



Deposited via The University of York.

White Rose Research Online URL for this paper:

<https://eprints.whiterose.ac.uk/id/eprint/108422/>

Version: Published Version

Article:

Dawson, David, Shaw, Jon and Gehrels, Willem Roland (2016) Sea-level rise impacts on transport infrastructure: the notorious case of the coastal railway line at Dawlish, England. *Journal of Transport Geography*.

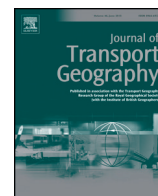
<https://doi.org/10.1016/j.jtrangeo.2015.11.009>

Reuse

This article is distributed under the terms of the Creative Commons Attribution-NonCommercial-NoDerivs (CC BY-NC-ND) licence. This licence only allows you to download this work and share it with others as long as you credit the authors, but you can't change the article in any way or use it commercially. More information and the full terms of the licence here: <https://creativecommons.org/licenses/>

Takedown

If you consider content in White Rose Research Online to be in breach of UK law, please notify us by emailing eprints@whiterose.ac.uk including the URL of the record and the reason for the withdrawal request.



Sea-level rise impacts on transport infrastructure: The notorious case of the coastal railway line at Dawlish, England



David Dawson^{a,*}, Jon Shaw^b, W. Roland Gehrels^c

^a School of Civil Engineering, University of Leeds, Leeds LS2 9JT, UK

^b School of Geography, Earth and Environmental Sciences, Plymouth University, Drake Circus, Plymouth PL4 8AA, UK

^c Environment Department, University of York, Heslington, York, YO10 5DD, UK

ARTICLE INFO

Article history:

Received 29 June 2015

Received in revised form 14 November 2015

Accepted 28 November 2015

Available online xxx

Keywords:

Climate change

Adaptation

Resilience

Semi-empirical

Rail network

Economic impact

ABSTRACT

Future climate change is likely to increase the frequency of coastal storms and floods, with major consequences for coastal transport infrastructure. This paper assesses the extent to which projected sea-level rise is likely to impact upon the functioning of the Dawlish to Teignmouth stretch of the London to Penzance railway line, in England. Using a semi-empirical modelling approach, we identify a relationship between sea-level change and rail incidents over the last 150 years and then use model-based sea-level predictions to extrapolate this relationship into the future. We find that days with line restrictions (DLRs) look set to increase by up to 1170%, to as many as 84–120 per year, by 2100 in a high sea-level rise scenario (0.55–0.81 m). Increased costs to the railway industry deriving from maintenance and line restrictions will be small (£ millions) in comparison with damage caused by individual extreme events (£10s of millions), while the costs of diversion of the railway are higher still (£100s of millions to billions). Socio-economic costs to the region are likely to be significant although they are more difficult to estimate accurately. Finally, we explain how our methodology is applicable to vulnerable coastal transport infrastructure worldwide.

© 2015 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

1. Introduction

There has been much discussion about the impacts of climate change on a variety of sectors and debate on how to model and measure these impacts (Bosello and De Cian, 2014), but comparatively little research has been conducted into the potential impacts of climate change on the functioning of transport systems (Koetse and Rietveld, 2009; Jaroszweski et al., 2010; Jaroszweski and McNamara, 2014; see also Ryley and Chapman, 2012). In the UK, for example, only recently have the government and other key bodies begun seriously to acknowledge the importance of resilient transport infrastructure in the face of future climate and weather-related threats (HM Government, 2011; Department for Transport, 2011, 2014a; ICE, 2009; RSSB, 2010; Highways Agency, 2011; Network Rail, 2014a). Hooper and Chapman (2012: 106) argue that in addition to studies focusing on how the transport sector can assist in mitigating the effects of climate change, largely by reducing carbon emissions (see Chapman, 2007; Banister et al., 2012), the “impacts of climate change on transport networks need careful consideration to allow the networks to continue operating effectively in the future.” In other words, a focus on adaptation as well as mitigation is important.

Jaroszweski et al. (2010) list seven causes of disruption to transport systems linked to climate change. Six mainly relate to inland areas (an increased number of hot days, fewer cold days, more heavy precipitation, seasonal changes, drought and a higher number of extreme events), but sea-level change is identified, unsurprisingly, as problematic for coastal zones. Indeed, Hooper and Chapman (2012) suggest that the threat of flooding from sea-level rise combined with that from more extreme precipitation events renders coastal transport infrastructure more at risk than its equivalent inland. It is thought that climate change could bring about a global sea-level rise of as much as 0.97 m by 2100, through processes of thermal expansion and the melting of ice caps (Church et al., 2013). The threat of coastal flooding will increase significantly, not least because of the increase in the occurrence of extreme water levels when strong winds and low atmospheric pressure combine to produce storm surges. Especially when coupled with high tides, the effects of such surges can be devastating (Haigh et al., 2010); the United Kingdom's North Sea coast, for example, experienced in the winter of 2013/2014 its highest recorded storm surges since 1953, reaching over 2 m above the predicted high tide and causing widespread damage and disruption in the east of England (BBC, 2013a; National Oceanographic Centre (NOC), 2014a; Huntingford et al., 2014). In the southwest of England, the Newlyn tide gauge recorded its highest ever water level on 3 February 2014 (Wadey et al., 2014). Globally, the potential impact of sea-level rise is hugely significant (Seneviratne et al., 2012), with 13 of the world's 20 ‘megacities’ (cities

* Corresponding author.

E-mail address: d.a.dawson@leeds.ac.uk (D. Dawson).

with populations exceeding eight million) situated on the coast (Nicholls et al., 2008) and transport infrastructure including ports, airports road and rail links all under threat. Evidence from the United States identifies the potential impacts on the transport infrastructure of Boston (e.g., Suarez et al., 2005), New York (e.g., Zimmerman, 2002; Jacob et al., 2007) and several other low lying regions of the eastern seaboard (Titus, 2002) as well as transport corridors along the Pacific coast of California (Heberger et al., 2009). Coastal transport routes in low-lying areas of northwest Europe (European Environment Agency, 2014) are also at risk.

Notwithstanding an increasing interest in sustainable 'soft' measures such as cliff stabilisation, dune regeneration, beach nourishment and coastal realignment (Department of Environment, Food and Rural Affairs, 2005), hard-engineered sea defences such as sea walls, rock armour and breakwaters have typically been built to protect coastal communities and services (Arns et al., 2013; Nicholls et al., 2013). In the British context, it is estimated that coastal defence structures protect around 1200 km – roughly one third – of the English and Welsh coastlines, with a particular concentration in southern England (Environment Agency, 1999; Hall et al., 2006; de la Vega-Leinert and Nicholls, 2008). Defence structures are built to a design standard based on the statistical return period of extreme water levels – 1 in 50 years, 1 in 200 years, etc. – but it is estimated that even small changes in sea level, of the order of centimetres, can have a significant effect on these return periods and the future probability of coastal flooding (Dixon and Tawn, 1995; Gehrels, 2006; Church et al., 2008; Haigh et al., 2011). It is thus unsurprising that future sea-level projections provide an important tool for strategic coastal planning (Hall et al., 2006; Nicholls et al., 2013). The most recent published projections of regional sea-level change are found in *UKCP09 Science Report: Marine and Coastal Projections* (Lowe et al., 2009) and are derived from model-based forecasts of changes in mean sea level and storminess. They also include a component of land subsidence or uplift, creating a spatial pattern of relative sea-level rise projections for the UK that are a reflection of the UK's glacial history (Shennan and Horton, 2002): the southwest of England, which is sinking at a rate of 1.1 mm/yr due to ongoing glacio-isostatic adjustment (GIA), will experience the highest rates of relative sea-level rise during this century (Gehrels et al., 2011).

The potential for disruption to transport infrastructure and the services it supports is of particular concern in countries like the UK that have under-invested in their transport operations for many decades (see Shaw and Docherty, 2014). This has been well illustrated by several recent incidents when sections of the railway network were forced to close for weeks after embankments and cuttings became damaged after heavy rain (e.g., Network Rail (NR), 2015). Perhaps most famously, winter storms in 2014 breached the sea wall in several places along a coastal stretch of the London to Penzance railway line at Dawlish, in Devon, leaving the railway tracks completely unsupported (Fig. 1) and closing the line for 2 months (Network Rail, 2014b). The importance of reliable transport (and, for that matter, other) infrastructure to socio-economic activity is not in doubt (Eddington, 2006): rail patronage in the far southwest of England has grown around 90% since 2004, strong future growth is expected (Network Rail, 2014c) and the line is seen as increasingly important for the region's seasonal tourist 'boom' upon which the economy heavily relies. Very quickly estimates of how much this breach cost the local economy began to emerge (House of Commons, 2014a, 2014b; PCCI, 2014). In reality a precise figure is not known (Marsden, 2014), but the impression given of a region 'cutoff' from the rest of the country was all too keenly felt (witness the #openforbusiness campaign on Twitter). As Ryley and Chapman (2012) note, climate change is a global phenomenon, but its impacts are often felt locally.

It is in this context that we aim to estimate the likely impact of sea-level change on the Dawlish stretch of the London to Penzance railway line. In so doing, we draw upon results derived from a study designed specifically to combine human and physical geography approaches, and to engage regional and national stakeholders in the production of

policy-relevant discussions and conclusions (Dawson, 2012). We have already published the data on which our sea-level projections are based (Gehrels et al., 2011), and here we consider the extent to which these projections are likely to impact upon the functioning of the line. The paper proceeds as follows. In the next section, we provide details of the study site, including a history of overtopping events along the Dawlish to Teignmouth sea front. Section three outlines the methodological approach we adopted and discusses the nature of the empirical relationship we identify between sea-level rise and historic rail incidents. In sections four and five, we estimate how and the extent to which the line will be disrupted during the remainder of the 21st century and consider the potential costs of these disruptions to both the railway industry and the region more broadly. A conclusion discussing the wider implications of both our findings and our methodology brings the paper to a close.

2. Rails along the sea wall

The London–Penzance railway links England's southwest peninsular counties of Cornwall, Devon and Somerset with the UK capital and connects at Taunton with lines to elsewhere in Great Britain. In Devon and Cornwall, a number of branch lines link with coastal resorts and other towns, and several freight-only lines also serve the region. The 6.4 km stretch between Dawlish and Teignmouth (Fig. 2) has been susceptible to frequent closure during high seas and storm events ever since it was built (see Kay (1993) for a complete history). The line, designed by I.K. Brunel who was Engineer to the Great Western and the Bristol and Exeter Railway, opened on 30 May 1846. On 5 October of that same year, breaches to the sea wall were reported and the line was closed, and as in 2014, the track was left hanging in mid-air. Third class passengers not protected by windows were "soaked to the skin", and Dawlish residents "thronged the Marine Parade at high tide to see the majestic mountains of foam thrown up against the wall" (*The Times*, 1846, p5). A temporary fix was achieved using green fir branches laid on top of the remains of the wall, but in contrast to the 2014 incident, the line reopened on 7 October after a blockage of just over 2 days (Kay, 1993).

Records indicate that major line closures or blockages typically occur around every 10 years (Dawson, 2012), but this is not to say that smaller events do not also cause problems. Table 1 summarises the typical damage associated with events categorised by severity. Some of the more severe damage over the years has taken a variety of forms. In February 1974, for example, the *Western Morning News* (1974) reported that the track was in ruins and the eastern end of the Dawlish Station platform was unusable for weeks. An incident on 27 October 2004 shut the 'down line' (i.e., the westbound track that takes trains away from London) for around 5 days. Reports noted that there was over a foot of standing water on the track bed and that boats had drifted across the line where it runs along the Exe estuary, just north of Dawlish Warren (*The Times*, 2004). The longest period of closure – exactly 2 months – was brought about by the winter storms of 2014. Interestingly, recent problems have extended to the rolling stock as well as the infrastructure. Voyager trains introduced in the early 2000s experience technical faults and shut downs due to system failures associated with saltwater intrusion (*The Mirror*, 2002). As of 2010, the Voyagers no longer run along the line during heavy seas (Network Rail, 2009), and this results in disruption for rail passengers having to transfer onto older rolling stock run by Great Western Railway.

The majority of overtopping events causing damage to infrastructure have taken place at the most exposed section of line at King Harry's Walk, Dawlish, where top of the sea defences are only 4.9 m above Ordnance Datum (Figs. 2 and 3). NR's typical response to the threat of incoming storms is to restrict train services and use of the track depending on the severity of event. Track restrictions run from Level 1 to Level 3 and have a range of impacts on rail traffic from 20mph (32kph) speed restrictions on the down line to full closure of both the up and the down lines until safety inspections (and any necessary

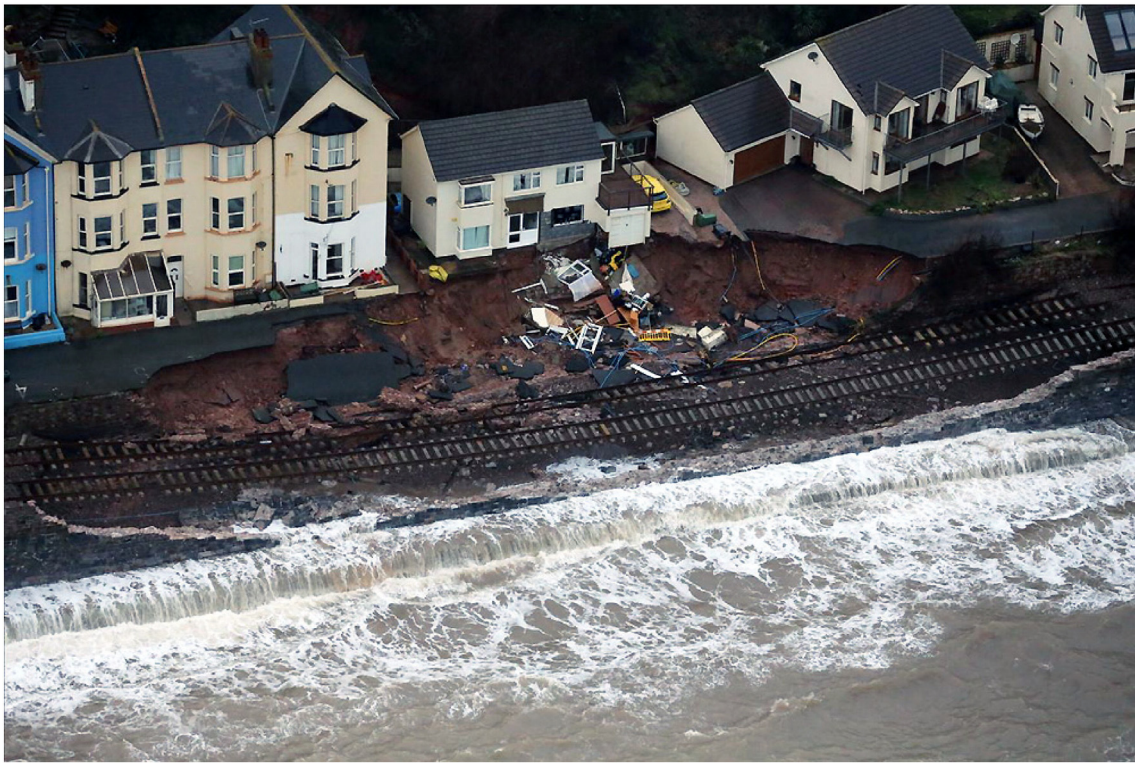


Fig. 1. The breach in the sea wall near King Harry's Walk at Dawlish, Devon, on 7 February 2014 (see Fig. 2 for map). The damage was caused by gales and high seas on 4 February, and the railway track was left hanging over the breach. Source: Network Rail, 2014d.

remedial works) have been completed (Table 1). In-sea sensors provide information to NR staff in advance of severe overtopping events in order to allow them to close the line before it becomes dangerous to passing rail traffic. The events of February 2014 amounted to a spectacular example of a Level 3 restriction, when the in-sea sensors returned the most extreme warning possible, a 'black alert' (Hogg, 2014).

The track immediately to the east and west of the Dawlish–Teignmouth section is less exposed to the effects of the open sea, but it is low-lying (see Fig. 3 profile) and as such susceptible to its own problems of inundation, as tales of standing water and boats appearing on the line attest. Planning for the long-term future of the line is complicated owing to potential conflicts of interest between the three agencies responsible for its protection. NR is responsible for the 6.8 km of frontage from Teignmouth to Langstone Rock, but defences immediately to the southwest are managed by Teignbridge District Council while those just to the northeast, including Dawlish Warren, fall under the purview of the Environment Agency. Despite the obvious threat from sea-level rise, a climate scoping study produced on behalf of the (now defunct) South West Regional Development Agency stated that much of the transport sector in southwest England had not yet adequately responded to climate change (Metcalfe et al., 2003; ICE, 2009), and indeed the issue is still under debate (House of Commons, 2014a, 2014b); one of the enduring characteristics of multi-agency governance has been the apparent inability of key regional stakeholders to coalesce around a coherent approach to the problem. The February 2014 storms appear to have forced some progress in this regard (Plymouth City Council, 2014).

3. Methods and data: a 'semi-empirical' modelling approach

Numerous parameters influence the overtopping of defence structures – wave processes, hydrological processes, storminess, geometric designs, structure materials, etc. – but these are complex and can be difficult to model accurately, particularly over long time scales. Attempts at modelling have been made (in the case of the Dawlish sea wall by O'Breasail et al., 2007), although they often inherit fundamental and statistical

uncertainties from the random processes of nature. While such uncertainties can be reduced by, for example, increasing and improving the data and refining the models, they can never be completely removed (Pullen et al., 2007; Williams et al., 2014). As an alternative to relying solely on numerical modelling, some scientists have developed a 'semi-empirical' modelling approach whereby historical observations are used to determine a relationship between variables before extrapolations of this relationship are made by drawing upon related numerical models. A good example is Rahmstorf's (2007) work that circumvents the use of complex and incomplete process-based sea-level models by instead finding a historical relationship between temperature and sea-level rise, and applying this to IPCC predictions of future global temperature to derive global sea-level estimates for the year 2100. (In justifying this approach, Rahmstorf (2007) draws an interesting parallel with tidal predictions, which are essentially based on 'experience', because calculations from first principles are too complex and provide results that are less accurate.) Since the work by Rahmstorf (2007), several other semi-empirical studies on future sea-level changes have been published (e.g., Vermeer and Rahmstorf, 2009; Grinsted et al., 2010; Bittermann et al., 2013; see also Church et al., 2013). Another example of this type of approach is Challinor et al.'s (2009) study on the impacts of climate change on crops.

In this study, we assume that the underlying driver of change in overtopping frequency and thus transport disruption is sea-level rise, and thus for the first, empirical, stage of the work, we seek to establish from observations a relationship between overtopping and sea-level change. This is not to say that we overlook the role of other drivers: storm intensity, storm frequency and low air pressure all lead to extreme sea levels which ultimately are responsible for damaging the railway. But it is long-term mean sea-level change that acts as a 'baseline' for the upward trend in extreme water levels (Woodworth and Blackman, 2004), and this upward trend increases the likelihood of storm-induced overtopping even if storm activity remains constant. The second, model-based, stage of our work combines the empirical relationship between historical sea-level trends and transport disruptions with the modelled projections of future sea-level rise (Lowe et al., 2009)

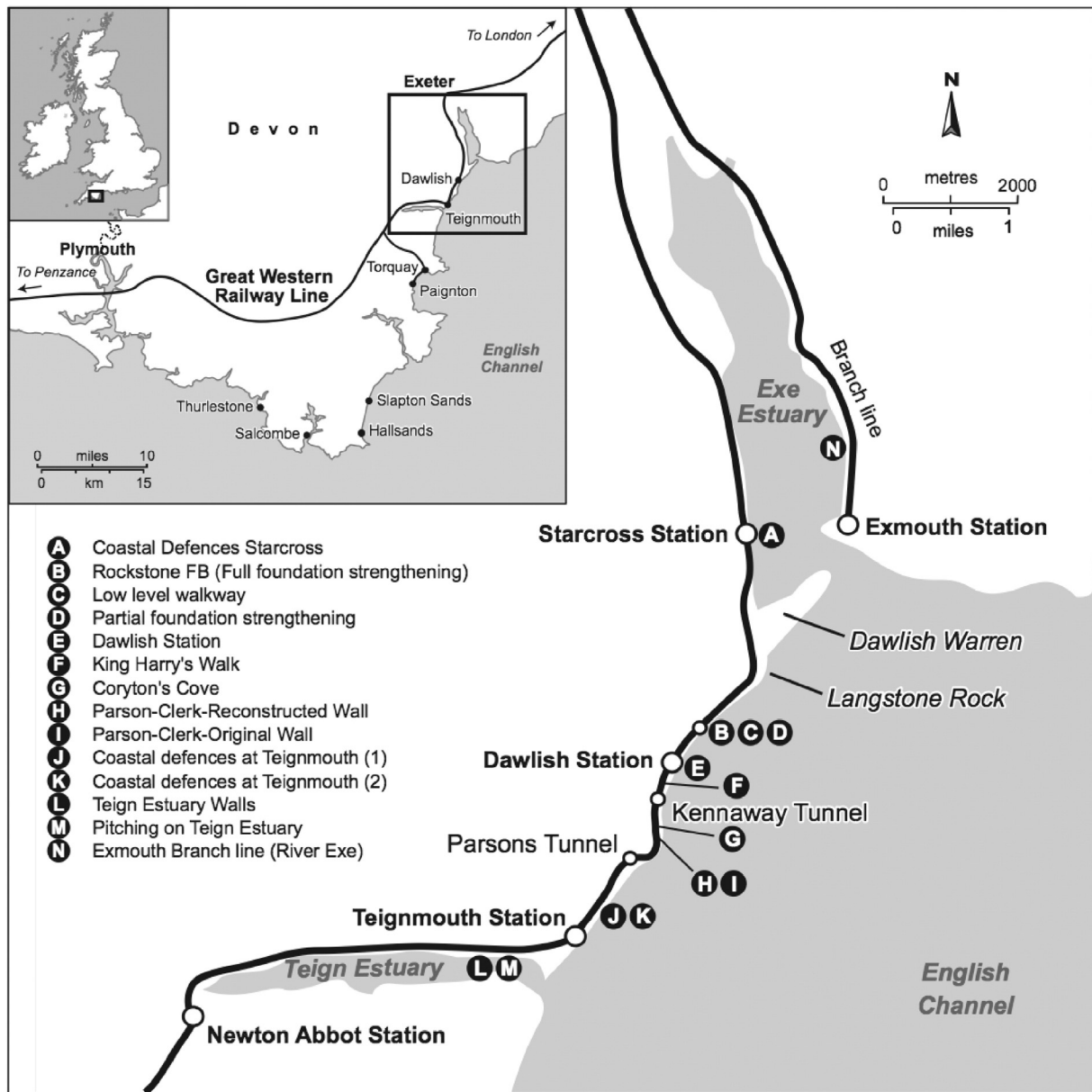


Fig. 2. Location of the Dawlish–Teignmouth section of the London to Penzance railway line. The section of line between Langstone Rock (location B) and King Harry's Walk (location F) is particularly susceptible to closure during high tides and storm events. Source of defences' locations (A–N): Rogers and O'Breasail (2006).

to calculate transport disruption in the future. In parallel with Rahmstorf (2007), therefore, our approach is partly based on observable 'experience' and partly on existing numerical model predictions. We compare our results with those presented in O'Breasail et al.'s (2007) fully model-based study later in the paper.

3.1. Sea-level change and historical service disruptions

Tide-gauge stations recording hourly changes in mean sea level (MSL) in the English Channel have produced some of the longest instrumental sea-level records available worldwide (Woodworth, 1987). Our MSL records were taken from stations at Brest and Newlyn (downloaded from the Permanent Service for Mean Sea Level at www.psmsl.org.uk/data/obtaining), which in combination provide a continuous record from 1861.¹ We used the Brest tide gauge from

¹ The Brest records actually date from 1711 (Wöppelmann et al., 2008) but are broken in places and the Newlyn records start in 1916.

1861 (data are missing from when the line opened in 1846 up until this point) until 1916, from which point the Newlyn tide gauge was relied upon as it provides a more continuous and proximal record.² Records from Newlyn and Brest correlate well since 1944, but an offset of ~2 cm is found for the period 1916–1943. The cause of this offset is unknown (Wöppelmann et al., 2008), but it has no bearing on the results of our paper because the relationship between sea-level rise and service disruptions is not significantly positive until after 1975 (see below). Data were smoothed by calculating central moving averages over 20-year periods (in alignment with the lunar nodal cycle) to remove fluctuations of annual sea-level change and allow a clearer trend of MSL to be determined.

We constructed a history of overtopping-related line disruptions (Dawson, 2012) based on accounts from local and regional newspapers

² Devonport (Plymouth) has the closest continuous recording tide-gauge station to the railway, but it dates only from 1964 and is somewhat fragmented, and in any case factoring in this record has a minimal effect on results.

Table 1

Categorisation of archive of impacts recorded including Network Rail's current adverse weather protocol and the recorded impacts to passenger services during these events. Based on data from 2000 to 2009. ESR = emergency speed restriction; HST = high-speed train; GWR = great western railway. Sources: Network Rail (2009); Rogers and O'Breasail (2006) and Dawson (2012).

Impact type	Track restriction	Duration	Description	Network Rail protocol	Recorded impacts to traffic
Low	Level 1	High tide (2 h either side)	<ul style="list-style-type: none"> Localised damage Masonry damage to defences (cracks and fractures) Coping stones removed 	<ul style="list-style-type: none"> 20 mph emergency speed restriction (ESR) on down line CrossCountry class 220/221 services on watch and likely to be suspended between Newton Abbot and Exeter Local stopping services thinned Up line working only CrossCountry and Voyagers suspended (bus service only) Maximum line capacity 6 trains p/h, and reduced to 3 if ESR imposed on whole track Emergency timetable imposed 1 × HST service each way per hour and 1 × GWR local sprinter each way per hour All class 1s stop at Newton Abbot Exeter-Paignton services withdrawn, similarly Exmouth and Barnstaple No services between Exeter and Newton Abbot Line will re-open as Level 2 Both line will remain closed until inspection has been completed 	<ul style="list-style-type: none"> Delays to all services between 5 and 20 min Class 2 services cancelled <45 trains affected Voyager halted (level 2) and train evacuation needed
Medium	Level 2	High tide (2 h either side)	<ul style="list-style-type: none"> Multiple damage Ballast washout Substantial lengths of copings removed or loosened Beach material removed (foundations exposed) Damage to groynes and breakwaters 	<ul style="list-style-type: none"> Emergency timetable imposed 1 × HST service each way per hour and 1 × GWR local sprinter each way per hour All class 1s stop at Newton Abbot Exeter-Paignton services withdrawn, similarly Exmouth and Barnstaple No services between Exeter and Newton Abbot Line will re-open as Level 2 Both line will remain closed until inspection has been completed 	<ul style="list-style-type: none"> Class 2 services severely affected Services up to 15–50 min late Up to 80 trains delayed 45 trains services cancelled Trains hit by objects, windscreens smashed
High	Level 3	Several high/low tides	<ul style="list-style-type: none"> Multiple breaches and flooding (substantial lengths) Large masonry damage and copings washed away (<6 m) Large cavities in sea wall and retaining walls (<3 m) Damage to the foundations and toe of the defence Subsidence or depressions of the track Dawlish station platform overtopped Complete destruction of the line (e.g., 1846 and 2014) All of the above damage (for multiple days) Extensive beach material removed Multiple voiding in wall and track (~30 m) Severe undermining of the foundations Top sections of wall washed away Dawlish station roof and platform lifted off Severe damage to breakwaters/walkways/footpaths (demolished) Wider rail damage—Starcross, Teignmouth, Paignton, Looe and Penzance 	<ul style="list-style-type: none"> Level 3 until line and defences have been inspected and repaired as needed 	<ul style="list-style-type: none"> Class 2 services cancelled Voyagers stranded >80 trains affected, of which 20 were Class 1 Typical Plymouth-Paddington service one hour late
Severe	Level 3 (cont)	Several high/low tides	<ul style="list-style-type: none"> Complete destruction of the line (e.g., 1846 and 2014) All of the above damage (for multiple days) Extensive beach material removed Multiple voiding in wall and track (~30 m) Severe undermining of the foundations Top sections of wall washed away Dawlish station roof and platform lifted off Severe damage to breakwaters/walkways/footpaths (demolished) Wider rail damage—Starcross, Teignmouth, Paignton, Looe and Penzance 	<ul style="list-style-type: none"> Level 3 until line and defences have been inspected and repaired as needed 	<ul style="list-style-type: none"> No services between Exeter and Newton Abbott. 134 daily services cancelled Replacement bus services adding an estimated one hour to journey times.

and literature, local and national libraries and rail historians, augmented with annual records of maintenance intervention (Rogers and O'Breasail, 2006). Two fragmented records were generated (Fig. 4), and although they cannot be combined because of the different reporting standards used in each archive, they do provide an empirical baseline of incidents. The findings were analysed and cross-referenced to produce as consistent and reliable a record as possible of all the known days of overtoppings and restrictions, which we refer to as days with known line restrictions (DLRs), during the period 1846–2010. Restrictions due to planned maintenance were not included in the analysis.

By comparing the sea-level records with a history of service restrictions associated with overtopping events, empirical trends between rising sea levels and rail problems over the last century and a half can be observed (Fig. 5a). During the lifetime of the railway, there has been ~0.20 m of sea-level rise in the English Channel, although nearly half of this occurred during the last 40 years (Haigh et al., 2009). The highest number of recorded DLRs has been in the last three decades. Plotting the 20-year moving annual average of DLRs against the average MSL height in the English Channel highlights two distinct periods (Fig. 5b). The first is between 1860 and 1975 and shows a fluctuating relationship with no clear trend, suggesting that sea-level change had little, or no, effect on the number of incidents. The second period, post 1975, is marked by a

clear inflection (or 'tipping point'). For sea levels higher than 7050 mm above Chart Datum,³ the linear trend between average DLRs per year and MSL is significantly positive.

We should of course acknowledge that other explanations could also account for the observed change in trend. One would be an increase in storm activity. Feser et al. (2015) concluded that there is evidence for an increase in storm activity over the North Atlantic from the 1970s to the mid-1990s, but only north of 55–60°N and not beyond the mid-1990s. Alexander et al. (2005) found an increase in storm intensity for the southern UK between 1959–1982 and 1983–2003 that was statistically significant. Long-term trends appear to be associated with decadal fluctuations of the winter North Atlantic Oscillation (NAO) index (Feser et al., 2015; Allan et al., 2009), however, and so although storminess may be a contributing factor for disruptions in the 1980s and 1990s, it cannot explain the sharp increase in railway line disruptions we observe from the mid-1970s until the present day. Indeed, Hanna et al. (2008) noted that storm activity in the Channel Islands peaked around 1980, while Zong and Tooley (2003) actually noted a decrease in the frequency of coastal floods in SW Britain since the 1950s.

³ Approximately the level of the lowest astronomical tide; in Newlyn Chart Datum is 3.05 m below Ordnance Datum.

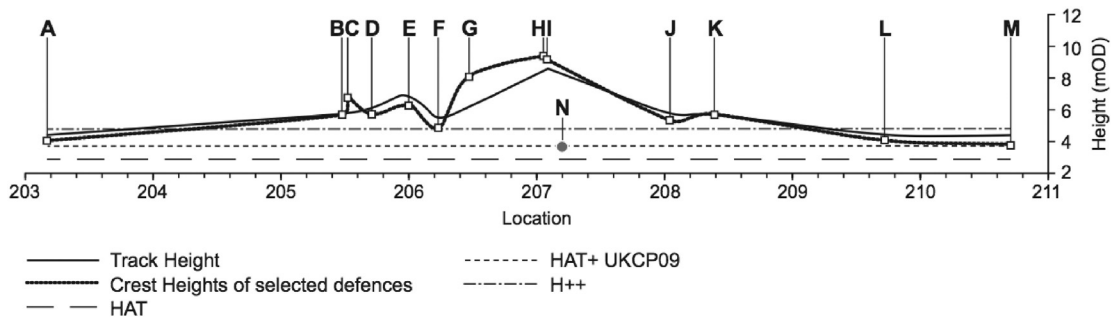


Fig. 3. Elevation profile (in metres relative to Ordnance Datum) of the Dawlish–Teignmouth section of the London to Penzance railway line (in chainage). Locations (A–M) correspond with Fig. 2. Crest heights have been compared with the current highest astronomical tide (HAT) and the UK Climate Impact Programme’s sea-level estimates (high & H++) for 2100 (Lowe et al., 2009).

Other explanations may include changes in coastal protection measures. Since the 1970s, there have been significant changes in national management approaches, such as less hard engineering, and a reduction in expenditure on coastal defences (French, 2004), although specific details of the long-term annual expenditure on the defences at Dawlish were not obtainable. It nevertheless remains that the height of the water level today is closer to the crest of the defences than has ever

been recorded: 150 years of sea-level rise has significantly reduced the available ‘freeboard’ (i.e., height of the crest of the defences above the water level) along the sea wall, allowing for more frequent overtopping events. In 2009, mean sea level at Newlyn based on smoothed trends was around 7100 mm above Chart Datum, and there is a 20-year moving annual average of around three DLRs per year. The analysis indicates that from 1975 to 2009 a 0.05 m rise in water

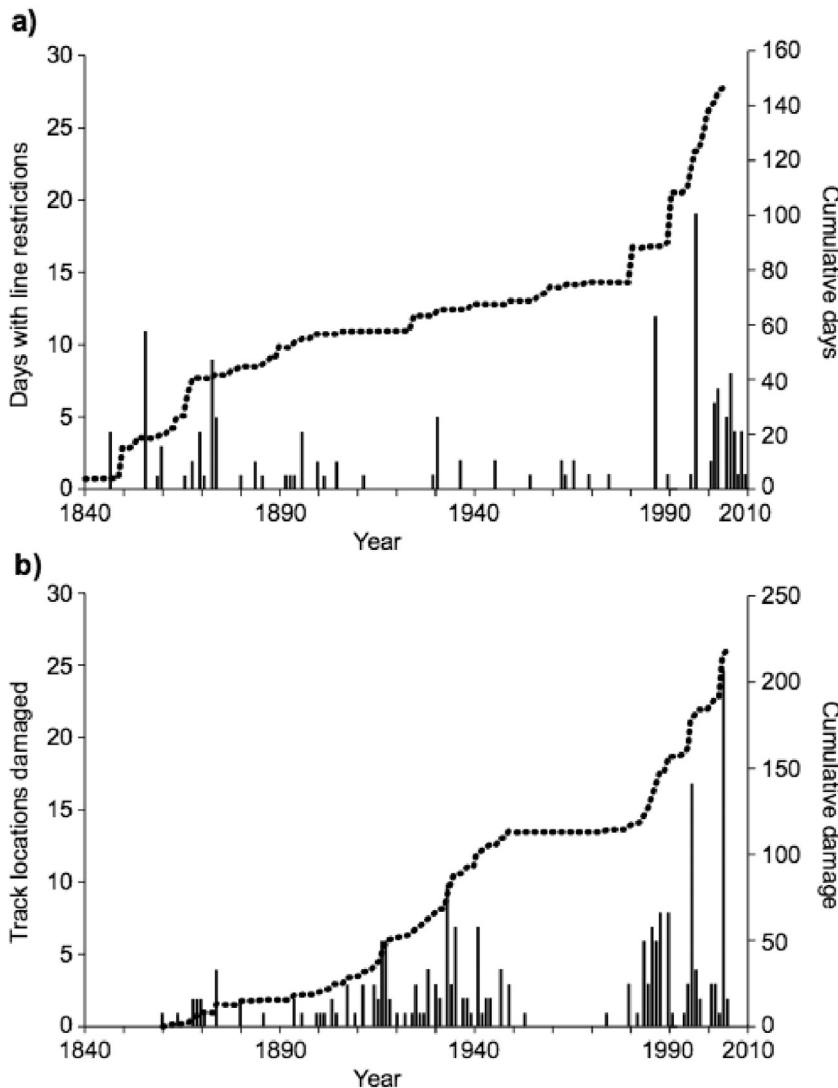


Fig. 4. Archival history of the Dawlish–Teignmouth railway line: (a) Published accounts of known days of line restrictions; (b) Network Rail’s frontage history record of locations recording damage (annually). Dotted lines represent the cumulative totals of incidents. Source: Dawson (2012).

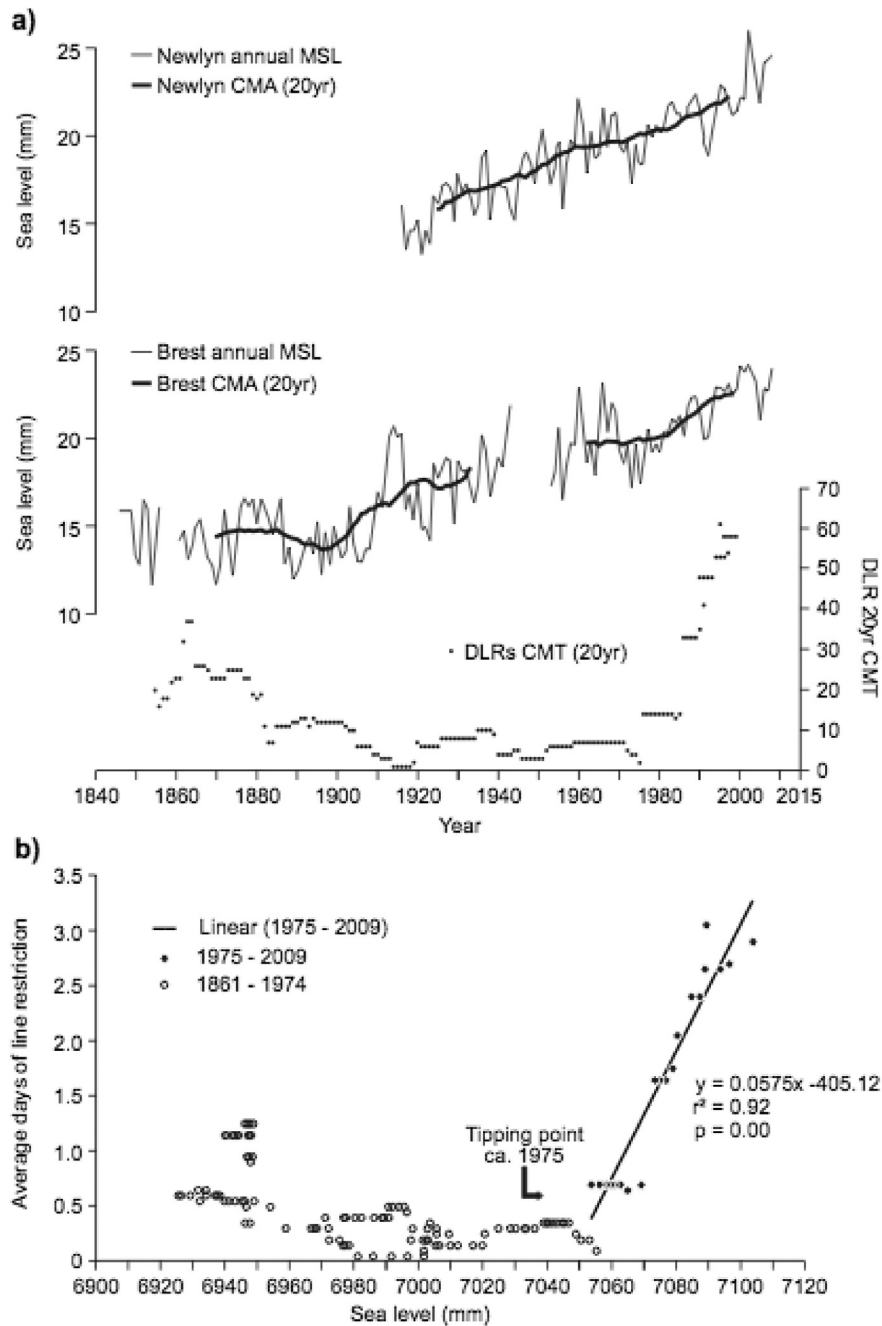


Fig. 5. (a) English Channel sea-level observations from tide gauges, including smoothed running average and compared with Days of known Line Restrictions (DLRs). DLRs presented as a smoothed 20-year central moving total. (b) Correlation of sea-level change and DLRs from 1861 to 2009. Source: Dawson (2012).

level occurred while the average number of DLRs per year quadrupled from 0.7 to 2.9.

3.2. Extrapolating into the future

In our analysis, we use the relationship identified between sea-level rise and DLRs per year for the period 1975–2009 as the basis from which to extrapolate estimates of the potential number of DLRs along the Dawlish–Teignmouth stretch of railway for the remainder of the century. Such an approach is open to challenge, but it provides a reasonable starting point for policy discussion given how quickly sea level has risen in the last 40 years and how significantly the average number of DLRs per year has increased since the ‘tipping point’ of 1975. Before any such extrapolation could be attempted; however, it was necessary

to calibrate our base data in two ways. First, in comparing our archival database against NR’s relatively recently devised TRUST delay attribution system (Fig. 6), the former appears to under-report. This is because it relies predominantly on newspaper articles – disruptions are only picked up where they were significant enough to warrant recording in print – rather than actual recordings of real-time delay information. The discrepancy is quite marked, with NR’s data showing an average of ~9.5 DLRs per year over the period 1997–2009, as opposed to an average of ~4.0 in the archival dataset when the trend line in Fig. 5b is extended to accord with the average MSL of 7115 mm over the same period. Since NR’s TRUST data are based on actual running information, and because the railway industry uses this currency to record delay events, we have applied a multiplier of 2.4 to adjust the figures in the archival database. This allows the recent records of incidents actually

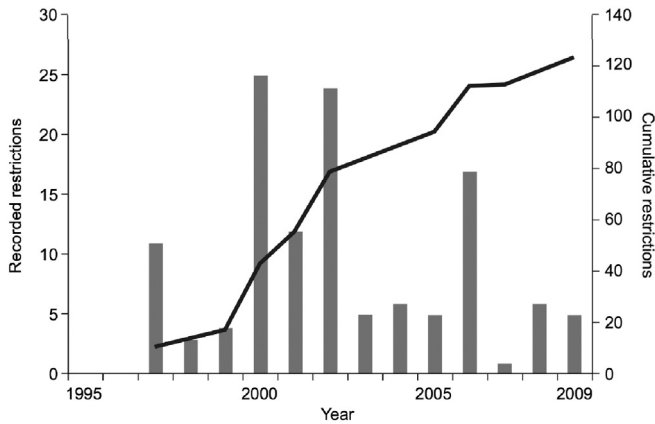


Fig. 6. Network Rail's TRUST service data (1997–2009): record of days with line restrictions. Dotted line represents the cumulative total of restrictions.

recorded on the line to be factored into the analysis. The multiplier is derived from dividing the 1997–2009 average NR value (9.5) by the average DLRs per year recorded over the same period in the archives (4.0).

Second, we updated existing sea-level predictions (Lowe et al., 2009) by collecting new geological evidence (published in Gehrels et al., 2011). The new data showed that the GIA model used for UK sea-level predictions underestimated the coastal subsidence rate by 14% (~0.16 mm/yr), implying an additional relative sea-level rise of 0.015 m by 2100 compared to values predicted by UK Climate Projections 2009 (UKCP 09) (Lowe et al., 2009) in its low, medium and high emissions scenarios. We have thus adjusted 21st century sea-level predictions to account for the additional sea-level rise. With these calibrations, we are better placed to extrapolate the relationships between sea-level rise and average DLRs per year, although the results presented remain inherently linked to current sea-level change predictions – and are therefore subject to change in light of future updated / anticipated estimates – as well as the assumptions described above about the nature of the relationship between MSL and DLRs per year.

4. Future line restrictions

In Fig. 7, we extrapolate the relationship between sea-level change and average number of DLRs per year from 2010 until 2100, showing the differing impact of the UK Climate Impact Programme's (UKCIP's) adjusted low, medium and high emissions predictions. Table 2 presents

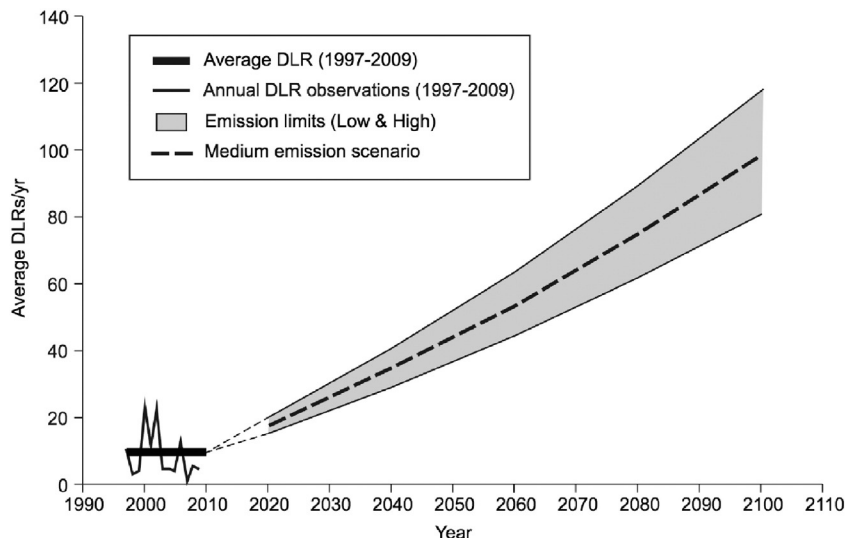


Fig. 7. Projections of average number of days with line restrictions (DLRs).

the data in more detail, breaking down the type of restriction into NR's Level 1 to Level 3 categories, again for each of UKCIP's scenarios. In deriving this detail, we have assumed the same percentages of warning level occurrences as recorded in NR's TRUST database between 1997 and 2009, although should future climate change result in the more frequent occurrence of stormy conditions later in the 21st century (see Lowe et al., 2009; Slingo et al., 2014), the balance between each of the categories could change. There might, for example, be more Level 3 episodes than we suggest here.

The 1997–2009 TRUST data indicate that an average of around five Level 1 (speed restrictions) and four Level 2 (down line closures) alerts occur each year, while Level 3 (total line closures) alerts occur once every 3 to 4 years. If our calculations are correct, and assuming sufficient maintenance to retain sea defences in their current condition, then in headline terms: sea-level rise of 0.05–0.07 m by 2020 means the average number of DLRs will double to 16–19 per year; by 2060, sea-level rise of 0.27–0.39 m will cause an annual average of 46–63 DLRs; and by the end of the century as many as 84–120 DLRs will occur each year as a result of a 0.55–0.81 m increase in sea level. This is more than five times the maximum number of annual DLRs recorded at any point in our archival database.

It is worth highlighting in more detail the extent of the impacts that could occur under the high emissions scenario. By 2020, we estimate that Level 1 restrictions will occur ten times per year on average, while Level 2 alerts could be expected 8.4 times per year and Level 3 alerts would affect the line biennially. By 2060, an average of around 34 Level 1 alerts and 28 Level 2 alerts will occur annually, and Level 3 alerts would now be expected twice a year. By the end of the century, line closures will occur on average 3.6 times per year and Level 1 and 2 alerts will occur 53 and 63 times a year respectively. In total this equates to an 1170% increase in the average number of DLRs predicted to affect the line by the turn of the century.

In the event of Network Rail carrying out significant work to improve the defences along the line – the company has now tabled this as an option (see below) – we can reasonably assume that the likelihood of further lengthy blockades such as that in early 2014 would reduce, although there is still the chance that some Level 3 episodes could bring about comparable disruption. Strikingly, Level 3 incidents are by the end of the century expected to increase twelve-fold from their 1997–2009 average and in this context multiple breaches, undermining and subsidence of the track, with extensive damage to footpaths and offshore breakwaters, can probably be expected. By 2060, with high-impact events occurring on average twice a year, the extent to which the railway would be able to maintain a credible service has to be brought

Table 2
Predicted sea-level rise and estimated days with line restrictions for the 21st century.

Year	Sea-level rise (cm)*	Average days with line restrictions	Increase in DLRs (%)	Level 1 (L1)	Level 2 (L2)	Level 3 (L3)	Annual restriction (%)
1997–2009	–	9.6	–	5.4	3.8	0.3	3
Low emissions							
2020	4.7	16	69	8.4	7.2	0.5	4
2040	15.1	30	220	16.0	13.6	0.9	8
2060	26.8	46	389	24.4	20.7	1.4	13
2080	40.0	64	581	34.0	28.8	1.9	18
2100	54.5	84	792	44.5	37.7	2.5	23
Medium emissions							
2020	5.7	17	83	9.1	7.8	0.5	5
2040	18.3	34	266	18.3	15.5	1.0	9
2060	32.6	54	474	28.6	24.3	1.6	15
2080	48.6	76	710	40.2	34.1	2.3	21
2100	66.4	100	964	53.1	45.1	3.0	27
High emissions							
2020	6.8	19	99	9.9	8.4	0.6	5
2040	22.0	40	320	20.9	17.8	1.2	11
2060	39.3	63	571	33.5	28.4	1.9	17
2080	58.9	90	856	47.6	40.4	2.7	25
2100	80.6	120	1170	63.3	53.8	3.6	33
H++ scenario							
–	90	132	1290	70.1	59.6	4.0	36
–	110	160	1584	84.6	71.8	4.8	41
–	130	187	1868	99.1	84.1	5.6	51
–	150	214	2153	113.5	96.4	6.4	59
–	170	242	2447	128.0	108.7	7.2	66
–	190	269	2732	142.5	121.0	8.1	74

* Sea-level predictions for the Dawlish area (relative to the present day 2010). Values represent the 95th percentiles taken from UKCP09's user interface (<http://ukclimateprojections.defra.gov.uk>; grid: 25757) corrected for an error of 0.16 mm/yr. H++ scenario is a high-impact estimate for the UK.

into question. Indeed, even by 2040, there are likely to be serious issues in relation to its *reliability*. Table 2 shows that by this time we can expect some kind of service restriction to be in place for up to 10% of days in the year (i.e., DLRs / 365 days), while by the end of the century this rises to fully one third of days in the year. Given, also, that most overtopping events occur during September–April, restrictions are likely to be bunched accordingly. Thus by 2060, under a high emissions scenario, a third of days in the winter period could be subject to some kind of service restrictions, rising to two-thirds by 2100. Even under the low emissions scenario winter services could be restricted in one way or another for over 40% of days in the year.

Out of interest, we have run our calculations in accordance with an additional high-impact scenario (H++ in Table 2) advanced by Lowe et al. (2009) that projects sea-level rise of 1.9 m by 2100. It is at least worth contemplating the effects of a scenario, albeit a low-probability one, that would render the line subject to restrictions for nearly 270 days (over 70%) of the year by the end of the century. This would be the result of more than 260 Level 1 and Level 2 alerts each year, and eight Level 3s. Maybe our calculations here are rather academic in the sense that this level of water would flood the estuary defences east and west of Dawlish even without a storm (Fig. 3).

While this study is the first to adopt a semi-empirical approach to predicting the impact of rising sea level on the stretch of line between Dawlish and Teignmouth, the Rail Safety Standards Board (RSSB) commissioned work on the future of the line several years ago (O'Breasail et al., 2007). In the RSSB's study, a modelling approach based on changes in extreme water levels relative to those observed in 2006 was used. The authors used sea-level projections from UKCIP02 (Hulme et al., 2002) – which predicted higher sea levels than the subsequent UKCP09 estimates – and they estimated the increased

impact of 1-in-1 year overtopping (that would affect the operation of the line) and 1-in-100 year overtopping (that would impact the structural integrity of the defences). So far as they are comparable, both studies arrive at broadly similar results until 2060, from which point O'Breasail et al.'s (2007) model estimates considerably more overtopping at King Harry's Walk (Fig. 8).

Differences between O'Breasail et al.'s analysis and our semi-empirical approach could result from the higher level of spatial resolution employed in the model-based study – as noted in Fig. 3 the elevations of the defence structures along the Dawlish–Teignmouth frontage vary considerably from the Exe estuary to the Teign estuary – and as such our work does not have the potential to predict non-linear trends of future overtopping at the more vulnerable sections of the coastal defence structures. At the same time, differences could also be due to O'Breasail et al.'s (2007) incomplete understanding of processes that are included in their model. What is clear from both studies, though, is that an increase in the number of overtopping events and associated service restrictions very much beyond current norms can be expected in future decades.

5. Costing future line restrictions

As rising sea levels increase the prospect of service disruptions and damage to the sea defences or the structural integrity of the railway line, a key area of concern for railway managers and policy makers alike will be the associated potential cost implications. These costs can be classified as 'internal' to the railway itself, and 'external' to the socio-economic functioning of the region more broadly. We consider three components to the internal costs.

First are internal costs associated with maintenance, due to additional 'wear and tear' to the sea defences. Network Rail's 'base' spend on maintaining the sea defences between Dawlish and Teignmouth – i.e., not including major repairs associated with events such as the breach of the sea wall in February 2014 – is around £800,000 per year (or £105,000 per km per year), plus an additional £5 million every 5 years to deal with one-off events such as landslips (Network Rail, 2014c). Perhaps unsurprisingly, it is already one of the most expensive stretches of line to maintain in the country (the national average is around £41,000 per km per year; see Railtrack, 1996; Clinnick, 2009; Network Rail, 2013). Multiplying the reported average annual cost of maintenance by the estimated increase in days with known line restrictions (DLRs) for a given year for the different sea-level rise scenarios – admittedly a rather rudimentary approach – we arrive at estimated annual maintenance costs of £5.8–£7.6 million per year by 2040 at current prices, as DLRs increase. This equates to costs of £0.9–£1.7 million per km per year.

Second are those costs associated with changing the timetable to deal with line restrictions. Under the complex financial arrangements of the privatised railway (see Gourvish, 2002, 2008), Network Rail must compensate train operators when the state of its infrastructure causes delays to or cancellation of services (ORR, 2013; Network Rail, 2014e). These payments are in turn used by the train operators to compensate passengers for inconvenience, or to provide alternative arrangements such as rail replacement bus services. Each minute of delay is estimated to cost the operator (or Network Rail) around £70 (National Audit Office, 2008; ORR, 2013), and on this basis we estimate the average annual delay charges between 1997 and 2009 to have been in the region of £270,000 (e.g., multiplying the TRUST recorded delay minutes by the estimated cost per minute) (ORR, 2013). Again under a high sea-level rise scenario, by 2040, compensation payments could rise to £1.1 million per year at current prices. To put this into perspective, passengers on the very busy Thameslink commuter network in the south east of England received £722,000 in compensation in 2012/13, and the operator (at the time, First Capital Connect) estimated that more than half of the delays that triggered compensation payments were the fault of Network Rail (BBC, 2013b).

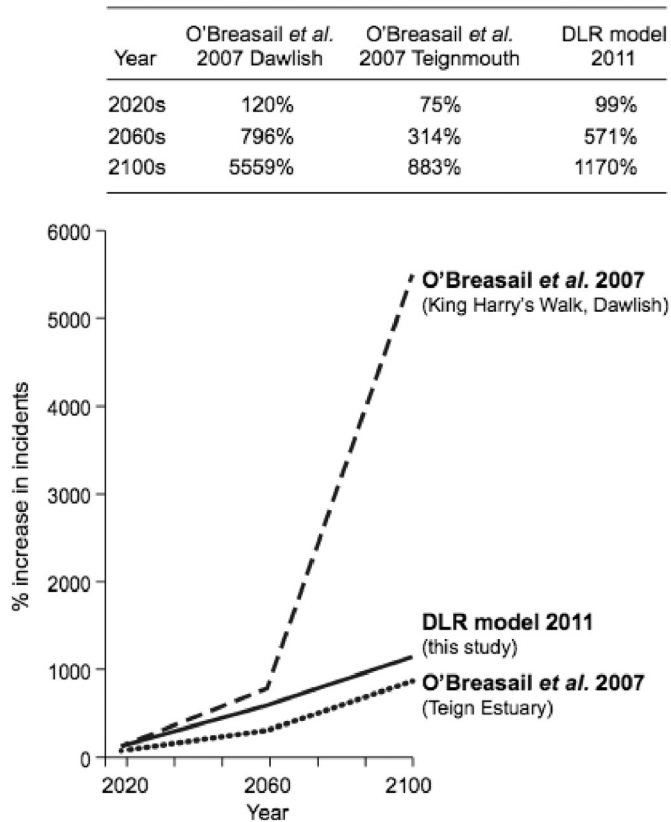


Fig. 8. Comparison of predicted increases in incidents from empirical trends (this study) and the predicted increase in 1 in 1 year overtopping by the Rail Safety Standards Board. Sources: Authors' calculations and O'Breasail et al., 2007.

Third, as highlighted in early 2014, are those costs associated with extreme individual events that cause damage beyond usual 'wear and tear'. Network Rail estimated the cost of the February 2014 storms to have been £50 m, and suggests that works to additionally protect the existing railway alignment (as well as to improve its effectiveness more generally) will cost between £398 million and £659 million over a 20-year period. The company is of the view that retaining the existing railway is better value for money than reopening an alternative line across the north of Dartmoor (costing up to £875 million) or building a brand new diversionary line between Exeter and Newton Abbot (which could cost up to £3.1 billion) (Network Rail, 2014c). Whatever the actual cost of the different options – these are contested as they contain an over-estimation (the so-called 'optimism bias') required by the UK government and a number of challengeable assumptions about operational matters (see Burningham and Phillips, 2014; Clinnick, 2014) – it is clear that running trains in Devon will cost the railway industry (and ultimately the government), even in a 'do nothing' scenario, rather more in the future than it has in the past.

The situation becomes more pronounced once 'external' costs are taken into account. While the internal costs are substantial, they do not include the wider socio-economic impacts of railway disruption to the South West Peninsula. External costs of this nature are somewhat difficult to calculate, but one favoured approach is based on the adaptation of standard appraisal techniques for transport investment, as outlined by the Department for Transport (DfT, 2014b). At the simplest level, conventional appraisal techniques try to capture the economic impacts of a given investment by examining two categories: costs and benefits to users, which are most commonly attributed to changes in travel time, and wider economic impacts that include agglomeration effects, changes in transport costs and labour effects (DfT, 2014b). Reducing

users' travel time is assumed to have direct benefit on GDP, and conversely, such as in episodes of disruption, increasing user travel time is expected to have a similar, but negative, effect (Metroeconomica, 2004; Lakshmanan, 2011).

The issue is not that we are unaware of some of the basic numbers to feed into the equation: in 2010, for example, four million passengers travelled through the Dawlish to Teignmouth section of line, an average of around 11,000 passengers per day, and trains are busier in the summer time, owing to increased tourist traffic. Patronage in the region grew by more than 70% between 2004 and 2013, and a further near-doubling is expected by the early 2040s (Network Rail, 2014c). Disruption events can also be extrapolated into the coming decades. The issue is in determining what other inputs go into the equation and, indeed, the equation itself. There are well-known problems with emphasising the monetary value of travel time in benefit–cost ratio (BCR) calculations, not only because it is often difficult empirically to determine that a reduction in travel time actually results in GDP growth (Wenban-Smith, 2010). BCRs can also be susceptible to significant variation (and, we would suggest, manipulation) depending on the underpinning assumptions made to the point that they can differ markedly between originators (see Shaw and Docherty, 2014).

In the case of the 2014 blockade, this problem was exacerbated by the fact that some local protagonists saw fit, putting it bluntly, to take liberties with the methodology. A 75% drop in tourist bookings was reported in one hastily assembled study, and Plymouth City Council somehow estimated the daily impact on the city's economy in lost trade, tourism and potential investment to be up to £4–5 million (Marsden, 2014). In reality, they could not have had any idea what the actual figure was: Marsden (2014, unpaginated) memorably commented that "[w]ithin hours of the news [of the blockade], calculations adorned the backs of hundreds of envelopes, producing seven, eight or even nine-figure sums of economic turmoil." More detailed and credible studies will no doubt emerge in the fullness of time – indeed in October 2014 Plymouth City Council revised its estimate of losses down to around £600,000 per day (House of Commons, 2014c) – but the point is that the economic effects of transport disruption on this scale are not well understood and will not necessarily be captured especially successfully by variations of conventional appraisal processes.

Writing as part of a wider discussion about transport and travel time, Metz (2008) suggests that an alternative means of deciding between infrastructure schemes – in this case, doing nothing, additionally protecting the existing line, reopening one or building something new entirely – might simply be to determine which interventions are most likely to achieve the stated aims of transport policy. We can apply this logic to the Dawlish example: if the decision is taken that it is not good for the far west of England to be cut off from the rest of the national rail network, then the question shifts from 'How much does it cost when the line is closed?' to 'How can we best ensure that so far as is possible this does not happen again?' Such an approach is already used in other government departments, and internationally it is common to place less emphasis on the BCR element of project appraisal than is routine at the DfT. In Italy, for instance, engineering works costing around €2 billion have been made along the Adriatic coast to improve passenger and freight travel in the context of vulnerability of coastal sections to storms and future sea-level rise (italferr, 2014). The secondary mainline along the Ligurian Sea from Ventimiglia to Genoa has also been moved away from the coast into near-by tunnels.

Of course, the DfT's approach to transport investment appraisal may well change over time, and since 2010 ministers certainly appear to have recognised much more the need to pursue a larger-scale capital investment programme to address historic under-investment in the UK's transport infrastructure (HM Treasury, 2013). This may well have been rather more by accident than design, but then there is nothing *inherent*ly predictable in the DfT's approach in the same way as there is nothing set in stone about the future direction of society more broadly. Lowe et al.'s (2009) range of sea-level scenarios in part reflect different

assumptions about human development trajectories, and by the same token any estimates of the likely impacts on the Dawlish–Teignmouth railway line or indeed the region more broadly need to contain sufficient flexibility to recognise the dynamism of economic, institutional and political processes (Adger et al., 2005; Jaroszweski et al., 2010), not to mention individual behaviour patterns. As Marsden and Docherty (2013) point out, albeit in a slightly different context, there is more and more evidence to show that travellers can adapt to a major change in network conditions rather more readily than policy makers currently assume; were such a major change the introduction of a regime of road user charging, rail patronage may increase to the point where such major disruption along the South Devon coast becomes a far greater test of public policy than it is today.

6. Conclusions and wider implications

We have investigated in this paper the likely impact of rising sea levels on the Dawlish to Teignmouth stretch of the London to Penzance railway line. We used a ‘semi-empirical’ modelling approach (see, for example, Rahmstorf, 2007) that involved two stages. The first was to establish an empirical relationship between sea-level rise and overtopping events along the railway line, assuming decadal-scale sea-level change to be the physical driver of such events. The post-1975 relationship between sea-level rise and overtopping events was then extrapolated to 2100 in accordance with modelled projections of future sea-level rise (Lowe et al., 2009), to estimate the likely impact of this trend on the functioning of the line. In all sea-level change scenarios, we expect the number of overtopping events to increase as the century progresses, and these are likely to impinge upon the ability of Network Rail and the train operating companies to run a reliable service along the line within a couple of decades. Even in the event of a significantly strengthened sea wall, it is reasonable to expect ongoing disruption because of continuing periodic overtopping of the sea defences. Whatever the policy response – from ‘do nothing’ to building a completely new diversionary route – there looks set to be a significant cost increase, possibly running into the billions of pounds, associated with running trains through Devon in the future.

In the context of all of this, the Dawlish to Teignmouth example poses key policy challenges. We have already noted that in the UK the institutional response to climate change adaptation has been relatively slow off the mark. Even assuming this can be resolved at the strategic level and sufficient funds are freed up to deal with emerging problems, there will remain the issue of how to operationalise strategic policy direction on the ground. Any successful response to the impact of sea-level rise on the railway in south Devon requires a genuinely multi-agency response on the basis that a range stakeholders is responsible for the protection of different but self-evidently interconnected stretches of line. Arranging such a response is by no means straightforward, in part because of the different spatial scales at which the agencies operate – national (DfT, Environment Agency), regional (Enterprise Partnerships and erstwhile Regional Development Agencies) and local (county, city and district councils) – but also because of the well-known problem that coastal management has been hindered by a lack of co-ordinated involvement and communication between elected bodies and statutory agencies. The politics of coastal management, in short, have become increasingly fragmented, polarised and contested (Fletcher, 2003; O’Riordan et al., 2006; Fletcher, 2007; Turner et al., 2007; de la Vega-Leinert and Nicholls, 2008).

More broadly, there are two aspects of our study that are of relevance beyond the specific example of the Dawlish to Teignmouth stretch of railway line. First, the findings confirm that there is merit in investigating the likely nature, frequency and socio-economic implications of disruption to other stretches of railway line – or, for that matter, any transport infrastructure – caused by sea-level rise in the future. In the UK alone, there are several vulnerable stretches of railway track, including the main lines in North and South Wales, the Cambrian Coast

line in Mid Wales, the Chatham main line in South East England, the Cumbrian coast line in North West England and the Ayrshire line in southwest Scotland. Internationally, we referred earlier to other studies that identify vulnerabilities around the USA and northern Europe, but the problem is obviously worldwide (see Koetse and Rietveld, 2009). Being able to predict the likely frequency and severity of overtopping (or more general flooding) events will help inform planning processes designed to ‘future-proof’ important coastal infrastructure.

Second, and relatedly, the methodology we have developed is applicable to other stretches of coast, especially where necessary records are available and empirical data exist or can be derived. Potentially vulnerable transport infrastructure in, for example, Boston, New York, Miami, San Francisco, Sydney, Manila, Bangkok and Mumbai is situated nearby some of the longest tide-gauge records in the world (Woodworth et al., 2009). Our methodology is particularly useful because it allows the prediction of disruption events and their frequency that are based on real data and thus bypasses the uncertainty – and expense – that comes with engineering models. It also provides a yardstick against which previous modelling approaches (in this case O’Breasil et al., 2007) can be tested or calibrated.

In utilising a semi-empirical approach, we should warn that care must be taken to avoid producing ‘nonsense correlations’ and sufficient evidence needs to be gathered to validate empirical trends. We also lacked the spatial resolution of model-based approaches and our ability to illustrate the impact of extreme events is limited to the extreme sea-level scenario included in the analysis. We did, however, incorporate regional socio-economic information into the findings (see Bosello and De Cian, 2014, for a discussion of related methodologies) by using our extrapolations of overtopping events to inform a discussion of policy implications. We provided illustrative examples of how internal (to the industry) and external (to society more generally) costs of predicted disruption events can be established, where these are useful or necessary. In the context of the UK, which relies heavily on a particular type of marketised railway industry structure and the deployment of BCRs as a means of justifying investment, developing an understanding of such costs (and benefits) is especially important in order to allow different engineering and other interventions to be compared. There is nothing, however, to suggest that institutions operating in other countries would be unable to generate something equivalent to address their own local needs (in any event, other European railways such as Deutsche Bahn and SNCF are already starting to develop internal markets with separate infrastructure and operating units). Finally, these estimated costs and benefits can easily be linked to scenario-planning exercises intended to provide integrated and holistic insights for debate and high-level guidance for policy makers concerned with addressing long-term social, economic and environmental imperatives.

Acknowledgements

Funding for the research reported in this paper was originally provided by Great Western Research, Network Rail, and Devon and Cornwall Councils, and further analysis has supported by the Leverhulme Trust (ECF-2014-177). We would like also to thank John Dora, at Network Rail, and Alistair Hunt, at the University of Bath, for their input into the wider project from which this work was developed, and Great Western Railway’s (now retired) Projects and Planning Director, Mike Hogg, for his comments on an earlier draft of this paper. Finally, we are extremely grateful to Tim Absalom for drawing the diagrams.

References

- Adger, W.N., Arnell, N.W., Tompkins, E.L., 2005. Successful adaptation to climate change across scales. *Global Environmental Change* 15, 77–86.
- Alexander, L.V., Tett, S.F.B., Jonsson, T., 2005. Recent observed changes in severe storms over the United Kingdom. *Geophysical Research Letters* 32, L13704.
- Allan, R., Tett, S., Alexander, L., 2009. Fluctuations in autumn-winter severe storms over the British Isles: 1920 to present. *International Journal of Climatology* 29, 357–371.

- Arns, A., Wahl, T., Haigh, I.D., Jensen, J., Pattiaratchi, C., 2013. Estimating extreme water level probabilities: A comparison of the direct methods and recommendations for best practise. *Coastal Engineering* 81, 51–66.
- Banister, D., Schwaben, T., Anable, J., 2012. Introduction to the special section on theoretical perspectives on climate change mitigation in transport. *Journal of Transport Geography* 24, 467–470.
- Bittermann, K., Rahmstorf, S., Perrette, M., Vermeer, M., 2013. Predictability of twentieth century sea-level rise from past data. *Environmental Research Letters* 8, 014013. <http://dx.doi.org/10.1088/1748-9326/8/1/014013>.
- Bosello, F., De Cian, E., 2014. Climate change, sea level rise, and coastal disasters. A review of modelling practices. *Energy Econ.* 46, 593–605.
- BBC, 2013a. Tidal surge hits east UK coastal towns after storm. <http://www.bbc.co.uk/news/uk-25253080> (Accessed on 08/01/14).
- BBC, 2013b. Millions paid to delayed South East rail passengers. <http://www.bbc.co.uk/news/uk-england-25452424> (Accessed on 08/01/14).
- Burningham, R. and Phillips, J. (2014) West of Exeter Resilience Study—an alternative approach. Unpublished report, available from the Devon and Cornwall Rail Partnership (r.burningham@plymouth.ac.uk).
- Challinor, A.J., Ewert, F., Arnold, S., Simelton, E., Fraser, E., 2009. Crops and climate change: Progress, trends, and challenges in simulating impacts and informing adaptation. *Journal of Experimental Botany* 60 (10), 2775–2789.
- Chapman, L., 2007. Transport and climate change: A review. *Journal of Transport Geography* 7, 354–367.
- Church, J.A., White, N.J., Thorkild, A., Wilson, S., Woodworth, P.L., Domingues, C.M., Hunter, J.R., Lambeck, K., 2008. Understanding global sea levels: Past, present and future. *Sustainability Science* 3, 9–22.
- Church, J.A., Clark, P.U., Cazenave, A., Gregory, J.M., Jevrejeva, S., Levermann, A., Merrifield, M.A., Milne, G.A., Nerem, R.S., Nunn, P.D., Payne, A.J., Pfeffer, W.T., Stammer, D., Unnikrishnan, A.S., Qin, D., 2013. Sea level change. In: Stocker, T.F., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P.M. (Eds.), *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
- Clinnick, R., 2009. The railway's wall against the waves. *Rail* 626, 48–55.
- Clinnick, R., 2014. Cost of Dawlish diversion could reach £3.1bn—NR. *Rail* 753, 6–7.
- Dawson, D.A. (2012) The impact of future sea-level rise on the London–Penzance railway line. Unpublished PhD Thesis, University of Plymouth.
- Department of Environment, Food and Rural Affairs, 2005. Making space for water: Taking forward a new government strategy for flood and coastal erosion risk management in England First Government Response to the Autumn 2004 Making Space for Water Consultation Exercise. DEFRA, London.
- Department for Transport, 2011. Winter resilience in transport: An assessment of the case for additional investment. DfT, London (57 pp).
- Department for Transport, 2014a. Transport resilience review: A review of the resilience of the transport network to extreme weather. DfT, London (161 pp).
- Department for Transport, 2014b. Transport analysis guidance: WebTAG Available at <https://www.gov.uk/transport-analysis-guidance-webtag> (Accessed 14/11/14).
- Dixon, M.J., Tawn, J.A., 1995. A semi-parametric 2011 model for multivariate extreme values. *Statistics and Computing* 5, 215–225.
- Eddington, R., 2006. The Eddington transport study: Transport's roles in sustaining the UK's productivity and competitiveness. HM Treasury, London.
- Environment Agency, 1999. The state of the environment of England and Wales: Coasts. The Stationery Office, London.
- European Environment Agency, 2014. Adaptation of transport to climate change in Europe: Challenges and options across transport modes and stakeholders. Report No 8/2014, Copenhagen, Denmark (ISSN: 1977-8449).
- Feser, F., Barcikowska, M., Krueger, O., Schenk, F., Weisse, R., Xia, L., 2015. Storminess over the North Atlantic and northwestern Europe—a review. *Q. J. R. Meteorol. Soc.* 141, 350–382.
- Fletcher, S., 2003. Stakeholder representation and the democratic basis of coastal partnerships in the UK. *Marine Policy* 27, 229–240.
- Fletcher, S., 2007. Influences on stakeholder representation in participatory coastal management programmes. *Ocean Coast. Manag.* 50, 314–328.
- French, P.W., 2004. The changing nature of, and approaches to, UK coastal management at the start of the 21st century. *The Geographical Journal* 170, 116–125.
- Gehrels, W.R., 2006. Sea-level rise and coastal subsidence in southwest England. *Transactions of the Devonshire Association for the Advancement of Science*. 138, pp. 25–42.
- Gehrels, W.R., Dawson, D.A., Shaw, J., Marshall, W.A., 2011. Using Holocene relative sea-level data to inform future sea-level predictions: An example from southwest England. *Global and Planetary Change* 78, 116–126.
- Gourvish, T., 2002. *British Rail, 1974–97: From integration to privatisation*. Oxford University Press, Oxford.
- Gourvish, T., 2008. Britain's railways, 1997–2005: Labour's strategic experiment. Oxford University Press, Oxford.
- Grinsted, A., Moore, J.C., Jevrejeva, S., 2010. Reconstructing sea level from paleo and projected temperatures 200 to 2100 AD. *Climate Dynamics* 34, 461–472. <http://dx.doi.org/10.1007/s00382-008-0507-2>.
- Haigh, I.D., Nicholls, R., Wells, N., 2009. Mean sea level trends around the English Channel over the 20th century and their wider context. *Continental Shelf Research* 29, 2083–2098.
- Haigh, I.D., Nicholls, R., Wells, N., 2010. A comparison of the main methods for estimating probabilities of extreme still water levels. *Coastal Engineering* 57, 838–849.
- Haigh, I.D., Nicholls, R., Wells, N., 2011. Rising sea levels in the English Channel 1900 to 2100. Proceedings of the Institution of Civil Engineers—Maritime. *Engineering* 164, 81–92.
- Hall, J.W., Sayers, P.B., Walkden, M.J.A., Panzeri, I., 2006. Impacts of climate change on coastal flood risk in England and Wales: 2030–2100. *Philosophical Transactions of the Royal Society A* 364, 1027–1049.
- Hanna, E., Cappelletti, J., Allan, R., Jonsson, T., Le Blancq, F., Lillington, T., Hickey, K., 2008. New insights into north European and North Atlantic surface pressure variability, storminess, and related climate change since 1830. *Journal of Climate* 21, 6739–6766.
- Heberger, M., Cooley, H., Herrera, P., Gleick, P.H., Moore, E., 2009. The impacts of sea-level rise on the California coast Prepared for the California Climate Change Center (May 2009, CEC-500-2009-024-F).
- Highways Agency, 2011. Climate change risk assessment Available at <http://www.highways.gov.uk/publications/climate-change-mitigation/> (Accessed 14/11/14).
- HM Government, 2011. Climate resilient infrastructure: Preparing for a changing climate Presented to Parliament by the Secretary of State for Environment, Food and Rural Affairs by Command of Her Majesty, May 2011. Downloaded at www.official-documents.gov.uk.
- HM Treasury, 2013. *National Infrastructure Plan 2013*. HM Treasury, London.
- Hogg, M., 2014. Coping with a soggy railway (Powerpoint presentation for First Great Western. Available with permission from corresponding author).
- Hooper, E., Chapman, L., 2012. The impacts of climate change on national road and rail networks. In: Ryley, T., Chapman, L. (Eds.), *Transport and climate change*. Bingley, Emerald, pp. 105–136.
- House of Commons, 2014a. Flooding: Support for businesses Available at <http://www.publications.parliament.uk/pa/cm201314/cmhansrd/cm140306/debtext/140306-0001.htm> (Accessed on 29/10/14).
- House of Commons, 2014b. Transport's winter resilience Available at <http://www.parliament.uk/business/committees/committees-a-z/commons-select/transport-committee/inquiries/parliament-2010/winter-weather/> (Accessed on 14/11/14).
- House of Commons, 2014c. Committee holds fourth evidence session on investing in the railway. House of Commons Transport Committee, 27 October, 2014 Available at: <http://www.parliament.uk/business/committees/committees-a-z/commons-select/transport-committee/news/investing-railway-ev4/> (Accessed 14/11/14).
- Hulme, M., Jenkins, G.J., Lu, X., Turpenny, J.R., Mitchell, T.D., Jones, R.G., Lowe, J., Murphy, J.M., Hassell, D., Boorman, P., McDonald, R., Hill, S., 2002. Climate change scenarios for the United Kingdom: The UKCIPO2 Scientific Report. Tyndall Centre for Climate Change Research, University of East Anglia, Norwich, UK 120 pp.
- Huntingford, C., Marsh, T., Scaife, A.a., Kendon, E.J., Hannaford, J., Kay, A.L., Lockwood, M., Prudhomme, C., Reynard, N.S., Parry, S., Lowe, J.a., Screen, J.a., Ward, H.C., Roberts, M., Stott, P.a., Bell, V.a., Bailey, M., Jenkins, A., Legg, T., Otto, F.E.L., Massey, N., Schaller, N., Slingo, J., Allen, M.R., 2014. Potential influences on the United Kingdom's floods of winter 2013/14. *Nat. Clim. Chang.* 4, 769–777. <http://dx.doi.org/10.1038/nclimate2314>.
- The Institute of Civil Engineers, 2009. The State of the Nation Briefing Sheet—South west. Defending Critical Infrastructure. ICE, London.
- Italferr, 2014. Conventional Line Projects: Adriatic Route Available at <http://www.italferr.it/cms/v/index.jsp?vgnextoid=475907660aeda110VgnVCM1000003f16f90aRCRD> (Accessed on 29/10/2014).
- Jacob, K., Gornitz, V., Rosenzweig, C., 2007. Vulnerability of the New York City Metropolitan Area to Coastal Hazards, including sea-level rise: Inferences for urban coastal risk management and adaptation policies. In: McFadden, L., Nicholls, R., Penning-Rowsell, E. (Eds.), *Managing Coastal Vulnerability*. Elsevier Publishing, Oxford.
- Jaroszowski, D., Chapman, L., Petts, J., 2010. Assessing the potential impact of climate change on transportation: The need for an interdisciplinary approach. *J. Transp. Geogr.* 18, 331–335.
- Jaroszowski, D., McNamara, T., 2014. The influence of rainfall on road accidents in urban areas: A weather radar approach. *Travel Behav. Soc.* 1, 15–21.
- Kay, P., 1993. Exeter–Newton Abbot: A Railway History. Platform 5, Sheffield.
- Koets, M.J., Rietveld, P., 2009. The impact of climate change and weather on transport: an overview of empirical findings. *Transp. Res. Part D: Transp. Environ.* 14 (3), 205–221.
- Lakshmanan, T.R., 2011. The broader economic consequences of transport infrastructure investments. *J. Transp. Geogr.* 19, 1–12.
- Lowe, J.A., Howard, T.P., Pardaens, A., Tinker, J., Holt, J., Wakelin, S., Milne, G., Leake, J., Wolf, J., Horsburgh, K., Reeder, T., Jenkins, G., Ridley, J., Dye, S., Bradley, S., 2009. UK Climate Projections Science Report: Marine and Coastal Projections. Met Office Hadley Centre, Exeter.
- Marsden, G., 2014. Will it be 'all change' on the railways after Dawlish? More likely just the usual service. *The Conversation* 26 February 2014. Available at <http://theconversation.com/will-it-be-all-change-on-the-railways-after-dawlish-more-likely-just-the-usual-service-23701> (Accessed 25/05/14).
- Marsden, G., Docherty, I., 2013. Insights on disruptions as opportunities for transport policy. *Transp. Res. A* 51, 46–55.
- Metcalfe, G., Chambers, F., Charlesworth, A., Forrest, V., Hunt, J., McEwen, L., Russell, K., Schofield, S., 2003. Warming to the Idea, Technical Report, South West Region Climate Change Impacts Scoping Study, Cheltenham, UK.
- Metroeconomica, 2004. Costing the impacts of climate change in the UK: Overview of guidelines. UKCIP Technical Report. UKCIP, Oxford.
- Metz, R., 2008. The myth of travel time saving. *Transp. Res. Rev.* 28, 321–336.
- The Mirror (2002) Wavy Line. *The Mirror*. (October 10, 15).
- National Audit Office, 2008. Reducing passenger rail delays by better management of incidents. <http://www.nao.org.uk/wp-content/uploads/2008/03/0708308.pdf> (Accessed 20 November 2014).
- National Oceanographic Centre, 2014a. UK real-time data, Immingham/Lowestoft, 5–6th December 2013. National tide and sea-level facility. National Oceanographic Centre (Available at <http://www.ntsif.org/data/uk-network-real-time>. Accessed on 29/10/14).
- Network Rail, 2009. Dawlish Sea Wall: Adverse Weather Operations Protocol Network Rail, London (Supplied by personal communication with NR, available from the corresponding author).

- Network Rail, 2013. CP5 activity and Expenditure Plans: maintenance Activity and Expenditure. SBPT222, Version 0.14. pp. 1–27.
- Network Rail, 2014a. Weather and climate change resilience: how our routes are mitigating the impact of weather and climate change to maintain an efficient service Available at <http://www.networkrail.co.uk/publications/weather-and-climate-change-resilience/> (Accessed on 14/11/14).
- Network Rail, 2014b. Dawlish Railway information Available at <https://www.networkrail.co.uk/timetables-and-travel/storm-damage/dawlish/> (Accessed on 10/04/2014).
- Network Rail, 2014c. West of Exeter Route Resilience Study Available at <http://www.networkrail.co.uk/publications/weather-and-climate-change-resilience/west-of-exeter-route-resilience-study/> (Accessed on 14/11/14).
- Network Rail, 2014d. Gallery. <http://www.networkrailmediacentre.co.uk/imagegallery/default.aspx?NewsAreald=28&MediaFilter=1> (Accessed 09/12/14).
- Network Rail, 2014e. Route weather resilience and climate adaptation plans, western route WRCCA plan. (42 pp). Available at <http://www.networkrail.co.uk/publications/weather-and-climate-change-resilience/> (Accessed on 14/11/14).
- Network Rail, 2015. Harbury tunnel landslide. <http://www.networkrail.co.uk/HarburyLandslip/> (Accessed 18 June 2015).
- Nicholls, R.J., Wong, P.P., Burkett, V., Woodroffe, C.D., Hay, J., 2008. Climate change and coastal vulnerability assessment: scenarios for integrated assessment. *Sustain. Sci.* 3, 89–102.
- Nicholls, R.J., Townend, I.H., Bradbury, A.P., Ramsbottom, D., Day, S.A., 2013. Planning for long-term coastal change: experiences from England and Wales. *Ocean Eng.* 71, 3–16.
- O'Breasail, B., Corgordan, F., Gibson, J.R., Fiadzibeg, E., 2007. Impact of climate change on coastal rail infrastructure. Prepared for Rail Safety Standards Board (RSSB). Mouchel Parkman, Surrey.
- O'Riordan, T., Watkinson, A., Milligan, J., 2006. Living with a changing coastline: exploring new form of governance for sustainable coastal futures. Technical Report 49 (Available at: <http://www.tyndall.ac.uk/sites/default/files/tr49.pdf> Accessed on 14/11/14).
- Office of Rail Regulation, 2013. Draft determination of Network Rail's outputs and funding for 2014–19. ORR, London.
- Permanent service for mean sea level. Tide gauge data. Available at: <http://www.psmsl.org/data/obtaining/> (Accessed on 29/10/2014).
- Plymouth Chambers of Commerce & Industry (PCCI), 2014. Survey results highlight impact of travel disruption for SW businesses Available from <http://www.plymouthchamber.co.uk/News/news-story.cfm?story=320> (Accessed on 9/06/14).
- Plymouth City Council, 2014. New peninsula rail task force sets out priorities Available at <http://www.plymouth.gov.uk/newsreleases?newsid%3D308861> (Accessed on 29/10/2014).
- Pullen, T., Allsop, N., Bruce, T., Kortenhaus, A., Schüttrumpf, H., van der Meer, J., 2007. EurOtop—wave overtopping of sea defences and related structures: assessment manual Available at <http://www.overtopping-manual.com/eurotop.pdf> (Accessed on 14/11/14).
- Rahmstorf, S., 2007. A semi-empirical approach to projecting future sea-level rise. *Science* 315, 368.
- Railtrack, 1996. The Dawlish Sea Wall: What's New? Service Information Series, Winter 96. Railtrack Great Western, Swindon.
- Rail Safety and Standards Board, 2010. Tomorrow's railway and climate change adaptation: T925 Research Brief Available at <http://www.rssb.co.uk/library/research-development-and-innovation/research-brief-T925.pdf> (Accessed on 29/10/14).
- Rogers, J., O'Breasail, B., 2006. Frontage Management Strategy, Dawlish to Teignmouth Seawall. Mouchel Parkman, Surrey.
- Ryley, T., Chapman, L., 2012. Transport and Climate Change. Bingley, Emerald.
- Seneviratne, S.I., Nicholls, R., Easterling, C.M., Goodess, S., Kanae, J., Kossin, Y., Luo, J., Marengo, K., McInnes, M., Rahimi, M., Reichstein, A., Sorteberg, C.V., Zhang, X., 2012. Changes in Climate Extremes and Their Impacts on the Natural Physical Environment. In: Field, C.B., Barros, V., Stocker, T.F., Qin, D., Dokken, D.J., Ebi, K.L., Mastrandrea, M.D., Mach, K.J., Plattner, G.-K., Allen, S.K., Tignor, M., Midgley, P.M. (Eds.), *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 109–230 A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change (IPCC).
- Shaw, J., Docherty, I., 2014. *The Transport Debate*. Policy Press, Bristol.
- Shennan, I., Horton, B., 2002. Holocene land- and sea-level changes in Great Britain. *J. Quat. Sci.* 17, 511–526.
- Slingo, J., Belcher, S., Scaife, A., McCarthy, M., Saulter, A., McBeath, K., Jenkins, A., Huntingford, C., Marsh, T., Hannaford, J., Parry, S., 2014. The Recent Storms and Floods in the UK. Met Office, Exeter, pp. 1–27.
- Suarez, P., Anderson, W., Mahal, V., Lakshmanan, T.R., 2005. Impacts of flooding and climate change on urban transportation: a systemwide performance assessment of the Boston metro area. *Transp. Res. Part D: Transp. Environ.* 10 (3), 231–244.
- The Times (1846) Regional News. October 13. The Times. London, 5.
- The Times (2004) Waves take trains by storm. The times, October 28, London, 15.
- Titus, J., 2002. Does Sea Level Rise Matter to Transportation Along the Atlantic Coast? Center for Climate Change and Environmental Forecasting: The Potential Impacts of Climate Change on Transportation. Federal Research Partnership Workshop October 1–2, 2002. Department of Transportation, Washington DC, USA.
- Turner, R.K., Burgess, D., Hadley, D., Coombes, E., Jackson, N., 2007. A cost-benefit appraisal of coastal managed realignment policy. *Glob. Environ. Chang.—Human Policy Dimens.* 17, 397–407.
- de la Vega-Leinert, A.C., Nicholls, R.J., 2008. Potential implications of sea-level rise for Great Britain. *J. Coast. Res.* 24, 342–357.
- Vermeer, M., Rahmstorf, S., 2009. Global sea level linked to global temperature. *Proc. Natl. Acad. Sci.* 106, 21527–21532. <http://dx.doi.org/10.1073/pnas.0907765106>.
- Wadey, M., Haigh, I., Brown, J., 2014. A century of sea level data and the UK's 2013/14 storm surges: an assessment of extremes and clustering using the Newlyn tide gauge record. *Ocean Sci. Discuss.* 11, 1995–2028.
- Wenban-Smith, A., 2010. Where's the evidence that time savings from new roads deliver tangible economic benefits? *Transport Times* (19 March, 18).
- Western Morning News, 1974. Huge seas, torrential rain bring havoc to Westcountry February 12, 9 Plymouth Library Archives, Devon.
- Williams, H.E., Briganti, R., Pullen, T., 2014. The role of offshore boundary conditions in the uncertainty of numerical prediction of wave overtopping using non-linear shallow water equations. *Coast. Eng.* 89, 30–44.
- Woodworth, P.L., 1987. Trends in U.K. mean sea level. *Mar. Geod.* 11, 57–87.
- Woodworth, P.L., Blackman, D.L., 2004. Evidence for systematic changes in extreme high waters since the mid-1970s. *J. Clim.* 17, 1190–1197.
- Woodworth, P.L., White, N.J., Jevrejeva, S., Holgate, S.J., Church, J.A., Gehrels, W.R., 2009. Evidence for the accelerations of sea level on multi-decade and century timescales. *Int. J. Climatol.* 29, 777–789.
- Wöppelmann, G., Pouvreau, N., Coulomb, A., Simon, B., Woodworth, P.L., 2008. Tide gauge datum continuity at Brest since 1711: France's longest sea-level record. *Geophys. Res. Lett.* 35, L22605.
- Zimmerman, R., 2002. Global climate change and transportation infrastructure: lessons from the New York area. Center for Climate Change and Environmental Forecasting: The Potential Impacts of Climate Change on Transportation. Federal Research Partnership Workshop 1–2, 2002. Department of Transportation, Washington DC, USA.
- Zong, Y., Tooley, M.J., 2003. A historical record of coastal floods in Britain: frequencies and associated storm tracks. *Nat. Hazards* 29 (1), 13–36.