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Future projections of temperature-related climate change impacts on the railway network of Great Britain

Erika J. Palin · Hazel E. Thornton · Camilla T. Mathison · Rachel E. McCarthy · Robin T. Clark · John Dora

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Abstract Great Britain's main line railway network is known to experience various temperature-related impacts, e.g. track buckling and overhead power line sag at high ambient temperatures. Climate change could alter the frequency of occurrence of these impacts. We have therefore investigated the climate change impact on various temperature-related issues, identified during workshops with rail industry specialists, using a perturbed physics ensemble (PPE) of the Met Office's regional climate model (RCM), HadRM3. We have developed novel approaches to combine RCM data with railway industry knowledge, typically by identifying key meteorological thresholds of interest and analysing exceedance of these out to the 2040s. We performed a statistical analysis of the projected changes for each issue, via bootstrapping of the unperturbed PPE member. Although neither the PPE nor the bootstrapping analysis samples the full range of uncertainty in the projections, they nonetheless provide complementary perspectives on the suitability of the projections for use in decision-making. Our main findings include projected increases in the summertime occurrence of temperature conditions associated with (i) track buckling, (ii) overhead power line sag, (iii) exposure of outdoor workers to heat stress, and (iv) heat-related delays to track maintenance; and (v) projected decreases in the wintertime occurrence of temperatures conditions associated with freight train failure owing to brake problems. For (i), the statistical significance varied with track condition and

John Dora is formerly at: Network Rail, Quadrant:MK, Elder Gate, Milton Keynes MK9 1EN, UK.

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E. J. Palin (✉) · H. E. Thornton · C. T. Mathison · R. E. McCarthy · R. T. Clark
Met Office Hadley Centre, FitzRoy Road, Exeter EX1 3PB, UK
e-mail: erika.palin@metoffice.gov.uk

J. Dora
John Dora Consulting Limited, 11 Wychwood Paddocks, Charlbury OX7 3RW, UK

location; for (ii) and (iii), with location; and for (iv) and (v), projected changes were significant across Great Britain. As well as assessing the changes in climate-related hazard, information about the vulnerability of the network to past temperature-related incidents has been summarised. Combining the hazard and vulnerability elements will eventually support a climate risk assessment for the industry.

1 Introduction

In this paper, a variety of possible temperature-related climate change impacts on the main line railway network of Great Britain are assessed. This railway network is a system comprising many components, overseen and managed by a variety of companies. These include Network Rail (who own and operate the rail infrastructure), train operating companies, and rolling stock manufacturers. Additionally, there are other stakeholders such as the Rail Safety and Standards Board (RSSB), Association of Train Operating Companies (ATOC), Office of Rail Regulation (ORR), etc. The railway's overall resilience is affected by complex interactions between physical, socioeconomic, regulatory and other processes, which may affect the whole railway, one or more of its subsystems (track, signalling, rolling stock, etc), and/or elements of the railway system that might be traditionally considered "outside" the railway (e.g. its electricity supply and ICT connectivity). Increasingly, infrastructure resilience is being considered in this systemic manner (e.g. Council for Science and Technology 2009; Hall et al. 2012), with climate change being a significant issue which could affect future resilience of either the infrastructure system as a whole, or one or more of its elements (energy, transport, ICT, etc: e.g. Royal Academy of Engineering 2011). Both adaptation to and mitigation of future climate change are issues of relevance in this regard; this paper focuses on adaptation-relevant science.

Through the UK Government Department for the Environment, Food and Rural Affairs' (Defra) Adaptation Reporting Power (ARP—Defra 2010), 91 key UK utilities and infrastructure providers, including Network Rail, have been asked to submit adaptation plans in response to directions to report under the Climate Change Act 2008. Much of the work described in this paper was undertaken as part of the "Tomorrow's Railway and Climate Change Adaptation" (TRaCCA) research project (T925), funded by the Department for Transport (DfT) through the RSSB-managed "Rail Industry Strategic Research Programme", and has informed Network Rail's contribution under the ARP. We have used an approach which includes analysis of (i) observed meteorological data; (ii) climate projections data from the UK Climate Projections 2009 (UKCP09; Murphy et al. 2009—the most recent suite of probabilistic climate projections for the UK, outlined in Section 2.1 below); and (iii) industry-supplied vulnerability data for the railway network.

1.1 Observed and projected changes in Europe/UK extreme temperatures

Many, though not all, of the topics discussed in this paper are concerned with conditions of very high or very low temperature. These are often referred to as "extreme temperatures", but the definition of "extreme" can vary considerably. It is commonly used when discussing values above the 90th or 95th percentile (for high temperatures) or below the 5th or 10th percentile (for low temperatures).

These thresholds are often used as a compromise; they are not actually particularly "extreme" but the statistics of exceedance are comparatively robust when compared to, say, the 99th percentile value (since, by definition, there are fewer observed occurrences of this value than those for lower percentiles). In addition, many studies are concerned not just with the exceedance of particular temperature thresholds, but also with the duration of exceedance (i.e. cold/heatwave conditions).

A warming climate is generally commensurate with decreased occurrence of cold extremes and increased occurrence of hot extremes (Rummukainen 2012). Since 1950, extreme daily minimum and maximum temperatures have warmed in most regions of the globe (Brown et al. 2008), and a recent IPCC Special Report on climate extremes ("SREX", IPCC 2012a) concluded that it was *likely*[1] (66–100 % probability) that an overall increase in the number of warm days and nights had occurred at the continental scale in Europe.

Various studies have assessed how temperature extremes are projected to change over the coming decades, globally (e.g. Orlowsky and Seneviratne 2012; IPCC 2012a), in the northern hemisphere (e.g. Clark et al. 2006), and over Europe specifically (e.g. Beniston et al. 2007; Koffi and Koffi 2008; Nikulin et al. 2011; Frias et al. 2012). Generally, an increase in the frequency and magnitude of warm daily temperature extremes is projected. The IPCC SREX deemed such changes at the global scale *virtually certain* (99–100 % probability). Additionally, increases in the length, frequency, and/or intensity of warm spells or heatwaves over most land areas are projected, with such changes being considered *very likely* (90–100 % probability) by IPCC SREX. However, it has been noted that the different ways of defining what constitutes a "heatwave" or "hot/warm spell" results in some uncertainty in the projected characteristics of such events (Orlowsky and Seneviratne 2012).

Observed and projected changes in the extremes of the temperature distribution can be due to a change in the mean, a change in the variability, or some combination thereof, and relative changes in extremes can differ from changes in the mean (IPCC 2012b). Simolo et al. (2011) show that the mean has a dominant role in explaining exceptionally hot events, while Ballester et al. (2010) showed that approximate values of frequency, length and intensity changes in warm and cold temperature extremes in Europe can be obtained from knowledge of three central statistics of the temperature probability distribution function.

Giorgi and Coppola (2009) assessed climate projections over Europe from two model ensembles—one of global climate models (GCMs), one of regional climate models (RCMs)—for variability, they found that temperature interannual variability decreased in winter over central and northern Europe, and increased in summer throughout Europe (with an associated increase in extreme hot seasons). Fischer and Schaer (2009) employed a methodology allowing the decomposition of daily temperature variability into different components and applied this to a particular RCM ensemble over Europe. For the UK specifically, they found that, in summer, total daily temperature variability was projected to increase in at least some of the UK across all models, but with considerable intermodel variation in interannual and intraseasonal variability components. A subsequent study (Fischer et al. 2012) found an increase in daily temperature variability in summer and a reduced winter daily

[1] In this section, italicised words accompanied by probabilities indicate usage which follows the IPCC guidelines (Mastrandrea et al. 2010).

temperature variability, concluding that hot extremes warm more strongly than the mean in summer and across central and southern Europe, and that cold extremes warm more strongly than the mean in winter and northern Europe.

Despite the obvious link between a warming climate and changes in the frequency of occurrence of hot and cold temperature extremes, it is recognised that this is only one factor, and that the atmospheric circulation conditions driving these extremes are also important, with or without climate change (e.g. Cony et al. 2010; Andrade et al. 2012; van den Besselaar et al. 2010). Another important point to note is that any changes to large-scale modes of variability could have an effect on the regional and seasonal occurrence of extremes that is potentially of similar magnitude to that arising from global warming, as exemplified for Europe by the effect of the NAO on European winter temperature extremes (Scaife et al. 2008).

Considering temperature extremes at the scale of the UK, in terms of observed trends (Jenkins et al. 2009) between 1961 and 2006, annual average daily minimum temperature has warmed almost everywhere in the UK, and annual average daily maximum temperature has warmed everywhere in the UK. Most parts of the UK have also seen a reduction in the annual number of air frost days between 1961 and 2006 (all changes based on linear trends).

UKCP09 (see Section 2.1, Murphy et al. 2009) also examines quantities relevant to climate extremes. For example, projected changes to the warmest day of the summer (in the 2080s, under the Medium emissions scenario, with respect to a 1961–1990 baseline) are very unlikely to be less than −4 to +2°C and very unlikely to be greater than +6 to +14°C, with a central estimate of between +2 and +6°C (Fig. 4.8 in Murphy et al. (2009)—ranges are quoted here to reflect the variation around the UK). This range in the probabilistic projections shows that there is therefore a chance—for the 2080s, under the Medium emissions scenario—that the warmest day of the summer could become cooler, but a greater probability that it could become warmer.

1.2 Overview of topics investigated

As an initial phase in this work, a series of workshops involving the Met Office and industry experts constructed a list of areas of concern where weather affects the rail industry, and therefore where climate change could also be an issue (RSSB 2010). Many of these are well-known to the industry (RSSB 2003) and academic partners alike; a recent review (Baker et al. 2010) discussed qualitatively the potential changes in impacts related to temperature, rainfall, sea level rise and storminess, with reference to the UKCIP02 climate projections. The temperature-related impacts included track buckling, earthworks desiccation and changes in demand for heating/cooling on board trains. The issue of track buckling has also been investigated quantitatively by Dobney et al. (2009), who found (for the south-east UK) that changes in standards would be necessary to reduce track buckling risk. Further analysis by Dobney et al. (2010) considered the whole UK, and found that costs associated with heat-related delays were projected to increase, but also suggested ways in which the network could be made more resilient. The first UK Climate Change Risk Assessment ("UK CCRA"—HR Wallingford 2012) also considered transport (Thornes et al. 2012), and assessed various risk metrics with relevance to the railway network, rail buckling risk being the only temperature-related one of these. An increase in track buckling incidents as a result of climate change was projected, with high confidence, but the financial impact of these was judged as "low to medium" compared with those for other risk metrics in the transport sector. A more recent study (Nguyen et al. 2012) has examined track buckling in Australia, using a Monte Carlo simulation method to investigate buckling probability, finding good agreement with observed buckles during the January 2009 heatwave, and noting the relevance of such studies for the future management of the rail network with respect to climate change.

Following the initial workshops, the list of areas of concern was then reassessed, resulting in a list of sixteen priority areas (hereafter "priorities"—see Table 1) which were assessed in varying degrees of detail (Thornton et al. 2011). In this paper we present the results for those priorities in Table 1 which are temperature-related, with many of the precipitation-related priorities to be the subject of a future paper, and the remainder being discussed briefly in Supplementary Material (Section SM.1).

A major outcome of this work has been to acknowledge and set in motion work to address the gap between scientific capability and the requirements of decision-makers. To this end, close collaboration with industry partners has allowed us to find novel ways to link the knowledge of rail sector experts with the results of state-of-the-art climate projections, in order to supply decision-makers with information which is both scientifically robust and appropriately communicated.

Table 1 The sixteen railway network priorities identified for detailed investigation following industry consultation

Group	Priority	Further notes
Temperature	Track buckling & temporary speed restrictions	Short ID: TB
Temperature	Windows of opportunity for track maintenance	Short ID: TM
Temperature	Incidence of sag of overhead line equipment	Short ID: OS
Temperature	Staff exposure to heat stress	Short ID: HS
Temperature	Passenger and freight risk from train failure in extreme weather	Short ID: PR (passenger) Short ID: FR (freight)
Temperature	Heat affecting lineside equipment	Short ID: HL
Fluvial flooding	Scour & flooding on bridges	To be discussed in a future paper
Fluvial flooding	Scour of embankments due to high river levels & culvert washout	To be discussed in a future paper
Fluvial flooding	Depots (TOC & maintenance)	To be discussed in a future paper
Fluvial flooding	Track & lineside equipment failure	To be discussed in a future paper
Pluvial flooding	Track & lineside equipment failure	To be discussed in a future paper
Pluvial flooding	Landslips	See Supplementary Material, Section SM.1
Groundwater flooding	Track & lineside equipment failure	See Supplementary Material, Section SM.1
Various	Trees growing on the lineside	See Supplementary Material, Section SM.1
Various	Leaves on line/"Signal Clear When Occupied" (SCWO)	See Supplementary Material, Section SM.1
Sea	Overtopping and damage of sea defences	See Supplementary Material, Section SM.1

Priorities discussed in this paper are given a short identification code for ease of reference herein

2 Methodology

This work uses Met Office observational data and regional climate projections produced by the Met Office Hadley Centre, together with industry-specific information provided by railway stakeholders, to assess the potential future impacts of climate change on the railway network of Great Britain. The overall goal is an understanding of the *risk* posed by climate change to aspects of the railway network. There are many definitions of "risk" in the literature; one definition is "risk = hazard × vulnerability" (e.g. Taubenböck et al. 2008). Therefore, as well as understanding the *hazards* posed by a changing climate-related quantity (temperature, in the case of this paper), a climate change risk assessment requires the characterisation of the *vulnerabilities* to those hazards—that is, the extent of the impacts of the changing hazards. In the following paragraphs we discuss the data and analytical techniques which have been used to assess the hazards. Whilst we have not reported the results of the vulnerability assessment, our approach is outlined in the Supplementary Material (Section SM.2) for completeness.

2.1 Data sources

The climate data used in this study have been developed as part of the UKCP09 methodology. UKCP09 is the fifth generation of climate change information for the UK. Its projections are based on a methodology designed by the Met Office and have been made available by Defra and another UK Government Department, the Department for Energy and Climate Change (DECC). Several organisations[2] have been involved in producing different elements of the UKCP09 suite of products. Further information about UKCP09 can be found on the UKCP09 website (http://ukclimateprojections.defra.gov.uk), and—for the climate change projections specifically—in Murphy et al. (2009).

The baseline observation data which we used are the 25 km gridded data sets generated by the Met Office as part of UKCP09. They are based on the archive of UK weather observations held at the Met Office, with regression and interpolation techniques being used to generate values on a regular grid from the irregular station network (Perry and Hollis 2005; Perry et al. 2009). The methodology used takes account of topographical features including altitude, coastal influences and the effects of urban land use. Data are available at 5 and 25 km grid resolution; we used the latter here, for consistency with the climate projections.

The climate projections used here are from the Met Office Hadley Centre RCM, HadRM3 (Jones et al. 1995). Eleven variants of HadRM3 were previously run using the SRES A1B emissions scenario (Nakićenović et al. 2000) as part of the UKCP09 methodology (Murphy et al. 2009). These simulations cover the period 1950–2099 and were run at 25 km resolution, with boundary conditions from the HadCM3 GCM (Gordon et al. 2000). The eleven variants constitute a perturbed physics ensemble

[2]Met Office, UKCIP, British Atmospheric Data Centre, Newcastle University, University of East Anglia, Environment Agency, Tyndall Centre and Proudman Oceanographic Laboratory.

(PPE—Collins et al. 2006); each variant has a different combination of values for certain key parameters within the model equations.

The RCM is used because it provides climate projections consistent with those from the driving GCM, but at higher resolution and thus allowing the realistic simulation of finer-scale detail such as orography. The representation of climate variability is thus improved with respect to the original GCM, and the PPE allows for some assessment of the modelling uncertainty and natural variability. Despite these advantages, some limitations must still be borne in mind. Firstly, the eleven RCM variants will not sample the full range of model uncertainty as all are versions of the same model. UKCP09 is able to sample this more widely, as the UKCP09 methodology incorporates information not just from the Met Office model but also from models of other institutes who participated in the IPCC's Fourth Assessment Report (Murphy et al. 2009).

Secondly, as all PPE members are derived from the same climate model, no account is taken of uncertainties in the CO_2 concentrations resulting from the A1B emissions scenario. Given the same emissions, the different carbon cycle representation between different models is what drives the different concentrations (Friedlingstein et al. 2006). Thirdly, the RCM data will contain some biases, mostly as a result of systematic errors in the driving GCM simulations. We have therefore bias-corrected the data (see Section 2.2 below).

Finally, the RCM ensemble was run under the A1B emissions scenario only, thereby not allowing for the potential influence of other emissions scenarios on the results presented here. This is relatively unimportant, however, as our results are based on 2040s projections, by which time relatively little difference is seen between projections under different emissions scenarios (Murphy et al. 2009; Hawkins and Sutton 2009).

2.2 Bias correction approach

It is recognised that climate models cannot perfectly represent the climate. For example, there may be certain climatic processes which are not currently well-understood, and hence poorly represented (or not at all) in models. Additionally, sub-gridscale processes have to be represented approximately, using parameterisations. These and other sources of uncertainty lead to biases in the models which—when identified using observations—can be broadly corrected according to past climate. This work has used a quantile mapping approach whereby the observed and modelled baseline data were sorted and divided into 100 equally-populated "bins", biases were calculated per percentile, and the biases were used to map the model baseline distribution back onto the observed baseline distribution. Any value falling below the minimum of the observed distribution was corrected using the bias for the lowest percentile bin. It should be noted that we have assumed that the bias corrections thus calculated for the baseline can also be applied to the future model data—i.e. that the bias remains constant with time. Similar approaches have been used in other studies (e.g. Wood et al. 2004; Hashino et al. 2007; Piani et al. 2010). The baseline which we used was 1971–2000 and the future period 2030–2059 (the UKCP09 "2040s" period). Percentile biases can be calculated as a difference between the baseline and observed percentile values, or as a ratio of these; we have used the former here.

2.3 Hazard assessment: determining relationships between weather/climate and industry decisions

In order to assess the hazard posed by a particular weather/climate parameter, it is necessary to understand the relationship between that parameter and its impact(s). There are various ways in which this can be achieved. In our previous work, undertaken for the electricity industry (McColl et al. 2012), we linked weather impact data (faults on the electricity network) and relevant climate variables via statistical relationships. In this work, however, we took a complementary approach: each temperature-related priority in Table 1 was discussed with industry experts in order to determine any weather-related decision thresholds. For example, operational standards and guidelines may exist within the industry which require actions to be taken at critical temperature thresholds. It was then necessary to translate these into quantities which could be modelled with the RCM, allowing an assessment of the hazard. Appropriate relationships were known or able to be determined for priorities TB, TM, OS, HS and FR. The outcomes of our investigations of these priorities are discussed below in Section 3. All of these assessments involved seasonal analysis, following expert advice about the seasonality of the issues experienced on the railway network. An associated minor limitation is that, in each case, climate model data from individual seasons were concatenated into a single continuous dataset, resulting in some temporal discontinuities from, say, the end of one summer to the beginning of the next. TM was an exception—the analysis was conducted per season, and results aggregated thereafter. The concatenation is therefore only a potential issue for HS, because the analysis considers consecutive days of data, but we believe that the discontinuities will make only a minor contribution to the overall uncertainty.

There were two priorities for which it was not possible to undertake a hazard assessment. These were priorities PR—that is, the thermal comfort of passengers on board trains during extremely hot conditions (RSSB 2006)—and HL. In both of these cases, an assessment would be contingent on being able to model the relationship between internal temperatures (on board the train for the former, inside the equipment for the latter) and external conditions (e.g. ambient air temperature, wind speed, etc). No appropriate relationships were known at the time of the study as there were few or no data regarding internal temperatures in either case.

2.4 Statistical assessment of results

We assessed the statistical significance of our results using bootstrapping (Efron 1979). This is a resampling technique which uses the observed data set to represent the underlying distribution. The purpose of using this method is to investigate the relative importance of natural variability in assessing projected changes in temperature-related quantities. For some quantities the variability is expected to be of comparable size to the climate change signal, and hence to have an effect on the significance of the changes in these quantities, as in these cases it will not be possible to distinguish statistically the difference between natural variability and climate change.

Bootstrapping was performed on the unperturbed member of the 11-member PPE, for the baseline and 2040s periods. For example, the TB case (see Section 3.1 below) considers the exceedance of thresholds of May–September daily maximum temperature. The method for this assessment would therefore be as follows:

(a) For the unperturbed ensemble member, randomly sample (with replacement) 30 times from the baseline and 2040s data (30 May–September periods in each case), to generate a "new" distribution of 30 May–September periods from the original distribution;
(b) Analyse this distribution in the same fashion as the original data (for the TB example, this involves calculating the change in threshold exceedance in the 2040s with respect to the baseline); and
(c) Repeat steps (a) and (b) 1,000 times, to generate a distribution of changes in threshold exceedance.

More details can be found in Supplementary Material (Section SM.3). The significance test is shown schematically in Fig. 1. We have chosen to use the 5 % level for our assessment. The change in the bootstrapped quantity (in the above example, daily maximum temperature threshold exceedance) is considered to be significant at the 5 % level if the 95 % confidence intervals of the distribution of changes in threshold exceedance does not contain zero. The details for each priority are discussed in the relevant sections below. Formally, in all cases the null hypothesis

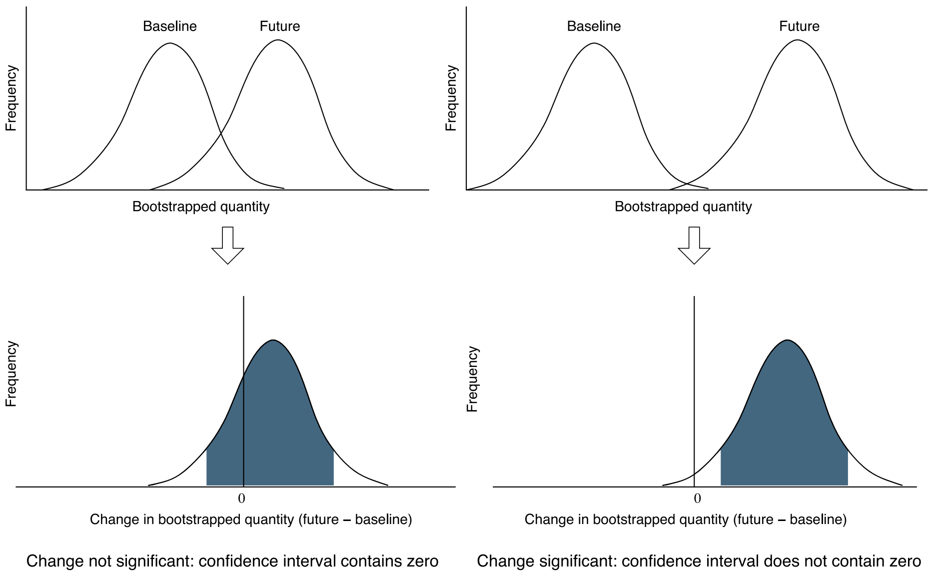

Fig. 1 Schematic of how bootstrapping can be used to demonstrate the significance (or not) of a projected change. The *top panels* show the baseline and future bootstrapped distributions of the quantity. The *bottom panel* shows the bootstrapped distribution of the change in the quantity (future–baseline values). On the *left*, the baseline and future bootstrapped distributions overlap. The distribution of change is not significant at a particular confidence level, because the corresponding confidence interval (*shaded blue*) contains zero. On the *right*, there is a larger difference between the baseline and future bootstrapped distributions, the confidence interval of the change does not contain zero, and the change is significant at the chosen confidence level

(H_0) being tested is: “In the unperturbed PPE member, there is no significant change between the baseline and future modelled values of the bootstrapped quantity of interest”. Thus, any statement of a “significant” change indicates that there is sufficient evidence (according to the above discussion and Fig. 1) to reject H_0.

Some assumptions have been made in undertaking this assessment. Firstly, the minor error associated with temporal discontinuities, discussed above in Section 2.3, will also be true of the bootstrapped timeseries. Secondly, we are assuming that bootstrapping on one ensemble member adequately represents the whole ensemble. Of course, this assumption is less likely to hold for precipitation-related quantities than for temperature-related quantities, as there is commonly a large spread across ensemble members for the former.

For the temperature quantities, although the magnitudes of projected changes will vary across the ensemble, we have confirmed by visual inspection that the behaviour of each ensemble member is *qualitatively* similar to the bootstrapped ensemble member (i.e. that the regional distribution of projected changes is similar in each member—not shown here). Nonetheless, it is possible that, had we bootstrapped on a different ensemble member (or the full PPE), the results could differ, and this is acknowledged as a limitation of the analysis. Further comment can be found in Supplementary Material (Section SM.4).

3 Results

Below we present the results of our assessments of priorities TB, TM, OS, HS and FR. A brief rationale for the industry’s interest in assessing each priority is given, together with an explanation of the weather/decision relationships used to assess it (as outlined in Section 2.3).

3.1 TB: Track buckling and temporary speed restrictions

Extremes of temperature can cause railway track to fail due to the forces produced by the rail steel expanding in hot conditions and contracting in cold conditions. Railway tracks are pre-stressed to withstand a range of temperatures (Chapman et al. 2008)—the stress-free temperature (SFT), a material property of the rail, is engineered as a compromise to balance the effects of hot and cold conditions.

To manage the safety hazards associated with rails buckling in hot conditions, a number of actions are currently taken at various critical rail temperatures (CRTs):

– CRT(W): a watchman will be in place to monitor the length of track concerned;
– CRT(30/60): a 30/60 mph speed restriction will be applied; and
– CRT(20): a 20 mph speed restriction will be applied.

Examples of the rail temperatures at which these actions are taken depend on the nature and condition of the track. Generally, track in better condition can withstand higher temperatures (the reasons for which are discussed in Section 3.2 below) and, of course, maintenance work on the track will change its overall condition. There are 13 tabulated track conditions in all (see Supplementary Material, Section SM.5). The following empirical relationship (Hunt 1994) between air temperature T_{air} and rail temperature T_{rail} was used to convert from CRTs to critical air temperatures (CAT):

$$T_{\text{air}} \approx \frac{2}{3} T_{\text{rail}} \tag{1}$$

where both temperatures are in °C. Since this relationship is approximate, all conversions have been rounded to the nearest °C.

Previous studies have examined track buckling in a variety of ways. Assessments by Dobney et al. (2009, 2010) used analogue techniques and a weather generator to make projections of the future numbers of buckling incidents, delays and costs thereof; the UK CCRA's transport sector report (Thornes et al. 2012) developed a simple response function relating track buckling incident numbers to mean summer Central England Temperature, and then used UKCP09 mean summer temperatures for the UK administrative regions to make projections of future buckling incident numbers.

This study takes a complementary approach to those of previous studies. Equation 1 was also used by Dobney et al. (2009, 2010) to relate rail and air temperatures, but the future climate data were obtained by use of a weather generator, rather than climate model output directly. Additionally, given the timing of those studies, the most recent projections (and weather generator) available were those from UKCIP02. Thornes et al. (2012) used the more recent UKCP09 as the source of climate information, but the weather-impact relationship derived was relatively simplistic (not surprisingly, given the overall scale of the UK CCRA, which examined around 100 risks in detail across eleven sector reports). Finally, although the baseline and future time horizons used in this work differ from those used in the other studies, our time horizons were those requested by Network Rail. An approach based on Monte Carlo simulation was taken by Nguyen et al. (2012) to assess track buckling, but this study was for the Australian rail network, and also focused more on being able to reproduce observed buckling incidents rather than how to project these into the future.

Our approach to investigating the potential impact of climate change on actions related to track buckling was to assess the frequency of exceedance of the CAT thresholds for each action and each track condition discussed above, using the RCM data. Since track buckling is most problematic during summer, data for May–September inclusive were used—i.e. summer months plus one month either side, in order to address any potential future change in seasonality.

Figure 2 shows an example result for exceedance of CAT = 24 °C, the temperature above which temporary speed restrictions of 20 mph are imposed for the track condition "3 or more consecutive slurried beds, where ballast is not compacted against the sleeper ends". The greatest number of exceedances of this threshold is in the south and east, but the largest projected *fractional* change is in the north and west. For this example track condition, in parts of southeastern England, conditions necessitating temporary speed restrictions of 20 mph occur around 10–20 % of the time in the baseline, and are projected to occur on average more than 30 % of the time in a similar area in May–September inclusive by the 2040s. The modelled ensemble range in the projected changes—i.e. the deviation from the average projected change—for this area is of the order of ±10 % in the 2040s. In parts of Scotland, by the 2040s, the fractional change in conditions necessitating 20 mph temporary speed restrictions

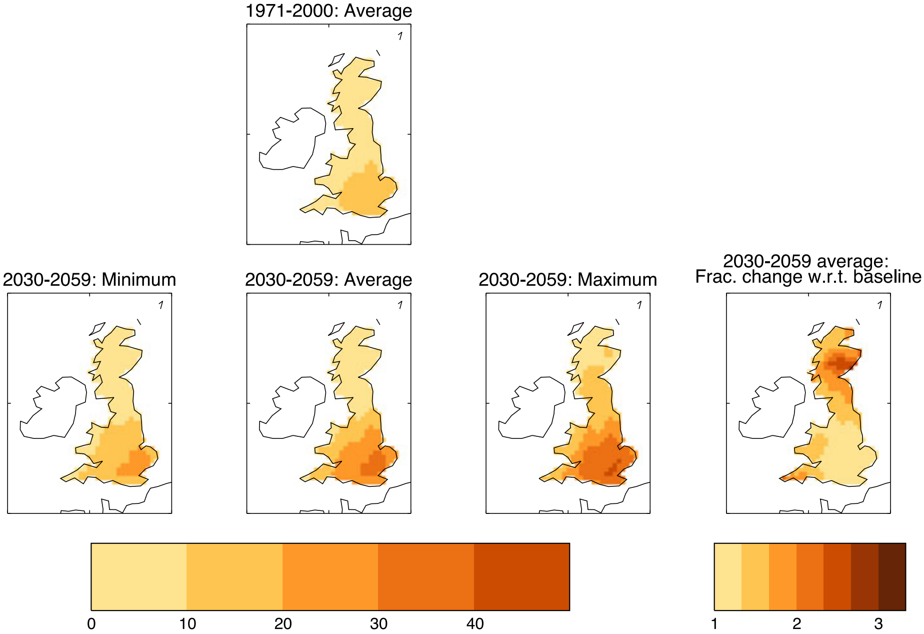

Fig. 2 Modelled percentage of May–September days per 30-year period per 25 km grid square with daily maximum temperature exceeding 24 °C (CAT(20) for the track condition "3 or more consecutive slurried beds, where ballast is not compacted against the sleeper ends"). *Top*: modelled baseline average, remaining panels: modelled range of outcomes for the 30-year period centred on the 2040s. The *rightmost panel* shows the fractional change between the modelled 2040s average and the baseline average, and grid squares superimposed with a white cross are those in which the change is not significant at the 5 % level according to the bootstrapping assessment (although in this case there is only one such grid square in western Scotland)

for this track condition is projected to be almost 2 on average (i.e. a trebling of the baseline frequency).

Bootstrapping analysis of the 24 °C threshold shows that the change in threshold exceedance in the 2040s with respect to the baseline is significant (i.e. there is sufficient evidence to reject H_0) at the 5 % level everywhere, except in one grid square on the west coast of Scotland.

Analogous results for exceedance of CAT = 31 °C (the temperature above which temporary speed restrictions of 30/60 mph are imposed for the track condition "Tamped/lines with slues/lifts up to 25 mm") are shown in Fig. 3. The pattern is similar to that for the 24 °C threshold but with much rarer exceedance (up to a projected maximum of approximately 3 % of May–September days). Bootstrapping analysis for the 31 °C threshold, however, indicated that the projected change in exceedance of this threshold in the 2040s with respect to the baseline is significant at the 5 % level for most of southern England, but for much less of Wales; and not significant in Scotland. Examples of the results obtained by bootstrapping (i.e. a real example of the schematic shown in Fig. 1) for arbitrarily-selected grid squares are also shown in Supplementary Material (Section SM.6).

Generalising across the range of CAT thresholds (i.e. track conditions), we found that the percentage of May–September days exceeding a particular CAT value is

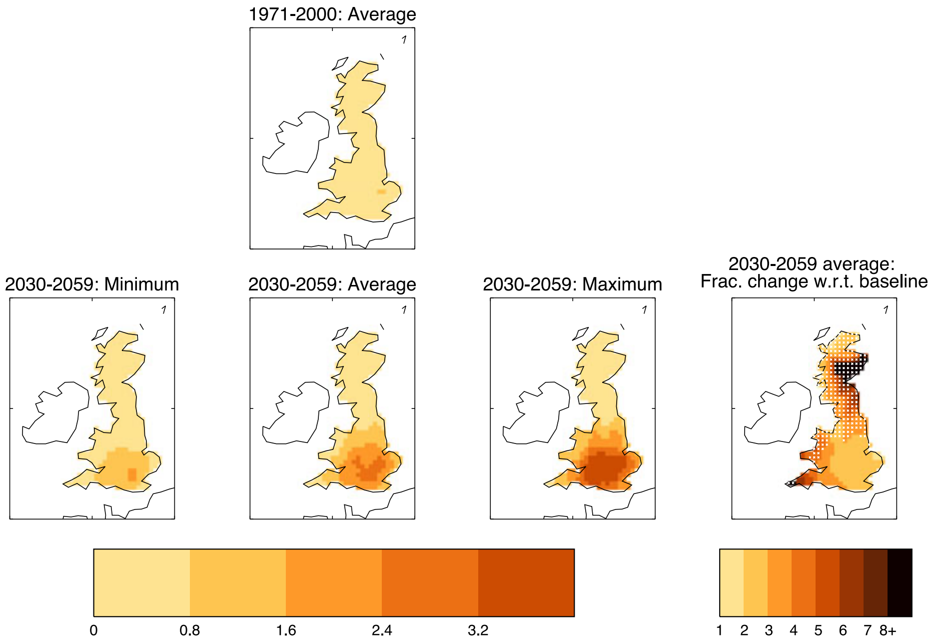

Fig. 3 Modelled percentage of May–September days per 30-year period per 25 km grid square with daily maximum temperature exceeding 31 °C (CAT(30/60) for the track condition "Tamped/lines with slues/lifts up to 25 mm"). *Top*: modelled baseline average, remaining panels: modelled range of outcomes for the 30-year period centred on the 2040s. The *rightmost panel* shows the fractional change between the modelled 2040s average and the baseline average, and *grid squares* superimposed with a *white cross* are those in which the change is not significant at the 5 % level according to the bootstrapping assessment

largest in the south and east of Great Britain (in both the baseline and future time periods). Additionally, although the greatest *number* of exceedances of CAT thresholds is in the south and east, the largest projected *fractional* change in future is in the north and west. Increases in exceedance are projected across Great Britain for almost all the CAT values studied, with the exception to this general conclusion being for the very highest CAT thresholds, which correspond to the best track conditions. For these, exceedance is rare or absent in the modelled baseline, and may remain rare or absent in future. Thresholds with rare baseline exceedance can give rise to very large projected fractional changes.

As stated above, the determination of threshold values is approximate, given the approximate nature of Eq. 1 and the likely variation in the SFT value in reality (Dobney 2010). As such, a brief examination of the effect of variations in these threshold values can be found in Supplementary Material (Section SM.7).

Results for other temperature thresholds for track buckling (not shown) indicate that for thresholds of 35°C or greater, either there is insufficient evidence to reject H_0, or there are insufficient numbers of exceedances to allow any statistical assessment to be made. These results suggest that any decisions taken based on the modelled exceedance of thresholds of 35 °C or greater should be treated with caution.

3.2 TM: windows of opportunity for track maintenance

Track structure and substructure play an essential role in limiting movement of the track caused by high temperatures. The propensity of the track to buckle with increasing temperature is dependent in part on the support offered by the ballast to the track. The ballast supports the sleepers longitudinally to maintain the pre-stressed rail and laterally to support against the heat-related expansion that causes buckles (Dobney 2010). Maintaining the stability of existing ballast is therefore extremely important; however after maintenance activity it takes time for the ballast to reform a stable mass. During normal temperature conditions this process does not pose a problem, but it is inadvisable to carry out ballast-disturbing maintenance during hot conditions. Guidance from Network Rail stipulates that such track maintenance should not be conducted when rail temperatures are above 32 °C or are predicted to exceed 38 °C within three days of work being carried out. Using Eq. 1, these two rail temperatures correspond approximately to air temperatures of 21 and 25 °C, respectively.

To assess the hazard, days with a maximum temperature exceeding 21 °C were counted as "non work" days. Days with a maximum temperature exceeding 25 °C were also counted as "non work" days, as were the preceding three days, if maximum temperature was less than 21 °C (days exceeding 21 °C are already counted). The percentage of May–September days that are "non work" days is shown in Supplementary Material (Section SM.8). Similarly to the preceding priority, the number of heat-related "non work" days is greatest in the south and east, for both time periods, and the fractional changes between the baseline and future periods are greatest in the north and west. For example, in much of southeastern England, over 20 % of May–September days during the modelled baseline period are "non work" days. This is projected to increase to around 40 % by the 2040s; the modelled ensemble range in the projected changes (i.e. deviation from the average projected change) in this region is around ±10 %. In southwestern England and parts of Wales, the fractional change in the average number of "non work" days between the baseline and the 2040s is at least 1 (i.e. at least twice as many "non work" days compared to the baseline), and in some parts of Scotland, the fractional change is almost 2 (i.e. almost three times as many "non-work" days compared to the baseline).

A statistical assessment of the modelled number of "non-work" days revealed that the change in this parameter was significant (i.e. there is sufficient evidence to reject H_0) at the 5 % level everywhere in Great Britain.

3.3 OS: incidence of sag of overhead line equipment

Overhead line equipment (OLE) supplies electricity to trains from a contact wire suspended over the track, to which a train connects via a pantograph. There are two types of OLE—auto-tensioned and fixed tensioned. The former is the most common, accounting for around 97 % of OLE, and uses balance weights to maintain a constant tension. The latter accounts for the remaining 3 % and is typically used in tunnels and large stations. It is essentially fixed at both ends and thus experiences variable sag depending on temperature.

Fixed tensioned OLE has a design temperature range of −18 to +38 °C (Network Rail 2006). Temperatures exceeding 38 °C could lead to excessive thermal expansion of the wire, and hence to sag exceeding the tolerances defined in the basic design, affecting contact with the pantograph. Auto-tensioned OLE has the same design temperature range (Network Rail, pers. comm.); within this range the tension can be maintained by the balance weights, but outside this range this mechanism can become ineffective.

OLE temperatures can differ from the ambient air temperature, depending on (for example) their exposure to direct solar radiation. Hence, OLE design specifications can be exceeded with air temperatures below 38 °C. This is supported by the fact that temperatures exceeding 38 °C have only been recorded twice in the UK,[3] yet data from Network Rail indicate that incidents of excessive sag have been experienced more commonly than this. Discussion with OLE engineers at Network Rail suggested that the difference between air and OLE temperature would not exceed 5 °C under most conditions. It is therefore feasible to assume that excessive sag could occur when air temperatures exceed 33 °C.

The modelled percentage of May–September days per 30-year period where the maximum temperature exceeds 33 °C is shown in Supplementary Material (Section SM.9). Modelled exceedance of this threshold is rare, with fewer than 0.3 % of May–September days exceeding in the baseline period across most of Great Britain (except in small parts of southeastern England, where the figure is 0.3–0.7 %). Patterns of exceedance are once again similar in the future projections. In central southern England, by the 2040s, just over 1 % of days could see maximum temperatures exceeding 33 °C; the modelled range in the projected changes across the ensemble (i.e. deviation from the average projected change) here is around ±0.5 %. Large fractional changes in exceedance are projected; however, bootstrapping indicates that most of these could be insignificant at the 5 % level (i.e. there is insufficient evidence to reject H_0). In areas where bootstrapping suggests a significant change, the largest fractional change is in parts of southwest England, with a fractional change of more than 6 (i.e. at least 7 times the number of days exceeding 33 °C by the 2040s compared to the baseline). We have already stated above that results for higher temperature thresholds should be treated with caution as a result of rare exceedance (see Section 3.1) and hence similar caution is required for this priority.

3.4 HS: staff exposure to heat stress

The rail industry employs a significant number of people who work outside and who could therefore experience heat stress during periods of hot weather. For example, heat watchmen are by definition outside during hot conditions. The potential impact of climate change on staff exposure to heat stress is therefore of interest.

Heat stress occurs when control of human internal body temperature becomes less effective. Several metrics have been devised to quantify heat stress, but these often involve complex relationships between several variables, some or all of which are either not included in the climate model formulation, or which are known not to be captured well by climate models; see e.g. Willett and Sherwood (2012) for a

[3] 38.5 °C was recorded near Faversham in Kent in 2003, and 38.1 °C at Kew Botanic Gardens in London in the same year, see http://www.metoffice.gov.uk/climate/uk/interesting/aug03maxtemps.html.

discussion of various thermal comfort indices and their underlying meteorological driving variables.

Because of the limitations of heat stress metrics and the difficulty in using them to make future projections, the Met Office Heat-Health Watch system has been used as a proxy for heat stress. The system triggers different levels of alert depending on the probability that threshold temperatures are reached in a particular region on at least two consecutive days and the intervening night. The use of both day-time and night-time temperatures is important: one of the reasons that prolonged periods of hot weather are difficult to tolerate is that not only are day-time temperatures high, but relatively high overnight temperatures mean that there is no respite from hot conditions.

In this work, a heat stress "episode" has therefore been defined as the combined exceedance of a particular maximum temperature threshold on two consecutive days and a particular minimum temperature threshold on the intervening night.

These temperature thresholds vary by region, as people living in different areas of the country will be acclimatised to different temperatures. The thresholds used were taken directly from the Heat-Health Watch system; see Supplementary Material (Section SM.10). No threshold temperatures are defined for Scotland, because the system does not operate there. The North East England thresholds were used for Scotland, as the maximum temperature threshold is lower for North East England than for North West England.

The modelled number of heat stress episodes is shown in Supplementary material (Section SM.10; note that these are raw numbers of episodes and not percentages). During the baseline 30-year period, almost all parts of Great Britain experienced fewer than 25 heat stress episodes. This is projected to rise to an average of around 50–75 in the 2040s in some parts of southern England. The range across the ensemble for this region is around 25–150 heat stress episodes by the 2040s. As was the case for the overhead line sag metric, some areas have very large projected fractional changes, but bootstrapping indicates that many of these could be insignificant at the 5 % level (i.e. there is insufficient evidence to reject H_0). In the region of significant change (where is sufficient evidence to reject H_0), across southern England and some of Wales, fractional changes of 2–7 are projected—i.e. three to eight times as many heat stress episodes by the 2040s compared with the baseline.

Examples of bootstrapping results for the number of heat stress episodes are given in Supplementary Material (Section SM.6), analogously with those for track buckling.

3.5 FR: freight risk from train failure in extreme weather

The "freight risk from train failure in extreme weather" priority considers the potential effect of cold conditions on the operation of the railway network. This was motivated in part by the recent cold winters experienced in the UK. For example, a freight train derailed near Carrbridge in Scotland in January 2010, and the ensuing accident report (Rail Accident Investigation Branch 2011) concluded that "the freight train's braking performance prior to derailing was much reduced from that which would normally be expected" and also noted that "[...] weather conditions were poor, although not extreme [...]. Temperatures were at or just above freezing and humidity values were high. [...] There was light falling snow on the route [...]".

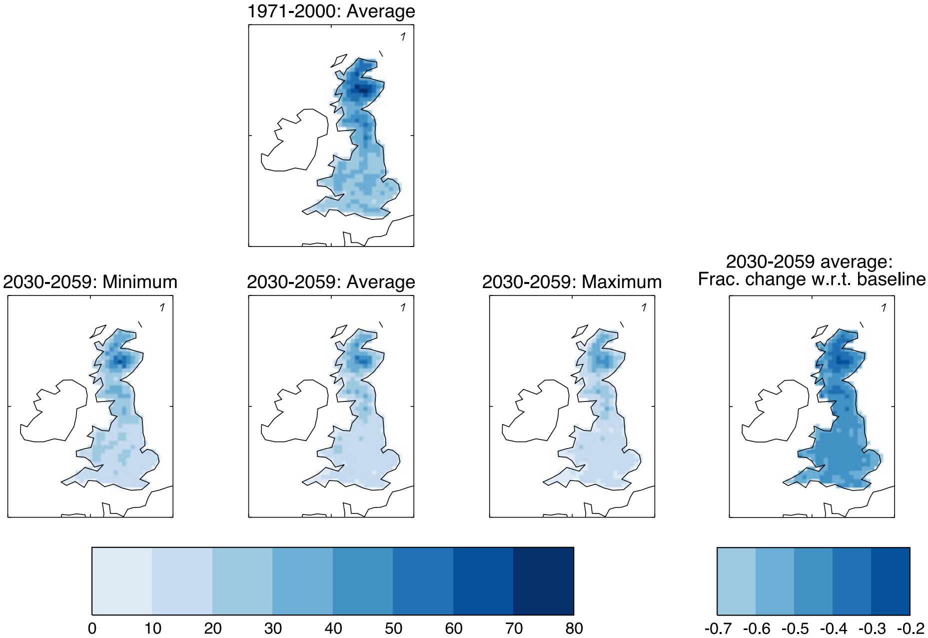

Fig. 4 Modelled percentage of November–March days per 30-year period per 25 km grid square with minimum temperature below 0 °C. *Top*: modelled baseline average, remaining panels: modelled range of outcomes for the 30-year period centred on the 2040s. The *rightmost panel* shows the fractional change between the modelled 2040s average and the baseline average. Bootstrapping results are not shown as the changes were found to be significant across the country

Other possible effects of cold conditions on the railway network include the potential for overhead line sag due to ice accretion on the conductors. It is therefore of interest to examine the future incidence of cold conditions which may be conducive to future performance issues on the railway network.

It was decided that the most appropriate way to address the issue of cold weather performance was to perform a threshold exceedance analysis of winter minimum temperatures. It is recognised that insights could be gained on specific points (such as winter overhead line sag) by including other parameters such as humidity, but the preference at this stage was to produce an overview that would be useful in a generic capacity.

Therefore, Fig. 4 shows the modelled percentage of November–March days where the minimum temperature falls below 0°C[4]. During the baseline period the highest percentage is over the Scottish Highlands, where more than 70 % of November–March days in the modelled baseline had minimum temperatures below freezing. A similar spatial pattern is projected into the future. In terms of fractional changes

[4]Note that the "minimum" and "maximum" responses are reversed in this figure with respect to other figures because we are considering a threshold with projected *decreases* in exceedance—so the minimum change is that which has a *larger* number of exceedances than the maximum change. To put it another way, the minimum change is always that which shows the smallest difference from the baseline, and the maximum is always that which shows the largest difference from the baseline.

in exceedance, the projected fractional change in the 2040s average exceedance compared to the baseline is of the order of –0.2 to –0.4 across Scotland and −0.3 to −0.7 across England and Wales. Projected fractional changes are largest around the coasts in all parts of Great Britain, and a statistical assessment of the modelled number of exceedances of 0°C revealed that the fractional change in this parameter was significant (there is sufficient evidence to reject H_0) at the 5 % level everywhere in Great Britain.

4 Recommendations to the industry

Upon completion of this work, recommendations for ways forward were made to the industry. These were either general in nature or specific to the vulnerability assessment. The overarching recommendations are discussed below and the vulnerability-specific recommendations in Supplementary Material (Section SM.11).

4.1 Weather/impact relationships—validation and data collection

The baseline relationships between weather and disruption on the railway network have not been validated—for example, we have not investigated whether the modelled baseline number of rail buckling incidents is truly representative of the actual number. Verifying relationships between weather and disruption would increase the confidence in making projections of quantities dependent on these relationships.

In addition, for two priorities (PR and HL), it was not possible to conduct an assessment of the hazard (see Section 2.3), and hence a vulnerability assessment was also not carried out. Further work is needed to address these areas, in terms of both collecting relevant data, and understanding the relationship between temperatures inside the train/equipment and external temperatures.

4.2 Future evolution of infrastructure and learning from other railway systems

Some of the climatic conditions which could cause problems to the GB railway network in future are already experienced—and managed appropriately—in other parts of the world. There is an opportunity to learn from these countries regarding the GB network's approach to adaptation. For example, in the context of track buckling, other countries use different SFT values to cope with a different range of ambient temperatures. In Australia, SFTs are higher (Dobney 2010; Nguyen et al. 2012), whilst in parts of the USA, a range of SFTs are applied, based on local rail usage and climate (Dobney 2010). Implicit in the choice of SFT is a trade-off between managing buckle risk at high temperatures and cracking/breaking risk at low temperatures. Using a seasonal stressing regime, where rails are re-stressed for winter and summer, has also been proposed (Dobney et al. 2009).

For priorities where vulnerability was assessed, this was necessarily restricted to consideration of the baseline vulnerability, since the future vulnerability may change, for example as a result of asset maintenance/renewal programmes, or technological and engineering advances leading to changes in infrastructure. Again considering track buckling, it is relatively easy to decrease vulnerability to this simply by ensuring that track is maintained to a high standard (Dobney et al. 2009, 2010; Nguyen et al.

2012). An example of a possible infrastructural change is changing the structural form of the track—e.g. replacing the traditional ballasted track with sleepers with continuous concrete slab track, as used on high-speed lines in (for example) Germany. Although this track generates more noise, it requires less maintenance than ballasted forms as the maintenance issues associated with ballast (outlined in Section 3.2 above) are removed (Cook 1988; Jones and Thompson 2001).

It should be noted that implementing some of the solutions discussed here would require significant investment, and these are therefore matters for the industry to consider.

4.3 Time periods considered

This work has considered timescales out to the 2040s, to cover the industry's 30-year Rail Technical Strategy. However, it is recognised that some aspects of railway infrastructure have a longer projected lifespan than would be covered by such timescales. Use of climate projections at longer range (e.g. out to 2100) would be useful in addressing adaptation for such assets.

5 Concluding remarks

This study has involved collaboration between Met Office Hadley Centre climate scientists and experts from the rail sector, with the aim of bringing together expertise from these two fields. Specifically, we sought to combine the insights that can be gained from appropriate use of climate modelling with knowledge of operationally-relevant climatic thresholds and actions taken to manage weather-related impacts on railway performance.

The results of this study indicate, for the 2040s (2030–2059) with respect to 1971–2000, that there are:

- Projected increases in the summer (May–September) daily occurrence of temperature conditions associated with track buckling and accompanying mitigation measures (heat-related speed restrictions and the deployment of heat watchmen). Increases are generally greatest in the north and west of Great Britain. The magnitude of these increases, and the statistical significance thereof, varies according to the track condition (and thus the critical temperature threshold exceeded);
- Projected increases in the summer (May–September) occurrence of temperature conditions associated with heat-related postponement of track maintenance. The increase is statistically significant at the 5 % level across Great Britain. The magnitude of the change is almost 200 % (i.e. a threefold increase) in some parts of Scotland;
- Projected increases in the summer (May–September) daily occurrence of temperature conditions associated with overhead line sag. The increase is statistically significant in the south and east of England only, where the magnitude of the increase is between 200 and 600 % (i.e. a threefold to a sevenfold increase);
- Projected increases in the summer (May–September) daily occurrence of temperature conditions associated with exposure of outdoor workers to heat stress. The increase is statistically significant in the south and east of England only,

where its magnitude is between 100 and 800 % (i.e. a twofold to a ninefold increase);

- Projected decreases in the winter (November–March) daily occurrence of temperature conditions associated with freight train failure risk. The change is statistically significant at the 5 % level across Great Britain, and its magnitude is between −70 and −20 %.

Although a full risk assessment has not been undertaken in this study, the quantification of climate hazard and vulnerability components provides the foundation for such an assessment, which could be undertaken in future in order to assist rail sector experts in developing business strategies which take appropriate account of the potential impacts of climate change. Indeed, the industry has recently announced plans for a further programme of research with the aim of building upon results from this and other studies in the sector.

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