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Abstract [up to 250 words]

In recent years, extreme weather events have caused substantial disruption to Great Britain's (GB's) railway infrastructure. In coming decades this vulnerability is unlikely to subside as the effects of climate change become more intense. Railway stakeholders in GB are strongly engaged with understanding climate change impacts on the railway system and how the industry could adapt to these impacts. Since 2010, Network Rail and RSSB have supported research into these topics under the "Tomorrow's Railway and Climate Change Adaptation" (TRaCCA) programme. Under TRaCCA, an analogue study was performed to determine whether lessons could be learned from other countries' weather management. Two types of analogue were used to identify suitable railway networks. First, climate data from twenty models of the Coupled Model Intercomparison Project phase 5 (CMIP5) were used to identify regions whose present-day climate is similar to the projected future GB climate for the mid- and end of the twenty-first century. The analogue locations were found to be largely insensitive to the climate indicators and the methods used to compare climate at different locations. Next, railway networks in many countries worldwide were studied to find those with similar physical and operational characteristics to the GB network. Those regions with both climate and railway analogues are France, Netherlands, Belgium, Germany and Denmark. These five countries are therefore good choices for further study to provide guidance on how the GB network could adapt to a changing climate. The methods described here could be used to identify analogues for other railway networks.

Keywords: Climate change, analogues, railway, climate models, GB, CMIP5

1 Introduction

1.1 Background to study

In Great Britain (GB), the railway network has a variety of stakeholders including infrastructure owners, rolling stock companies and train operating companies as well as regulatory bodies such as the Office of Rail Regulation (ORR) who all have interests and responsibilities in ensuring future service operation. A recent project funded by the UK Department for Transport (DfT), through the Rail Industry Strategic Research Programme (managed by RSSB under the Tomorrow's Railway and Climate Change Adaptation (TRaCCA) programme), included studies of a variety of possible temperature-related climatic impacts on the main line railway network of Great Britain (Palin *et al.*, 2013). Subsequent research under TRaCCA (RSSB reference T1009) aims to deliver step changes in climate science, knowledge of climate change vulnerabilities, and the development of support tools, to increase the weather and climate resilience of the GB railway.

One outcome of the initial TRaCCA-funded work was that the GB railway network acknowledged that it could potentially learn from the management of railway systems in other countries (Palin *et al*., 2013). Specifically, some of the conditions which could affect the GB railway network in future may already be managed appropriately in other countries. However, in order to draw such lessons it is important to acknowledge the need for a twofold similarity in both climate and the railway network in these other locations. Therefore, a study to determine these locations was undertaken as the first stage in assessing this potential for adaptation knowledge transfer.

A variety of observations show that Great Britain's climate has warmed during the twentieth century. For example, Parker and Horton (2005) detected an increase in annual mean temperatures of 0.077°C per decade in the Central England Temperature record between 1900 and 2004. Climate modelling studies indicate that further increases in temperature are projected for Great Britain during the twenty-first century (Murphy *et al*., 2009; IPCC, 2013a). These changes could increase the occurrence of conditions conducive to the imposition of speed restrictions, the excessive sag of overhead power lines, the exposure of outdoor workers to heat stress (Palin *et al.*, 2013) and track buckling events (Dobney *et al.*, 2009) – assuming that no action were taken to decrease the vulnerability of the railway to these changes.

Projected changes in rainfall are less clear. Winter rainfall could increase, but summer rainfall may decrease (Murphy *et al*., 2009; IPCC, 2013a). However, the proportion of summer rainfall falling in short duration downpours may increase (Kendon *et al*., 2014) which would raise the chance of flash flooding events and failure of earthworks in cuttings and embankments.

1.2 Analogue methods

In this study, two types of analogue – climate and railway – are used to identify suitable railway networks that could provide guidance on adaptation of the GB network to climate change. First, climate analogues are identified (Veloz *et al*., 2012). Indicators are calculated which describe aspects of the climate at two locations. These indicators are based on temperature and rainfall. If the climate at one location is similar to the climate at another, according to some pre-defined criteria, then one location is said to be an analogue of the other. Analogues may be used to identify where the present day climate at a location might exist in the future. In the present study, regions where the projected climate for GB exists in the present day are required.

Two key choices for any study using climate analogues are which indicators to use, and how to compare indicators at two locations statistically. These choices may affect which analogues are identified. It should be borne in mind that weather and climate at two locations will never be identical, so the use of analogues will always involve a degree of approximation. In some cases, even the closest analogues may be a poor representation of the climate of a location of interest. Climate change could generate new climates that do not presently exist, at least in the vicinity of the area of interest (Williams *et al*., 2007; Kopf *et al*., 2008). Similarly, some types of present-day climate may disappear altogether in the future (Williams *et al*., 2007).

To date, climate analogues have been used to assess climate change impacts on many sectors. Hallegatte *et al*. (2007) and Kopf *et al*. (2008) used analogues to search for cities in Europe whose present climates could be considered as reasonable representations of the simulated climate for the 2080s of selected European cities. They calculated three different climate indicators to assess the similarity of the projected climate of the selected cities and the current climate of the potential analogues. The indicators were calculated from temperature and rainfall simulated by regional climate models. For many cities, analogues were found at more southerly latitudes within Europe.

Grenier *et al.* (2013) used simulated climate for north-east Canada from a regional climate model for two periods (1971 - 2000 and 2041 - 2070) to identify analogues for the city of Montreal (Quebec, Canada). They used six different dissimilarity metrics (see Section 4) in an attempt to identify the best metric for selecting analogues. They found that the six metrics identified similar analogues at a relatively large scale, but the locations of the best analogues differed substantially between some of the indices.

The second set of analogues used was based on the characteristics of the various railway networks. The International Union of Railways (UIC) publishes annual summary data of the railway operations in many countries worldwide, together with details of the structure of these railways (UIC, 2014). These data were used to calculate several indicators of railway networks and operations which could be used to identify those networks which are most similar to the GB network. Previous use of such indicators has generally been in the field of economic ‘benchmarking’ of railway undertakings and a variety of approaches have been developed (Oum *et al.*, 1999; De Borger *et al.*, 2002; Pisu *et al.*, 2012). These approaches have been applied both nationally and internationally (Hansen *et al.*, 2013) but do not appear to have been used for climate studies.

Previous studies have largely identified specific locations as the analogue of a point of interest, for example a city area. However, given the nature of railway networks, the aim of present study was to identify regions whose present day climate is similar to that projected for GB, and whose railway networks are similar to the GB network. Results from an ensemble of climate models (Taylor *et al.*, 2012) were used so that some of the uncertainty in the climate projections could be included (Section 2). Indicators were calculated which describe aspects of the climate of each location, and are described in Section 3. These indicators were compared using statistical measures of climatic similarity (Section 4) to identify possible analogues. The analogue locations identified are described in Section 5, where the sensitivity of the results to the indicators and similarity measures is explored. In Section 6, the physical and operational characteristics of railway networks around the world are compared to identify networks that are similar to the GB railway network. The results are summarised in Section 7, together with a discussion of the benefits and limitations of the analogue approach.

2 Climate Model Data

The Coupled Model Intercomparison Project phase 5 (CMIP5; Taylor *et al.*, 2012) provided a set of coordinated climate model experiments. Modelling centres around the world participated, and results from over 30 climate models were submitted and analysed to answer key scientific questions for the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2013a). These experiments included historical simulations, where the models were driven using observed levels of greenhouse gases and aerosols, solar variability and emissions from volcanoes. The results from the historical simulations have been evaluated against observations on global and continental scales. The simulations reproduced important aspects of global and regional climate (Flato *et al.*, 2013), and so are suitable for the present study.

The same models were used to project the future climate under four plausible but different greenhouse gas “representative concentration pathways” (RCPs; van Vuuren *et al.*, 2011). These are similar to the emissions scenarios used in previous climate model simulations, but with future greenhouse gas evolution described in terms of the atmospheric concentrations of these gases, rather than the amounts emitted from various sources. Measured greenhouse gas emissions have been compared with emissions derived from the concentrations under each RCP (Sanford *et al.*, 2014). Current emissions are just above those in the scenario with the highest concentrations (called RCP8.5) and are increasing at a very similar rate. Hence climate model simulations using this scenario were analysed. Using median values, the climate of the UK is projected to warm by 1.0-1.5°C by the middle of the 21st century, and by 3-4°C during late 21st century under the RCP8.5 scenario. Rainfall is projected to increase by up to 10% and 10-20% between October and March during the mid- and late 21st century respectively. Between April and September, projected changes in rainfall range from very little change to a 20% reduction over most of the UK (IPCC, 2013b: Annex I). All these changes were calculated relative to 1986 – 2005.

A subset of 20 models was used for this study (Table 1) owing to restrictions on use of results from some models and data availability. An evaluation of the relative biases in the global and seasonal climatologies of surface temperature and rainfall from the models showed that, of the models listed in Table 1, only one had a high warm bias. The biases in rainfall from all the models were generally small or moderate. Overall, none of the models used in this study would be considered outliers. All model data were interpolated to a common resolution of 1.875° × 1.25° before use. This resolution is used by the Met Office's HadGEM2 global climate models, and lies roughly at the middle of the range of resolutions used by the other CMIP5 models.

3 Indicators

Climate can be thought of as the average weather conditions at a given location. As stated in Section 1, indicators are calculated which quantify the relevant climatic attributes of locations of interest (Williams *et al.*, 2007). These indicators may then be compared statistically to identify analogues. Many previous studies using indicators have included at least one based on temperature and another based on rainfall (Hallegatte *et al.*, 2007; Williams *et al.*, 2007; Kopf *et al.* 2008; Veloz *et al.*, 2012; Grenier *et al.*, 2013), and this approach will be followed here. There are many impacts of hot and cold temperature on the railways (Dobney *et al*., 2009; Palin *et al*., 2013). Heavy or prolonged rainfall can also cause flooding. Temperature and rainfall effects have also been identified as being of key interest in the TRaCCA project.

Analogues were identified in many previous studies using three indicators, which is a compromise between a sufficient number of indicators to characterise climate but not too many as to make identifying analogues difficult. The indicators used in this study are annual total precipitation (ATP), warm days per year (days with maximum temperatures of 18°C or warmer) and cold days (days with minimum temperatures less than or equal to 0°C). These thresholds are lower than those used in the management of the GB rail network. This was necessary to allow for the relatively coarse resolution of the global climate models (~100 – 200 km) used to determine analogues in this study, which averages out very high and low temperatures seen on smaller spatial scales. Similar indicators have been used in other studies (Kopf *et al.*, 2008; Grenier *et al.*, 2013). The exact values of the thresholds for warm and cold days may not be important, as days above or below similar thresholds will be closely correlated (Kopf *et al.*, 2008). These three indicators are calculated using daily maximum and minimum temperatures and daily rainfall data from the climate models. Use of days above or below a given threshold means that any global variations in seasonality will not affect the result. This situation would arise if locations in the northern and southern hemispheres were compared. The sensitivity of the results to the thresholds used to define warm and cold days, and to an alternative rainfall indicator (number of wet days per year) will also be investigated (see Sections 5.2 and 5.3).

Each set of indicators is calculated annually for thirty year periods, providing thirty values for each indicator. It is assumed that the average over thirty years is representative of the central decade. The use of a longer time period minimises the risk that any change in climate was caused by natural variations rather than a change resulting from external influences on the climate system. Two future time periods will be analysed: mid twenty-first century (2035 – 2064) and late twenty-first century (2070 – 2099). Analogues were searched for using modelled data for 1971 – 2000 to represent the present day climate.

Extremes in temperature and rainfall (i.e. hot and cold days and nights, periods of heavy rainfall) are not addressed by the indicators used here. The CMIP5 models reproduce some characteristics of observed temperature and rainfall extremes (Flato et al., 2013), but there is disagreement between the observational extremes datasets, especially for precipitation, making evaluation of modelled extremes difficult (Hartmann *et al*., 2013).

4 Dissimilarity Metrics

Dissimilarity metrics are used to evaluate differences in a set of variables between two locations. They provide a statistical description of the similarity (or dissimilarity) of the variables and may be used to quantify the difference, allowing the best analogues to be identified.

There are a wide range of dissimilarity metrics. Grenier *et al.* (2013) compared six different metrics and recommended use of the Zech-Aslan energy statistic (Zech and Aslan, 2003; Aslan and Zech, 2005) for identification of analogues. The Zech-Aslan metric favours analogues with balanced departures from the reference climate, in terms of average and standard deviation. Analogues having medium departures for all climate indicators would be favoured over those analogues having a high departure in one climate indicator but low departures in the others. The calculation of the Zech-Aslan energy statistic is described in Section S1.

5 Method and Results

Daily minimum and maximum temperatures and daily rainfall totals were obtained for each global climate model listed in Table 1. The three climate indicators were calculated for the mid- and late 21st century over GB land points (Figure 1). Next, the same three indicators were calculated over all land points using daily data from the historical simulation for the period 1971 – 2000 from the same model. Some land areas where analogues would not occur (for example, Antarctica) were excluded from the analysis. The Zech-Aslan dissimilarity metric was used to compare the simulated future climate of each UK land point with the modelled present-day climate of all land points, as represented by the three indicators. In a similar approach to Grenier *et al.* (2013), the potential analogue locations were ranked using values of the Zech-Aslan metric. Locations with low ranks would be considered to be analogues, whereas those with high ranks would not. The time series of the indicators at the two locations (i.e., a GB location and the closest analogues) were compared by eye as a check on how close the analogues were.

The consistency of the analogue locations derived from the climate models was then assessed. For each GB land point, the number of times each location appeared in the top 50 analogues identified from each model was calculated. Locations with a score close to the total number of models may be considered as robust analogues of the future GB climate. Locations with low scores are identified by only a small number of models and would be less robust.

5.1 Analogue locations

Analogue locations for south-east England and north-east Scotland in the mid-21st century are shown in Figure 2. The figures show the number of times each location appears in the top 50 ranks. For south-east England, the closest analogues are northern and western France. The north coast of the Iberian Peninsula is also identified by about 10 models. A smaller number of models suggest southern Argentina and Chile, New Zealand and northern coastal regions of the Mediterranean as potential analogues.

Some of the same locations were identified as analogues for north-east Scotland, but there were also some important differences. Ireland represents the closest analogue to the projected climate for the mid-21st century. Approximately half of the models indicate much of Great Britain and the south island of New Zealand as potential analogues. A smaller number of models suggest southern Argentina and Chile as analogues, but the Mediterranean is not an analogue.

Closer examination of the analogues shows there are important differences between western and eastern coasts of Scotland. Rainfall on western coasts of the UK is higher than on eastern coasts (Murphy *et al.*, 2009, Figure 5.1), which impacts on the analogues identified. In Scotland, the difference in rainfall totals between the east and west coasts is the greatest. Wales and south-western England are potential analogues for north-west Scotland, but not for north-east Scotland.

In some cases, the target location was identified as its own analogue. An analysis of the indicators for the present and future climate for the 2050s showed that the ranges of annual rainfall totals and numbers of cold days overlapped in a number of models. The numbers of cold days were smaller in the future, as expected, but the high variability in their numbers mean the numbers of cold days in the present day and future were similar in some years. Future rainfall was generally slightly larger in the future, but eh change was small compared with the year-to-year variability. The numbers of warm days were almost always much larger in the future than present, although they did overlap slightly in a few models. The overlap in rainfall totals and numbers of cold days in the modelled present day and future climate explains why some locations are their own analogue.

The climate analogue locations for the four GB regions shown in Figure 1 for the mid- and end of 21st century climate of Great Britain are summarised in Tables 2 and 3, using ranks derived from the Zech-Aslan statistic.

There are many similarities in the locations of the analogues for the two time periods, but also some important differences. For example, north-west France is an analogue for southern England and Wales during both the mid- and end of 21st century, although locations in Spain and Portugal are also identified for the end of the 21st century. Similarly, New Zealand and southern South America are identified for most of the UK in both time periods. For the end of the twenty-first century, there were important differences in the analogue locations between the east and west parts of Scotland and northern England. Some differences were also noted for the mid-21st century, but they were smaller and less pronounced.

5.2 Sensitivity to Dissimilarity Metric

The identification and ranking of analogues was repeated for the mid- and end of 21st century using two alternative dissimilarity metrics, the Euclidean distance (ED) and the CCAFS similarity measure (see Section S1 for a description of their calculations).

Similar analogue locations were identified by all three dissimilarity metrics although the number of models which identified each location was sometimes different. For example, when considering analogues for southern England in the mid-21st century, the ED metric favoured the northern coasts of Spain and Portugal as well as north and western regions of France. The number of models which identified the south-eastern coast of Australia was also larger. The CCAFS similarity measure tended to produce “noisier” results; a few scattered locations in South Africa and India were identified as analogues by a small number of models for southern England during the late 21st century as well as those listed in Tables 2 and 3. Overall, the choice of dissimilarity metric has made little difference to the analogue locations in either time period.

5.3 Sensitivity to Climate Indicators

The sensitivity of the analogue locations to the climate indicators was also explored. First, an alternative rainfall metric, the number of wet days per year, was used. All days with a total rainfall of 0.1 mm or larger were identified. Next, the 90th percentile of the daily rainfall totals from those days was calculated for each UK land point (Figure 1) and climate model simulation, using daily rainfall data for the mid-21st century. Any day whose total rainfall was equal to or exceeded this threshold would be classed as a wet day in that model.

The same threshold was then applied to daily rainfall data from the same model for the present-day period (1971 – 2000) and used to calculate the number of wet days per year over all land points. The numbers of wet days, together with the days above and below the appropriate temperature thresholds (Section 3), were then compared using the Zech-Aslan dissimilarity metric and used to identify analogue locations.

The use of wet days per year instead of annual total precipitation had little effect on the analogue locations identified. There was a minor impact on analogues identified for locations in southern England. Fewer models indicated New Zealand as an analogue, and the analogues in Chile and Argentina were located slightly further north. Otherwise, the analogue locations and model consensus were very similar to those obtained using the standard set of indicators (Figure 2; Tables 2 and 3).

The calculation of the climate indicators and analogue locations was repeated using a range of alternative thresholds for hot and cold days. The temperature thresholds used to calculate the climate indicators are lower than the thresholds used by Network Rail for relevant decision-making processes such as deploying heat watchmen and imposing speed restrictions. Climate models simulate an average temperature over a large area (approximately 150 km × 150 km), and so would not reproduce very high temperatures observed during the summer months. Hence, the thresholds used here are lower. For this series of tests, the original rainfall metric (annual total precipitation) was used. The maximum temperature threshold was increased from 18°C to 26°C, and the minimum temperature threshold was changed from –4°C to +4°C. Both thresholds were increased in steps of 2°C. These changes were made incrementally, meaning analogues were identified using 24 new threshold pairs.

There were some small differences in the ranking of the analogues but the same broad locations were identified for each region of the UK for all the different temperature thresholds. This result applies to both the mid-21st and end of 21st century. Hence, the locations that are given in Tables 2 and 3 (based on analyses with daily maximum temperatures greater than 18°C and daily minimum temperatures below 0°C) are also appropriate across the other temperature thresholds tested.

Most of the differences seen when performing this set of sensitivity tests lie with the degree of model consensus for the given locations. The consensus seemed to reduce as the daily maximum temperature threshold was increased to 22°C and higher, and the daily minimum temperature reduced (particularly those below 0°C). However, some of the change in consensus was caused by the change in number of events across the different models. For the highest maximum temperature thresholds, the number of events above the threshold was very low or zero for a number of the models. This result suggests that the highest thresholds are not appropriate for the UK climate at the resolution of the global climate models. The original choice of daily maximum and minimum temperature thresholds of 18°C and 0°C (Table 4, sensitivity test 1) appear suitable for the present study.

The spatial coverage and extent of analogues found in South America, South-East Australia and New Zealand also varied with the temperature thresholds used. The clearest case of this was for the analogues found in South-East Australia. The coastal areas around Melbourne only appeared for some of the thresholds as the daily maximum temperature threshold was increased.

A few analogues were found in south-eastern parts of South Africa as the daily maximum temperature threshold was increased. These locations were not present when lower temperature thresholds were used. Analogues in South Africa generally only appeared for the end of the 21st century.

In summary, very similar analogue locations were identified regardless of the temperature thresholds and rainfall metric used. The top ranked locations are located in Northern Europe and secondary locations further afield include Chile, New Zealand, South Australia and the north-western coast of the USA (see Tables 2 and 3 for more detail).

6 Railway analogues

In this section, an analysis of railway networks across the world is presented that highlights systems which have similarities in type, operation and efficiency to the GB main line network. Although in theory all railway undertakings are similar, in practice there are many distinctions in technology, operations and efficiency which limit the value of drawing direct comparisons. Examples include traffic patterns, which effectively define who the railway is primarily serving, and staffing levels, which highlight differing approaches to disruption recovery operations. Thus comparing the operation of a primarily freight-oriented rail network to a primarily passenger-orientated railway is likely to yield unhelpful results as they may well have very different goals, for example in terms of acceptable track alignment and ride comfort. Similarly, a high-staff railway approach to maintenance is different to that of a high-technology, low-staff rail network even though the endpoint may be similar. It is therefore helpful to identify broadly where similarities exist in railway undertakings to assist in focusing the search for overseas practices which may be of direct relevance to the GB railway in a future climate.

The analysis presented here used data from the International Union of Railways (UIC, 2014; further details are provided in Section S2). Data from railway companies within a single country were aggregated to calculate total network length, single/ multiple track lengths, electrified track length, total staff numbers, passenger-kilometres and freight tonne-kilometres travelled. From these raw data a number of indicative parameters were calculated as shown in Table 4. These parameters give a broad overview perspective of railway operations in each country. Network utilisation, for passenger (NU-P) and freight (NU-F) operations, shows the level of revenue traffic per kilometre of the network and the balance between these two revenue activities on the network overall. Staffing level shows the number of staff required to operate this level of activity across the network on a basis that can be compared across countries. Finally, passenger operation efficiency (POE) combines network utilisation and staffing in an overall parameter which effectively shows number of passenger-kilometres achieved per staff-kilometre of the network. From the UIC data, parameters for 84 countries were calculated.

The balance between passenger and freight network utilisation shows that the GB network is passenger orientated. Rank ordering the 84 countries shows that GB is 10th in NU-P and joint 40th in NU-F which supports this conclusion. The top 20 countries, ranked by NU-P together with their associated NU-F values are listed in Table S2. These countries therefore provide the most likely analogues for GB from a railway systems perspective. A review of the parameters calculated for the remaining countries showed decreasing similarity, and therefore a cut-off of the top 20 was considered reasonable.

To evaluate these potential analogues further, other railway network parameters were also considered, which were the lengths of single and multiple track railways and the percentage of electrified track. It was not required that an exact numerical value be achieved to be a reasonable analogue but rather that the parameters be generally aligned with those of the UK. Parameter values for the top 20 countries are listed in Table S1.

The UK is a mixed railway both in having single and multiple track lines and partial electrification. These characteristics are likely to continue into the future, although the proportion of electrified track is likely to increase. Overseas railways with a mixed nature should be considered as better analogues than those with extremes of these parameters.

Railway systems with high NU-F compared to NU-P may have a different overall focus to the UK and thus be poor analogues. Staffing is also very important and countries with a staff per km value of over twice that of the value for GB appear to be different in character and therefore poor analogues. The POE parameter highlights railways with very high (or low) density passenger traffic patterns. Again, the UK appears to have a mixed pattern and moderate value. Countries with POE values that are much higher or lower than the GB value would not be considered as suitable analogues.

This analysis suggests that the following nine countries be considered as potential overseas analogues for the GB rail system. In Europe: Austria, Belgium, Denmark, France, Germany, Italy and the Netherlands; and outside Europe, Morocco and Japan. The Republic of Korea and Switzerland are not considered to be suitable analogues, as they differ from GB in one important criterion (staff per km in Korea, and percentage of network electrified in Switzerland).

In making these recommendations the limitations of this analysis should be considered. This analysis was made at the country level because of the available UIC data, and could overlook regions of similarity. For example, the northeast corridor in USA and Canada has a potentially more European character than the rest of North America. It is also possible that overseas railway networks with very different characters to the GB network could nonetheless have particular elements of strategies which are useful in a GB context for adaptation.

The analyses in Sections 4, 5 and 6 have used complementary perspectives to identify analogues. The simplest way to combine these complementary perspectives is to assess which countries appear on the lists of both climate analogues and railway analogues. The countries thus identified are France, Netherlands, Belgium, Germany and Denmark. There are therefore no countries outside Europe which are both climate and railway analogues according to the above methodologies.

7 Summary

In this study, climate and railway analogues for Great Britain have been identified. The climate analogues were identified using results from twenty global climate models under a high emissions scenario (RCP8.5) for the mid- and end of the twenty-first century. The use of results from multiple models allows some of the uncertainty in the analogue locations to be included. The most robust analogues (those locations identified by the majority of the models) are located in France, Spain, Portugal, New Zealand and southern parts of Chile and Argentina. Projections from a few models also identified coastal regions in south-east Australia and the west coasts of the USA and Canada, around Seattle and Vancouver. Analogues for a given region of the UK are generally located in more southerly latitudes, owing to the warmer temperatures.

It is important to note that the underlying atmospheric circulation in some of the analogue locations could be different to that of Great Britain. Some aspects of the analogues' climate may be very different, such as maximum summer temperatures or seasonal variation in rainfall. Even the best analogues may not be an accurate representation of all aspects of the future climate of Great Britain.

In the present study, similar analogue regions have been identified for the mid- and late 21st century. Temperatures projected for these two time periods are different, but the changes in precipitation are (on average) more similar owing to the large spread in projections amongst the models. Hence, the precipitation indicators appear to exert the strongest control on the analogue locations, which agrees with the findings of Veloz *et al.* (2012).

The use of three different dissimilarity metrics, used to compare the climate at different locations and identify analogues, did not have a large effect on the analogues identified. However, the degree of consensus amongst the models was different in some locations. Similarly, the use of an alternative rainfall indicator and different temperature thresholds had very little effect on the locations of the analogues. Hence, the analogue locations appear to be fairly robust.

The climate analogue analysis has limitations and procedural issues. The most critical are the choice of climate indicators and metrics used to compare indicators at different locations and time periods. In the present study a simple set of indicators based on temperature and precipitation have been used. Other indicators based on extremes of climate could have been used. However, the ability of the CMIP5 models to reproduce known extremes and their trends varies considerably, and disagreement between databases of extremes means model evaluation is difficult (Hartmann *et al*., 2013). The choice of indicators could be further tuned for the railway industry. For example, accumulated rainfall over several days could be used to identify conditions likely to cause flooding. The indicators could be weighted based on their perceived importance. Nevertheless, the analogue locations identified have been shown to be fairly insensitive to the temperature thresholds or the rainfall metric used, and the judgement of dissimilarity. The results from this study are therefore useful for identifying suitable analogues.

Key physical and operational characteristics of railways in many countries all over the world were compared with those for the GB network. Railways in nine countries were identified as possible railway analogues, of which five had also been identified as possible climate analogues. These five countries were France, Netherlands, Belgium, Germany and Denmark. It is recommended that railway operations and management in these countries should be studied in further detail to provide useful guidance on how the GB railway network could adapt to climate change over the coming decades.

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Supporting information

The following material is available as part of the online article:

Section S1. Calculation of dissimilarity metrics

Section S2. International Union of Railways

Table S1. Railway network and other parameters derived from the UIC data

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Table 1. CMIP5 models used in this study. Further details of these models are given by Flato *et al.* (2013). The horizontal resolutions for some models are approximate.

Model Name	Institution	Horizontal resolution
BCC-CSM1-1	Beijing Climate Centre	2.81° × 2.81°
BNU-ESM	Beijing Normal University	2.81° × 2.81°
CanESM2	Canadian Center for Climate Modelling and Analysis	1.875° × 1.875°
CCSM4	US National Center for Atmospheric Research	1.25° × 0.94°
CMCC-CM	Centro Euro-Mediteraneo per i Cambiamenti Climatici	0.75° × 0.75°
CMCC-CMS	Centro Euro-Mediteraneo per i Cambiamenti Climatici	1.875° × 1.875°
CMCC-CESM	Centro Euro-Mediteraneo per i Cambiamenti Climatici	3.75° × 3.75°
FGOALS-g2	Institute of Atmospheric Physics, Tsinghua University	2.81° × 1.66°
GFDL-CM3	NOAA Geophysical Fluid Dynamics Laboratory	approx. 2° × 2°
GFDL-ESM2G	NOAA Geophysical Fluid Dynamics Laboratory	2.5° × 2°
GFDL-ESM2M	NOAA Geophysical Fluid Dynamics Laboratory	2.5° × 2°
HadGEM2-CC	UK Met Office Hadley Centre	1.875° × 1.25°
HadGEM2-ES	UK Met Office Hadley Centre	1.875° × 1.25°
INM-CM4	Russian Institute for Numerical Mathematics	2.0° × 1.5°
IPSL-CM5A-LR	Institut Pierre Simon Laplace	3.75° ×1.90°
IPSL-CM5A-MR	Institut Pierre Simon Laplace	1.25° × 2.5°
IPSL-CM5B-LR	Institut Pierre Simon Laplace	3.75° × 1.90°
MPI-ESM-LR	Max Planck Institute for Meteorology	1.875° × 1.875°
MPI-ESM-MR	Max Planck Institute for Meteorology	1.875° × 1.875°
NorESM1-M	Norwegian Climate Centre	2.5° × 1.9°

Table 2. Locations of analogues for the mid-21st century GB climate. The Best Locations are those regions ranked in the top 50 analogues by the majority of the models. The other regions ("Also Consider") were identified by fewer models.

Region	Best Locations	Also Consider
Southern England	Northern and Western France	Northern Spain South of France Southern Argentina and Chile Coastal strip of Australia around Melbourne North Island of New Zealand Western USA (between San Francisco and Portland)
Central England	Southern England Northern France, Netherlands, and Belgium	South Island of New Zealand Southern Argentina Southern Chile
Scotland and Northern England	Central and Southern England Wales Ireland Coastal strip of Germany Denmark	South Island of New Zealand Southernmost parts of Argentina and Chile Western USA (between San Francisco and Portland)
Wales	Southern England and Northern France	Netherlands, Belgium Northern Spain South Island of New Zealand Southern Argentina and Chile Western USA (between San Francisco and Portland)

Table 3. Locations of analogues for the end of the 21st century GB climate. The Best Locations are those regions ranked in the top 50 analogues by the majority of the models. The other regions ("Also Consider") were identified by fewer models but could still be worth considering.

Region	Best Locations	Also Consider
Southern England	France (excluding south-east quadrant) Portugal; Northern and Western Spain Coasts of Croatia and Bosnia South-East Australia North Island of New Zealand	North Mediterranean coasts Chile (between Santiago and Puerto Montt) Western USA (between San Francisco and Portland)
Central England	South-West England North and Western France North coast of Spain and Portugal	New Zealand Coasts of Croatia and Bosnia Southern Argentina and Chile Western USA (between San Francisco and Portland)
Scotland and Northern England (Western parts)	Wales, South-West England Ireland Western coast of France South Island of New Zealand	Northern Spain Chile (between Santiago and Puerto Montt) Coastal parts of Japan Western USA (between San Francisco and Portland)
Scotland and Northern England (Eastern and central parts)	Ireland Western coast of France Southern England and Wales	Northern Spain and Northern Portugal Chile (between Santiago and Puerto Montt) New Zealand Western USA (between San Francisco and Portland)
Wales	Western France Northern Portugal Northern Spain Southern England	New Zealand Southern Argentina and Chile Western USA (between San Francisco and Portland)

Table 4. Indicative parameters used in the analysis. These parameters were derived from UIC data for 2012. The GB value excludes Northern Ireland (NI); including NI made very little difference.

Parameter	Calculation	GB Value
Network Utilisation (passenger)	Total passenger-kilometres divided by total network length	3.98×10^6
Network Utilisation (freight)	Total freight tonne-kilometres divided by total network length	1.33×10^6
Staffing level (number per km)	Total railway staff divided by total network Length	5
Passenger operation efficiency (dimensionless)	Total passenger-kilometres divided by (total network length multiplied by total railway staff)	47

Figure 1. GB land grid boxes at the resolution of the HadGEM2 global climate model. Analogues were found separately for each box, and then the analogues for Scotland (dark grey), Central England (medium grey), southern England (light grey) and Wales (pale grey) were amalgamated.

Figure 2. Level of agreement for analogue locations for south-east England. Locations with scores close to the total number of models (13-20), shown in red and purple, are identified as analogues by most models. Locations in blue and yellow are identified by fewer models.

Figure 3. Level of agreement for analogue locations for north-east Scotland. Locations with scores close to the total number of models (13-20), shown in red and purple, are identified as analogues by most models. Locations in blue and yellow are identified by fewer models.

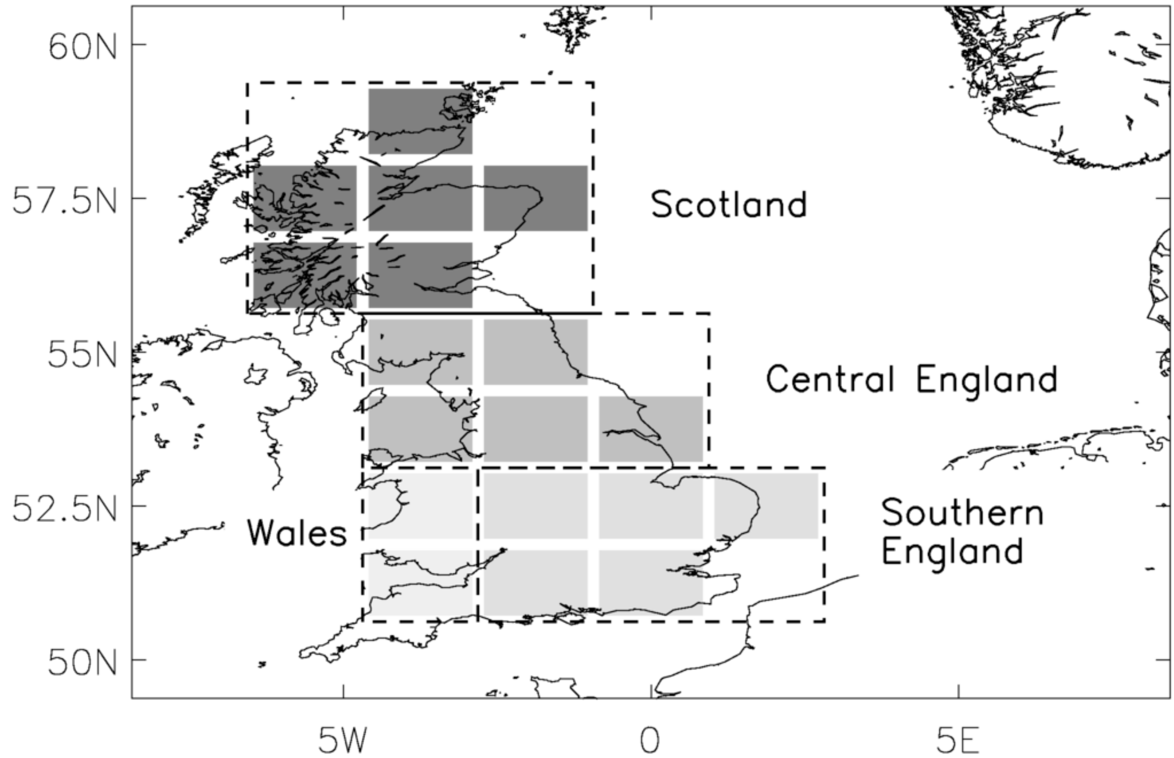

Figure 2. GB land grid boxes at the resolution of the HadGEM2 global climate model. Analogues were found separately for each box, and then the analogues for Scotland (dark grey), Central England (medium grey), southern England (light grey) and Wales (pale grey) were amalgamated.

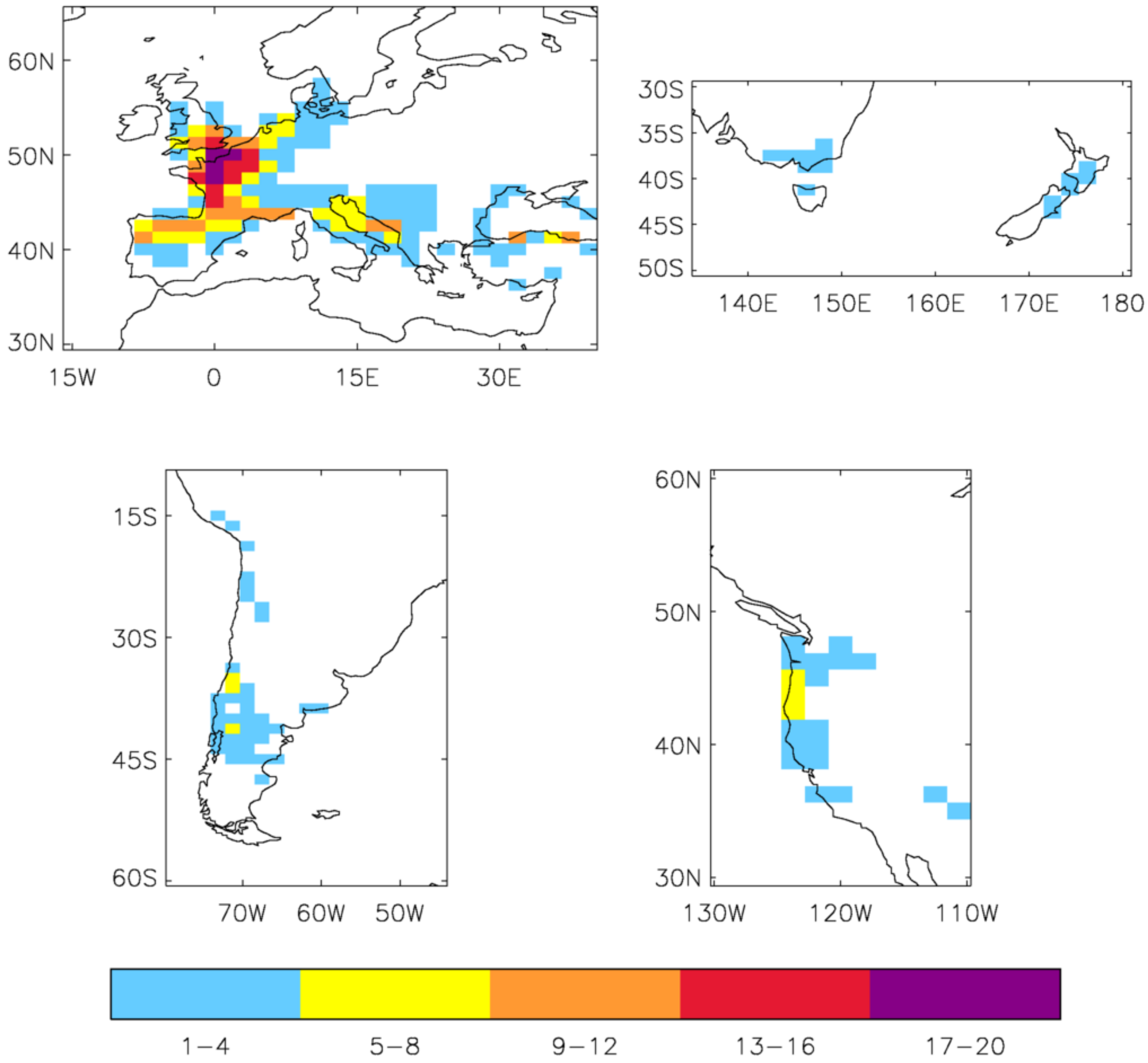

Figure 2. Level of agreement for analogue locations for south-east England. Locations with scores close to the total number of models (13-20), shown in red and purple, are identified as analogues by most models. Locations in blue and yellow are identified by fewer models.

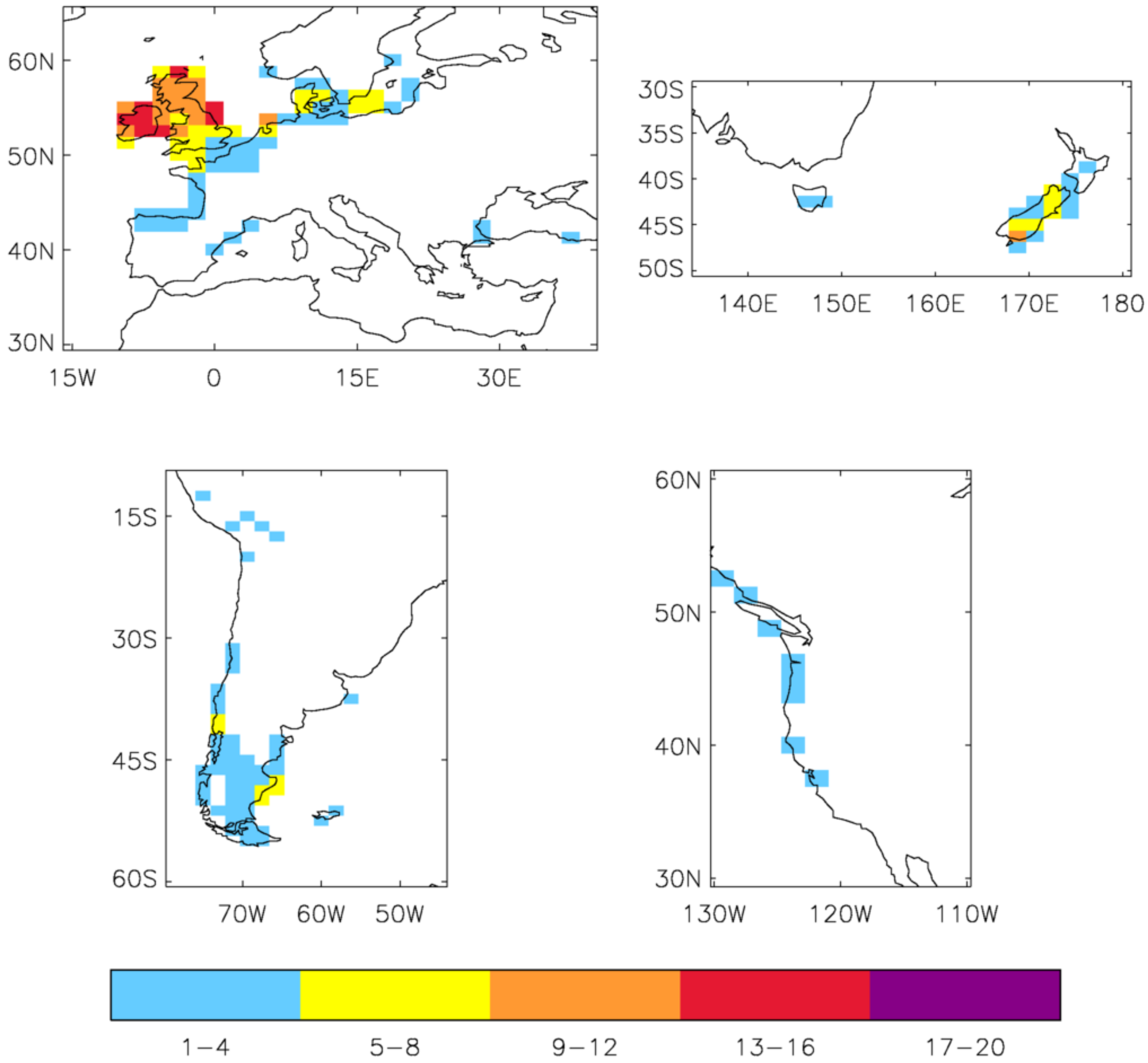

Figure 3. Level of agreement for analogue locations for north-east Scotland. Locations with scores close to the total number of models (13-20), shown in red and purple, are identified as analogues by most models. Locations in blue and yellow are identified by fewer models.