objectives/scope statement	Date	Project website
ARISCC	ARISCC focuses on an integrated management of weather and climate related natural hazards such as flooding, severe storms, landslides, rock fall, avalanches, etc. in a way that keeps and improves railway infrastructure performance and avoids or minimizes damage to railway infrastructure assets. It starts with natural hazard management under today's weather conditions and develops solutions and strategies to prepare for the changed weather and climate conditions of the future.	2009–2011	http://www.ariscc.org
FP7 EWENT	To assess the impacts and consequences of extreme weather events on EU transport system. These impacts will be monetized. To evaluate the efficiency, applicability and finance needs for adoption and mitigation measures which will dampen and reduce the costs of weather impacts.	2009–2012	http://virtual.vtt.fi/virtual/ewent/index.htm

TABLE A1 (Continued)

Project name	Project objectives/scope statement	Date	Project website
FP7 WEATHER	To analyze the economic costs of more frequent and more extreme weather events on transport and on the wider economy and explores adaptation strategies for reducing them in the context of sustainable policy design.	2009–2012	https://www.weather-project.eu/weather/index.php
FUTURENET	To determine the • Nature of the UK transport system in 2050 (taken as the mid-point of the UK Climate Projections scenarios), both in terms of its physical characteristics and its usage Shape of the transport network in 2050 that will be most resilient to climate change	2009–2013	https://www.arcc-network.org.uk/futurenet/
FP7 SMART RAIL	In order to effectively manage aging railway infrastructure a reliability-based framework was developed for an optimized whole life management of rail infrastructure elements including bridges, tracks and slopes	2011–2014	http://smartrail.fehrl.org
MOWE-IT	To identify existing best practices and to develop methodologies to assist transport operators, authorities and transport system users to mitigate the impact of natural disasters and extreme weather phenomena on transport system performance	2012–2014	http://www.mowe-it.eu
TRaCCA	See Box 1	2013–2017	https://www.rssb.co.uk/en/Research-and-Technology/Sustainability/Tomorrow-s-Railway-and-Climate-Change-Adaptation--TRaCCA
FP7 RAIN	The project developed an operational analysis framework which considers the impact of weather events on land-based infrastructure systems through robust risk and uncertainty modeling.	2014–2017	http://rain-project.eu
H2020 DESTination RAIL	DESTination RAIL provided a number of novel solutions for Rail infrastructure managers to identify, analyze and remediate critical assets. These solutions are implemented using a decision support tool, which allows rail infrastructure managers to make rational investment choices, based on reliable data.	2015–2018	http://www.destinationrail.eu

APPENDIX B: IPCC FINDINGS—IMPACT OF CLIMATE CHANGE ON EXTREMES

Table A2 summarizes recent IPCC assessments that have explored climate change effects on weather extremes. IPCC assessments use particular confidence and likelihood terminology; the meaning of such words appearing in Table A2 is described in Mastrandrea et al. (2011).

TABLE A2 Headline messages, from recent IPCC literature syntheses, about the effect of projected climate change on extremes (Collins et al., 2013—labeled "[1]" in the table; Seneviratne et al., 2012—"[2]"), including at different warming levels (IPCC, 2018—"[3]")

Parameter	Nature of future projections	Source
Extreme temperatures	"It is virtually certain that, in most places, there will be more hot, and fewer cold, temperature extremes as global mean temperatures increase."	[1]
	"Models project substantial warming in temperature extremes by the end of the 21st century."	[2]
	"Temperature extremes on land are projected to warm more than global mean surface temperature (high confidence): extreme hot days in mid-latitudes warm by up to about 3°C at global warming of 1.5°C and about 4°C at [global warming of] 2°C, and extreme cold nights in high latitudes warm by up to about 4.5°C at [global warming of] 1.5°C and about 6°C at [global warming of] 2°C (high confidence). The number of hot days is projected to increase in most land regions, with highest increases in the tropics (high confidence)."	[3]
Extreme precipitation	"Over most of the mid-latitude land-masses and over wet tropical regions, extreme precipitation events will very likely be more intense and more frequent in a warmer world."	[1]
	"It is likely that the frequency of heavy precipitation or the proportion of total rainfall from heavy rainfalls will increase in the 21st century over many areas of the globe."	[2]
	"Risks from heavy precipitation events are projected to be higher at 2°C compared to 1.5°C of global warming in several northern hemisphere high-latitude and/or high-elevation regions, eastern Asia and eastern North America (medium confidence). Heavy precipitation associated with tropical cyclones is projected to be higher at 2°C compared to 1.5°C global warming (medium confidence)."	[3]
Extreme winds	"There is generally low confidence in projections of changes in extreme winds because of the relatively few studies of projected extreme winds, and shortcomings in the simulation of these events."	[2]
Extreme coastal water levels	"It is very likely that mean sea level rise will contribute to upward trends in extreme coastal high water levels in the future."	[2]
	"Sea level will continue to rise well beyond 2100 (high confidence), and the magnitude and rate of this rise depend on future emission pathways."	[3]
Floods	"Projected precipitation and temperature changes imply possible changes in floods, although overall there is low confidence in projections of changes in fluvial floods."	[2]
	"As a consequence of heavy precipitation, the fraction of the global land area affected by flood hazards is projected to be larger at 2°C compared to 1.5°C of global warming (medium confidence)."	[3]
Droughts	"There is medium confidence that droughts will intensify in the 21st century in some seasons and areas, due to reduced precipitation and/or increased evapotranspiration."	[2]

APPENDIX C: IPCC DEFINITIONS OF KEY TERMS

- *Risk* is "the potential for consequences where something of value is at stake and where the outcome is uncertain, recognizing the diversity of values. Risk is often represented as probability of occurrence of hazardous events or trends multiplied by the impacts if these events or trends occur. Risk results from the interaction of vulnerability, exposure, and hazard." (IPCC, 2014)
- *Hazard* is "the potential occurrence of a natural or human-induced physical event or trend or physical impact that may cause loss of life, injury, or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, ecosystems, and environmental resources." (IPCC, 2012)

- *Vulnerability* is "the propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts and elements including sensitivity or susceptibility to harm and lack of capacity to cope and adapt." (IPCC, 2014)
- *Sensitivity* is "the degree to which a system or species is affected, either adversely or beneficially, by climate variability or change. The effect may be direct (e.g., a change in crop yield in response to a change in the mean, range, or variability of temperature) or indirect (e.g., damages caused by an increase in the frequency of coastal flooding due to sea level rise)." (IPCC, 2014)
- *Impacts* are "effects on natural and human systems [...] the term 'impacts' is used primarily to refer to the effects on natural and human systems of extreme weather and climate events and of climate change. Impacts generally refer to effects on lives, livelihoods, health, ecosystems, economies, societies, cultures, services, and infrastructure due to the interaction of climate changes or hazardous climate events occurring within a specific time period and the vulnerability of an exposed society or system. Impacts are also referred to as consequences and outcomes. The impacts of climate change on geophysical systems, including floods, droughts, and sea level rise, are a subset of impacts called physical impacts." (IPCC, 2014)
- *Exposure* is "the presence of people, livelihoods, species or ecosystems, environmental functions, services, and resources, infrastructure, or economic, social, or cultural assets in places and settings that could be adversely affected." (IPCC, 2014)