UNECE

Climate Change Impacts and Adaptation for Transport Networks and Nodes

UNITED NATIONS

UNITED NATIONS ECONOMIC COMMISSION FOR EUROPE

Climate Change Impacts and Adaptation for Transport Networks and Nodes

UNITED NATIONS

Geneva, 2020

Note

Requests to reproduce excerpts or to photocopy should be addressed to the Copyright Clearance Center at copyright.com.

All other queries on rights and licenses, including subsidiary rights, should be addressed to:

United Nations Publications,
405 East 42nd Street
S-09FW001
New York, NY 10017
United States of America
Email: permissions@un.org; website: https://shop.un.org.

This report is a product of work of the Group of Experts on Climate Change Impacts and Adaptation for Transport Networks and Nodes during its 2015-2019 mandate. This work as well as preparation of the report was coordinated by Mr. Konstantinos Alexopoulos and Mr. Lukasz Wyrowski (United Nations Economic Commission for Europe). The Group was chaired by Mr. Jerzy Kleniewski (Poland) and Mr. Piet de Wildt (Netherlands). Invaluable inputs to the Group's work and to developing the report were provided, in particular, by Mr. Paul Bowyer (Climate Service Center Germany), Ms. Stephanie Hänsel (Deutscher Wetterdienst, Germany), Ms. Elizabeth Smalley (Transport Canada), Mr. Adonis Velegrakis (University of the Aegean, Greece) and Mr. Martin Dagan (United Nations Economic Commission for Europe). A more detailed list of acknowledgments is provided on page 5.

The designations employed and the presentation of material on any map in this work do not imply the expression of any opinion whatsoever on the part of the United Nations concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries.

United Nations publication issued by the United Nations Economic Commission for Europe.

Copyright © United Nations, 2020

All rights reserved world wide.

ECE/TRANS/283
UNITED NATIONS PUBLICATION
Sales No. E.20.II.E.23
ISBN 978-92-1-117237-9
eISBN 978-92-1-004779-1

United Nations Economic Commission for Europe (ECE)

The United Nations Economic Commission for Europe (ECE) is one of the five United Nations regional commissions, administered by the Economic and Social Council (ECOSOC). It was established in 1947 with the mandate to help rebuild post-war Europe, develop economic activity and strengthen economic relations among European countries, and between Europe and the rest of the world. During the Cold War, ECE served as a unique forum for economic dialogue and cooperation between East and West. Despite the complexity of this period, significant achievements were made, with consensus reached on numerous harmonization and standardization agreements.

In the post-Cold War era, ECE acquired not only many new member States, but also new functions. Since the early 1990s the organization has focused on analyses of the transition process, using its harmonization experience to facilitate the integration of central and eastern European countries into global markets. ECE is the forum where the countries of western, central and eastern Europe, Central Asia and North America – 56 countries in all – come together to forge the tools of their cooperation. That cooperation concerns economic cooperation and integration, statistics, environment, transport, trade, sustainable energy, forestry and timber, housing and land management and population. The Commission offers a regional framework for the elaboration and harmonization of conventions, norms and standards. The Commission's experts provide technical assistance to the countries of South-East Europe and the Commonwealth of Independent States. This assistance takes the form of advisory services, training seminars and workshops where countries can share their experiences and best practices.

Inland Transport Committee (ITC) — Centre of United Nations Transport Convention

Transport in Economic Commission for Europe

The ECE Sustainable Transport Division is the secretariat of the Inland Transport Committee (ITC) and the ECOSOC Committee of Experts on the Transport of Dangerous Goods and on the Globally Harmonized System of Classification and Labelling of Chemicals. The ITC and its 17 working parties, as well as the ECOSOC Committee and its sub-committees are intergovernmental decision-making bodies that work to improve the daily lives of people and businesses around the world, in measurable ways and with concrete actions, to enhance traffic safety, environmental performance, energy efficiency and the competitiveness of the transport sector.

The ECOSOC Committee was set up in 1953 by the Secretary-General of the United Nations at the request of the Economic and Social Council to elaborate recommendations on the transport of dangerous goods. Its mandate was extended to the global (multi-sectoral) harmonization of systems of classification and labelling of chemicals in 1999. It is composed of experts from countries which possess the relevant expertise and experience in the international trade and transport of dangerous goods and chemicals. Its membership is restricted to reflect a proper geographical balance between all regions of the world and to ensure adequate participation of developing countries. Although the Committee is a subsidiary body of ECOSOC, the Secretary-General decided in 1963 that the secretariat services would be provided by the ECE Sustainable Transport Division.

ITC is a unique intergovernmental forum that was set up in 1947 to support the reconstruction of transport connections in post-war Europe. Over the years, it has specialized in facilitating the harmonized and sustainable development of inland modes of transport. The main results of this persevering and ongoing work are reflected, among other things, (i) in 59 United Nations conventions and many more technical regulations, which are updated on a regular basis and provide an international legal framework for the sustainable development of national and international road, rail, inland water and intermodal transport, including the transport of dangerous goods, as well as the construction and inspection of road motor vehicles; (ii) in the Trans-European North-south Motorway, Trans-European Railway and the Euro-Asia Transport Links projects, that facilitate multi-country coordination of transport infrastructure investment programmes; (iii) in the TIR system, which is a global customs transit facilitation solution; (iv) in the tool called For Future Inland Transport Systems (ForFITS), which can assist national and local governments to monitor carbon dioxide (CO_2) emissions coming from inland transport modes and to select and design climate change mitigation policies, based on their impact and adapted to local conditions; (v) in transport statistics – methods and data – that are internationally agreed on; (vi) in studies and reports that help transport policy development by addressing timely issues, based on cutting-edge research and analysis. ITC also devotes special attention to Intelligent Transport Services (ITS), sustainable urban mobility and city logistics, as well as to increasing the resilience of transport networks and services in response to climate change adaptation and security challenges.

In addition, the ECE Sustainable Transport and Environment Divisions, together with the World Health Organization (WHO) – Europe, co-service the Transport Health and Environment Pan-European Programme (THE PEP). Finally, as of 2015, the ECE Sustainable Transport Division is providing the secretariat services for the Secretary-General's Special Envoy for Road Safety, Mr. Jean Todt, and as of 2018 the secretariat services for the United Nations Road Safety Fund.

Contents

Introduction **1**

I. Summary 2
II. Background 3
III. Implications for transport from climate change: A short review 5

Part I. Main ECE transport infrastructure networks and nodes exposed to potential impacts from climate change **13**

Chapter 1 Main transport networks and nodes in the ECE region **14**
I. Main roads, railways, waterways and nodes 14
II. Main roads 14
III. Railways 18
IV. Euro-Asian Transport Links network 23
V. Waterways. 24

Chapter 2 Climate Variability and Change: Observed changes and projected trends . 28
I. Recent trends and projections 28

Chapter 3 Analysing future climate impacts **42**
I. Climate information in adaptation planning. 42
II. Methods and data 43
III. Results and analysis 47

Chapter 4 Lessons learned and recommendations **82**
I. Lessons learned. 82
II. Recommendations 84

Part II. Case studies **89**

Chapter 1 Case studies on approaches, practices, methodologies and tools developed and applied by countries for analysing current and future climate change impacts on transport systems and/or for testing transport adaptation options **90**

Case study 1 (Germany)
Adapting the German transport system to climate change 91

Case study 2 (Germany)
Reviewing railway operation regulations and policies regarding potential climate change. 96

Case study 3 (Canada)
Methodology for assessing infrastructure vulnerability to climate change in Canada 101

Case study 4 (France)
Measures concerning transport from the National plan for Adaptation to Climate Change and case study on risk analysis methodology applied to the road network of the Interdepartmental Directorate for Mediterranean Roads (DIR Med) . . . 105

Case study 5 (Poland)
Polish practice in carrying out sensitivity, vulnerability and risk analysis for the identification of hotspots on transport infrastructure due to climatic factors . . . 110

Case study 6 (the Netherlands)
Development of a Climate Adaptation Strategy for the InnovA58 highway in the Netherlands . . . 116

Case study 7 (Romania)
Early Warning Intelligent System for Road Transportation Risks . . . 122

Case study 8 (United Nations Conference on Trade and Development)
Climate change impacts on coastal transport infrastructure in the Caribbean: Enhancing the adaptive capacity of Small Island Developing States (SIDS) . . . 128

Chapter 2 Case studies on diverse socioeconomic impacts and implications from climate change on various transport infrastructure studied in countries . . . 136

Case study 1 (Canada)
All-Season Roads in Northern Canada and Implications of Climate Change . . . 137

Case study 2 (Canada)
Winter Roads in Canada and the Implications of Climate Change . . . 143

Case study 3 (Finland)
New Guidelines for Winter Maintenance of Roads in Finland . . . 147

Case study 4 (Germany)
Low flow extremes of the Rhine river – Causes, impacts and adaptation of the most important inland waterway in Europe . . . 150

Case study 5 (Germany)
Impact of climate change on the water managementof the Kiel Canal . . . 157

Case study 6 (Germany)
Influence of weather and climate extremes on supra-regional traffic flows – Stress test scenario Middle Rhine . . . 161

Case study 7 (Iceland)
Sea level changes, guidelines and adaptation . . . 168

Annex . . . 175

Analysis of responses to the climate changeadaptation questionnaire 2016 . . . 176
References . . . 189

List of figures

Figure I.1.1 The E Roads network. . . . 15
Figure I.1.2 The Canadian National Highway System 16
Figure I.1.3 The E Road network censuses: AADT for 2005 (red), 2010 (purple) and 2015 (green). The width of the line represents traffic volume 17
Figure I.1.4 The TEN-T rail network. . . . 19
Figure I.1.5 Rail-road terminals from the comprehensive TEN-T Network 20
Figure I.1.6 The main Canadian rail network. . . . 21
Figure I.1.7 The E rail network censuses: number of trains (transport of goods) (combined for 2010 and 2015). . . . 22
Figure I.1.8 The Euro-Asian Transport Links network (rail and road routes, inland and maritime ports). Rail routes are shown in green, road routes in purple, inland ports in light blue and maritime ports in dark blue 23
Figure I.1.9 The E Waterways network (waterways in blue and ports as light blue triangles) 24
Figure I.1.10 Ports from the comprehensive and core TEN-T Network: inland and maritime ports are in green, maritime ports only are in dark blue, inland ports only are in light blue, and other types of ports are in grey. . . . 25
Figure I.2.1 Change of climatic factors. Each line represents an independently derived estimate. In each panel all data sets have been normalized to a common period of record. . . . 29
Figure I.2.2 Average global temperature changes in 2013–2017, as compared to the average of 1951–1980 30
Figure I.2.3 Projected (a) spring snow cover extent (SCE) in the Northern Hemisphere (NH) (March to April average) and (b) near-surface permafrost changes in NH for four RCPs (CMIP5 model ensemble). . . . 31
Figure I.2.4 Arctic and Antarctic sea ice extent (SIE). . . . 32
Figure I.2.5 Map of the northern circumpolar permafrost zone. Areas in yellow and red show the extent of the Yedoma permafrost 33
Figure I.2.6 (a) Estimated sea level change (mm) since 1900
(b) Global mean sea-level (seasonal cycle removed). . . . 34
Figure I.2.7 (a) SLR projections for 2100
(b) Global SLR in the twenty-first century relative to 1986-2005 35
Figure I.2.8 Deadly climatic conditions in 2100 under different emission scenarios. . . . 37
Figure I.2.9 Top: Current incidence (244) of Category 4 and 5 tropical and extratropical storms. Bottom: Incidence (313) of Category 4 and 5 storms under 2°C global warming relative to the pre-industrial times (in 2100, under RCP4.5) (Taalas, 2019). Key: x axis (latitude) in degrees and y axis (longitude) in degrees. . . . 39
Figure I.2.10 Return period of the present day 100-year ESLs along the European coastline under RCP4.5 and RCP8.5 in 2050 (a) and 2100 (b). Colored boxes express the ensemble mean value and colored patches the inter-model variability (best-worst case). . . . 40

Figure I.3.1 Risk of climate-related impacts results from the interaction of climate-related hazards (including hazardous events and trends) with the vulnerability and exposure of human and natural systems. 43

Figure I.3.2 Change in the warm spell duration index (WSDI) under a) RCP8.5 and b) RCP2.6 for period 2051-2080 with respect to the 1971-2000 baseline period. The maps show the multi-model mean values, and changes are in units of days per year.. 47

Figure I.3.3 Change in the warm spell duration index (WSDI) under RCP8.5, for a) 10th percentile values and b) 90th percentile values.. 48

Figure I.3.4 Change in the number of very hot days (VHD) under a) RCP8.5 and b) RCP2.6. Change is calculated from the 1971-2000 baseline period, for a future time period of 2051-2080. The map shows the multi-model mean values, as days per year. 49

Figure I.3.5 Change in number of very hot days (VHD) under RCP8.5, for a) 10th percentile values and b) 90th percentile values 50

Figure I.3.6 Change in the number of icing days (ID) under a) RCP8.5 and b) RCP2.6. Change is calculated from the 1971-2000 baseline period, for a future time period of 2051-2080. The map shows the multi-model mean values, and changes are in units of days per year. 51

Figure I.3.7 Change in number of icing days (ID) under RCP8.5, for a) 10th percentile values and b) 90th percentile values 52

Figure I.3.8 Change in the number of days with precipitation above 20mm (R20mm) under a) RCP8.5 andb) RCP2.6. Change is calculated from the 1971–2000 baseline period, for a future time period of2051-2080. The map shows the multi-model mean values, and changes are in units of days per year. 53

Figure I.3.9 Change in the number of days with precipitation above 20mm (R20mm) under RCP8.5, for a) 10th percentile values and b) 90th percentile values 54

Figure I.3.10 Change in the maximum 5-day consecutive precipitation amount (Rx5day) under a) RCP8.5 and b) RCP2.6. Change is calculated from the 1971-2000 baseline period, for a future time period of 2051-2080. The map shows the multi-model mean values, and changes are in per cent. 55

Figure I.3.11 Percentage changes in maximum 5-day consecutive precipitation amount(Rx5day) under RCP8.5, for a) 10th percentile values and b) 90th percentile values 56

Figure I.3.12 Change in consecutive dry days (CDD) under a) RCP8.5 and b) RCP2.6. Change is calculated from the 1971-2000 baseline period, for a future time period of 2051-2080. The map shows the multi-model mean values, and changes are in units of days per year 57

Figure I.3.13 Change in consecutive dry days (CDD) under RCP8.5, for a) 10th percentile values andb) 90th percentile values 58

Figure I.3.14 Change in the number of very hot days (VHD) under a) RCP8.5 and b) RCP2.6. Change is calculated from the 1971-2000 baseline period, for a future time period of 2051-2080. The map shows the multi-model mean values, as days per year. 59

Figure I.3.15 Change in number of very hot days (VHD) under RCP8.5, for a) 10th percentile values and b) 90th percentile values 60

Figure I.3.16 Change in the number of icing days (ID) under a) RCP8.5 and b) RCP2.6. Change is calculated from the 1971-2000 baseline period, for a future time period of 2051-2080. The map shows the multi-model mean values, and changes are in units of days per year. 61

Figure I.3.17 Change in number of icing days (ID) under RCP8.5, for a) 10th percentile values andb) 90th percentile values 62

Figure I.3.18 Change in the number of days with precipitation above 20mm (R20mm) under a) RCP8.5 and b) RCP2.6. Change is calculated from the 1971-2000 baseline period, for a future time period of2051-2080. The map shows the multi-model mean values, and changes are in units of days per year. 63

Figure I.3.19 Change in the number of days with precipitation above 20mm (R20mm) under RCP8.5, for a) 10th percentile values and b) 90th percentile values 64
Figure I.3.20 Change in the consecutive dry days (CDD) under a) RCP8.5 and b) RCP2.6. Change is calculated from the 1971-2000 baseline period, for a future time period of 2051-2080. The map shows the multi-model mean values, and changes are in units of days per year. 65
Figure I.3.21 Change in the consecutive dry days (CDD) under RCP8.5, for a) 10th percentile values and b) 90th percentile values 66
Figure I.3.22 Change in warm spell duration index (WSDI) under RCP8.5, mean values, E Roads (red lines) and TEN-T railways (green lines) in northern part of the ECE European subregion 68
Figure I.3.23 Change in warm spell duration index (WSDI) under RCP8.5, mean values, E Roads (red lines) and TEN-T railways (green lines) in southern part of the ECE European subregion 68
Figure I.3.24 Change in the number of very hot days (VHD) under RCP8.5, mean values, E Roads (red lines) and TEN-T railways (green lines) in southern part of the ECE European subregion 69
Figure I.3.25 Change in number of very hot days (VHD) under RCP8.5, mean values, Canadian National Highway System (red lines) and Canadian railway network (green lines) in the Southern Alberta, Saskatchewan, Manitoba, and Southern Ontario and Quebec 69
Figure I.3.26 Change in number of icing days (ID) under RCP8.5, mean values, E Roads (red lines) and TEN-T railways (green lines) in northern part of ECE subregion 70
Figure I.3.27 Change in number of icing days (ID) under RCP8.5, mean values, Canadian National Highway System (red lines) and Canadian railway network (green lines) in Western Canada. 71
Figure I.3.28 Change in number of icing days (ID) under RCP8.5, mean values, Canadian National Highway System (red lines) and Canadian railway network (green lines) in Eastern Canada 71
Figure I.3.29 Change in the number of days with precipitation above 20mm (R20mm) under RCP8.5, mean values, E Roads (red lines) and TEN-T railways (green lines) in northern part of the European ECE subregion. 72
Figure I.3.30 Change in the number of days with precipitation above 20mm (R20mm) under RCP8.5, mean values,E Roads (red lines) and TEN-T railways (green lines) in the Alps and eastern coast of Adriatic Sea 73
Figure I.3.31 Change in the number of days with precipitation above 20mm (R20mm) under RCP8.5, mean values,E Roads (red lines) and TEN-T railways (green lines) in the southern and eastern coast of Black Sea 73
Figure I.3.32 Change in the number of days with precipitation above 20mm (R20mm) under RCP8.5, mean values, Canadian National Highway System (red lines) and Canadian railway network (green lines) for the west coast of Canada. 74
Figure I.3.33 Change in the number of days with precipitation above 20mm (R20mm) under RCP8.5, mean values, Canadian National Highway System (red lines) and Canadian railway network (green lines) in Eastern Canada. 75
Figure I.3.34 Percentage changes in maximum 5-day consecutive precipitation amount (Rx5day) under RCP8.5, mean values, E Roads (red lines) and TEN-T railways (green lines) in northern and central part of European ECE subregion 75
Figure I.3.35 Change in in the number of consecutive dry days (CDD) under RCP8.5, mean values, E waterways (blue lines) and ports (light blue triangles) 76
Figure I.3.36 Present flood hazard projections for the European part of the UNECE region (100-year event), data from EC-JRC 77
Figure I.3.37 Projections of extreme sea levels (in m) for the 100-year event (ESL100) at the end of the twenty-first century under the RCP8.5 scenario for the studied ECE subregion (data from EC-JRC, see also Section II.E).. 78

Figure I.3.38 Major cargo seaports in Europe (Christodoulou and Demirel, 2018). Ports handling more than 10 million tonnes of goods per year are represented by the red scaled bars). . . . 79

Figure I.3.39 Gross weights of cargo handled in ports affected by present-day ESL100 (based on Christodoulou et al, 2018). The different colours correspond to different ESLs as indicated by the legend.. . . . 79

Figure I.3.40 Ports handling more than 2 million tonnes annually projected to be exposed to a 100-year event with extreme sea levels higher than 3 m (source: Christodoulou et al, 2018). In dark grey the EU28 countries. . . . 80

Figure II.1.1 Organizational flowchart of the project work within topic 1 of the BMVI Network of Experts. . . . 92

Figure II.1.2 Schematic illustration of the climate impact assessment within the BMVI Network of Experts . . . 94

Figure II.1.3 Excerpt of the standardised results matrix of Deutsche Bahn regulation 836. The left side (in blue) shows an example for the identification of entries and while on the right side (in red) the respective assessment is given . . . 96

Figure II.1.4 Five main categories of railway infrastructure each with up to four subcategories. For example DIN EN 12812 (“Supporting Structures – Requirements, dimensioning and design”) was assigned to category Structural engineering and subcategory Supporting structures. . . . 97

Figure II.1.5 Distribution of the 1650 entries according to the climate change parameters. Absolute values and their percentage proportion are given for each parameter. . . . 98

Figure II.1.6 Distribution of the 1650 entries according to their need for adjustment. Absolute values and their percentage proportionare given for each category. . . . 99

Figure II.1.7 The PIEVC Protocol. . . . 101

Figure II.1.8 Risk analysis flow chart . . . 107

Figure II.1.9 An example of a vulnerability rating of DIR Med road segment in the event of heat waves in a distant time horizon (2017-2100) for RCP8.6 scenario – with modification of the actual results . . . 108

Figure II.1.10 Maps portray levels of flooding risk on selected hot spots near the (a): city of Tczew (the Vistula river, Pomorskie Voivodeship), (b) city of Przemyśl (the San river, Podkarpackie Voivodeship), (c) village of Łęka (the Ner river and the Warta river, Wielkopolskie Voivodeship), (d) village of Sługocin (the Warta river, Wielkopolskie Voivodeship) . . . 114

Figure II.1.11 Vulnerability map of potential vulnerable locations for subsidence of road embankments . . . 119

Figure II.1.12 An example of adaptation paths (associated with pluvial flooding) . . . 120

Figure II.1.13 Geomorphological and meteorological risks in Romania . . . 123

Figure II.1.14 a) 3D image (Digital Elevation Model) of the road risk sector using drone imagines (done by project team), b) current situation plans (including aerophotography) . . . 124

Figure II.1.15.a The design of the application . . . 125

Figure II.1.15.b Architecture design . . . 126

Figure II.1.16 Interactive map (goo.gl/QDfz5j) . . . 127

Figure II.1.17 Location of the transportation assets of Jamaica and St Lucia considered as part of the case studies. Key: Jamaica - DSIA, Sangster International Airport; HFCP, Historic Falmouth Cruise Port; NMIA, Norman Manley International Airport; KCT, Kingston Freeport and Container Terminal; Saint Lucia - HIA, Hewanorra International Airport; VFSP, Vieux Fort Seaport; GCIA, George Charles International Airport; and CSP, Port Castries. Digital Elevation Model data from SRTM DTM . . . 129

Figure II.1.18 Coastal flooding – Jamaica. Inundation maps for: (a, e, i) DSIA, (b, f, j) KCT, (c, g, k) NMIA, and (d, h, l) HFCP, under a 1-100 year extreme sea level event - ESL100 (for 1.5°C temperature increase, 2030), 1-50 year extreme sea level event - ESL50 (2050, RCP4.5) and ESL100 (2100, RCP8.5) 131
Figure II.1.19 Coastal flooding – Saint Lucia, Inundation maps for (a, c, e) GCIA and CSP and (b, d, f) HIA and VFSP under ESL100 (1.5 °C, 2030), ESL50 (2050, RCP4.5) and ESL100 (2100, RCP8.5) 131
Figure II.1.20 Schematic overview of 'Climate Risk and Vulnerability Assessment Framework for Caribbean Costal Transport Infrastructure' 133
Figure II.2.1 Differential settlement associated with permafrost thaw along an abandoned section of Northwest Territory Highway 4, east of Yellowknife. 138
Figure II.2.2 Illustration of heat exchange in a thermosyphon. 139
Figure II.2.3 Canada's National Road Network 144
Figure II.2.4 The number of times when the temperature was below 0°C in three different winter periods in Finland 148
Figure II.2.5 Road weather information system in Finland. 149
Figure II.2.6 Left: Map of the globe highlighting stronger polar than equatorial temperature rise in the 20th century (taken from IPCC, 2014); Center: Location map showing the catchment of the Rhine River, the German waterway network, and the gauging station of Kaub; Right: Graphs showing flow regimes in different parts of the catchment (period 1961-1990, green = snow-dominated, yellow = rain-dominated, blue = complex). 150
Figure II.2.7 Time series showing annual maximum duration of low flow situations at Kaub (flow continuously lower than 783 m3/s; corresponding to a water depth of 190 cm). The duration of the situation 2018 is indicated by the red hatched line. Subsequences of the events were pooled by a smoothing technique (10 day running mean) neglecting minor interruptions. Data: German Federal Waterway and Shipping administration 153
Figure II.2.8 Time series showing annual number of low flow days at Kaub (flow lower than 760 m3/s as 30 year running mean based on (black) observed data, (grey) 20 projections of the future, and (red, purple) time slices that were highlighted in the KLIWAS research program (2021–2050, 'near' future; 2071–2100, 'distant future'). Source: Nilson & Krahe (2013, observed data updated to include the year 2018) 154
Figure II.2.9 Map of a stretch of the Middle Rhine showing water depths in the fairway during low flow conditions occurring, on average, 20 days per year under current (top figure) and 'distant future' (2071-2100, bottom figure) conditions, the latter representing the lower range of projected low flows. Additional shoals due to changes of low flow conditions (i.e. water depths below current fairway depth of 1.9 m) are shown in shades of red. 155
Figure II.2.10 Relation of water level difference (between Elbe and NOK) with dewatering potential at Brunsbüttel (Ebner von Eschenbach, 2017) for three possible usages of the sluice gates. 158
Figure II.2.11 Dewatering potential under RCP8.5 scenario with/without effect of land subsidence and an estimation of additional polar ice melting. The black line indicates the actual yearly amount of dewatering needed (600 mill m^3/year). 159
Figure II.2.12 Transport infrastructure of the Middle Rhine region 164
Figure II.2.13 Changes in car and truck traffic due to the extreme flooding of the left bank of the Rhine Riverat Oberwesel. 165
Figure II.2.14 Changes in rail freight traffic due to the extreme flooding of the left bank of the Rhine River at Oberwesel 166

Figure II.2.15 Flooding in the area of Oberwesel (forecast 2030) – Traffic load in rail freight trains per day . . . 166
Figure II.2.16 Flooding in the area of Oberwesel (forecast 2030) – Inland waterway transport over the section of Oberwesel by regions . . . 167
Figure II.2.17 The core transport infrastructure is coastal with few exceptions. Fishing being a main industry towns and villages are based on port facilities. The impact of climate change differs from the SE where the island's largest glacier is retreating fast, causing coastal uplift, to the SW region where sea level changes are enhanced by subduction. (red lines show domestic air routes) . . . 169
Figure II.2.18 Changes in vertical height over the 11 years period from 1993 and 2004 measured at the ISNET campaign GPS stations. Positive numbers indicateuplift and negative are subsidence, Valsson et al. 2007. . . . 170
Figure II.2.19 Changes in vertical height over the 12 years period from 2004 and 2016 measured at the ISNET campaign GPS stations. Positive numbers indicate uplift and negative are subsidence. Preliminary results from the National Land Survey of Iceland. . . . 171

List of tables

Table I.1 Summary table of climate change impacts on transportation infrastructure and operations . . . 10
Table I.3.1 Description of the six climate indices analysed in this report, and their associated relevance to the modes of transport and related climate hazards and impacts . . . 44
Table I.3.2 Details of the global climate model (GCM) and regional climate model (RCM) pairs (RCM) used to generate the multi-model ensembles analysed in this work. . . . 45
Table I.3.3 CMIP5 Models used for statistical downscaling for Canada . . . 46
Table II.1.1 Breakdown of evaluated PIEVC climate risk assessment recommendations . . . 104
Table II.1.2 Association of extreme weather event with one or more climate change variables . . . 107
Table II.1.3 InnovA58 climate adaptation approach. . . . 117
Table II.1.4 Identified key risks and possible measures. . . . 118
Table II.2.1 Number of events per 30-year period of low waters (LW) at Brunsbüttel higher than the design water level at Kiel-Canal, for one up to 6 consecutive low waters . . . 159
Table II.2.2 Overview of the scenarios applied in the stress test for the Middle Rhine Valley and its hinterland . . . 162
Table II.2.3 Vertical velocities at selected locations around Iceland based on GPS measurements. Names of some locations have been changed over to the nearest town. . . . 171
Table II.2.4 Changes in vertical height measured by GPS around Iceland. Noticeably retreating glaciers are causing swift uplift in the south and south east. From the report Global Climate Change and their impact in Iceland by The Scientific Committee on Climate Change: www.vedur.is/loftslag/loftslagsbreytingar/loftslagsskyrsla-2018. . . . 172

Introduction

Introduction

I. Summary

Inland transport networks and nodes (main roads, railways, waterways, terminals, ports) are instrumental to the safe, efficient and reliable movements of people to their destinations and goods to market. Transportation plays a significant role in supporting local, national and regional economies. Medium to longer-term disruptions to these networks and nodes may lead to adverse economic and social effects.

Extreme weather events, some of which are increasing in intensity and frequency, as well as slower onset climate changes (for example, sea level rise) and cumulative effects can result in transportation infrastructure damages, operational disruptions, and pressures on supply chain capacity and efficiency. As such, the United Nations Economic Commission for Europe (ECE) Group of Experts on Climate Change Impacts and Adaptation for Transport Networks and Nodes (the Group of Experts) has been analysing the impacts of climate change on main transport assets in the ECE region, as presented in this report.

The Group of Experts considered the main networks and nodes in the ECE region, observed climate changes, as well as future projections. In this context, the report presents the analyses of several climate variables relevant to transport networks and nodes within the ECE region. Regional maps have been produced in Geographical Information System (GIS) format, showing the main transportation networks, which have been overlain by the spatial distribution of the climate change projections, thereby presenting an initial perspective of areas of potential risk which could warrant more in-depth assessment.

The Group of Experts has also reviewed and presented country experiences in the form of case studies, demonstrating a range of efforts that have been undertaken to analyse climate change impacts on transport assets and operations.

With its work, the Group of Experts wishes to raise awareness on the importance of considering climate change and extreme weather (for example, in planning, construction, maintenance and operations) and of strengthening the climate resilience of inland transport assets, networks and nodes. It also aims to stimulate the continuation of work to establish the necessary analytical basis to facilitate local or regional assessments, leading to the identification of specific transport assets at risk which may require adaptation efforts.

The Group of Experts, within this report, also formulated a series of lessons learned which have served as a basis to recommend future action at national and international levels towards improved transportation system climate resilience (the full list of recommendations is provided in Chapter 4 of Part I).

It is especially recommended to invest efforts in:

- Creating awareness and understanding of the urgent need to understand and assess the impacts from climate change on inland transport infrastructure and operations, and to identify and implement adaptation measures;
- Obtaining consistent climate projection data sets for the entire ECE region;
- Analysing a broader range of climate indices so that current knowledge on impacts from a changing climate and extreme events on inland transport infrastructure can be strengthened and made available to countries through a ECE Geographical Information System; and

- Conducting projects that seek to more fully understand vulnerabilities to climate change and extreme weather across countries' inland transportation systems, and with the results supporting the creation of a knowledge base to share experiences, lessons learned and good practices.

II. Background

A. Establishment of a Group of Experts on Climate Change Impacts and Adaptation for Transport Networks and Nodes

At its seventy-seventh session (Geneva, 24–26 February 2015), the Inland Transport Committee (ITC) acknowledged the importance of continued work aimed at the identification of inventories of inland transport assets (networks and nodes) that may be impacted by a changing climate and would require adaptation to changing conditions. The Committee, at the request of the Working Party on Transport Trends and Economics, re-established the Group of Experts on Climate Change Impacts and Adaptation for Transport Networks and Nodes (the Group of Experts) and approved its 2015 Terms of Reference.

The Group of Experts' general objective has been focused on bringing together transport and climate change adaptation specialists to analyse impacts from the changing climate and identify an inventory of inland transport assets in the ECE region which may be at risk. In accordance with the ECE Guidelines for the Establishment and Functioning of Teams of Specialists, participation in the Group of Experts was open to all member States of the United Nations, intergovernmental and non-governmental organizations, as well as industry, rail and freight companies.

The original duration of the mandate of the Group of Experts had been approved until 30 June 2017. The Committee at its eightieth session (Geneva, 20–23 February 2018) extended the mandate until 30 June 2019, requiring the Group of Experts to submit its report to the September 2019 session of the Working Party on Transport Trends and Economics for review.

At its meeting of 31 May 2015, the Executive Committee approved the re-establishment of the Group of Experts and its 2015 Terms of Reference and on 18 May 2018 approved its extension.

B. Terms of Reference for the Group of Experts on Climate Change Impacts and Adaptation for Transport Networks and Nodes

The Group of Experts was tasked to identify inventories of main inland transport infrastructure assets (networks and nodes) in the ECE region that could potentially be impacted by climate change. In doing so, the Group was asked to use or develop models for the evaluation of climate change impacts including changes in extreme events under the different climate change Representative Concentration Pathways (RCPs) scenarios and overlay them on the ECE transport networks and nodes. The inventories were to be developed using Geographical Information System software as far as it would be possible. Given the focus on inland transport, the Group of Expert's work focused primarily on road, rail and inland waterways.

The Group was also tasked to review and present case studies of countries' work on transport infrastructure adaptation to climate change and their research on socioeconomic impacts from climate change on transport infrastructure.

To deliver on its tasks, the Group of Experts met twelve times between 3 June 2015 and 6 June 2019. The meeting agendas and reports as well as documents submitted by experts are available at: http://www.unece.org/trans/main/wp5/wp5_ge3_intro.html. Experts from the following countries and organisations participated in the work of the Group of Experts:

- ECE member States: Azerbaijan, Belgium, Canada, Croatia, Czechia, Denmark, Finland, France, Germany, Iceland, Italy, Malta, Netherlands, Poland, Portugal, Republic of Northern Macedonia, Romania, Russian Federation, Slovenia, Spain, Turkey, Uzbekistan;
- Other United Nations member States: Australia, Japan; and
- International organisations and others: United Nations Conference on Trade and Development, World Meteorological Organization, Secretariat of the United Nations Framework Convention on Climate Change, International Union of Railways, Climate Service Center Germany, University of the Aegean, Greece.

During the course of their work, the Group of Experts concluded that the identification of transport asset inventories at risk to climate change in the ECE region is a complex and long-term endeavour, for which its efforts to overlay downscaled climate projections with the location of transportation infrastructure data within this report, is an important first step. Determining potential transport networks or nodes at risk requires additional analysis. This could include, for example, more specific assessments considering key aspects such as: (i) natural and anthropogenic factors modifying the risks (i.e. underlying geomorphology, geology and land use), and (ii) transport asset characteristics (like its nature (e.g. social and economic significance), age, conditions, quality and technical specifications). Furthermore, impact modelling and in-depth knowledge on cause-effect relationships between climate parameters and impacts on the infrastructure could enable more specific evaluations of climate change impacts on the transport system. Also, defining of a set of factors to assess assets' criticality would also be required (e.g., this could include current and future trade flows, land use, connectivity and access).

The Group of Experts focused their efforts on the main transport assets in the ECE region and matching them with climatic projections for two RCP scenarios (RCP 2.6 and RCP 8.5). This overlay of transport assets with projected changes for selected climate indices gives a first indication of areas where major transport assets potentially face higher risks due to climate change than other areas of the ECE region.

The results of this work are presented in Part 1 of this report. More specifically, Part I begins with a description and brief analysis of several of the main ECE transport networks such as E Roads, the Canadian National Highway System, E Rail network, the Canadian rail network, and E Waterway, as well as nodes such as TEN-T Rail-road terminals, E Ports and TEN-T ports. It then provides a summary, based on the findings published by the Intergovernmental Panel on Climate Change (IPCC), the World Meteorological Organization (WMO) and other research, of observed and projected trends related to climate variability and change. Such changes in average climate parameters and specifically those related to extreme weather events are important considerations in the context of identifying and understanding impacts on transportation, and in strengthening climate resilience. This section of the report also describes the methods and data used to develop a selection of proxy climate change indices for Europe and Canada, and the overlay of the transportation assets with their projections. Finally, this part of the report concludes with lessons learned from the work of the Group of Experts during 2015-2019 mandate and their recommendations for future areas of work.

To support the analysis, ECE produced maps in GIS to showcase the projected changes for RCP.8.5 and RCP.2.6 for the selected indices, for the mean values, as well as 10th and 90th percentile values.

The ECE GIS can be consulted at https://unece.maps.arcgis.com/apps/webappviewer/index.html?id=5ecbe091d4d6417c8f11273762e24972. For this report, only selected maps have been included while others can be viewed at the link above.

To support its analysis for Part 1, in 2016, the Group of Experts prepared and disseminated a survey on climate change adaptation. The survey sought to: (a) collect information on the criticality of the networks in the ECE region; (b) assess the level/hierarchy of 'felt' climatic impacts over different modes of transportation; and (c) assess the awareness of and the plans to respond to the challenges posed by climate variability and change. The survey received a limited number of responses (15 responses). Their analysis is provided in Annex of this report.

The Group of Experts also gathered and reviewed a range of case studies on transportation adaptation and the socioeconomic impacts from climate change on transport infrastructure from other countries. The case studies can be found in Part II of this report.

The Group of Experts appreciates contributions from Paul Bowyer (Climate Service Center Germany), Stephanie Hänsel (Deutscher Wetterdienst, Germany), Elizabeth Smalley (Transport Canada), Adonis Velegrakis (University of the Aegean, Greece), Martin Dagan and Lukasz Wyrowski (ECE) in preparing Part I of this report.

The Group of Experts further appreciates preparation of case studies by the following countries and organisations: (i) Part II, Chapter 1: Canada, France, Germany, the Netherlands, Poland, Romania and United Nations Conference on Trade and Development, and (ii) Part II, Chapter 2: Canada, Finland, Germany and Iceland.

The Group of Experts would also like to acknowledge the World Climate Research Programme's Working Group on Regional Climate and the Working Group on Coupled Modelling, former coordinating body of CORDEX and responsible panel for CMIP5. The Group thanks the EURO-CORDEX consortium and climate modelling groups for producing and making available their model outputs for the European part of the ECE region and the Canadian Centre for Climate Services, in particular Carrington Pomeroy, for the provision of Canadian data for selected climate indices. It also acknowledges the Earth System Grid Federation infrastructure, an international effort led by the U.S. Department of Energy's Program for Climate Model Diagnosis and Intercomparison, the European Network for Earth System Modelling and other partners in the Global Organisation for Earth System Science Portals (GO-ESSP).

The Group of Experts further acknowledges European Commission-Joint Research Centre for providing information used in this report for assessing the riverine and coastal floods and Alexa Bradley from Transport Canada for editing this report.

III. Implications for transport from climate change: A short review

A previous review (ECE, 2013) of climate change impacts and adaptation for international transport networks has found that: (a) transportation assets tend to be at risk to both incremental climate change and extreme events (e.g. heat waves, heavy downpours, high winds and extreme sea levels and waves); (b) transport assets are particularly at risk from extreme events whose occurrence is considered relatively unlikely in comparison to typical weather variability; and (c) maintenance, traffic conveyance and safety are generally more at risk to climate influences than physical assets, as

thresholds for e.g. delaying/cancelling transport services are generally lower than those associated with damages to infrastructure. For example, the superstructure of the Gulf Coast bridges in the United States of America were heavily impacted by loading from direct wave impacts due to the unprecedented coastal sea levels induced by the storm surge of the Hurricane Katrina (2005) (USDOT, 2012).

Increases in the frequency/duration of heat waves pose substantial challenges to railway, road (and airport) operations and services, due to, for example, the buckling of rail tracks, the implementation of speed restrictions (reduced train speeds once certain heat threshold is reached), road pavement damages (e.g. pavement softening, rutting, flushing, bleeding) and reductions in aircraft payloads (Palko, 2017). Projected increases in the number of very hot days (Vogel et al., 2017) could lead to increases in road infrastructure failures. Drier and hotter summers may cause pavement to deteriorate and/or subsidence, which can affect performance and resilience (PIARC, 2012). The World Road Association, PIARC, initiated work adaptation strategies and methodologies to increase the resilience of road infrastructure at the policy, strategic, system level and project specific level; and refinement of an International Climate Change Adaptation Framework for Road Infrastructure (developed in 2015) (PIARC 2015).

Model projections (EC, 2012) estimate that the additional annual cost for the upgrade of asphalt binder for the European Union under the IPCC SRES scenario A1B[1] is € 38.5–135 million between 2040 - 2070 and € 65-210 million between 2070 - 2100. Nevertheless, it should be noted that road surfaces are typically replaced every 20 years; therefore, climatic impacts could be considered at the time of replacement. Heat waves could also significantly affect transport personnel, passengers and freight, particularly when combined with high relative humidity (Mora et al., 2017; Monioudi et al., 2018).

Warming temperatures are potentially creating new opportunities for international marine transportation networks, including a longer operating season and the opening up of shipping routes in Arctic waters. However, such warming is associated with navigational risks, including the increasing mobility of summer sea ice, greater coastal erosion due to increased coastal wave activity (e.g. Lantuit and Pollard, 2008) and extreme sea levels (Vousdoukas et al., 2018) at the northern coastlines of Canada, the Russian Federation and the United States of America. These all represent ongoing difficulties for shipping, exploration, and associated coastal infrastructure (Palko, 2017). There may be new economic opportunities for Arctic communities, as reduced sea ice extent (SIE) could facilitate access to substantial hydrocarbon deposits (at Beaufort and Chukchi Seas), improve community resupply, and increase international trade. Both northern and southern regions of the ECE are experiencing changes in temperature and thus increased freeze-thaw cycles, which can damage transportation infrastructure. For example, in Canada, freeze-thaw cycles can lead to damages/deterioration to airport runways and taxiways and roads (Palko, 2017).

Permafrost thawing (e.g. Streletskiy et al., 2012; Schuur et al. 2015; Palko, 2017) presents significant challenges for transportation, increasing costs in the development and maintenance of transport infrastructure (ECE, 2015). For example, many Arctic highways are located in areas with discontinuous permafrost, and involve substantial maintenance costs as well as usage restrictions (Karl et al., 2009). Thaw impacts include ground settlement, slope instability, drainage issues, and cracking, that can affect the structural integrity and load-carrying capacity of infrastructure in these regions (ECE, 2013). Such degradation is anticipated to increase substantially under the projected increases in the extent/depth of permafrost thaw (EEA, 2015a).

1 This scenario is roughly equivalent to the IPCC AR5 scenario RCP6.0.

Hydro-meteorological extremes, such as heavy rainfall/floods and droughts can cause substantial damages to transport infrastructure, operations and services. Extreme precipitation may result in river floods that can be costly for inland transport networks (Hooper and Chapman, 2012), as many main roads and railways are located within and/or crossing flood plains. Extreme precipitation can also affect bus/coach stations, train terminal facilities and inland waterway operations. There can be direct damages or wash-out of infrastructure such as roads, bridges or railway tracks during, and immediately after, a heavy precipitation event that may require emergency response as well as measures to support the structural integrity and maintenance of roads, bridges, drainage systems, and tunnels (USDOT, 2012; Palko, 2017). Future costs for bridge protection against flooding have been estimated at over € 500 million per year for the European Union (EC, 2012; ECE, 2015). Adaptive construction and maintenance practices can include the construction of adequate drainage and the use of permeable pavements and polymer modified binders (Willway et al., 2008).

In addition to infrastructure damages, downpours/floods may also result in an increase in rain-related road accidents (due to vehicle and road damages, reduced vehicle traction and poor visibility), delays, and traffic disruptions (Hambly et al., 2012; Palko, 2017).

Regions where flooding is already common will face more frequent and severe problems. Seasonal flooding due to the spring melt can be an issue for northerly areas where seasonal flooding by quick thaws or larger than normal snow packs can challenge transport infrastructure and operations. Standing flood waters could also have severe impacts and high costs.

The safety, efficiency and reliability of rail transportation can also be compromised by extreme precipitation and associated standing waters (Palko, 2017). Amongst others, the following damages can occur: track and line side equipment failure; flood scours at bridges and embankments due to high river levels and culvert washouts; flooding of below-grade tunnels; obstructions of railway tracks and embankments, bridges and culverts; landslides, mudslides and rockslides; and, problems associated with personnel safety and the accessibility of fleet and maintenance depots. In the United Kingdom of Great Britain and Northern Ireland, costs related to extreme precipitation/floods and other extreme events, which had been estimated as £ 50 million a year (2010), might increase to up to £ 500 million per year by the 2040s (Rona, 2011).

Extreme winds are also projected to be more catastrophic in the future (Rahmstorf, 2012), particularly in coastal areas where they can cause coastal defence overtopping and flooding of coastal/estuarine railways. Extreme winds can also cause transport infrastructure failures and service interruptions through wind-generated debris (PIARC, 2012; ECE, 2013; 2015), railcar blow-overs, rail line or road obstructions from, for example, fallen power lines or trees (Palko, 2017).

Inland waterways (IWW)[2] can also be affected by both floods and droughts. Floods can have major impacts such as the suspension of navigation, damage to port facilities due to increased loads on structures, damage of banks and flood protection works (ECE, 2013), silting, changes in the river morphology (PIANC, 2008). Inland waterways can also be affected by low water levels during droughts, which are considered a greater hazard for inland waterways than floods (Christodoulou and Demirel, 2018). Lower freshwater levels can also inhibit access by heavier vessels. A case study[3] on the Rhine–Main–Danube (RMD) corridor has found that the average annual losses due to low

2 According to the TRANSTOOLS8 reference scenario, in 2005 approximately 293 million tons of freight were transported within the EU countries (excluding national trade) using IWWs, a tonnage slightly less than the tonnage transported by rail and about one third of tonnage hauled by road

3 EU FP7-ECCONET Project, www.tmleuven.be/project/ecconet/home.htm

water levels were about € 28 million over a period of 20 years (Jonkeren et al., 2007). Projections from different climate models, however, did not show significant impacts on the RMD corridor by low flow conditions until 2050; nevertheless, 'dry' years might lead to a 6 - 7 per cent increase in total transport costs compared to 'wet' years.

Impacts of climate variability and change on European transport system were studied in several European projects.[4] It was found that there is a lack of reliable information relevant to the vulnerability of the different modes of transportation. Direct costs borne by the transport sector, such as those from infrastructure repair/maintenance and vehicle damage and increased operational costs, have been estimated at € 2.5 billion annually for the period 1998 - 2010, and indirect costs from transport disruptions at €1 billion annually. Rail has been the most affected mode of transportation, with 'hot spots' in Eastern Europe and Scandinavia, whereas the effects on roads (mainly from weather related road accidents) have been found to be more evenly distributed.[5]

A recent study focusing on the current multi-hazard exposure/risk of the road and rail infrastructure (Koks et al., 2019) has indicated that about 27 per cent of all global road and railway assets are exposed to at least one hazard and about 7.5 per cent to the 1 in 100-year flood event. Global Expected Annual Damages (EAD) due to direct damages were found to be up to 22 billion US dollars, 73 per cent of which are related to surface (pluvial) and riverine (fluvial) flooding. Although global EADs are small relative to the global GDP, in some countries EADs could amount to 0.5 to 1 per cent of GDP (the same order of magnitude as annual national transport infrastructure budgets). Cost-benefit analysis has indicated that increasing flood protection might have positive returns for about 60 per cent of thE Roads exposed to a 1 in 100-year flood event.

Coastal transport infrastructure (i.e. coastal roads, railways, seaports and airports) will be disproportionally impacted by climate variability. In addition to the above challenges, they will have to adapt to an increase in marine coastal flooding. A recent study focusing on climate risks for seaports and coastal airports in the Caribbean region has found that marine coastal flooding will be a significant risk as early as in the 2030s, which will require significant technical adaptation measures (Monioudi et. al., 2018). In the ECE region, mean sea level rise (SLR) and increasing storm surges and waves, particularly along North-Western Europe, the Baltic Sea and the Northern Pacific coast of the United States of America and Canada (e.g. Vousdoukas et al., 2016; 2018), may induce impacts, including flooding of roads, rail lines and tunnels in coastal areas. Coastal inundation can render transportation systems unusable for the duration of the event and damage terminals, intermodal facilities, freight villages, storage areas and cargo and, thus, disrupt supply chains for longer periods of time (ECE, 2013; 2015). Pecherin et al. (2010) have estimated that a 1 m increase in the extreme sea levels (ESLs) above the inundation level of the current 1-in 100 year-storm event,[6] would result in damages and repair costs of up to € 2 billion for mainland French A-roads, excluding operational and connectivity costs.

4 The EU-FP7 WEATHER www.weather-project.eu and EWENT Projects www.weather-project.eu/weather/inhalte/research-network/ewent.php

5 For more information, please see 4 www.weather-project.eu and www.weather-project.eu/weather/inhalte/research-network/ewent.php

6 Costs assumed in the study: average linear property cost at €10 million/km of road surface; repair costs at about €250 thousands/km

Another study (EC, 2012) has provided an initial estimate of future risks to European coastal transport infrastructure from mean SLR and storm surges on the basis of a comparison between the coastal infrastructure elevation and the combined level of 1 m mean SLR and the 100-year storm surge height. It was found that coastal transport infrastructure (e.g. coastal roads) at risk represents 4.1 per cent of the total, with an asset value of about € 18.5 billion. However, as more detailed projections on future extreme sea levels-ESLs and coastal waves start to emerge (Vousdoukas et al., 2016; 2018; Camus et al., 2017) for the ECE region (and beyond), it would be worthwhile to again assess the potential inundation impacts on ECE coastal transport infrastructure under different emissions scenarios.

A recent study focusing on ports (Christodoulou and Demirel, 2018) has found that over 60 per cent of the European Union seaports may be under high inundation risk by 2100 under the maximum SLR (about 1 m) (IPCC,2013) and ESLs of about 3 m; (for the distribution of projected ESLs along the European coastline see Vousdoukas et al., (2018)). Impacts could include disruptions to operations and damages to port infrastructure and vessels, which will also affect hinterland connections. Seaports in Greece (169), the United Kingdom (165) and Denmark (90) will be affected by 2080, when the number of European Union seaports facing inundation risks is expected to increase by 50 per cent relative to 2030 (852 ports). This trend is particularly noticeable along the North Sea coast, where according to the Geographical Information System of the Commission (GISCO) database, over 500 ports with traffic accounting for up to 15 per cent of the world's cargo transport are situated (EUCC-D, 2013). A recent global port industry survey carried out by United Nations Conference on Trade and Development (UNCTAD) has indicated that there is a lack of information and data required for effective adaptation and low levels of preparedness across global ports (Asariotis et al., 2017).

It should also be noted that the transport industry is a demand-driven industry. Climate change can have significant effects in almost all sectors of the economy, and thus indirectly affect transportation services through, for example, changes in commodity demand and tourism (ECE, 2015).

Lastly, responses from the 2016 survey confirm that (i) heavy precipitation/floods, fog and high temperatures are major climatic stressors/hazards, particularly for the road network; and (ii) storm surges/waves have already had noteworthy impacts not only to ports, as expected, but also on coastal road and rail networks.

Table I.1 provides a summary of climate change impacts on transport infrastructure and operations.

Table I.1 Summary table of climate change impacts on transportation infrastructure and operations

Factor/hazard	Impacts		
	Road	Rail	Inland waterways, ports, and airports
Temperature			
Higher mean temperatures; heat waves/ droughts; changes in the numbers of warm and cool days	Thermal pavement loading and degradation; asphalt rutting; thermal damage to bridges; increased landslides in mountainous roads; asset lifetime reduction; increased needs for cooling (passenger and freight); occupational health and safety issues during extreme temperatures; shorter maintenance windows; increased construction and maintenance costs; potential changes in demand; reduced integrity of winter roads and their shortened operating seasons	Track buckling; infrastructure and rolling stock overheating/ failure; slope failures; signalling problems; speed restrictions; asset lifetime reduction; higher needs for cooling; shorter maintenance windows; higher construction and /maintenance costs; demand changes; occupational health and safety issues during extreme temperatures	Damage to infrastructure (e.g. runways, taxiways), equipment (e.g. navigational equipment) and cargo; decreased traction on runways; higher energy consumption for cooling; air transport payload restrictions (due to reduced lift during aircraft take-off) and runway length extensions required; potential reductions in snow/ice removal costs; occupational health and safety issues during extreme temperatures
Reduced snow cover and arctic land and sea ice; permafrost degradation, quick ice thawing	Damage and deterioration of roads; decreases in travelling days; slope instability and embankment failures; coastal erosion affecting coastal roads	Rail track damages (e.g. buckling of rail tracks); slope instability and embankment failures; freight and passenger restrictions	Damages to port and airport infrastructure (for example, runways and taxiways); potential for longer shipping seasons, new navigation opportunities and less fuel costs, but higher support service costs and hazards to vessel navigation due to more mobile sea ice, changes in location of ice jams
Precipitation			
Changes in the mean values; changes in intensity, type and/or frequency of extremes (floods and droughts)	Inundation, damage and wash-outs of roads and bridges; increased landslides, mudslides; bridge scouring earthwork and equipment failures; poor visibility that can increase accidents; reduced vehicle traction; more frequent slush flows; delays; changes in demand	Flooding, damage and wash-outs of bridges; bridge scouring; problems with drainage systems and tunnels; flooding of below-grade tunnels; landslides, mudslides and rockslides; embankment and earthwork damages; operational problems; delays; changes in demand	Port infrastructure inundation and/or damage to port facilities; poor manoeuvrability of locks and vessels due to increased water level and velocity; flooding of airport runways/ taxiways and damage to airport structures and equipment; under extreme low rainfalls, marine vessel navigation restrictions in IWWs due to droughts/ diminished river water levels; decreased traction on airport runways (for example, due to freezing rain); increased use of pavement de-icers (runways) and increased use of aircraft de-icing and anti-icing

Table I.1 (Continued)

Factor/hazard	Impacts		
	Road	Rail	Inland waterways, ports, and airports
Windstorms			
Changes in frequency and intensity of events	Damages to fences; increased risk for road accidents due to reduced vehicle stability; damage to road structures (including signage and traffic signals); obstructions (e.g. due to fallen power lines/trees); bridge closures	Damages to installations and catenary; overvoltage; rail line obstructions (e.g. due to fallen power lines/trees); rail car blow-overs; disruption to operations	Problems in vessel navigation and berthing with ports; cancellations/delays at airports (e.g. aircraft not being able to land or take-off); damages to airport terminals and navigation equipment
Sea levels/storm surges			
Mean sea level rise (SLR)	Increased risks of permanent inundation; erosion of coastal roads; flooding, damage and wash-outs of roads and bridges	Bridge scour, installation and catenary damage of coastal assets; flooding, damage and wash-outs of railway tracks and embankments, bridges and culverts; flooding of below-grade tunnels	Port infrastructure inundation and/or damage to port facilities; flooding of airport runways/taxiways and damage to airport structures and equipment; increased access to ports (e.g. heavier vessels); dredging requirements; increased costs of port protection; effects on key transit points (e.g. the Kiel Canal)
Increased extreme sea levels (ESLs); changes in wave energy and direction	Structural damages to coastal roads; temporary inundation rendering thE Roads unusable; delays/diversions of traffic	Structural damages to coastal railways, embankments and earthworks; restrictions and disruption of coastal train operations	Asset inundation; higher port construction/maintenance costs; navigation channel sedimentation; people/ business relocation

Note: List is not exhaustive

Photo: graphicdesignerka / shutterstock.com

Part I.

Main ECE transport infrastructure networks and nodes exposed to potential impacts from climate change

This part of the report consists of four chapters:

***Chapter 1** describes the main transport networks and nodes in the ECE region that have been included within the analysis and illustrates them in maps produced using a Geographical Information System (GIS). It also provides information on the use of the networks (where available) and makes initial network assessments as to whether disruptions on the networks could trigger potential negative socioeconomic impacts.*

***Chapter 2** presents a discussion on a range of climate change factors which can affect transportation networks and nodes in the ECE region. These include temperature, precipitation (rainfall), snow, ice and sea level rise as well as extreme events. It focuses on their recently observed and projected trends.[7]*

***Chapter 3** presents the methods and data used to prepare and analyse a selection of climate indices, and the results of the overlay of the climate indices with the transportation networks.*

***Chapter 4** provides lessons learned by the Group of Experts during the course of its work. It also contains recommendations which the Group of Experts formulated based on the lessons learned and which should serve as a basis for continuation and advancing the ECE work of the adaptation of inland transport infrastructure to climate change in an effective way.*

7 Information on these climatic factors until 2013 has been presented in a previous ECE report (ECE, 2013).

Chapter 1 Main transport networks and nodes in the ECE region

I. Main roads, railways, waterways and nodes

The ECE region is widely linked by interconnected networks of roads, railways and waterways. In the European part of the ECE region, the main networks are established in the framework of International Agreements administered by ECE. These networks are focused on in this report. For the Canadian part of the ECE region, the National Highway System (NHS) was first identified by the Council of Ministers Responsible for Transportation and Highway Safety in 1988 and later extended in 2005 to define a network of interprovincial highways linking together major population centres and critical intermodal facilities and major land border crossings. The Canadian railway network is a mix of trunk lines owned by the two Class I freight railways and feeder lines operated by shortline railways.

The road and rail networks, inland waterways and their nodes discussed in this chapter represent only a fraction of the entire network (namely those routes with specific relevance for inter-regional traffic flows). For rerouting within one mode of transport, in the event of disruption, there are more options available (specifically for the road networks) than visible in the figures provided in this chapter.

II. Main roads

A. E Roads network

A major road network in the European part of the ECE region has been established in the framework of the European Agreement on Main International Traffic Arteries (AGR). The Agreement was done at Geneva on 15 November 1975 and entered into force on 15 March 1983. It lays down a coordinated plan for the construction and development of roads of international importance, the E Roads network.

The Agreement distinguishes between the referencE Roads and intermediatE Roads. ReferencE Roads, also called class-A roads, have two-digit numbers assigned. Branch, link and connecting roads, also called class-B roads, are numbered with three digits.

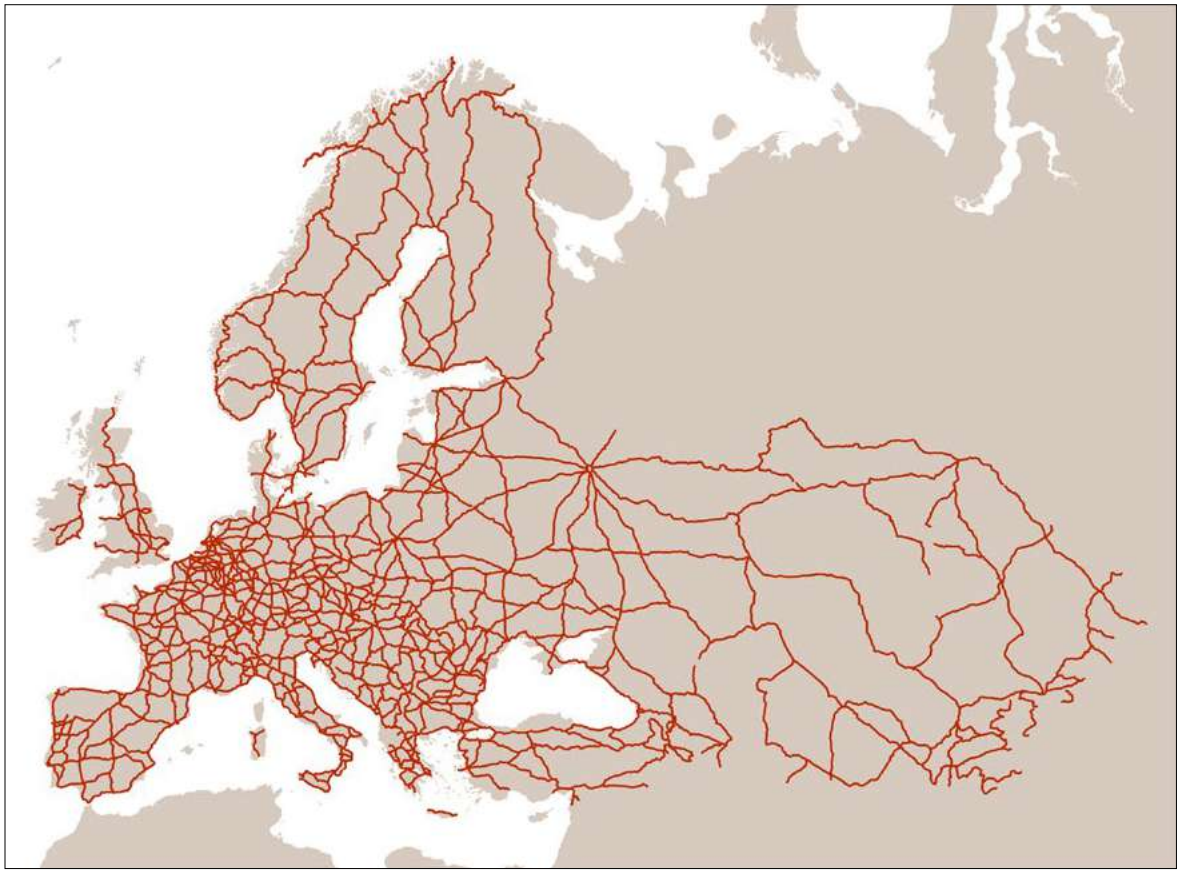
The Agreement also classifies roads based on their geographical orientation. North-south orientated referencE Roads have two-digit odd numbers ending in ‘5’ and are in ascending order from west to east. East-west orientated referencE Roads have two-digit even numbers ending in ‘0’ and are in

ascending order from north to south. IntermediatE Roads have respectively two-digit odd and two-digit even numbers in between the numbers of the referencE Roads between which they are located (e.g. E12, E14 are intermediatE Roads located in between referencE Roads E10 and E20). Class-B roads have three-digit numbers, the first digit being that of the nearest reference road to the north, and the second digit being that of the nearest reference road to the west; the third digit is a serial number.

The E Roads network has been put into the ECE GIS by the secretariat, using open source data coming from OpenStreetMap (Figure I.1.1). The accuracy of the geographical location of E Roads presented in the map relies on the accuracy of this data source. Basic data verification has been done to compare the E Roads network described in the AGR Agreement with the network available in OpenStreetMap data, however gaps may exist. The AGR Agreement describes thE Roads as chains of cities, without giving information on the paths which connect these cities.

The OpenStreetMap data was downloaded from Geofabrik[8] for Europe and Asia. The package data was then extracted and filtered[9] in order to keep only motorways, primary roads and trunk roads, containing reference to “E Roads” in their attributes (field “int_ref”).

Figure I.1.1 The E Roads network



Source: ECE

8 download.geofabrik.de

9 Using osmfilter.exe. Command line given here as example for a file named “fr.o5m”: osmfilter fr.o5m --keep= --keep-ways=”(highway=motorway =primary =trunk) and int_ref=*E*” --keep-tags=”all highway int_ref” -o=fr.osm

B. Main roads network in Canada

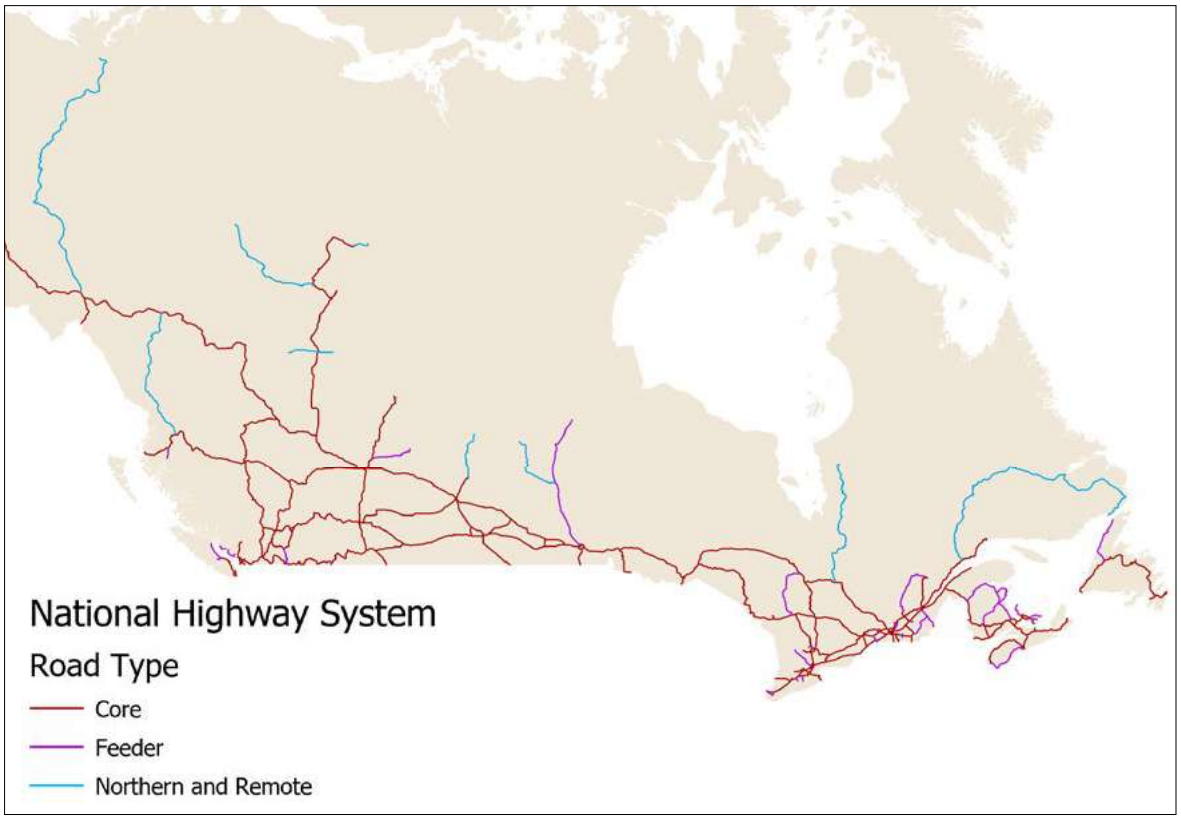
The Canadian highway network included in this study is the National Highway System (NHS) which consists of about 38,000 route-km divided into three sub-networks:

(a) Core Routes (27,600 route-km) – key interprovincial and international corridor routes joining capital cities and other major population centres and links to key intermodal facilities and major border crossings.

(b) Feeder Routes (4,500 route-km) – key linkages to the Core Routes from regional population and economic centres.

(c) Northern and Remote Routes (5,900 route-km) – key linkages to Core and Feeder routes that provide the primary means of access to northern and remote areas, economic activities and resources.

Figure I.1.2 The Canadian National Highway System



Source: Natural Resources Canada, National Road Network; Route definition: Council of Ministers Responsible for Transportation and Highway Safety, National Highway System Review Task Force Report, 2005

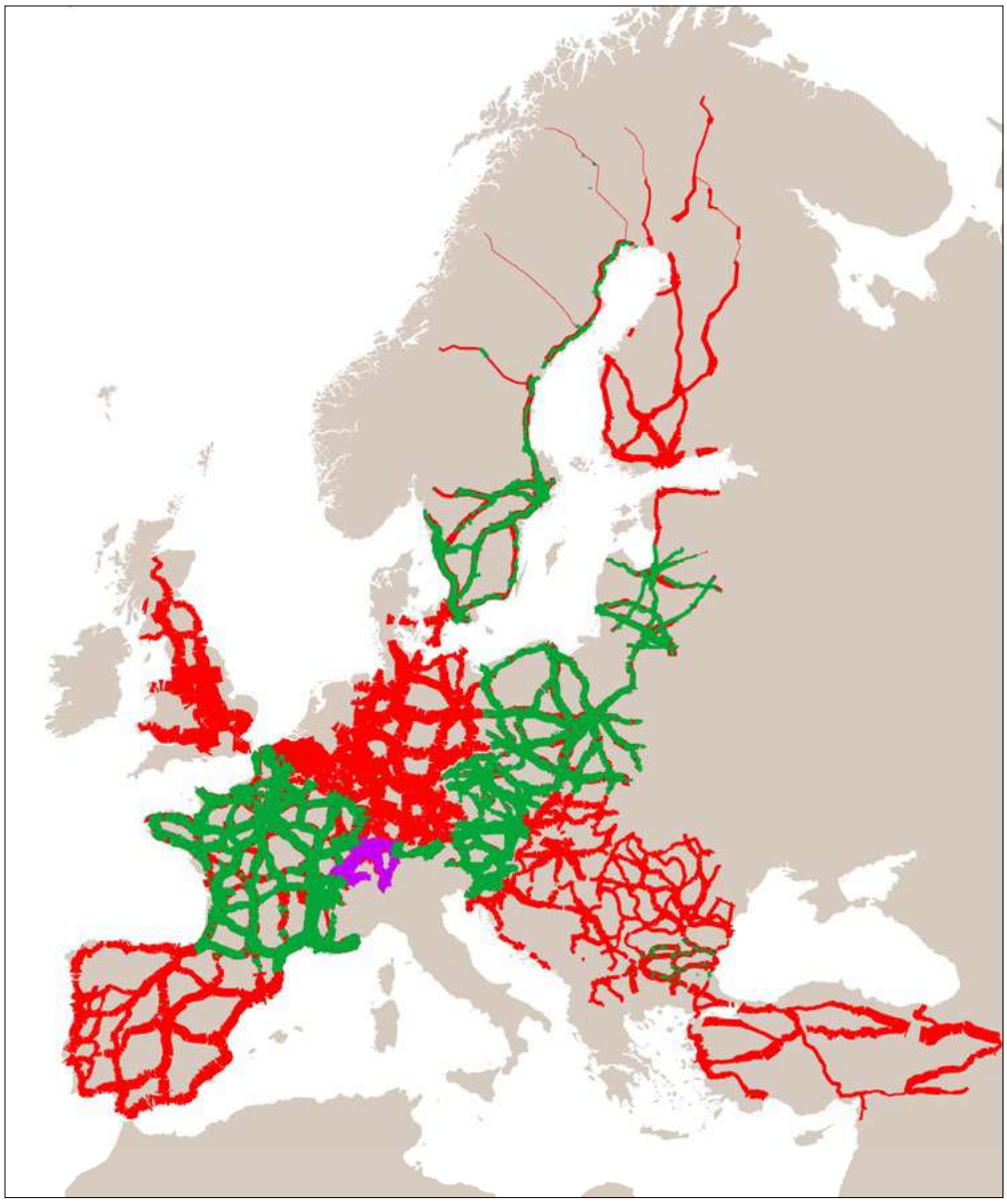
C. Traffic flows on E Roads

Traffic on the E Roads is measured by means of a census conducted by the ECE every five years. The 2005, 2010 and 2015 E Roads censuses are presented in this study. Data is collected for individual segments as defined by the member States, based on the standards set out in Annex II to the AGR Agreement. This data includes the number and size of lanes, and traffic information measured as the Annual Average Daily Traffic (AADT). The ADDT measures the total number of motorized vehicles that

pass through each particular segment of an E Road in a given year, divided by the number of days in the year. While this measure does not record the type of vehicle, travel times or seasonality factors, it is a useful headline measure of traffic, and potentially congestion; thus it can be considered as a proxy indicator to initially determine the criticality of the transport network (Figure I.1.3).

The geographic location of the counting posts, in other words, devices that measure traffic flow, were determined using ECE member States' responses to the census questionnaire, and the traffic flow values are those measured at those counting posts. Therefore, the maps generated using data from the counting posts do not always show road segments that line up perfectly to the real network. It shows instead straight-line paths between counting posts. Moreover, the maps represent data as collected by member States. In some cases, traffic counts have only been conducted on specific points and not on every segment.

Figure I.1.3 The E Road network censuses: AADT for 2005 (red), 2010 (purple) and 2015 (green). The width of the line represents traffic volume



Source: ECE

D. Roads networks analysis

The E Roads constitute a dense network except for its northern and eastern parts (Figure I.1.1). In Canada the main road network is particularly dense in the south and sparse otherwise (Figure I.1.2).

Generally, where the road network is dense, it can provide more flexibility to its users for a selection of routes between a trip origin and its destination. Thus some transportation networks, due to the presence of redundancy in the network (for example, multiple routes, more than one mode of transportation available), offer some capability to adjust to the disruptions posed by climate change. Areas where there is only one major route connecting the origin and its destination may be particularly vulnerable to disruptions.

Rerouting vehicles could work as long as the alternative route is capable of accommodating the additional traffic. If the alternative route is incapable of accommodating more vehicles, this could further disrupt the network.

The E Rail and the Canadian rail networks discussed in Section III (Railways) below may provide alternative rerouting possibilities. However, in cases where the road and rail networks run parallel to one another, both networks may be disrupted at the same time due to extreme weather conditions. Furthermore, for transport of big cargo units, rail-road terminals are required for transhipment. Again, rerouting will only be viable as long as the rail network is able to effectively and efficiently accommodate additional passengers and or/cargo units. There are also opportunities in some cases to shift to inland waterways.

Network stress tests can be performed to determine traffic levels which cannot be absorbed by the network in the event of a disruption on a given segment of the network (an example of stress test is presented in Chapter 2 of Part II, case study 6). Data on average daily traffic volumes may be assessed as proxies for selection of sections of the road network that should be prioritized for stress tests. Where the rail network could serve as alternative, the average daily traffic volumes/number of trains should be looked at for each network and analysed against the network's capacity.

The available average daily traffic volume data, as presented in Section C above, show a rather significant usage of E Road network in transit countries. The sparse network is used less intensively. However, detailed local analyses are required to determine whether any road or part of the network would stop to serve its function in the case of occasional disruption and hence trigger severe socioeconomic impacts. They will show how critical roads or sections of the networks are.

III. Railways

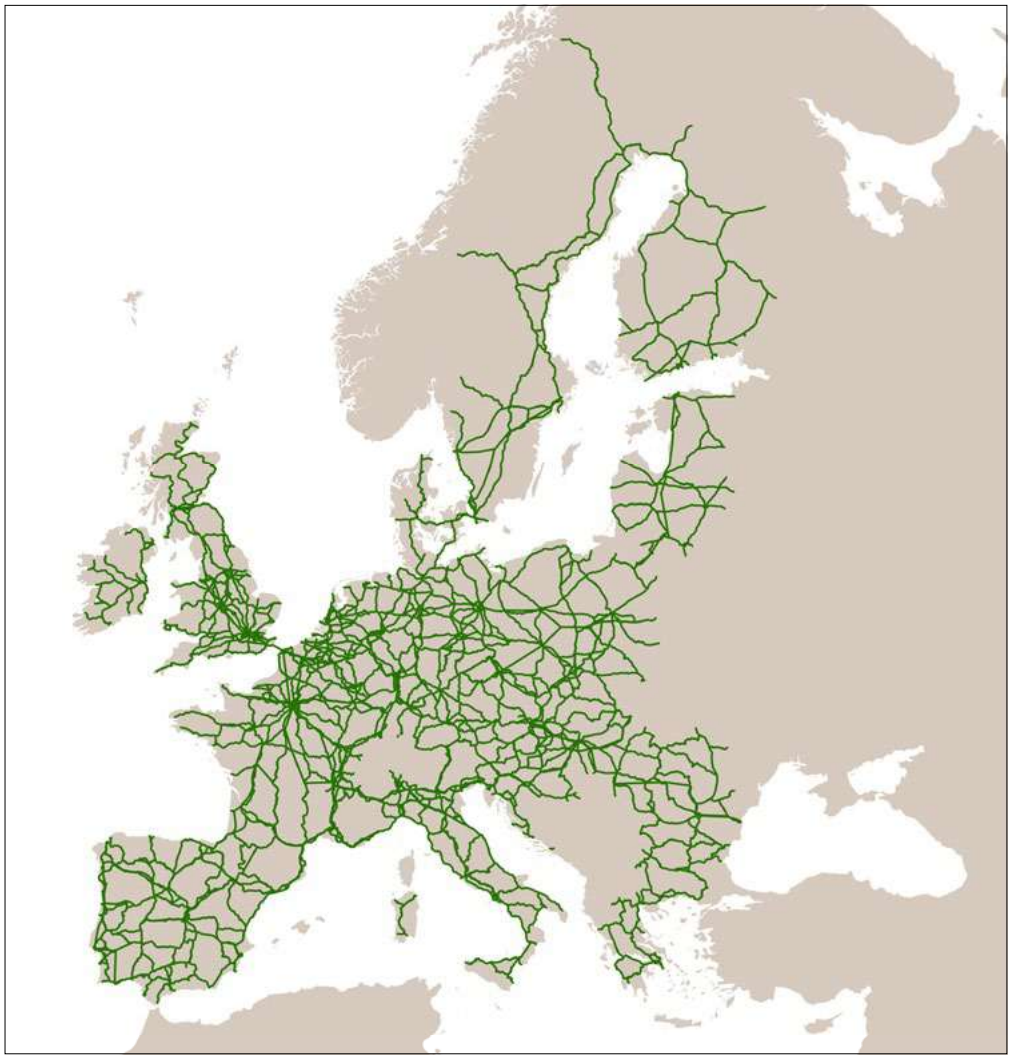
A. E Rail network and rail-road terminals

The rail network of international importance in the European part of the ECE region has been established in the framework of the European Agreement on Main International Railway Lines (AGC). The Agreement was done in Geneva on 31 May 1985 and entered into force on 27 April 1989. It identifies railway lines of major international importance, the E Rail network. It also provides the technical characteristics as a basis for further development of the European railway infrastructure.

The E Rail network has yet to be fully geocoded and so is not available in a GIS environment. Therefore, this study used data from the Trans-European Transport Network (TEN-T)[10] (Figure I.1.4). The TEN-T network is a European Commission policy directed towards the implementation and development of a Europe-wide network of roads, railway lines, inland waterways, maritime shipping routes, ports, airports and rail-road terminals. The Trans-European Rail Network is made up of the Trans-European high-speed rail network as well as the Trans-European conventional rail network. The map is available from the European Commission.

Rail-road terminals important for international combined transport have been defined in the European Agreement on Important International Combined Transport Lines and Related Installations (AGTC). This Agreement was done in Geneva on 1 February 1991 and entered into force on 20 October 1993. As these terminals have not yet been geocoded, data on TEN-T rail-road terminals are used for this study. This data was extracted from the TEN-T Comprehensive Network, for European Union Member States and neighbouring countries (Figure I.1.5).

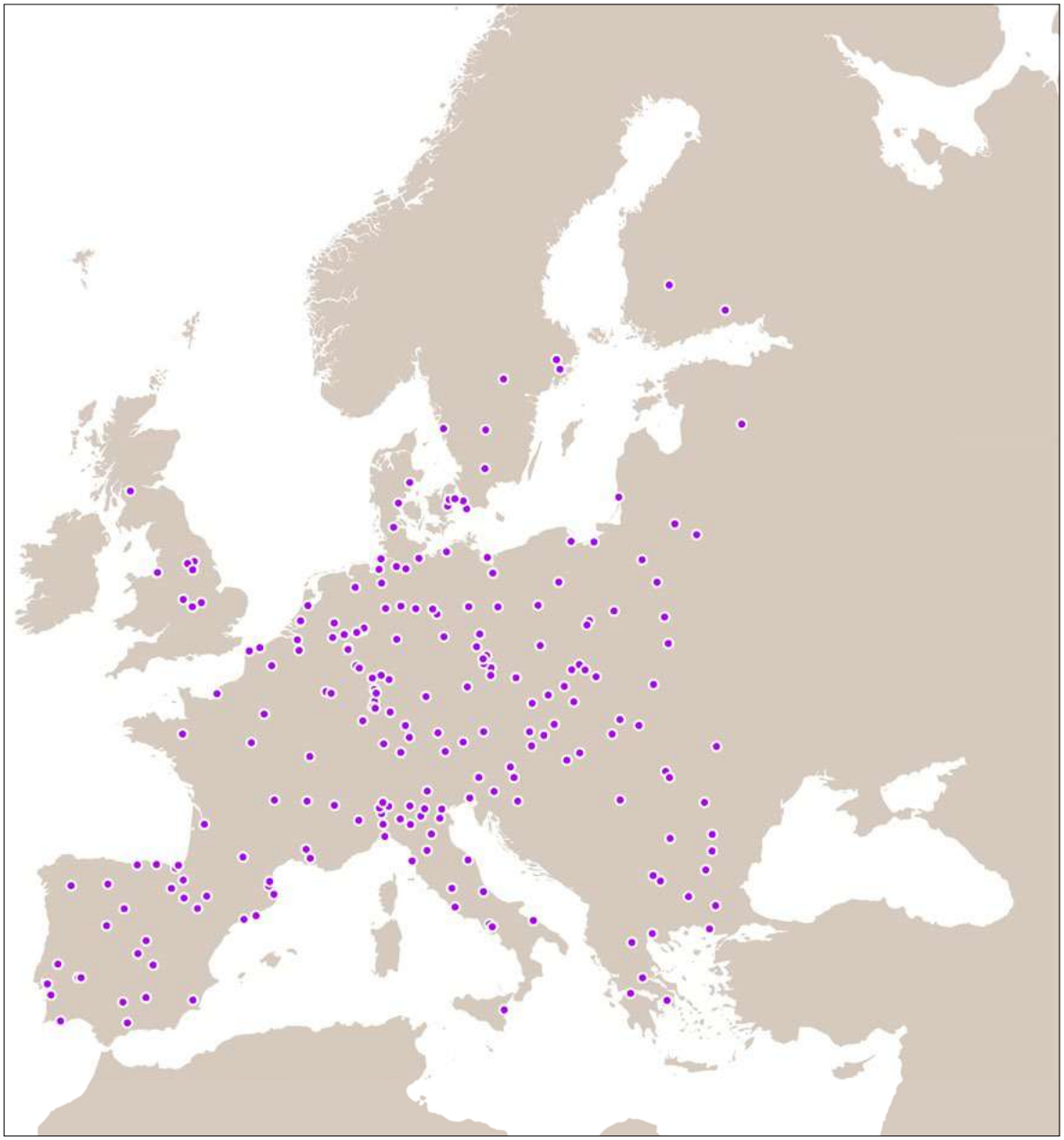
Figure I.1.4 The TEN-T rail network



Source: European Commission

10 For more information, see ec.europa.eu/transport/themes/infrastructure_en

Figure I.1.5 Rail-road terminals from the comprehensive TEN-T Network



Source: European Union, 2018

B. Main rail network in Canada

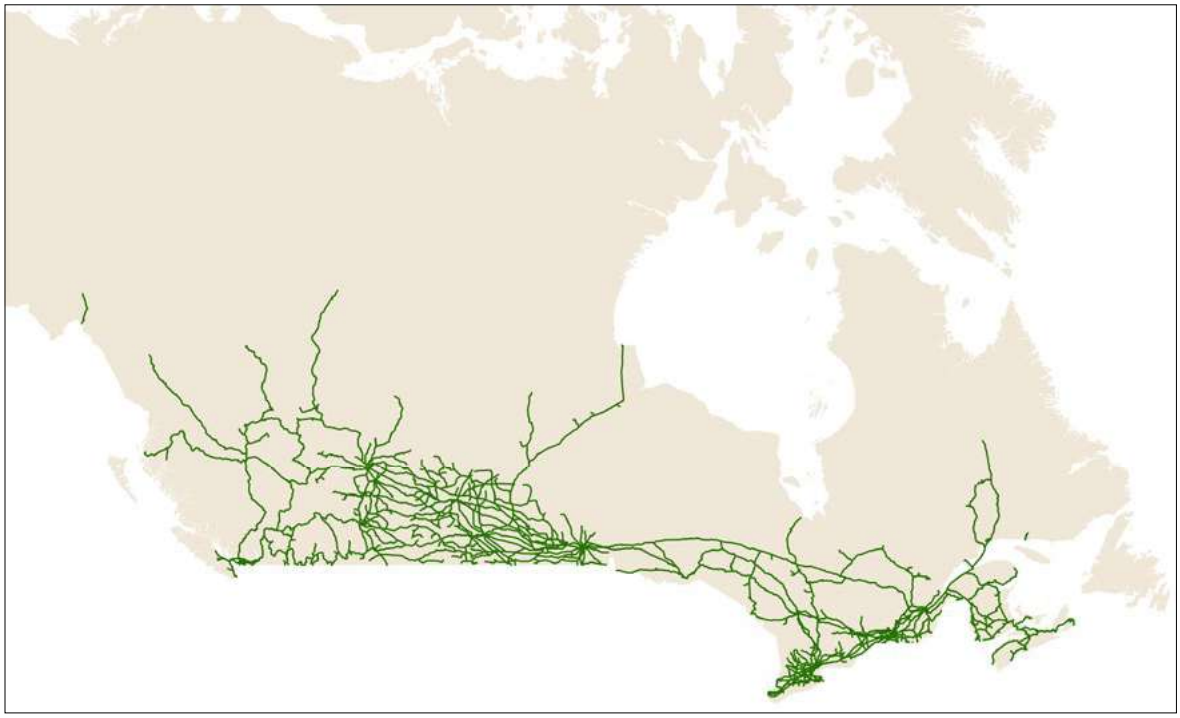
The Canadian railway network consists of two principal networks:

(a) Trunk routes owned and operated by the large Class I freight railways, Canadian National and Canadian Pacific, and

(b) A network of regional and feeder lines owned and operated by shortline railways under a mix of federal and provincial regulation.

The length of the trunk network is about 35,000 km while the shortline network is about 7,000 km in length.

Figure I.1.6 The main Canadian rail network



Source: Natural Resources Canada, National Railway Network

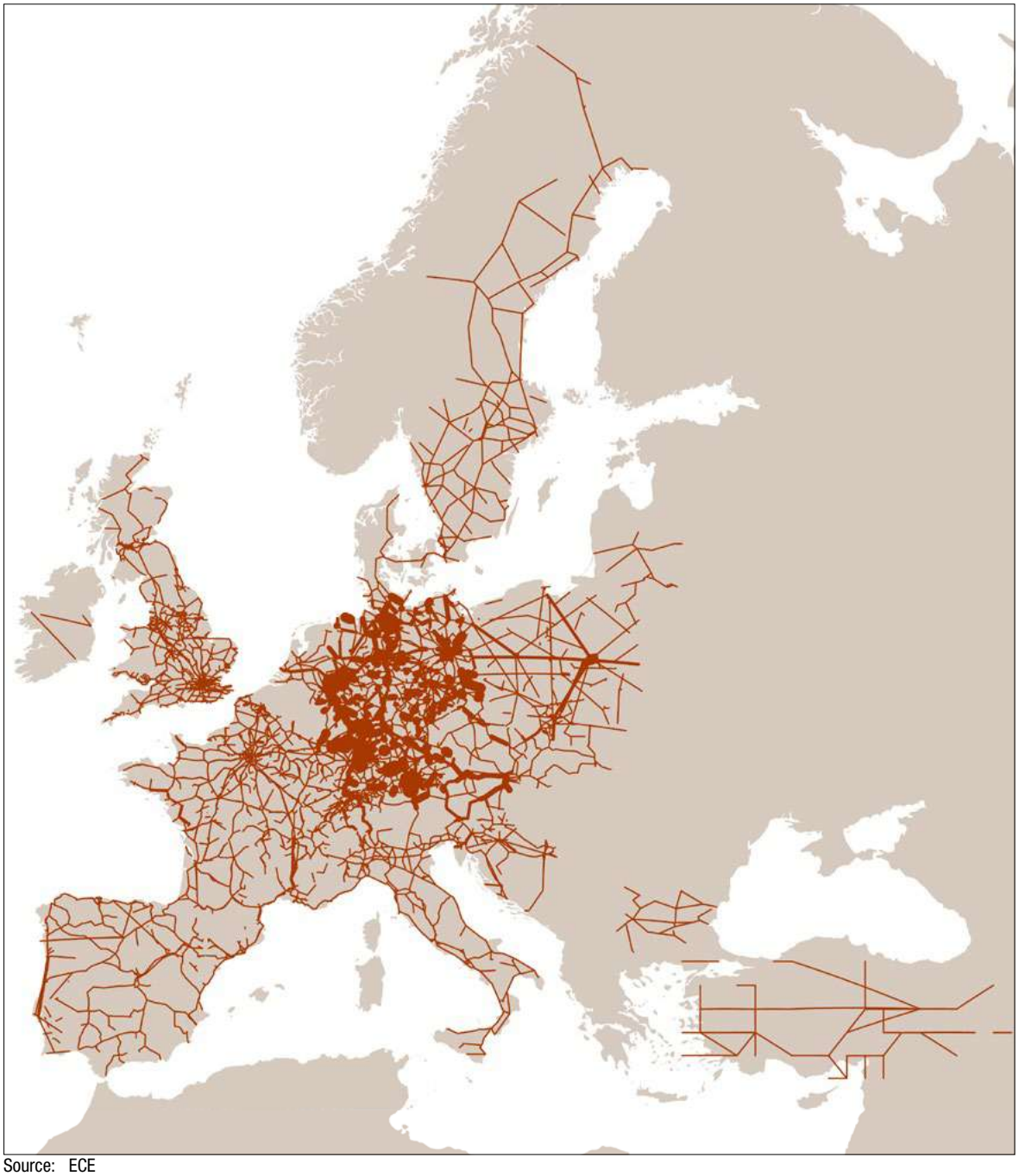
C. Traffic flows on E Rail network and rail-road terminals

As with the E Roads, to respond to new data requirements and changes in traffic patterns, censuses related to the E Rail network are conducted by ECE every five years. Information on the types of trains and railway routes being used helps improve land use management and enables better integration of rail traffic into countries' planning processes. It allows, at the international level, adequate maintenance, renewal and improvement programmes. This information also contributes to finding solutions to traffic congestion and facilitates the study of environmental issues, rail safety and energy consumption. The census is done for the rail lines listed in Annex 1 of the AGC Agreement, lines listed in AGTC Agreement and covers lines of the Trans-European Rail Network.

Two categories of trains were considered: passenger and freight trains. For each E railway line in an ECE member State, the annual number of trains, per network segment, by direction and by train category is recorded. This data serves as a possible indicator defining the criticality of the rail transport network (Figure I.1.7). The accuracy of the network presented depends on the geographical information on the rail segments communicated by the ECE member States in their answers to the census questionnaire. Similarly as for the road census, the rail census map does not always show rail segments that line up perfectly with the real network; it may show instead straight-line paths.

There was no public data on the volumes of freight processed in the rail-road terminals available to include in this analysis.

Figure I.1.7 The E rail network censuses: number of trains (transport of goods) (combined for 2010 and 2015)



Source: ECE

D. E Rail network analysis

Similar to the E Roads, the E Rail network is rather dense except for its northern and eastern parts (Figure I.1.3). In Canada, the rail network is dense in the south but sparse in the North (Figure I.1.6). Unlike the road network; however, it is much more difficult to reroute trains following service disruptions. Whenever rerouting is possible, the segment of track to which train traffic is rerouted should have the capacity to accommodate additional traffic. Modal shifts to road or inland waterway transport, may be considered viable options. For freight trains; however, a modal shift can only occur if intermodal (e.g. road-rail) terminals are available along the route.

The data on the annual number of trains (Section C above) shows significant use of the rail network in the central parts of the European part of the ECE region (Austria, Germany, Poland and Switzerland) and a few other selected routes. Other segments appear to be used less. Comparable data for the Canadian system was not publicly available.

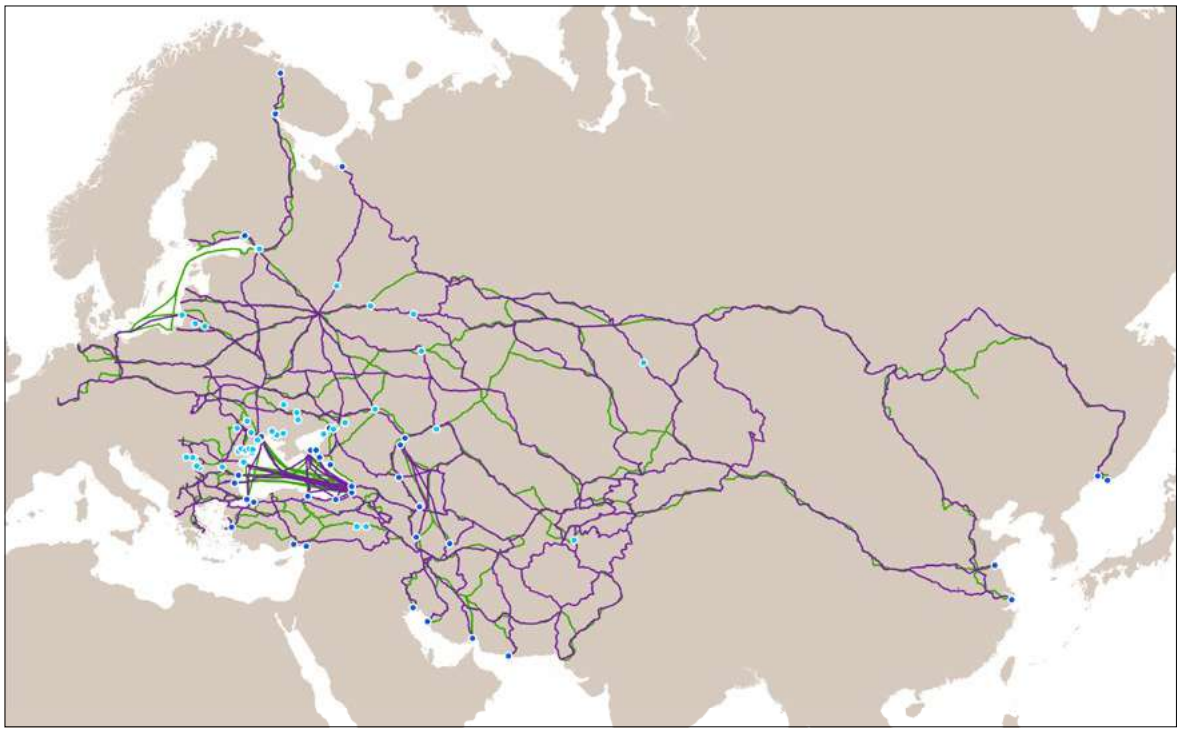
Stress tests of specific routes/segments of the rail network should be performed to define their criticality. At such routes/segments, disruptions may trigger considerable socioeconomic impacts.

IV. Euro-Asian Transport Links network

Inland links between Europe and Asia have received increased attention, in particular those used to transport freight by block trains. Freight volumes along these links are expected to increase, largely due to the growth of e-commerce. This being the case, the Euro-Asian Transport Links (EATL), both roads and rail, were included in this study. They have been identified by the Euro-Asian Transport Linkages project facilitated by ECE[11] (Figure I.1.8). These networks should be also gaining importance in the context of the One Belt One Road initiative.

No data on annual number of trains or average daily traffic for the EATL rail road networks were available for this study.

Figure I.1.8 The Euro-Asian Transport Links network (rail and road routes, inland and maritime ports). Rail routes are shown in green, road routes in purple, inland ports in light blue and maritime ports in dark blue



Source: ECE

11 More information about the project can be found at: www.unece.org/trans/main/eatl.html

V. Waterways

A. E Waterway network and Ports

The Waterway network in the European part of the ECE region has been developed in the framework of the European Agreement on Main Inland Waterways of International Importance (AGN). The Agreement was done in Geneva on 19 January 1996 and entered into force on 26 July 1999. It establishes a plan for the development and construction of E Waterway network and covers inland waterways, coastal routes and ports of international importance.

The European Inland Waterways of international importance are those belonging to classes IV to VII. The class of a waterway is determined by the horizontal dimensions of motor vessels, barges and pushed convoys, and primarily by the main standardized dimension, namely their beam or width. Main inland waterways which primarily follow north-south direction providing access to sea ports and connecting one sea basin to another are numbered 10, 20, 30, 40 and 50 in ascending order from west to east. Main inland waterways which follow mainly west-east direction are numbered 60, 70, 80 and 90 in ascending order from north to south.

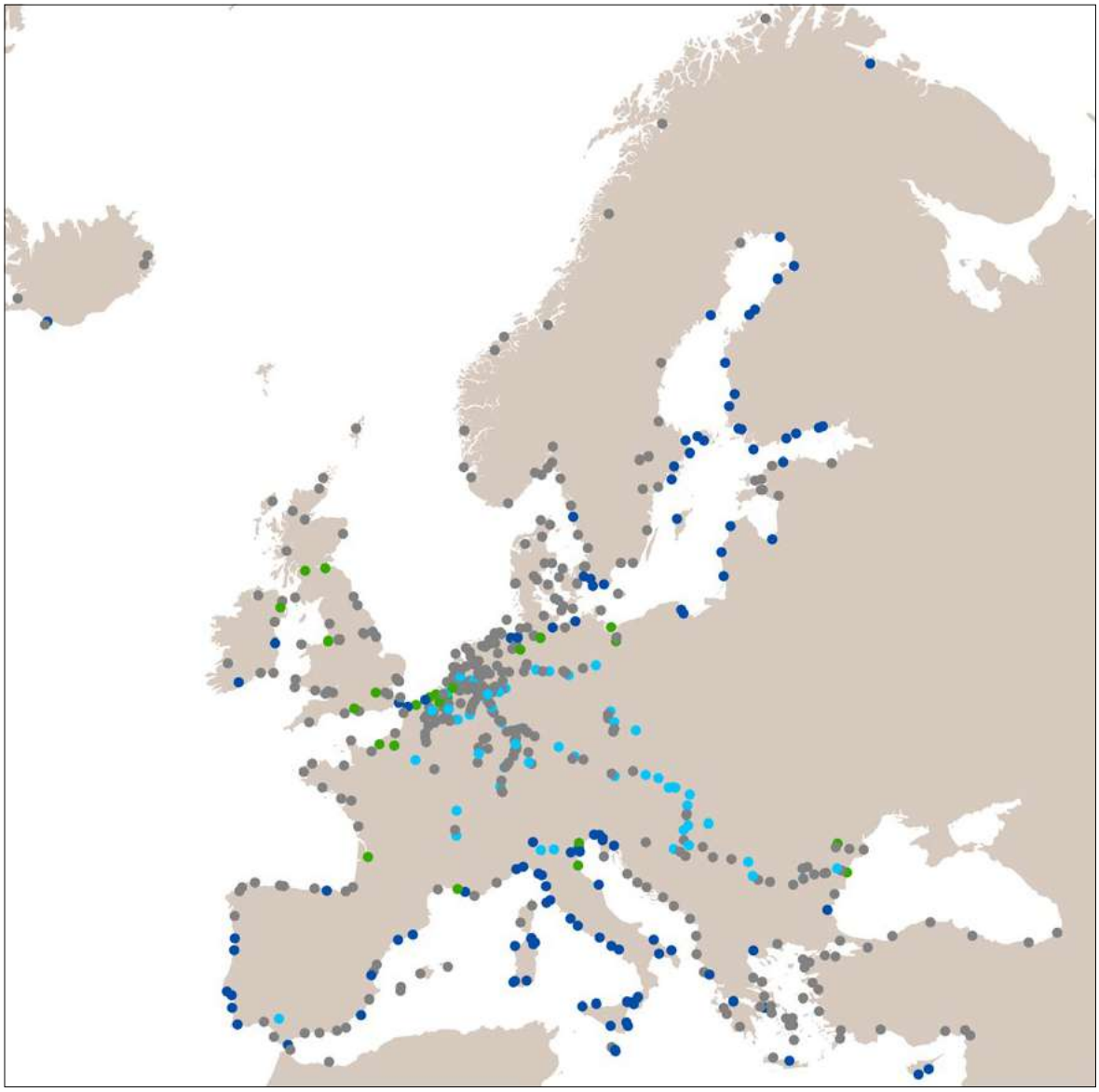
The E Waterway network and E Ports have been put into the ECE GIS by the ECE secretariat (Figure I.1.9). Additional data from the ECE Inventory of Main Standards and Parameters of the Waterway Network (Blue Book) are also included and offer an inventory of existing and envisaged standards and parameters of E-Waterways and Ports. The geocoded Canadian inland waterways and ports data was not available for inclusion at the time of this report's preparation.

Figure I.1.9 The E Waterways network (waterways in blue and ports as light blue triangles)

Source: ECE

The TEN-T data for ports was also considered, which in addition to inland ports also includes the maritime ports along the coasts. This data was extracted from the TEN-T Comprehensive Network, for European Union Member States and neighbouring countries, and covers inland and maritime core and comprehensive ports (Figure. I.1.10).

Figure I.1.10 Ports from the comprehensive and core TEN-T Network: inland and maritime ports are in green, maritime ports only are in dark blue, inland ports only are in light blue, and other types of ports are in grey



Source: European Union, 2018

B. Traffic flows on E Waterway network

Currently there is no public data available on E Waterway traffic flows collected at the regional level. Nevertheless, the Working Party on Inland Water Transport supported the collection of inland waterway traffic data through a census similar to those for E Roads and the E Rail network at its meeting in 2018. It was expected at the time of preparing this report that the census would be held in

2020. In addition to AADT, other measurements of inland waterways that could be taken into account include their seasonal nature and low water periods when navigation is stopped or hindered. This information could also contribute to considerations around modal shift from other inland transport modes and facilitate the study of environmental issues, safety and energy consumption of inland water transport. An additional objective of the E Waterway traffic census would be the measurement of the performance of the waterway network, expressed mainly in tonne-kilometres, by the different types of vessels counted.

Freight volumes processed by E Ports was not publicly available for this study.

C. E Waterway network analysis

The E Waterway network is sparse compared to the E Rail or E Roads networks. Its main objective is to provide alternative transport opportunities for freight travelling along main waterways running north-south and west-east. Disruptions along the network are relatively rare. If they occur, it would result in socioeconomic losses. In such a case, the objective is to minimise the losses. The freight can be temporarily warehoused until normal operations are restored or alternatively modal change needs to be considered. Given that bulk goods are often transported on waterways, in such case a modal shift can pose a challenge.

Photo: Henrik Larsson / shutterstock.com

Chapter 2 Climate Variability and Change:[12] Observed changes and projected trends

I. Recent trends and projections

There is overwhelming evidence that the planet has been warming since the 1850s (from the upper atmosphere to the depths of oceans) with changes observed in many climatic factors/stressors and indices. Climate models project that many of these changes will intensify throughout the twenty-first century. It appears that various climatic hazards that can pose risks to transportation infrastructure and operations (ECE, 2013) will deteriorate. Global warming of 2°C above pre-industrial level[13] has been widely suggested as a threshold beyond which climate change risks become unacceptably high (IPCC 2018). Without effective mitigation measures, this threshold is likely to be reached by 2050 under the RCP8.5 scenario.

A. Temperature

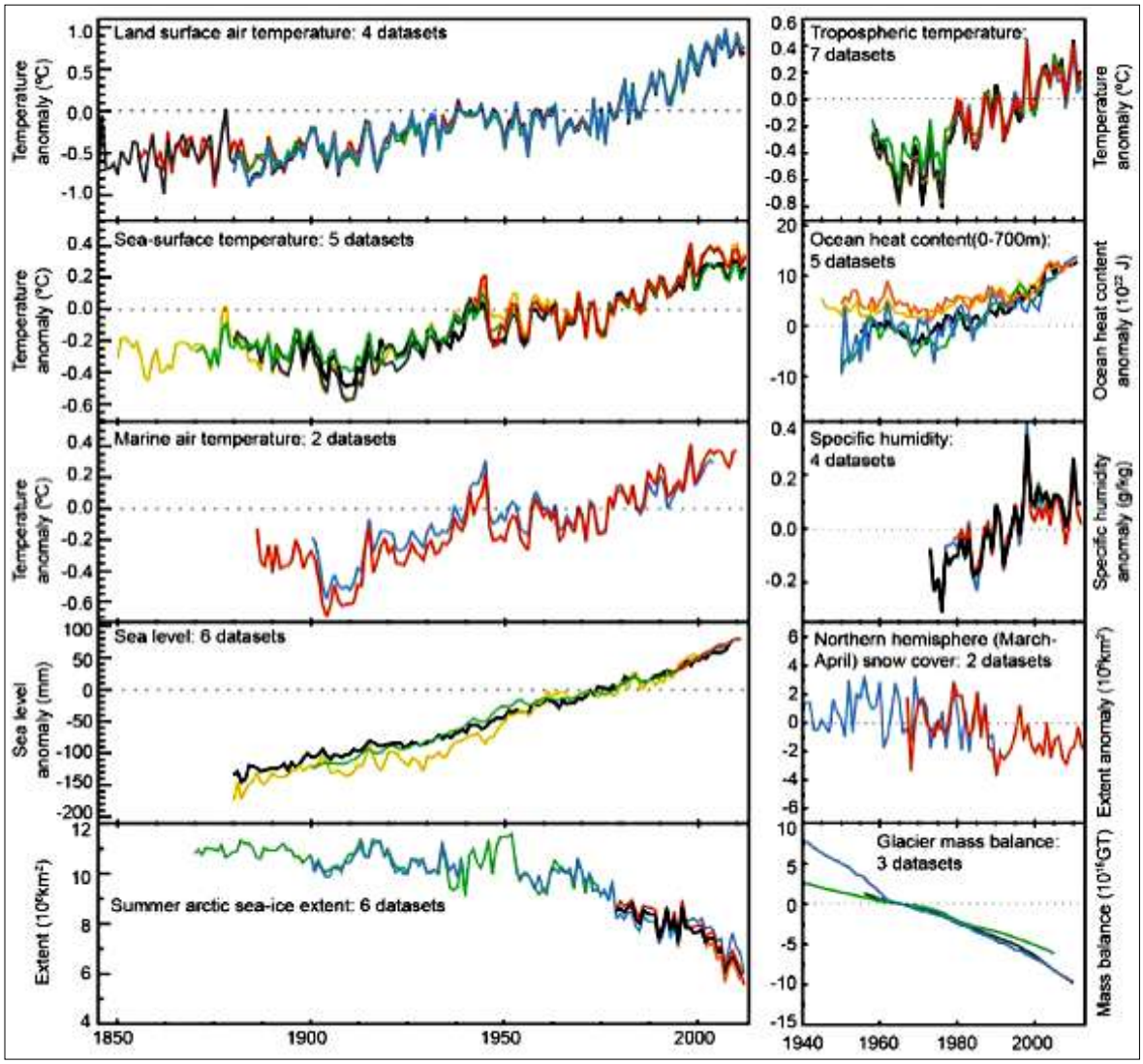
Globally-averaged, near-surface temperature change is the most cited indicator of climate change, as it is directly related to both climate change causes (i.e. the increase in cumulative greenhouse gas (GHG) emissions) (IPCC, 2013), risks and impacts (Arnell et al., 2014). Notwithstanding some short-term variability, a steady warming trend has been visible in near-surface temperature since the 1970s (Figure I.2.1).

The five-year mean temperature in 2013–2017 (Figure I.2.2) is the highest on record with values of 0.4°C above the 1981–2010 average and 1.0°C above pre-industrial values. Climate is controlled by the heat inflow and outflow and its storage dynamics (IPCC, 2013). Most of the heat storage occurs in the ocean which absorbs most of the heat added to the system (Cheng et al., 2019a). Changes in the ocean heat content, for instance, lead to regional shifts in the oceanic and atmospheric circulation. This in turn may lead to more intense or more frequent extreme storms as well as heavy precipitation

12 Note that Climate Variability and Change refers to the variability and sustained change of climatic conditions relative to a base line period (e.g. 1961–1990, 1986–2005 or 1981–2010).

13 The limit goal of the 2015 Paris Agreement (unfccc.int/process#:a0659cbd-3b30-4c05-a4f9-268f16e5dd6b)

Figure I.2.1 Change of climatic factors. Each line represents an independently derived estimate. In each panel all data sets have been normalized to a common period of record



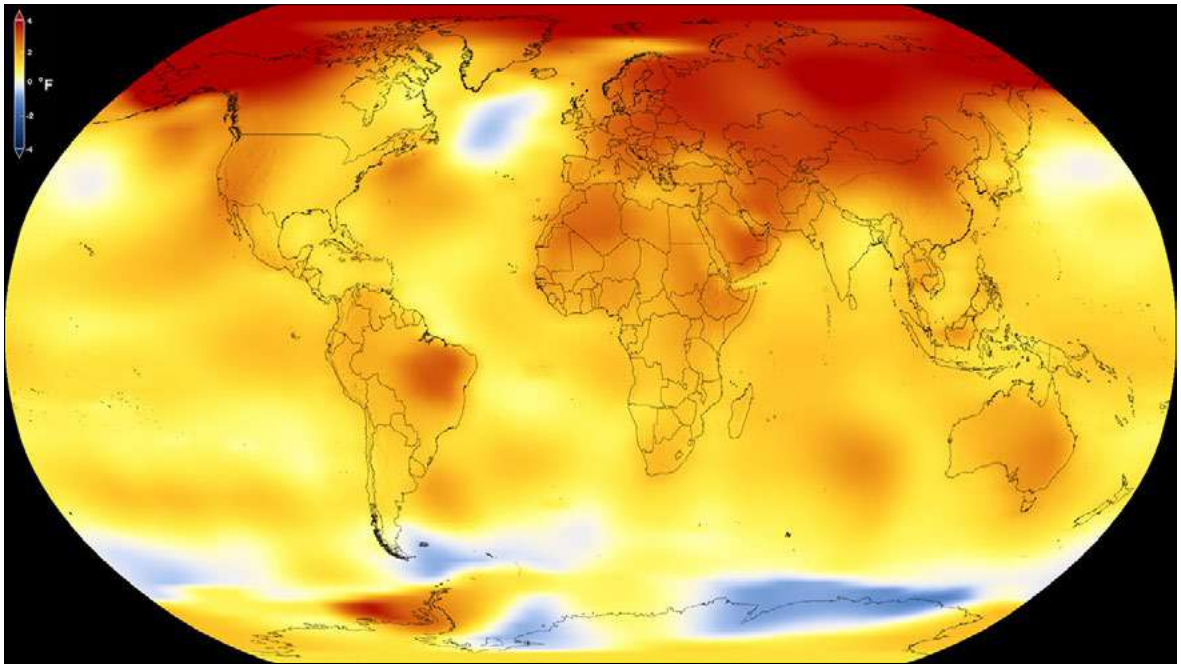
Source: IPCC, 2013

events in certain areas, as well as prolonged droughts in other regions. In recent decades, there has been evidence of an increasing ocean heat content (Dieng et al., 2017a). Similar to the near-surface temperature, the past 5 years (2014–1018) have also been the warmest on record for the upper ocean (Cheng et al., 2019b).

The atmospheric temperature is projected to increase by 1.0°C–3.7°C (mean estimates) until the end of the twenty-first century, depending on the GHG concentration scenario.[14] The ocean will also warm, with most warming expected to take place in the upper ocean (upper 100 m) by 0.6°C under a RCP2.6 scenario to 2.0°C under a RCP8.5 scenario by 2100 (IPCC, 2013).

14 Since the last IPCC Assessment Report AR5 (2013) forecasts are made on the basis of the Representative Concentration Pathways-RCP scenarios and not the previously used IPCC SRES scenarios. The CO_2 equivalent concentrations have been set to: RCP 8.5, 1370 CO2-equivalent in 2100; RCP 6.0 850 CO2-equivalent in 2100; RCP 4.5, 650 CO2-equivalent in 2100; and RCP 2.6, peak at 490 CO2-equivalent before 2100 (Moss et al., 2010).

Figure I.2.2 Average global temperature changes in 2013–2017, as compared to the average of 1951–1980



Source: NASA Goddard Institute for Space Studies, climate.nasa.gov/news/2671/long-term-warming-trend-continued-in-2017-nasa-noaa

The climate does not and will not change uniformly. Temperatures will generally rise faster at higher latitudes. Even under a global warming of 1.5°C and 1.5°C–2°C above the pre-industrial levels, increases in the hot extremes are projected for most inhabited regions with high confidence (IPCC, 2018). Under all emissions scenarios, large temperature increases have been projected by global and regional models over the ECE region, particularly for its northern areas (IPCC, 2013).

B. Precipitation

Global land rainfall data show an increasing trend, especially in middle and high latitudes (EPA, 2015). Schneider et al. (2017) suggest that a warming of about 1°C relative to pre-industrial time can result to a 2–3 per cent increase in global precipitation. Land precipitation shows a stronger natural variability in time and space than earth surface temperature. For example, it is strongly influenced by the El Niño-Southern Oscillation (ENSO) leading to regionally differentiated rainfall (both above and below average).

Precipitation is expected to change in an even more complex manner than temperature. Increases in heavy precipitation are projected for some regions (medium confidence), while droughts and precipitation deficits are expected to increase in other regions (medium confidence) (IPCC, 2013; 2018). Changes in precipitation patterns are projected for the European part of the ECE region, with the north generally becoming wetter and the south drier (see also Chapter 3). In Canada, annual and winter precipitation is projected to increase across the country over the twenty-first century, with larger percentage changes in northern Canada. Summer precipitation is projected to decrease over southern Canada under a high emissions scenario toward the end of the twenty-first century, but only small changes are projected under a low emissions scenario (Zhang at al., 2019).

At the same time, although summers may become (overall) drier, downpours could become heavier. In the United Kingdom, for instance, simulations indicate that intense downpours that may generate flash floods (> 30 mm in an hour) could become almost five times more frequent by 2100 (MetOffice, 2014). Widespread droughts have been also projected for most of southwestern North America for the mid to late twenty-first century. By comparison, Central Europe, the Mediterranean and parts of North America are projected to show shorter and less intense droughts (Milly et al., 2008; IPCC, 2013; Dai, 2013; IPCC, 2018).

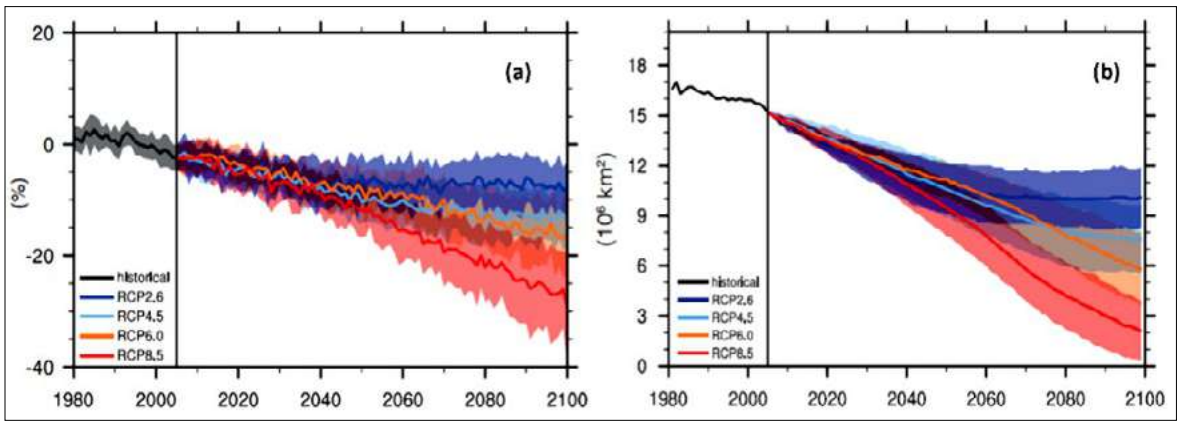
C. Snow, sea ice and permafrost

Assessments of snow cover, sea ice, glaciers, ice sheets and permafrost and their current state/trends and future projections are particularly important for transportation in the Arctic ECE regions (for example the Russian Federation, Canada and the United States of America).

The spring snow cover extent (SCE) has decreased across the northern hemisphere (its snow cover accounts for about 98 per cent of the global snow cover) since the 1950s (IPCC, 2013; NSIDC, 2017). Between 1967 and 2012 the SCE in the northern hemisphere has declined by 11.7 per cent per decade in June (EEA, 2015a). However, the trend is not uniform. Some regions (e.g. the Alps and Scandinavia) showed consistent decreases in their snow cover depth at low elevations but increases at high elevations, whereas in other regions (e.g. the Carpathians, Pyrenees, and Caucasus) there were no consistent trends (EEA, 2012).

Arctic snowfall is projected to increase. Winter snow depth will increase over many areas, with the most substantial increase (15 to 30 per cent by 2050) taking place in Siberia. However, the snow has been projected to remain for 10 to 20 per cent less time each year over most of the Arctic, due to earlier spring melt (AMAP, 2012). The spring SCE in 2100 is projected to decrease by approximately 25 per cent under RCP8.5 (Figure I.2.3). Mountain glacier mass has been also projected to decrease by 10 to 30 per cent by 2100 (AMAP, 2012).

Figure I.2.3 **Projected (a) spring snow cover extent (SCE) in the Northern Hemisphere (NH) (March to April average) and (b) near-surface permafrost changes in NH for four RCPs (CMIP5 model ensemble)**



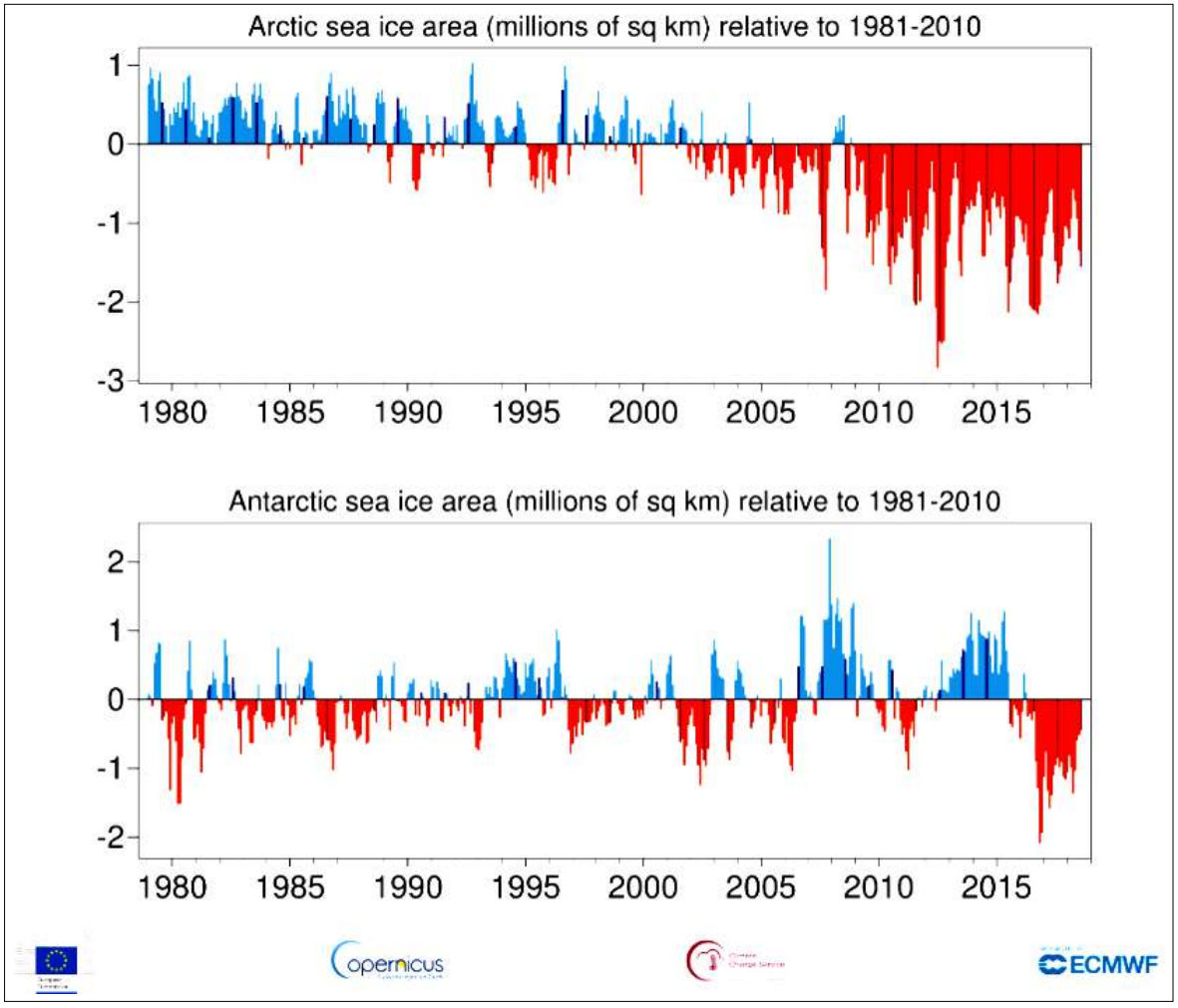
Source: IPCC, 2013-Stocker et al, 2013 (see above)

Despite the overall high temperatures of the most recent period, there were still episodes of abnormal cold and snow. A prolonged period of extreme cold affected central and western Europe in early 2012, the worst cold spell since 1987. The winters of 2013–2014 and 2014–2015 were significantly

colder than normal in the central and eastern regions of United States of America and southern Canada, with persistent low temperatures for extended periods (WMO, 2016). In 2016, the mean annual SCE in the northern hemisphere was 0.5 million km^2 below the 1967–2015 average (24.6 million km^2), despite the large January snow storms in North America (NOAA, 2017a).

Arctic sea ice is in decline (Figures I.2.1 and I.2.4) and further decreases are projected by the CMIP5 model ensemble, with considerable inter-annual variability. Minimum Arctic sea ice extent has declined by about 40 per cent since 1979; most records in ice minima occurred in the last decade (NOAA, 2017a). Arctic sea-ice extent (SIE) was at a record low for most of 2016 (WMO, 2017). In 2017, the SIE was well below the 1981–2010 average in both the Arctic and Antarctic. In 2081–2100, reductions in SIE of 8–34 per cent (in February) and 43–94 per cent (in September) have been projected relative to the average SIE of 1986–2005 (IPCC, 2013).

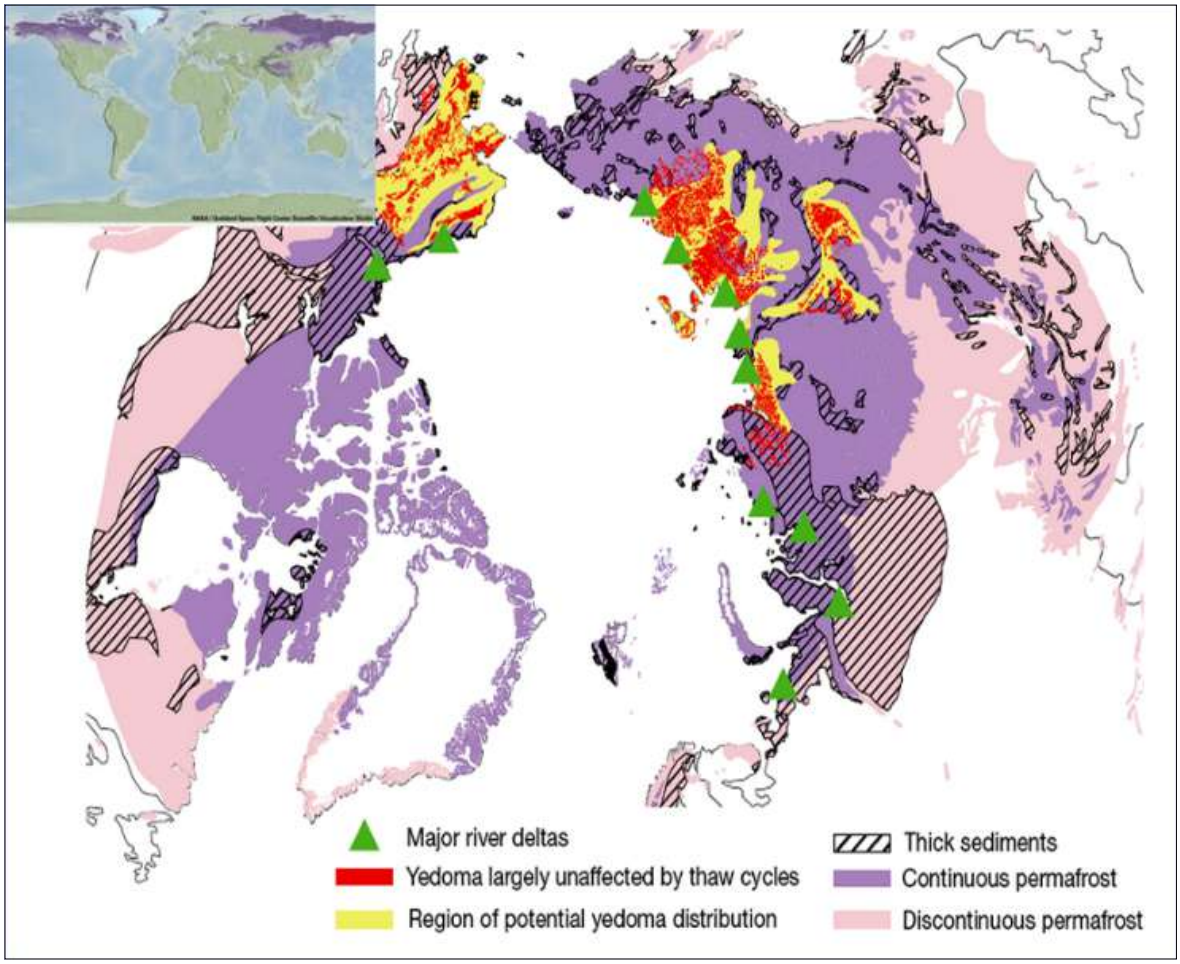
Figure I.2.4 Arctic and Antarctic sea ice extent (SIE)



Source: P. Taalas, WMO, 2019

In northern permafrost regions (Figure I.2.5), there has been a warming down to 20 m depth. Temperatures have increased in most regions by up to 2°C since 1980, leading to thawing and significant infrastructure damage. Generally, the thickness of the northern hemisphere permafrost has decreased by 0.32 m since 1930 (IPCC, 2013).

Figure I.2.5 Map of the northern circumpolar permafrost zone. Areas in yellow and red show the extent of the Yedoma permafrost



Source: Schuur et al., 2015

Accelerated permafrost thawing is projected due to, for example, rising global temperatures and changes in the snow cover. Although there are challenges in the assessment of permafrost dynamics, permafrost extent is expected to decrease by 37–81 per cent by the end of the twenty-first century (medium confidence), depending on the emissions scenario (see also Figure I.2.3 b). These changes in the extent of permafrost could pose problems to the development and maintenance of Arctic infrastructure due to thaw-related ground instability (ECE, 2013). This in turn could limit the development of transport networks that take advantage of potential new Arctic Ocean routes made possible by projected Arctic sea ice melt.

The (land) ice mass balances of Antarctica and Greenland are extremely important as they control (amongst others) the mean sea level rise (SLR). The Greenland surface mass balance-SMB has started decreasing since the early 1990s. Velicogna et al. (2014) have estimated ice sheet loss rates in Greenland of 280 ± 58 Gt year−1, accelerating by 25.4 ± 1.2 Gt year−1. This has resulted in a statistically significant contribution to the mean sea level rise (SLR) rate (Hansen et al., 2016). For the Antarctic land ice there have been worrying signs recently. It appears that the total mass loss increased from 40 ± 9 Gt year−1 in 1979–1990 and 50 ± 14 Gt year−1 in 1989–2000, to 166 ± 18 Gt year−1 in 1999–2009 and 252 ± 26 Gt year−1 in 2009–2017. The contribution to SLR from this land ice mass melt averaged 3.6 ± 0.5 mm per decade with a cumulative 14.0 ± 2.0 mm contribution since 1979 (Rignot et al., 2019). An ice mass loss rate of 74 ± 7 Gt year−1 was also observed in the

Canadian glaciers and ice caps with an acceleration of 10 ± 2 Gt year−1. Generally, mountain glaciers continued their melt. In recent years, the western North American glaciers have lost 117 ± 42 Gt of mass, showing a fourfold increase in loss rate between 2000–2009 (2.9 ± 3.1 Gt yr-1) and 2009–2018 (12.3 ± 4.6 Gt yr-1), Menounos et al., 2018).

Global warming will impact the Greenland Ice Sheet, the surface mass balance (SMB) of which has recently shown an accelerating decreasing trend. By comparison, the SMB of the Antarctic Ice Sheet has been projected to increase under most RCP scenarios due to increasing snowfall (Velicogna et al., 2014; Hansen et al., 2016); however, this would amount to a reversal of the lately observed decreasing trends (Rignot et al., 2019). It should be noted that model ensembles show potential for Antarctica to contribute more than 1 m to sea level rise to 2100 in the high-end scenario RCP8.5 (De Conto and Pollard, 2016).

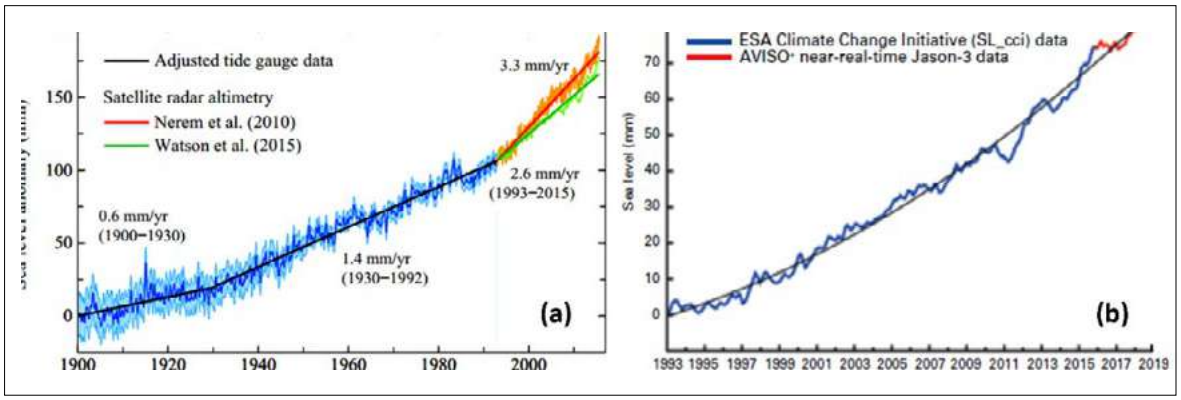
D. Sea level and waves

The oceans, which may have absorbed more than 80 per cent of the excess energy associated with the increased emissions since the 1970s, show very significant increases in their heat content (Dieng et al., 2017a; Cheng et al., 2019a) which have resulted in sea level rise due to the thermal (steric) expansion of the ocean volume, a major contributor to the SLR (Hanna et al., 2013). In recent decades, the SLR rate increased sharply above the relatively stable background rates of the previous 2000 years (Church et al., 2013).

Since 1860, global sea level has increased by about 0.20 m; during this period, global SLR rates averaged 1.3–1.8 cm per decade (Church et al., 2013; Hay et al., 2015). Since 1993, however, satellite and tide gauge observations (Figure I.2.6) indicate a global SLR of 3.3 ± 0.25 cm per decade (Church et al., 2013). Recent evidence suggests that this acceleration can mainly be attributed mainly due to ice mass balance changes rather than steric effects (Dieng et al., 2017b; Rignot et al., 2019).

There is considerable regional (spatial) variability in coastal sea level rise (Menendez and Woodworth, 2010). In Europe, sea levels have increased along most of its coast in the last four decades, with the exception of the northern Baltic coast (EEA, 2012). Some regions experience greater SLR than others, the tropical western Pacific for example. Sea level rise has been more consistent in the Atlantic and Indian Oceans, with most areas in both oceans showing rates similar to the global average (WMO, 2016).

Figure I.2.6 **(a) Estimated sea level change (mm) since 1900**
(b) Global mean sea-level (seasonal cycle removed)



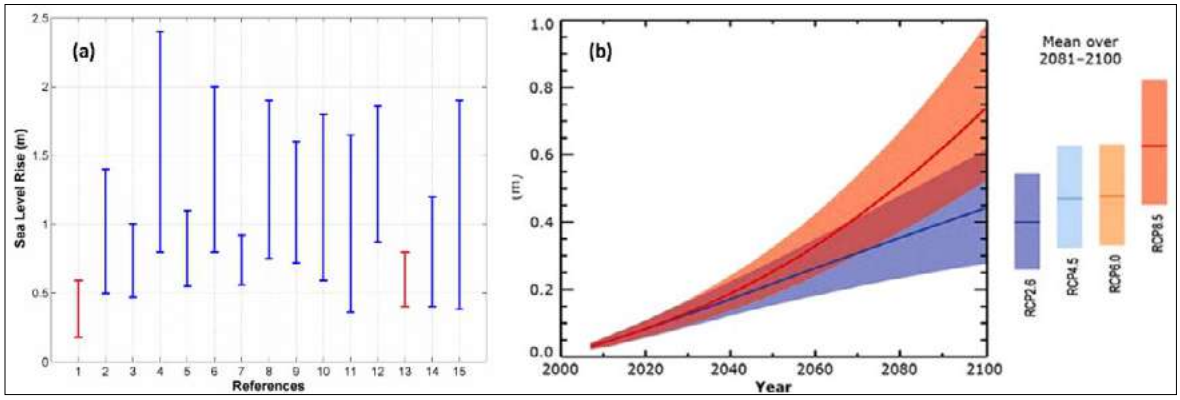
Source: (a) Data through 1992 are tidal gauge records with the change rate multiplied by 0.78, so as to yield a mean 1901–1990 change rate of 1.2 mm year−1 (Hansen et al.)
(b) January 1993–January 2018, from satellite altimetry. Data from AVISO web platform (www.aviso.altimetry.fr/en/home.html) (2016 Collecte-Localisation-Satellite (CLS) – Laboratoire d'Etudes en Géophysique et Océanographie Spatiales (LEGOS) (WMO, 2018))

SLR projections are constrained by uncertainties around the response to global warming and the variability of: the GIS and AIS mass balances (Hansen et al., 2016; Rignot et al., 2019); the steric changes (Cheng et al., 2019a; 2019b); contributions from mountain glaciers (Menounos et al., 2018); as well as groundwater pumping for irrigation purposes and the storage of water in reservoirs (Wada et al., 2012).

SLR of 0.26–0.54 m (RCP2.6) to 0.45–0.82 m (RCP8.5) are projected for 2081–2100 as compared to 1986–2005 (IPCC, 2013). It should be noted that the IPCC has consistently provided conservative estimates[15] (Figure I.2.7). Due to the large spatial SLR variability that has been observed and projected, regional trends should be considered when assessing potential impacts along a particular coast. In addition to the influences of global processes, regional factors can also contribute to coastal sea level changes, such as changes in ocean circulation, differential rates in regional glacial melting, glacial-isostatic adjustment (post-glacial rebound) and the subsidence of coastal sediments (King et al., 2015; Carson et al., 2016; Jevrejeva et al., 2016). As an example, relative sea level across Canada is projected to rise or fall, depending on local vertical land motion. Parts of Atlantic Canada are projected to experience relative sea-level change higher than the global average during the coming century due to land subsistence (Greenan, B.J.W et al.2018).

Sea level rise will continue beyond 2100 (Jevrejeva et al., 2012), due to the rising ocean heat content (Cheng et al., 2019a) that will induce increasing thermal (steric) expansion for (at least) several centuries, whereas the lately observed dynamic ice loss in Greenland and Antarctica may also continue into the future; unchecked mean temperature rise might induce runaway sea level rise.

Figure I.2.7 (a) SLR projections for 2100
(b) Global SLR in the twenty-first century relative to 1986-2005



Source: (a) Key: 1, IPCC (2007), 0.18 - 0.59 m; 2, Rahmstorf et al. (2007); 3, Horton et al. (2008); 4, Rohling et al. (2008); 5, Vellinga et al. (2008); 6, Pfeffer et al. (2008); 7, Kopp et al. (2009); 8, Vermeer and Rahmstorf (2009); 9, Grinsted et al. (2010); 10, Jevrejeva et al. (2010); 11, Jevrejeva et al. (2012); 12, Mori et al. (2013); 13, IPCC (2013); 14, Horton et al. (2014); and 15, Dutton et al. (2015). The variability reflects differences in assumptions /approaches
(b) IPCC, 2013

15 The collapse of marine-based sectors of the Antarctic ice sheet, if initiated, could cause global mean sea level to rise substantially above the likely range during the twenty-first century. This potential additional contribution cannot be precisely quantified but there is medium confidence that it would not exceed several tenths of a meter of sea level rise during the twenty-first century (See also Dieng et al. (2017b) and Rignot et al.(2019) www.ipcc.ch/site/assets/uploads/2018/02/WG1AR5_Chapter13_FINAL.pdf.

In addition to SLR, the impacts on coastal transport infrastructure/operations can also depend also on other factors/hazards, such the mean and extreme wave conditions and storm surges. Camus et al. (2017) have provided global multi-model projections of wave conditions (e.g. significant wave height[16]) under climate change to assist with assessments on the impacts of changing climate on coastal transport infrastructure (Asariotis et al., 2017). The annual mean significant wave height has been projected to increase in the Southern Ocean and the eastern Pacific Ocean and to decrease in the north Atlantic Ocean, the north-western Pacific Ocean and the Indian Ocean, with the magnitude of the increases being about four times higher than those of the decreases. If these projections are considered together with the SLR, seaports in some areas could be compromised by increased sensitivity of their (low) breakwaters (Camus et al., 2017).

E. Extreme Climate Events

Climate change is often associated in the public discourse with the increase in global mean temperature. However, for the transportation industry, as well as for the broader society, economy and the environment, regional conditions and changes in the climatic extremes can be the most relevant (Vogel et al., 2017). Changes in the mean climate can lead to changes in the frequency, intensity, spatial coverage, duration, and timing of some weather and climate events, potentially resulting in unprecedented extremes. These extremes can, in turn, modify the distributions of the future mean climatic conditions (IPCC SREX, 2012). Extreme events can cover a large spectrum, such as sudden and transient temperature changes, rapid retreats of sea ice, bouts of abnormally high precipitation, intense storms, storm surges, extended droughts, heat waves, wildfires, sudden water releases from melting glaciers and permafrost slumping. All these, by themselves or in combination, can have significant and costly impacts on transport infrastructure and operations.

Extreme hydro-meteorological events, such as floods and storms have accounted for about 44 and 28 per cent, respectively, of all natural disasters recorded between 1998 – 2017 (Taalas, 2019). In recent years, there have been many extreme events that have affected the ECE region and its transport infrastructure and operations, with some of those causing very severe damages and losses. For example, Hurricane Sandy in the Caribbean and the United States of America (2012), droughts in the southern and central regions of the United States of America (2012 and 2013), floods in central Europe (May-June 2013) and the 2017 hurricane season that affected the United States of America and Caribbean overseas territories of ECE member States. In terms of economic losses, the 1980 – 2016 average was 5.5 events per year with costs in excess of 1 US$ billion (Consumer Price Index (CPI)-adjusted), whereas the annual average for 2012 – 2016 was 10.6 such events (NOAA, 2017c).

Many climate extremes show changes consistent with global warming, including a widespread reduction in the number of frost days in mid-latitude regions and discernible evidence that warm extremes have become warmer and cold extremes less cold in many regions (IPCC SREX, 2012). There is also a general change in the frequency of high impact temperature and precipitation extremes over land, irrespective of the type of dataset and processing method used (MetOffice, 2014).

In many cases, the impacts of such extremes can be exacerbated by the simultaneous presence of several hazards. Combined hazards can include, for example, marine and riverine flooding (Forzieri et al., 2016) or the combination of extreme heat with high relative humidity (Monioudi et al., 2018). Of note, recent research (Mora et al., 2017) indicates the presence of a 'deadly threshold' for surface air temperature/relative humidity over which the human thermoregulatory capacity is exceeded.

16 Annual significant wave height (Hs) is the mean of the highest one third of the waves recorded at a site in each year.

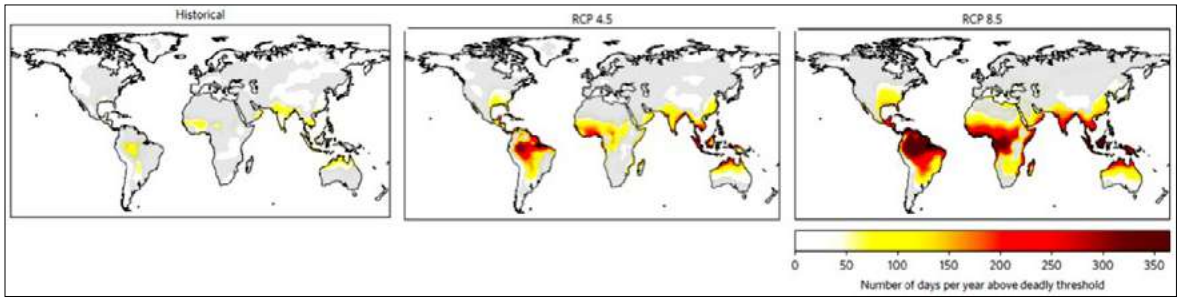
1. Temperature extremes - Heat waves

Climate observations show increases in the frequency and intensity of heat waves (e.g. Beniston and Diaz, 2004; IPCC, 2013). Attribution studies suggest that the occurrence probability of recent heat extremes and heat waves is considerably higher under anthropogenic influences than under natural conditions (e.g., MetOffice, 2014; Coumou and Rahmstorf, 2012). Model studies show further increases in the occurrence probability of very hot summers and heat waves during the twenty-first century (e.g., Dole et al., 2011; Coumou and Robinson, 2013). Greater changes in hot (seasonal) extremes are expected to take place in the subtropics and the mid-latitude regions, whereas the frequency of cold events will decrease in all regions.

In western and central Europe, the worst heat wave since 2003 was recorded in early July 2015, with Spain, France and Switzerland breaking all-time temperature records. In 2017 there were also numerous heat waves which affected Turkey, Cyprus, Spain, Italy and the Balkans. Record high temperatures were also observed in Death Valley (California, USA) (WMO, 2018). The combination of extreme heat with high relative humidity may have very significant implications for the health/safety of personnel and passengers in most modes of transport.

Projections (Mora et al., 2017) indicate substantial exceedances of the 'deadly threshold' by the end of the century, which will be particularly severe under the now 'business as usual' emissions scenario (RCP8.5), with direct impacts on southwestern United States of America and the Mediterranean ECE region (Figure I.2.8).

Figure I.2.8 Deadly climatic conditions in 2100 under different emission scenarios



Source: Conditions refer to the number of days per year exceeding the threshold of temperature and humidity beyond which climatic conditions become deadly, averaged between 1995 and 2005 (historical experiment), and between 2090 and 2100 under RCP 4.5 and RCP 8.5. Results are based on multi-model medians. Grey areas indicate locations with high uncertainty (multi-model standard deviation larger than the projected mean) (Mora et al., 2017)

2. Heavy rainfalls and droughts

Extremes linked to the water cycle (heavy rainfalls, floods and droughts) are already causing substantial damages. As temperature rises, average precipitation will exhibit substantial spatial variation. Heat waves are often associated with severe droughts (as for example during the 2003 heat wave in Europe). Droughts have become more severe in some regions, a trend that is projected to hold (and possibly increase) in the twenty-first century (IPCC, 2013).

An increasing frequency and intensity of heavy precipitation events (downpours) is discernible in observations for many parts of the world; these increases have caused most of the observed increases in overall precipitation during the last 50 years. Extreme precipitation events will be more intense over most of the mid-latitude and wet tropical regions (IPCC, 2013). For central and north-eastern Europe, large increases (25 per cent) in heavy precipitation are projected for the end of the century. High resolution climate models indicate that extreme seasonal rainfalls could also intensify with climate change. In the United Kingdom, for instance, although summers will become drier overall, the occurrence of heavy summer downpours (more than 30 mm in an hour) could increase by approximately five-fold (MetOffice, 2014). Hazards connected to heavy precipitation events like slope failures and landslides have also increased in mountainous areas (Karl et al., 2009).

River flooding from sustained above average precipitation is a serious and widespread hazard (King et al., 2015). Riverine floods are caused by both physical and socio-economic factors. The former depends on the hydrological cycle, which is influenced by changes in temperature, precipitation and glacier/snow melt, whereas the latter by land use changes, river management schemes, and flood plain development (EEA, 2010). In the ECE region, floods are an ever present hazard. In Europe, annual water discharges have generally increased in the north and decreased in the south (e.g. EEA, 2012).

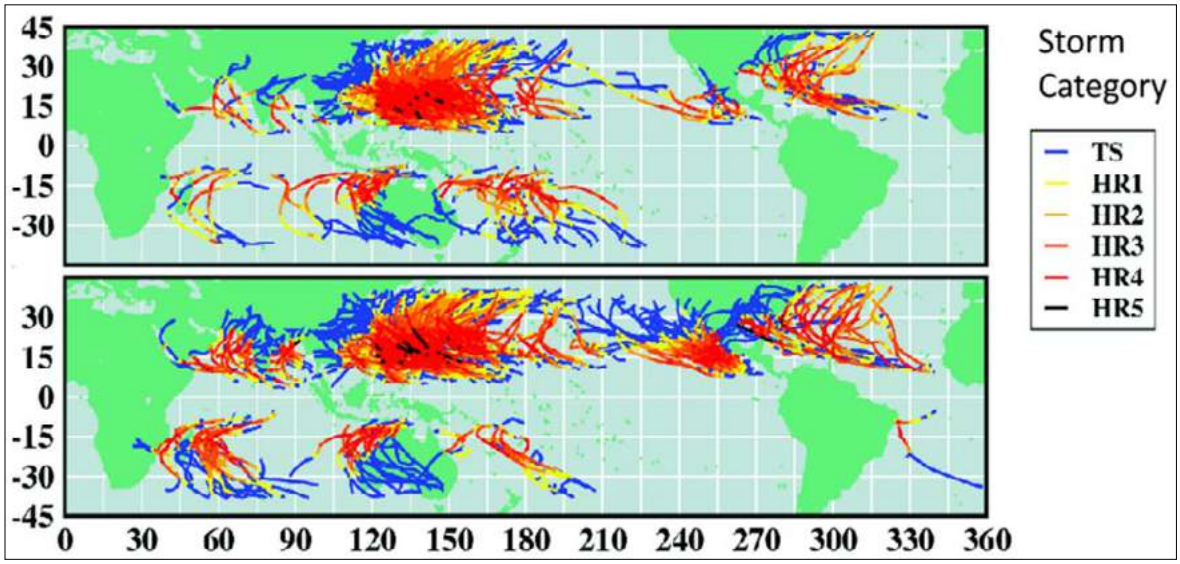
Substantial increases in flood risks are projected for central and western Europe (Alfieri et al., 2015, 2018). The expected flood damages under a 1.5°C temperature rise since the pre-industrial times (IPCC, 2018) are assessed to be twice as high (€ 15 billion/year) as the average costs of the 1976–2005 period. Damages from riverine floods are expected to be generally higher in the north than in the south (Alfieri et al., 2015; 2018)

3. Storms and high winds

Storms and windstorms are difficult to project and the annual incidence of tropical storms has not changed with time (WMO, 2018). However, as severe tropical and extra-tropical storms (which are usually associated with extreme winds, rainfall and coastal flooding) are fed by the increasing upper ocean heat content and surface temperatures, it is expected that their destructiveness will increase in the future (e.g. Emanuel, 2005; Ruggiero et al., 2010; WMO, 2014). An attribution study for the storm Harvey in late August 2017 indicated that this event had been made three times more likely by anthropogenic climate change (Trenberth et al., 2018).

It has been suggested that a modest temperature rise of 1°C in the upper ocean might result in storm wind speed increases of up to 5 m/s as well as increased incidence of the most destructive (Category 5) cyclones (Steffen, 2009); this can have severe effects on coastal (and inland) transport infrastructure (e.g. Becker et al., 2013). Recent research also projects increases in the incidence of the most intensive tropical storms by the end of the century, even under a moderate warming scenario (Figure I.2.9). The implications for coastal communities and transport infrastructure could be severe due to, amongst others, increases in extreme sea levels (ESLs) and waves (Vousdoukas et al., 2018; Monioudi et al., 2018). It should be noted that storms can induce combined hazards (e.g. both riverine and coastal flooding and high wind damages).

Figure I.2.9 Top: Current incidence (244) of Category 4 and 5 tropical and extratropical storms
Bottom: Incidence (313) of Category 4 and 5 storms under 2°C global warming relative to the pre-industrial times (in 2100, under RCP4.5). Key: x axis (latitude) in degrees and y axis (longitude) in degrees



Source: Taalas, 2019

4. Extreme sea levels and waves

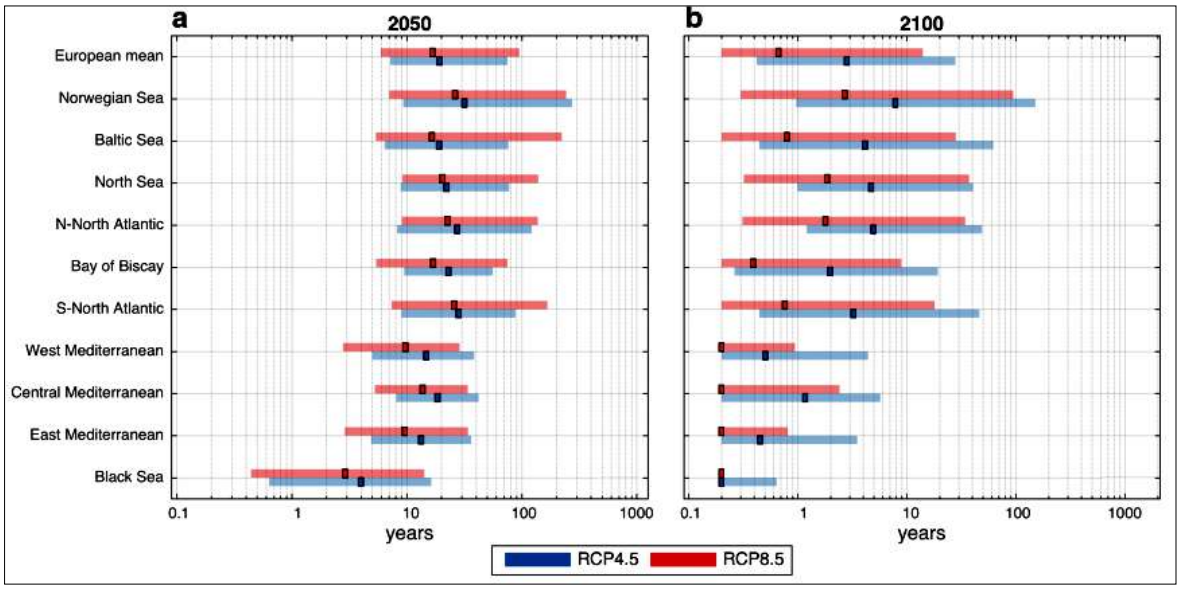
Coastal transport infrastructure can be affected by coastal erosion and flooding which are driven by factors such as wave action, storm surges and sea level (e.g. Losada et al., 2013; Ranasinghe, 2016; Rueda et al., 2017). Extreme sea levels (ESLs) are considered as the sum of the mean sea level (MSL), the astronomical tide and the episodic coastal water level rise due to storm surges and wave set ups. Therefore climate-driven changes in any of the above components will affect also the ESLs. Extreme sea levels can pose a particular threat to highly developed, low-lying coasts such as river deltas which are considered hotspots of coastal erosion/vulnerability due to their commonly high relative SLRs (ECE, 2013).

Mean SLR amplifies ESLs (Marcos et al., 2011), as do increases in storm surges. Documented changes in the intensity and frequency and/or the patterns of extreme waves (Ruggiero, 2013; Bertin et al., 2013; Pérez et al., 2014; Mentaschi et al., 2017) also affect ESLs, as higher waves induce higher coastal wave set ups. Coastal erosion and/or inundations are expected to increase in the future due to the accelerating SLR, under the assumption that other contributing factors like land uplift being equal (Hallegatte et al. 2013; Vousdoukas et al., 2017).

Global projections show that ESLs will increase during the twenty-first century in all areas, although there will be also regional variability. With regard to the storm surge component of ESL, projections for Europe show larger storm surge levels for the Atlantic and Baltic coasts (and ports) (Vousdoukas et al., 2016a; Vousdoukas et al., 2017). Increases in storm surges are projected for the North Sea, particularly along its eastern coast as well as for the Atlantic coast of the United Kingdom and Ireland. By comparison, studies in the Mediterranean indicate small decreases or no future changes (Conte and Lionello, 2014; Androulidakis et al. 2015, Vousdoukas et al., 2016a). This is consistent with historical trends (Menéndez and Woodworth 2010).

ESLs are currently characterised by considerable regional variability, with large tracts of the northern ECE coast (e.g. western and eastern Canada, the North Sea and eastern Russian Federation) showing very high values compared to the Mediterranean and Black Sea coasts (Vousdoukas et al., 2018). Projections show that averaged over Europe's coastlines, the present 100-year ESL (ESL100) will occur approximately every 11 years by 2050, and every 1–3 years by 2100 (Figure I.2.10). Hence, 5 million Europeans (and their transport infrastructure) may be flooded on an almost annual basis by the end of the century (Vousdoukas et al., 2016b; 2017).

Figure I.2.10 **Return period of the present day 100-year ESLs along the European coastline under RCP4.5 and RCP8.5 in 2050 (a) and 2100 (b). Colored boxes express the ensemble mean value and colored patches the inter-model variability (best-worst case).**



Source: Vousdoukas et al., 2017

Photo: Nancy Beijersbergen / shutterstock.com

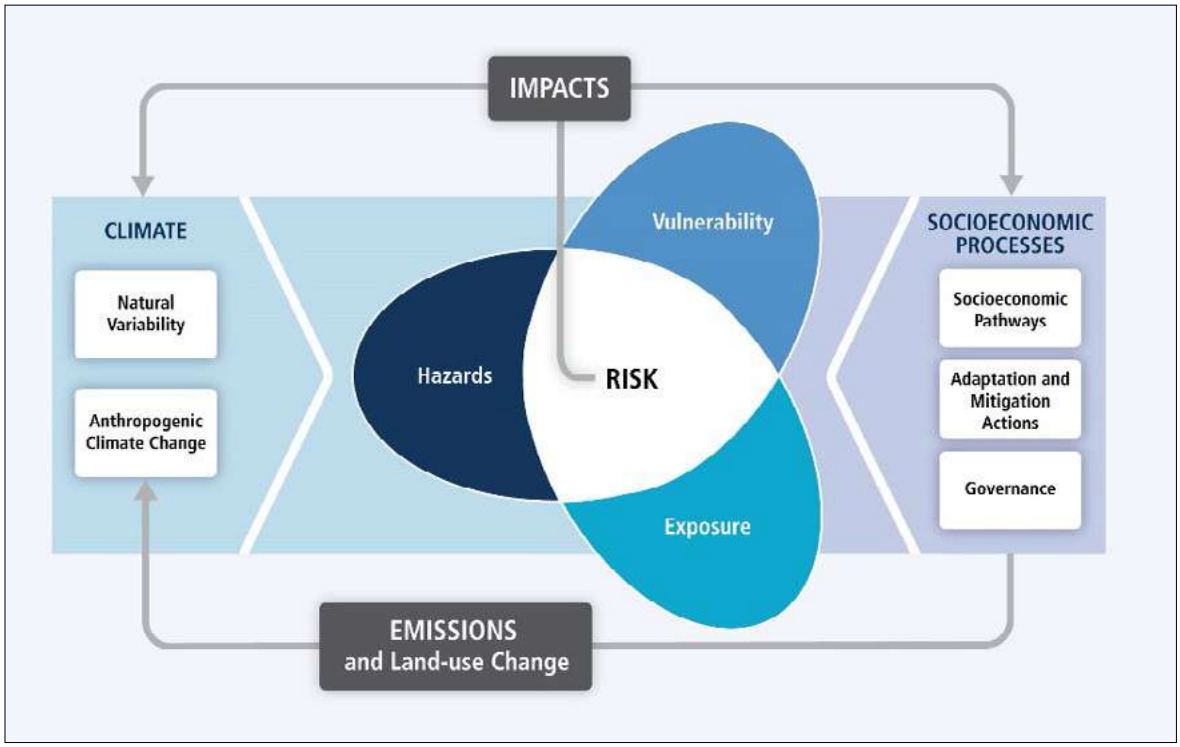
Chapter 3 Analysing future climate impacts

I. Climate information in adaptation planning

Heatwaves, changes in hot and cold temperature extremes, flash flooding, low river flow levels, and riverine and coastal flooding, have been identified as being some of the key climate-related hazards that pose risks to inland transport infrastructure and operations (see the Introduction for further information). The magnitude and frequency of these climate-related hazards is likely to change due to a changing climate (IPCC 2012 SREX). Given that these hazards have wide ranging impacts on transport infrastructure and operations (Table I.1), it is important that an understanding of how the future climate may change is established. In doing so, it is then possible to consider how this information may inform adaptation planning, and thus more resilient transportation infrastructure and operations. The risks posed from climate-related hazards are generated as a result of the interplay of a number of climatic and non-climatic factors, and this is summarised schematically in Figure I.3.1. Non-climatic factors, however, also need to be considered in adaptation planning. This is something that this report does not address, as the focus is on understanding how climatic factors may change, in order to raise awareness of the importance of this issue.

There exists a range of options for obtaining information on how the climate may change, all of which have their associated pros and cons (Wilby et al. 2009). In this section, a number of climate indices which have been derived from the output of climate model simulations, and which are used as proxies for changes in the climate-related hazards, have been analysed. In addition, some analysis is provided on changes in riverine and coastal flooding that have been obtained from impact model simulations.

Figure I.3.1 Risk of climate-related impacts results from the interaction of climate-related hazards (including hazardous events and trends) with the vulnerability and exposure of human and natural systems.



Source: IPCC (2014).

II. Methods and data

A. Climate indices

Six different climate indices are analysed in this report. These indices are related to the climate-related hazards that are considered to be of significant importance to transportation, and these are detailed in Table I.3.1. It is important to state that these indices are only indirectly related to the climate-related hazards, and that some of the indices may provide a stronger connection to the hazards than others, for example the number of very hot days, and the number of days when daily precipitation is greater than 20mm. Other indices, for example, the number of consecutive dry days, provides a rather weak connection to the climate-related hazard of low river flows, because there are a number of other factors that contribute to river flows, which this simple index cannot capture.

These limitations notwithstanding, analysing projected changes for these climate indices serves as a useful first-step in understanding how changes in climate may impact transport infrastructure and operations, and thus help raise awareness of the importance of this issue.

Table I.3.1 Description of the six climate indices analysed in this report, and their associated relevance to the modes of transport and related climate hazards and impacts

Climate index	Definition	Transport mode	Related climate hazards and impacts[1]
Warm spell duration index (WSDI)[2]	Annual count of days with at least six consecutive days when daily maximum temperature is higher than the 90th percentile in the base period	Road, rail networks, ports and airports	*Heatwaves*, rail track buckling, damage to infrastructure, thermal pavement loading and degradation
Very hot days (VHD)	Annual count of days when daily maximum temperature is greater than 30° C	Road, rail networks, ports and airports	*Extreme heat*, rail track buckling, occupational health and safety issues, payload restrictions
Icing days (ID)	Annual count of days when daily maximum temperature is less than 0° C	Road, rail networks, ports, and airports	*Permafrost thaw*, road and rail maintenance costs, airport operational costs (de-icing)
R20mm	Annual count of days when daily precipitation amount is greater than 20mm	Road, rail networks, ports, and airports	*Flash flooding*, slope instability and landslides, speed restrictions
Rx5day[2]	Maximum precipitation amount over a 5 day period calculated on annual basis	Road, rail networks, ports, airports, and river navigation	*River flooding*, slope instability, embankment failure
Consecutive dry days (CDD)	Maximum number of consecutive dry days (where precipitation is less than 1mm)	Waterways	*Low river flow levels*, reduced cargo loads on inland ships

These indices are part of the ETCCDI see: http://etccdi.pacificclimate.org/list_27_indices.shtml

1 This column contains a list of some selected climate hazards and impacts that changes in the climate index may be related to. This list is not meant to be exhaustive, more detail on the kinds of climate hazards and impacts that may be important for the inland transport sector are detailed in table I.1. Italicised text identifies the climate hazard.

2 Changes in these indices were analysed for the European part of the ECE region only.

B. Projecting changes in climate indices

When using climate models to simulate future changes in climate indices, it is important that adequate consideration is given to the issue of uncertainty. There are three main sources of uncertainty in climate projections, and these are natural variability, future emissions of greenhouse gases, and uncertainty in the climate response as represented by the climate models (Hawkins and Sutton 2009). In this analysis, uncertainty in future greenhouse gas emissions was considered by analysing projections for two emissions scenarios (Moss et al. 2010). One is the RCP8.5 scenario, which may be considered to be a "business-as-usual" scenario, and the other is RCP2.6 which is a scenario that represents stringent climate mitigation action, and may accordingly be consistent with meeting the goals of the Paris Agreement. To address uncertainty in the climate system response, simulations from multiple climate models were made, in what is known as a multi-model ensemble.

For practical reasons, two different approaches to projecting changes in the climate indices were used. For the European part of the ECE region, regional climate models (RCMs) were used which

dynamically downscale the output from global climate models. For the Canadian part of the region, a statistical downscaling approach was used. These two different approaches are described in more detail in sections C and D. While using these two different approaches does prevent direct comparisons between the European and Canadian parts of the ECE region, this was not a problem for the way in which the analysis was done in the different countries.

Changes in the climate indices were calculated using a model baseline period of 1971-2000, and a future time period of 2051-2080. Four of the six climate indices were made available and analysed for Canada. These include the number of very hot days, number of icing days, number of days with rainfall over 20mm, and number of consecutive dry days.

To account for uncertainty due to potential climate model structural inaccuracies, multiple climate models are grouped into climate model ensembles. The results that are described in Section III, Sub-sections A and B below focus primarily on changes in the mean of the multi-model ensemble (the multi-model mean) in order to succinctly summarise the uncertainty in the model simulations. However, as adaptation to climate change is an issue of risk management, it is essential to consider the uncertainty in the projections, and therefore the 10th and 90th percentiles were also analysed, so that a more complete picture of potential changes that may impact inland transport infrastructure is given (IPCC 2014). However, it should be emphasized that this range does not represent the full uncertainty in the projections.

C. Climate projections in the European part of ECE region

For the European part of the ECE region, an analysis of regional climate model (RCM) projections was carried out. This data was generated by dynamically downscaling global climate model simulations to the regional level. The data used in this analysis came from the EURO-CORDEX project (Jacob et al. 2014, Giorgi 2019), and have a spatial resolution of ~12.5 km (EUR11 simulations). The models used to generate the data that was analysed are detailed in Table I.3.2.

Table I.3.2 Details of the global climate model (GCM) and regional climate model (RCM) pairs (RCM) used to generate the multi-model ensembles analysed in this work.

	RCM name					
GCM name	CCLM	REMO 2009	REMO 2015	RACMO	RCA4	HIRHAM 5
EC-Earth						
HadGEM2						
MPI-ESM						
IPSL-CM5A						
MIROC						
GFDL-ESM2G						
CanESM2						
NorESM1						

D. Climate projection data for Canada

Statistically downscaled multi-model ensembles with a spatial resolution of 10 km were used for Canada[17]. They have been constructed using output from twenty-four global climate models from the Coupled Model Intercomparison Project Phase 5 (CMIP5), for both RCP8.5 and RCP2.6. The models used are detailed in table I.3.3.

Table I.3.3 CMIP5 Models used for statistical downscaling for Canada

BNU-ESM	FGOALS-g2	IPSL-CM5A-LR	MPI-ESM-MR
CCSM4	GFDL-CM3	IPSL-CM5A-MR	MRI-CGCM3
CESM1-CAM5	GFDL-ESM2G	MIROC-ESM	NorESM1-M
CNRM-CM5	GFDL-ESM2M	MIROC-ESM-CHEM	NorESM1-ME
CSIRO-Mk3-6-0	HadGEM2-AO	MIROC5	bcc-csm1-1
CanESM2	HadGEM2-ES	MPI-ESM-LR	bcc-csm1-1-m

E. Riverine and coastal storm flooding

The information used for assessing the riverine and coastal floods was provided by European Commission-Joint Research Centre (EC-JRC) and relates to the European region of the ECE. Information on riverine flooding was only provided for the baseline period whereas coastal flooding simulations are available for both the baseline period and for the remainder of the twenty-first century (to 2099) under RCP8.5.

Extreme riverine flooding in Europe (an event with a 100-year return period) has been assessed using climate projections from the EURO-CORDEX initiative, by downscaling three General Circulation Models (GCMs) with four Regional Circulation Models (RCM) on a grid resolution of 0.11^{0}, i.e. ~12.5 km in Europe (Alfieri et al., 2018). The LISFLOOD model was used to simulate rainfall-runoff and river routing processes at 5 km resolution; the model was calibrated at 693 river cross sections with extreme value analysis being used to identify return periods (Alfieri et al., 2015; 2018).

Extreme coastal flooding, which is driven by extreme waves and sea levels (e.g. Rueda et al., 2017), was considered as the sum of the mean sea level (MSL), the astronomical tide and the episodic coastal water level rise due to storm surges and wave setups. Projections of extreme sea levels (ESLs) and waves for the twenty-first century under the RCP8.5 emissions scenario were obtained from the dataset presented in Vousdoukas et al. (2018) which provides time series of the ESLs and their components for every 25 km along the coastline. Non-stationary extreme value analysis has been used to obtain extreme values for different return periods (e.g. for the 1 in 100 years ESL (ESL_{100})).

17 The BCCAQv2 statistical downscaling method is described in the following paper: https://journals.ametsoc.org/doi/abs/10.1175/JCLI-D-14-00754.1 and was developed by the Pacific Climate Impacts Consortium

III. Results and analysis

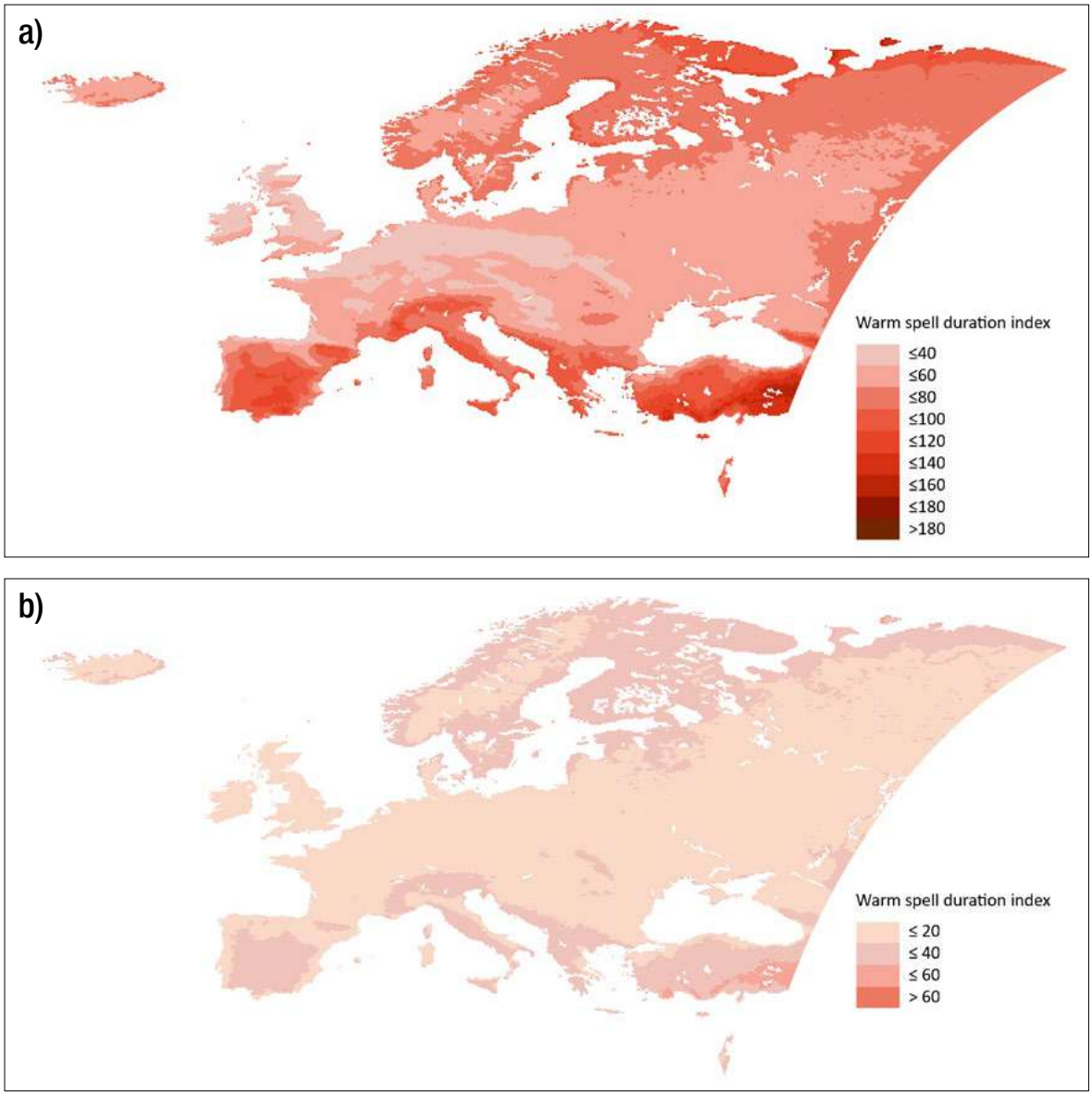
A. European part of the ECE region

All six selected indices were analysed for the European part of the ECE region.

1. Warm spell duration index

Substantial increases in the multi-model mean of the warm spell duration index (WSDI) are projected across Europe under both the RCP8.5 and RCP2.6 scenarios (Figure I.3.2 a. and b.). Projected changes are however, at least twice as large under RCP8.5 scenario. For both scenarios the largest changes are projected in the southern and northern continental European part of the region.

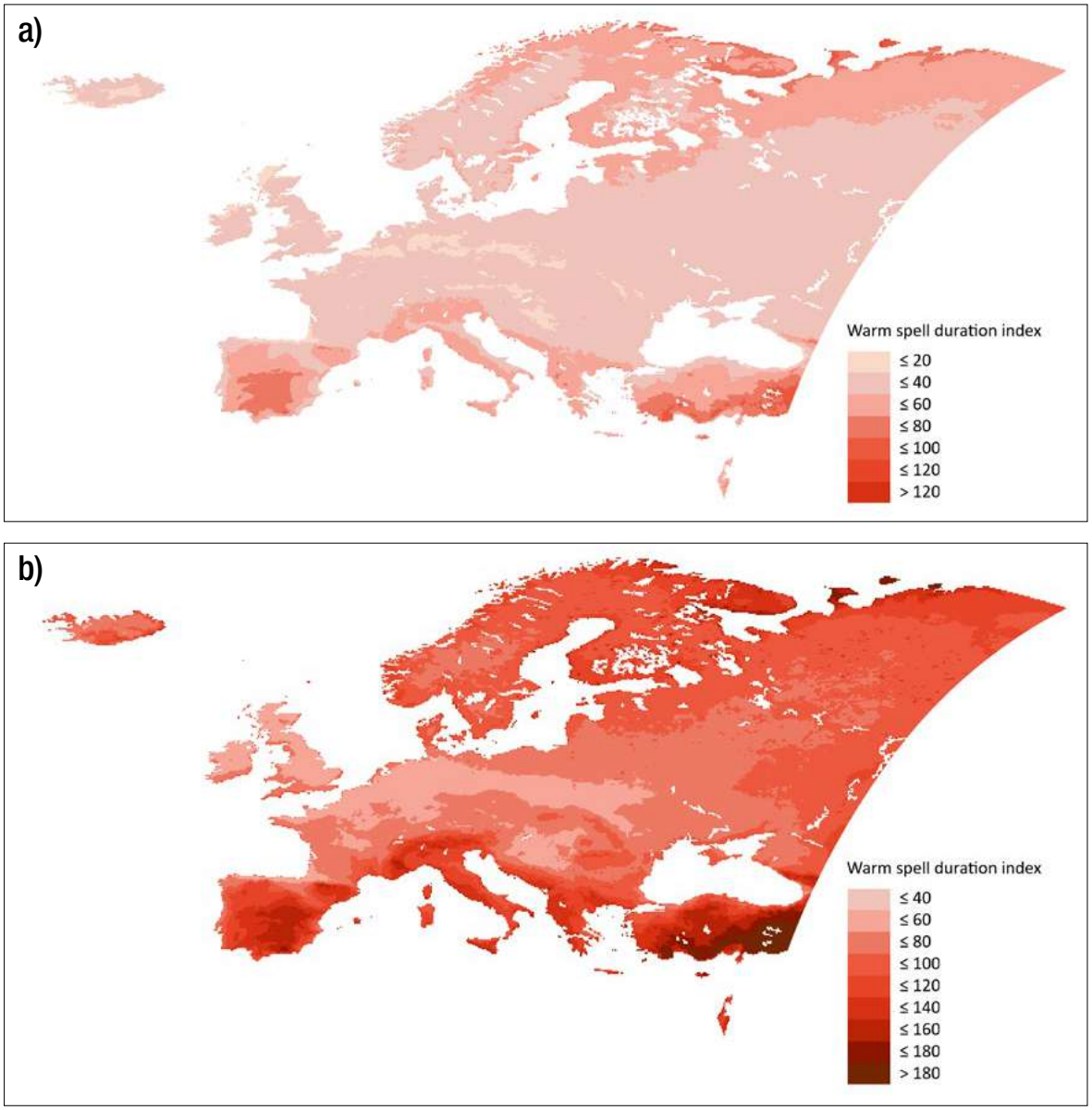
Figure I.3.2 **Change in the warm spell duration index (WSDI) under a) RCP8.5 and b) RCP2.6 for period 2051-2080 with respect to the 1971-2000 baseline period. The maps show the multi-model mean values, and changes are in units of days per year.**



Source: ECE

For RCP8.5 scenario, there may be an increase of more than 80 WSDI days over large areas of southern Europe (and Israel) and by up to 80 WSDI days over large areas of Scandinavia and northern Russia. Smaller increases of up to 60 WSDI days are projected for the more central parts of the region. Overall, the largest increases are projected in parts of Spain and Turkey. Uncertainty in the projected increases ranges from around 40 days at the 10th percentile (Figure I.3.3.a), and up to 100 WSDI days at the 90th percentile (Figure I.3.3.b), over large areas of southern and northern continental Europe.

Figure I.3.3 Change in the warm spell duration index (WSDI) under RCP8.5, for a) 10th percentile values and b) 90th percentile values.



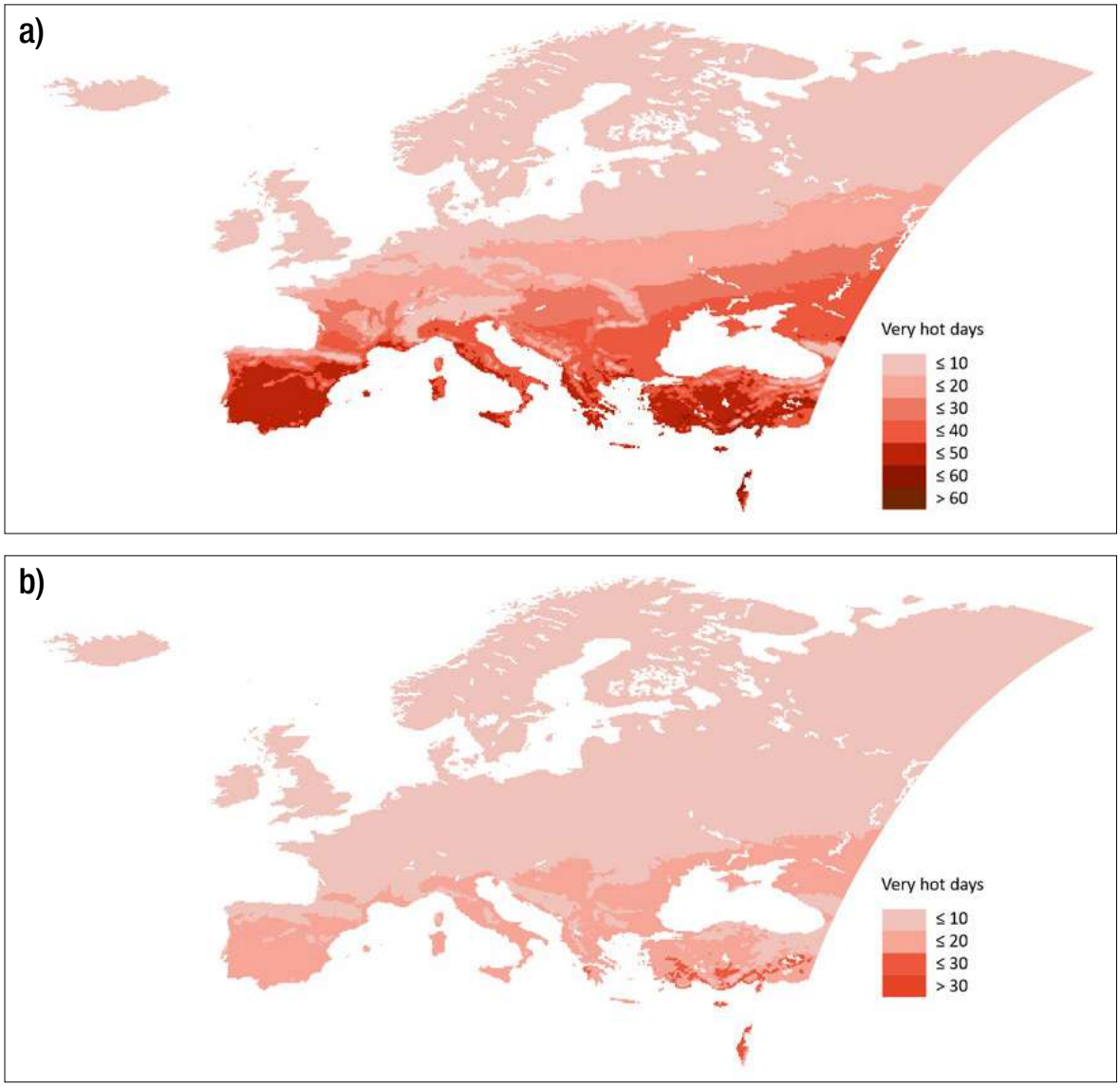
Source: ECE

For RCP2.6 scenario, southern and northern parts of Europe show projected increases of around 20 to 40 WSDI days per year (see Figure I.3.2 b). Uncertainty in the projected increases ranges from generally small increases at the 10th percentile to up to 60 WSDI days at the 90th percentile (these maps can be viewed in the online ECE GIS).

2. Number of very hot days

Under both RCP8.5 and RCP2.6 scenarios, all areas of Europe show a projected increase in the number of very hot days (VHD), with a clear latitudinal gradient in the pattern of increase, with already warmer southern areas having larger projected increases in the number of VHD than those in the cooler northern parts of the ECE region (Figures I.3.4 a. and b.).

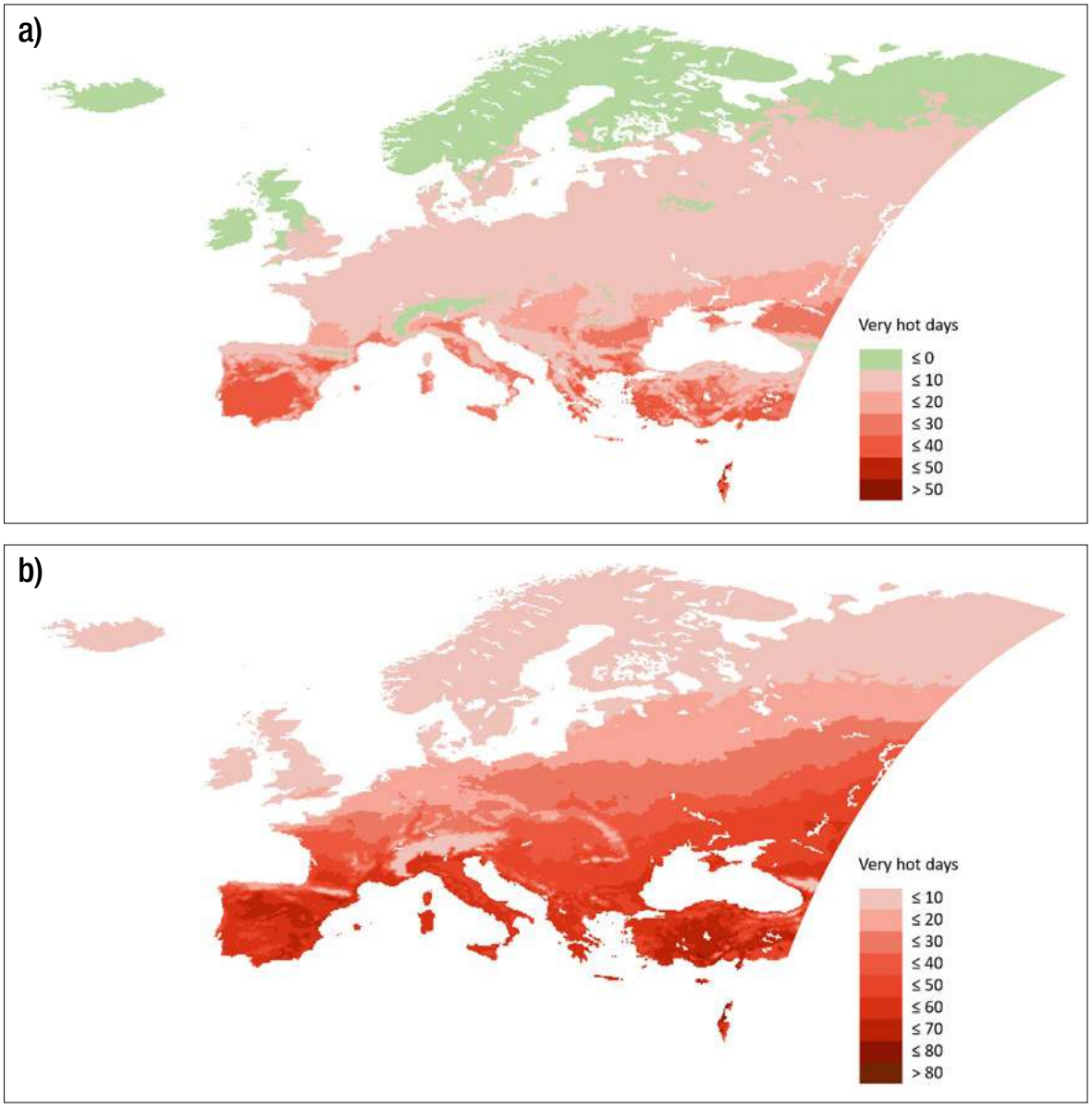
Figure I.3.4 **Change in the number of very hot days (VHD) under a) RCP8.5 and b) RCP2.6. Change is calculated from the 1971-2000 baseline period, for a future time period of 2051-2080. The map shows the multi-model mean values, as days per year.**



Source: ECE

For RCP8.5 scenario, large areas of southern Europe are projected to have an increase of 40 to 50 VHD per year, with significant parts of Portugal, Spain, France, Italy, Greece, and Turkey having areas where projected changes may be as large as 50 to 60 VHD per year. Areas in central Europe may see up to 20 to 30 more VHD per year by the 2051-2080 time period, with more northerly areas seeing changes of up to 10 additional VHD per year. Uncertainty in the projected increases ranges from up to 40 VHD at the 10th percentile (Figure I.3.5.a), and up to 70 to 80 VHD at the 90th percentile (Figure I.3.5.b), for areas in southern Europe.

Figure I.3.5 Change in number of very hot days (VHD) under RCP8.5, for a) 10th percentile values and b) 90th percentile values



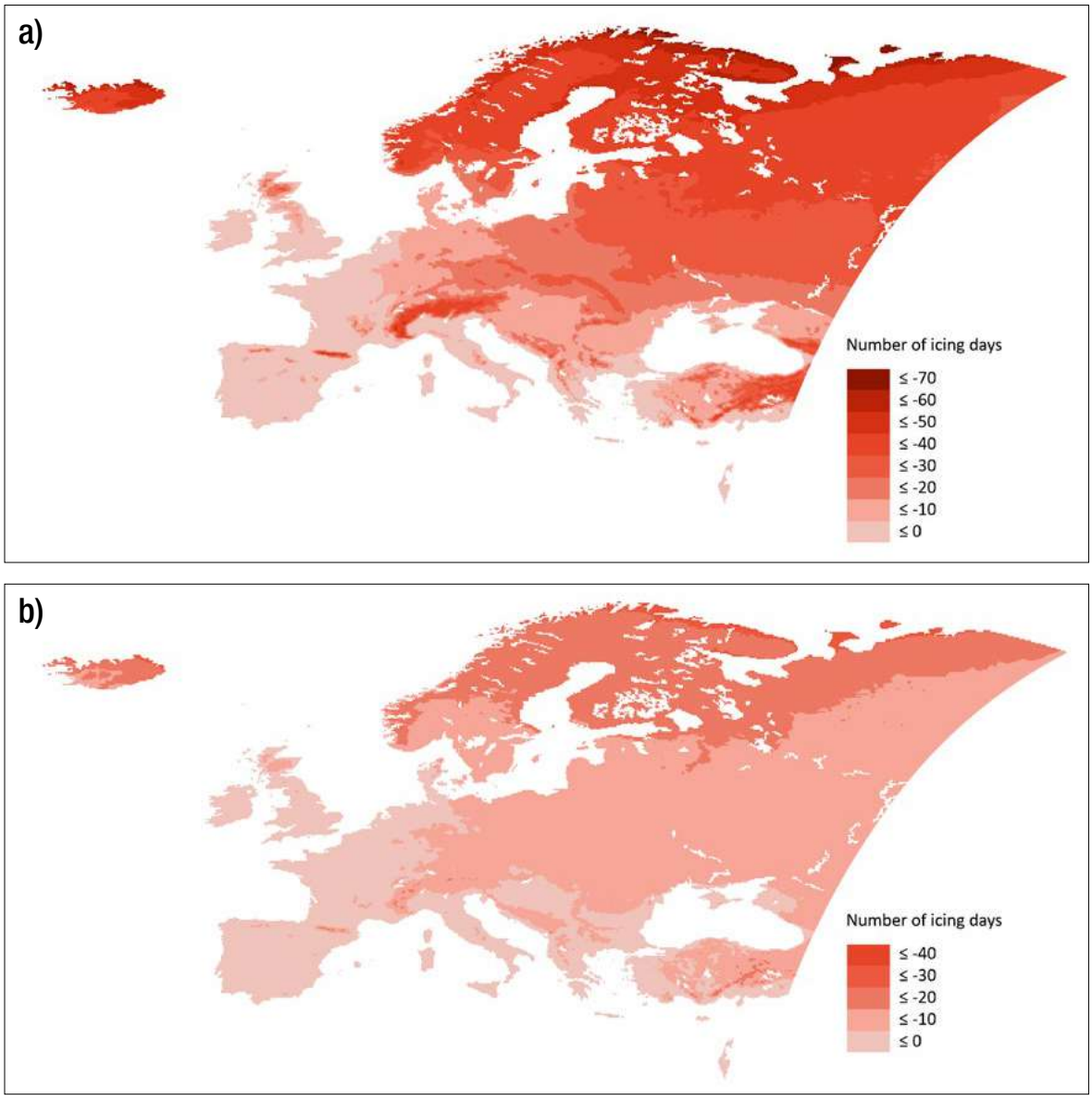
Source: ECE

For RCP2.6 scenario, projected increases are smaller than those at RCP8.5, with large areas of southern Europe having projected increases of up to 20 VHD per year (Figures I.3.4.b). Uncertainty in the projected increases ranges from around 10 VHD at the 10th percentile, to up to 60 VHD at the 90th percentile (these maps can be viewed in the online ECE GIS).

3. Number of icing days

Substantial decreases in the number of icing days (ID) are projected across northern, eastern and central Europe under both RCP8.5 and RCP2.6 scenarios (Figures I.3.6 a. and b.). For both emissions scenarios the largest projected decreases are in Scandinavia and high-mountain areas (e.g. the Alps), where there may be 40 to 50 fewer ID per year under RCP8.5 scenario, with generally around 20 to 30 fewer ID under the RCP2.6 scenario, although more limited areas of high-mountain areas show this level of decrease.

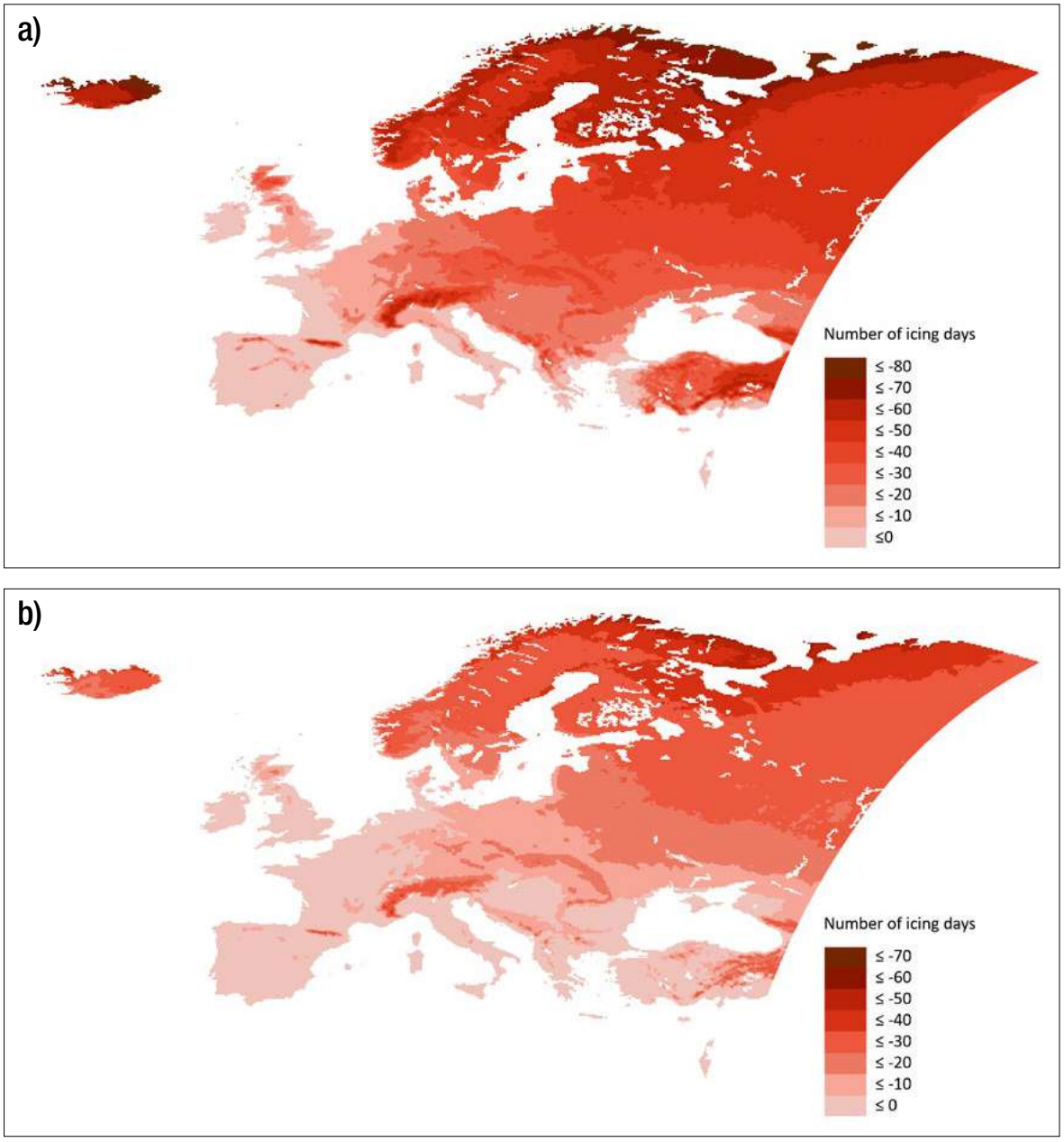
Figure I.3.6 **Change in the number of icing days (ID) under a) RCP8.5 and b) RCP2.6. Change is calculated from the 1971-2000 baseline period, for a future time period of 2051-2080. The map shows the multi-model mean values, and changes are in units of days per year.**



Source: ECE

Uncertainty in the projected decreases in these areas under the RCP8.5 scenario ranges from around 50 to 70 ID at the 10th percentile (Figure I.3.7.a), and 30 to 40 ID at the 90th percentile (Figure I.3.7.b). Uncertainty in the projected decreases under the RCP2.6 scenario ranges from 30 to 40 ID at the 10th percentile, and 10 to 20 ID at the 90th percentile (these maps can be viewed in the online ECE GIS).

Figure I.3.7 Change in number of icing days (ID) under RCP8.5, for a) 10th percentile values and b) 90th percentile values

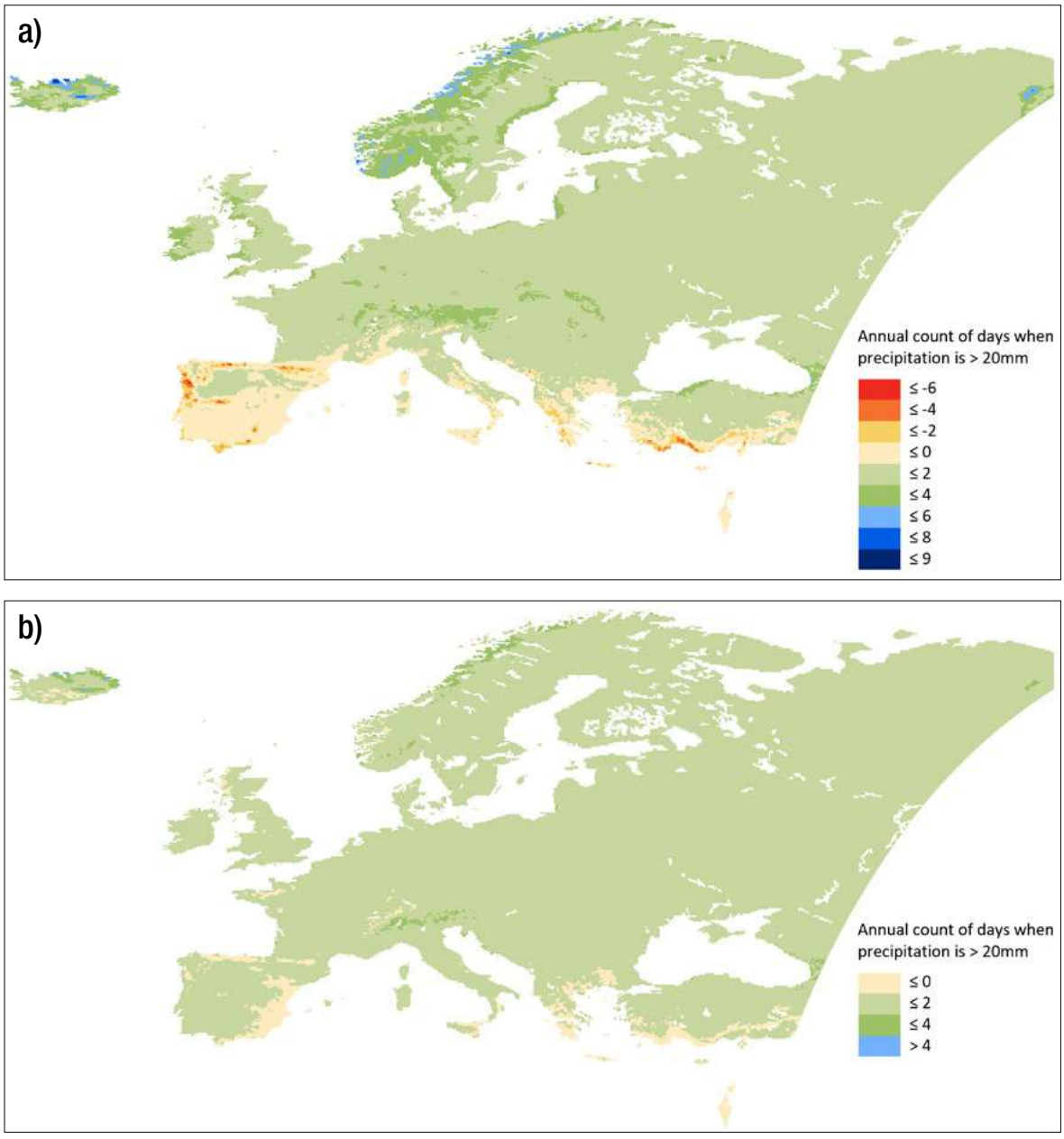


Source: ECE

4. Daily precipitation above 20 mm

There is a spatial divide in the projected changes in the number of days when daily precipitation is greater than 20mm (R20mm) for the north and south regions of the ECE under for both emissions scenarios (Figures I.3.8 a. and b.). The changes and spatial pattern are more marked under RCP8.5 than RCP2.6. Increases of around 4 R20mm days were projected for northern and some high-mountain areas of Europe. In large areas of the Iberian Peninsula, and more limited areas of Italy, Greece, and Turkey decreases were projected, with some more isolated areas in these regions showing decreases of around 4 to 6 R20mm days per year. For the rest of Europe, the vast majority of areas show a projected increase in R20mm of around 1 day, and this is true under both emissions scenarios.

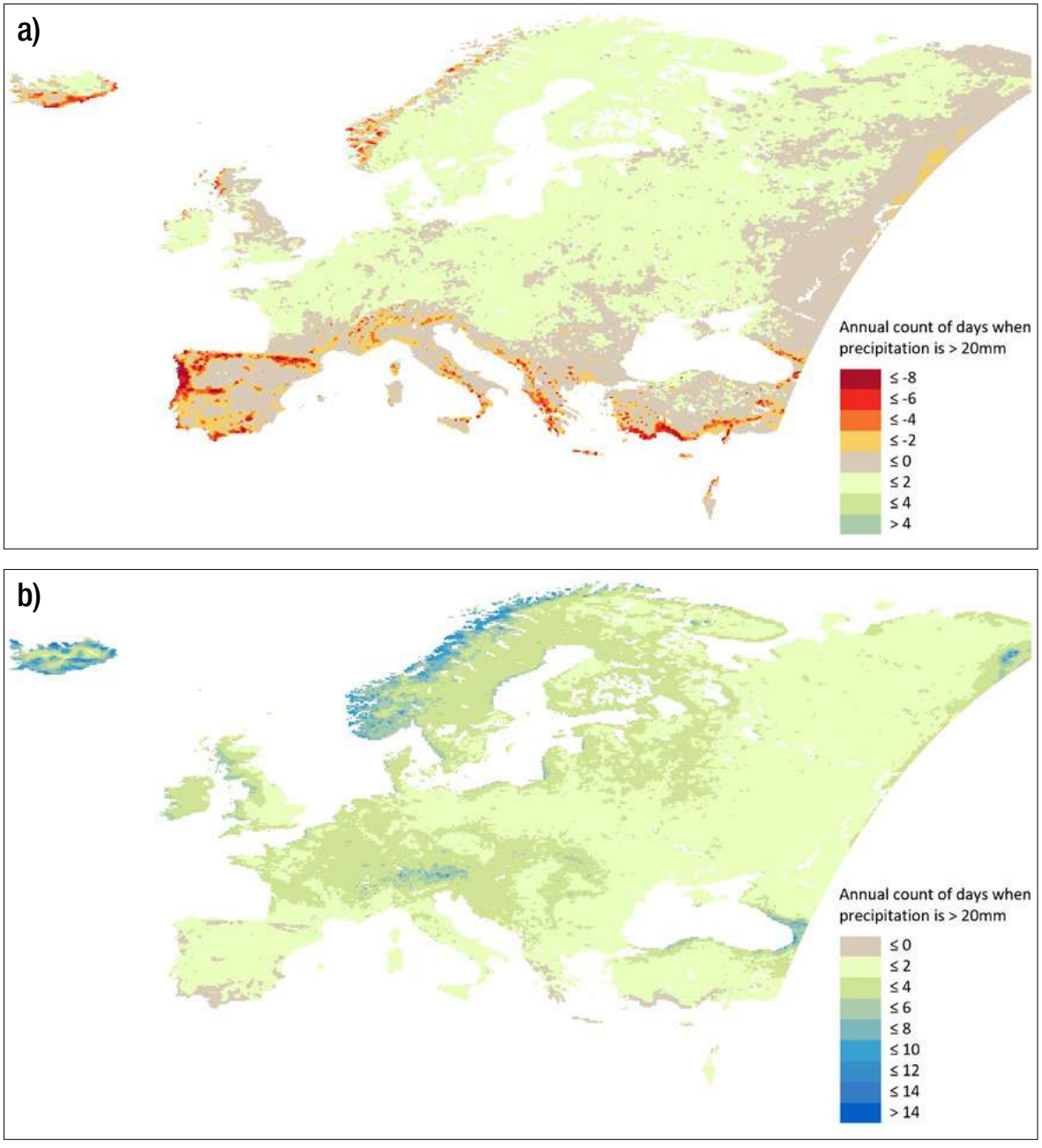
Figure I.3.8 **Change in the number of days with precipitation above 20mm (R20mm) under a) RCP8.5 and b) RCP2.6. Change is calculated from the 1971–2000 baseline period, for a future time period of 2051-2080. The map shows the multi-model mean values, and changes are in units of days per year.**



Source: ECE

Uncertainty in the projected changes under the RCP8.5 scenario is high, at the 10th percentile, northern parts of the region are also projected to see a reduction in R20mm, while in southern Europe projected decreases are more widespread and larger, with up to 8 fewer R20mm days projected in some areas (Figure I.3.9.a). At the 90th percentile all areas are projected to see an increase in R20mm, with the largest increases being seen in Norway and higher elevation areas (Figure I.3.9.b).

Figure I.3.9 Change in the number of days with precipitation above 20mm (R20mm) under RCP8.5, for a) 10th percentile values and b) 90th percentile values



Source: ECE

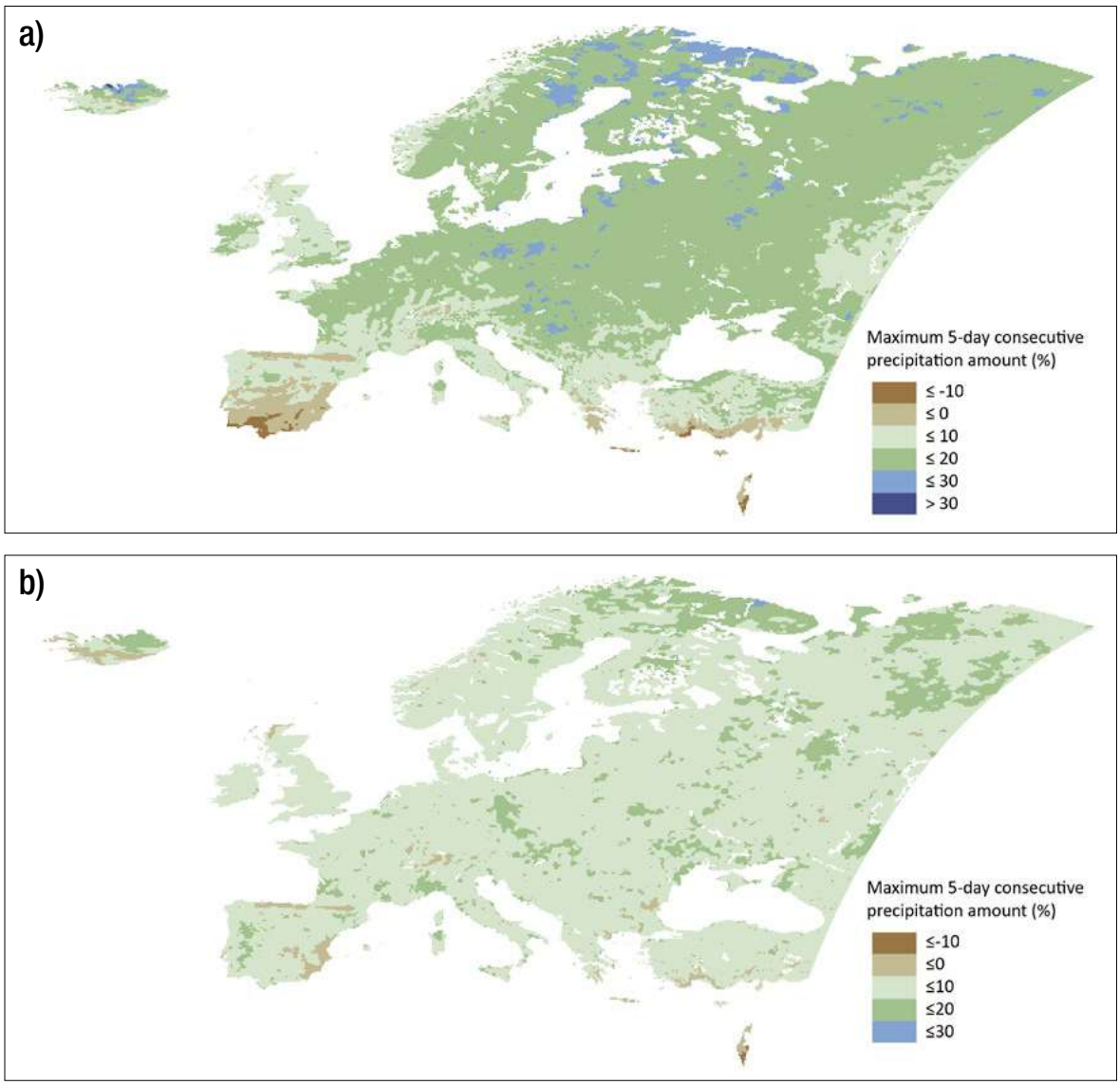
Under the RCP2.6 scenario, at the 10th percentile, the vast majority of areas are projected to see a reduction in R20mm but changes are small on the order of 1 day, while at the 90th percentile all areas show an increase with the overall pattern being similar to that under the RCP8.5 scenario (these maps can be viewed in the online ECE GIS).

5. Maximum 5-day consecutive precipitation amount

Changes in the maximum precipitation amount over a 5-day period (Rx5day), are projected to increase across Europe for both scenarios (Figures I.3.10 a. and b.), with the exception of large parts of the Iberian Peninsula, fewer areas of Greece and Turkey, and some isolated areas in central Europe under the RCP8.5 scenario, which are projected to see a decrease in Rx5day of around 10 per cent (Figure I.3.10.a).

Under the RCP8.5 scenario, projected increases in Rx5day are generally around 10 to 20 per cent, with some more isolated areas with projected increases of 30 per cent. Under the RCP2.6 scenario projected increases are on the order of 10 to 20 per cent (Figure I.3.10.b).

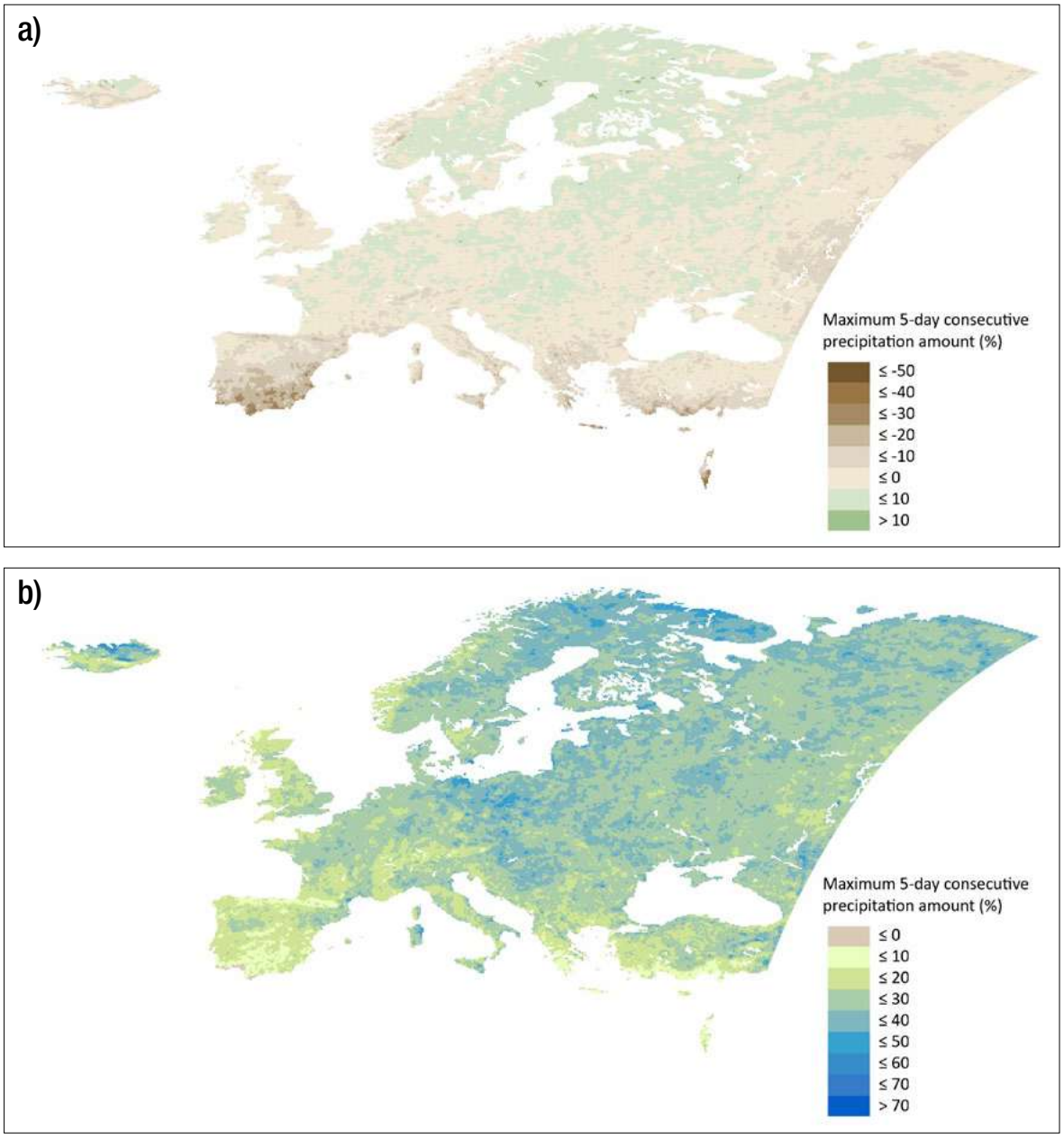
Figure I.3.10 Change in the maximum 5-day consecutive precipitation amount (Rx5day) under a) RCP8.5 and b) RCP2.6. Change is calculated from the 1971-2000 baseline period, for a future time period of 2051-2080. The map shows the multi-model mean values, and changes are in per cent.



Source: ECE

Uncertainty in the projected changes under the RCP8.5 scenario is high with large areas projected to see a decrease in Rx5day at the 10th percentile (Figure I.3.11.a), while at the 90th percentile all areas are projected to see an increase (Figure I.3.11.b). Under the RCP2.6 scenario, uncertainty is also high with areas of no and small increase at the 10th percentile, and increases of up to 20 to 30 per cent at the 90th percentile (these maps can be viewed in the online ECE GIS).

Figure I.3.11 Percentage changes in maximum 5-day consecutive precipitation amount (Rx5day) under RCP8.5, for a) 10th percentile values and b) 90th percentile values

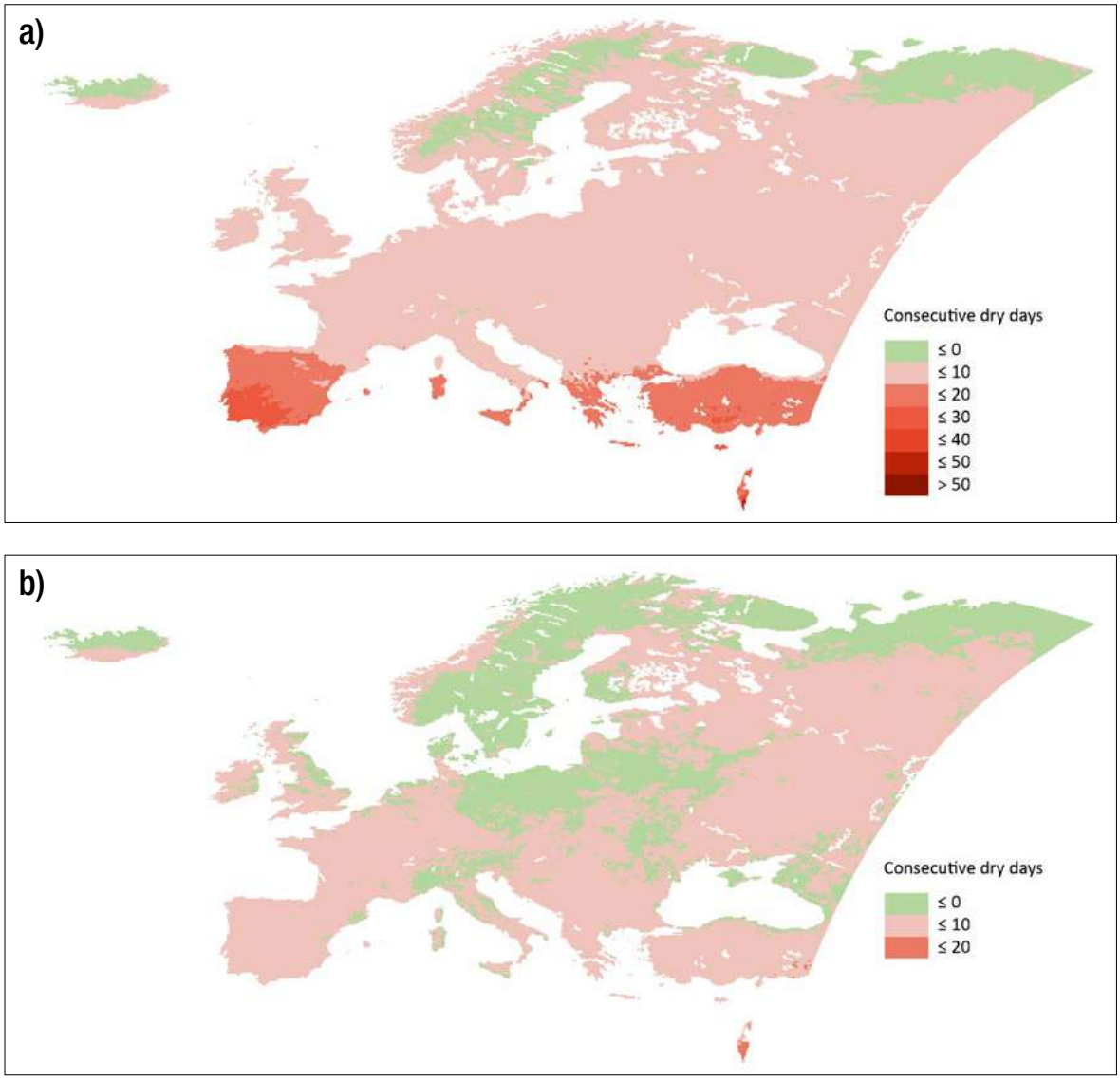


Source: ECE

6. Consecutive dry days

There may be an increase of around 10 to 20 consecutive dry days (CDD) across Europe under the RCP8.5 scenario, with some areas in the Iberian Peninsula, Turkey and Israel that may see increases of up to 30 CDD. However, there are also some large areas in northern Europe that are projected to see small decreases in CDD (Figure I.3.12.a). Under the RCP2.6 scenario, large areas are projected to see an increase in CDD but increases are smaller than under RCP8.5 on the order of 10 CDD. However, there is an increase in the number of areas that are projected to see decreases in CDD compared to RCP8.5 (Figure I.3.12.b).

Figure I.3.12 Change in consecutive dry days (CDD) under a) RCP8.5 and b) RCP2.6. Change is calculated from the 1971-2000 baseline period, for a future time period of 2051-2080. The map shows the multi-model mean values, and changes are in units of days per year

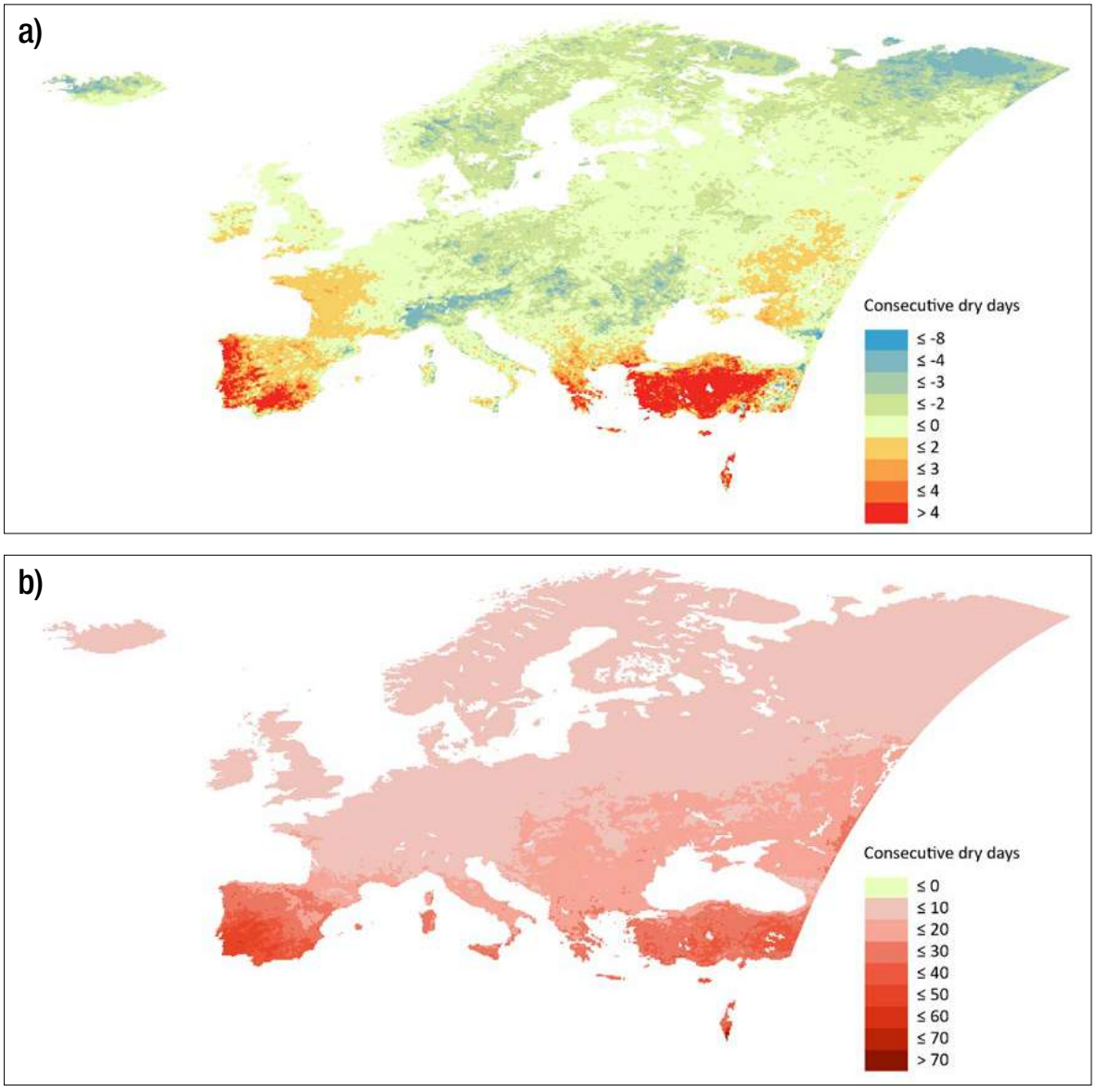


Source: ECE

Under the RCP8.5 scenario, uncertainty in the projected changes is high. At the 10th percentile a complex picture emerges, with some southern areas projected to see an increase in CDD of up to 4 days (Figure I.3.13.a), whereas central, eastern, and northern areas may experience a decrease in CDD on the order of 2 to 4 days is projected. At the 90th percentile however, all areas are projected

to see an increase in CDD, with areas in southern Europe seeing the largest increases of up to 50 CDD (Figure I.3.13.b). Uncertainty in the RCP2.6 scenario is also high, at the 10th percentile the vast majority of the region is projected to see a decrease in CDD, whereas at the 90th percentile all areas are projected to see an increase in CDD (these maps can be viewed in the online ECE GIS).

Figure I.3.13 Change in consecutive dry days (CDD) under RCP8.5, for a) 10th percentile values and b) 90th percentile values



Source: ECE

B. Canada

The following four indices have been analysed for Canada: number of very hot days, number of icing days, number of days with rainfall over 20mm, and number of consecutive dry days. Data for these indices was provided by the Canadian Centre for Climate Services.[18]

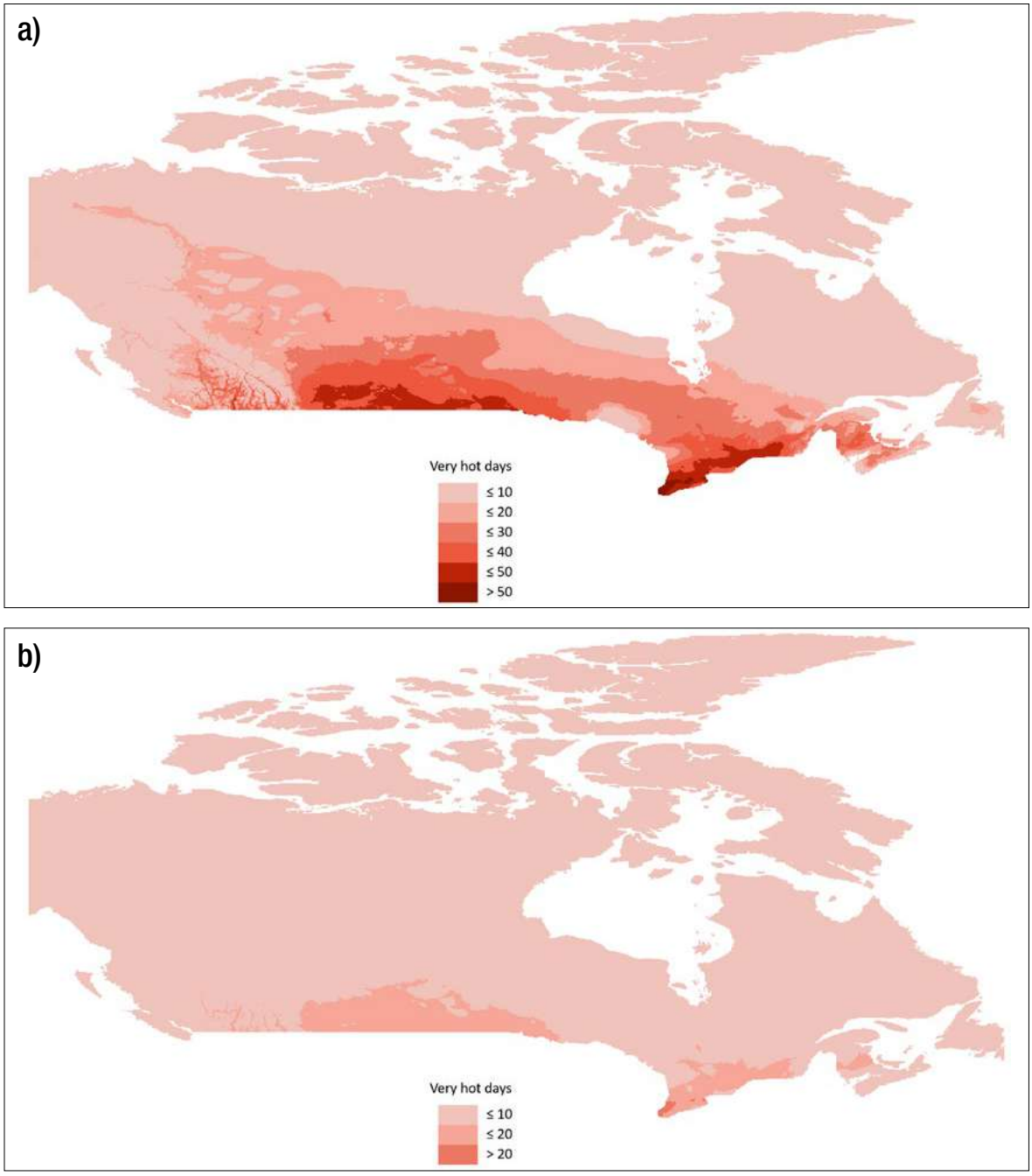
18 This data can be found at www.climatedata.ca

1. Number of very hot days

The number of VHD is projected to increase across Canada under the RCP8.5 scenario, with the highest projected increases being between 40 to 50 VHD per year for the southern parts of Alberta, Saskatchewan, Manitoba, Ontario and Quebec and increases exceeding 50 VHD for the southern part of Ontario (Figure I.3.14.a).

Under the RCP2.6 scenario, projected changes are smaller than those under RCP8.5, with the same aforementioned areas projected to see increases of up to 20 VHD per year (Figure I.3.14.b).

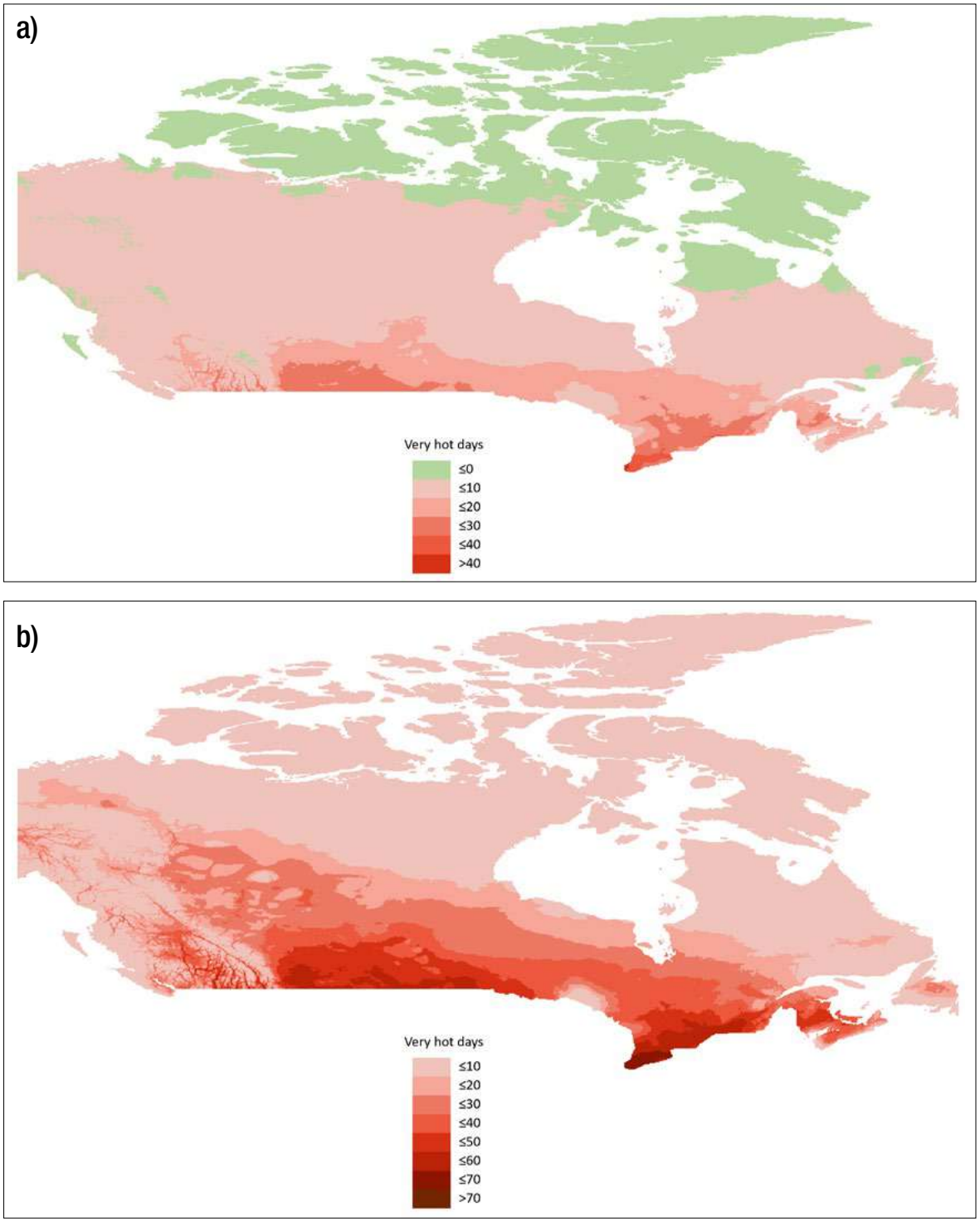
Figure I.3.14 Change in the number of very hot days (VHD) under a) RCP8.5 and b) RCP2.6. Change is calculated from the 1971-2000 baseline period, for a future time period of 2051-2080. The map shows the multi-model mean values, as days per year.



Source: ECE

Under the RCP8.5 scenario, uncertainty in the projected increases ranges from 30 VHD at the 10th percentile (Figure I.3.15.a) to 50 to 60 VHD at the 90th percentile (Figure I.3.15.b) for southern parts of Alberta, Saskatchewan, Manitoba, Ontario and Quebec. For the RCP.2.6 scenario, uncertainty in the projected increases ranges from 10 VHD at the 10th percentile to 30 VHD at the 90th percentile (these maps can be viewed in the online ECE GIS).

Figure I.3.15 Change in number of very hot days (VHD) under RCP8.5, for a) 10th percentile values and b) 90th percentile values



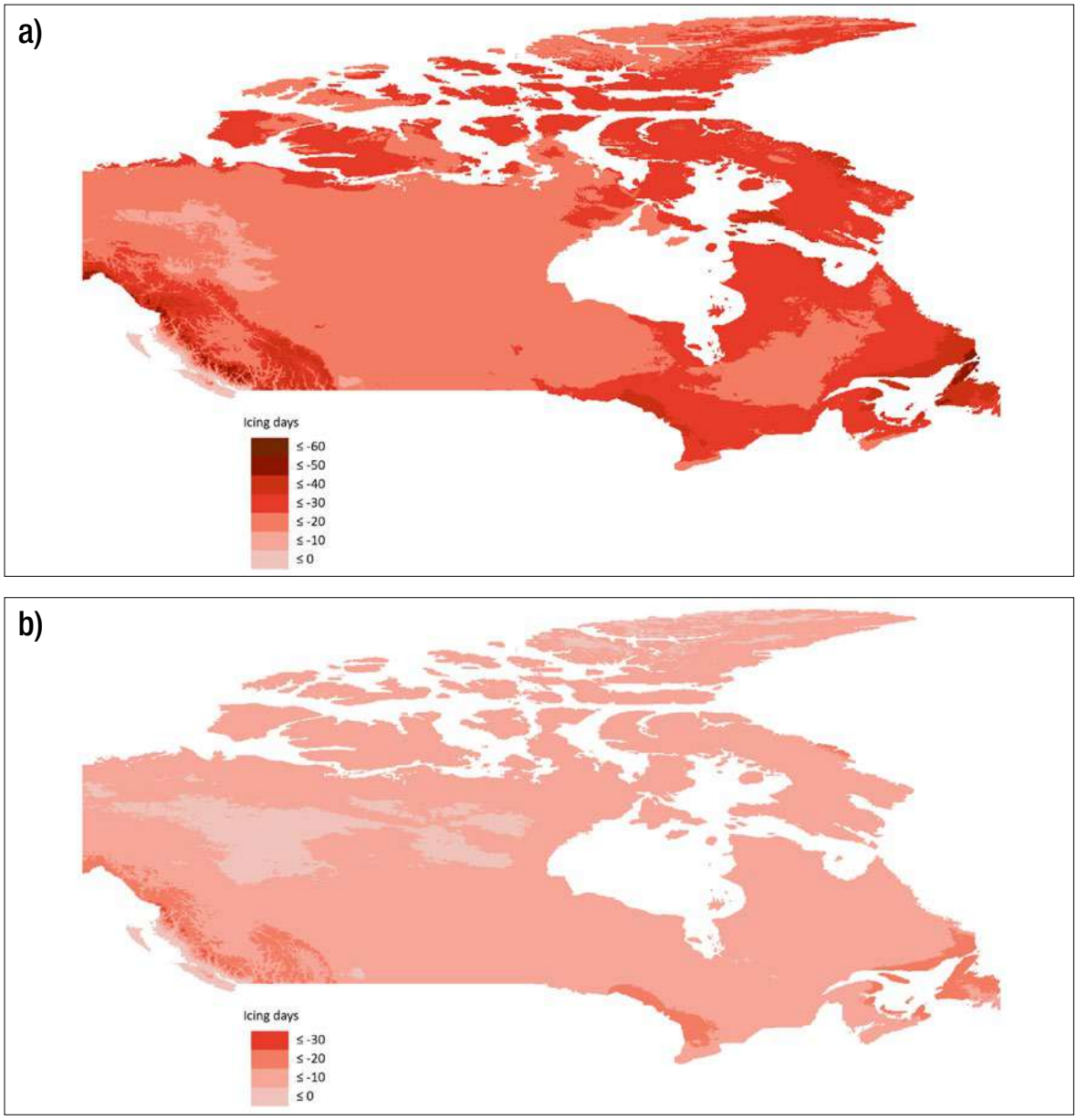
Source: ECE

2. Number of icing days

Under the RCP 8.5 scenario, there is a projected 20 ID decrease per year across most of Canada. In parts of Labrador (Newfoundland and Labrador), the Ungava Peninsula (Quebec), Baffin Island (Nunavut), Banks Island (Northwest Territories), Ellesmere Island (Nunavut), the Rocky Mountains (British Columbia/Alberta), southern Quebec and into the eastern maritime provinces, the Great Lakes region (Ontario), and southern Quebec and into the eastern maritime provinces decreases of 30 ID are projected. Localised areas of the west and east coasts of Canada show projected decreases of more than 50 ID per year (Figure I.3.16.a).

Under the RCP2.6 scenario, the decrease of 10 ID is projected for most of Canada and 20 ID in localized areas of British Columbia, Alberta, the Great Lakes region (Ontario), and parts of Atlantic Canada (Figure I.3.16.b).

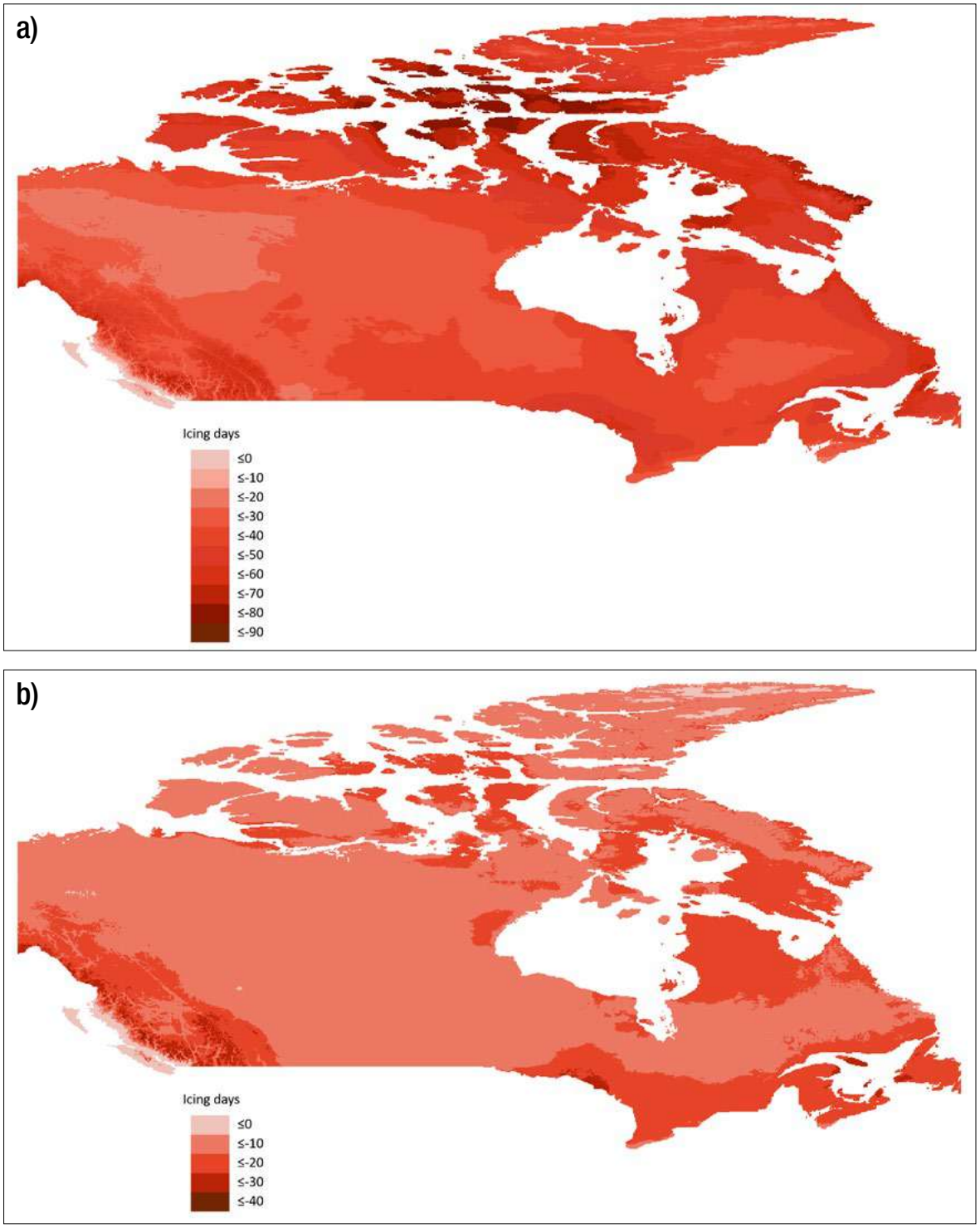
Figure I.3.16 Change in the number of icing days (ID) under a) RCP8.5 and b) RCP2.6. Change is calculated from the 1971-2000 baseline period, for a future time period of 2051-2080. The map shows the multi-model mean values, and changes are in units of days per year.



Source: ECE

Uncertainty in the projected decreases under the RCP8.5 scenario ranges from 30 to 70 ID at the 10th percentile (Figure I.3.17.a) and 10 to 20 ID at the 90th percentile (Figure I.3.17.b) for most of Canada. Uncertainty in the projected decrease for these areas under the RCP2.6 scenario ranges from 10 to 30 ID at the 10th percentile to 10 ID at the 90th percentile (these maps can be viewed in the online ECE GIS).

Figure I.3.17 Change in number of icing days (ID) under RCP8.5, for a) 10th percentile values and b) 90th percentile values



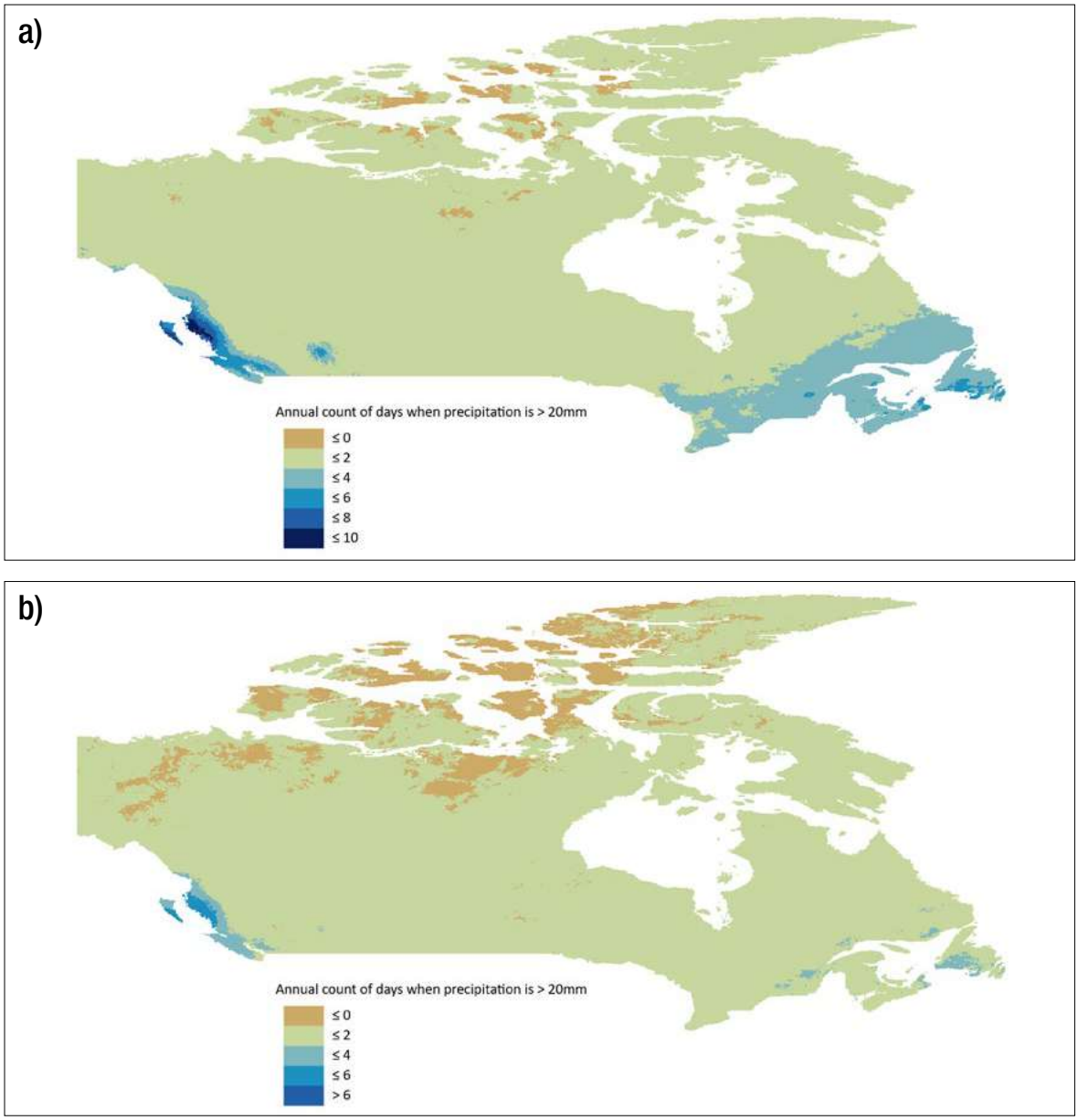
Source: ECE

3. Daily precipitation above 20mm

Under the RCP8.5 scenario, an increase in daily precipitation above 20mm of 2 days is projected for most of Canada. The west coast of Canada as well as southern regions of Ontario, Quebec, and Atlantic Canada, could see an R20mm increase of 4 or more days per year. The majority of Northern Canada will also experience an increase in R20mm of approximately 2 days, with very few localized regions not projected to see an increase in R20mm (Figure I.3.18.a).

Under the RCP2.6 scenario, projected changes in R20mm also show increases of 2 days per year for nearly the entire country. Regions may see a R20mm increase of up to 4 days, possibly 6 for the west coast. Under this scenario, a large portion of Northern Canada is projected to not see an increase in days with daily precipitation above 20mm (Figure I.3.18.b).

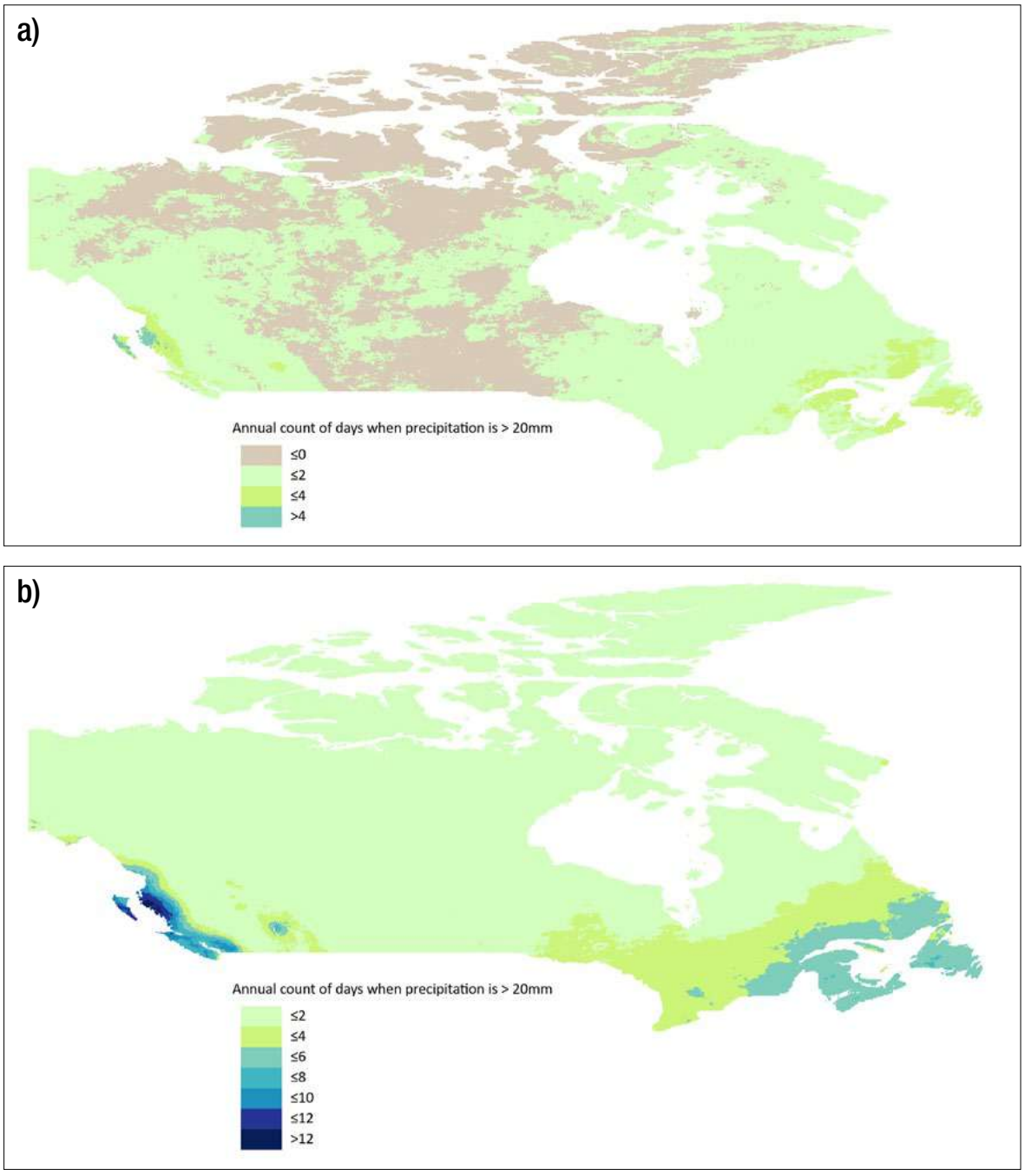
Figure I.3.18 **Change in the number of days with precipitation above 20mm (R20mm) under a) RCP8.5 and b) RCP2.6. Change is calculated from the 1971-2000 baseline period, for a future time period of 2051-2080. The map shows the multi-model mean values, and changes are in units of days per year.**



Source: ECE

Uncertainty in the projected changes under the RCP.8.5 scenario ranges from 0 to 2 days at the 10th percentile (4 days along the west coast of Canada and Atlantic Canada) (Figure I.3.19.a) to 4 days for most of Canada at the 90th percentile (10 to 12 days for the west coast and 6 to 8 for Atlantic Canada) (Figure I.3.19.b). For RCP2.6, at 10th percentile no changes are projected except for the west coast of Canada and the Ontario and Quebec with increases projected at 2 days. At the 90th percentile increases are projected at 2 days for most of Canada, and 4 to 6 days in southern Ontario and Quebec and 8 to 10 days along the west coast (these maps can be viewed in the online ECE GIS).

Figure I.3.19 Change in the number of days with precipitation above 20mm (R20mm) under RCP8.5, for a) 10th percentile values and b) 90th percentile values

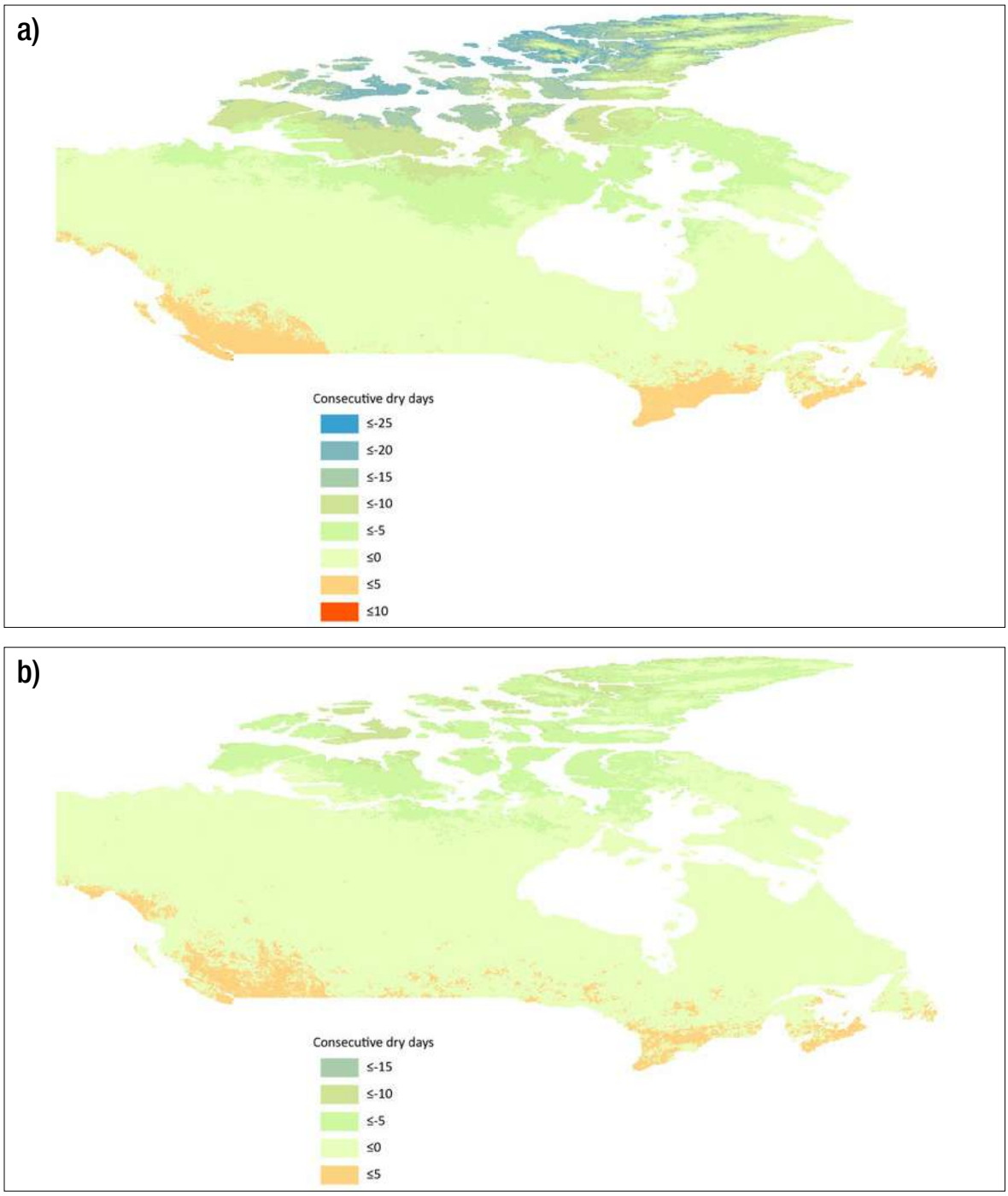


Source: ECE

4. Consecutive dry days

Under the RCP8.5 scenario, there is a projected 5 CDD increase along the west coast of Canada, Southern Ontario and Quebec, and in the Atlantic provinces. For most of the rest of the country, there is no change in CDD projected, with the exception of Northern Canada where 5 to 25 CDD decrease is possible (Figure I.3.20.a). Under the RCP2.6 scenario, the spatial distribution is similar, though the projected decreases for Northern Canada are smaller (5 to 15 CDD) (Figure I.3.20.b).

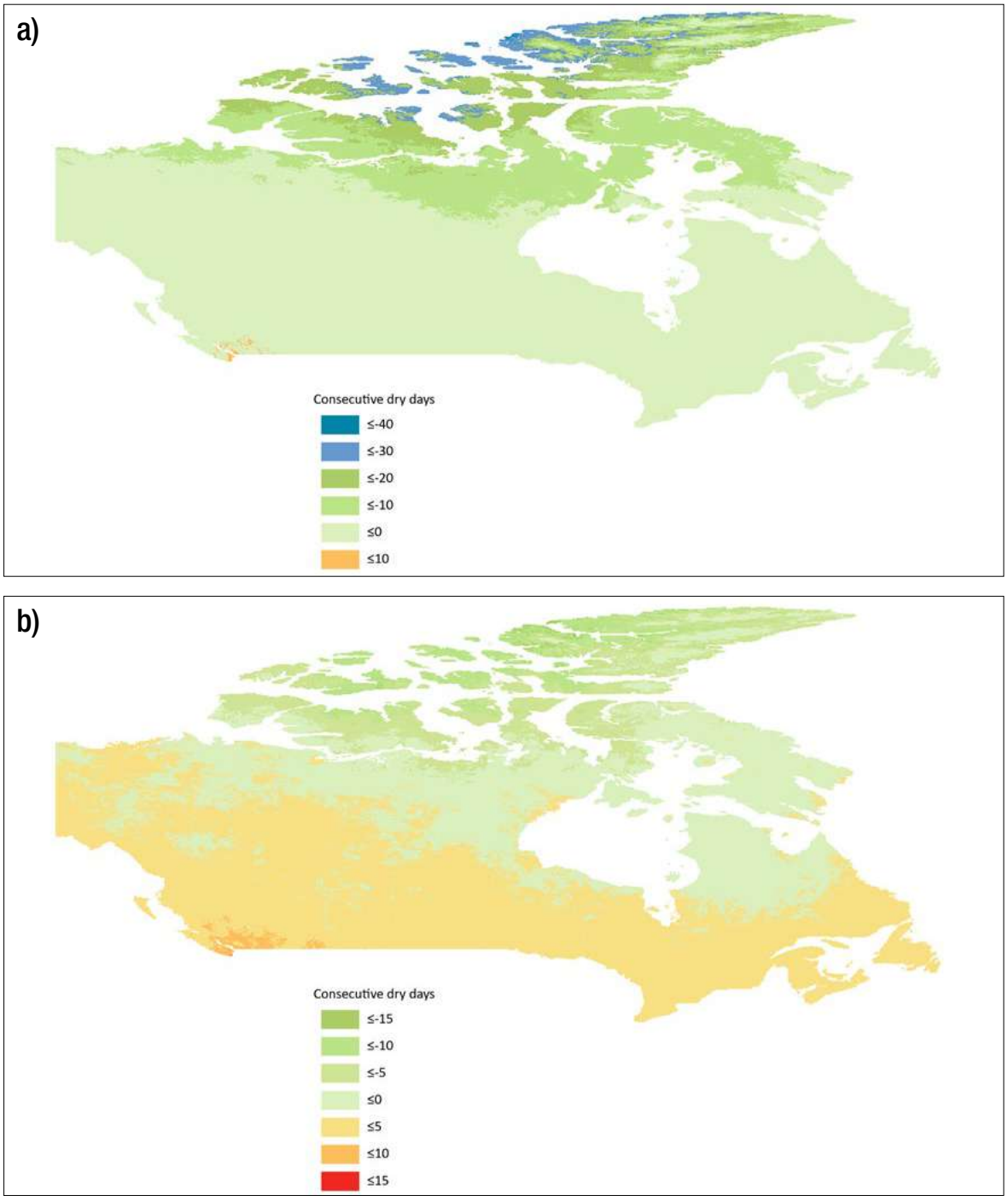
Figure I.3.20 **Change in the consecutive dry days (CDD) under a) RCP8.5 and b) RCP2.6. Change is calculated from the 1971-2000 baseline period, for a future time period of 2051-2080. The map shows the multi-model mean values, and changes are in units of days per year.**



Source: ECE

Uncertainty in the projected changes under the RCP8.5 scenario ranges from 0 CDD at 10th percentile to increases of 0 to 5 CDD at 90th percentile for most of Canada (except the northern parts). The northern parts are projected to see decreases between 10 to 40 CDD at the 10th percentile and 5 to 15 CDD at the 90th percentile). Under the RCP2.6 scenario, uncertainty ranges again from 0 CDD at the 10th percentile to an increase of 0 to 5 CDD at the 90th percentile for most of the Canada. The northern parts may see decreases of 10 to 20 CDD at 10th percentile while there are increases of 0 to 5 CDD (and in localized areas of 10 CDD) at the 90th percentile.

Figure I.3.21 Change in the consecutive dry days (CDD) under RCP8.5, for a) 10th percentile values and b) 90th percentile values



Source: ECE

C. Discussion

Of the six climate indices analysed as part of this report, three relate to temperature and three relate to precipitation. The impact these temperature and precipitation related indices may have on inland transportation and adaptation planning are discussed below.

1. Temperature-related climate indices

While we used changes in WSDI as a proxy for heatwaves, the fact that this index is calculated over the full calendar year means that the number of days increase in the WSDI will also be composed of days from seasons other than summer, when maximum temperatures occur in the northern hemisphere. This needs to be borne in mind when analysing the results shown in figures I.3.2. The projected changes, especially under the RCP8.5 scenario, appear to be of magnitude that may have considerable impacts on road and rail infrastructure. Similarly, the projected increases in the number of VHD for both the European and Canadian areas analysed (see Figures I.3.4 for Europe and I.3.14 for Canada), suggest that these changes may also have significant impacts on road and rail networks. Taken together, the projected increases in both these climate indices may have a range of possible impacts on transportation assets and operations, and thus implications for adaptation planning. However, further analysis would be required.

For example, for road infrastructure, excessive warmth during summer days may lead to road pavement degradation, asphalt rutting or thermal damage of bridges. For rail infrastructure, this may lead to track buckling, infrastructure and overheating of locomotives or signalling problems. In addition, these changes may impact on transport operations, which will lead to an increased need for cooling.

Degradation of road and rail infrastructure may negatively impact passenger comfort and more importantly safety. For instance, asphalt rutting would likely lead to the implementation of speed restrictions and make travelling on roads dangerous, especially in rainy conditions. Vehicle load restrictions, or road closures for repair work, may impact the efficient movement of goods, resulting in economic losses. Moreover, an increase in the number of days of excessive warmth will likely have a negative impact on drivers. Excessive warmth during summer days may lead to driver fatigue as well as heat exhaustion, which may cause inattention and result in dangerous situations on the road.

Using Europe as an example, all areas within this region show an increase in WSDI and VHD, and thus risk assessments and adaptation planning should take these climate indices into account. It is important, however, to recognize that small changes in climate indices do not necessarily mean that the risks or need for adaptation in a given area are low, as risks are the result of numerous factors, as shown in Figure I.3.1. Therefore, projected increases or decreases in climate indices should be examined within a broader context.

This caveat notwithstanding, in view of the spatial patterns shown in figures I.3.22 – I.3.24, when merely looking at the highest increases in excessive warmth, areas that may be considered particularly worthy of more detailed analysis include E Roads such as E39 and E18 in Norway, E06, E04 and E22 in Sweden and E08 in Finland in the northern European area of the ECE region. In the south of the ECE region it would merit to analyse the impacts on E80 and E712 in south-east of France (reference to Case study 4, Part II, Chapter 1), E45, E55 and E80 in Italy, E65 in the Western Balkans, E01, E80, E82 and E90 in Portugal, E05 and E15 in Spain, E55 in Greece, and E84 and E87 in Turkey.

For the E Rail network, it would be beneficial when looking at the highest increases, to analyse the impact of both temperature related indices on railways E45, E55 and E10 in northern Europe and E35, E45 in Italy, E90 which spans France, Italy and Spain, E053 in Spain, and E751 and E753 in Croatia.

Figure I.3.22 Change in warm spell duration index (WSDI) under RCP8.5, mean values, E Roads (red lines) and TEN-T railways (green lines) in northern part of the ECE European subregion

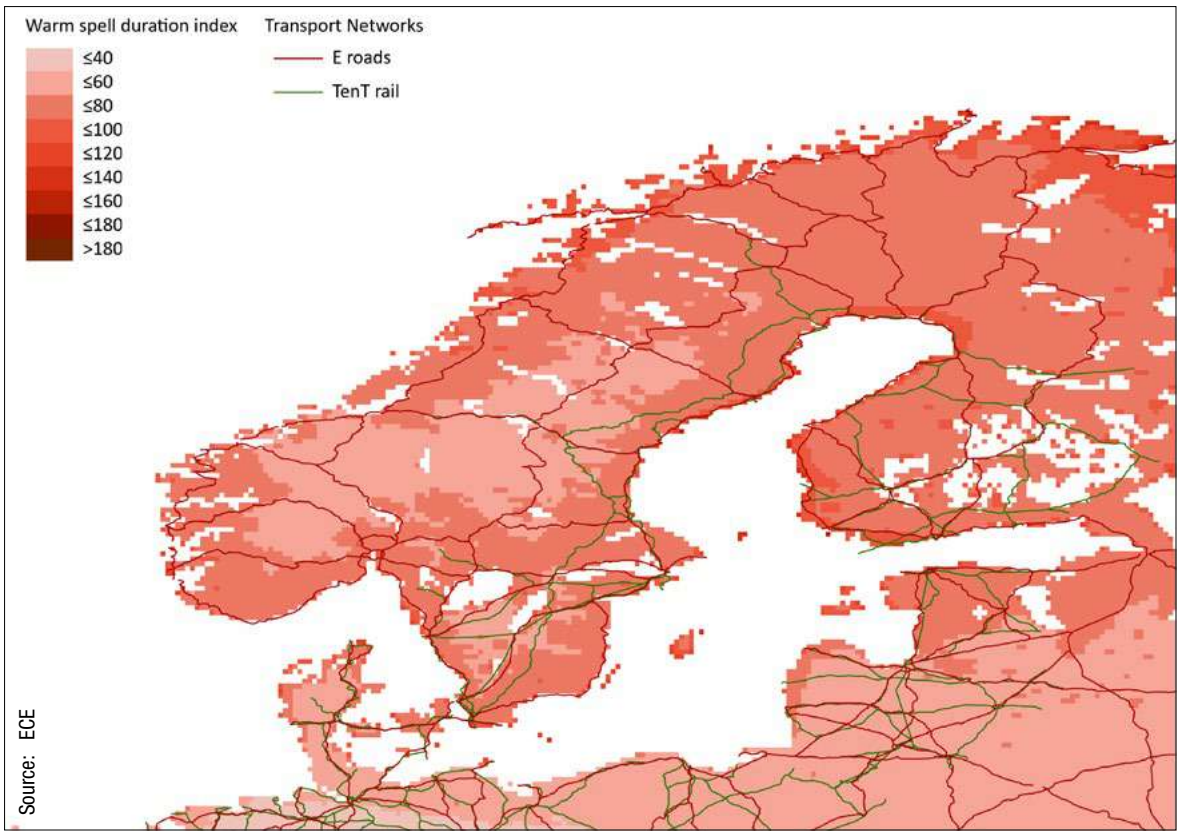
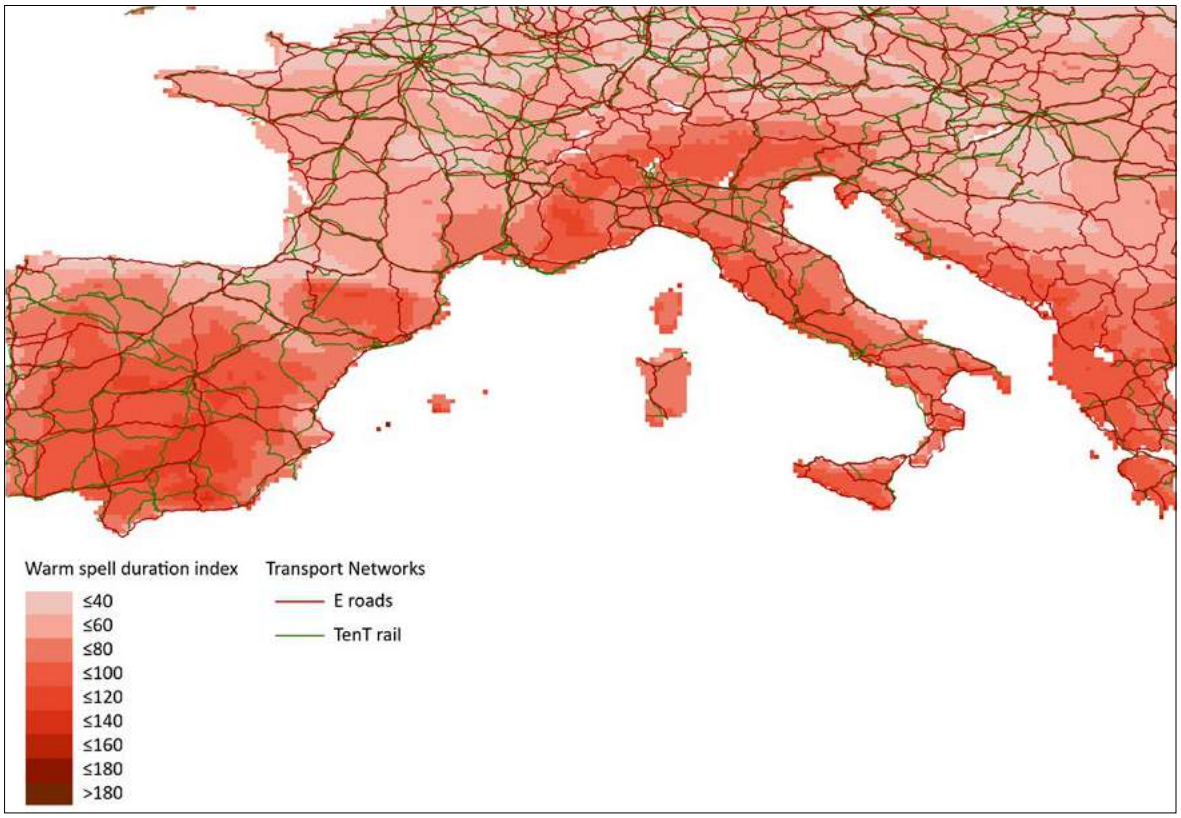
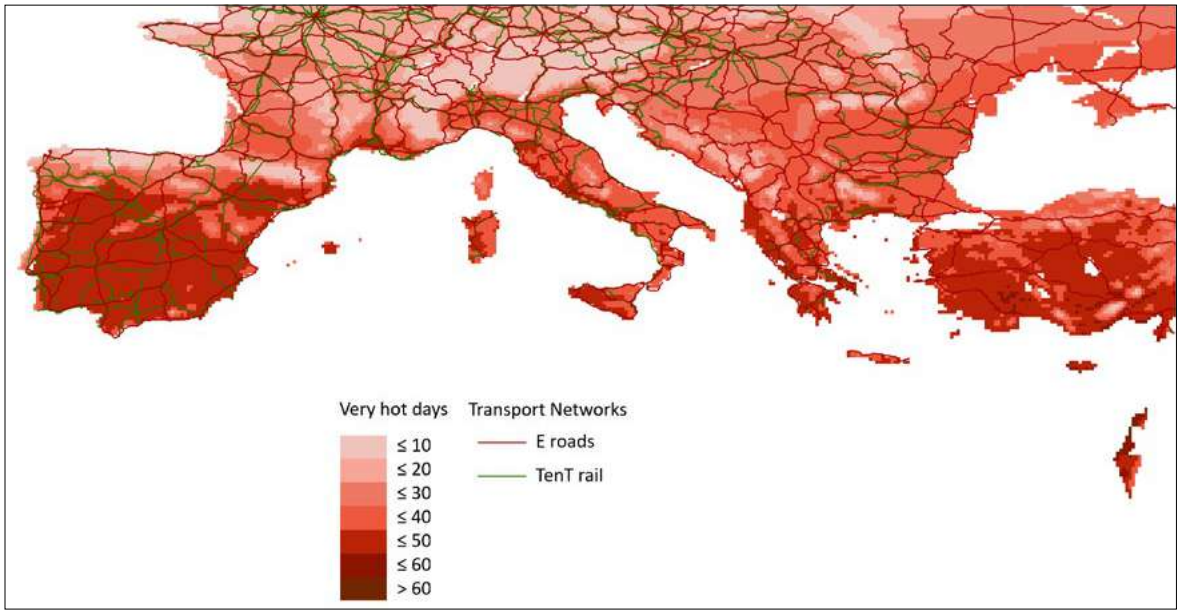


Figure I.3.23 Change in warm spell duration index (WSDI) under RCP8.5, mean values, E Roads (red lines) and TEN-T railways (green lines) in southern part of the ECE European subregion



Source: ECE

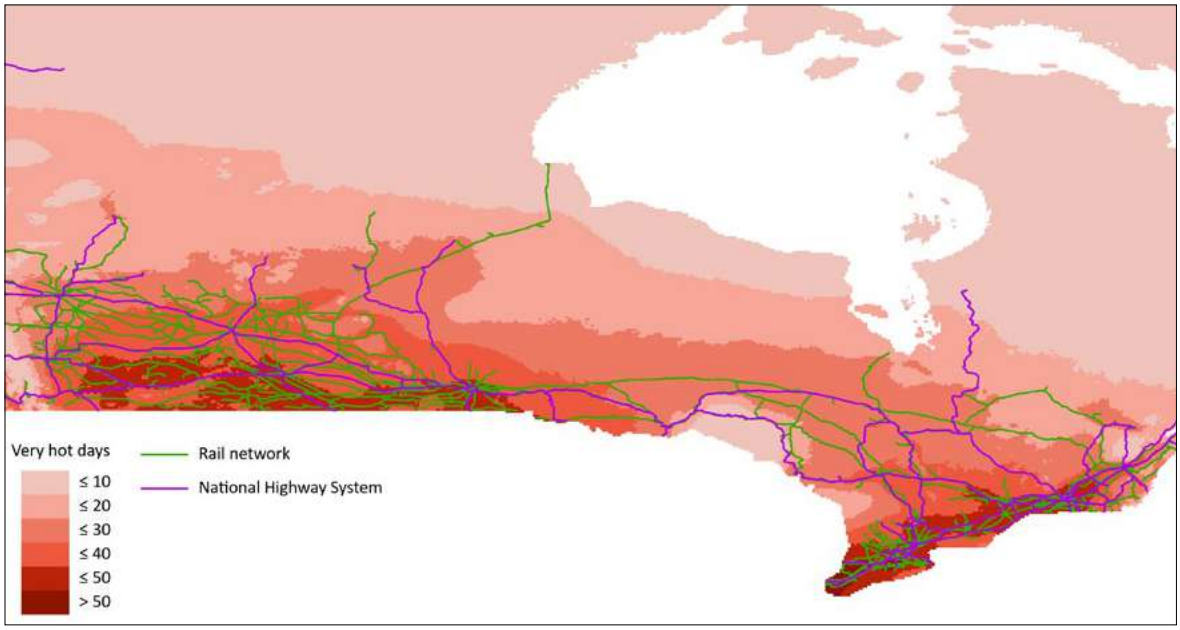
Figure I.3.24 Change in the number of very hot days (VHD) under RCP8.5, mean values, E Roads (red lines) and TEN-T railways (green lines) in southern part of the ECE European subregion



Source: ECE

Additionally, the visual representation of projected changes in the number of very hot days in Canada, highlight regions for which more detailed analyses could be warranted (Figure I.3.25).

Figure I.3.25 Change in number of very hot days (VHD) under RCP8.5, mean values, Canadian National Highway System (red lines) and Canadian railway network (green lines) in the Southern Alberta, Saskatchewan, Manitoba, and SouthernOntario and Quebec

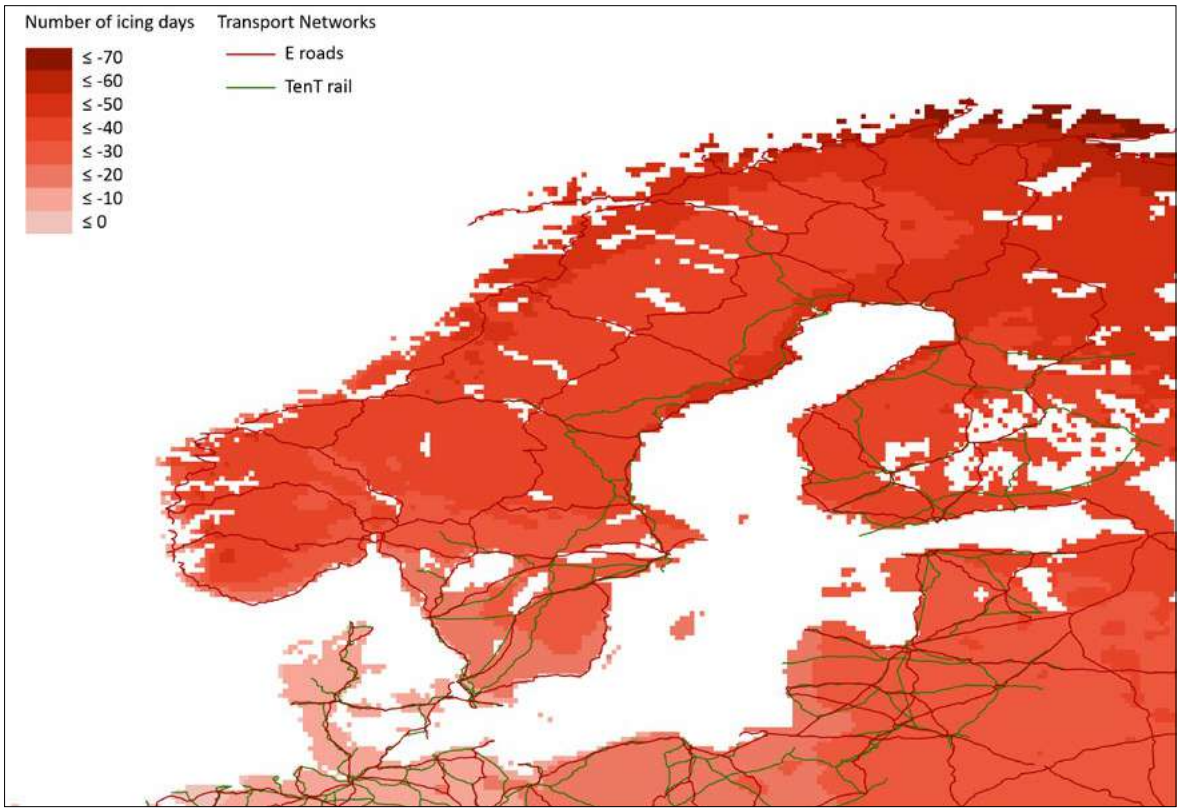


Source: ECE

Other reasons to analyse a particular area in more detail could include: the economic value or social importance of a particular route; transport volumes; current known vulnerabilities and adaptive capacity; and geopolitics (i.e. transboundary railways).

With respect to the number of ID, a decrease may significantly impact the maintenance of the transport infrastructure, particularly in high-latitude regions such as Scandinavia, and high-mountain areas. A complementary piece of analysis to this work could analyse the changes in the freeze-thaw cycle and zero crossings (i.e. the number of days when temperatures are both above and below 0°C). It would merit to undertake such an additional piece of analysis for E Roads and E Rails specified above for the northern part of the analysed European subregion (Figure I.3.26) as well as for various regions in Canada. Figures I.3.27 – I.3.28 show the rail and road networks in parts of Canada which are projected to see the largest decreases in the number of icing days.

Figure I.3.26 Change in number of icing days (ID) under RCP8.5, mean values, E Roads (red lines) and TEN-T railways (green lines) in northern part of ECE subregion

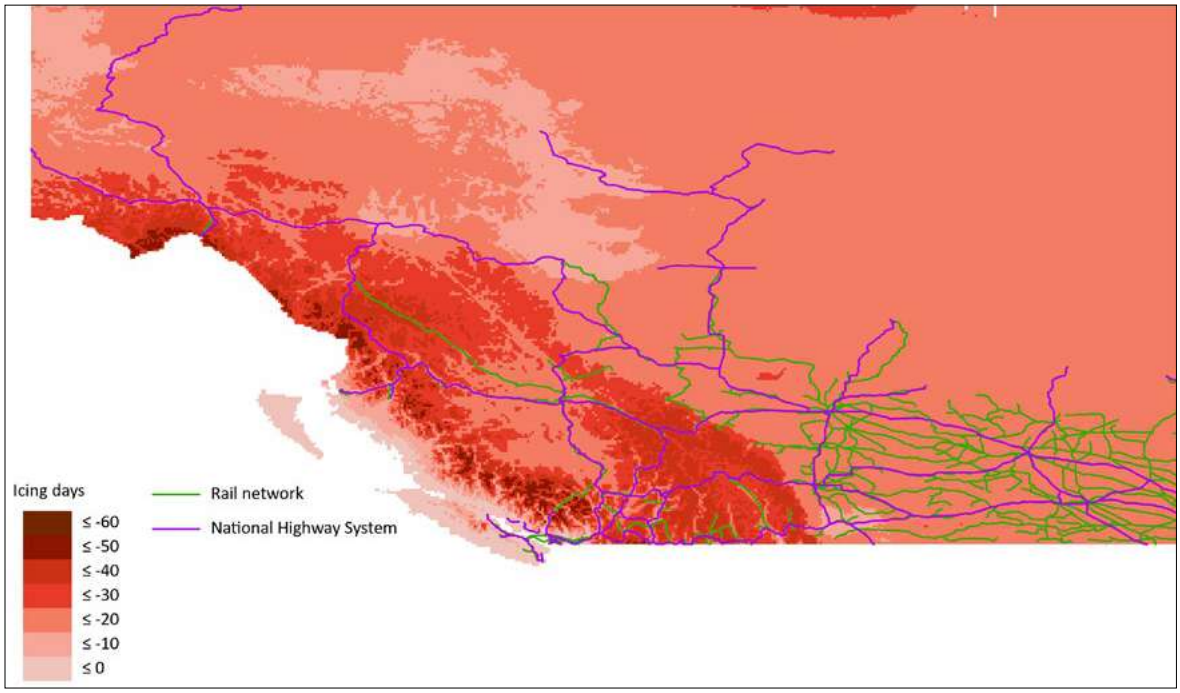


Source: ECE

At the same time, while "icing days" is a general indicator of warming trends, in looking at the adaptation of transportation in arctic regions, a number of other factors contribute to vulnerability in a changing climate. Days with a mean air temperature below 0°C are relevant to maritime operations and transportation on ice or winter roads, where ice cover and ice thickness relate directly to the traversability (or impassability) of a transportation route.

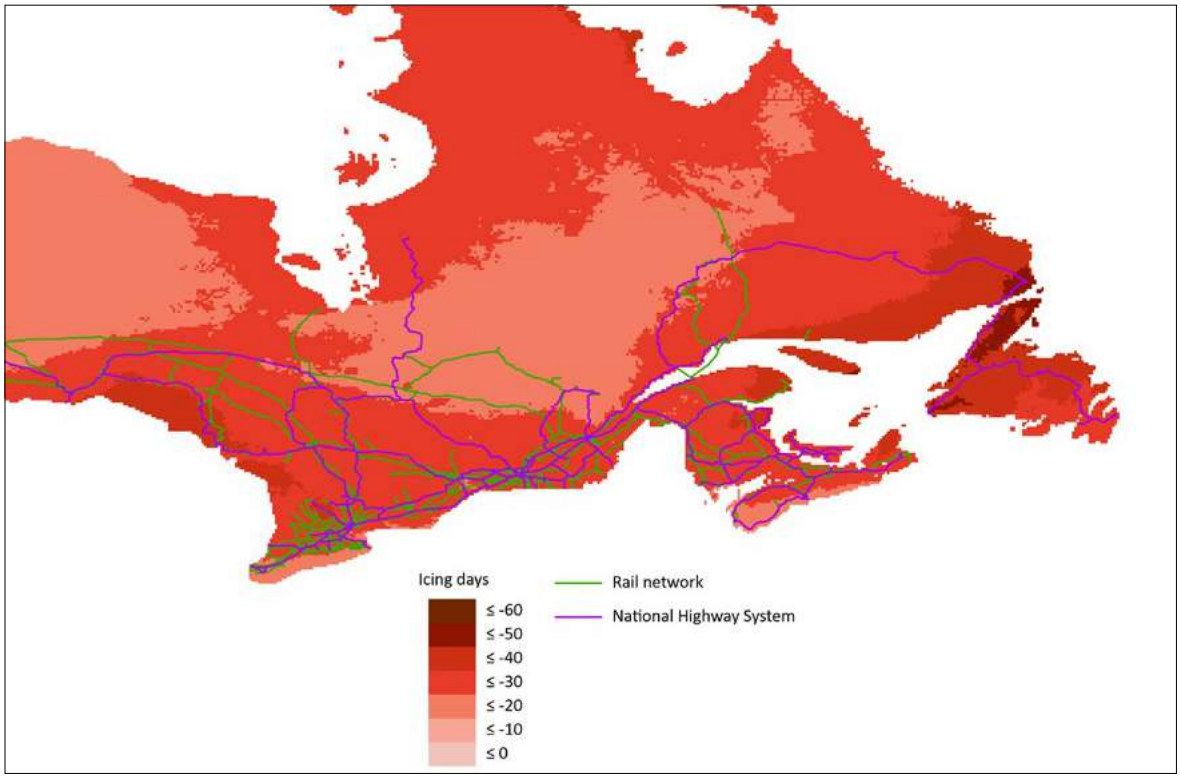
In a permafrost context, the more important indicator is thawing degree days (or thawing index) as both duration of temperatures exceeding 0°C and extent to which temperatures exceed 0°C are an indication of the amount of heat that may be absorbed by the ground. The effect of changes in the thawing index on northern transportation infrastructure depends on whether the permafrost is thaw sensitive, or ice-rich. Areas with low ice content are less susceptible to subsidence when the ground warms. Other factors, such as snow cover, vegetation, thermal properties of the soil, and salinity can also influence the degree to which warming air temperature affects permafrost. The number of days which an ice/winter road could be used during a particular winter season can also be measured directly.

Figure I.3.27 Change in number of icing days (ID) under RCP8.5, mean values, Canadian National Highway System (red lines) and Canadian railway network (green lines) in Western Canada



Source: ECE

Figure I.3.28 Change in number of icing days (ID) under RCP8.5, mean values, Canadian National Highway System (red lines) and Canadian railway network (green lines) in Eastern Canada



Source: ECE

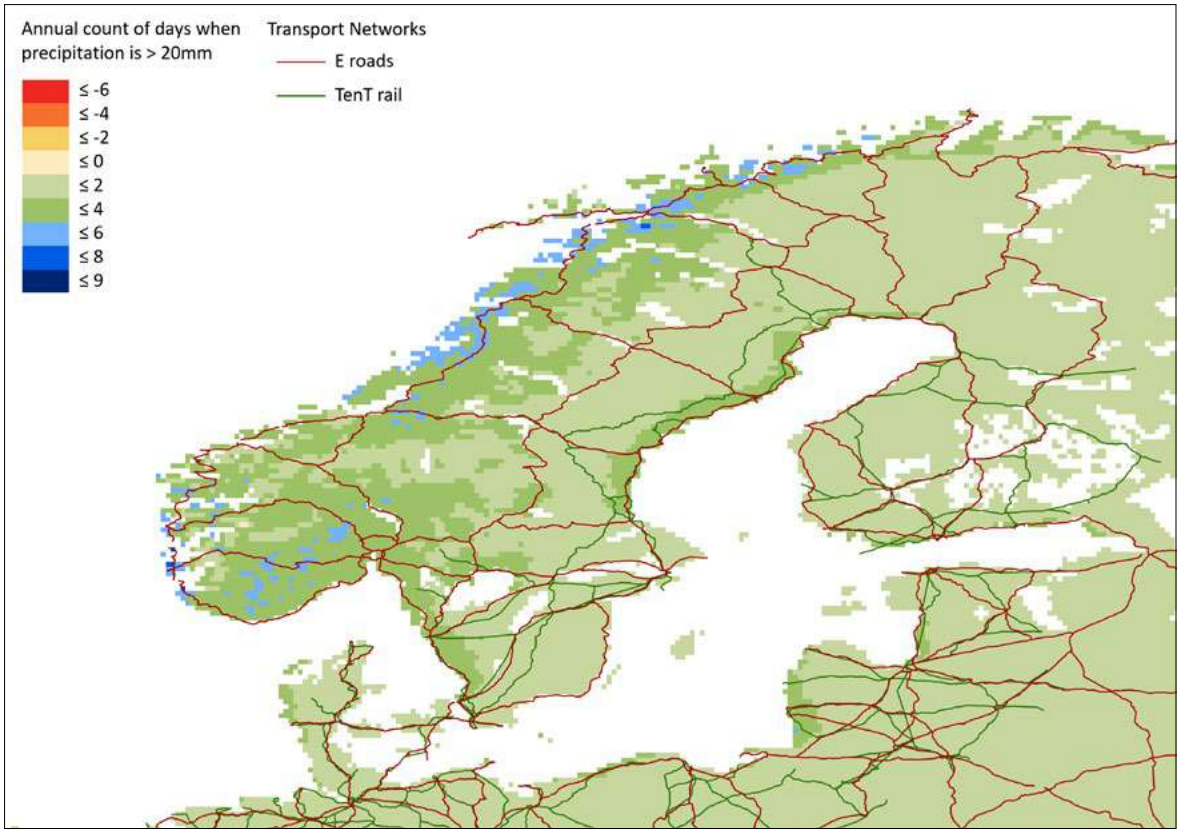
2. Precipitation-related climate indices

Projected changes in the number of days when precipitation is greater than 20 mm (R20mm) are, on the whole, relatively small (see Figures I.3.8 for Europe and I.3.18 for Canada). Nevertheless, even a small increase in the number of extreme events may significantly impact transportation networks, motivating the need to take action.

For example, extreme precipitation may lead to flash floods and slush flow which can cut off a road or railway from the rest of the network. For roads, vehicles may be swept away when trying to cross flooded areas. Downpours usually cause poor visibility, which may lead to dangerous driving conditions, compromising road safety.

As stated for the temperature related climate indices, there are a number of reasons that may be used to motivate more detailed analysis of impacts on transport networks and the need for adaptation. Looking purely on the highest projected changes in R20mm, a more detailed analysis would seem to be necessary for E Roads in Europe such as E04, E06 and E18 in the north, E35, E45 and E55 crossing through the Alps; E65 in the Balkans; E50 and E58 crossing through the Carpathians; and E70 and E97 along the eastern and south-eastern coast of the Black Sea. For E Rails, it would seem to be worth analysing the E45 in the north, E25, E35 and E45 through the Alps (Figures I.3.29-I.3.31).

Figure I.3.29 Change in the number of days with precipitation above 20mm (R20mm) under RCP8.5, mean values, E Roads (red lines) and TEN-T railways (green lines) in northern part of the European ECE subregion

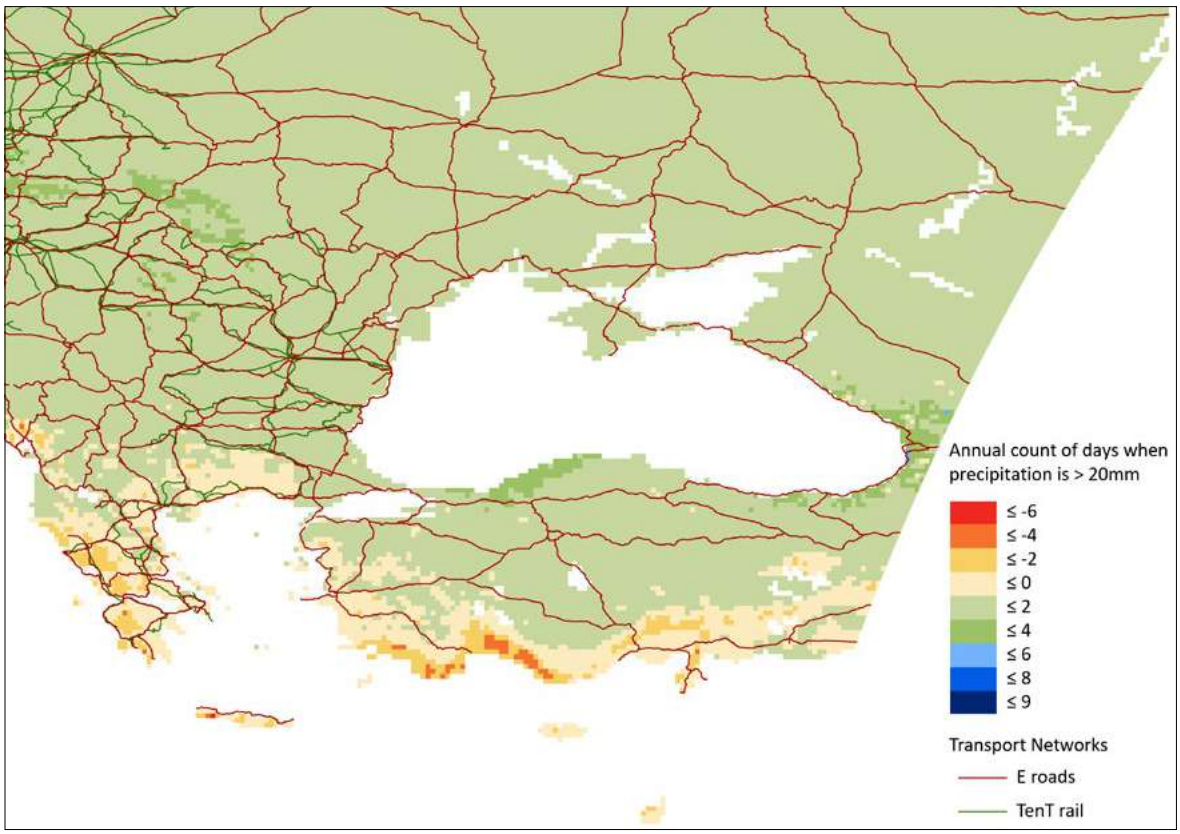


Source: ECE

Figure I.3.30 Change in the number of days with precipitation above 20mm (R20mm) under RCP8.5, mean values, E Roads (red lines) and TEN-T railways (green lines) in the Alps and eastern coast of Adriatic Sea

Source: ECE

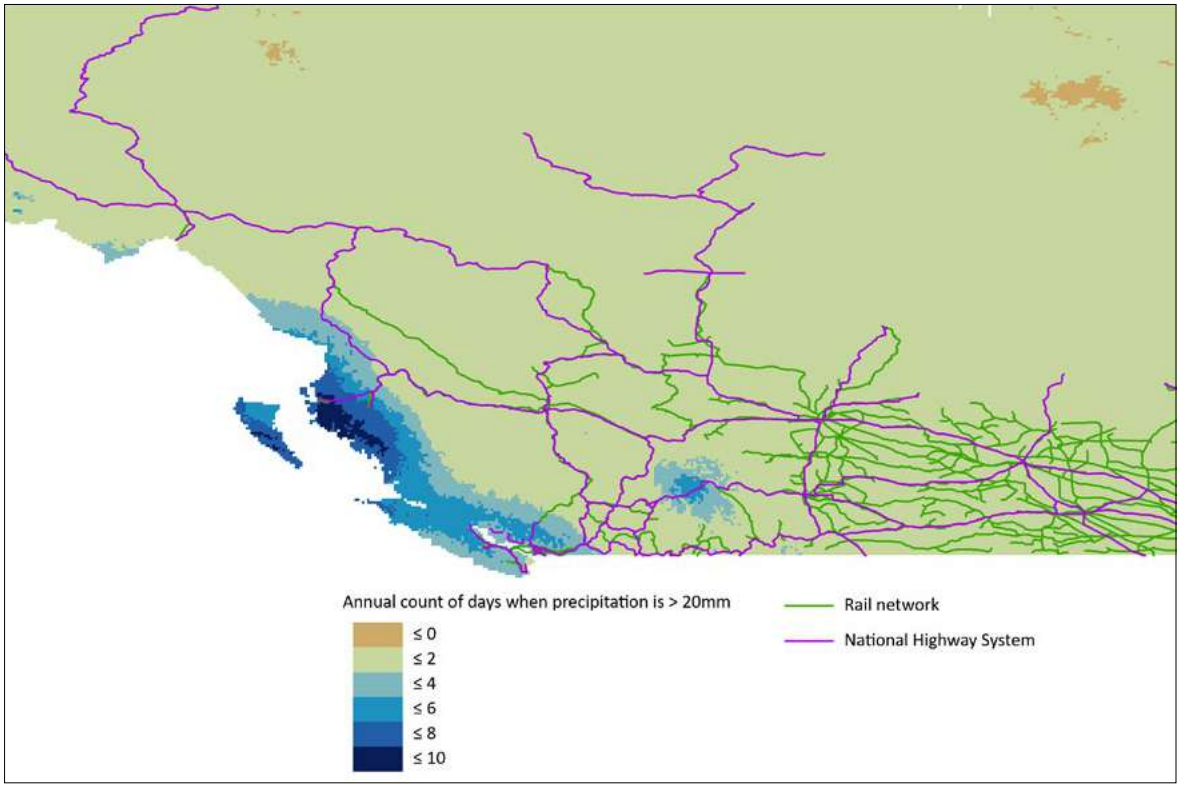
Figure I.3.31 Change in the number of days with precipitation above 20mm (R20mm) under RCP8.5, mean values, E Roads (red lines) and TEN-T railways (green lines) in the southern and eastern coast of Black Sea



Source: ECE

In Canada, the overlay of projected changes in R20mm with the main transportation networks, highlights several regions, for example, coastal British Columbia as well as Eastern Canada, where increased extreme precipitation events could pose challenges to the transportation system (see Figures I.3.32 - I.3.33). More specifically, on the west coast of Canada, both Vancouver and Prince Rupert, which are major gateways to Asia, with extensive infrastructure, may see substantial increases in the number of days of heavy rain under the RCP8.5 emissions scenario. As with the European region, decisions to undertake more regional or local vulnerability assessments are often driven by a range of factors, and would also necessitate the assessment of a broader range of climate and extreme weather risks.

Figure I.3.32 Change in the number of days with precipitation above 20mm (R20mm) under RCP8.5, mean values, Canadian National Highway System (red lines) and Canadian railway network (green lines) for the west coast of Canada

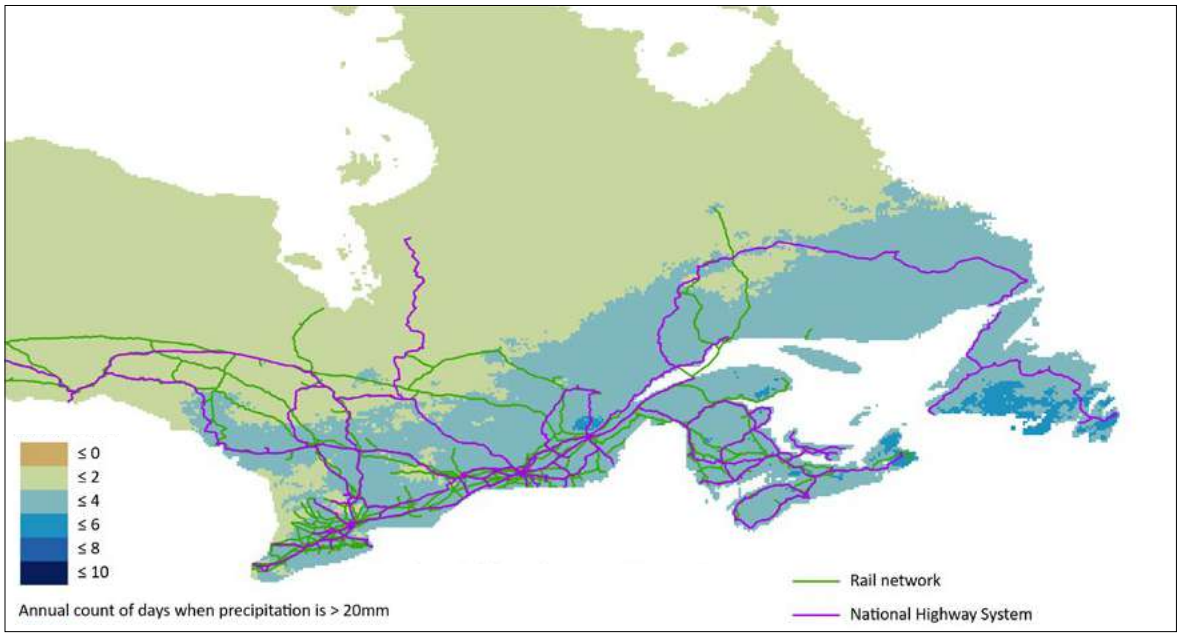


Source: ECE

Projected changes in the maximum precipitation amount over a 5 day period (Rx5day) (see Figure I.3.10) for Europe are high meaning there is an increased likelihood of transportation infrastructure being significantly impacted. For road infrastructure, increased precipitation may contribute to local inundations, landslides and slope failures. For rail infrastructure, this may lead to track submersion, problems with drainage systems and tunnels, bridge scouring or embankment damages. Increased precipitation may also affect transport operations (i.e. implementation of speed restrictions). For road transport, it may lead to an increased number of accidents, compromising road safety.

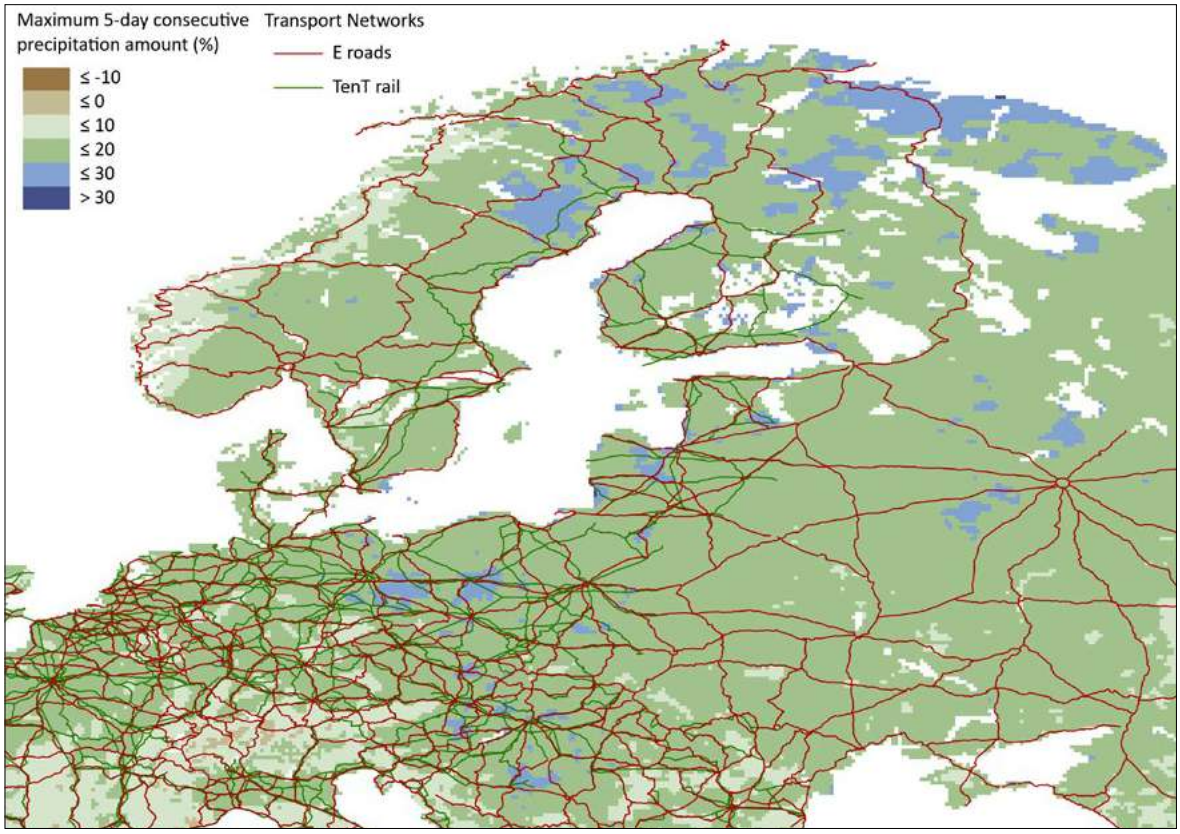
Again, when looking at the areas with the highest projected increases in Rx5day, it may be worth analysing in more detail, impacts to Northern European E Roads such as the E45, E10 in Sweden; E63 in Finland; E105 in the Russian Federation; and E67 and E77 in the Baltic countries. In central Europe, it may be worth considering in more detail the impacts on E30 and E 40 in Germany and Poland, and E70 in Serbia. For the E-rail network it may be worth considering a more detailed analysis of E 20 in central Europe (Figure I.3.34).

Figure I.3.33 Change in the number of days with precipitation above 20mm (R20mm) under RCP8.5, mean values, Canadian National Highway System (red lines) and Canadian railway network (green lines) in Eastern Canada



Source: ECE

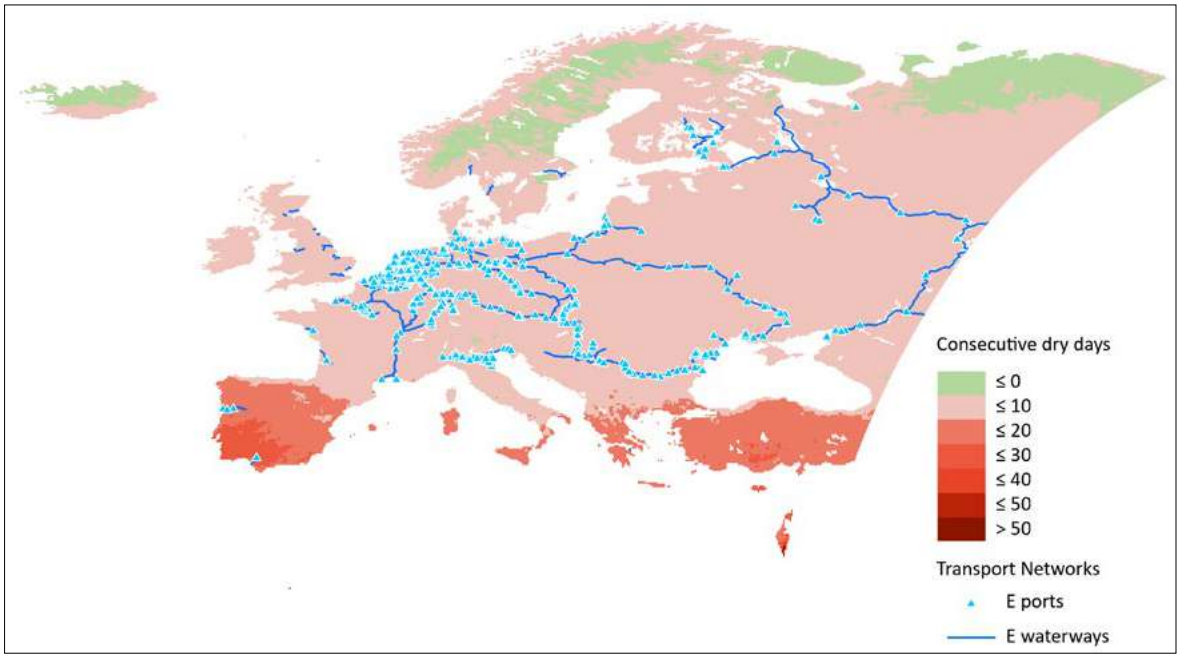
Figure I.3.34 Percentage changes in maximum 5-day consecutive precipitation amount (Rx5day) under RCP8.5, mean values, E Roads (red lines) and TEN-T railways (green lines) in northern and central part of European ECE subregion



Source: ECE

Projected changes in the number of consecutive dry days (CDD), which are used in this report as a proxy for changes in river flow levels, suggests that there are large areas of Europe that may experience an increase in the number of consecutive dry days (see Figure I.3.12). Evidently, such changes (Figure I.3.35) would have significant implications for the use of rivers to transport goods or people, which is already problematic in parts of central Europe. However, given the uncertainty of these projections, coupled with the fact that this index does not capture the range of factors involved in determining water flow levels, these changes should be viewed as preliminary. A more detailed analysis using hydrological models over whole catchments together with management practices, should be conducted for areas and countries where the transportation of goods along rivers is an important part of the transportation system (BMVI (2015) KLIWAS[19]; Hänsel at al (2018)).

Figure I.3.35 Change in in the number of consecutive dry days (CDD) under RCP8.5, mean values, E waterways (blue lines) and ports (light blue triangles)



Source: ECE

In general, the projected changes shown in figures I.3.2 – I.3.21 in Section III subsection A and B provide a preliminary analysis of projected changes in the climate indices under different RCP scenarios. These indices relate to key hazards that have the potential to negatively affect inland transport infrastructure in the ECE region. A key aspect that needs to be considered in climate risk assessments and adaptation planning decisions, is the issue of uncertainty, and this is particularly important for indices such as R20mm, Rx5day, and CDD. For example, some areas at the 10th percentile are projected to experience fewer R20mm days, while at the 90th percentile they are projected to experience more.

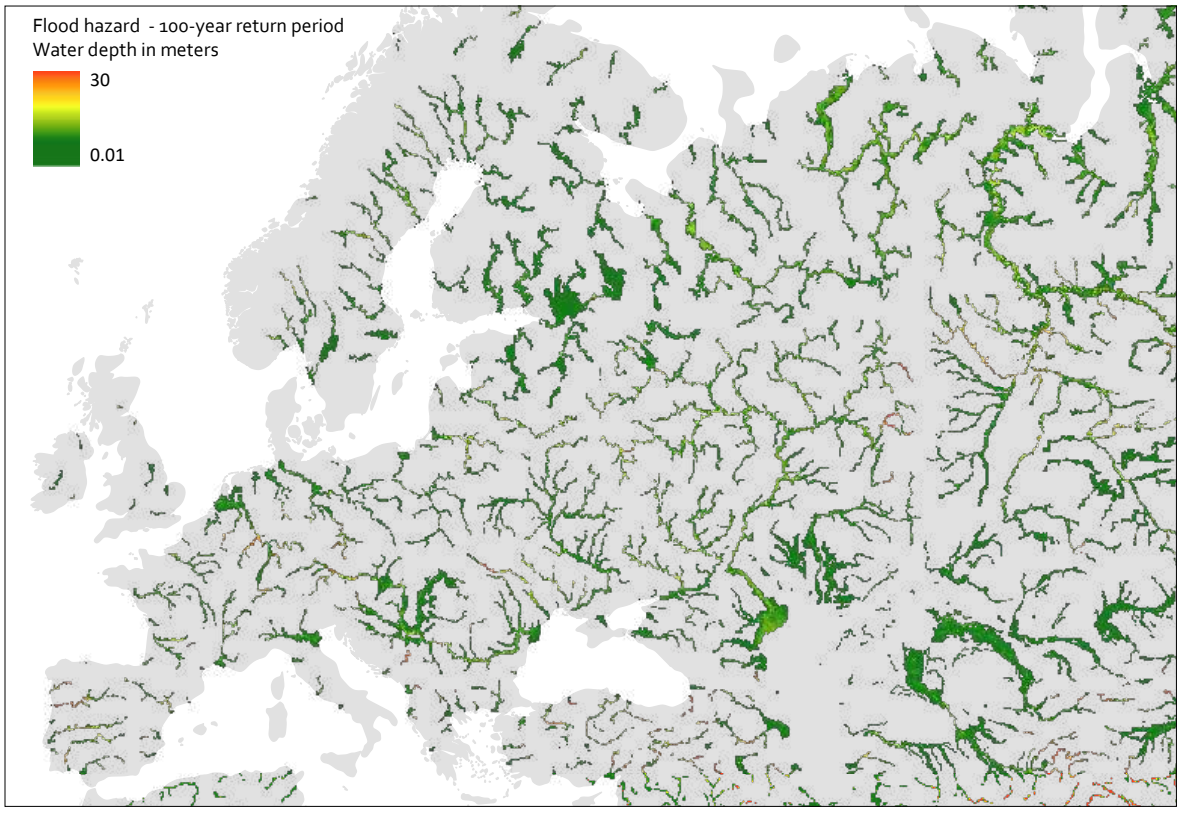
19 KLIWAS- Impacts of Climate Change on Waterways and Navigation in Germany. Concluding report of the BMVI, Bonn, Germany

D. Riverine and coastal storm flooding

Extreme riverine flooding can be caused by a variety of factors, such as the timing, frequency and the intensity of precipitation, geomorphology and land use. The precipitation indices (i.e. R20mm and Rx5day, Sections III, A.4 and A.5) cannot provide information on the frequency or intensity of extreme river flood events. To examine this, numerical flood modelling conducted by JRC-EC was used (Figure I.3.36).

The results show that there is already considerable and spatially variable flood exposure in the European part of the ECE region. For a 100-year return period event (Figure I.3.36) exceptionally high flood levels are estimated for confined (mostly upstream) sections of the river basins where normally no transport infrastructure of transregional importance is situated. However, in addition to the flood level height, the severity of the flood impacts (and damages/losses) also depends on the spatial extent and the population/infrastructure density of the flooded areas. The results indicate that many areas highly populated/developed middle and low basins of major European rivers (e.g. those of the Danube, Rhine, Elbe, Po, Dnieper, Don and Volga rivers) are exposed to flooding under the 100-year event (Figure I.3.36). Flood impacts are expected to deteriorate further in the future, particularly under the RCP8.5 emissions scenario (Alfieri et al., 2015; 2018).

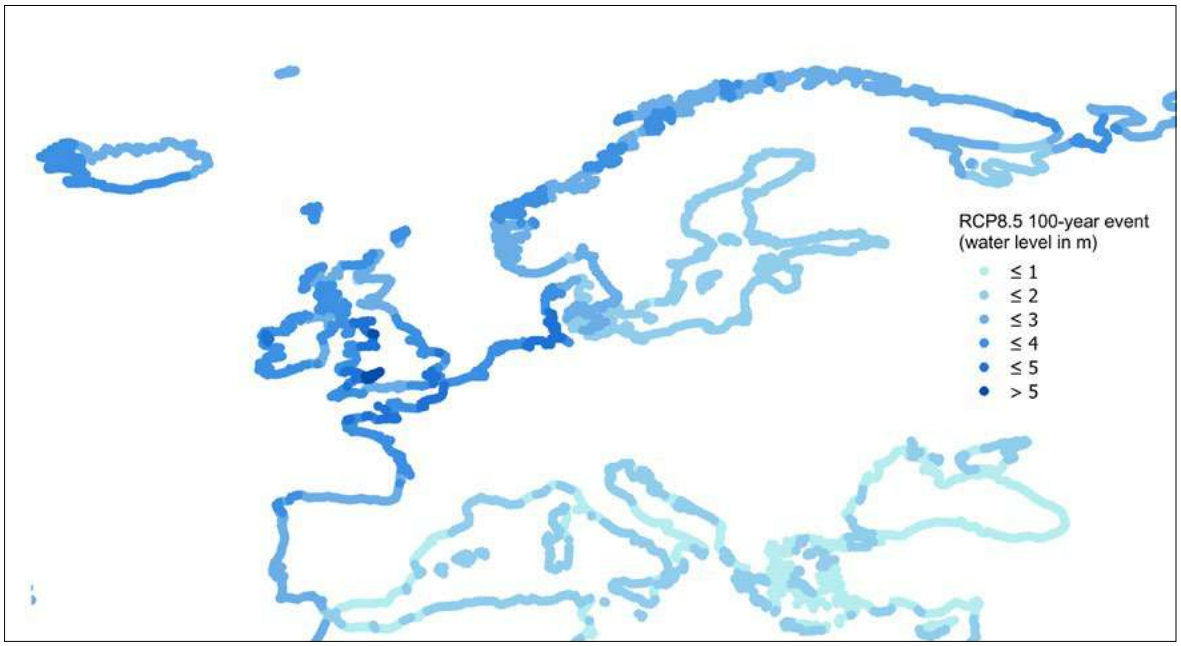
Figure I.3.36 Present flood hazard projections for the European part of the UNECE region (100-year event), data from EC-JRC



Source: ECE

Figure I.3.37 shows total water levels (in m) along the coastline of the studied ECE subregion projected for the end of the twenty-first century (RCP8.5) under a 1 in 100-year extreme sea level event (ESL100). The highest ESLs are projected for the Northern Atlantic and North Sea coasts where many major seaports (in terms of cargo handling) are located (Christodoulou and Demirel, 2018). By comparison, the Mediterranean and Black sea coasts are projected to experience much lower ESL100s.

Figure I.3.37 Projections of extreme sea levels (in m) for the 100-year event (ESL100) at the end of the twenty-first century under the RCP8.5 scenario for the studied ECE subregion (data from EC-JRC, see also Section II.E).



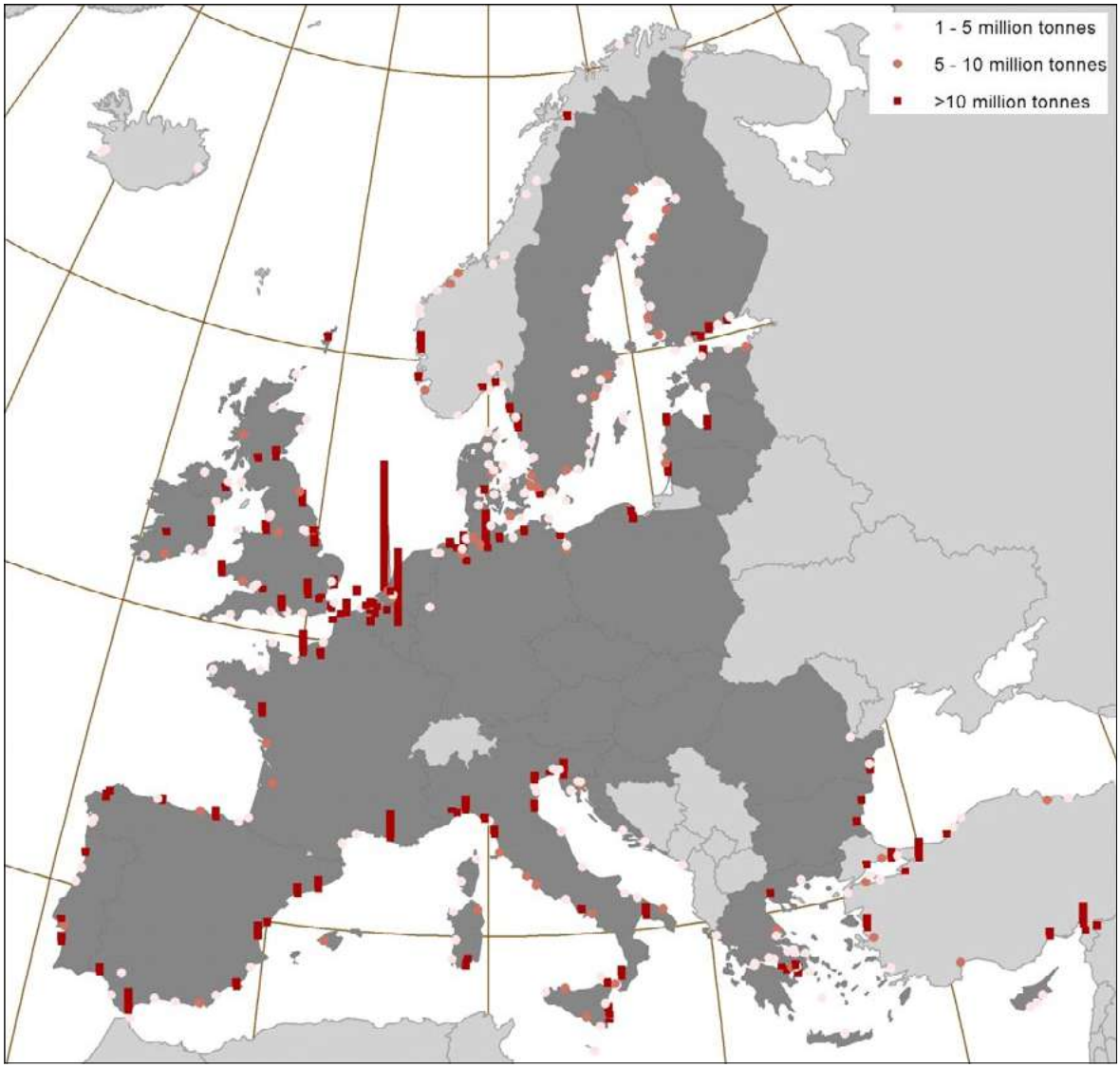
Source: ECE

Vousdoukas et al. (2018) have suggested that ESLs will not change much (in terms of magnitude) from the baseline period and, thus, future impacts might depend also on other (vulnerability) factors. For example, coastal areas that already experience high ESLs are likely to be better prepared/protected, as there is already a higher degree of awareness and 'know-how' (e.g. in the Netherlands, the United Kingdom and Denmark). Particular attention should be placed on the Arctic coast. The Arctic ice melt (Chapter 2) which may provide new trade/transport opportunities (ECE, 2013) will also result in increased exposure of these coasts to extreme sea levels/waves which can promote widespread coastal erosion (Lantuit and Pollard, 2008) resulting in adverse effects on the coastal transportation infrastructure and operations.

The impacts of climate change on European seaports were analysed in the PESETA III (Projection of Economic impacts of climate change in Sectors of the European Union based on bottom-up Analysis) and HELIX (High-End cLimate Impacts and eXtremes,) projects. The results are summarised in Christodoulou et al (2018). In Figure I.3.38, the European Union cargo ports that handle more than 1 million tonnes of goods per year are shown.

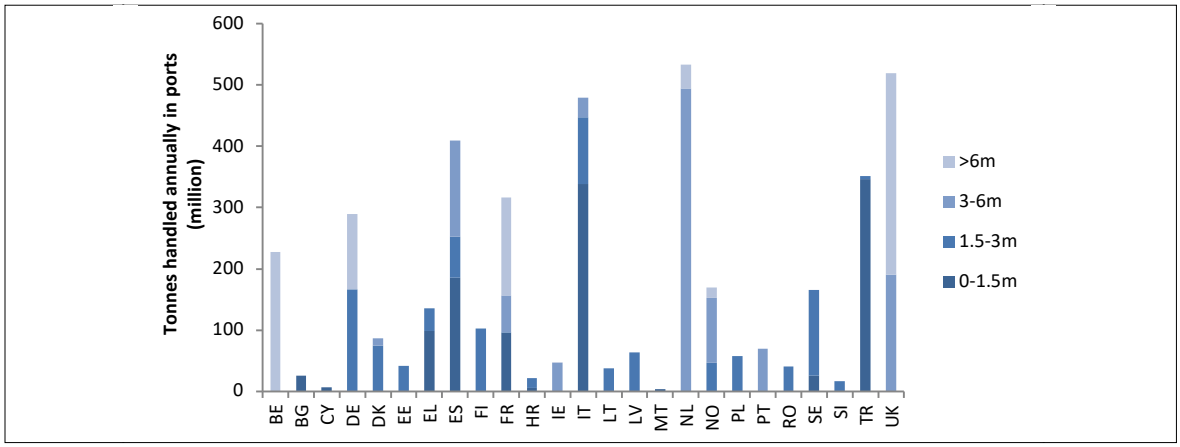
Using the ESL projections by Vousdoukas et al. (2018), the study has estimated the total amounts of cargo handled in European ports that would be affected by the different extreme sea levels (Figure I.3.39). Projections also show that after 2050 (under RCP8.5) extreme sea levels higher than 3 m will cause disruptions at ports that handle in total more than 2 billion tonnes of cargo annually (Christodoulou et al, 2018).

Figure I.3.38 Major cargo seaports in Europe (Christodoulou and Demirel, 2018). Ports handling more than 10 million tonnes of goods per year are represented by the red scaled bars).



Source: Christodoulou and Demirel, 2018

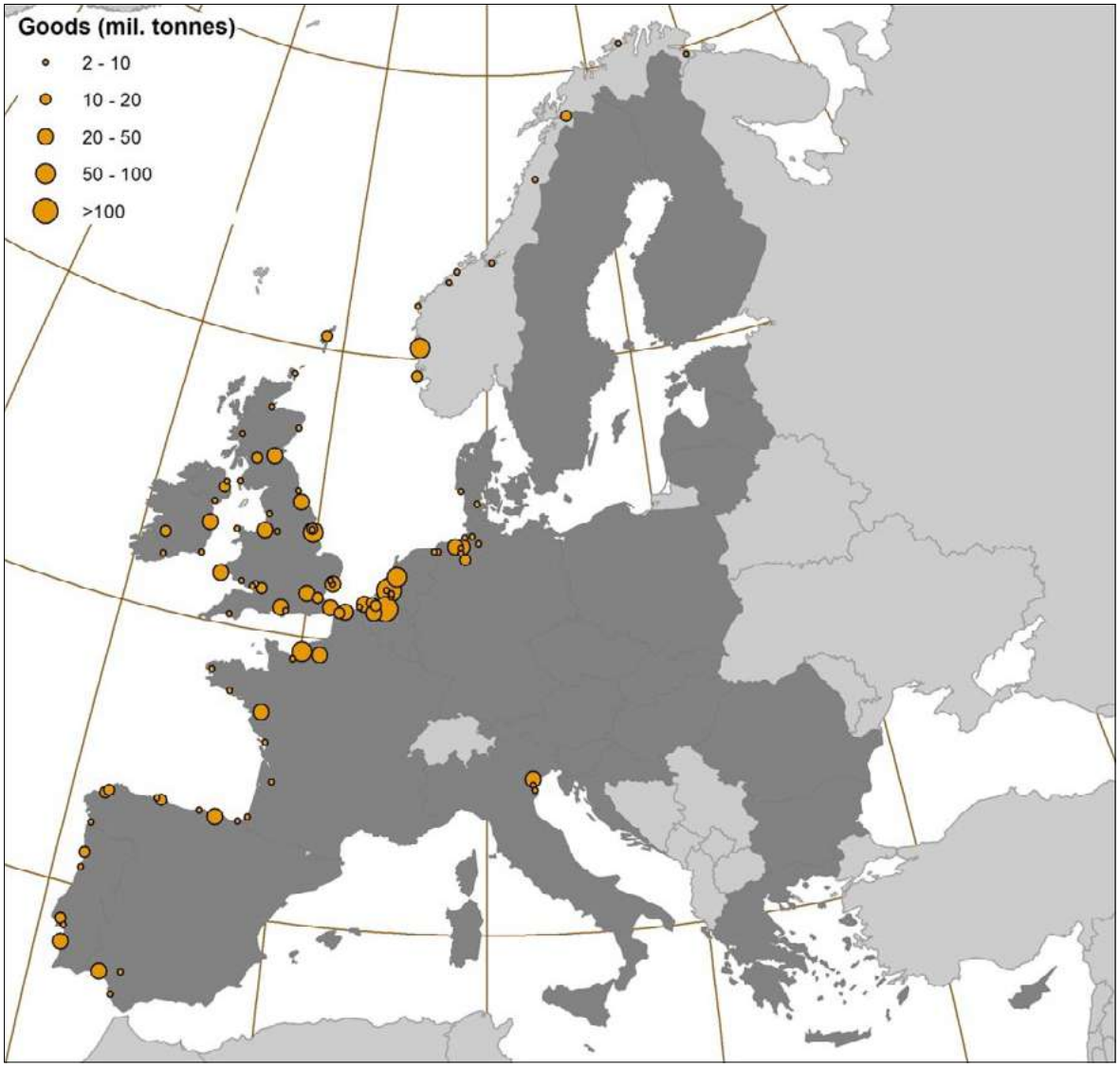
Figure I.3.39 Gross weights of cargo handled in ports affected by present-day ESL100 (based on Christodoulou et al, 2018). The different colours correspond to different ESLs as indicated by the legend.



Source: Christodoulou et al, 2018)

Finally, Figure I.3.40 shows the ports that handle more than 2 million tonnes of cargo annually and are projected to be exposed to ESLs higher than 3 m during a 100 year event.

Figure I.3.40 **Ports handling more than 2 million tonnes annually projected to be exposed to a 100-year event with extreme sea levels higher than 3 m (source: Christodoulou et al, 2018). In dark grey the EU28 countries.**



Source: Christodoulou et al, 2018

Photo: Lucky Team Studio / shutterstock.com

Chapter 4 Lessons learned and recommendations

The Group of Experts was able to learn valuable lessons in course of its work, which was aimed at the identification of main inland transport infrastructure assets in the ECE region that might be potentially impacted by the changing climate. Section I of this chapter presents these lessons learned.

Based on the lessons learned, the Group of Experts has formulated a number of recommendations as provided in section II of this chapter. These recommendations should presumably serve as a basis for continuation and advancing the ECE work on adaptation of inland transport infrastructure to climate change in an effective way.

I. Lessons learned

The following are lessons learned by the Group of Experts from the implementation of its 2015–2019 mandate:

(a) The identification of inland transport asset inventories at risk to climate change is a complex and long-term endeavour, in which the consideration of accurate transport infrastructure data with relevant – at appropriate spatial resolution – climatic projections is just a first step, yet a challenging one.

(b) While more climate resilient transportation systems are important for many reasons (e.g. social, economic, safety, cultural), the limited responses to the questionnaire suggest that many countries do have suitable information for analysing climate change impacts that have affected or would be expected to affect their transport infrastructure. It appears that countries have only quite recently started building capacities on transportation adaptation, while the major focus of climate change efforts is generally given to climate change mitigation. The case studies provided in Part II of this report show a growing capacity and expertise in some countries in the analysis of climate risks and impacts for the transportation systems. Discussing and sharing this expertise can help raise awareness of potential approaches or solutions among climate change transportation practitioners across the ECE region.

(c) Data limitations can preclude the consideration of climate risks to transportation. For example, data sets on inland transport infrastructure and its usage (for example, traffic volumes, freight processed) are not widely available across the ECE countries. This may be due to lack of collection and processing of such data, or a lack of publication or sharing. The availability of

such information in a uniform and readily accessible way would allow for a more comprehensive analysis of network criticality, which is an important condition for prioritizing adaptation needs.

(d) Harmonized climatic data do not exist for the entire ECE region at the spatial resolution finer than 200km. Different approaches to downscaling climate data were used in this report. While this does not present a problem for analyses in climate changes separately for Europe and Canada as done in this report, the results of the analyses are not directly comparable.

(e) Analyses undertaken on six climate indices for the European part of the ECE region and four indices for Canada as proxies for assessing changes in the potential impacts of climate change and extreme events on inland transport infrastructure are a good starting point towards raising awareness of possible future climatic impacts on inland transport assets and operations in the ECE region. It should encourage interest and commitment for more comprehensive and complete analysis covering the entire region and covering more specific indices as well as explicit impact modelling where possible. Ideally, such analysis should benefit from a data set produced with a consistent methodology.

(f) The analyses enabled a preliminary identification of potential areas that may be affected in the future by highest absolute increases in events as assessed with the proxy indices. Matching these changes with the infrastructure data gave a first indication on the sections of networks and nodes that are located in areas exposed to highest absolute changes and which may be exposed to increased risks in the future. At the same time, analysis of changes in relative terms could also provide interesting results in terms of projected changes and needs for adaptation measures. A combination of analysis in absolute and relative terms could be envisaged in the future.

(g) This first step analyses, however, are insufficient to understand whether a specific node or section of network may be affected from slow onset climate changes and/or extreme events, and what disruptive impacts such changes and events could have. Complementary analyses are needed, as a second step. These include, for example, assessing natural and anthropogenic factors (like underlying geomorphology, geology and land use) and an evaluation of individual characteristics of a specific transport asset (like its age, conditions and quality and its specific structures and their corresponding thresholds to extreme weather events). They may include further downscaling of projections, impact modelling and assessment of cause-effect relationships between climate parameters and impacts on the transport assets and operations, including socio-economic objectives. They should also include intermodal dependencies and may include cross-sectoral dependencies. Such complex analyses were not in scope of the 2015–2019 mandate of the Group of Experts but would be worth pursuing in the future.

(h) There is more than one way to assess climate change impacts and related risk to the transportation systems. Several of them have been introduced by the case studies in Chapter 1 of Part II. Although there are slight differences in the approaches, terminology and level of detail, and thus the required input data, there are a lot of similarities with respect to the final result of such analyses that help in identifying and prioritizing adaptation needs. Sharing the existing national approaches and methodologies may support others in identifying and pursuing approaches to assess and address climate change risks.

(i) It became clear during the process of this work that assessment of impacts on transport assets and operations from climate change and identification of suitable adaptation measures should also consider intermodal and cross-sectoral interactions, for the latter, for example with the energy and water sectors. Such considerations are important in order to avoid maladaptation. In addition to cross-sectoral interactions, it is also important to consider transboundary climate impacts and adaptation measures. Efforts such as this may be worth pursuing in the future.

II. Recommendations

The Group of Experts, drawing from the lessons learned in the process of the implementation of the 2015–2019 mandate, recommends the following:

(a) The results achieved within the 2015–2019 mandate of the Group of Experts should be widely disseminated to create awareness and understanding of the urgency of work in analysing the impacts from climate change on inland transport infrastructure and operations and in identifying adaptation measures, as well as to obtain support for such work at all levels.

(b) Decision-makers and transport experts, from both the public and private sectors should be made aware of approaches, tools and methodologies which exist or can be developed to analyse the risks that climate change poses to inland transportation infrastructure and operations. To this end, specific awareness-raising material based on the Group of Experts' report should be prepared for publication in various sectoral media and for presentation at climate change adaptation fora and conferences.

(c) Public administration should consider making available geographical data for inland transport networks and nodes, at least for infrastructure of international importance. The ECE Working Parties responsible for administering the infrastructure agreements such as AGR[20], AGC[21], AGN[22] and AGTC[23] should ensure that the E Roads, E Rail and E Waterways networks as well as rail-road terminals are made available as geographical data showing the specific passage and location of the networks and nodes in GIS environment. To this end, it is recommended that each contracting party to the infrastructure agreements provides or confirms the geographical data for the E infrastructure networks and nodes on their territories with the ECE secretariat. Other ECE member States are encouraged to also provide geographical data for their main networks. The ECE secretariat should manage the ECE GIS for the infrastructure agreements.

(d) ECE member States should also consider establishing, if not done so yet, their infrastructure, including local networks, in GIS. The ECE secretariat should explore modalities for offering a possibility to ECE member States to use the ECE GIS when they do not have capacities to establish their own GIS.

(e) ECE member States should be urged to participate in transport censuses conducted periodically by ECE under the auspices of the Working Party on Transport Statistics. In this way, data on volumes of traffic for international road, rail and waterways networks are collected, processed and shared by ECE. Availability of such data is important to the analysis of network and node criticality, which in turn is important to the prioritization of adaptation needs. Mechanisms for an automatic harvest of data such as on traffic volumes published electronically by relevant national agencies should be explored by ECE secretariat with ECE member States.

(f) Effort should be devoted to obtaining a consistent climate projections data set for the entire ECE region. There will be possibilities for obtaining such data, for example, from the CORDEX-Core project.

20 European Agreement on Main International Traffic Arteries

21 European Agreement on Main International Railway Lines

22 European Agreement on Main Inland Waterways of International Importance

23 European Agreement on Important International Combined Transport Lines and Related Installations

(g) Analysis of the six selected indices should be done for the entire ECE region. The analysis should be done in absolute and relative terms, be expanded to additional indices, as appropriate, so that more knowledge on impacts from a changing climate and extreme events on inland transport infrastructure can be established and made available to countries through ECE GIS. Also, as a next step, the overlay of the climate indices with the main transportation networks and nodes (including, where possible, ports and airports), should be expanded across the ECE region. This would enable broader analysis and supplement the transportation adaptation experiences and expertise of the Group of Experts during its 2015-2019 mandate.

(h) Countries should consider, using the efforts presented by the Group of Experts within this report, the advancement of further projects that seek to more fully understand vulnerability to climate change and extreme weather across their inland transportation systems. This could include, for example, analysis on the impacts from the projected changes taking into account the natural and anthropogenic factors modifying the risks to specific transport asset, assessment of the asset's characteristic, assessment of supply chains or intermodal shift, and possibly analysis on cross-sectoral interdependencies as well as bringing in relevant stakeholders and data into the process as required. Additionally, such projects should look to identify potential adaptation solutions for implementation, including through cross-sectoral analysis. The identification of adaptation measures could also benefit from exploration of potential synergies with mitigation measures.

(i) Countries with developed expertise should seek to share their knowledge and lessons learned gained from national or sub-national projects, programmes and initiatives with their international colleagues, to help build the information, knowledge and capacity across the ECE region and beyond to undertake climate change risk assessment and adaptation work relevant to the transportation system. They should share the knowledge from projects at all scales and involving all stakeholders. The case studies included in Part II of this report present one way that practitioners, in addition to those beginning to take steps towards strengthened climate resilience, can learn from each other's experiences.

(j) Countries with little experience in climate change adaptation work and those who have not yet engaged in the work of the Group of Experts should consider the notable opportunities presented by participation in such work, in particular from the valuable peer-to-peer exchanges and information sharing. They may consider to engage in such work in the future. They may also consider to develop, where possible with international assistance, national projects during which data could be analysed to better understand future impacts from climate change on their inland transportation system.

(k) The national projects should allow establishment of a knowledge database from the second-step analysis containing information on: (i) features and conditions that make a section of a network or a node in a higher risk area a "hotspot" due to that risk, and (ii) adaptation measures proposed and their cost-effectiveness to limit identified risks. The knowledge database could further include indicators for monitoring and evaluating adaptation measures. It could also include, if such information can be collected from the national projects, information on adaptation-mitigation convergent measures.

(l) The national projects should also contribute to elaboration of guidance and/or mechanisms for better integration of climate change impacts and projections into planning and operational processes. Effort should be made to develop such guidance and mechanisms and share among respective administrations.

Much advancement in climate change impact analysis on transport networks and nodes is still necessary. The Group of Experts, re-established under a new mandate and supported by the ECE secretariat in collaboration with WMO and other partners, would be well-placed to assist in such an advancement. In view of the recommended future actions, it would be sensible that a five-year workplan is considered.

Funding should be explored in support of the future activities. Countries from outside of the ECE region should be encouraged to participate in the future activities, both to contribute to these activities, and to learn from them.

Photo: Herr.Stock / shutterstock.com

Photo: Elena Larina / shutterstock.com

Part II.

Case studies

This part of the report consists of two chapters:

***Chapter 1** contains case studies which present approaches, practices, methodologies and tools developed and applied by countries for analysing current and future climate change impacts on transport systems and/or for testing transport adaptation options. The case studies often include information about the policies that provide the necessary basis for such work.*

***Chapter 2** presents case studies which discuss diverse socioeconomic impacts and implications from climate change on various transport infrastructure, as studied in several countries.*

Chapter 1

This Chapter provides case studies on approaches, practices, methodologies and tools developed and applied by countries for analysing current and future climate change impacts on transport systems and/or for testing transport adaptation options

Case study 1 (Germany)
Adapting the German transport system to climate change

I. Introduction

This case study presents the multi-modal approach and respective tools used to analyse climate change impacts on the Federal German transport system. These analyses form an important basis for the identifications and prioritization of the adaptation needs for the road, railway and inland waterway networks in Germany. This case study was prepared by: Stephanie Hänsel.

II. The German Adaptation Strategy

In order to undertake climate change adaptation in Germany within a political framework, the federal government adopted the German Strategy for Adaptation to Climate Change (DAS) in December 2008 (German Federal Government, 2008). The DAS aims at reducing vulnerability to climate change impacts and maintaining or enhancing the adaptability of natural, societal, and economic systems. It considers both the impact of gradual climate changes and the consequences of increasing extreme events. The DAS presents possible consequences of climate change in different fields of action (Buth et al., 2015) and suggests potential courses of action (Adaptation Action Plan, APA) in order to make Germany more resilient to climate change impacts.

III. Research programs – The German Federal Ministry of Transport and Digital Infrastructure Network of Experts

The challenges posed by climate change and extreme events to the German transport system are addressed by a series of research programs financed by the German Federal Ministry of Transport and Digital Infrastructure (BMVI). Starting in 2009 the KLIWAS[24] programme investigated specific effects on German waterways (BMVI, 2015). Likewise, the AdSVIS program with the RIVA project (Auerbach et al., 2014; Korn et al., 2017) addressed climate impacts on federal roads including a risk analysis for specific road sections. Starting in 2016, the expertise and competencies of seven departmental research institutes were pooled into a new program focusing on "Adapting transport and infrastructure to climate change and extreme weather events" (www.bmvi-expertennetzwerk.de/EN, BMVI (2017)). By integrating perspectives on road, railway and waterway transport, the program fosters the interdisciplinary exchange of knowledge and skills. Thereby it creates the potential for innovative solutions for climate change adaptation and sustainable development of the German transport system in a dialogue between science, policy and practice. Together, seven Federal authorities address complex challenges affecting strategic planning at the level of the transport network as well as technical adaptation measures for traffic routes and individual infrastructure

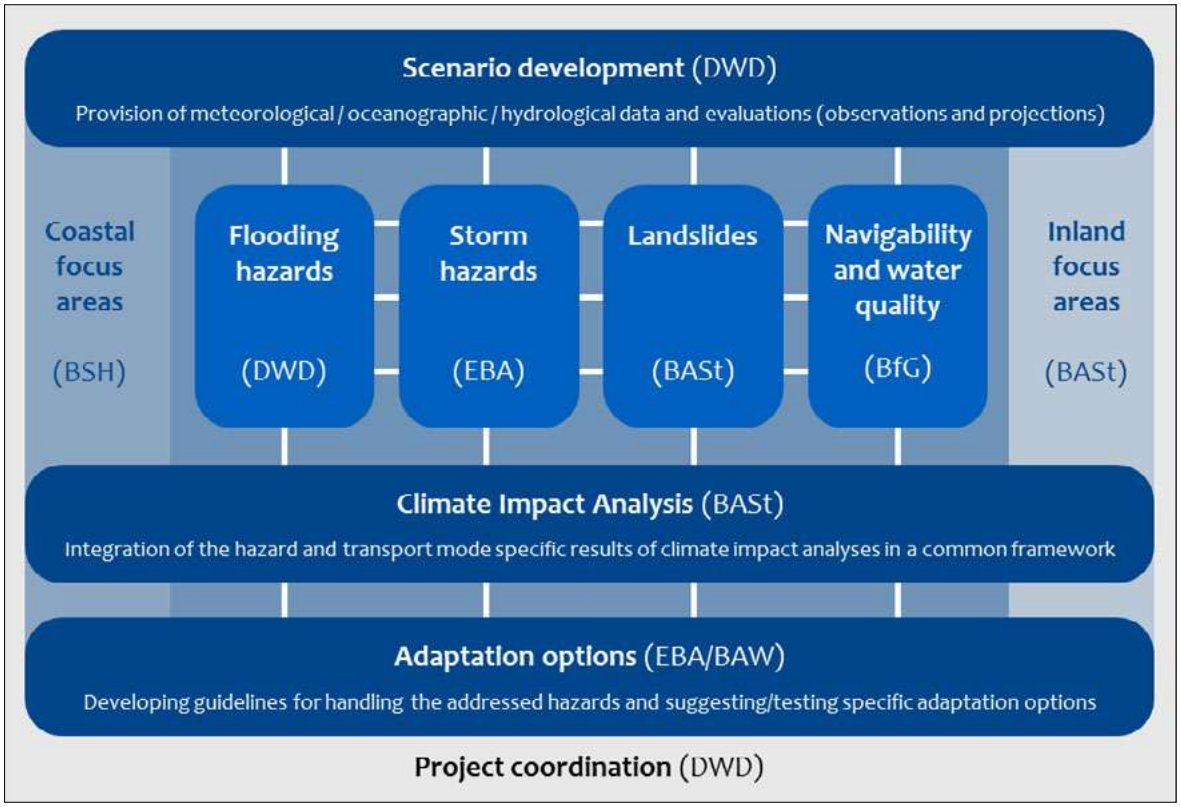
24 Climate-Water-Navigation

elements. Thereby, expertise in climate sciences (Germany's Meteorological Service Deutscher Wetterdienst (DWD), Federal Maritime and Hydrographic Agency (BSH)) is combined with practical knowledge on the modes of transport (road: Federal Highway Research Institute (BASt); rail: Federal Railway Authority (EBA); waterways: Federal Institute of Hydrology (BfG), and Federal Waterways Engineering and Research Institute (BAW); goods: Federal Office for Goods Transport (BAG)).

IV. Adapting transport and infrastructure to climate change and extreme weather events

Within topic 1 of the BMVI Network of Experts, knowledge about the spatial pattern of observed and expected future climate change impacts is generated and connected with evaluations about the vulnerability and criticality of transport infrastructure in order to develop, test and implement specific adaptation options for gradual climatic changes and extreme weather events. The scientific work is categorized into nine interrelated sub-projects, each coordinated by one of the partner institutions (Figure II.1.1).

Figure II.1.1 Organizational flowchart of the project work within topic 1 of the BMVI Network of Experts



Within the sub-project "scenario development", a common framework for the impact analyses in the hazard specific sub-projects is agreed upon and a consistent set of scenario data, including climate, land use and transport scenarios is compiled, created and provided. Respectively, an ensemble of regional climate projections is processed for the user-specific needs and provided to all partners. Additionally, oceanic and hydrological data including derived products are created and distributed.

Based on these data, specific impact analyses are done within four sub-projects focusing on floods, storms, landslides and waterway specific hazards affecting navigability and water quality. The results of these impact studies, obtained for different modes of transport and different climate hazards, are then integrated into a GIS-based assessment method to evaluate the exposure, sensitivity and criticality of transport infrastructure. This method aims at providing information relevant to climate change adaptation at the network level and for specific sections of the transport network.

Based on classification and evaluation systems, current climate impacts on infrastructure are represented and projected into the future. Those assessments of potential risks under current and future climate conditions are a valuable support for decisions on the (re)construction and management of transport infrastructures. Finally, guiding principles for the handling of the addressed hazards and specific adaptation options are developed. The studied adaptation measures encompass the following aspects: technical guidelines and rules (reference to Case study 2, Part II, Chapter 1), adjusting management practices (e.g., changes in the water and sediment management connected to altered flow conditions) and developing new materials and technical constructions (e.g., adaptation of road surface materials to a higher spread of extreme temperatures or constructive aspects connected to changes in flooding or storminess). The impact assessment is complemented by regional case studies integrating different risks and encompassing different modes of transport in higher detail. These studies are conducted in several inland and coastal focus areas that allow addressing specific, intermodal risks like those posed by sea level rise in coastal areas (reference to Case study 5, Part II, Chapter 2) or those connected to widespread flooding or low flow situations in the inland (reference to Case study 4, Part II, Chapter 2). These focused analyses allow the application of specific impact models and to identify cause-effect relationships that may be transferred to a larger scale.

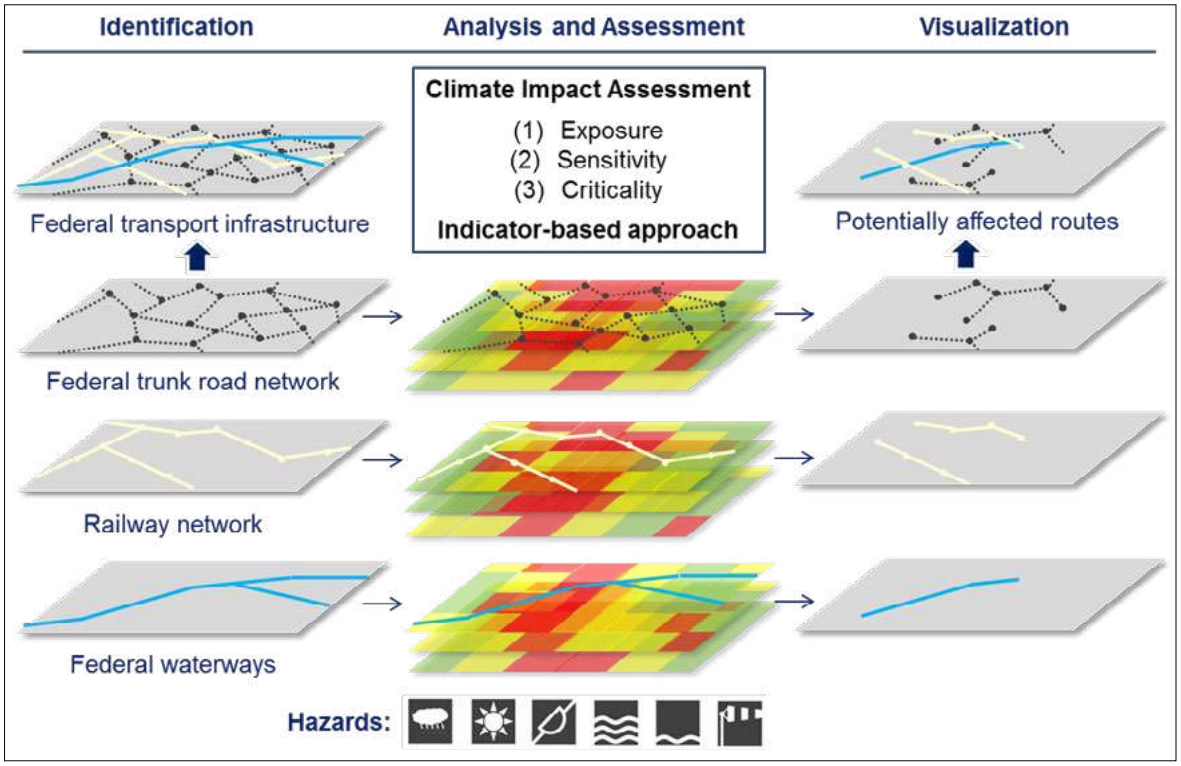
V. Integrated climate impact assessment

Climate impact analyses for specific hazards and modes of transport are integrated in a common assessment tool in order to provide a robust basis for climate adaptation measures in the transport sector. In order to obtain comparable results, the following evaluation framework is used:

- analysis periods (base period: 1971–2000, Future: 2031–2060 & 2071–2100),
- underlying scenarios (Representative Concentration Pathways RCP2.6 and RCP8.5; traffic scenarios according to the federal infrastructure planning with a reference (2010) and a target network (2030)),
- reference datasets,
- ensembles of climate projections (e.g., display of ensemble bandwidth, 15th and 85th percentile).

This common evaluation framework forms an important basis for the climate impact assessments. The methodology of the impact assessment is inspired by the Guidelines for Climate Impact and Vulnerability Assessments (Buth et al., 2017) that shall support the German adaptation strategy DAS. The analytic steps of the impact assessment (Figure II.1.2) encompass a sensitivity analysis that aims at identifying the network sections exposed to climate impacts, and a sensitivity analysis that identifies the network sections specifically sensitive to climate impacts. The relevant climate impacts are evaluated by analysing the criticality of impacted network sections that assesses how critical the network sections are within the entire transport system.

Figure II.1.2 Schematic illustration of the climate impact assessment within the BMVI Network of Experts



The impacts of climate change and extreme weather events on transport infrastructure and mobility may be assessed using impact models or climate indices. While the evaluation for the waterways is largely based on impact models (simulating for instance runoff, hydrodynamics, and morphodynamics) and related impact indices, the assessments for rail and road are generally based on climate indices directly derived from climate projections. These indices are based on expert opinion and research results. In the climate impact assessment framework these impact and climate indices are combined with other indices describing the sensitivity of specific sections of the federal road, rail and waterway networks and the criticality or importance of the sections for the transport system. A list of climate indices was compiled in a preliminary catalogue that has been discussed with scientists, engineers and practitioners in the agencies responsible for road, rail and waterway transport. In order to provide climate indices relevant to impact and risk analysis, a scientific exchange within the BMVI Network of Experts is essential. The challenging task is to address both, the demands of practitioners for data on extreme events and the technical capabilities of regional climate projections. Climate indices with practical relevance for damages to the infrastructure are often characterized by sub-daily timescales and high return periods, while climate simulations are generally provided in daily resolution and are most robust for average climate conditions. Thus, compromises need to be made, particularly with respect to extreme precipitation and wind indices.

VI. Conclusions and Outlook

As a research network the BMVI Network of Experts develops data, methodologies and tools for assessing climate change impacts on the German Federal transport system. It delivers climate impact assessments at the national level for the transport sector that are going to be integrated in the National climate impact und vulnerability assessment. For selected focus areas more detailed data and evaluations are provided and exemplarily specific adaptation options are tested. The implementation of the adaptation measures is done by the operators of the transport infrastructure, which are the Federal Waterways and Shipping Administration (GDWS; Agency of BMVI), Deutsche Bahn AG (rail) and Road administrations of the Federal States. Thereby, a regular dialogue between science and practice is established. Furthermore, GDWS supports the integration of climate change aspects into planning by preparing a climate proofing handbook for the administrative staff.

By combining climatological expertise and application knowledge of different transport modes within one network the BMVI takes steps towards a resilient transport system. Mobility is maintained and developed as an important foundation for our entire social development and the projected long-term developments are integrated into investment decisions of the BMVI. The results obtained for the Federal transport system are also relevant for other stakeholders at the regional level and form an important contribution to the implementation of the German Adaptation Strategy.

Case study 2 (Germany)
Reviewing railway operation regulations and policies regarding potential climate change

I. Introduction

The expected impacts of climate change, particularly with respect to the rising frequency and/or intensity of severe weather events, pose increasing challenges that concern all walks of life. In order to provide the necessary political framework for adaptation to the consequences of climate change, in 2008 the German federal government adopted the "German Strategy for Adaptation to Climate Change" (DAS).

In the process of infrastructure development, policies, regulations and standards are applied to ensure the structure's reliability and usability of the infrastructure for the coming decades. A lack of climate change considerations in those policies and regulations regarding future climatic changes results in the urgent need to review them to allow for early adaptations.

This case study presents the process undertaken in Germany to review policies, regulations and standards to identify their provisions for possible adjustments in the context of climate change impacts. This case study was prepared by: Maike Norpoth and Carina Herrmann (German Railway Authority).

II. Process and methodology

The government-founded interdisciplinary BMVI[25] Network of Experts[26] initiated the review[27] of 59 relevant railway infrastructure policies and regulations,[28] including an additional 18 appendixes. Each has been systematically searched for the potential impacts of specific climate change parameters (e.g. terms, words or phrases related to *Temperature, Precipitation, Distribution of lightning and Storm*[29]), and the identified provisions were assembled in a standardised results matrix (Figure II.1.3).

Figure II.1.3 Excerpt of the standardised results matrix of Deutsche Bahn regulation 836. The left side (in blue) shows an example for the identification of entries and while on the right side (in red) the respective assessment is given

Page	Chapter	Para-graph	Abbre-viation	What is affected?	Previously considered	Impact of climate change	Need for adjustment	Statement of reasons	Usability	Structural safety
836.4103 p. 6	4	8	N-T-GV	Installation of weather-sensitive building materials	superficial	high	high	Risk of base failure or cracks due to dryness	yes	no
-	-	-	N-R-HW	Storm surge	not considered	low	medium	Risk of storm surge especially increased at the North Sea	no	no
836.0509 p. 2	1	3	N-R-HW	Measures for water protection against pollutants	good	low	none		no	no
836.4502 p. 3	2	7	N-R-HW	Scour protection at passages with free water level	superficial	low	low	Large regional differences for flood events, risk of storm surge increased particularly at the North Sea	no	no

25 Federal Ministry of Transport and digital Infrastructure (Bundesministerium für Verkehr und digitale Infrastruktur), abbreviated BMVI

26 www.bmviexpertennetzwerk.de/EN/Home/home_node.html

27 Final report published, www.eba.bund.de/SharedDocs/Downloads/DE/Forschung/Forschungsberichte/2018/EBA-Forschungsbericht_2018-08a.pdf?__blob=publicationFile&v=8

28 The most relevant policies of Technical Specification for Interoperability (TSI), European Standards (EN), German Institute for Standardisation (DIN), Association of German Transport Companies (VDV), Deutsche Bahn (DB Ril)

29 Temperature (high and low), precipitation (rain and drought), distribution of lightning and storm (wind).

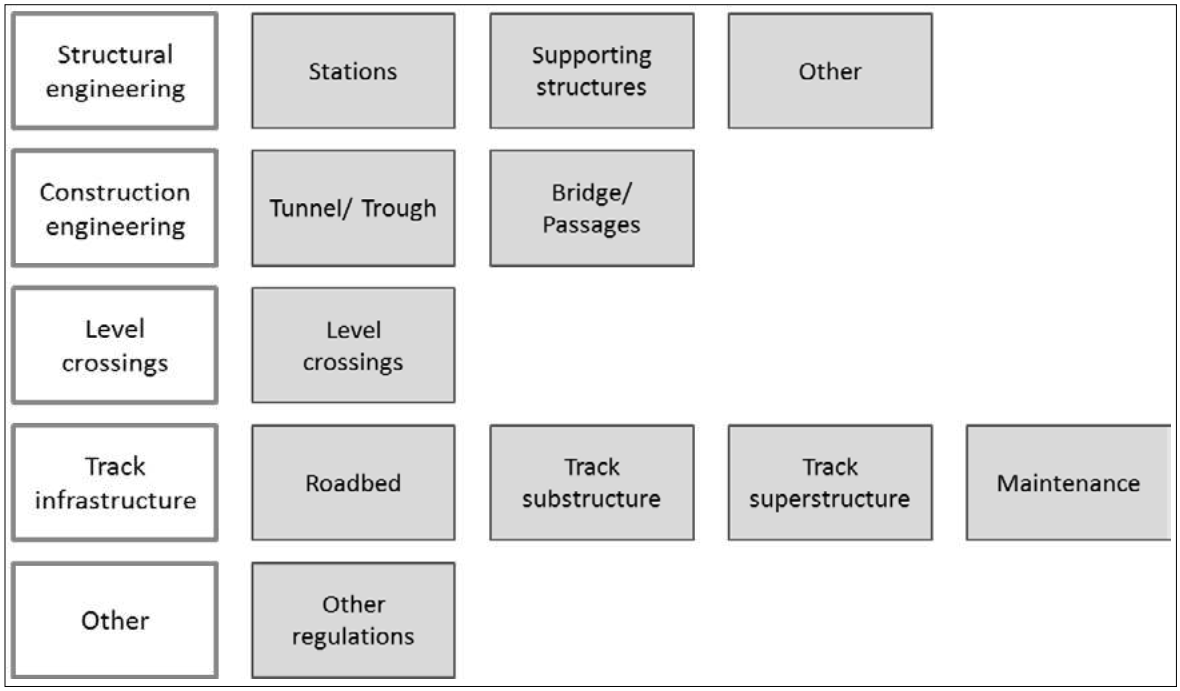
The methodology was broken down into two steps: *Identification* and *Assessment*.

Identification

This preliminary step included:

- Categorization of policies and appendixes depending on content (according to categories of railway infrastructure, Figure. II.1.4).
- Identification of potential climate change outcomes relevant to the railway infrastructure. Key words were highlighted for each outcome based on existing studies of extreme weather events and their impact on infrastructure and safety.
- Search of policies and appendixes on previously defined key words and identification of relevant text (Figure II.1.3 a).
- Repetition of process with re-defined/adapted key words if necessary.

Figure. II.1.4 Five main categories of railway infrastructure each with up to four subcategories. For example DIN EN 12812 ("Supporting Structures – Requirements, dimensioning and design") was assigned to category Structural engineering and subcategory Supporting structures.



Assessment

This secondary step included:

- Assessment of collected entries based on known climate impacts and expert knowledge[30]. Assessment covered four areas: *Impact of climate change, Need for adjustment, Usability and Structural safety* (Figure. II.1.3, a).
- Statement of reasons given for *Need for adjustment*.

30 Infrastructure was reviewed by the Institute for Transport, Railway Construction and Operation (IVE) and the Institute of Geoecology (IGÖ), both from the TU Braunschweig, Germany.

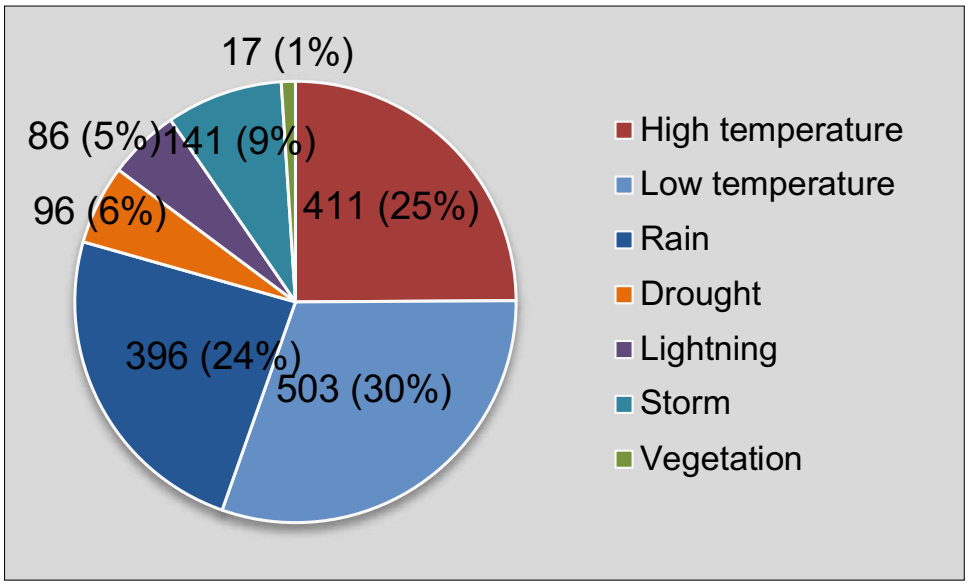
The German Climate Atlas[31] was the primary source used to compile the climate profiles[32]. These profiles were then used to estimate the impact of the climate parameters on the different infrastructure components. The Need for adjustment was determined based on the severity of the climate impact (e.g. rising temperatures have a high Impact of climate change on materials used for the railway infrastructure (i.e. metal or wood), but the Need for adjustment is high for metal but only medium for wood). To ensure traceability of the estimations and assessments, statements of reasons were added.

III. Results

The review of the policies, regulations and standards led to the identification of a total of 1650 entries which may require adjustments in the context of impacts of climate change. Some of the entries were repeated due to multiple causes of climate impacts (e.g. the same text passage from a regulation was collected twice in the results table, because in that passage the climate impacts connected to high temperature and low temperature are both addressed).

Figure II.1.5 shows the distribution of the entries according to the climate change parameters and highlights the potential impact of both temperature (high and low) and rain. During the evaluation another potential category of hazard was identified and included in the chart (vegetation).

Figure II.1.5 Distribution of the 1650 entries according to the climate change parameters. Absolute values and their percentage proportion are given for each parameter.

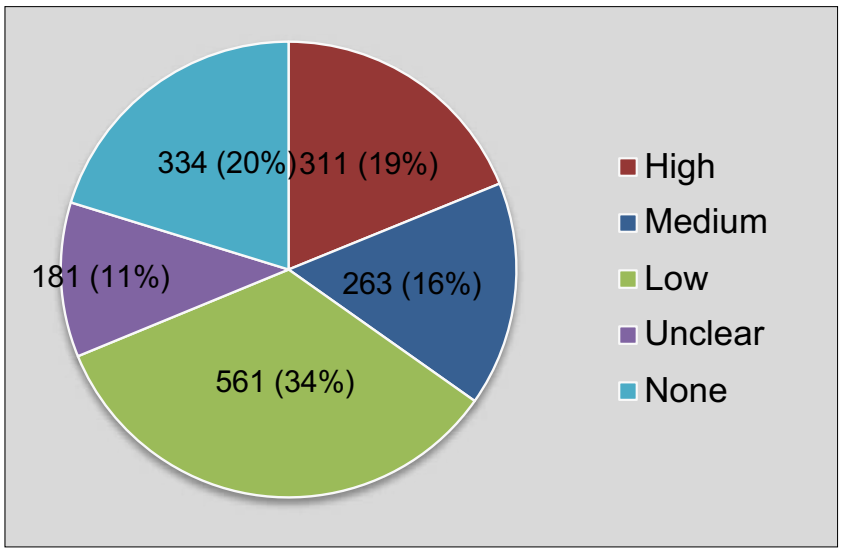


During the review and assessment, approximately 20 per cent of the provisions had been assigned a high need for adjustment as shown in Figure II.1.6.

31 https://www.dwd.de/EN/ourservices/germanclimateatlas/germanclimateatlas.html

32 https://www.eba.bund.de/SharedDocs/Downloads/DE/Forschung/Forschungsberichte/2018/EBA-Forschungsbericht_2018-08a_Anhang_1.pdf?__blob=publicationFile&v=4

Figure II.1.6 **Distribution of the 1650 entries according to their need for adjustment. Absolute values and their percentage proportion are given for each category.**



The identified provisions constitute a necessary basis to incorporate climate change in the future revision of regulations and policies. Evaluation of the *Need for adjustment* and the resulting recommendations highlight a clear prioritisation of necessary actions.

IV. Conclusions

The primary objective of this study was to obtain an overview of necessary adaptation measures and to encourage the integration and consideration of climate change during the planning and design stage of (re)construction work. The results of this work should be used to inform and consult the respective boards and committees (i.e. TSI, EN, DIN, VDV and DB Rail) and to facilitate discussion on the recommended actions needed to revise the policies and regulations.

However, the follow-up process to this project is dependent on the individual committees. For example, the German Institute for Standardisation (DIN) has a designated committee that deals with climate change adaptation (KU-AK 4). The final report and results of this project were expected to be presented to this committee in October 2019. This committee would then inform the DIN bodies responsible for elaboration and review of the respective standards of the reports results. The experts within the committees should then discuss and decide whether and how changes in the regulations should be included. If the DIN standard is a transposition of a European or International Standard (ISO), the review work would need to be done in the international committees. The entire procedure is a lengthy process and can take up to several years.

The revision procedure is similar for the guidelines of the *Deutsche Bahn* (DB Rail). After the respective committees are informed, they would decide whether adjustments were necessary based on their expert knowledge. Depending on the guidelines and the type of adaptation recommended, cost-benefit analysis is done. The question of how to finance any adaptation measures depends on the outcome of the cost-benefit analysis which leads to negotiations between the *Deutsche Bahn* and the German government (represented by the Federal Railway Authority and/or the Federal Ministry

of Transport and digital Infrastructure). Additional research projects may be required to obtain further relevant information.

For example, an ongoing research project assessed the design of railway track drainage facilities due to the expected increased precipitation due to climate change. The project objectives were to review respective regulations, assess given design specifications and to recommend action if necessary.

Although this study and its results are railway-specific, several of the reviewed regulations and policies can be used for other engineering structures. Furthermore, the applied method/approach can be adapted to other sectors.

Case study 3 (Canada)

Methodology for assessing infrastructure vulnerability to climate change in Canada

I. Introduction

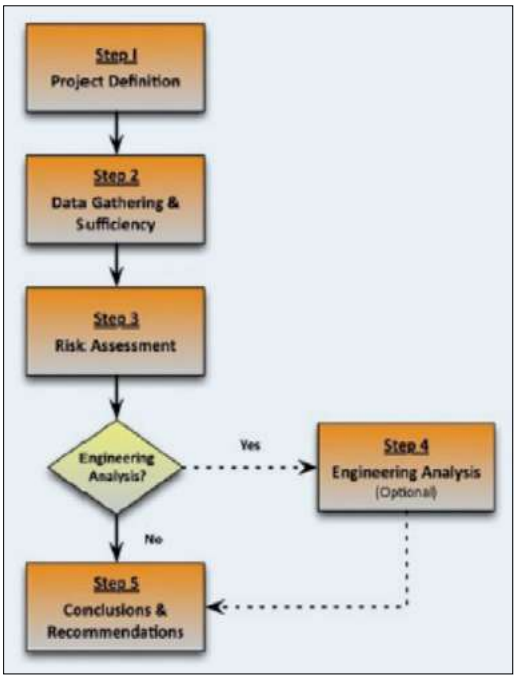
The purpose of this case study is to introduce the reader to a methodology for assessing infrastructure vulnerability that is used in Canada, including the key steps and inputs required, as well as the range of professional specializations that should be engaged. Through a presentation and analysis of the methodology's application in the Canadian transportation sector, combined with Transport Canada's experience in the assessment of climate risks, a series of recommended practices and lessons learned are presented for the consideration of transportation practitioners and with the aim of strengthening the process of climate risk assessment as a whole. While various climate risk assessment tools exist and the Government of Canada does not promote the use of any tool in particular, the PIEVC protocol is highlighted here as it is publicly available, free of charge, and versatile enough to be applied to multiple types of assets. This case study was prepared by: Allison Kader, Transport Canada

II. The Public Infrastructure Engineering Vulnerability Committee (PIEVC) Engineering Protocol

While engineers have long considered climate parameters in engineering design work, this has usually meant looking back at historic trends. Given the current rate of climate change, this is no longer a reliable approach. The Public Infrastructure Engineering Vulnerability Committee (PIEVC) Engineering Protocol, led by Engineers Canada, was developed as a five-step process based on risk science principles to analyse the engineering vulnerability of individual infrastructure systems based on current climate and future climate projections (Figure II.1.7 outlines these steps).

The information gained can be used to make informed engineering judgments on what components require adaptation as well as recommendations on how to adapt them.

Figure II.1.7 The PIEVC Protocol



III. Application of the PIEVC Protocol within Canada's Transportation System

The PIEVC protocol is a flexible and versatile climate risk assessment tool, proving to be applicable to various transportation modes in various geographic locations. Since 2008, the protocol has been applied to a wide variety of infrastructure types (including transportation) both in Canada, as well as internationally in over 60 projects. Within the Canadian transportation sector, assessments have been undertaken on: municipal roads and associated structures; culverts; bridges; highways in mountainous regions, Arctic and southern regions of the country; urban transit systems and, airports.

Engineers Canada encourages users of the PIEVC protocol to post final reports on the Engineers Canada website. Using these publicly available PIEVC climate risk assessment reports, Transport Canada has undertaken a review of climate risk assessments for Canadian transportation assets and has established an understanding of common recommendations. Within the Canadian context, 16 PIEVC climate risk assessments have been completed for transportation assets for air and surfaces modes and none to date for Canadian marine transportation assets. Of the 16 climate risk assessment reports, 12 are currently publicly available. Of these, four are focused on air transportation assets in Ontario and the Northern Territories; and, eight are for surface transportation assets in Atlantic Canada, Ontario, and the Pacific region.

IV. Inputs and Professional Specializations

Through the PIEVC protocol, the practitioner applying it evaluates an infrastructure's vulnerability to a changing climate based on:

(a) Infrastructure type and condition;

(b) The climate (historic, recent, and projected); and

(c) Historic and projected responses of the infrastructure to the climate.

As a result, the PIEVC protocol requires the input of multiple and various data sources. For the infrastructure assessment, these include, but are not limited to: physical components, location, material of construction, age, importance within region, physical condition, existing and archival operations and maintenance practices, and operations and management (e.g. insurance, policies, guidelines, regulations, laws). In terms of climate parameters, the PIEVC protocol highlights data sources, such as Intensity-Duration-Frequency curves, flood plain mapping, regionally specific climate modelling scenarios, and heat units. It is important to note that infrastructure data sources (e.g. element lists, plans, policies) and climate data sources vary depending on the mode, location, characteristics, and nature of the asset being evaluated.

A successful climate risk assessment is facilitated by the presence and participation of representatives from the evaluated asset's operations/management, technical services, and environmental services. In addition, the PIEVC protocol does not require the development of any new skill sets within the engineering and science communities. For example, training for the PIEVC protocol can be completed in approximately 10 hours.

The following professional specializations have been identified to be part of the project team to maximize the success of the application of the PIEVC protocol:

(a) **Project Manager** who is responsible for the overall management of the project, including the management of a multi-disciplinary project team;

(b) **Climate Specialist** who is responsible for collecting, analyzing, and interpreting climate data, climate modelling, and projections forecasting, as well as any other relevant climate information necessary for the project;

(c) **Engineering Analyst** who is responsible for the coordination of engineering tasks and output of engineering deliverables, in particular will oversee the infrastructure assessment components of the project;

(d) **Climate Risk Assessment Tool Lead** who is responsible for leading the climate risk assessment tool aspects of the project and for tracking and preparing the documentation required by the risk assessment process to ensure compliance with these requirements;

Transport Canada's five-year Transportation Assets Risk Assessment (TARA) initiative funds the assessment of climate risk for federally-owned transportation assets and many TARA-funded projects have employed the PIEVC protocol. As a result, the department has identified an additional professional specialization that may be of benefit for climate risk assessments of transportation assets:

(e) **Transportation Modal Expert** who is responsible for providing the relevant required technical transportation infrastructure knowledge, analysis, and operations expertise for the project as well as providing input on applicable codes, standards, and jurisdictional requirements.

Generally, the owner/operator of an asset does not have access to all five professional specializations in-house. Common practice is to hire a consulting firm that meets the requirements to complete the climate risk assessment. As such, the owner/operator of an asset generally takes on the following roles:

- Provide access to the project site and supporting documentation required to complete the project (e.g. plans, policies, infrastructure element list)
- Receive deliverables from consultant and provide feedback
- Participate in the climate risk assessment workshop. This is especially relevant for representatives from capital planning and operations
- Respond to the consultant's recommendations at the conclusion of the climate risk assessment.

V. Climate Risk Assessment Recommended Practices and Lessons Learned

Through the PIEVC climate risk assessment review, as well as the implementation of the TARA initiative, Transport Canada has established a series of recommended practices and lessons learned in terms of climate data acquisition and analysis, the climate risk assessment process, and project management. These include, but are not limited to:

A. Climate Data

Much of the cost and time associated with a climate risk assessment of multiple assets at a singular site are due to the process of identifying the climate impacts. Climate impacts vary based on the climate model(s) and emissions scenarios (representative concentration pathways (RCPs)) employed during a climate risk assessment and currently there is no significant guidance as to which model(s)

and RCPs may best be employed. Nevertheless, project teams will need to establish at the outset of a project a method of identifying which climate model(s) and RCPs are most appropriate for a particular asset, based on its mode, region, and management/maintenance plan.

Climate risk assessments produce the most useful information when the timescale that is considered for the climate projections is determined in accordance with the lifecycle of the observed asset. Climate projections should correspond to the asset's management/maintenance plan as to account for points of major recapitalization.

When employing a climate risk assessment tool, such as the PIEVC protocol, it is important to consider the cumulative impacts of climate parameters, if possible. For example, sea level rise, storm surge, and king tide events occurring simultaneously is a greater risk to coastal infrastructure than the occurrence of an individual event. It is important to meet early with asset managers and operators to identify which cumulative impacts should be focused on. While this might require more travel, which could increase the overall cost of a climate risk assessment, the final analysis and results will prove to be stronger and more useful for the asset.

B. Climate Risk Assessment Tools

It is important to recognize that most climate risk assessment tools, including the PIEVC protocol, are not decision-making tools in and of themselves. However, the PIEVC's versatility and flexibility to include periods of return and identified confidence levels to evaluate climate risk over time can produce results that inform an asset's maintenance and capital planning activities. Including this type of an analysis into a traditional climate risk assessment can assist decision-making by helping to determine the optimum time at which an action should take place, the point in time a certain level of climate vulnerability will require immediate action, and when risk tolerance thresholds become critical.

The PIEVC's application in the Canadian transportation sector has tended to generate recommendations focused on: development/update of policies and previous evaluations; studies and instrumentation; monitoring; management and operational changes; engagement to gather additional information and/or further apply assessment results; engineering solutions; and vulnerability ranking and development of criticality parameters. These recommendations do not tend to be major strains in terms of time, cost, or resources. In fact, Table II.1.1 illustrates that, of the 12 PIEVC climate risk assessment reports evaluated, only a small number of recommendations are capital intensive engineering solutions, all of which relate to an ice road in the Northwest Territories. At the time of the assessment, this ice road was experiencing significant climate change impacts requiring immediate action.

Table II.1.1 Breakdown of evaluated PIEVC climate risk assessment recommendations

Type of recommendation	Development/ update of policies and previous evaluations	Studies and instrumentation	Monitoring	Management and operational changes	Engagement to gather additional information and/or further apply assessment results	Engineering solutions	Vulnerability ranking and criticality parameters
Number of recommendations	35	33	24	6	5	5	2

Case study 4 (France)

Measures concerning transport from the National plan for Adaptation to Climate Change and case study on risk analysis methodology applied to the road network of the Interdepartmental Directorate for Mediterranean Roads (DIR Med)

I. Introduction

This case study discusses the National Plan for Adaptation to Climate Change adopted in France and its specific measures concerning the transport sector. It then presents an approach developed and tested in France to assess the risks of climate change to transport infrastructure, systems and services. This case study was prepared by: Charles Simone (Ministry for the Ecological and Inclusive Transition, Directorate-General for Infrastructure, Transport and the Sea).

II. The National Plan for Adaptation to Climate Change: Measures concerning transport

Pursuant to article 42 of Act No. 2009-967 of 3 August 2009, which put in place a national roundtable on the environment (the Grenelle de l'Environnement), in 2011 France published its first National Plan for Adaptation to Climate Change (PNACC), covering a period of five years. This cross-cutting, interministerial plan addresses 20 different fields, including transport infrastructure and services. It identified four adaptation measures to assess the impact of climate change, prevent vulnerabilities in transport systems and improve infrastructure resilience in order to ensure the continuity and security of passenger and freight transport:

- **Measure No. 1:** Review and adapt technical standards for the construction, maintenance and operation of transport networks (infrastructure and equipment) in metropolitan France and in the French overseas territories;

- **Measure No. 2:** Study the impact of climate change on demand for transport and determine the effects this has on the supply of transport;

- **Measure No. 3:** Develop a harmonized methodology to assess the vulnerability of land, sea and air transport infrastructures and systems;

- **Measure No. 4:** Take stock of the vulnerability of land, sea and air transport networks in metropolitan France and in the French overseas territories; and prepare appropriate strategies to progressively respond to the global and regional problems posed by climate change.

In December 2018, France published its second PNACC,[33] covering a further period of five years, with the objective of protecting the population against extreme weather events and building resilient economic sectors (for example, in agriculture, industry, tourism and transport). Unlike the first plan, which was structured on the basis of economic sectors, this one adopts a thematic approach. It contains measures in respect of transport to:

- Continue adapting technical standards for the operation, maintenance and construction of transport infrastructure and equipment;
- Continue to analyse risks and improve the methodology used, based on lessons learned and encourage infrastructure and network managers to independently conduct vulnerability studies;
- Mobilize a network of contact points and experts;
- Carry out a forecast of changes in the major global trade routes;
- Analyse the consequences of voluntary restrictions of transport and movement in times of crisis.

Thus, as part of measure No. 4 of the first PNACC, risk analyses have been conducted on various transport systems, including the Interdepartmental Directorate for Mediterranean Roads, presented in the case study below.

III. Case study: Risk analysis methodology applied to the road network of the Interdepartmental Directorate for Mediterranean Roads (DIR Med)

A. Purpose of the study

In 2017/2018, under the supervision of Cerema[34] (the Expert Study Centre on Risks, the Environment, Mobility and Planning), Carbone 4[35] carried out a risk analysis of a highway network in the south-eastern part of France, applying the methodology developed by Cerema and entitled "Risk analysis of extreme weather events for transport infrastructures, systems and services – A conceptual anthology". The Interdepartmental Directorate for Mediterranean Roads (DIR Med), three agencies under the Ministry for an Ecological and Solidary Transition and experts in transport infrastructure, also took part in the working group. The aim of the study was to determine the vulnerability of the road network in the face of climate change and to test the methodology.

B. Scope of study and description of methodology

The network that was studied consists of 750 km of roads and contains approximately 1,000 types of infrastructure such as bridges, tunnels and viaducts. Some of its segments are part of the European road network (A7/E714, A51/E712). The area of study includes a wide variety of both terrain (e.g. such as mountainous areas, coastal plains, forests, calanques and ponds) and climates (e.g. Mediterranean, semi-Mediterranean, semi-continental and high-mountain climates).

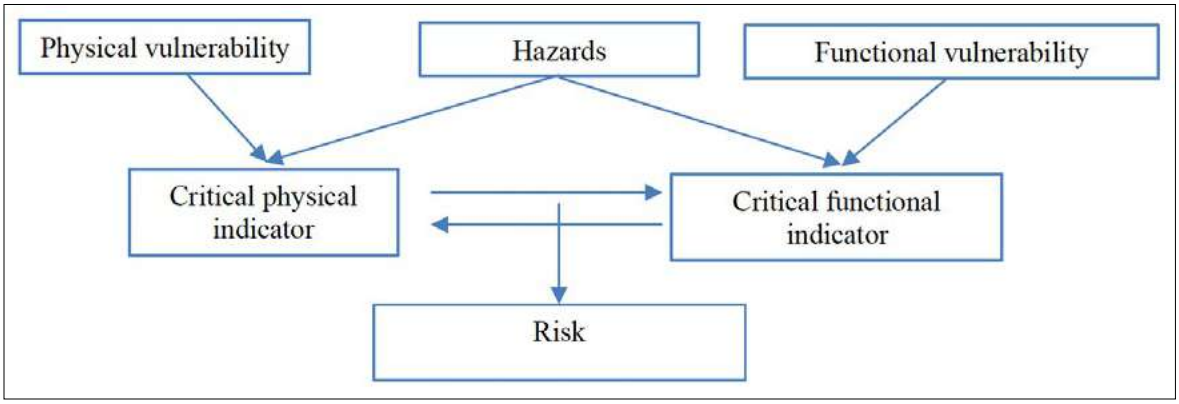
33 www.ecologique-solidaire.gouv.fr/adaptation-france-au-changement-climatique

34 Cerema (the Expert Study Centre on Risks, the Environment, Mobility and Planning) is a public body providing support for public policies under the dual supervision of the Ministry for an Ecological and Solidary Transition and the Ministry of Territorial Cohesion.

35 Carbone 4 is a consulting firm that specialized in energy transition and adaptation to climate change.

The methodology consisted in rating extreme weather events, physical vulnerabilities and functional vulnerabilities so as to determine risk levels by combining the ratings. It is of interest to look at the critical physical and functional indicators separately. They can subsequently be cross-checked to avoid counting the same hazards twice.

Figure II.1.8 Risk analysis flow chart



C. Rating of extreme weather events

The area that was studied is exposed to various types of weather hazards: sea flooding and fires along the Mediterranean coast, flooding in Camargue, a significant number of days of freezing weather in the Hautes-Alpes region and heat waves in Isère.

Each extreme weather event is associated with one or more climate change variables that characterize the event's intensity, frequency, duration or location (Table II.1.2):

Table II.1.2 Association of extreme weather event with one or more climate change variables

Extreme weather event	Associated variable	Characterization
Extreme heat	90th percentile of Txi (Tmax for day i)	Intensity
Number of days of freezing weather	Number of days when Tmin ≤ 0 °C	Frequency
Floods	Number of days with accumulated precipitation ≥ 20 mm)	Intensity + duration
	Location of flood-prone areas (indices of levels 0–1)	Location

The climate data was extracted from DRIAS[36] and the model used was CNRM 2014 (ALADIN), with a spatial resolution of 8 km. Each climate variable was rated from 1 to 4 to take into account the road network's exposure in each scenario and time horizon:

- Time horizons: 1961–1990 (reference period), 2021–2050 and 2071–2100;
- Climate scenarios: RCP 2.6, RCP 4.5 and RCP 8.5.

36 www.drias-climat.fr

D. Rating of physical vulnerability of infrastructure

Analysis of the physical vulnerability of infrastructure was carried out in four steps:

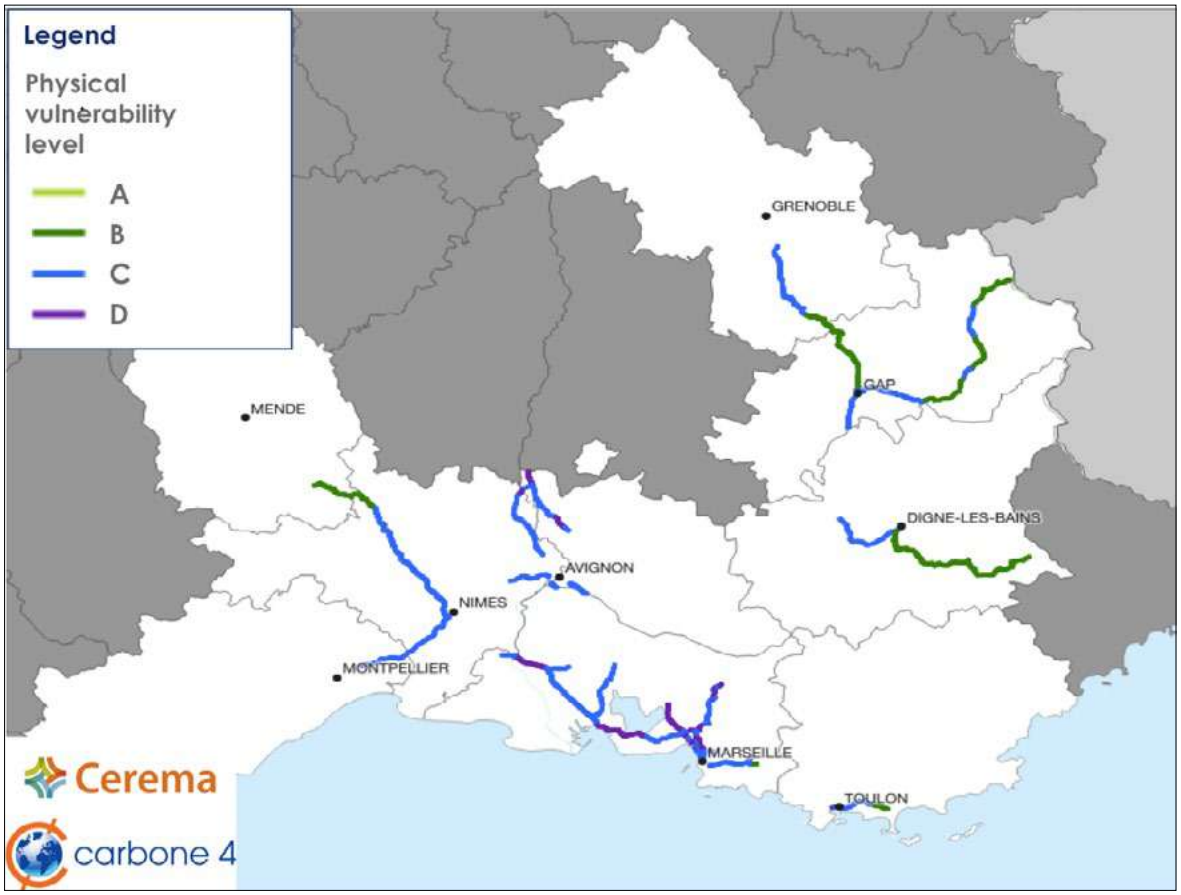
(a) Classification of the road network by category of infrastructure (road, bridge, tunnel, retaining wall, etc.) and their components (surfaces, road signage, etc.);

(b) Identification of the physical impacts of extreme weather events on systems. For example, landslides can cause the complete or partial destruction of the road and roadway structures, and freezing and thawing cycles produce potholes on roads and corrode metal fittings of roadway structures;

(c) Identification of aggravating factors, based on the type of material (concrete, steel, etc.) and the conditions of the infrastructure (sealed surface, high-traffic area, etc.);

(d) Assignment of a rating corresponding to the type of response necessary for the operator to deal with the potential physical damage resulting from extreme weather events.

Figure II.1.9 An example of a vulnerability rating of DIR Med road segment in the event of heat waves in a distant time horizon (2017-2100) for RCP8.6 scenario – with modification of the actual results



Source: Cerma, DIR Med and Carbone 4 Rating: Carbone 4

E. Rating functional risk for roads

The functional risk for roads was evaluated in two steps:

(a) Identification of the actual impact (complete blockage or slowdown of traffic) and the economic stakes for each road segment, based on traffic data, in order to obtain ratings of functional vulnerability;

(b) Combination of vulnerability ratings with climate hazard ratings.

F. Conclusions and way forward

The use of the methodology on the Mediterranean DIR road network has made it possible to take stock of the network's vulnerability to climate hazards, to make recommendations for further development of that methodology and to make the methodology available to all network operators wishing to carry out risk analyses of their road networks. There are still some methodological issues to take up in subsequent studies, in particular how to select and prioritize adjustments, and also how to analyse the economic importance of the segments of a road network. Traffic indicators have made it possible to estimate their economic importance, but such an approach does not take into account the presence of users and sites that are of strategic importance to the economy and the network's absorption or re-routing capacities in the event of disruptive weather events.

Case study 5 (Poland)

Polish practice in carrying out sensitivity, vulnerability and risk analysis for the identification of hotspots on transport infrastructure due to climatic factors

I. Introduction

This case study presents Polish practices for carrying out sensitivity, vulnerability and risk analysis for the identification of hotspots on transport infrastructure due to climatic factors. This case study was prepared by: Piotr Czarnocki (Ministry of Environment).

II. Responsible authority for climate change adaptation policy in Poland

The responsible authority on matters of climate change adaptation is the Ministry of Environment (Department for Sustainable Development and International Cooperation). Supportive services are provided by the Institute of Meteorology and Water Management (IMGW-PIB), the Institute of Environmental Protection (IOŚ-PIB), and the Institute for Ecology of Industrial Areas (IETU). IMGW-PIB gathers climate change data.

III. National adaptation strategy and related acts

The Polish National Strategy for Adaptation to Climate Change for sectors and areas sensitive to climate change by 2020 with a vision to 2030 (NAS), adopted in 2013, is used as a framework by relevant authorities to monitor and assess the need for adaptation action at the national, regional and local levels, including in the transport sector. NAS contains description of the general characteristics of the climate, climate change from 2007–2011, scenarios and impact on sensitive sectors until 2030. It includes an analysis of climate change trends and impacts on biodiversity, water management, forestry, power engineering, coastal zones, mountain areas, agriculture, transport, spatial economy and urbanised areas, construction and health.

NAS was developed further to a project "*Development and implementation of a strategic adaptation plan for the sectors and areas vulnerable to climate change* (Klimada)". Klimada, as a platform, maintains general information and data on climate change trends and climate change scenarios. It contains a diagnosis of the vulnerability of 12 sectors (including Health, Tourism, Mining, Construction, Transport etc). The Crisis Management Act, developed by the Government Security Centre and adopted on 26 April 2007 addresses the response, among others, to crises triggered due to climate change. It provides the characteristics of hazards and assessment of their occurrences. It specifies the critical infrastructure (including risk maps and hazard maps) and the duties and responsibilities of relevant stakeholders in crisis management in the form of safety net, a statement of the forces and resources planned for use in crises.

The revised 2017 Law on Environmental Impact Assessments requires relevant authorities to undertake climate risk analysis in the course of EIA procedure. This applies mainly to projects of type I (in the EIA Report), and some projects of type II, if EIA Report is obligatory. This legal requirement does not cover other projects.

IV. Adaptation plans for 44 cities project

The Ministry of Environment, through a project on the Development of Urban Adaptation Plans for cities with more than 100,000 inhabitants supports 44 cities in identifying and analysing potential adaption challenges. More specifically, the Ministry drafts plans for local authorities, indicates sources of funding and raises awareness for the need for adaptation, including adaptation to the climate change of the public urban transport system.

V. Carrying out sensitivity, vulnerability and risk analysis for the identification of infrastructure hotspots due to flooding

Identification of infrastructure hotspots was carried out using data collected and generated by process of assessing and mapping the hazard and flood risk in Poland. This process included:

- Preliminary assessment of flood risk - the objective is to designate areas endangered by flooding (i.e. areas at significant risk of flooding or where the occurrence of high risks is likely);
- Flood hazard maps and flood risk maps – developed within IT System for Protection of the Country Data (ISOK) project;
- ISOK - holds information about water management, natural hazards, threatened areas etc. Its objective is to improve the operation of crisis management systems at all levels, but it can also be used in spatial planning (in the context of flood hazard in river valleys);
- Flood risk management plans - to reduce the potential negative impacts of floods on human life and health, the environment, cultural heritage and business. This should be achieved by implementing measures to minimise the identified risks (diagnostic part).

Moreover, the identification was done following the methodologies contained in the Guide to Investment Preparation Respecting Climate Change Mitigation and Adaptation as well as Resilience to Natural Disasters (Ministry of Environment, 2015).

Following this methodology, sensitivity (S) involves the determination of the size and significance of risks to changes in input parameters, while vulnerability (V) is the result of multiplication of exposure (E) by sensitivity (V=ExS). Vulnerability analysis covers evaluation of the sensitivity and exposure of infrastructure to climate change.

Sensitivity is related to the size of the road traffic and the type of road infrastructure. Exposure is determined by the height of the flood wave (flooding depth) and by the likelihood of flooding.

The depth of water is included on the depth layers for individual flood scenarios. In the depth layers there is a "Głębokość" (depth) field, which contains depth intervals divided into four classes described by attributes:

1: = < 0.5 m (less or equal to 0.5 m),

2: 0.5-2 m (from 0.5 m to 2 m),

3: 2-4 m (from 2 m to 4 m),

4: > 4 m (above 4 m).

These ranges have the following reference to flood risk:

(1) water depth less than or equal to 0.5 m – indicates a low risk for people and building objects, but high risk in terms of transport (moderate risk up to 0,2 m. and low risk up to 0,1 m.),

(2) water depth greater than 0.5 m and less than or equal to 2 m – indicates an average risk to people due to the possible requirement for evacuation to higher floors of buildings, high due to material losses and very high risk in terms of transport;

(3) water depth greater than 2 m, and less than or equal to 4 m – indicates a high risk to people and very high due to material losses; not only the ground floors but also the first floors of buildings may be flooded; extremely high risk in terms of transport,

(4) water depth greater than 4 m – indicates a very high risk to people and a very high risk of total material loss, extremely high risk in terms of transport.

Applying such an analysis, risk maps are developed that portray levels of flooding risk across a geographical area. Data include the likelihood of flooding at Q=0,2%, Q=1% and Q=10%. These specific maps may include information concerning flood water depth, water flow velocity and directions of flood water flow.

The maximum elevations of the flood water table are included as points on the "maximum water level". In the table of this layer, there are "Level" or "Ordinate" attributes for particular scenarios of flood occurrence, which have water elevation values in meters above sea level in the Kronstadt 86 altitude system.

The above-mentioned probabilities of floods may be related to the forecasted climate changes. The likelihood of flooding is changing in a very precisely defined range according to the adopted climate change scenario.

As a next step, a layer portraying specific sensitive infrastructure network – Trans-European Transport Networks (TEN-T) was selected – is added to the risk map on flooding. This data includes the type of roads, their width, the type of their surface and some additional data.[37]

37 The description of the structure of the database containing the description of individual layers and fields (in Polish) can be found at: www.kzgw.gov.pl/files/mzp-mrp/zal4.pdf

VI. Results

Following the sensibility and vulnerability analysis, TEN-T network hotspots due to flooding have been identified and included on GIS maps. Also, numerical data in GIS format are provided, which in turn may be subject to further processing using available GIS tools.

Figure II.I.10 (on next page) contains GIS maps with analysed hotspots. The figures present two scenarios: one in which the flood embankments are damaged and another in which they are retained. Detailed information contained in the GIS system, described in Section V above, such as a velocity of water, directions of water flow etc. was not presented on the maps.

VII. Conclusions and outlooks

It should be stressed that the use of GIS tools is essential for the analysis of hotspots. Infrastructure hotspots were identified on flood risk maps in GIS environment. These hotspots are shown in relation to the probability of flooding (road network and nodes layers and layers of water with a specific depth associated with the probability of flooding). This work, done in accordance with the recognized methodology provided in the Guide to Investment Preparation Respecting Climate Change Mitigation and Adaptation as well as Resilience to Natural Disasters, presents a crucial step for identification of sections of infrastructure that may be prioritized for adaption to make them more resilient to climate changes.

Figure II.1.10 Maps portray levels of flooding risk on selected hot spots near the (a): city of Tczew (the Vistula river, Pomorskie Voivodeship) , (b) city of Przemyśl (the San river, Podkarpackie Voivodeship), (c) village of Łęka (the Ner river and the Warta river, Wielkopolskie Voivodeship), (d) village of Sługocin (the Warta river, Wielkopolskie Voivodeship)

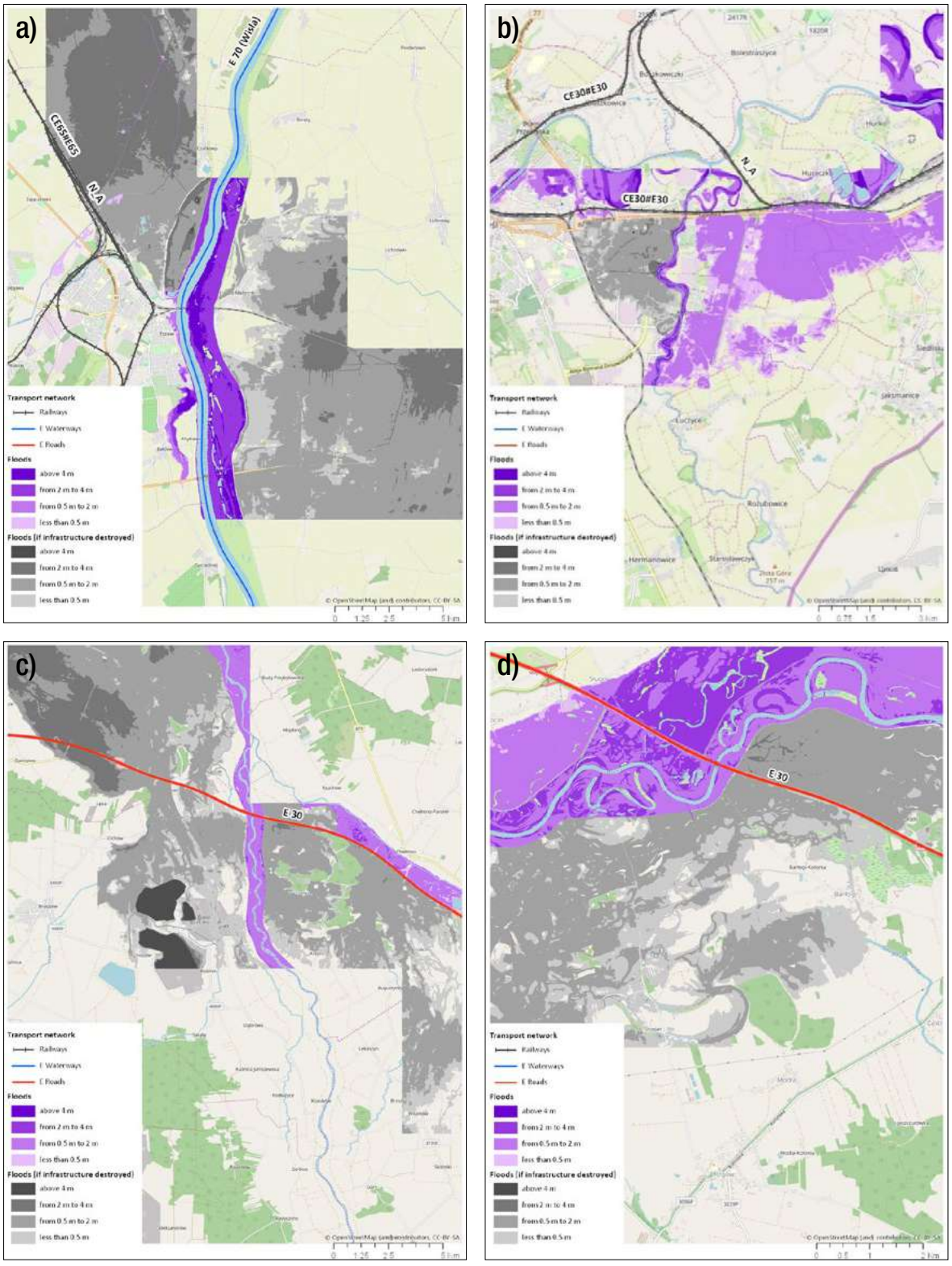
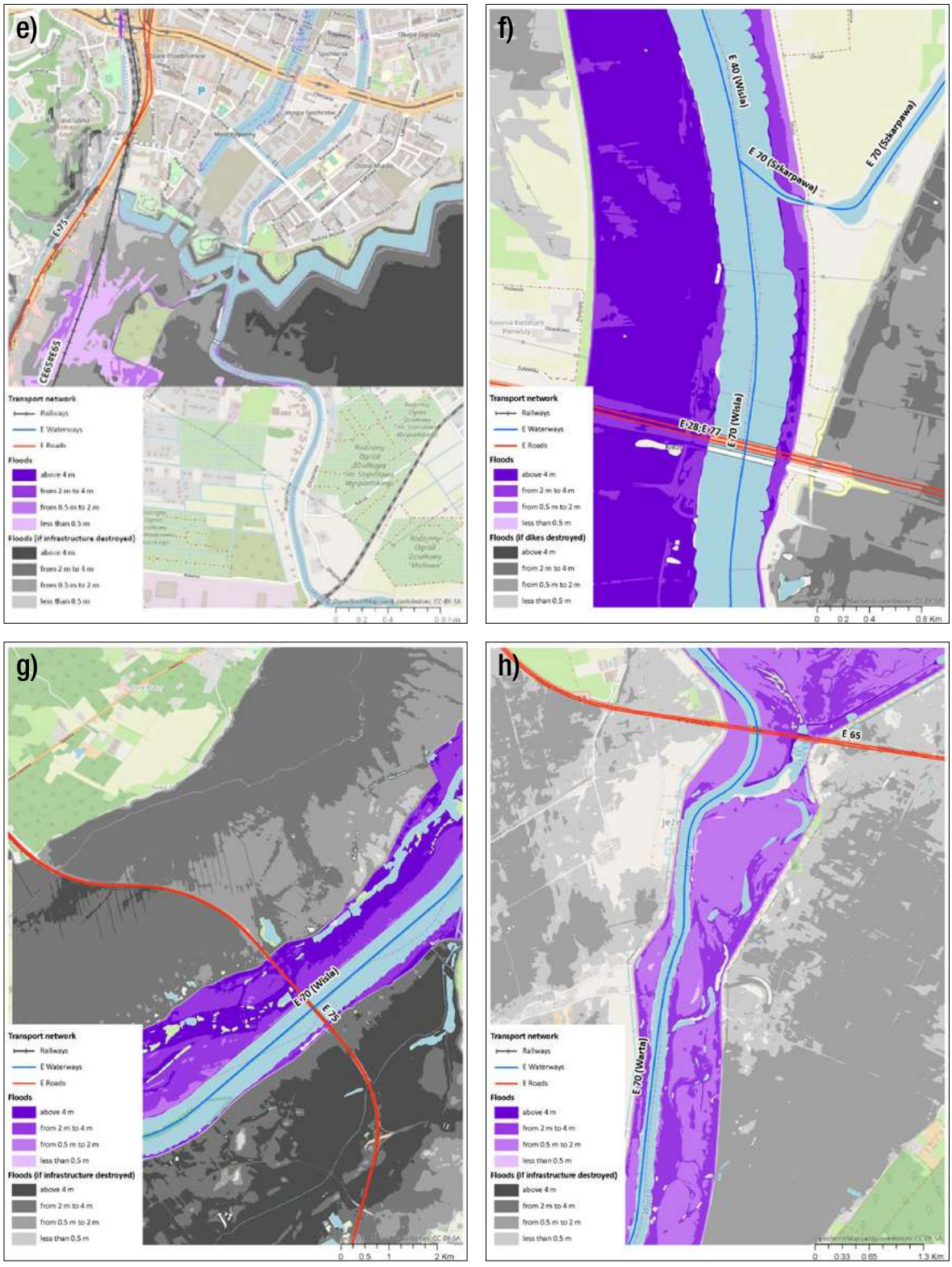


Figure II.1.10 (figure continued) (e) city of Gdańsk (the Motława river, Pomorskie Voivideship), (f) village of Kiezmark (the Vistula river, Pomorskie Voivodeship), (g) city of Grudziądz (the Vistula river, Kujawko-Pomorskie Voivodeship) and (h) village of Jeże (the Warta river, Lubuskie Voivodeship)



Case study 6 (the Netherlands)

Development of a Climate Adaptation Strategy for the InnovA58 highway in the Netherlands

I. Introduction

This case study discusses the development of a climate adaptation strategy for the InnovA58 highway in the Netherlands.[38] This case study was prepared by: Kees van Muiswinkel (Rijkswaterstaat, the Directorate-General for Public Works and Water Management).

II. Brief information on the national framework as basis for conducting infrastructure climate change impact assessments

The impact of climate change on roads is mainly associated with extreme weather events related to temperature and precipitation, like heat, drought and intense rainfall. Also changes in hydrogeological conditions, like the rise of sea levels and ground water levels, may affect road infrastructure. In the Netherlands climate adaptation is particularly concerned with the impact of extreme drought, heat, precipitation and floods. The Delta Programme describes these as the 'four threats' of climate change, which need specific attention.[39] The impact of these threats is context dependent, hence, when it comes to adapting to climate change, localized solutions are required. When it comes to infrastructure, attention should be paid to the fact that most parts of road networks cross multiple borders managed by multiple authorities and tiers of government. Therefore, a regionally tailored approach provides an opportunity to create better and more sustainable infrastructure development. With area-oriented approaches, innovative and effective combinations between road infrastructure and other spatial policy sectors, like recreation, water, nature, housing and agriculture, including climate adaptation measures in the area not directly related to the road, can be made.

In short, the road infrastructure system needs persistence, adaptability, transformability and preparedness to be able to cope with the impact of new and uncertain climate situations in the future. For this, an area-oriented approach is crucial, since climate change has an effect on thE Roads in relation to the surrounding environment and vice versa. Moreover, this approach offers the possibility of smart combinations of measures by combining other challenges in the surrounding environment with the climate adaptation challenge of the road infrastructure (Leijstra et al., 2018).

38 Leijstra, M., Muiswinkel, K. van, Leendertse, W. and Bles, T. 2018. Development of a Climate Adaptation Strategy for the InnovA58 highway in the Netherlands. Proceedings of the 7th Transport Research Arena TRA 2018, Vienna, Austria

39 Delta Programme (2014) Synthesis of Spatial Adaptation. https://ruimtelijkeadaptatie.nl/deltabeslissing/deltabeslissing/

III. Process for assessments

To develop climate adaptation strategies for the Dutch highway network, InnovA58, part of the A58 highway, situated in the provinces of Zeeland and Noord-Brabant in The Netherlands, was used as a case. The InnovA58 project, consists of both an extension of the existing A58 highway (with extra driving lanes) over 50 km in length as well as major maintenance and refurbishment. Besides that, InnovA58 is part of a broader regional program focused on the integration of urban, natural, recreational and environmental challenges. The project offered the opportunity to imply an area-oriented approach.

To assess the risks, vulnerability and possible adaptation measures, a process was designed to develop an adaptation strategy for InnovA58 and the surrounding environment from September 2016 to February 2017. Attention was paid to the surrounding environment, since possible adaptation measures that contribute to the resilience of the road can be found in the surrounding environment. However, increased resilience in one place may lead to decreased resilience elsewhere and therefore involvement of local stakeholders and experts was of high priority in this process.

After the scope was determined, a stepwise process was designed to develop an adaptation strategy. The process consisted of three steps according to the ROADAPT[40] methodology and a fourth step using the Dynamic Adaptation Policy Pathways[41]. In the first step, climate threats, key risks and potential adaptation measures were scanned, through two joint workshops, with experts and asset managers from Rijkswaterstaat, Deltares and local stakeholders, like municipalities, water boards and provinces. In the second step, the key risks were mapped to determine the places where the key risks could occur on the road. Output from the first two steps were then analysed based on costs, benefits and effectiveness. Finally, an adaptation strategy was developed with the Dynamic Adaptation Policy Pathways. In Table II.1.3 the aforementioned steps are summarized.

Table II.1.3 InnovA58 climate adaptation approach

Process steps	Actions taken
Quick scan	Two Workshops: – To determine climate threats for the A58 infrastructure and surrounding environment – To determine key risks and potential measures
Vulnerability Assessment	Assessment GIS-methodology for mapping distinctive vulnerabilities in the road network
Socio-economic Impact Assessment	Two methods: – Cost Effectiveness Analysis – Cost Benefit Analysis
Adaptation Strategy	Dynamic Adaptation Policy Pathways to determine an adaptation strategy

40 'Roads for today adapted for tomorrow' ROADAPT project, granted under the CEDR call 2012 'Road owners adapting to climate change'. ROADAPT adopts a risk based approach using the RIMAROCC framework (Risk Management for Roads in a Changing Climate).

41 Haasnoot, M., Kwakkel, J., Walker, W., Ter Maat, J. (2013). Dynamic Adaptive Policy Pathways: A method for crafting robust decision for a deeply uncertain world. Global Environmental Change, 23, 485-498.

IV. Assessment methodologies

In the Quickscan-workshops, experts from Rijkswaterstaat, Deltares and local stakeholders identified extreme events of current and future weather that pose the greatest risks to the A58 highway and its surrounding environment. These risks were then combined in risk matrices.

For the risk assessment, a semi quantitative approach was adopted. This means that both likelihood and impact have been factored using classes 1 to 4. The classes themselves were determined during the workshops. The higher the number for probability, the higher the likelihood; the higher the impact class, the higher the consequences. Due to climate change, the probability of these risks may change in the future. After conducting risk evaluation with the stakeholders, five key risks were identified (Table II.1.4) including possible adaptation measures for an adaptation strategy.

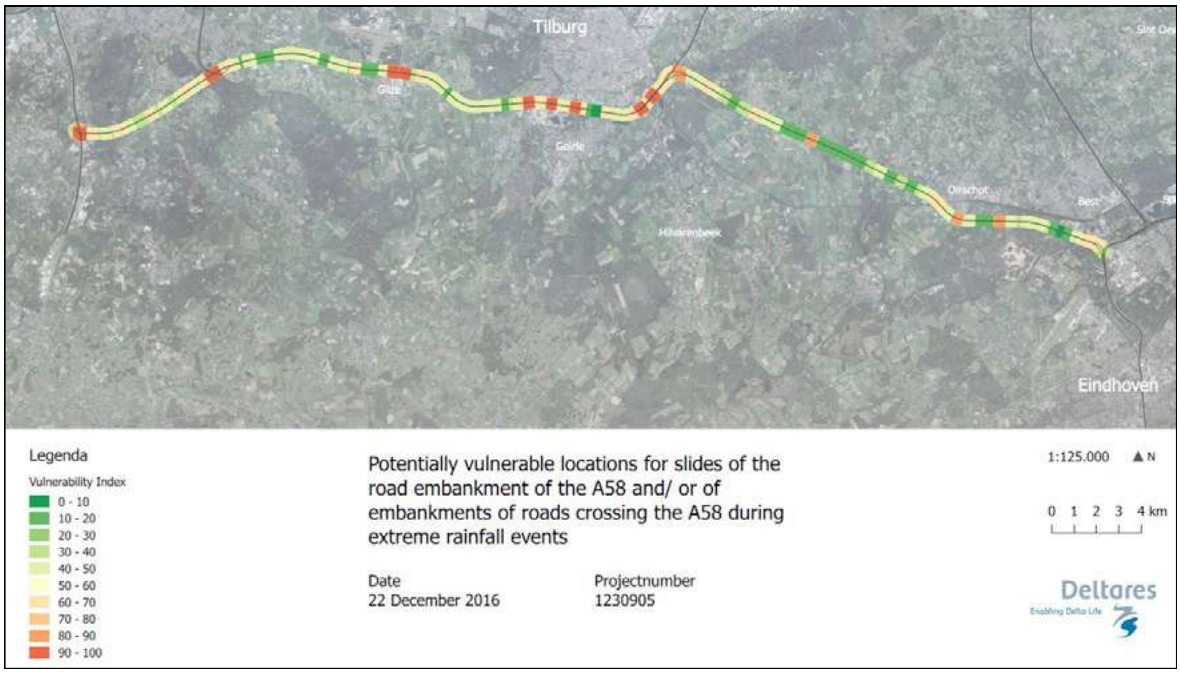
Table II.1.4 Identified key risks and possible measures

Key risks	Possible measures (examples)
Flooding of infrastructure as a result of inundation	– Enlarge capacity of the existing bridges (wider/higher) – Improving water storage of rainwater drainage of the road (slower discharge into the streams) – Laying the road higher – Adjusting road design so that road may flood plus diversions – Realizing upstream water storage ('room for the ditches/streams', other vegetation, slower afflux to the stream) – Pumping water from the one side to the other side of the road when there's high water
Flooding of infrastructure due to extreme precipitation	– Increase capacity of rainwater drainage system – Use gutters rather than gullies – Guarantee flatness of longitudinal profile of the road – Build water storage under or next to the road – Dimension/ design intersections for intense precipitation – Use of 'pluvial flooding culverts'
Erosion of Embankments	– Improving erosion protection
Loss of safety due to splash and spray	– Better-draining asphalt (thicker) or vertical/central drains under the asphalt – Lowering the emergency lane – Better management and maintenance of the verges and rainwater drainage – Adaptive lighting/ notification on the road
Flooding of streams and urban areas due to extreme precipitation	– Pumps' longitudinally to road, from wet to dry places – Store water and add it again during drought ('wadis') – Infiltration of pump water into aquifers – Make sure rainwater does not drain into urban drainage system

The ROADAPT Vulnerability Assessment was then carried out to analyse the vulnerability of InnovA58 for related current- and future weather circumstances in more detail. The vulnerability assessment resulted in several vulnerability maps, presenting the most vulnerable locations of the project (Figure II.1.11). This provided the starting point for a more detailed location specific analysis, to examine whether a key risk constitutes an unacceptable risk for the road and the environment, and whether or not measures can and should be taken.

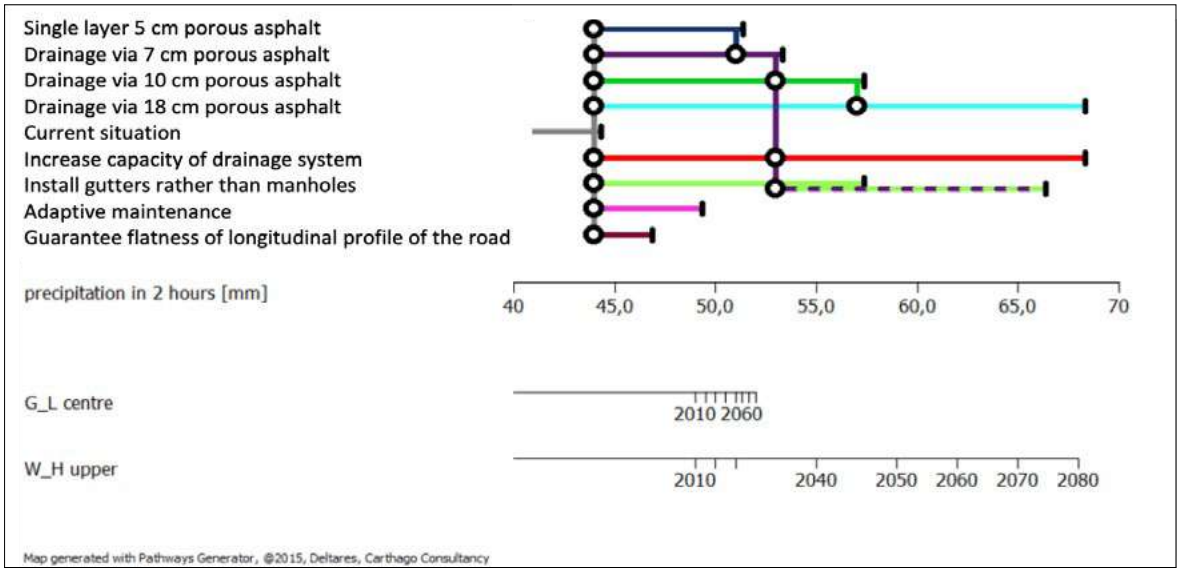
Subsequently, the ROADAPT Socio-economic Impact Assessment provided an analysis of whether specific climate change adaptation measures could be potentially viable. This analysis was conducted by assessing the economic impact of congestion (related to the loss of travel time) due to climate related events and the probability of these events. Furthermore, the benefits of adaptation measures were scored using a multi criteria approach: relevance/effectiveness, flexibility, robustness, maintenance and lifecycle costs and secondary benefits. Then, a cost effectiveness analysis and cost benefit analysis of the adaptation measures were completed.

Figure II.1.11 Vulnerability map of potential vulnerable locations for subsidence of road embankments



Finally, Dynamic Adaptation Policy Pathways (Haasnoot et al., 2013) were used to visualize potential measures of time. In a Dynamic Adaptation Policy Pathway, the effectiveness of a measure is plotted against the normative climate parameter, for example, a precipitation intensity. Different time scales corresponding to different climate scenarios may then be linked to this. By means of the overview thus created, different paths become visible that may be taken in order to be ready for future climate change. An adaptation path or strategy is a combination of one or more measures in time. For the InnvoA58 highway an adaptation pathway were delivered for each of the associated key risks (Figure II.1.12, and for more detail Leijstra et al.2019).

Figure II.1.12 An example of adaptation paths (associated with pluvial flooding)



V. Conclusions and outlooks

Literature on resilience and adaptive planning approaches for infrastructure mainly focus on the need of regionally tailored approaches to foster resilience and climate adaptive environments. However, literature on the actual design of resilience and adaptive planning for infrastructure is scarce.

The ROADAPT method provides a clear structure of identifying risks, opportunities, consequences and possible adaptation measures. In addition, the Dynamic Adaptation Policy Pathways provide insight into which adaptation measures can be integrated into an adaptation strategy. However, the methodology is highly dependent on the input of involved experts. Local knowledge is essential, since local stakeholders often have location specific knowledge that can lead to realistic and better solutions. Examining the surrounding environment, rather than merely focusing on the road, is important to increase climate resilience, since knowledge about local water systems, ecology and urban planning is crucial to match possible adaptation measures for the road to adaptation measures that are beneficial for the environment and vice versa. For the A58 project 'matching solutions' with other goals provided opportunities to achieve multiple goals (Leijstra et al., 2019).

However, during the process it proved difficult to integrate information from stakeholders on the surrounding area with information on the road. The ROADAPT methodology was primarily designed for roads, being line- and object oriented, rather than area-oriented. The methods are also technical in nature and focus primarily on the functionality of the road. This made it more difficult to make an integral assessment of the climate resilience of the road as an integral part of the surrounding environment. Also, attention should be paid to stakeholders varying perceptions of urgency when applying an area-oriented approach. Climate resilience for road infrastructure is a new issue for Rijkswaterstaat, whereas several stakeholders in the InnovA58 project area have already experienced the impacts of extreme weather events on the environment. However, within the Rijkswaterstaat organization, the lack of urgency and knowledge makes it difficult to translate resilience and adaptive planning into practice.

The Dynamic Adaptation Policy Pathways may help to address these issues, since the pathway plots potential adaptation measures against normative climate parameters. This may help authorities and engineers to assess which adaptation measures are needed and when they are needed to achieve climate resilient roads and environments, whilst still being able to make adjustments in the future.

The ROADAPT methodology aims to increase the robustness of the A58, through the vulnerability assessment and the development of potential physical measures. The adaptation pathways provide a means to design a road with measures that increase resilience, whilst still being able to adjust to future circumstances. This fosters the adaptability and transformability of the road and the surrounding environment. 'Matching solutions' with other goals for the A58 provided a further chance to increase the adaptability of the infrastructure.

Case study 7 (Romania)
Early Warning Intelligent System for Road Transportation Risks

I. Introduction

This case study presents a project implemented in Romania to put in place an early warning intelligent system for road transportation risks. The project was funded by the European Commission, Connecting Europe Facility Program (CEF), the Innovation and Networks Executive Agency (INEA). This case study was prepared by Robert Dobre (PhD), Project Manager of the Ministry of Transport of Romania.

II. The National Plan for Adaptation to Climate Change – The Romanian General Transport Master Plan

In 2016, Romania put in place a transport development strategy: the General Transport Master Plan (GTMP) of Romania. This strategy foresees major investments in the transport sector by 2030. The planning and ranking of investments included in the GTMP also refers to climate change components, both in areas of climate change mitigation and adaptation.

III. Issue and solutions

Romania's TEN-T network is seriously affected by natural hazards such as landslides, torrential erosion, rock falls, avalanches, floods and heavy snow. These natural hazards lead to numerous road accidents which cause important casualties and material losses every year (Figure II.1.13). With the changing climate, these hazards are expected to increase.

In order to minimize the effects of these hazards, a project was developed to:

(i) identify and describe hazards and the risk of their occurrence which can affect road transportation;

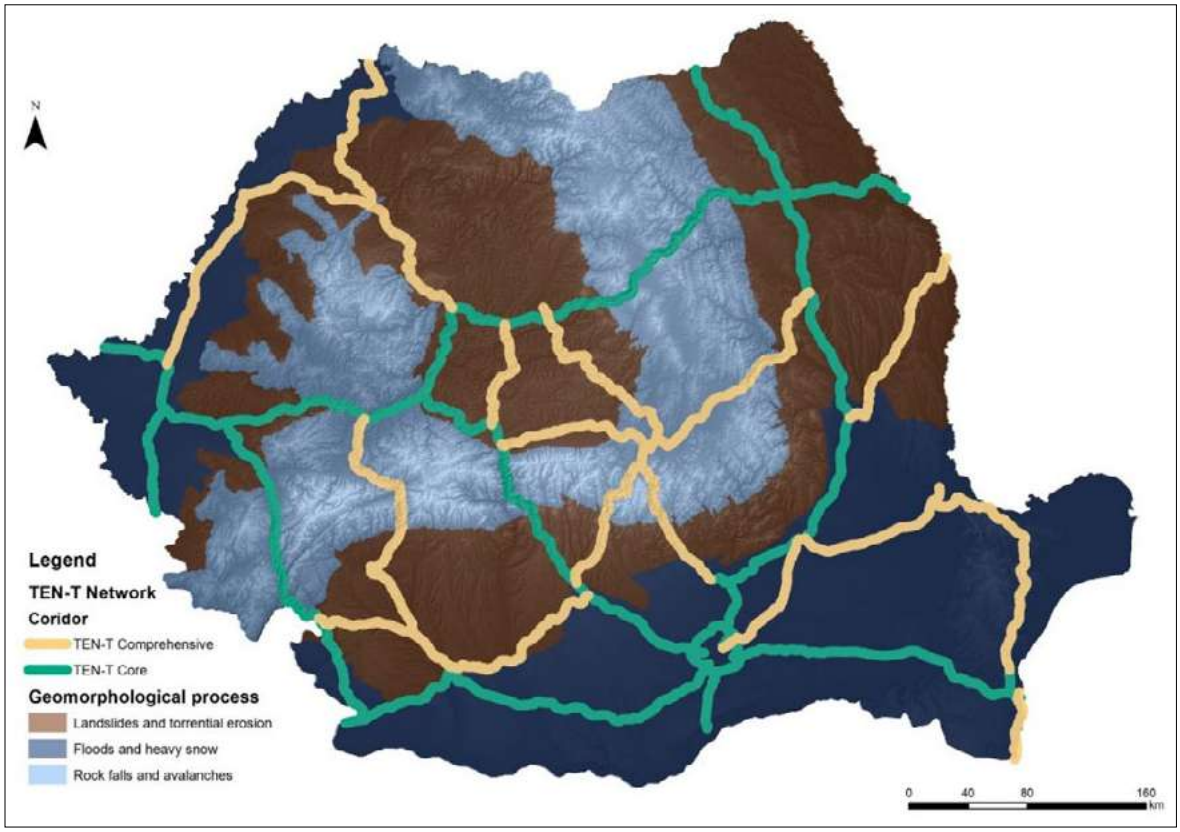
(ii) provide real-time safety-related traffic information services to road users via well-functioning web and mobile applications;

(iii) inform all groups of stakeholders about the availability of the services.

IV. Scope of study and description of methodology

The total length of roads classified as TEN-T corridors in Romania is approximately 2500 km. Because data was collected and recorded for both directions, the total length of roads under assessment was 5000 km.

Figure II.1.13 Geomorphological and meteorological risks in Romania



To identify all the hazards on the assessed roads, the data sources with information on that hazards were determined.

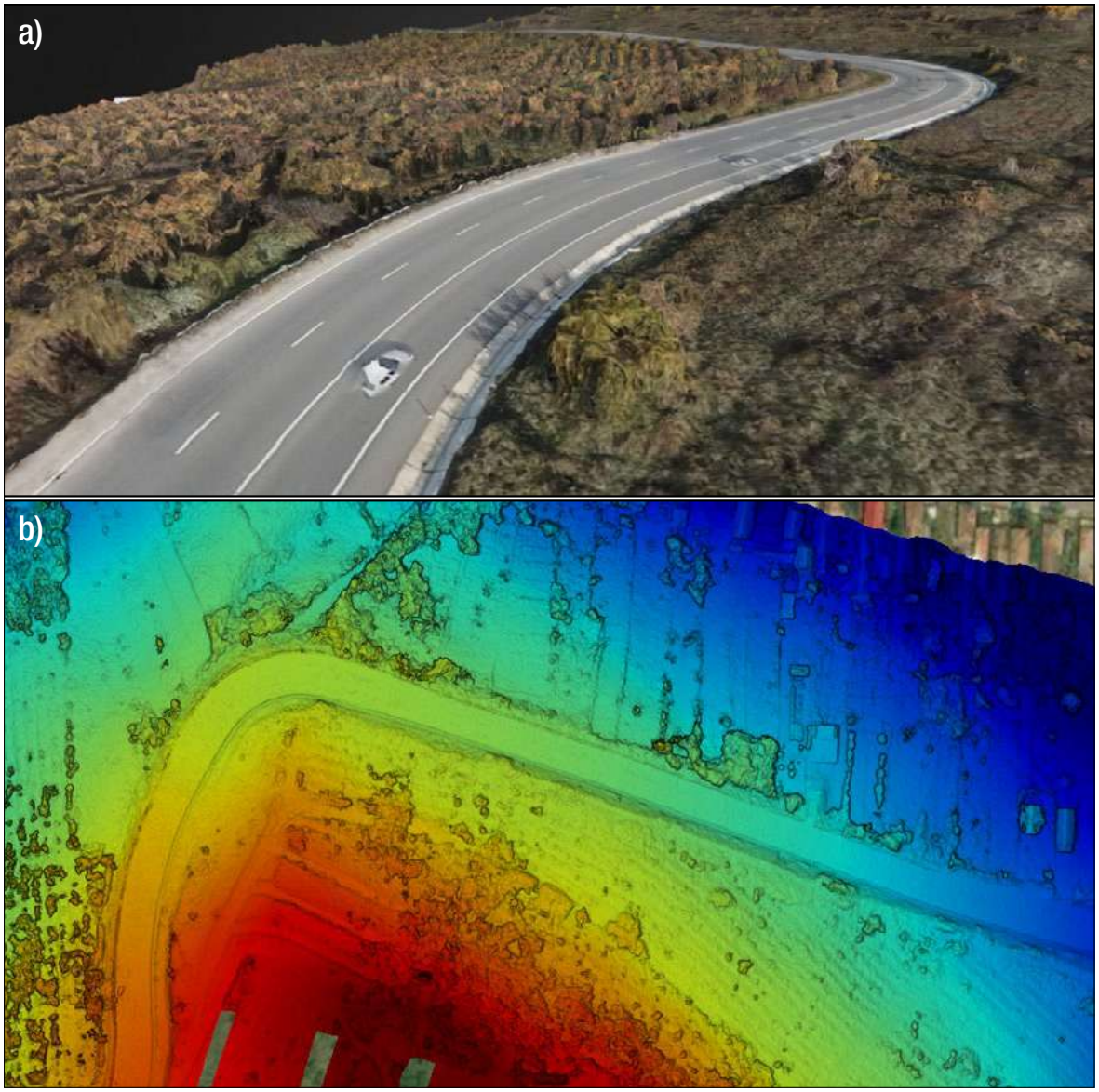
A total of 48 categories of hazardous events or conditions were identified. Among them were meteorological risks, hydrological risks, geomorphological risks (generated by the morphology / road characteristics or generated by the state of the road or traffic characteristics). For 22 of the categories of events or conditions, hazard information was collected from relevant institutions in accordance with agreements concluded within the project. For the remaining categories, the project team collected field data (II.1.14.a).

Two types of road transportation data were taken into account: static and dynamic road data.

Static data was collected from the field and integrated into an innovative geo-database that can be accessed via an interactive map. Over 5000 km of roads and motorways were mapped in detail in the field and were transposed in GIS environment/geo-database. Over 100 hours of video were recorded in the field campaign. In this activity, over 5500 road features and environment characteristics were mapped and transposed in GIS and 10 road critical areas were identified and analysed.

For the video, a drone was used to obtain high-resolution images with a high-level of detail and current information. The creation of numerical altimetric models and the elaboration of detailed and current situation plans (including aerophotography) was to be used to validate the information identified on the field (II.1.14.b).

Figure II.1.14 a) 3D image (Digital Elevation Model) of the road risk sector using drone imagines (done by project team), b) current situation plans (including aerophotography)



Dynamic data was sourced from three institutions: National Company for Road Infrastructure Administration (CNAIR), National Meteorological Administration (ANM), General Inspectorate for Emergency Situations (IGSU), for which relevant collaboration agreements were concluded. These institutions in accordance with the agreements will continue to provide the data: CNAIR data regarding closed roads, sections of road under construction and traffic congestion, ANM data on weather conditions on the TEN-T Core road network (in particular weather code warnings, for example, Nowcasting); and IGSU, data regarding real time major accidents and other associated risks (fire, floods, geological processes).

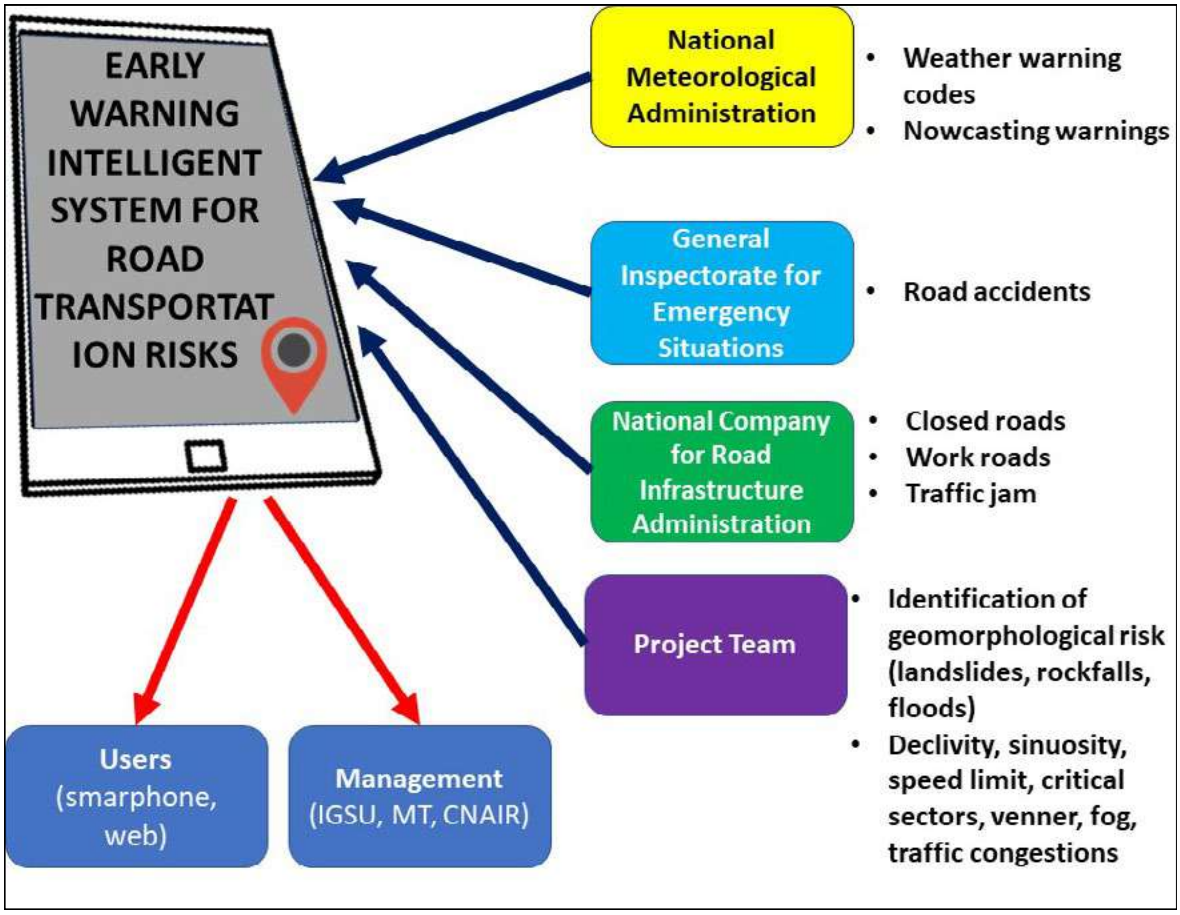
Both static and dynamic data were integrated into geo-database, which is compatible with other TEN-T Core network databases. The geo-database is to be also made compatible with similar applications in order to have a positive impact on reducing the number of accidents and decreasing pollution on the TEN-T Core network in Romania. The geo-databases contain raster information (images), vectors, and a large quantity of films about roads: sinuosity, declivity, slippery roads, speed, traffic congestion, wind side, veneer, fog, rock fall, landslide, floods, critical areas.

V. Application architecture

The web and mobile applications were designed to consist of two modules (Figure II.I.15 a and b):

- *module one for the general public*
- *module two for the institutions involved in TEN-T operation and management* (National Meteorological Administration, General Inspectorate for Emergency Situations, National Company for Road Infrastructure Administration, Ministry of Transport).

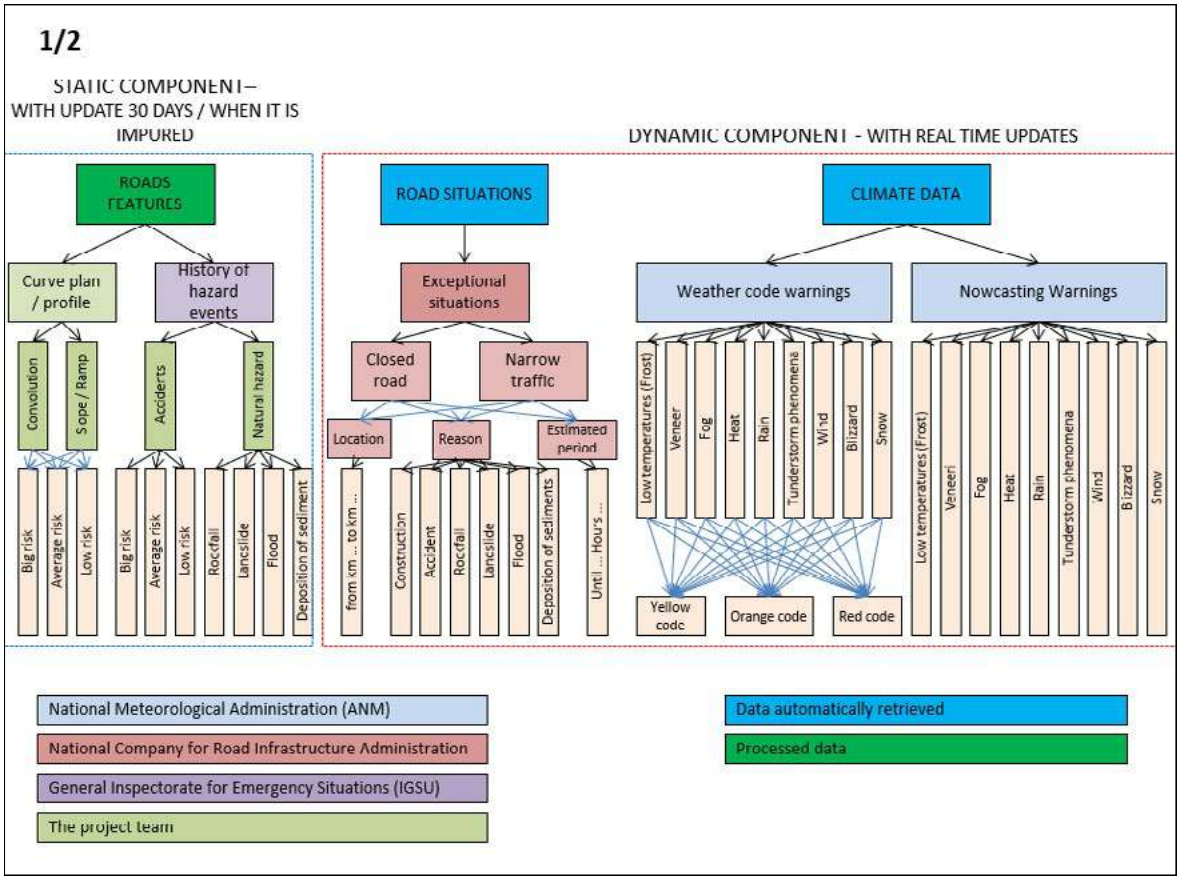
Figure II.1.15.a The design of the application

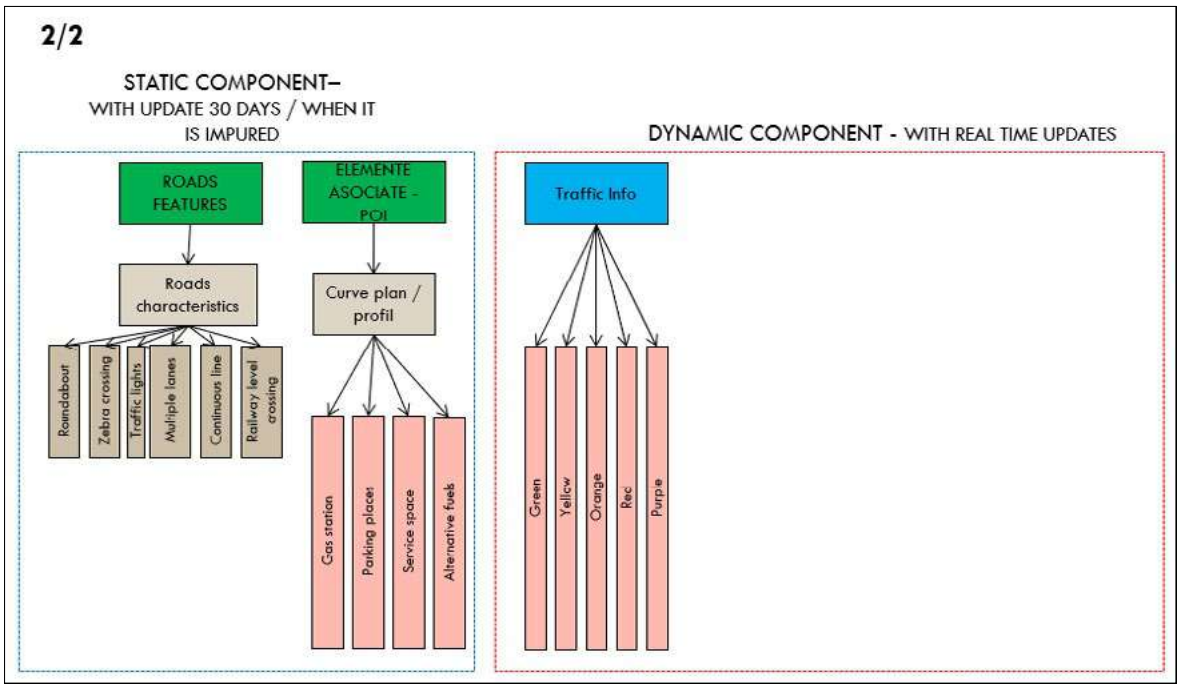


Module one provides both dynamic (which will be automatically retrieved and updated in real time) and static (referring to the infrastructure features - which will update every 30 days or when required) data.

Module two allows for better collaboration and intervention of public authorities by offering a management tool. It is also offers public authorities information regarding a road hazards occurrence in order to plan the future actions and interventions.

Figure II.1.15.b Architecture design

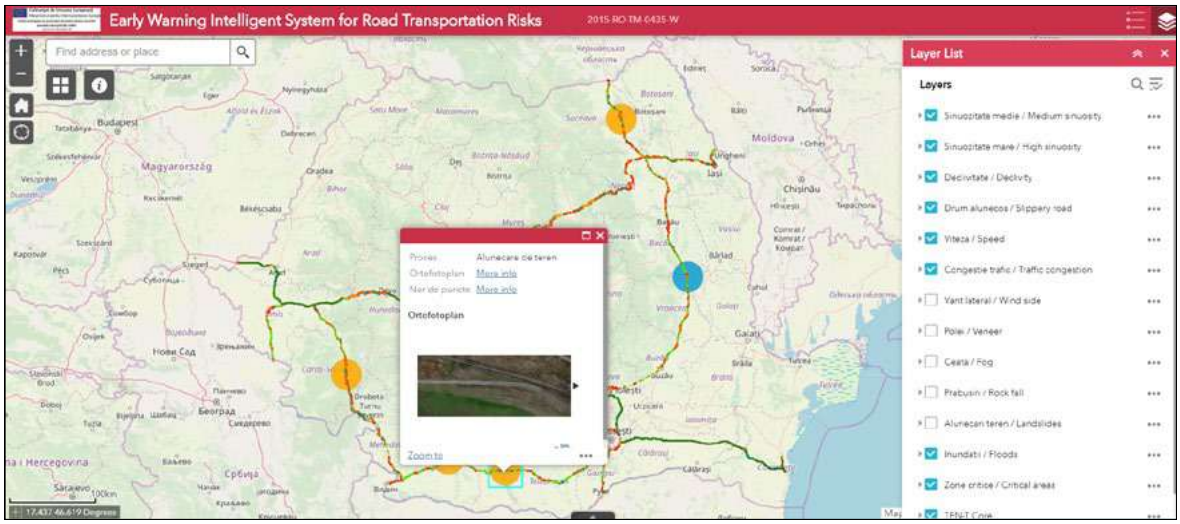




VI. Conclusions and way forward

At the time of the preparation of this case study the geo-database was put in place and was made accessible through a GIS interactive map, which ensures availability of accurate and current data of the TEN-T Core network in Romania (II.1.16).

Figure II.1.16 Interactive map (goo.gl/QDfz5j)



The project was key in creating the first Romanian GIS geo-database containing information on transport hazards.

Case study 8
(United Nations Conference on Trade and Development)
Climate change impacts on coastal transport infrastructure in the Caribbean: Enhancing the adaptive capacity of Small Island Developing States (SIDS)

I. Introduction

This case study discusses an UNCTAD technical assistance project on "Climate change impacts on coastal transport infrastructure in the Caribbean: Enhancing the adaptive capacity of Small Island Developing States (SIDS)" (UNDA 14150). This case study was prepared by: Regina Asariotis, UNCTAD.

II. Background and project scope

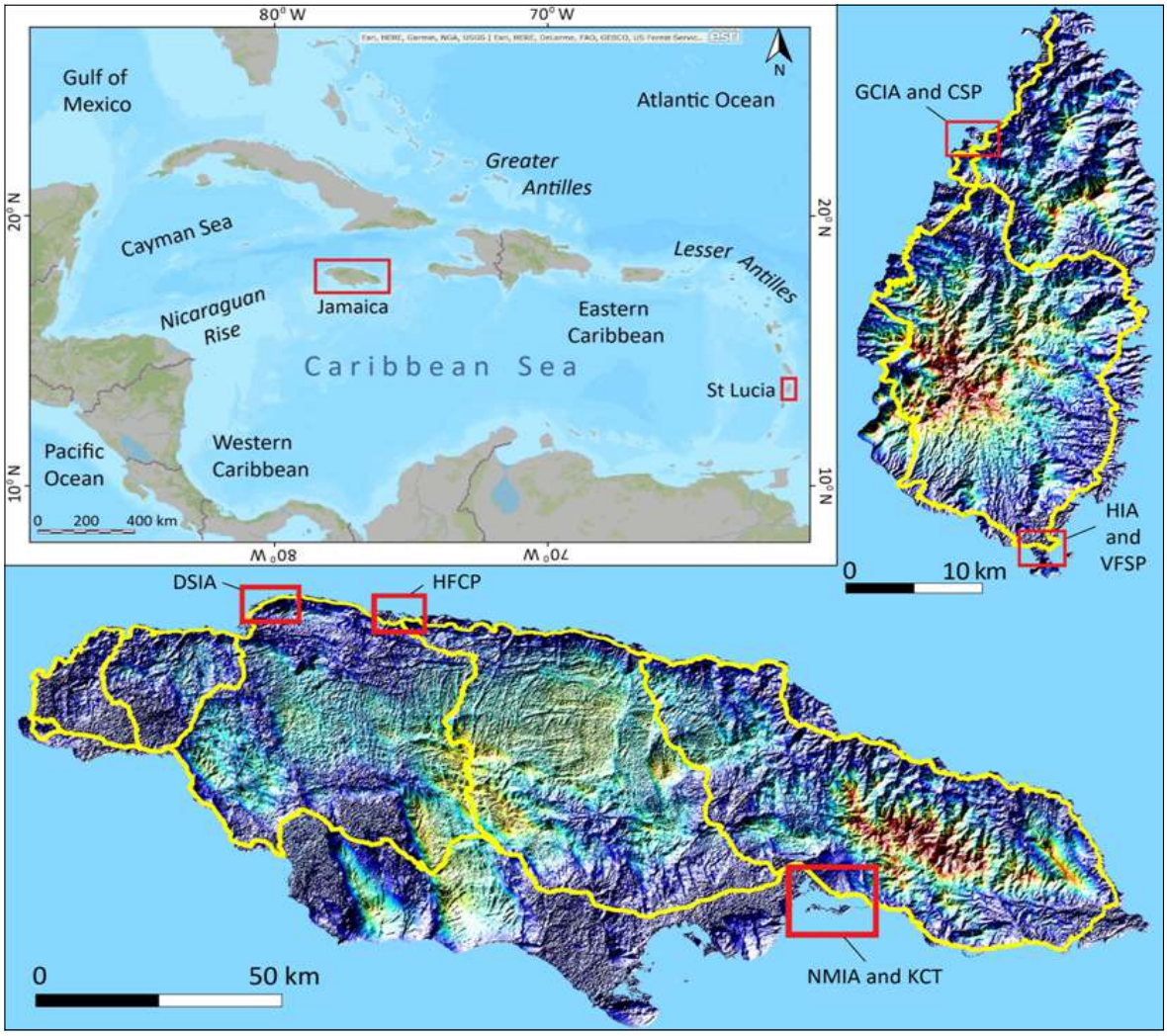
Coastal transport infrastructure vulnerability varies across regions, and depends on many factors, including the type of risks faced, the degree of exposure and the level of adaptive capacity. Small Island Developing States (SIDS) are among the most vulnerable, as they are both prone to being affected by climate change-related (and other) natural disasters and have low adaptive capacity. The significance of weather and climate-related threats has been underscored by the recent impacts of Hurricanes Irma and Maria that wreaked havoc in the Caribbean, including in some of the overseas territories of UNECE member States, during the 2017 hurricane season. SIDS share a number of socioeconomic and environmental vulnerabilities that challenge their growth and development aspirations. Their climate, geographical, and topographical features as well as their critical reliance on coastal transport infrastructure, in particular seaports and airports, exacerbate these vulnerabilities, including their susceptibility to climate change factors, such as sea-level rise and extreme weather events. Furthermore, in many SIDS, including the overseas territories of UNECE member States, international tourism, which is highly dependent on secure and reliable international transport connections, is a major economic activity and a key purveyor of revenues, jobs and foreign exchange earnings. Enhanced climate resilience, climate change adaptation and disaster risk reduction for key coastal transport infrastructure is therefore critical for the overall sustainable development prospects of these vulnerable economies.

Against the above background, and drawing on UNCTAD's earlier related work since 2008, including a number of expert meetings as well as research and analysis,[42] a technical assistance project on "Climate change impacts on coastal transport infrastructure in the Caribbean: enhancing the adaptive capacity of SIDS" was implemented by UNCTAD over the period 2015–2017, in collaboration with a range of partners, including UNECLAC, UNDP, UNEP, the Caribbean Community Climate Change Centre, OECS Commission, as well as the ECJRC and international and regional academic experts. Case studies focusing on ports and airports in two vulnerable SIDS in the Caribbean (Jamaica and

42 See unctad.org/en/Pages/DTL/TTL/Legal/Climate-Change-and-Maritime-Transport.aspx

Saint Lucia) were carried out to (a) enhance the knowledge and understanding at the national level and (b) to develop a transferable methodology for assessing climate-related impacts and adaptation options in SIDS. The case studies and methodology were reviewed and refined at a technical expert meeting and were presented and discussed at national and regional capacity-building workshops, bringing together seaports and airports authorities as well as a range of other stakeholders, experts, development partners, and organizations from 21 countries and territories in the Caribbean; full documentation, as well as guidance and training materials and additional resources are available on the project web-platform SIDSport-ClimateAdapt.unctad.org.

Figure II.1.17 Location of the transportation assets of Jamaica and St Lucia considered as part of the case studies. Key: Jamaica - DSIA, Sangster International Airport; HFCP, Historic Falmouth Cruise Port; NMIA, Norman Manley International Airport; KCT, Kingston Freeport and Container Terminal; Saint Lucia - HIA, Hewanorra International Airport; VFSP, Vieux Fort Seaport; GCIA, George Charles International Airport; and CSP, Port Castries. Digital Elevation Model data from SRTM DTM



Key project outcomes include assessment of potential operational disruptions and marine inundation risk to 8 coastal international airports and seaports of Jamaica and Saint Lucia (Figure II.1.17), under different climatic scenarios. Relevant substantive findings and technical details of the methodology

developed under the project were presented and discussed in a peer-reviewed scientific paper[43] and have informed the IPCC's recent assessment of "*Impacts of 1.5 ºC global warming on natural and human systems*",[44] highlighting substantial increases in risk to SIDS's critical coastal transportation infrastructure from climate changed-induced marine inundation as early as in the 2030s, when the AOSIS advocated temperature increase cap of 1.5 °C (SWL) will be reached, unless further climate change adaptation is undertaken.

III. Results of the risk and vulnerability assessment of critical coastal transport infrastructure[45]

Projections showed that the critical transportation assets of both SIDS would face rapidly increasing marine inundation risks compared with the current situation, with those of Saint Lucia being at higher risk than those of Jamaica. The results also suggest that, even under the 1.5 °C temperature increase cap, some of the critical assets of the islands will face increased direct marine inundation under extreme events, which will deteriorate very significantly and involve other assets later in the century. The flood maps (Figures II.1.18 and II.1.19) illustrate the vulnerability to marine flooding of key international transport assets in both countries.

Results of the study also suggest that transport operations will be affected in Jamaica and St. Lucia due to future Climate Variability and Change (CV & C). The projected increases in the frequency of hot days will likely affect the ability of staff to work safely outdoors, require reductions in aircraft payloads and increase energy costs. Inter alia, the following operational disruptions are projected:

- **Outside working conditions:** By the early 2030s, staff working outdoors at the Jamaican and Saint Lucian international transportation assets could be at "high" risk for 5 and 2 days per year, respectively. By 2081–2100, such days could increase to 30 and 55 days per year, respectively.
- **Aircraft take-off:** By 2030, Boeing 737-800 aircraft that serve all studied airports, will have to decrease their take-off load for 65 days per year at Sangster International Airport-SIA and 24 days per year at Norman Manley International Airport- NMIA (both in Jamaica), whereas by the 2070s such days could increase at least twofold for SIA and fourfold for NMIA, assuming no targeted aircraft design changes.
- **Energy needs:** a 1.5 °C temperature rise will increase energy requirements by 4 per cent for 214 days per year for Jamaican seaports, whereas a 3.7 °C rise (2081–2100) will increase energy requirements by 15 per cent for 215 days per year. Saint Lucia seaports are projected to experience similar trends.

43 Monioudi, I.N., Asariotis, R., Becker, A. et al. Reg Environ Change (2018) 18:2211–2225. Climate change impacts on critical international transportation assets of Caribbean Small Island Developing States (SIDS): The case of Jamaica and Saint Lucia. doi.org/10.1007/s10113-018-1360-4; rdcu.be/Q1OY.

44 IPCC, 2018. Global Warming of 1.5°C, an IPCC special report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. Chapter 3: Impacts of 1.5ºC global warming on natural and human systems. October 2018, available at: www.ipcc.ch/site/assets/uploads/sites/2/2019/02/SR15_Chapter3_Low_Res.pdf

45 For further details, see the case studies and methodology available at SIDSport-ClimateAdapt.unctad.org, as well as Monioudi et.al (2018).

Figure II.1.18 Coastal flooding – Jamaica. Inundation maps for: (a, e, i) DSIA, (b, f, j) KCT, (c, g, k) NMIA, and (d, h, l) HFCP, under a 1-100 year extreme sea level event - ESL100 (for 1.5°C temperature increase, 2030), 1-50 year extreme sea level event - ESL50 (2050, RCP4.5) and ESL100 (2100, RCP8.5)

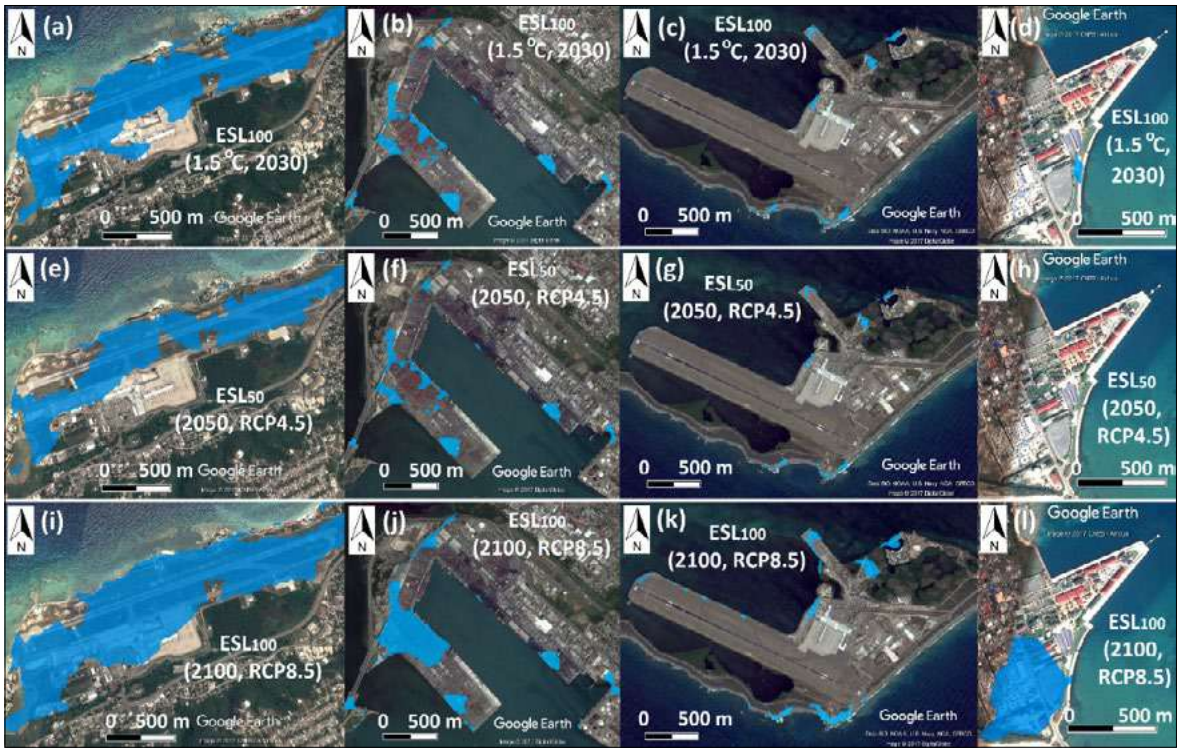
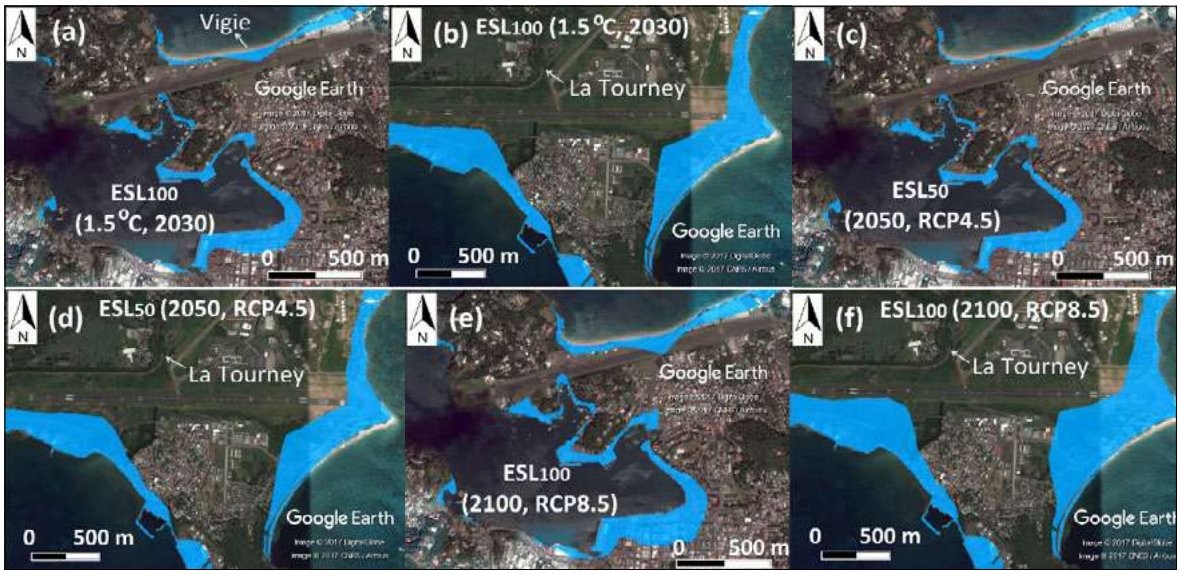


Figure II.1.19 Coastal flooding – Saint Lucia, Inundation maps for (a, c, e) GCIA and CSP and (b, d, f) HIA and VFSP under ESL100 (1.5 °C, 2030), ESL50 (2050, RCP4.5) and ESL100 (2100, RCP8.5)



Finally, the dominant 3S ('Sea-Sand-Sun') tourism model of Saint Lucia (and other Caribbean island destinations) is projected to be challenged by increasing beach erosion, which, by 2040, may overwhelm between 11 and 73 per cent of its beaches,[46] with negative ramifications for tourism, the main driver of many Caribbean SIDS' economy, accounting for between 11 per cent and 79 per cent of their GDP.[47] Due to the strong nexus between tourism and the facilitating transport infrastructure, this will also have negative impacts on transportation demand.

IV. Methodology: A climate risk and vulnerability assessment framework for Caribbean coastal transport infrastructure

A methodology was developed under the project to assist transport infrastructure managers and other relevant entities in SIDS in assessing climate-related impacts and adaptation options in relation to coastal transport infrastructure ('*Climate Risk and Vulnerability Assessment Framework for Caribbean Costal Transport Infrastructure*'[48]). The methodology provides a structured framework for the assessment of climate-related impacts with a view to identifying priorities for adaptation and effective adaptation planning for critical coastal transport infrastructure (Figure II.1.20); it takes a practical approach that uses available data to inform decision-making at a facility, local, and national level. Technical elements include an 'operational thresholds' method, to determine the climatic conditions under which facility operations might be impeded, as well as marine inundation modelling (see Section II, above). The methodology is transferable, subject to location specific modification, for use in other SIDS within the Caribbean and beyond.

V. Key findings and main lessons learnt

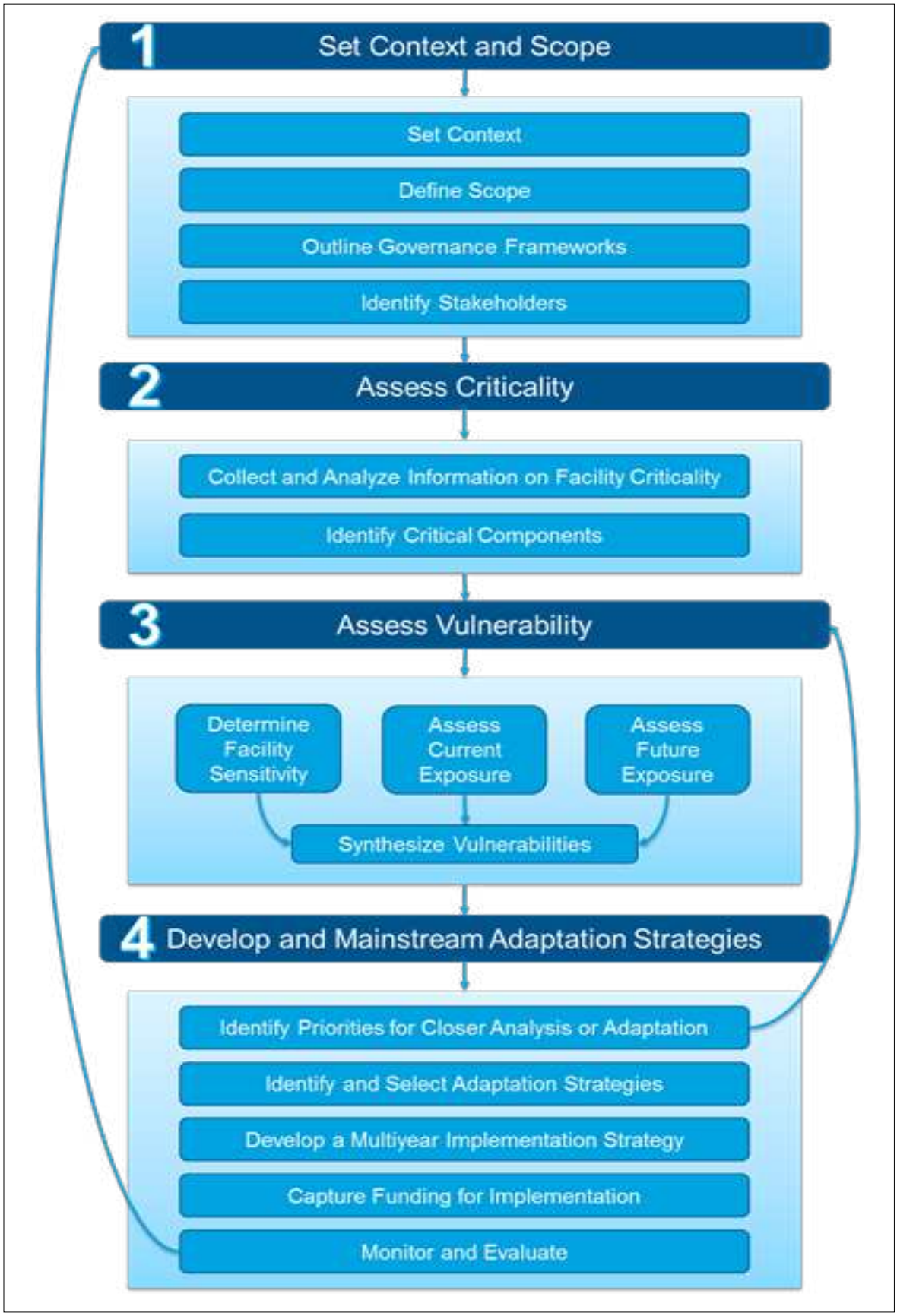
As already noted, the study results show high and increasing potential vulnerabilities to climatic changes of the critical international transportation assets (airports and seaports) of Jamaica and Saint Lucia involving both operational disruptions and coastal inundation from extreme events. Flooding is projected for the airport runways of some of the examined airports and for most seaports, from as early as the 2030s, and the exposure of these assets to coastal flooding is projected to deteriorate as the century progresses. In the absence of timely planning and implementation of requisite adaptation measures, the projected impacts on critical transport infrastructure may have serious implications for the connectivity of SIDS to the international community and global markets, as well as broad economic and trade-related repercussions, which may severely compromise the sustainable development prospects of these vulnerable nations. Against this background, better and more targeted data, further research, including detailed technical studies, as well as collaborative concerted action at all levels are urgently required.

46 UNCTAD, 2017. Climate Change Impacts on Coastal Transportation Infrastructure in the Caribbean: Enhancing the Adaptive Capacity of Small Island Developing States (SIDS). SAINT LUCIA: A Case study. UNDA 14150, available at: SIDSport-ClimateAdapt.unctad.org.

47 UNECLAC, 2011. An assessment of the economic impact of climate change on the transportation sector in Barbados.

48 UNCTAD, 2017. Climate Change Impacts on Coastal Transportation Infrastructure in the Caribbean: Enhancing the Adaptive Capacity of Small Island Developing States (SIDS). *Climate Risk and Vulnerability Assessment Framework for Caribbean Costal Transport Infrastructure*. UNDA 14150, available at: SIDSport-ClimateAdapt.unctad.org.

Figure II.1.20 Schematic overview of 'Climate Risk and Vulnerability Assessment Framework for Caribbean Costal Transport Infrastructure'



Some of the other major lessons learnt as part of the project fall into the following three categories:

(a) Data:
- Data collection efforts take time; many SIDS lack baseline data; better Digital Elevation Models (DEMs) are required
- Site visits and interviews with local stakeholders are essential ('the map is not the terrain')
- Steps to validate stakeholder input from facility managers can ensure high-quality inputs
- Identifying facility specific sensitivity thresholds can help streamline and improve the vulnerability assessment process

(b) Awareness and coordination:
- Communication and collaboration among public and private sector stakeholders is key
- Ports/airports already taking action to increase resilience should share their success stories
- There is a need for regional cooperation, and to build a knowledge base and community of practice around vulnerabilities

(c) Implementation:
- Organizational "best practices" can increase resilience, and vice-versa.
- "Mainstream" adaptation activities into existing planning and decision-making processes
- Climate change adaptation often comes down to a policy decision related to risk tolerance
- Financing for capital projects remains a major hurdle
- Ecosystem enhancements can play a significant role in reducing natural hazard risks, including coastal hazards and inland flooding.

Photo: Fotosr52 / shutterstock.com

Chapter 2

This chapter provide case studies on diverse socioeconomic impacts and implications from climate change on various transport infrastructure studied in countries

Case study 1 (Canada)
All-Season Roads in Northern Canada and Implications of Climate Change

I. Introduction

This case study discusses the implications of climate change on all season roads in Northern Canada. This case study was prepared by: Lukas Arenson, BGC Engineering Inc.

II. Background

Compared to global warming trends, the Canadian Arctic is experiencing an accelerated trend in air temperature increase. For example, the global warming trend was ~0.8°C between 1948 to 2014, but ~1.6°C in Canada. Moreover, the Arctic Tundra region of Canada warmed by 2°C, and the Northwest Territories' Mackenzie District by 2.6°C during the same period.[49] In addition, extended winter heat waves, a high number of blizzards and record summer precipitation have had a negative impact on Canada's northern transportation infrastructure.

Canada's northern road network is critical to the function of communities and industry. This network includes roads that are only operational in the winter (for instance built over ice or compacted snow) as well as all-season roads built through permafrost regions. In the territories of Yukon (YT) and the Northwest Territories (NWT) the approximately 4700-km all-season road network includes the Alaska, North Klondike, Dempster, Mackenzie, Inuvik to Tuktoyaktuk highways, and Highway 3 to Yellowknife. While there are no highways linking Nunavut or Nunavik (Quebec) communities with each other or with southern road networks, vital all-season roads exist within northern communities themselves (e.g. the ~3 km long Salluit airport access road in Nunavik). Very few of thesE Roads are paved -- most are gravel or surfaced with bituminous surface treatment. Soil conditions underlying these roadways range from bedrock to massive ice and ice wedge terrain.

Most of thesE Roads in the YT or NWT serve as the only all-season land route to isolated communities, including to larger centres in Inuvik, Whitehorse, or Yellowknife, and enable transport of goods and people between the Canadian south and the community hubs in Northern Canada. From these hubs, waterways, airports or winter roads are used to continue moving goods and people to and from outlying communities.

These roadways are typically open and accessible year-round. However, some cross rivers, requiring the use of ferries in the summer and ice bridges in the winter. During freeze-up and break-up, when neither of these means of crossing can be used, some northern communities connected via these infrastructures are isolated and reliant on air transport. Uncertainties with regard to the length of the freeze-up and break-up seasons, as well as the feasibility of building ice bridges during the winter, are expected to increase in response to climate change. Hence additional bridges, such as the CAD

49 Pendakur, K. (2017). Northern Territories. In K. Palko and D.S. Lemmen (Eds.), Climate risks and adaptation practices for the Canadian Transportation Sector 2016 (pp. 27–64). Ottawa, ON: Government of Canada.

$202 million, Deh Cho Bridge along Highway 3 in the NWT that opened November 2012, will have to be constructed in response. Industry depends on road links for the cost-effective transport of resources and equipment to and/or from mines or other industrial sites, often using winter roads until reaching the main network. During the winter, a 'winter load tolerance' allowance gives the trucking industry the opportunity to increase load capacity on all-season roads. However, shorter and warmer winters are expected to reduce the duration over which such higher loads are allowed.

Permafrost roadway design practice typically aims to preserve the permafrost (permanently frozen soil) and limit the seasonal thawing to within the embankment fill or depth of the original (prior to construction) active layer (the layer on top of the permafrost that thaws in the summer and refreezes in the winter)[50]. However, warming air temperatures are deepening the active layer beyond its original depth, thereby degrading the permafrost and affecting infrastructure stability within and surrounding the road right-of-way. This can lead to embankment settlement or differential settlement within the embankment and ultimately result in damage to the road surface, such as cracks or surface treatment disintegration, or more severe hazards to road safety, such as bumps or sinkholes (Figure II.2.1).

Figure II.2.1 Differential settlement associated with permafrost thaw along an abandoned section of Northwest Territory Highway 4, east of Yellowknife

Source: Transport Canada, page 41 of 'Climate Risks & Adaptation Practices for the Canadian Transportation Sector 2016' report

Other thaw-induced failures (active layer detachment slides, retrogressive thaw slumps, sinkholes, etc.) related to the destabilizing effect of resulting changes to the groundwater and thermal regime may also occur in the right-of-way or in the surrounding terrain. Changing trends in precipitation and warmer fall seasons have anecdotally increased the occurrences of washouts or icings (known as Aufeis), where groundwater movement is impeded and flows to the surface. This can cause formation of ice adjacent to, or over roadways, and block culverts or bridges. Aufeis can limit or completely prevent the free flow of water through the embankment or under the bridge and, in combination with increasing freshet in spring, is of particular concern as it can cause severe damage to the highway infrastructure and isolate communities for an extended period of time.

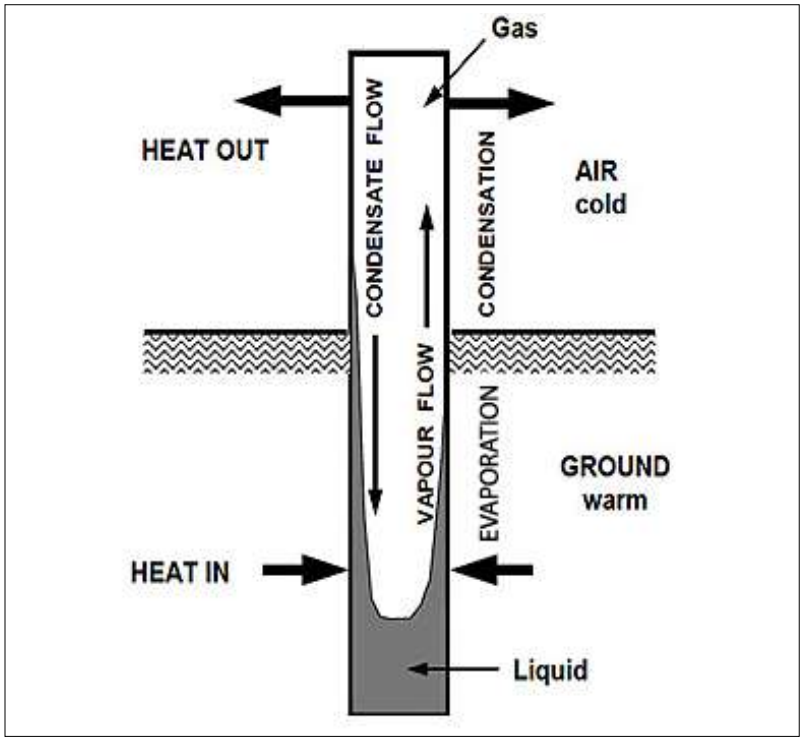
50 McGregor, R., Hayley, D., Wilkins, G., et al. (2010). Guidelines for Development and Management of Transportation Infrastructure in Permafrost Regions. Ottawa, ON: Transportation Association of Canada.

III. Responses to the Impacts of Climate Change

In general, there are two responses to the effects of climate change on all-season roadways, either: (1) adaptation methods are used to facilitate additional heat extraction during the winter months, or limit heat input; or (2) increased maintenance or structural elements are used to ensure the roadway's level of service is not impacted. In other words, the first response improves the thermal condition and protects the permafrost, whereas the second minimizes the negative impacts of deteriorating thermal conditions. Typical adaptation techniques in line with response (1) include:[51]

- Natural Convection[52]
  - Air convection embankments– the large air voids initiate convective heat transfer.
  - Heat drains – a geosynthetic placed in the embankment allows air flow through the soil via a chimney system.
  - Air ducts – a culvert system is placed in the embankment, similar to the heat drain.
- Thermosyphons – This is a passive method to extract heat using a working fluid within a pressurized system that extracts heat via the transfer of the latent heat of evaporation of the working fluid from the permafrost via an air-exposed condenser section (Figure II.2.2). If required, active cooling can be added.

Figure II.2.2 Illustration of heat exchange in a thermosyphon



Source: Transport Canada, page 48 of 'Climate Risks & Adaptation Practices for the Canadian Transportation Sector 2016' report

51 Doré, G., Niu, F. and Brooks, H. (2016). Adaptation methods for transportation infrastructure built on degrading permafrost. Permafrost and Periglacial Processes, 27(4), 352-364. DOI: 10.1002/ppp.1919

52 The movement of a fluid due to density changes from temperature fluctuations. In this case, air movement due to higher density cold air during the winter months.

- High albedo surfacing – These coatings (bituminous surfacing or using light coloured aggregate in bituminous surface treatments) reflect solar radiation during the summer, reducing the heat transferred to the permafrost.
- Gentle embankment side slopes – Snow is insulative and its presence adjacent to an embankment can degrade the underlying permafrost. Using gentle embankment side slopes that approximate the natural snow drift angle prevents the accumulation of snow and the degradation of permafrost at the toe of the embankment.

Some measures aligned with response (2) include:

- Flexible surface – The use of a gravel surface instead of pavement or other types of surface treatment allows for economic repairs if required.
- Geosynthetics[53] – The reinforcement of high embankment fills with geosynthetics can help increase the stability of the fill end reduce the materiel requirement by allowing the use of steeper side slopes.
- Drainage – Controlling water through and adjacent to the embankment fill limits the negative impact on the structure. Sufficient flow capacity including projected changes due to climate change helps in preventing damages to the highway in the future.

The above adaptation methods are a mix of proven methodologies for which design guides are available and research methodologies that have been proven on a smaller scale. Some of the above may require reconstruction of the roadway for them to be implemented at a cost ranging from approximately 5 to 20 times more than that of traditional construction methods.

Given the increased costs of adaptation methods, some roadways are managed such that their level of service is maintained via grading or other construction/maintenance activities (see north Alaska Highway case study)[54].

Government partners and researchers are working towards or have produced documents to assist engineering practitioners in the construction and maintenance of all-season roadways, including in collaboration with the Transportation Association of Canada[55]. These documents present design guidelines for roadways on permafrost and research in support of transportation infrastructure on permafrost, including research test sites and case studies.

53 De Guzman, E.M. et al. (2016). Geotextile-Reinforced Fill Slope along a Highway to Canada's Arctic Coast. In GeoAmericas. 3rd Pan-American Conference on Geosynthetics. Miami Beach, FL, USA.

54 Dominie, S. (2019) Cost of constructing and maintaining highways on permafrost. Presentation at Northern Transportation Adaptation Initiative (NTAI): Climate Change Impacts and Adaptations for Canadian Highways Built on Permafrost: Feb 19-21, 2019, Whitehorse, Yukon Territory.

55 Transport Association of Canada (TAC). (2010). Guidelines for Development and Management of Transportation Infrastructure in Permafrost Regions. ISBN: 978-1-55187-295-1.

Case study: Implications for the North Alaska Highway, Yukon Territory

The Alaska Highway is a 2,200 km long roadway that was originally constructed during World War II to provide an overland link between Alaska and the United States mainland. The highway remains the only all-season over-land transportation route to Alaska. The northernmost Canadian section from Destruction Bay, YT to the Alaska/Canada Border (~200 km) is constructed in the sporadic and extensive discontinuous permafrost region. Research has identified ~46% and ~33% of this section as having high and moderate vulnerability to climate change (based on thaw settlement). Thus, warming air temperatures throughout the year have been identified as a concern for the resilience and longevity of the road.

Climate trends: Climate projections for the north Alaska Highway include temperature increases of 2.5°C to 4°C by 2050. Increases in precipitation of 10 to 30 mm per year are projected by 2050 depending on the global climate model. Permafrost temperatures are already warm (-1.5°C to -0.3°C) in some sections, and these increases in temperature and precipitation are likely to induce severe permafrost degradation (partial or complete) along the roadway.

Adaptation methodologies and costs: This section is a research corridor with work completed and in progress. At the Beaver Creek Test Section, Laval University and others are testing different methods to increase heat extraction or limit heat input and carrying out thaw settlement vulnerability studies in which, based on future climate projections and road embankment foundation properties, areas that are sensitive to thaw in response to climate change are mapped. At Dry Creek, the Yukon Government is presently piloting the use of thermosyphons to mitigate the thaw of buried massive ice. Finally, ongoing maintenance activities are performed to provide the necessary roadway level of service. A review of 26 years of construction data determined that permafrost regions of this highway section require CAD $22k to CAD $36k additional expenditures per year per km when compared to non-permafrost regions.

Case study is based on sources cited in footnotes 51 and 54 above and the following references:

- Calmels, F., et al. (2015). Vulnerability of the North Alaska Highway to Permafrost Thaw: A field Guide and Data Synthesis. Whitehorse, Yukon: Northern Climate ExChange, Yukon Research Centre.
- Elmer, K (2019). Design and Installation of thermosyphons at Dry Creek. Presentation at Northern Transportation Adaptation Initiative (NTAI): Climate Change Impacts and Adaptations for Canadian Highways Built on Permafrost: Feb 19-21, 2019, Whitehorse, Yukon Territory.

Case study: Implications for the Salluit Airport access road, Nunavik, northern Quebec

The Quebec Government Salluit Airport Access Road is an approximately 3 km roadway connecting the village of Salluit (population approx. 1,500), located in a narrow valley, to its airport, on a plateau. While goods can be shipped via marine operations during the summer, the village's sole year-round connection is through its airport. Existing permafrost degradation and road embankment damage in the form of significant differential settlement, active layer detachment landslide at the embankment toe, and culvert damage have been observed along the access road which is located on ice-rich, glaciomarine sediments and on a sloped region of the northern valley wall.

Climate trends: Consistent air temperature warming of 3.3°C has been observed since 1993 with continued warming of between 2.3°C and 4.5°C, and 3.3°C and 7.9°C projected by 2050 and 2080, respectively. General increases in precipitation are also projected. Warming air temperatures, together with increase in rain will have negative effects on the permafrost regime underlying the roadway.

Adaptation strategy, techniques and costs: In response to observed permafrost degradation problems, the Ministère de Transports du Québec (MTQ), in collaboration with researchers at Laval University, modified the embankment, improved water drainage and installed heat drains to thermally and mechanically stabilize the vulnerable section of the access road. Gentle side slopes were placed on the upslope section, with water collection systems leading water to the culvert locations. (paragraph continued on the next page)...

Case study: Implications for the Salluit Airport access road, Nunavik, northern Quebec (continued)

...(paragraph continued from the previous page) Additional culverts were installed where water seepage through the embankment was observed. Surfaces surrounding the culvert openings were sealed with bentonite to limit infiltration into the fill. Dispersion blankets were positioned at culvert outlets to minimize the potential of thermal erosion and active layer detachment. Downslope, heat drains were placed in the embankment to maintain and, if possible, cool the permafrost. The construction of the 1 km road section cost about CAD $5.5 million. The MTQ has installed instrumentation to monitor the effectiveness of these measures, and thermal and mechanical responses. This includes the innovative use of fibre optic technology to gather data on the evolution of the thermal regime under and at the edge of the embankment, information which is expected to inform updated design criteria for transport infrastructures built on sensitive permafrost over the next few years.

Case study is based the following references:

- LeBlanc, A-M. (2013). Modélisation tridimensionnelle du régime thermique du pergélisol de la vallée de Salluit au Québec nordique en fonction de différents scénarios de réchauffement climatique. Doctoral thesis, Laval University, Québec City, Québec.
- AMAP (2018). Adaptation Actions for a Changing Arctic: Perspectives from the Baffin Bay/Davis Strait Region. Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway.
- Périer, L., et al. (2016). Suivi du comportement thermique et mécanique de la route d'accès de Salluit et expérimentation d'une méthode de détection de la dégradation de pergélisol le long des structures linéaires. Bureau de la coordination du Nord-du-Québec, Ministère des Transports de Québec, Ville de Rouyn-Noranda, Québec, Canada.

Case study 2 (Canada)

Winter Roads in Canada and the Implications of Climate Change

I. Introduction

This case study presents the implications of climate change on winter roads in Canada. This case study was prepared by: Transport Canada, with contributions from the Northern Territories chapter (Pendakur, K. (2017)) of the '*Climate Risks & Adaptation Practices for the Canadian Transportation Sector 2016*' report.

II. Background information

The Canadian North has experienced some of the most significant warming observed anywhere on the planet. From 1948 to 2014, the warming trend was about 0.8°C globally, and 1.6°C in Canada. However, over the same time period, the Arctic Tundra region of Canada warmed by 2°C, and the Northwest Territories' Mackenzie District experienced 2.6°C of warming.[56] These increased air temperatures have had a negative impact on transportation in northern Canada.

Canada's northern road network is critical to the functioning of communities and industry in the territories of Yukon and the Northwest Territories (NWT), and in northern parts of several provinces (Figure II.2.3).

This network includes over 8000 km of winter roads – roads built seasonally over land (on compacted snow), across frozen lakes or rivers, or over sea ice fastened to the shore. They are managed by either local communities, provincial/territorial governments, or the industrial sector (e.g., mining or energy companies).

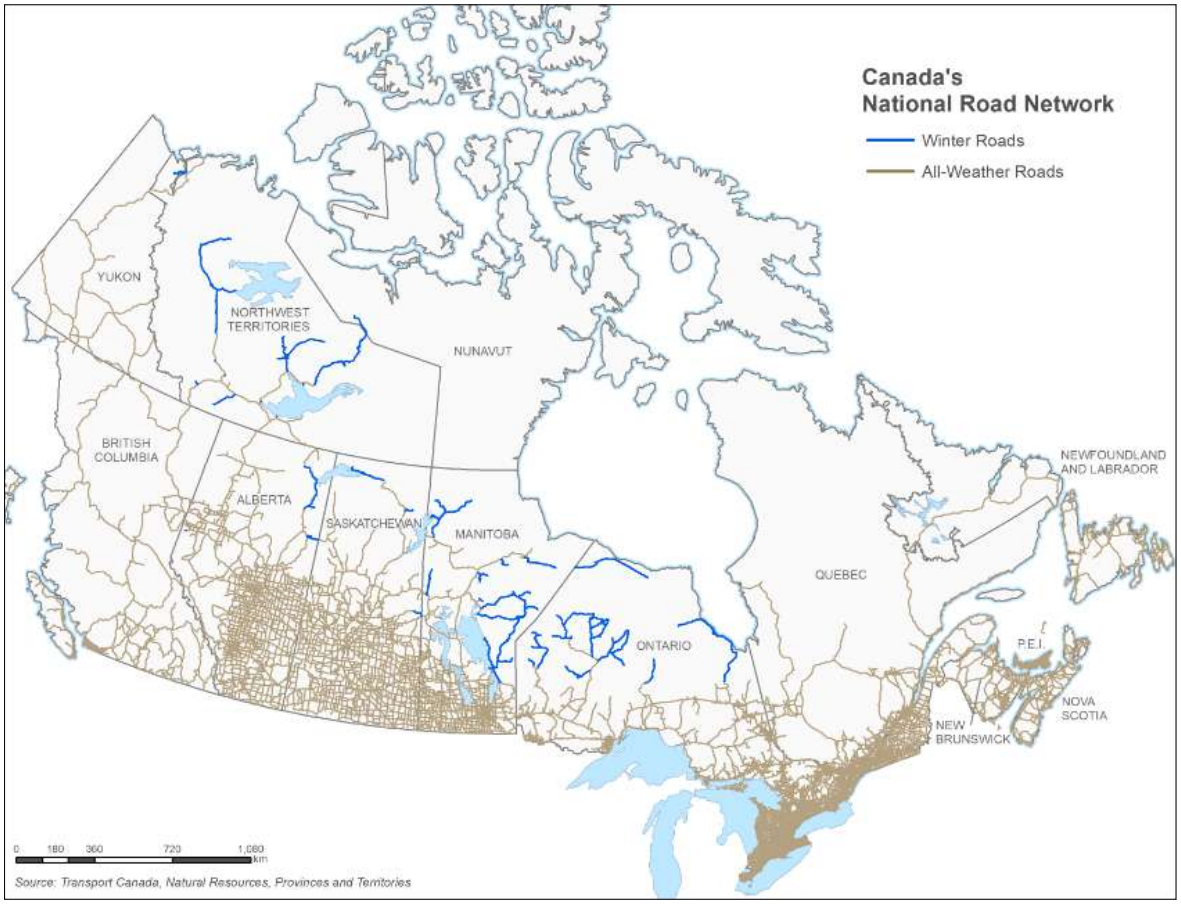
Winter roads (or portions of them) that cross frozen bodies of water are also known as icE Roads or ice bridges. To construct them, light vehicles remove the snow layer from the ice surface, in order to accelerate the growth of ice, since otherwise snow acts as an insulator. Then the ice surface is flooded with water or with spray ice, to artificially increase the thickness to the required target level.[57]

Winter roads facilitate travel to isolated areas of the North otherwise only accessible by air, or by water after the ice cover has melted. They enable travel between remote communities, allow residents to access goods and service available in larger population centres, and provide a way for remote communities to bring in supplies such as bulk fuel, dry goods, or building materials. Some northern industries also rely on winter roads in order to cost-effectively transport equipment to (or resources from) mines or other industrial sites by truck.

56 Pendakur, K. (2017). Northern Territories. In K. Palko and D.S. Lemmen (Eds.), Climate risks and adaptation practices for the Canadian transportation sector 2016 (pp. 27–64). Ottawa, ON: Government of Canada.

57 Barrette, P and Charlebois, L. National Research Council, Ottawa. Paper prepared for presentation at the Climate Change Adaptation and Mitigation Solutions for Transportation Design and Construction session at the 2018 Conference of the Transportation Association of Canada, Saskatoon, SK.

Figure II.2.3 Canada's National Road Network



Source: Transport Canada

The majority of Canada's winter roads are in the Northwest Territories (NWT) and the provinces of Manitoba and Ontario. Manitoba has approximately 2500 km of winter roads, which serve some 30,000 people in 28 communities, while Ontario has over 3000 km of winter roads linking 29 Indigenous communities to the provincial highway network. [58] The NWT has approximately 1600 km of publicly constructed winter roads, compared to 2200 km of all-weather roads.[59] Some jurisdictions also have winter roads that are privately constructed and maintained, such as the approximately 600 km Tibbitt to Contwoyto winter road (see Case Study below), which provides access to several mining operations in the NWT and Nunavut.

58 news.ontario.ca/mndmf/en/2018/11/ontario-supporting-far-north-winter-roads-network.html?_ga=2.58268330.1897309838.1547838263-2131115851.1547838263

59 Pendakur, K. (2017).

Winter roads are typically open for only a few months each year, and the duration of their operating season can vary annually, dependent on having conditions suitable to construct and maintain the road. In many locations, increasing temperatures related to climate change are reducing the length of the seasonal operation and resulting in mid-season closures. Warmer temperatures are also making it more difficult to reach a sufficient ice thickness for over-ice segments, which affects the safety and effectiveness of this infrastructure. Ice thickening through flooding or spray icing are measures that are becoming insufficient in the face of climate change. Thinner ice can mean a shorter operating season[60], slower travel speeds and/or reduced load capacity, which can result in delays, reductions in industry production, or other costly adjustments.

III. Responses to the Impacts of Climate Change

In some cases, all-season road segments or structural bridges are being constructed in areas where warming temperatures are severely affecting the operability of winter roads. In other cases, techniques to enhance the resilience of winter roads are being used. These can include:[61]

- Planning route selection over ice carefully, considering bathymetry and other factors.
- The pre-emptive removal of snow, to allow freezing fronts to penetrate the ground faster, removing heat from the ground and promoting ice formation.
- The construction and maintenance of snow caches (stockpiles of snow used as supporting material for degraded segments of winter roads). These can be constructed near difficult land crossings, to allow overland sections to be rebuilt quickly.
- Operational practices that include spraying winter roads and bridges with water to thicken ice and delay closure.
- Enforcing speed limits on over-ice segments.
- Towards the end of the operating season as temperatures rise, operators restricting hauling to night-time, since temperatures are lower and the ice sheet is stronger than during the day.

Several Canadian organizations have produced documents to assist practitioners in the construction and maintenance of winter roads, including the Transportation Association of Canada, the Government of the Northwest Territories, the Canadian Standards Association Group, National Research Council, and the Standards Council of Canada's Northern Infrastructure Standardization Initiative. These guidelines discuss general ice safety, ice behaviour under loading, ice-cover management, and end-of-season management (among other things).

60 For example, future projections estimate that Manitoba's ice-road season will be shortened by an average of eight days by the 2020s, 15 days by mid-century, and 21 days by the 2080s. Phillips, A., and Towns, W. (2017). The Prairies. In K. Palko and D.S. Lemmen (Eds.), Climate risks and adaptation practices for the Canadian transportation sector 2016 (pp. 105–137). Ottawa, ON: Government of Canada.

61 Barrette, P and Charlebois, L. National Research Council, Ottawa. Paper prepared for presentation at the Climate Change Adaptation and Mitigation Solutions for Transportation Design and Construction session at the 2018 Conference of the Transportation Association of Canada, Saskatoon, SK.

Case study: Implications of a changing climate for the Tibbitt to Contwoyto Winter Road[62]

This Case Study was included in the Government of Canada report "Climate Risks & Adaptation Practices for the Canadian Transportation Sector 2016" (Available at: www.nrcan.gc.ca/environment/resources/publications/impacts-adaptation/reports/assessments/2017/19623).

The Tibbitt to Contwoyto Winter Road (TCWR) is a 570-km private industrial road (also used by the public) in the Northwest Territories and Nunavut. It provides access and supplies to three active diamond mines and other mining locations. The majority of the road is built over frozen lakes, and both the construction and operation of the road are sensitive to climate variations. Thus, winter warming trends have been identified as a concern for the longevity of the road.

TCWR Facts:

- The TCWR is the busiest heavy-haul winter road in the world, moving a record 10,922 loads (330,002 tonnes) in 2007. It provides access to a region served by no other highways.
- The minimum ice thickness required for very light loads is 70 cm, while 107 cm is required for maximum loading (42 tonnes). Ground-penetrating radar is used to measure ice thickness.
- Construction of the road takes approximately 5 to 6 weeks prior to opening each year.
- The TCWR is typically operational for 8 to 10 weeks, starting between January 26 and February 11 and ending between March 21 and April 16.

Climate trends: Analysis of regional climate data demonstrates that the TCWR's operating season length correlates with temperature and related variables, including freezing-degree days, melting-degree days, and ice thickness – of these, the strongest indicator of a longer season is the accumulation of freezing-degree days. Winter temperatures in the region have increased significantly over recent decades; correspondingly, freezing-degree days and observed annual maximum ice thickness have both decreased, while melting-degree days have increased.

Future projections are consistent with observed trends. Climate change scenarios (in the absence of adaptation measures) project that the length of the winter road operating season will decrease from approximately 65 days in 2010 to 58 days by 2020 and 49 days by 2050 (with a 6 to 8 day margin of error per season).

Adaptation costs: It is possible that the winter road will remain viable through 2050, although there may be significant costs associated with flexible scheduling and increased construction and maintenance requirements. These costs are estimated in the range of $55 to 155 million over a 35-year horizon (net present net values in 2015 dollars with a 4 per cent discount rate applied).

There is also a significant risk of disruptions associated with late opening, early closure, or non-opening of the road. If the TCWR season length drops to fewer than 45 days, the road will no longer be able to accommodate an average season's demand. This has direct implications for mine production. In these circumstances, the most significant costs are likely to be associated with a shift to other modes of transportation. The total estimated cost of this scenario over 35 years is approximately $213 million, with a maximum cost of $1.8 billion (consisting mainly of production losses).

In summary, changes to the TCWR's operational season length create significant economic risks for both operators and users, assuming demand for the road increases or remains stable. Improved understanding of climate thresholds and associated costs for road owners and users may help to inform future economic and vulnerability assessments for winter roads.

62 Written based on findings from: Perrin, A., Dion, J., Eng, S., Sawyer, D., Nodelman, J.R., Comer, N., Auld, H., Sparling, E., Harris, M., Nodelman, J.Y.H., and Kinnear, L., (2015). Economic implications of climate change adaptations for mine access roads in Northern Canada. Northern Climate ExChange, Yukon Research Centre, Yukon College.

Case study 3 (Finland)

New Guidelines for Winter Maintenance of Roads in Finland

I. Introduction

This case study presents the economic impacts from climate change on the maintenance of Finland's road network. This case study was prepared by Soile Knuuti (Finnish Transport Infrastructure Agency).

II. New Guidelines for Winter Road Maintenance in Finland

The winter maintenance guidelines have been renewed based on climate change and customer feedback. The Minister of Transport and Communications initiated the development programme of winter management in February 2018. The previous guidelines were from 2008. The new guidelines will be implemented in two phases: (a) updating the maintenance classification of 11,000 km of statE Roads on 1st January 2019, and (b) updating quality requirements in contracts by tendering contracts from 2019 to 2024 using a new performance-based contract model and target price, which will distribute the cost risk due to, for example, climate change between the infrastructure manager and contractors. Awarding criteria in the bidding process have also been renewed; contractors will submit performance and quality promises, such as ability to react, response time and proactive actions. The new guidelines and quality requirements have been developed with the goal of safe and smooth traffic. The new guidelines concentrate on the demands of heavy traffic and commuting, the effects of climate change and targeted maintenance.

There is a total of 78,000 km of statE Roads in Finland. ThE Roads are classified into main roads and minor roads, which are further divided into maintenance classes, mostly according to traffic volumes and the volume of heavy traffic. Maintenance is contracted out, and there are 79 maintenance area contracts, mostly for 5-year periods. Maintenance is financed through the government budget. The cost of winter maintenance is approximately 55 per cent of the total maintenance costs. The Finnish Transport Infrastructure Agency defines the national policy, quality standards and guidelines of the procurement process.

In the new quality requirements, the action times for friction and snow removal (ploughing) are shorter, and the ploughing threshold is lower for low and medium traffic roads. There is a new requirement for extra equipment for combating slipperiness in extreme weather conditions. The use of alternative de-icing chemicals, such as potassium formate, is mandatory on areas where chloride has decreased the quality of the ground water.

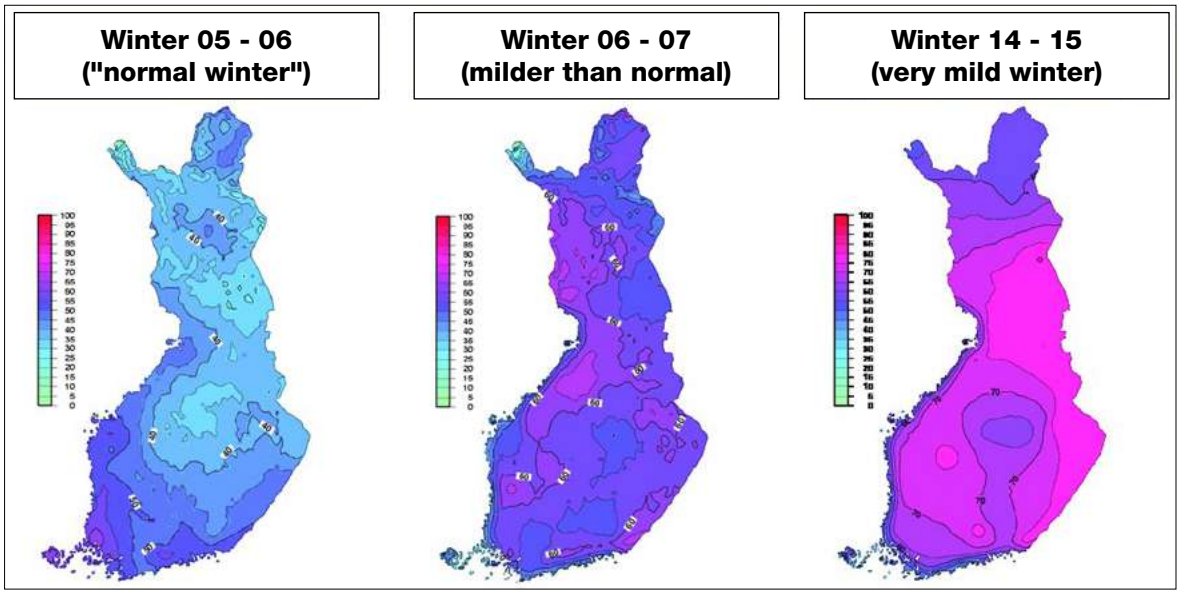
III. Weather conditions

Due to climate change, warmer weather conditions occur not only in early and late wintertime but also in the middle of winter, which is the reason for similar maintenance requirements in mid-winter. Figure II.2.4 shows the number of times when the temperature crossed 0°C degrees in three

different winter periods in Finland. The winter of 2005–2006 was a “normal” winter, while the winter of 2006–2007 was warmer than normal and the winter of 2014–2015 was even warmer. Warmer winters have increased the need for de-icing thE Roads, especially in inland Finland; the typical “coastal weather conditions” have spread to inner parts of the country.

The mean winter temperature has been 1°C to 4°C higher than the long-term average in Finland. Freeze-thaw cycles are occurring more often than before. It rains more often in northern Finland in wintertime, and heavy snowing occurs more often. However, the amount of extreme weather events has not clearly increased. The road drainage problems that have usually occurred in summer months now occur in wintertime also. Pavements are more often wet, and de-icing chemicals are needed more.

Figure II.2.4 The number of times when the temperature was below 0°C in three different winter periods in Finland

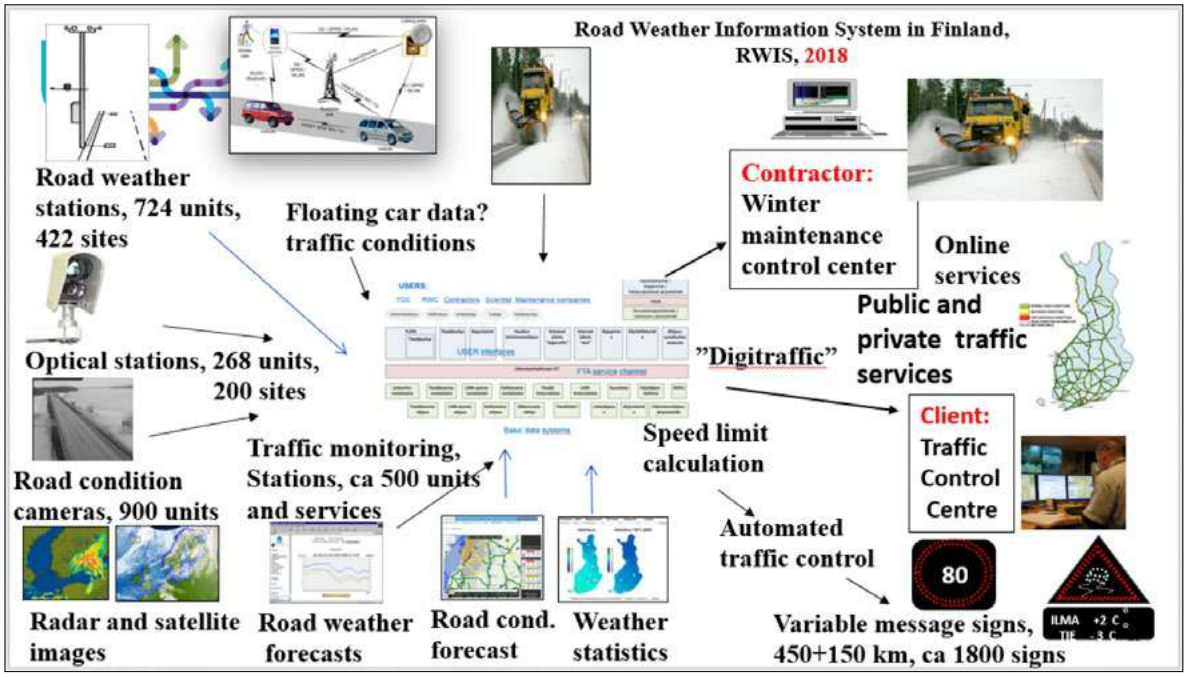


The changes in weather types have been occurring faster than before, which has increased the importance of good weather forecasts and proactive information. Road weather is monitored with road weather stations, road condition cameras and radar and satellite images. This information, together with weather forecasts and statistics, is combined with the road weather information system, which is used by contractors, traffic control centres and public and private traffic services (Figure II.2.5). The system also calculates the speed limits for variable message signs (ca 1800 signs).

IV. Effects

The new guidelines consolidate the quality requirements of the winter maintenance of main roads, which enables clear quality assurance and maintenance methods. The new guidelines more accurately take into account the needs of heavy traffic. In urban areas, requirements for busy cycle paths have also been raised.

Figure II.2.5 Road weather information system in Finland



Business and transport will benefit from the changes, customer satisfaction is expected to be higher, the morning traffic on minor roads will benefit from the changes, and the number of injury accidents and seriously injured is predicted to be lower. The lifecycle of fragile pavements will be longer due to using mostly sand instead of salt to meet the friction requirements.

It is predicted that salting will increase by 20–25 per cent and sanding by 25–30 per cent. In classified ground water areas, salting will be minimised and potassium and sodium formates utilised to meet safety regulations, and new ground water protections will be built as part of the new road projects.

V. Costs

The total annual cost of winter road maintenance in Finland has been, on average, €100 million. After adopting the new winter maintenance guidelines by 2023, the costs are predicted to be €120 million/year. Additional financing of €15 million was budgeted for winter maintenance of roads for 2019.

In the twenty-first century, the expenses of gravel road maintenance have increased by at least 10 per cent, due to climate change/warmer winters. Shortened ground frost periods have resulted in the need of more frequent pavement repairs, and the potholes that occur all year round and those have become more difficult to repair in winter. The cost of asphalt repairs has increased by 50 per cent over the last ten years.

Case study 4 (Germany)

Low flow extremes of the Rhine river – Causes, impacts and adaptation of the most important inland waterway in Europe

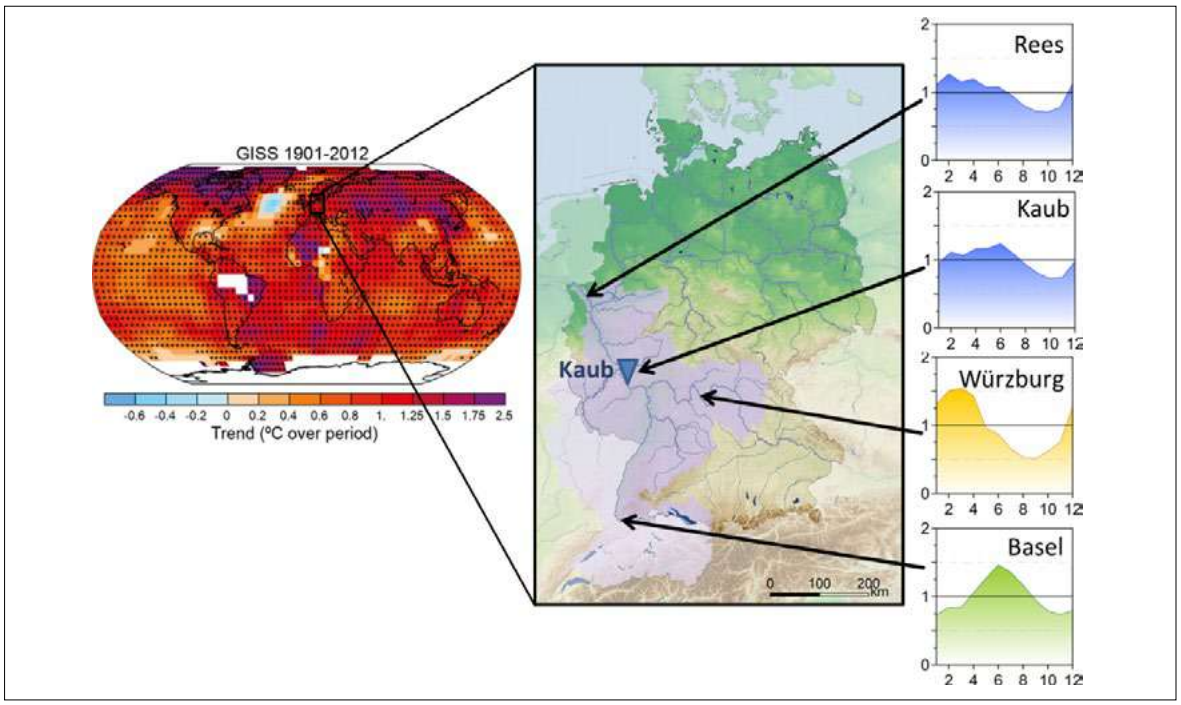
I. Introduction

This case study discusses causes and impacts of low flow extremes on the Rhine River. It further presents possible adaptation measures. This case study was prepared by Dr. Enno Nilson (German Federal Institute of Hydrology), Dr. Sven Wurms (German Federal Waterways Engineering and Research Institute)

II. Background

Theoretical considerations, observations, and climate models indicate that global climate change may lead to more persistent pressure systems over Europe. Due to relatively rapid Arctic warming (Figure II.2.6, left, purple color), polar-equatorial temperature gradients are projected to be reduced and planetary zonal wind systems to be weakened and become more stationary (Mann et al., 2018 and references therein). Consequently, wet and dry spells may persist longer over Europe and hydrological extremes (droughts and floods) in Germany may last longer and become more intense. These extremes can impact economic and ecological systems in many ways.

Figure II.2.6 **Left: Map of the globe highlighting stronger polar than equatorial temperature rise in the 20th century (taken from IPCC, 2014); Center: Location map showing the catchment of the Rhine River, the German waterway network, and the gauging station of Kaub; Right: Graphs showing flow regimes in different parts of the catchment (period 1961-1990, green = snow-dominated, yellow = rain-dominated, blue = complex)**



Here, we outline a cause-and-effect-chain involving climate, hydrology, inland navigation, the transport market, industry, people, and national economy, using the Rhine River as an example for an extreme low flow situation in 2018. Furthermore, we show exemplary measures that help (a) to keep the affected sectors informed about consequences of climate change and (b) to manage waterways in times of climate change.

III. Hydrological and economical setting

A. The Rhine River as an international river

The Rhine River catchment (Figure II.2.6, center) covers a total of ten countries, mainly Switzerland, Germany, France, and the Netherlands (upstream – downstream). The Rhine River has three major flow regimes (Figure II.2.6, right). The southern, alpine part is described as nival controlled by snow (and ice) processes leading typically to winter low flows and summer high flows (e.g., gauge Basel). The tributaries in the mid mountain areas show a pluvial regime, particularly rain dominated with high flows and low flows peaking typically in winter and summer, respectively (e.g., the Main river, gauge Würzburg). In the Middle and Lower Rhine flow regimes above overlay ('complex regime'), leading to a relatively equalized annual cycle with low flows occurring typically in late summer and fall (gauges Kaub and Rees, respectively). The Rhine River is free flowing in most of its course (except for the Upper Rhine) and therefore vulnerable to hydrometeorological changes in the catchment.

B. The river Rhine as a waterway

The Rhine River is the most important inland waterway in Europe. In 2017 it accounted for about 75% of total German inland water transport (by weight, DESTATIS, 2018) which accounts for approximately 6% of total cargo transported in Germany (DESTATIS, 2019a). It is part of the Trans-European Network (TEN) and, as such, plays an important role in the hinterland transport of the major 'ARA-seaports' (Amsterdam, Rotterdam, Antwerp) in the Netherlands. The waterway network in the Rhine area consists, apart of the Rhine River (downstream of the city of Basel (Switzerland) up to the North Sea delta (Netherlands)), also of major tributaries, such as the Neckar, the Main (connecting to the Danube via the Main-Danube canal), and the Moselle (connecting to France).

Due to the favorable navigation conditions and river management, ship sizes have significantly increased since the mid-20th century (WSV, 2017). Between 1969 and 2017 the specific capacity of cargo and tanker vessels approximately doubled. Inland waterway transport (IWT) is limited by the more shallow river stretches, for example, around the city of Kaub in the Middle Rhine, where today a fairway depth of 190 cm is available, on average, a minimum of 345 days per year.

The type of goods transported via IWT is dominated by dry and liquid bulk cargo. For example, more than 25% of the overall amount of coal, crude oil, and natural gas is transported by IWT in Germany (DESTATIS, 2019b). For these type of goods IWT is economically very efficient. Due to industrial change, transport of goods like steel and coal has decreased since the 1970s, while container transport has increased since the 1980s. The total amount of IWT transported goods has remained more or less constant in recent years, while transport totals (road, rail) have increased resulting in a relative loss of the IWT market position.

C. The Rhine River catchment as an industrial area

The favorable navigation conditions on the Rhine River have contributed significantly to regional industrial development. Today, about 58 million people work and live in the Rhine River catchment area. Several important industrial areas developed along the river, including the Main-Neckar and the Ruhrgebiet industrial centers, making the Rhine River catchment area an economical hot spot. The regional gross valued-added of the manufacturing and producing industries, as well as the gross domestic product per capita, ranks among the highest in Germany and Europe (year 2018, DESTATIS, 2019c).

IV. Sensitivity of the system: The drought of 2018

Drought is the hydrometeorological extreme which mostly affects IWT, resulting in low flow situations, which are particularly critical for the transport sector (Nilson et al., 2012). These low flows usually last much longer than high flow or ice blockage situations and can limit transport over several weeks in extreme cases. The low flow situation of 2018 triggered a cause-and-effect-chain, including climate, hydrology, inland navigation, the transport market, related industries, people, finally impacting national economy.

A. The cause-and-effect chain

Extreme low flow situations can occur over longer periods from extreme low precipitation and high temperatures (high evaporation rates), when river flows decline. Below set minimum thresholds, the cost of transport rises, as ships transport less goods with ship operation costs (fuel, personal etc.) remaining level or even increasing, due to reduced speed/longer transport times. Larger ship types are generally more sensitive to low flow conditions than smaller ones.

Typically, two things occur when per ship capacity is reduced: (1) ships navigate more often and/or (2) goods are shifted to other transport modes. Limited shipping capacity, combined with the limited capacity of alternative transport modes, cause transport market prices to rise, resulting in industry losses dependent on a timely transport of raw materials and products. More extreme low flow conditions in terms of persistency and intensity and a dependency on larger ships would inevitably result in more extreme repercussions. If transport capacity reaches critically low levels, production processes have to be modified or even halted, slowing down economic activity in the process.

B. The situation in 2018

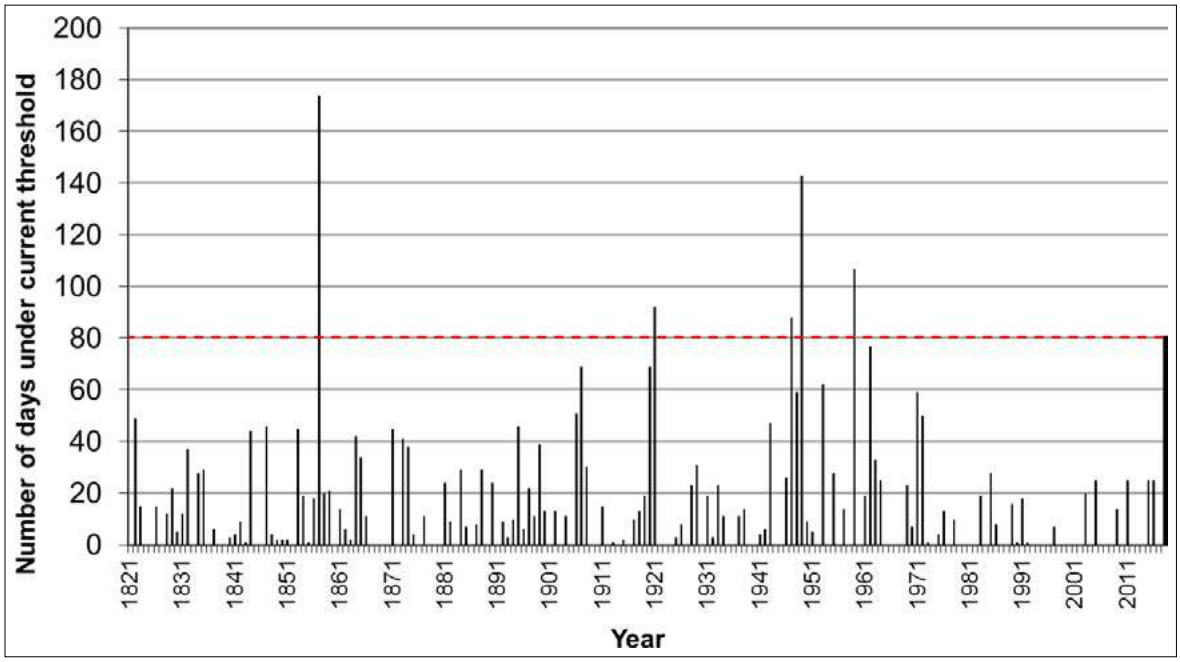
In 2018 a persistent high pressure system dominated Europe from February to November. The result, an exceptional long dry spell, was associated with a precipitation deficit of about 45% between April to November over Germany compared to the long term mean of 1981–2010 (Deutscher Wetterdienst, 2019).

From a hydrological perspective, the duration of the low flow situation of 2018 at Kaub was extreme, although not the most extreme on record (II.2.6). The average fairway water depth of 190 cm was not reached for 81 consecutive days (apart from a 12 day interruption in September). Figure II.2.7 shows longer recorded periods of drought occurred on five occasions only, another three were in the same order of magnitude. Statistically, the 2018 event occurs once every 20 to 50 years.

Nevertheless, the economic impact of the 2018 drought was profound, due to the combined effects of the low water levels and relatively large ship types. The average load factor of vessels, with a maximum draught of 3 m passing Kaub, was below 60% during the second half of 2018 (CCNR, 2019). As a result, the per ton prices of IWT increased significantly. Also, about 20% less goods were transported on the Upper Rhine and the Main rivers (WSV, 2018) and freight handled on some ports decreased significantly. The annual amount of goods handled in 2018 in the port of Mannheim was 23% less than in 2017 (Binnenschifffahrt, 2019). Single months (e.g. October) and specific goods (e.g. iron and steel) recorded reductions of 65% (Binnenschifffahrt, 2018).

Preliminary estimates of economic impacts showed the industrial production growth in Germany was temporarily slowed by 0.8% and 0.4% in the 3rd and 4th quarter of 2018, respectively (Ademmer et al. 2019). As industrial production accounts for approximately 31% of gross value added (average 1991-2018; DESTATIS, 2019c), the 2018 drought impacted macro-economic indicators. Several overlying effects (Ademmer et al. 2019), however, complicate an exact quantification.

Figure II.2.7 **Time series showing annual maximum duration of low flow situations at Kaub (flow continuously lower than 783 m3/s; corresponding to a water depth of 190 cm). The duration of the situation 2018 is indicated by the red hatched line. Subsequences of the events were pooled by a smoothing technique (10 day running mean) neglecting minor interruptions. Data: German Federal Waterway and Shipping administration**



V. Climate change research, information services and adaptation options

A. Concerted interinstitutional research

The impact of changing hydrometeorological and hydrological conditions on the transport sector, the industrial sector and the national economy, as well as on river ecology and water quality, is considered significant. As a consequence, the German Ministry of Transport (BMVI) since 2007 concerted major research activities to systematically collect and combine relevant information on future climate impacts, and to transfer the gathered information into practical management.

The first milestone was reached with the research program KLIWAS (2009–2013). The program, an institutional network consisting of the upper authorities of the BMVI (Federal Institute of Hydrology, BfG, coordination; Federal Waterways Engineering and Research Institute, BAW; the German Weather Service, DWD; the Federal Maritime and Hydrographic Agency, BSH), supported by several other research institutions and universities, was commissioned to integrate information on climate change impacts on inland and coastal waterways, including aspects of navigation, water quantity, water quality, transport dependent industries, and ecology. Main targets of the research included (a) the determination of the robustness of climate projections of the 21st century by multimodel ensembles, (b) the setup of a holistic modelling framework to allow for the interdisciplinary climate impact assessments for waterways, (c) the user oriented design of data and information products, and (d) the development and evaluation of specific adaptation measures. The results (BMVI, 2014) serve as a general knowledge base for many management questions related to major rivers, as well as coastal and inland water ways. Figure II.2.8 displays an exemplary result at the gauge station in Kaub (Nilson & Krahe, 2013; Nilson et al., 2014).

Figure II.2.8 **Time series showing annual number of low flow days at Kaub (flow lower than 760 m3/s as 30 year running mean based on (black) observed data, (grey) 20 projections of the future, and (red, purple) time slices that were highlighted in the KLIWAS research program (2021–2050, 'near' future; 2071–2100, 'distant future'). Source: Nilson & Krahe (2013, observed data updated to include the year 2018)**

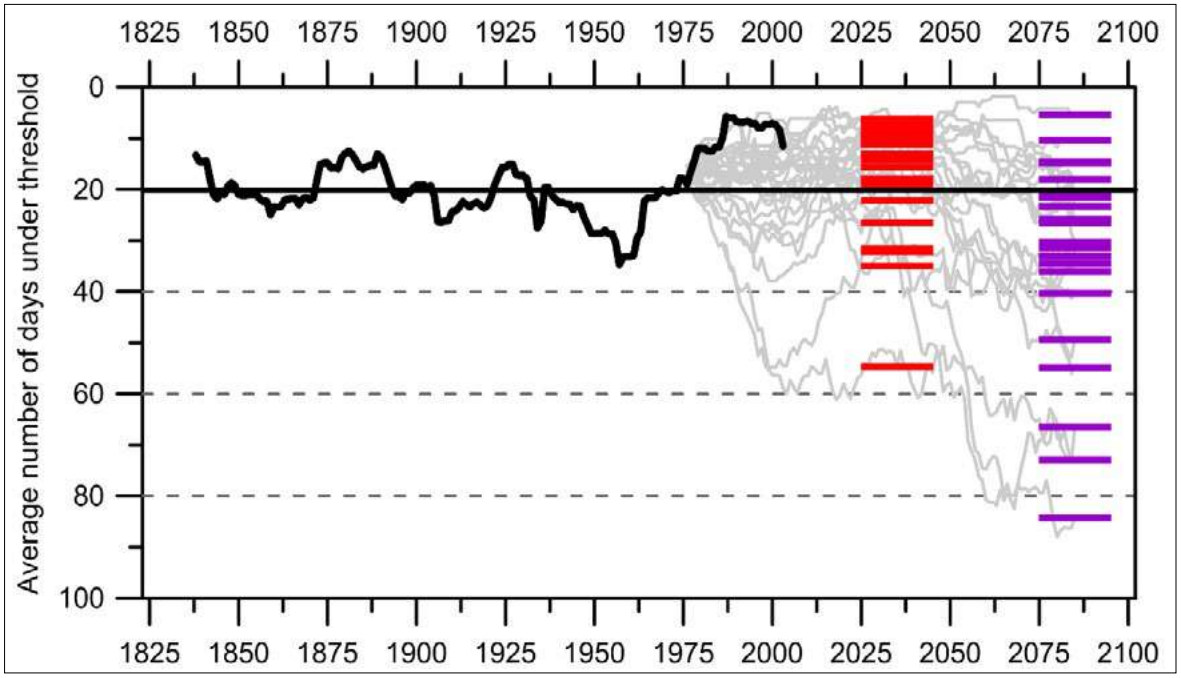
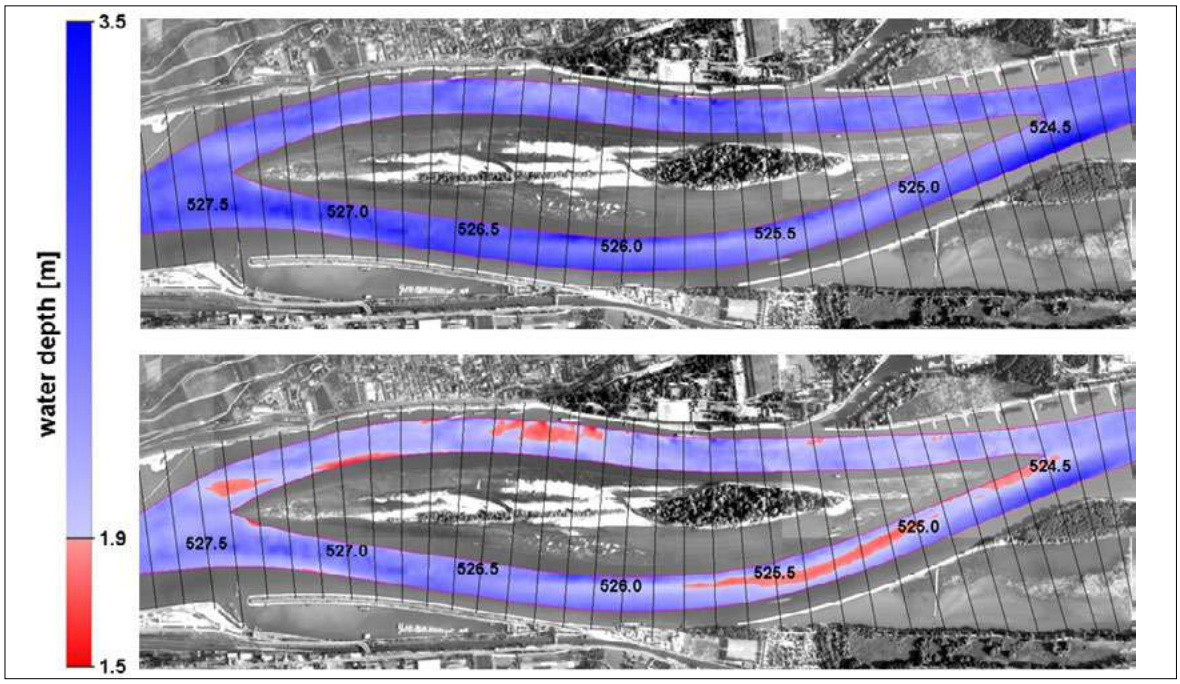


Figure II.2.8 shows that (a) low flow situations are projected to remain in the historically observed range (black line) until mid-twenty first century (red symbols), but that (b) a majority of climate projections shows more frequent low flow situations in the second half of the 21st century (purple symbols). While these data show there is still time to react, it is also necessary to consider possible unfavorable conditions in future planning processes.

Next, hydraulic analyses were conducted to reveal, where shoals could be expected to (re)appear in the Rhine River. To this end, a two-dimensional numerical model was employed on a section of the Middle Rhine, that is a major hydraulic bottleneck already today (Schröder & Wurms, 2014).

Figure II.2.9 **Map of a stretch of the Middle Rhine showing water depths in the fairway during low flow conditions occurring, on average, 20 days per year under current (top figure) and 'distant future' (2071-2100, bottom figure) conditions, the latter representing the lower range of projected low flows. Additional shoals due to changes of low flow conditions (i.e. water depths below current fairway depth of 1.9 m) are shown in shades of red.**



Several adaptation measures were evaluated for this situation, including ship construction and operation, forecasting systems, logistic chain adjustments, and river training measures. River training measures, such as longitudinal dykes or groynes aiming at the adaptation to climate-induced changes of flow and morphologic conditions, will remain as individual case solutions, as they are planned in accordance with site-specific characteristics of the river. The example of the Middle Rhine section indicates the complete bandwidth of projected hydraulic and morphological changes would be manageable by a combination of river training measures, increased maintenance activities and a modified sediment management.

The work of the KLIWAS (2009-2014) research program has continued as part of the "Network of Experts" of the BMVI since 2016 (reference to Case study 1, Part II, Chapter 1) and has been extended to other transport modes (rail, road) that may be affected by low or high flows along German rivers. Models and methods have been improved and the latest climate scenarios were evaluated to update or consolidate the KLIWAS results.

B. From science to service

The low flow year of 2018 is one of a number of low flow events in recent years (2003, 2011, 2015) signaling a continuously growing need for consolidated climate change information.

Data products from several research programs are planned as part of a regular climate service. Currently, a prototype of such a sectoral climate service for IWT is being set up for the Rhine River and Elbe. The “projection service waterways and shipping” (ProWaS) (Nilson et al. 2019) will offer specific information that support IWT managers in planning processes.

Further information products are under development, not only for inland and coastal waterway transport, but also for road and rail transport, and other sectors (agriculture, energy etc.), as part of the German National Adaptation Strategy (D.A.S.). This overarching approach is an important step to improve coherency of climate change assessments and long term strategic decisions in the transport sector and beyond.

Case study 5 (Germany)

Impact of climate change on the water management of the Kiel Canal

I. Introduction

This case study presents the impacts of climate change on the water management of the Kiel Canal. It was prepared by: Nils H. Schade (Federal Maritime and Hydrographic Agency, Hamburg), A.D. Ebner von Eschenbach (German Federal Institute of Hydrology, Koblenz), A. Ganske (Federal Maritime and Hydrographic Agency, Hamburg), J. Möller (Federal Maritime and Hydrographic Agency, Hamburg), V. Neemann (Directorate General for Waterways and Shipping, Kiel).

II. Background

The Kiel Canal ("Nord-Ostsee-Kanal" (NOK)) is the world´s busiest man-made-water-way navigable by seagoing ships. Approximately 100 million tons of cargo are transported on the waterway each year. The canal provides a direct link for the North Sea ports to the Baltic Sea region. Moreover, the NOK is Schleswig-Holstein's biggest artificial receiving body of water, draining over 1500 km^2. An important task within the Network of Experts of the Federal Ministry of Transport and Digital Infrastructure (BMVI) is the investigation of the dewatering of the Kiel Canal under climate change scenarios.

When balancing the interests of shipping, for example, the requirements of the ferry crossings and hydrological and meteorological conditions, the drainage for the NOK must be controlled such that the water does not exceed or fall below its maximum and minimum levels respectively. A sea level rise (SLR) of approximately 20 cm in the past 100 years has already noticeably reduced the drainage times available. Climate change will result in a further rise in sea level, as well as in changes in the inland hydrology. Since it can be expected that the water levels in the tidal areas of the Elbe River and the Baltic Sea will continue to rise as well, this brings up the question of whether the frequency of dewatering will change in the future and, if so, how strongly the NOK and its catchments will be affected.

III. Methods

Two different approaches were taken:

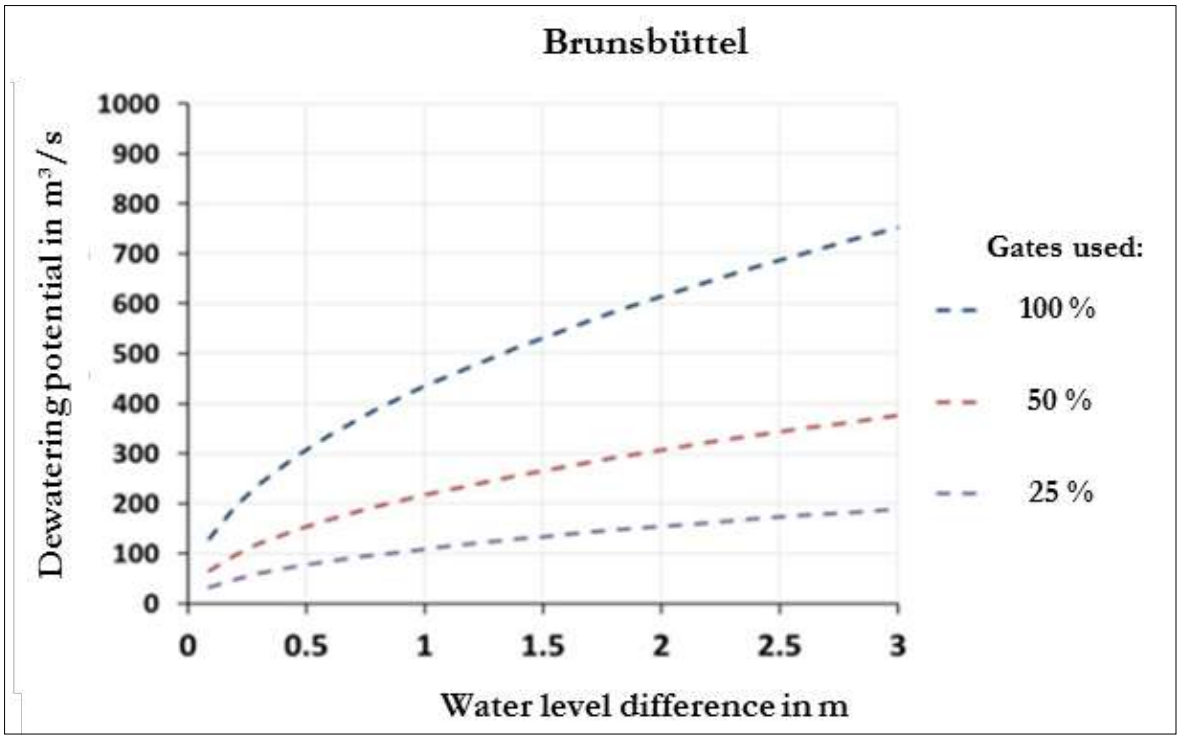
(1) On demand of the Federal Waterway and Shipping Agency (WSV), the Federal Institute of Hydrology (BfG) has developed a water balance model to simulate the runoff into the NOK from its catchment, as well as a canal balance model to simulate the NOKs water levels and drainage facilities.

(2) In addition, the Federal Maritime and Hydrographic Agency (BSH) has investigated the serviceability limit states of the NOK based solely on oceanographic and atmospheric parameters without running an extensive model setup. This way, both approaches, (1) "model system" and (2) "proxies/predictors", can be compared. The "proxies/predictors" method has already been applied to the results of the climate model MPI-OM (Mathis et al., 2017) and possible future changes in long lasting precipitation and high outer water levels have been studied.

IV. Results

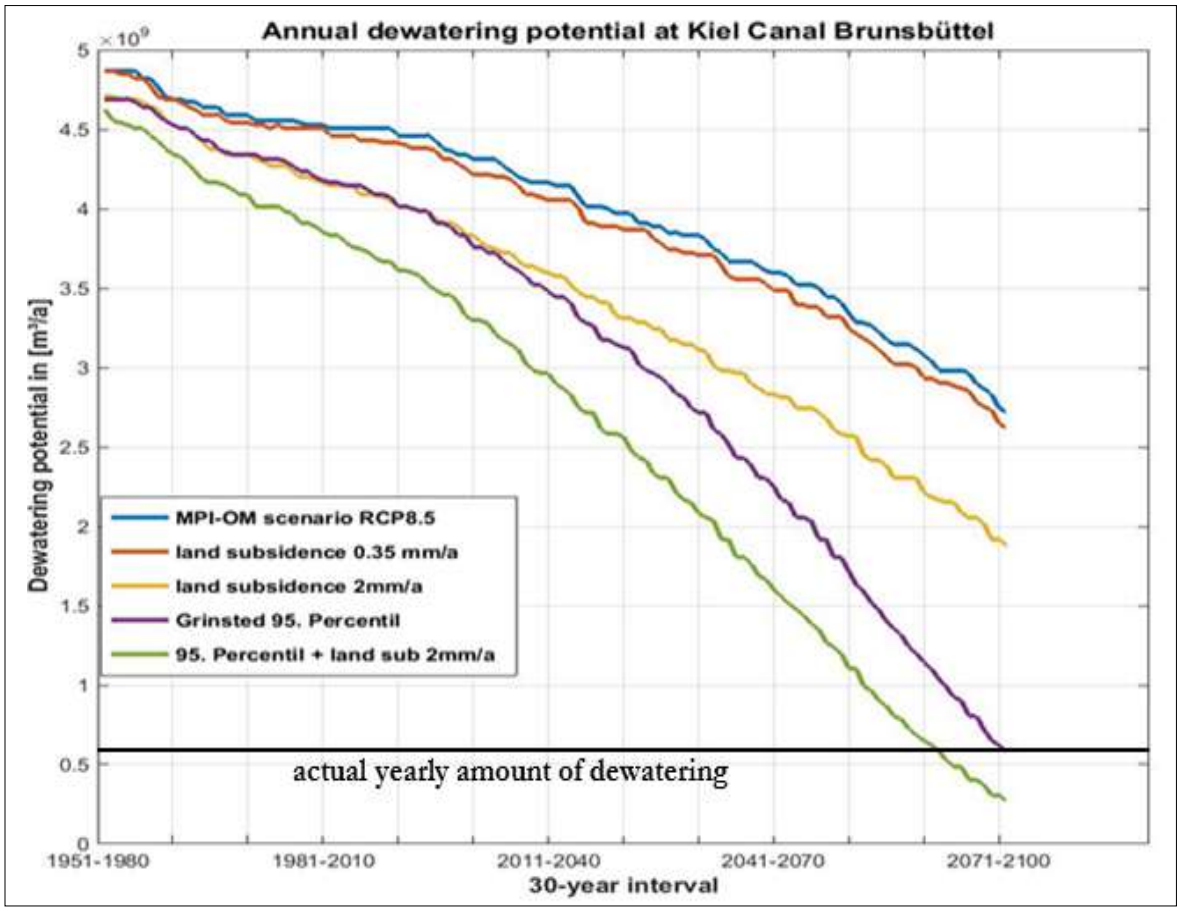
The potential for drainage was calculated with the use of a correlation index from the water level difference between NOK and Elbe (Figure II.2.10). The NOK can be drained into the Elbe and into the Baltic See, when the water level of the Elbe or the sea level of the Baltic Sea is lower than the water level of the canal. Drainage is required, if the canal water level reaches the upper limit. In the majority of cases, the canal water level is regulated by using the lock at the southwestern part (Brunsbüttel) in the Elbe. This is because the water level difference between NOK and Elbe permits a more efficient dewatering at the north-eastern part via Kiel-Holtenau into the non-tidal Baltic Sea. Therefore, only the drainage potential at Brunsbüttel is pictured here.

Figure II.2.10 Relation of water level difference (between Elbe and NOK) with dewatering potential at Brunsbüttel (Ebner von Eschenbach, 2017) for three possible usages of the sluice gates.



The climate model MPI-OM provides hourly water levels at the Elbe for the past (in the historical run, 1961-2005) and for the future (here in the "business as usual"-scenario RCP8.5, 2006-2100). The correlation of the hourly water level difference leads to an amount for the yearly drainage potential. The results are displayed in Figure II.2.11. The impact of SLR on drainage potential is crucial; even an expected SLR of 55 cm would reduce the drainage potential of the NOK around about 40 per cent (Figure II.2.11, blue line represents a SLR of about 55 cm until 2100). The future land subsidence in south-western Schleswig-Holstein (yellow and orange lines) and more and heavier precipitation will reduce the drainage potential even further.

Figure II.2.11 Dewatering potential under RCP8.5 scenario with/without effect of land subsidence and an estimation of additional polar ice melting. The black line indicates the actual yearly amount of dewatering needed (600 mill m³/year).



Extremely high tidal low waters reduce or even prevent the possibility of drainage. While it is not difficult to bridge a gap of one tide without dewatering, it is a major challenge in case there are two (or more) consecutive low waters higher than the water level in the NOK (at least 480 cm above gauge normal level). Table II.2.1 displays the events of "no possibility to drainage" per 30-year period for different numbers (1 to 6) of consecutive low waters above the critical water level (480 cm): A rapid increase of consecutive high low waters in the future is apparent and statistically highly significant (at the 99 per cent level). While on average 10–12 events per year with low water levels higher than the respective water level in the NOK can be observed today, these events will occur much more frequently in the future due to the sea level rise.

Table II.2.1 Number of events per 30-year period of low waters (LW) at Brunsbüttel higher than the design water level at Kiel-Canal, for one up to 6 consecutive low waters

LW Event	1951–1980	1981–2010	2011–2040	2041–2070	2071–2100
N=1	347	516	564	965	1 752
N=2	89	136	185	329	702
N=3	31	54	73	165	377
N=4	8	17	24	63	167
N=5	2	4	11	33	90
N=6	1	0	3	15	45

V. Applications

With the help of the model system outlined above, serviceability limit states of the NOKs water management have been identified and possible changes in the occurrences thereof due to climate change have been derived. These analyses provide an important contribution to the Federal adaptation strategy on climate change. This task is characterized in the report "Adaptations to the global Climate Change" ("Fortschrittsbericht Deutsche Anpassungsstrategie an den Klimawandel, APA II, 2015") of the German government: One of the federal adaptation strategy's activities is focused on a resilient traffic infrastructure for the NOK. The operating agency of the NOK, the WSV, regards the model studies described above as an essential basis for decision-making to counteract the restriction for drainage of the NOK due to sea level rise and changing precipitation. Therefore, two options will be considered: (1) – an adapted water resources management and (2) – new construction of sluices.

Due to the results of the above described studies, the WSV investigates prospective approaches, for example, long-term options for action, such as the creation of floodplains or the construction of a new Kiel Canal pumping station.

The substitution of sluices which ensure the undisturbed shipping traffic at the NOK will be planned with new findings about the accelerated sea level rise. The WSV will consider SLR of about 1.74 m (Grinsted et al., 2015) instead the 0.50 m formerly considered in the "General Plan on Coastal Protection" ("Generalplan Küstenschutz des Landes Schleswig Holstein - Fortschreibung 2012"). In this process, the sluice gates in Kiel-Holtenau will be planned in such a way that it will be possible to adapt the construction along with the actual SLR which in turn allows optimization of the consumption of resources in line with demands. The planned construction of the flood-gates for example was changed according to the optimization process.

VI. Outlook

The long-term objective is to determine the risks from combined climate impacts (i.e. high outer water levels & heavy precipitation) using an ensemble of climate models. Also, this method will be used to examine possible future changes in the dewatering of other river catchments in coastal areas, where no model setup exists.

Case study 6 (Germany)

Influence of weather and climate extremes on supra-regional traffic flows – Stress test scenario Middle Rhine

I. Introduction

This case study is part of Topic 1 "Adapting transport and infrastructure to climate change and extreme weather events" of the BMVI Network of Experts.[63, 64] The case study refers to the research project FE 69.0001/2017 "Influence of weather and climate extremes on supra-regional traffic flows – Stress test scenario Middle Rhine". This research project was conducted by TTS TRIMODE Transport Solutions GmbH and HTWG Hochschule Konstanz Technik, Wirtschaft und Gestaltung. Author of this case study is Stefanos Kotzagiorgis (TTS TRIMODE Transport Solutions GmbH).

II. Background

The Middle Rhine Valley is one of the most important transport corridors in Germany (Figure II.2.12). It is part of the European TEN-T Core Network and consists of important routes for road, rail and water transport. Weather- or climate-induced traffic disruptions along this corridor may have significant impacts on transport and the economy. This scenario-based stress test for water, rail and road transport simulates potential traffic impacts of disruptive extreme weather events in the Middle Rhine Valley and its hinterland for the year 2010 and 2030.[65]

III. Scenario-based stress test

The traffic simulation is based on traffic data, relevant assumptions about traffic development and transport networks developed within the framework of the German Federal Transport Infrastructure Plan.[66, 67, 68, 69]

63 www.bmvi-expertennetzwerk.de/EN/Home/home_node.html;jsessionid=D3CBB4DA6E843339C0BD 5743335 A8A1A.live11291 (last accessed: 28.05.2019)

64 Federal Ministry of Transport and Digital Infrastructure (2017): BMVI Network of Experts Knowledge – Ability – Action. Available at: https://www.bmvi-expertennetzwerk.de/DE/Publikationen/Medien/Brochure-Expertennetzwerk.pdf?__blob=publicationFile&v=2 (last accessed: 28.5.2019)

65 TTS TRIMODE Transport Solutions GmbH, HTWG Hochschule Konstanz Technik, Wirtschaft und Gestaltung (2019): Einflüsse von Wetter- und Klimaextremen auf überregionale Verkehrsströme – Stresstestszenario Mittelrhein. Schlussbericht (unveröffentlicht), Freiburg – Konstanz (FE 69.0001/2017)

66 Federal Ministry of Transport and Digital Infrastructure (2016): The 2030 Federal Transport Infrastructure Plan, Berlin

67 BVU, ITP, IVV, PLANCO (2014): Verkehrsverflechtungsprognose 2030 (Lose 3 bis 6), Freiburg – München – Aachen – Essen (FE 96.982/2011, FE 96.982/2011, FE 96.983/2011, FE96.984/2011)

68 BVU, TNS, KIT (2016): Entwicklung eines Modells zur Berechnung von modalen Verlagerungen im Güterverkehr für die Ableitung konsistenter Bewertungsansätze für die Bundesverkehrswegeplanung. Freiburg – München – Karlsruhe (FE 96.1002/2012)

69 PTV Group, TCI, Hans-Ulrich-Mann (2016): Methodenhandbuch zum Bundesverkehrswegeplan 2030, Karlsruhe – Berlin – Waldkirch – München (FE 97.358/2015)

Table II.2.2 Overview of the scenarios applied in the stress test for the Middle Rhine Valley and its hinterland

	Middle Rhine Valley			Hinterland	
Scenario	1: Gravitational mass movement	2: High water	3: Low water	4: Extreme event (not specified)	5: Extreme event (not specified)
Year	2010 / 2030	2010 / 2030	2010 / 2030	2030	2030
Scenario specific duration of closure for the affected network in days					
Road	21	21	–	180	–
Rail	21	21	–	–	180
Inland waterway	–	21	180	–	–

Five different stress test scenarios (Table II.2.2) were designed on the basis of a literature and media analysis and historical data. Each scenario is based on assumptions about the affected network sections and the duration of their closure. Based on the analysis of the Federal Institute of Hydrology (BfG), the Federal Waterways Engineering and Research Institute (BAW) and the HTWG Konstanz – University of Applied Sciences, gravitational mass movements and flooding were identified to usually cause short-time blockages, while low flow was identified as event that could lead to long-lasting restrictions of inland waterway transport.

The following main research questions were addressed by this stress test:

- Can the affected traffic be shifted to alternative routes?
- Is the capacity on alternative routes sufficient to absorb the additional traffic?
- Or must the traffic be rejected or shifted to other modes of transport?
- How will travel times and travel distances be affected in consequence of the rerouting? and
- How will transport costs change through modal and intermodal shifts, especially in freight transport?

IV. Scenario 2 – Flooding of the Rhine River

Scenario 2 describes an extreme flooding event affecting water, rail and road transport. This scenario assumes the closure of network sections around the city of Oberwesel (Upper Middle Rhine Valley) for 21 days. The closure affects water transport on the Rhine River, the ferries crossing the river as well as the federal highway (B 9) and the railway line (route number 2630) along the left river bank. The results of scenario 2 are presented using the example of the forecast traffic and infrastructure situation of the year 2030.

V. Results of scenario 2

The flooding of the federal highway and the closure of the ferries will lead to a rerouting of around 7,000 vehicles per day. This rerouting (Figure II.2.13) leads to additional travel distances of approximately 16 km in passenger and 9 km in freight traffic.

The railway line between the cities of Oberwesel and Lorch will be used in 2030 by 6.6 million long-distance passengers (56 long-distance trains per day), 0.5 million passengers in local public traffic (78 local trains per day) and 119 freight trains per day. While local public rail traffic can be maintained by setting up a replacement service with busses, long-distance passenger and freight trains are rerouted, in particular via the railway line on the right bank of the Rhine River. The rerouting causes an increase in travel time by 25 minutes for long-distance rail passenger traffic.

Rail freight traffic will also be routed mainly via the railway line on the opposite riverside and the Rhine-Sieg railway line between the cities of Cologne, Siegen, Giessen and Frankfurt (Figure II.2.14). But due to limited rail capacities, around 20% of the rail freight traffic needs to be transported on the road by truck. This intermodal shift leads to about 900 additional trips or 676,000 additional truck km per day.

Figure II.2.16 shows the high importance of international inland waterway transport via the affected section. In 2030, cargo of about 250,000 t per day will be transported through this area by inland waterway vessels. Approximately 30 % of this freight traffic consists of iron ore, coal, crude oil and mineral oil products. For these product groups, storage capacities of three to four weeks are usually available, which enables a temporal shift of the affected freight traffic. The remaining cargo (about 176,000 t per day) needs to be shifted to alternative modes of transport.

Due to limited rail capacities, only about 57 % of the remaining cargo can be shifted to the rail, which corresponds to approximately 346 additional freight trains per day. As a result of the increase in freight traffic, several railway lines are overloaded and cannot take any additional traffic (Figure II.2.15). The cargo affected by these capacity limitations is finally shifted to the road. The additional daily load of approximately 5,400 trucks or 2.8 million truck km does not cause significant changes in traffic quality of the road network.

In summary, the flooding scenario for the forecast traffic and infrastructure situation of the year 2030 leads to a significant rerouting and intermodal shift of passenger and freight traffic, which causes additional costs of € 2.5 million per day of closure.

Figure II.2.12 Transport infrastructure of the Middle Rhine region

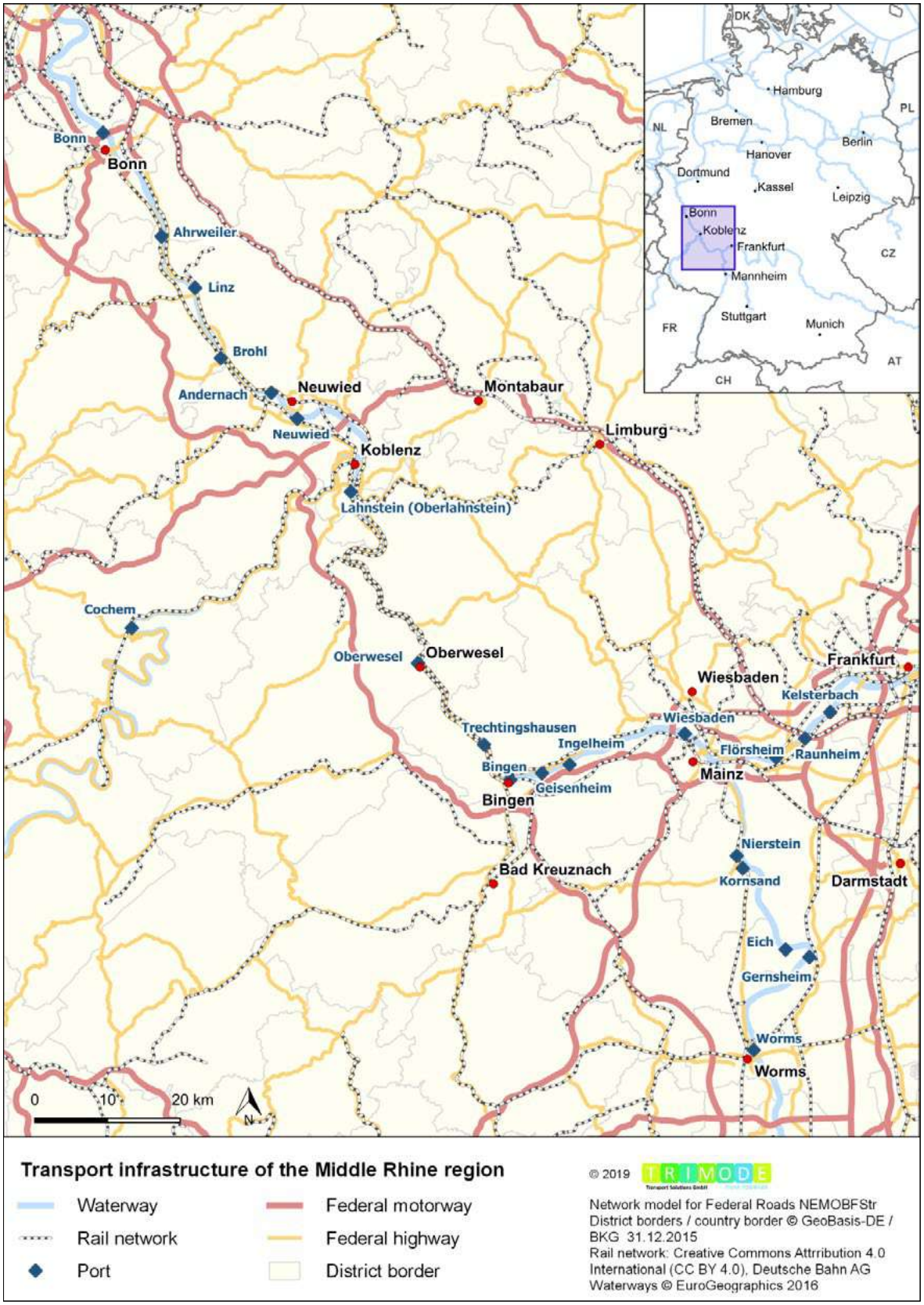


Figure II.2.13 Changes in car and truck traffic due to the extreme flooding of the left bank of the Rhine River at Oberwesel

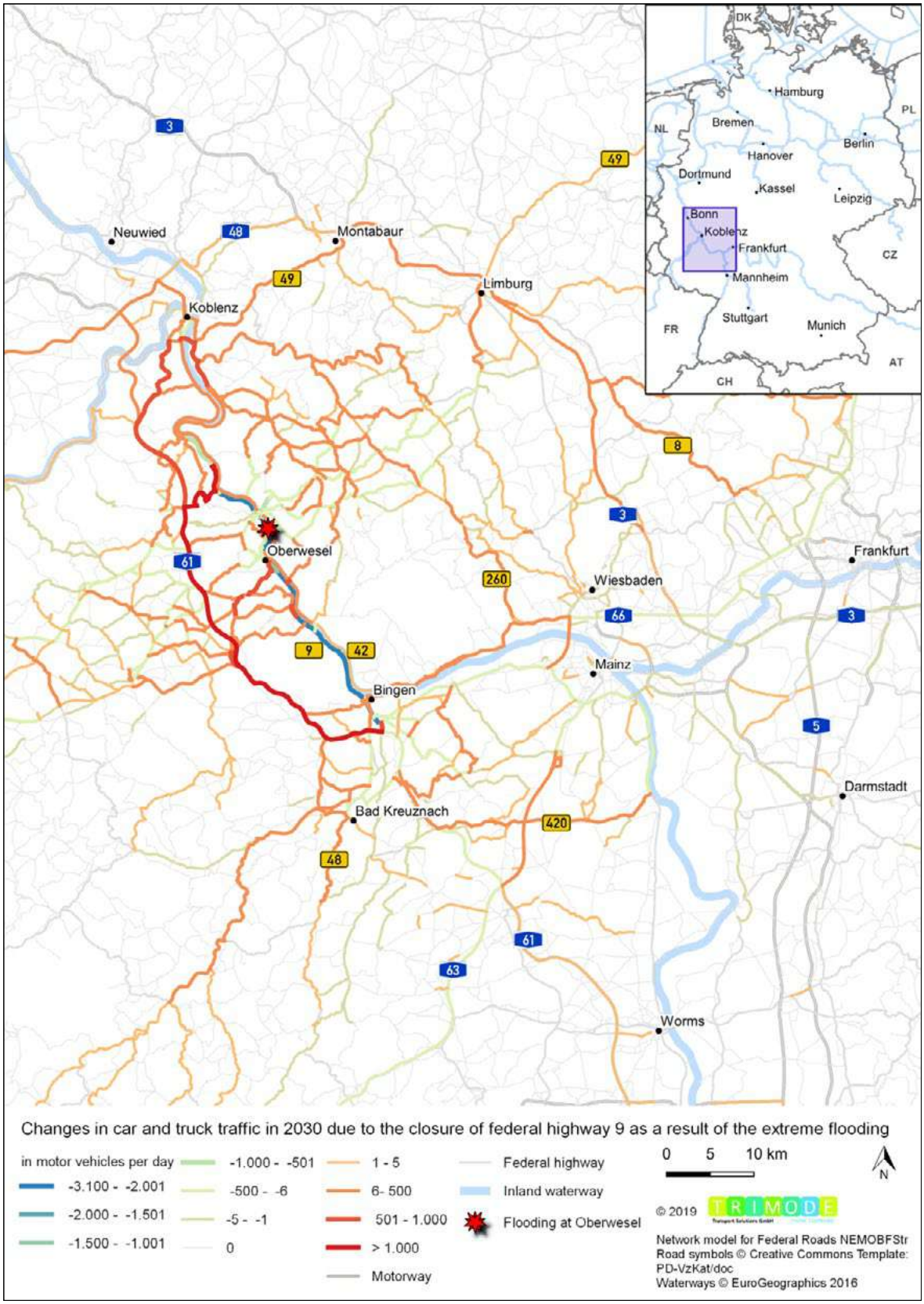


Figure II.2.14 Changes in rail freight traffic due to the extreme flooding of the left bank of the Rhine River at Oberwesel

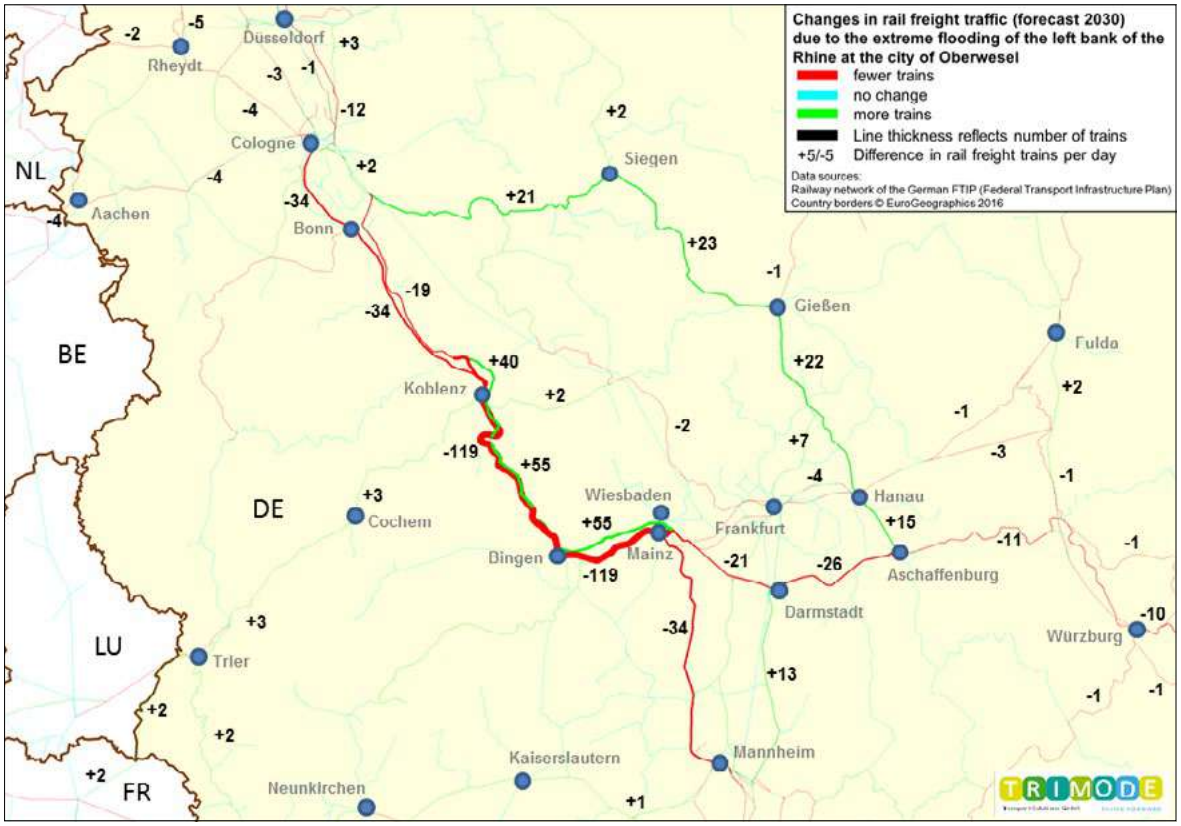


Figure II.2.15 Flooding in the area of Oberwesel (forecast 2030) – Traffic load in rail freight trains per day

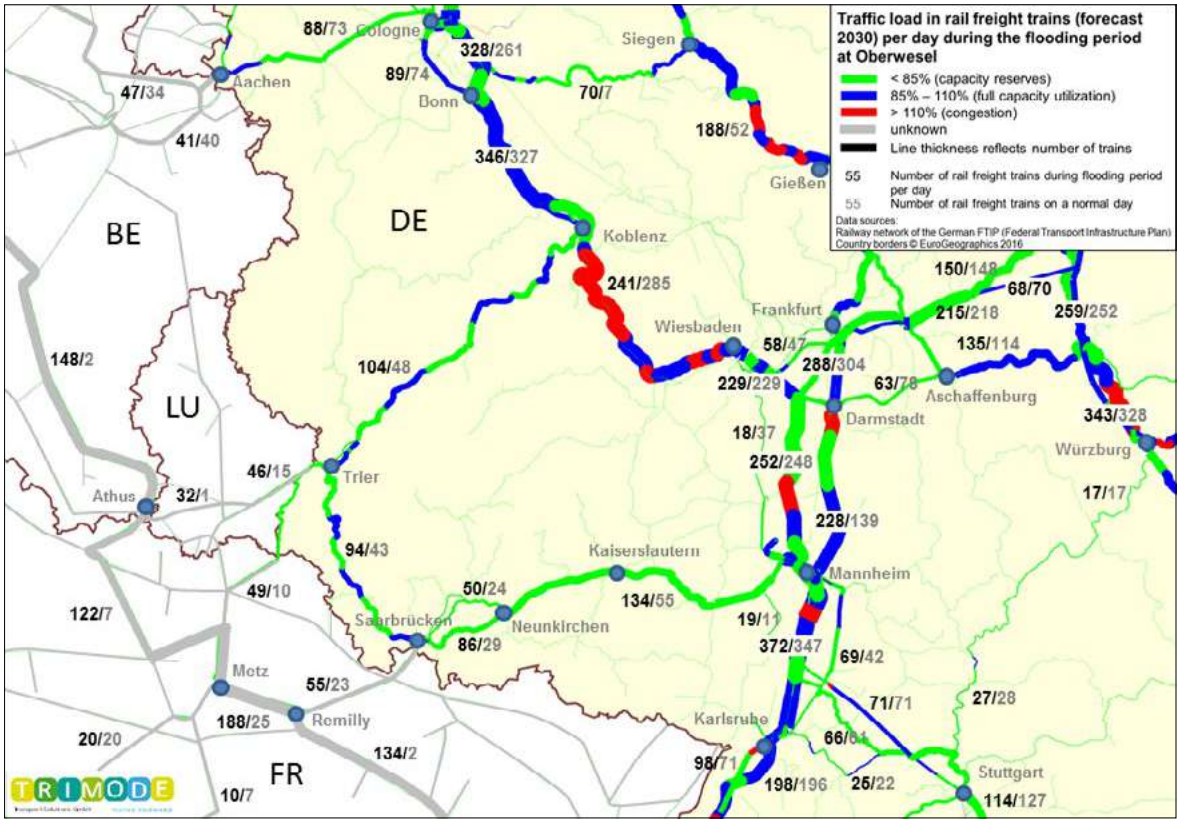
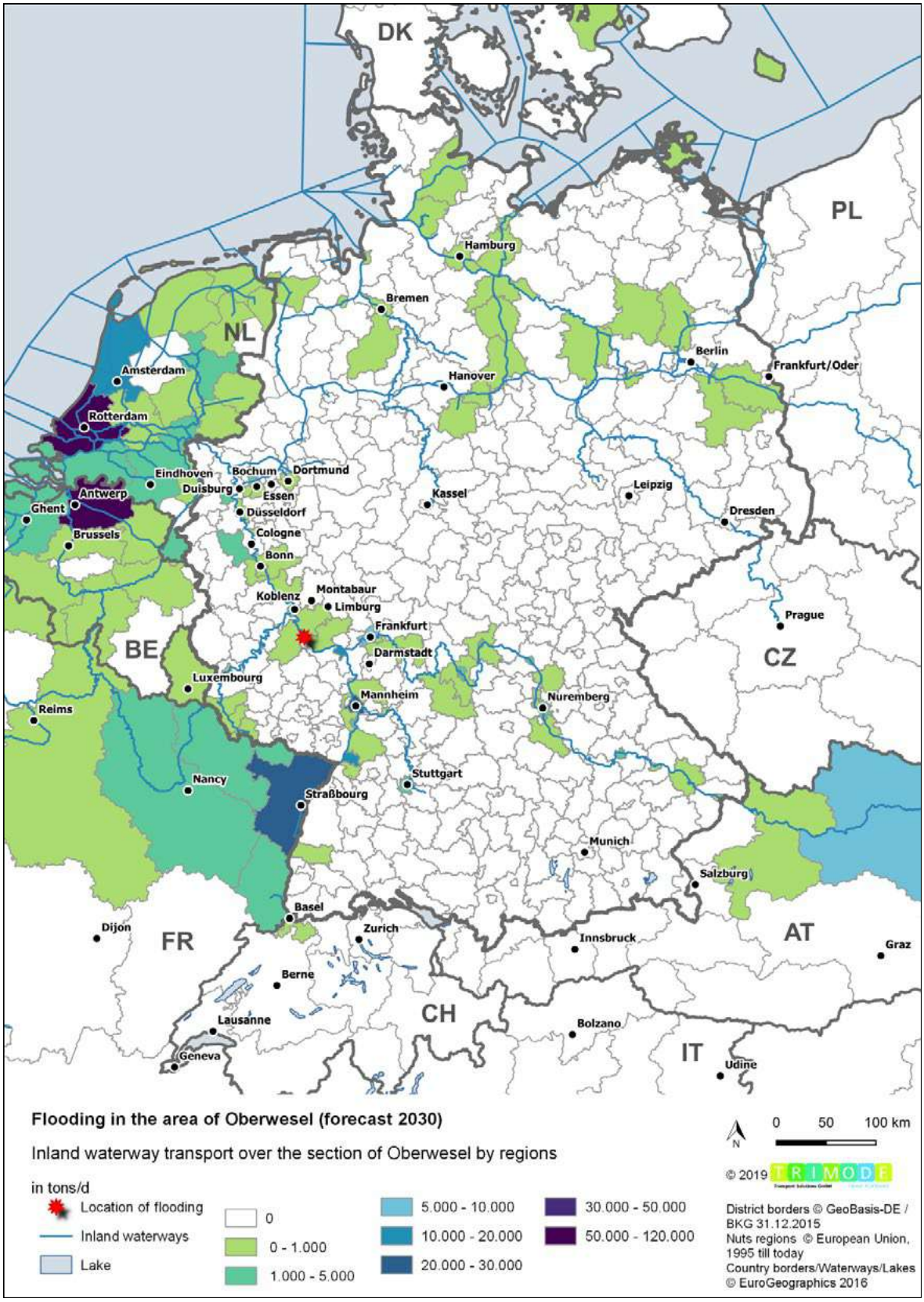


Figure II.2.16 Flooding in the area of Oberwesel (forecast 2030) – Inland waterway transport over the section of Oberwesel by regions



Case study 7 (Iceland)
Sea level changes, guidelines and adaptation

I. Introduction

This case study discusses sea level changes in Iceland and the preparation of guidelines to facilitate adaptation for transport assets in coastal area. It was prepared by: Ásta Thorleifsdóttir (Ministry of Transport and Local Government) and Sigurður Sigurðsson (The Road and Coastal Administration).

II. Background

The Arctic is experiencing a fast changing climate. The government of Iceland announced, in September 2018, a new Climate Strategy, including a proposal for a national framework as a basis for cutting emissions and conducting infrastructure climate change impact assessments. Simultaneously a nationwide plan for mitigation and adaptation, including that of the transport system, is in progress. Expected sea level rise is accounted for in the construction of new harbour facilities, as well as in maintenance and reconstruction of older infrastructure. Recommendations are regularly updated by the Road and Coastal Administration and the current, issued in 2018, the baseline of construction in low-lying areas was raised by 30 cm.

Iceland is experiencing the impact of climate change fast. Since 1980 the average mean temperature has risen by 0,5°C, more than 10 per cent and climate induced sea level changes are visible as in all other coastal states. What makes Iceland's situation unique, however, is that it is (i) situated just south of the Arctic circle, residing above a mantle plume on the Mid Atlantic Ocean ridge and (ii) about 10 per cent of its surface area is covered by fast retreating glaciers and (iii) the inhabitation as well as most transport infrastructure is in coastal areas (Figure II.2.17).

Various processes are active in causing relative changes to sea-level. Firstly, the global sea level is rising due to climate change. Secondly, the isostatic movements displayed by the rise or subduction of the crust give the sea-level rise different characteristics to most parts of the world. Finally, due to the proximity to the Greenland glacier the hypothesis is, that due to Greenland's Gravitational pull as it rises due to its melting glaciers, only a part of the global seal level rise is predicted to be realised in Iceland.

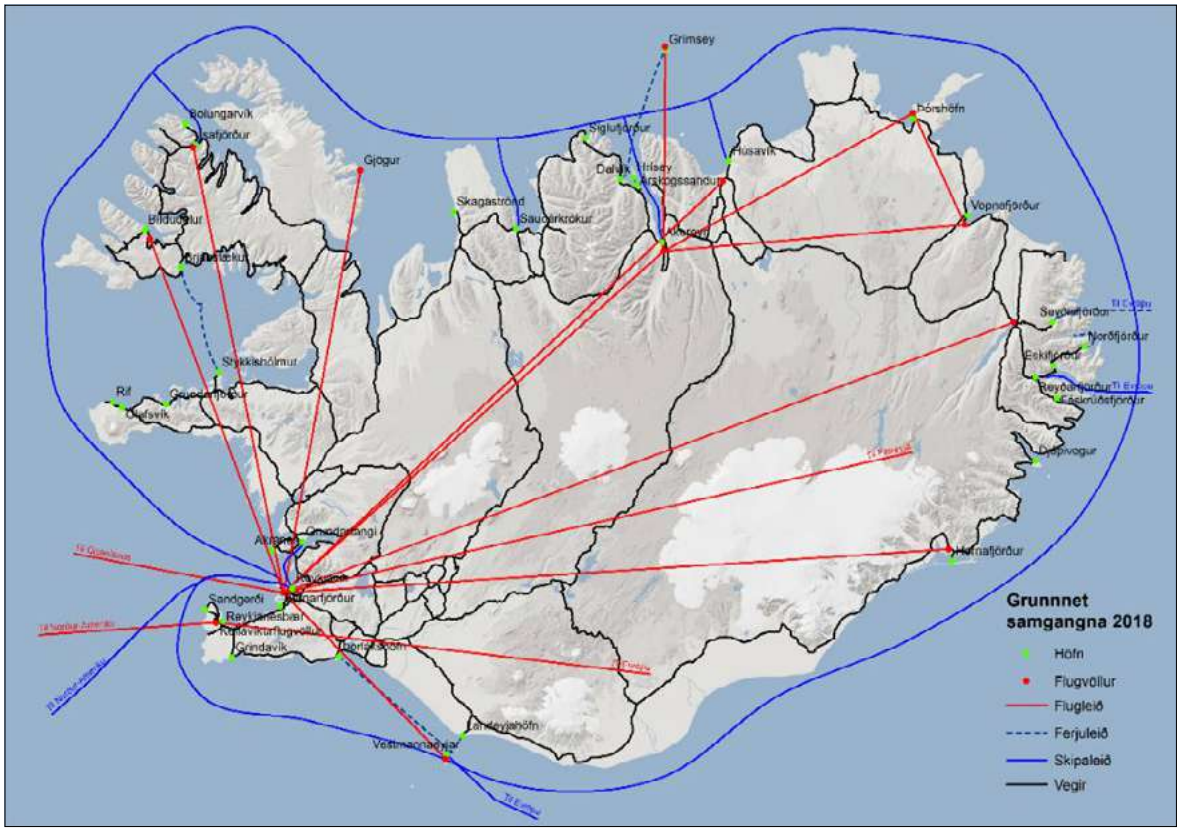
The relative changes in sea to land level have different implications. In Iceland, like all over the world, the population is concentrated around the coast. More and more coastal areas are being developed, both naturally low-lying areas as well as constructing on landfills, requiring official guidelines of acceptable land level in a changing environment.

In harbours, due to the sea level rise, quays and harbour areas must be raised in a timely manner to avoid flooding. In some areas, breakwater and revetment exposed to depth limited waves must be strengthened, while sea level rise has a positive influence on water depth in harbours.

Rising sea level relative to land causes coastal erosion. Large areas in Iceland are and have been for considerable time affected by erosion. Up to recently this erosion was more likely to be caused by isostatic changes and crustal movements rather than climate change.

The tidal inlet of Hornafjörður lies at the foothills of the Vatnajökull glacier in the southeast coast of Iceland. Within the inlet lies an important fishing harbour. Within the bay area of the inlet, the rapid lifting of land, due to the loss of ice mass, is already affecting tidal prisms and the navigational depth over ebb shoals near the harbour.

Figure II.2.17 The core transport infrastructure is coastal with few exceptions. Fishing being a main industry towns and villages are based on port facilities. The impact of climate change differs from the SE where the island's largest glacier is retreating fast, causing coastal uplift, to the SW region where sea level changes are enhanced by subduction. (red lines show domestic air routes)



III. Preconditions: Tidal measurements and crustal movements in Iceland

The process for assessments is based on two sets of measurements; (1) tidal measurements in harbours and (2) continuous GPS measurements of isostatic changes due to geological processes, as well as, climatological ones.

A. Tidal measurements

According to Annals and other historical written sources there are records of up to 290 storm surges and related floods in Iceland's coastal areas. Some of them minor, but others causing vast damages, such as the Basendafloð in 1799, when a powerful storm, combined with high spring tide, produced the worst, known flood in the southwest of Iceland. The storm surge and related flood is named after a small trading post and fishing harbour, washed away and destroyed during the event.

Iceland has only one time-series of reliable tidal measurements. This is the record from the old harbour in Reykjavik, done continuously since 1956 and thus spans more than 60 years.

Statistical analysis of the tidal record from Reykjavik shows that with a 30 cm rise in sea level, the 100 to 200-year flood will have a 2-year return period.

The Icelandic Road and Coastal Administration is planning to install a system of roughly 20 tidal recorders, which will be distributed around the Icelandic coast and placed within harbours.

B. Isostatic Land level changes

Iceland is located on the Mid-Atlantic Ridge, a divergent tectonic plate, which mostly results in horizontal crustal movements: the rate of seafloor spreading being on the average 2 cm/year. As the plates move away from the plate boundary, the crust cools, densifies and subducts slowly, as is the case of the Northwest and the East of the island, geologically the oldest parts of the country. In some areas there are, as well, local vertical movements, such as the tip of the Reykjanes peninsula, were the lowering of land, subduction, adds to the sea level rise. Thirdly, the crustal response of the increasingly fast melting of the Icelandic glaciers, some of which are predicted to lose all their ice-mass before the turn of the century. New geodetic data reveals an increasing uplift, exceeding 40 mm/year and based on a time series from 1992 the uplift in the Vatnajökull region has increased in a logarithmic manner which correlates to the increase in temperature during the same period (Figure II.2.19, Table II.4). The loss of ice mass is causing relatively fast uplift in the southeast, where the rising of land more than outweighs the sea level rise due to climate change considerably on the coast, causing a unique problem for harbour infrastructure and its access through a narrow channel (Figure II.2.18, Table II.3).

Figure II.2.18 Changes in vertical height over the 11 years period from 1993 and 2004 measured at the ISNET campaign GPS stations. Positive numbers indicate uplift and negative are subsidence, Valsson et al. 2007.

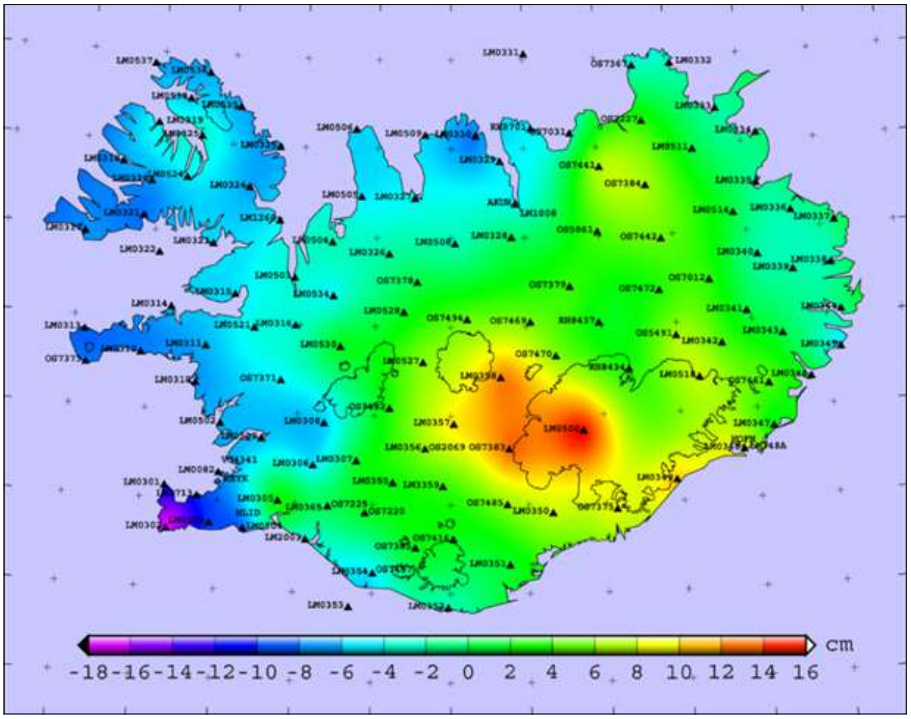


Table II.2.3 Vertical velocities at selected locations around Iceland based on GPS measurements. Names of some locations have been changed over to the nearest town.

Location	Measured period	Vertical velocites (mm/year)
Reykjavík, SW	1996–2015	–1.49 [-1.56 – -1.42]
Ísafjörður, NW	2009–2015	–1.82 [-2.08 – -1.56]
Siglufjörður, N	2008–2012	–2.32 [-2.65 – -2.00]
Grímsey, N	2008–2014	–4.72 [-4.97 – -4.48]
Akureyri, N	2001–2015	3.39 [3.31 – 3.47]
Húsavík, NE	2002–2015	0.15 [0.07 – 0.23]
Raufarhöfn, NE	2001–2015	0.27 [0.22 – 0.33]
Hornafjörður, SW	1997–2015	12.03 [11.96 – 12.11]
Vestmannaeyjar, S	2000–2012	3.18 [3.12 – 3.24]
Þorlákshöfn, SW	2000–2007	–1.04 [-1.18 – -0.91]
Sandgerði, SW	2006–2014	–4.62 [-4.71 – -4.53]

Figure II.2.19 Changes in vertical height over the 12 years period from 2004 and 2016 measured at the ISNET campaign GPS stations. Positive numbers indicate uplift and negative are subsidence. Preliminary results from the National Land Survey of Iceland.

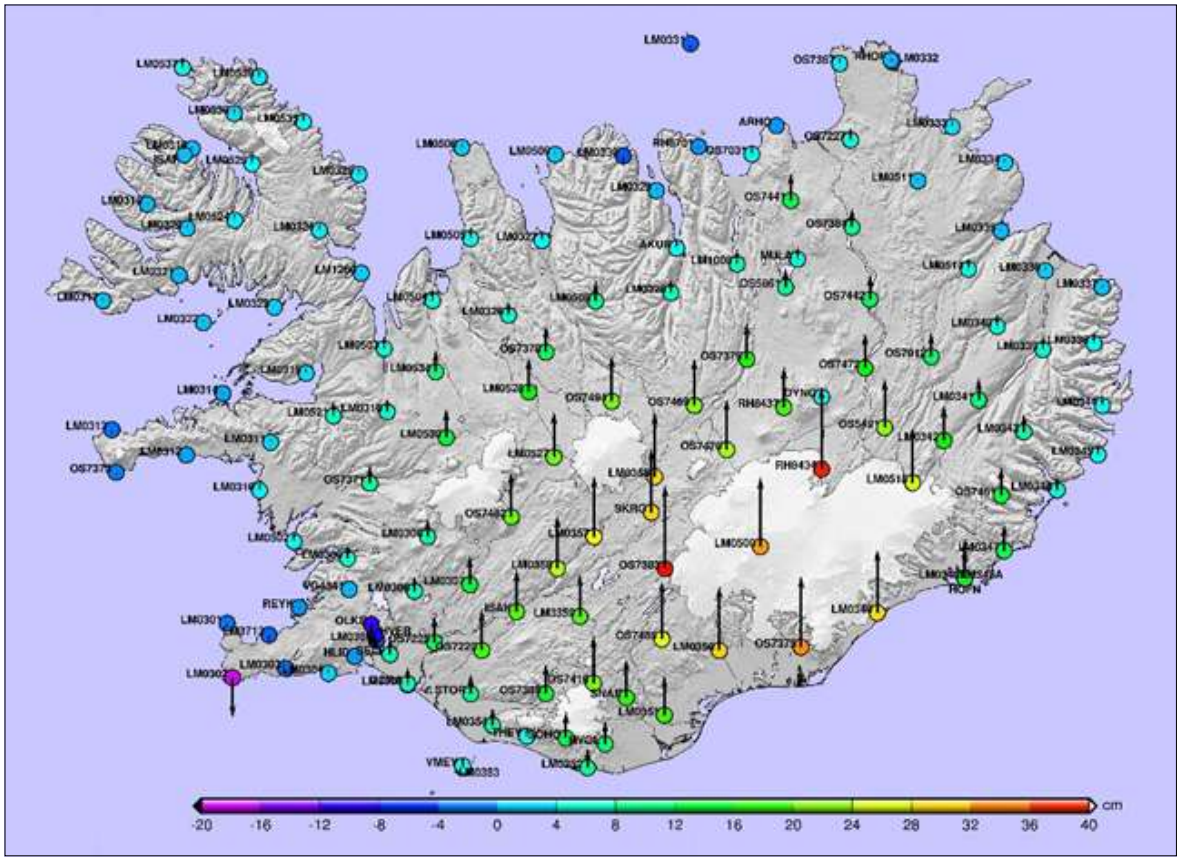


Table II.2.4 Changes in vertical height measured by GPS around Iceland. Noticeably retreating glaciers are causing swift uplift in the south and south east. From the report Global Climate Change and their impact in Iceland by The Scientific Committee on Climate Change: www.vedur.is/loftslag/loftslagsbreytingar/loftslagsskyrsla-2018.

Region	Crustal elevation changes (cm)	Part of global climatic SLR	Global climatic SLR		
			50 cm	75 cm	100 cm
			Total local SLR (cm)		
SW to NW Iceland	–20 to –10	30 to 34 %	25 to 37	33 to 45	40 to 54
NW and inland N Iceland	10 to 30	28 to 30 %	–16 to 5	–9 to 13	–2 to 20
Promontories on N Iceland	–30 to –10	28 to 30%	24 to 45	31 to 53	38 to 60
E part of N Iceland	0 to 20	30% to 32%	–5 to 16	3 to 24	10 to 32
NE Iceland	0 to 10	32 to 38%	6 to 19	14 to 29	22 to 38
E Iceland	0 to 20	38 to 40%	–1 to 20	9 to 30	18 to 40
SE Iceland	100 to 200	20 to 28%	–190 to –86	–185 to –79	–180 to –72
S Iceland	20 to 40	30 to 32%	–25 to –4	–18 to 4	–10 to 12
S and W Reykjanes peninsula	–30 to –10	32 to 34%	26 to 47	34 to 56	42 to 64

IV. The Icelandic guideline for construction in low-lying areas

Ports are critical infrastructure assets that serve as catalysts of economic growth and development, especially on an island, whose freight in and out of the country depends on the ports. The Icelandic Maritime council, as well as other stakeholders, are aware of the importance of raising the level of knowledge on resilience and preparedness for ports

To prepare for sea level rise is necessary. In 2018, the Icelandic Road and Coastal Administration published recommendations, a new guideline, for construction in low-lying areas, including harbour infrastructure. In the guideline, some 30 cm are added to the former minimum land-height due to rising sea-level. Due to the varying conditions along the coast (i.e. due to isostatic movement, mainly due to melting glaciers) the guidelines recommendations must be interpreted accordingly.

The guidelines also have an impact on the design and construction of roads in coastal areas.

The case of The Associated Ports in Southwest Iceland

Although the present recommendation by the Icelandic Road and Coastal Administration for new construction and larger maintenance projects is that the minimum land-height should be raised by 30 cm, the harbours in the Metropolitan area around the Faxafloi bay – The Associated Icelandic Ports, have taken a step further. In the construction of the new Skarfabakki berth, with a life expectancy of 50 years, the minimum land height is 70 cm higher due to the estimated impact of sea level changes. Even though it is a costly process, the board of directors has stated that it is a safer move, with the extra cost justified by less uncertainty.

V. Conclusions and forecast

Iceland is already experiencing the impact of sea level changes on its coastal infrastructure. The impact varies from one part of the country to another due to its young geology, and active glaciers causing crustal movements or drifting and isostatic uplift as the glaciers retreat and lose their ice mass. Different models predict different results although most agree that Iceland may experience the average sea level changes. To begin with, the Southeast of the country, sea level rise will be slower than the isostatic uplift due to the swift loss of ice-mass, whereas in other parts the ocean will rise faster due to the subduction of the cooling crust. The greatest uncertainty for Iceland lies with the prediction of the impact of the Gravitational pull of Greenland, due to the uplift of the landmass as the glacier melts, on the sea level around Iceland.

The Road and Coastal Administration as well as the Ministry of Transport and its Maritime council are effectively working on an adaption plan to minimize the economic impact of the changes by knowledge sharing and already the official recommendation is to heighten infrastructure in low-lying areas to meet the challenges of our fast-changing environment.

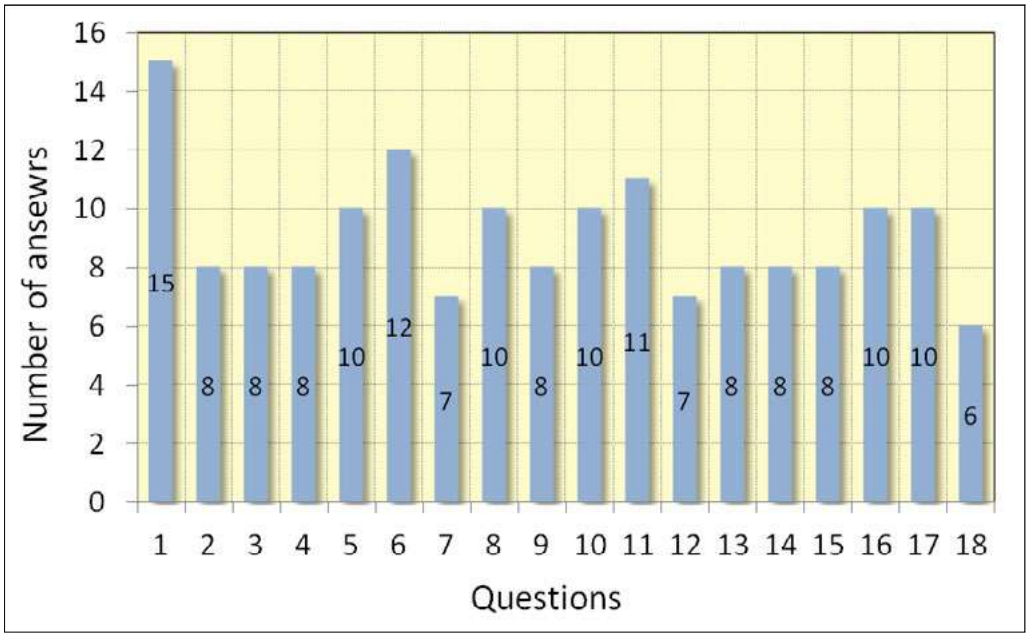
Photo: Teerapong Yovaga / shutterstock.com

Annex

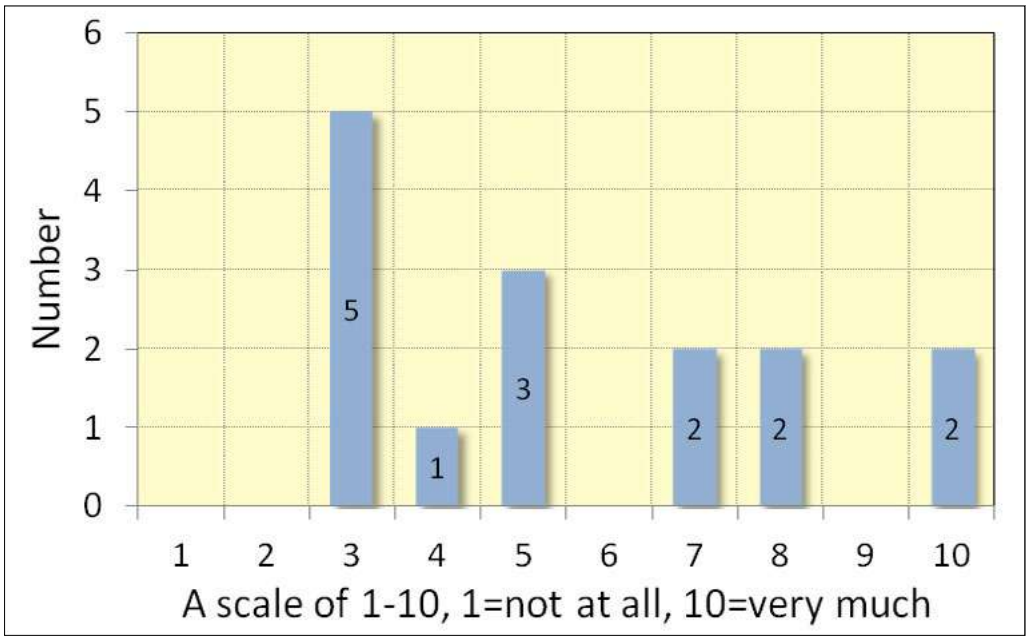
Analysis of responses to the climate change adaptation questionnaire 2016

15 questionnaires were analysed. Questions statistically analysed (figures): 1, 2, 3, 4, 5, 6, 8, 9, 10, 11, 12, 13, 14, 15 and 16, Descriptive questions: 7, 17 and 18

Number of countries that answered each question



Question 1: To which extent do you consider climate change and/or extreme weather events to be a problem for transport in your country/region (on a scale of 1–10)

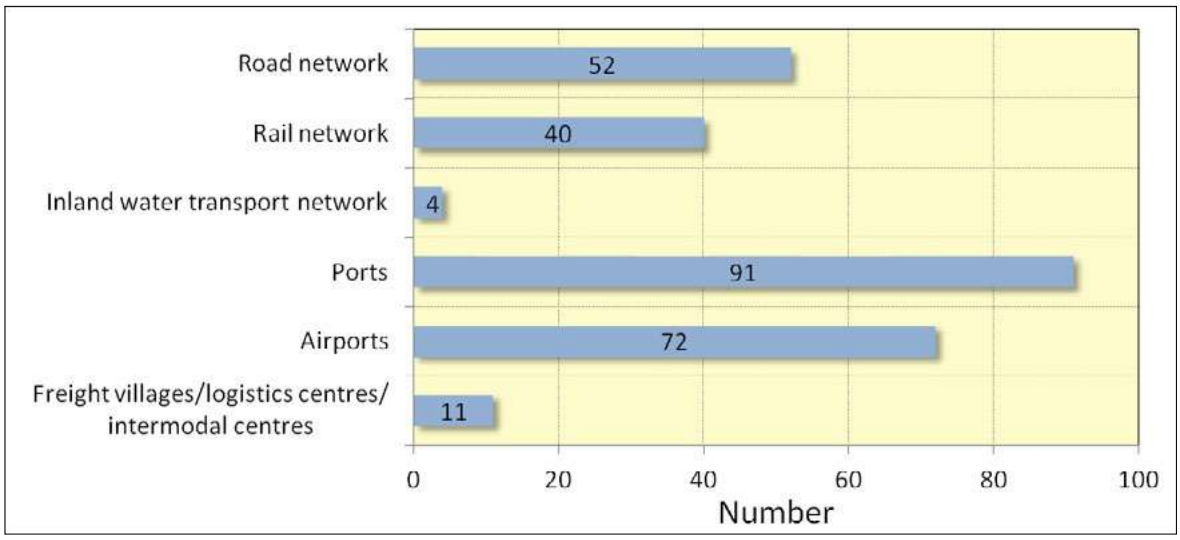


Question 2: Critical transport infrastructure: Please list below the transport arteries (road, rail, inland water transport) and nodes (ports, airports, freight villages/ logistics centers/ intermodal centers) considered as critical in your country/region and specify their criticality.

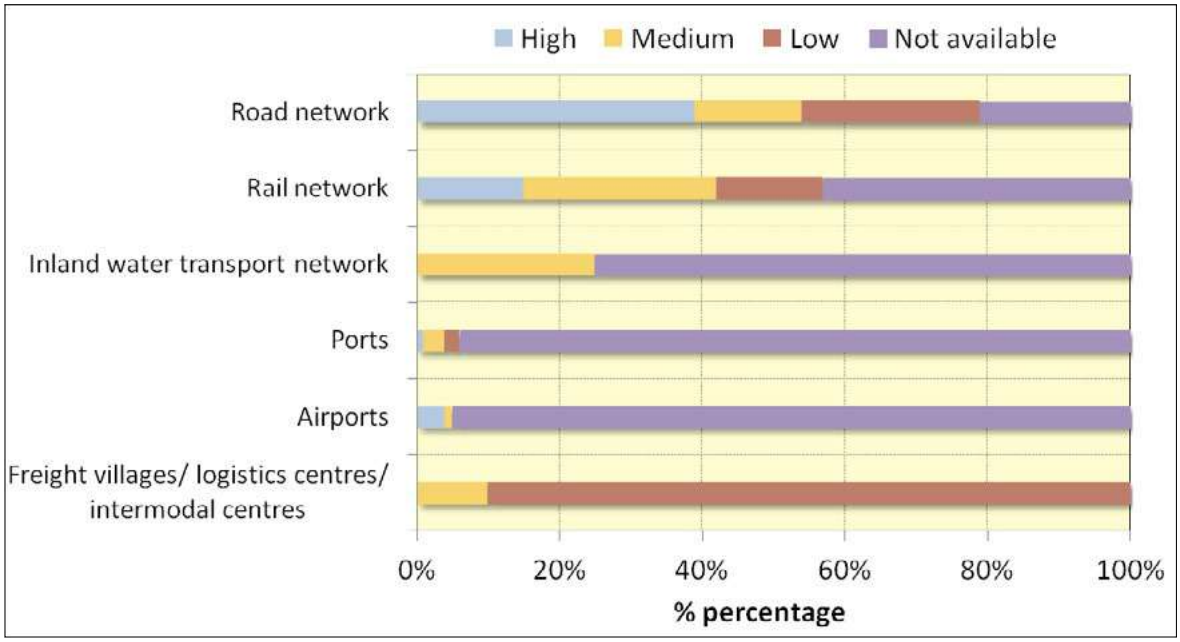
The number of the critical assets recorded by 8 countries who answered the question.

Turkey gave 2 Annexes with the list of airports (55) and seaports (71) but do not specify if they are all critical; All have been counted.

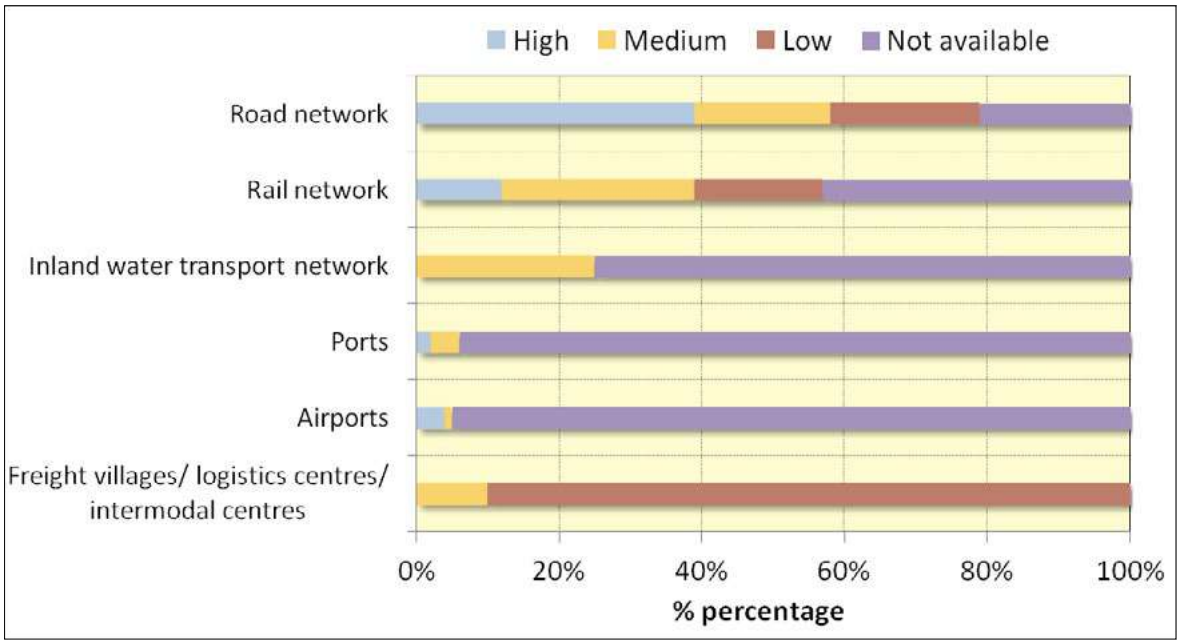
Reported number of critical transport infrastructure



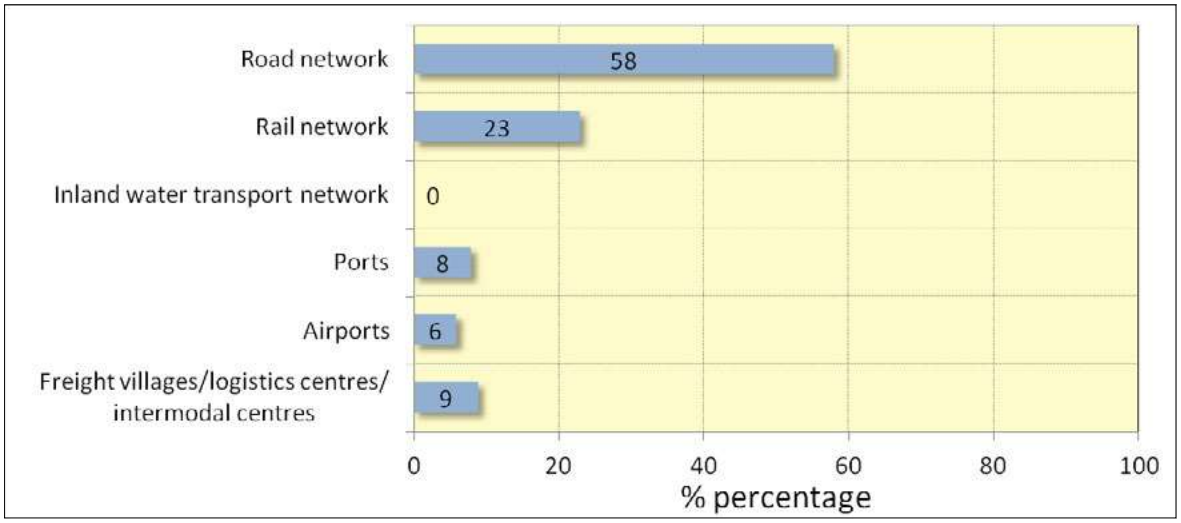
Estimated number of users affected

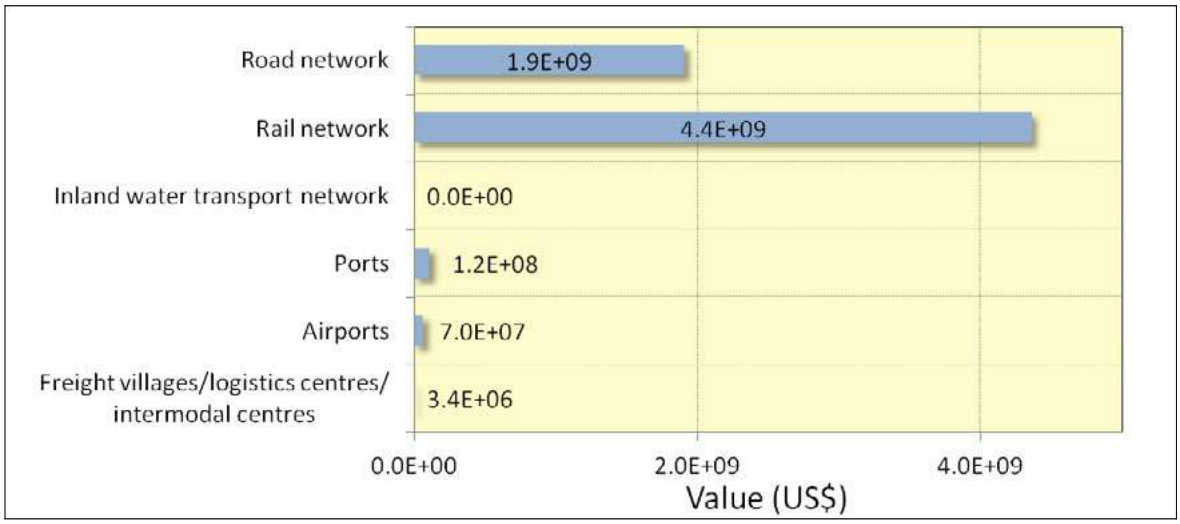


Estimated economic loss



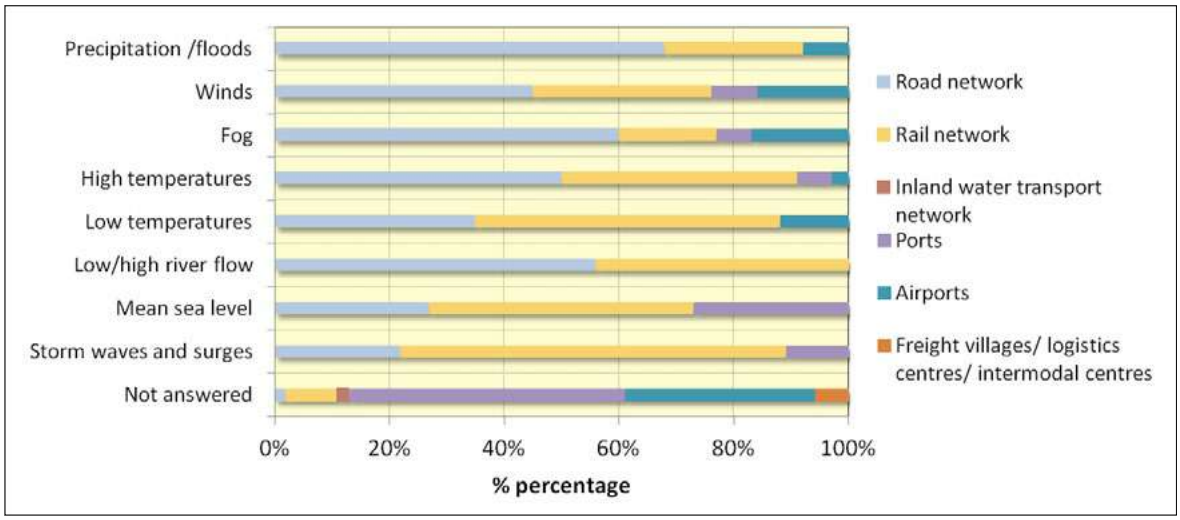
Question 3: Do your Government / organization plan any investments in the next 5 years in the above-mentioned critical infrastructure? If yes, please specify the investment and indicate its total value (in million US$). Do planned investments in the above indicated critical infrastructure consider impacts of extreme weather and/or other climate related factors? If yes, please specify for each investment.





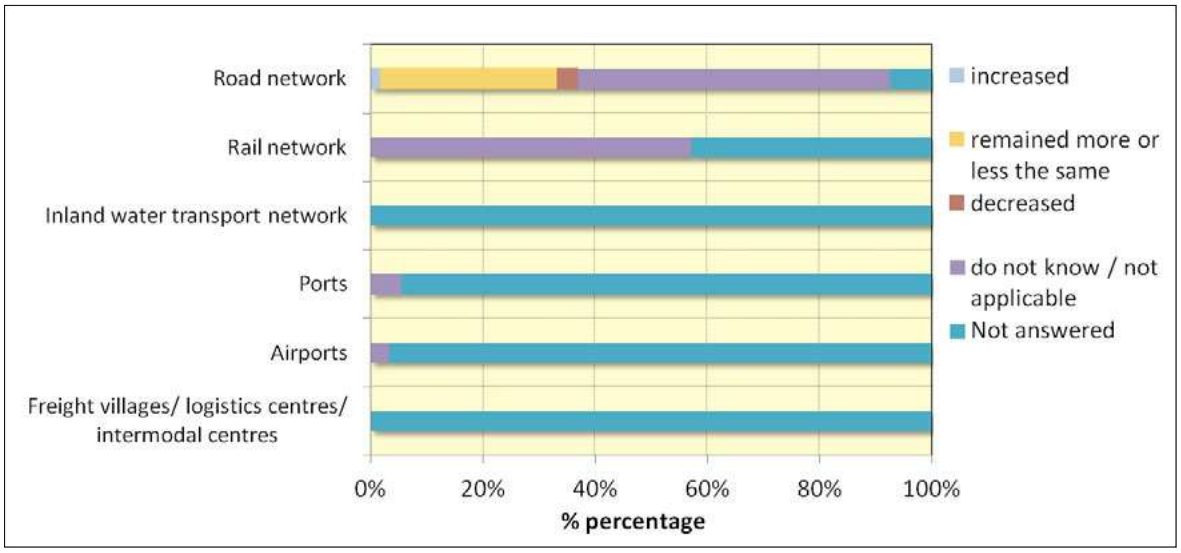
* The value was not available for all the above investments.

Question 4: Which of the following weather or climate related factors have impacted your critical infrastructure mentioned above (check all that apply)



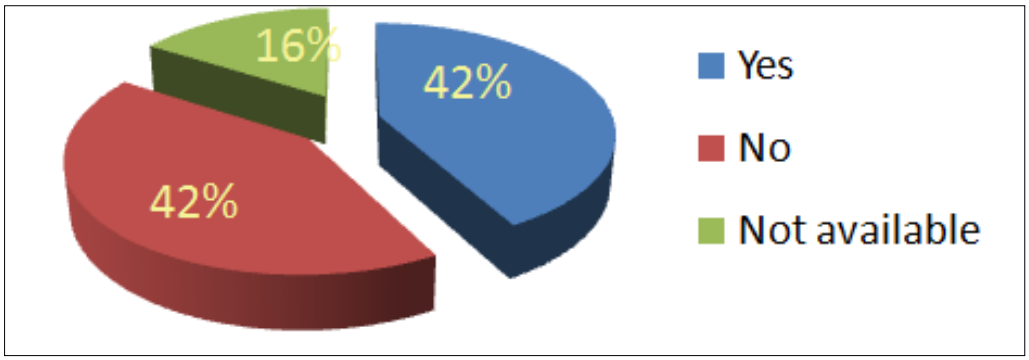
* Not answered: a list of assets was given in question 2 but in the following questions there was no information for all them, those with no information are included in the category not answered; the assets listed in the Turkey's annexes are also included.

Question 5: Over time, has the magnitude of damage and/or disruption caused by weather or climate related events:



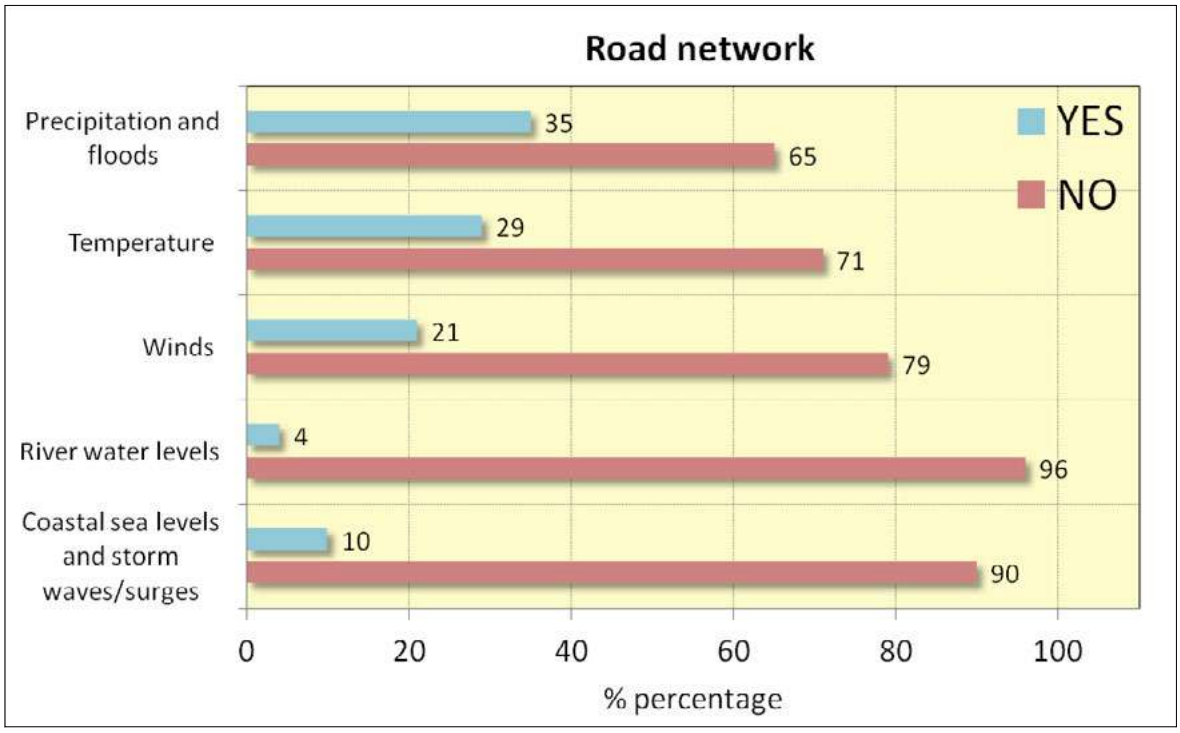
* Not answered: a list of assets was given in question 2 but in the following questions there was no information for all them, those with no information are included in the category not answered; the assets listed in the Turkey's annexes are also included.

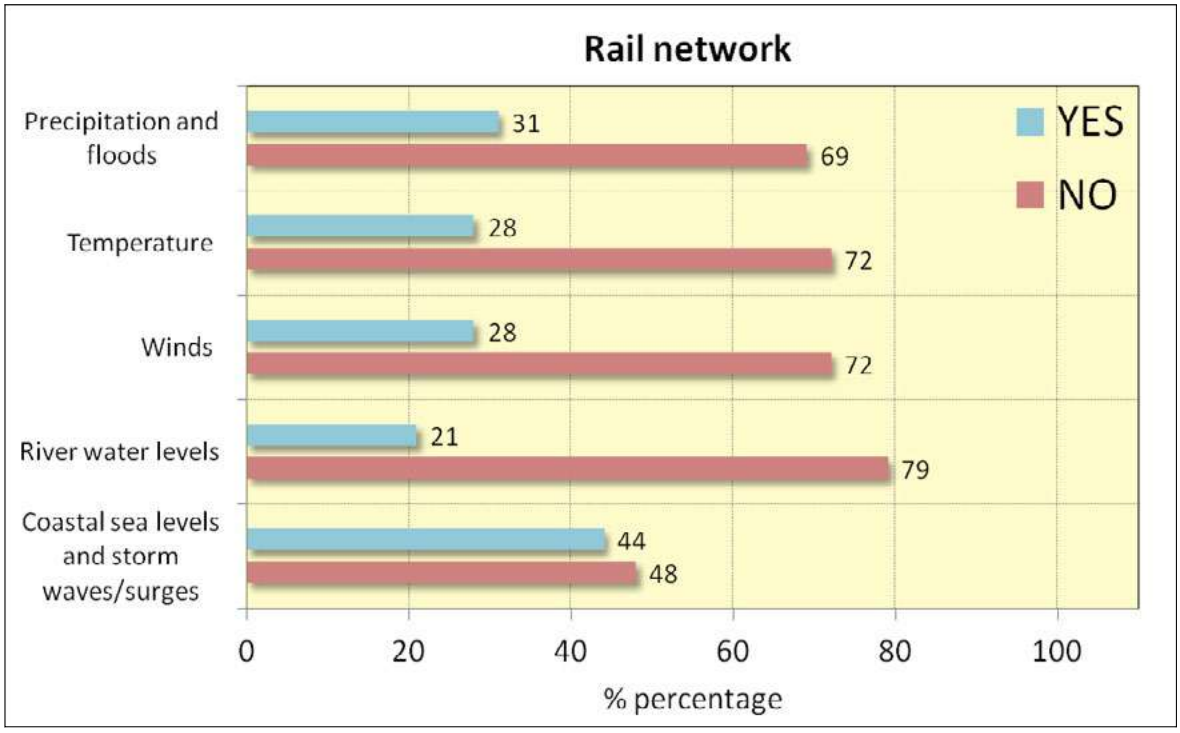
Question 6: Have users of the critical infrastructure requested implementation of effective response measures?

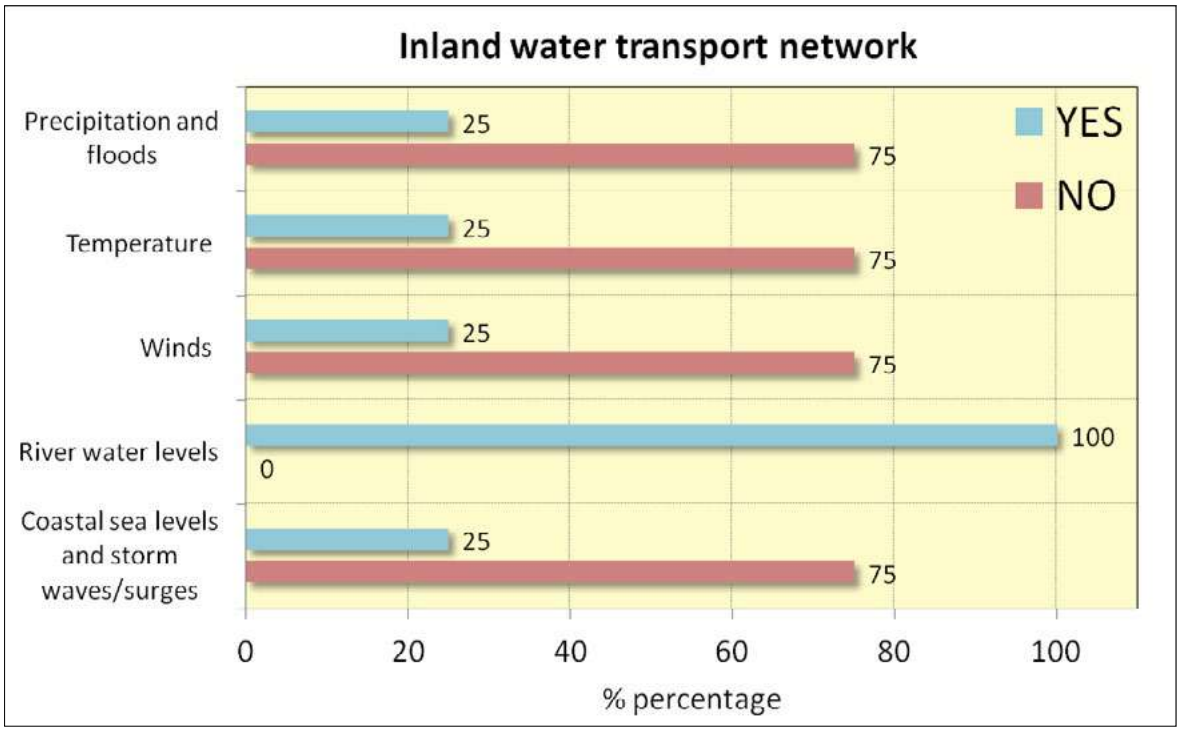


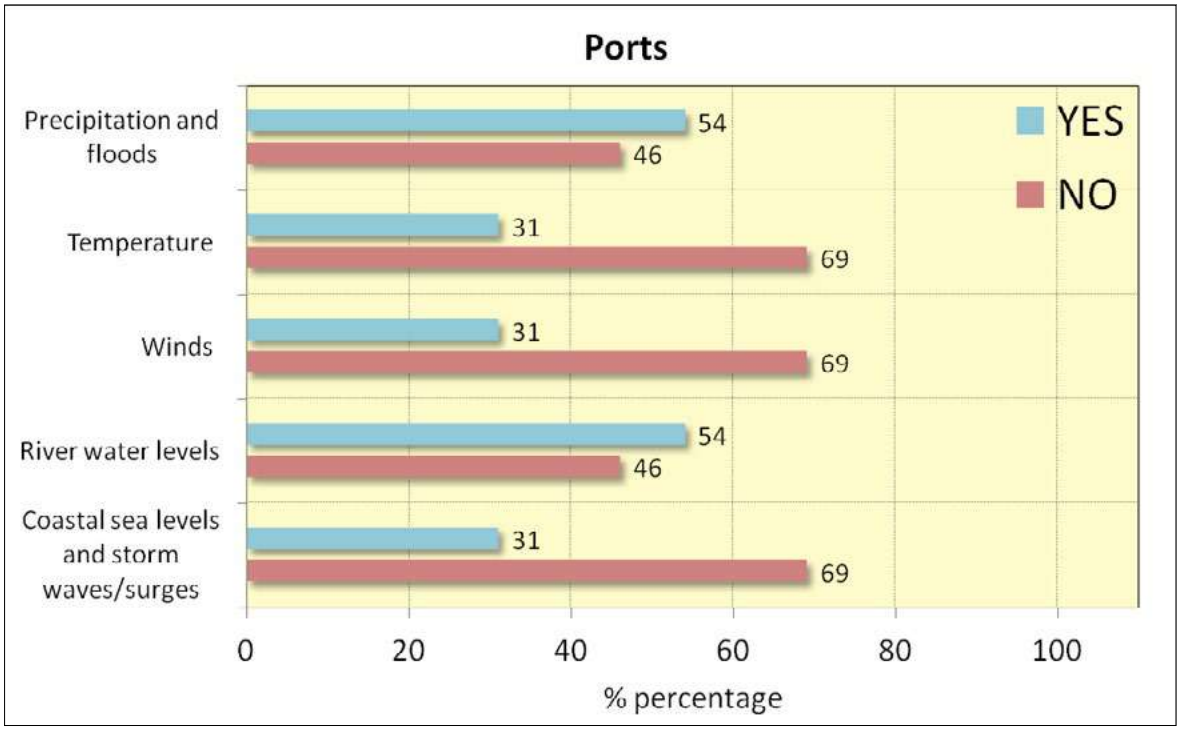
Question 8: Is there information available on the following climate change impacts that have affected or will potentially affect critical infrastructure in your country/region/organization?

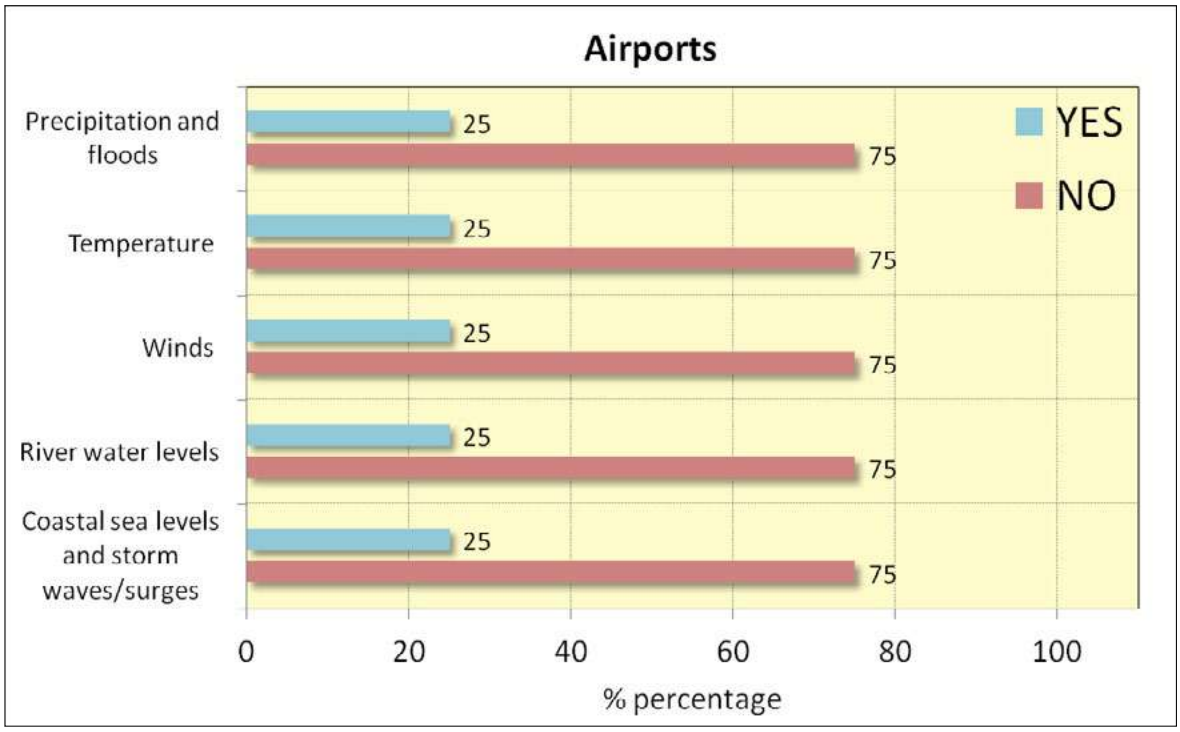
(There was no information for the assets listed in the Turkey's annexes and are not included)





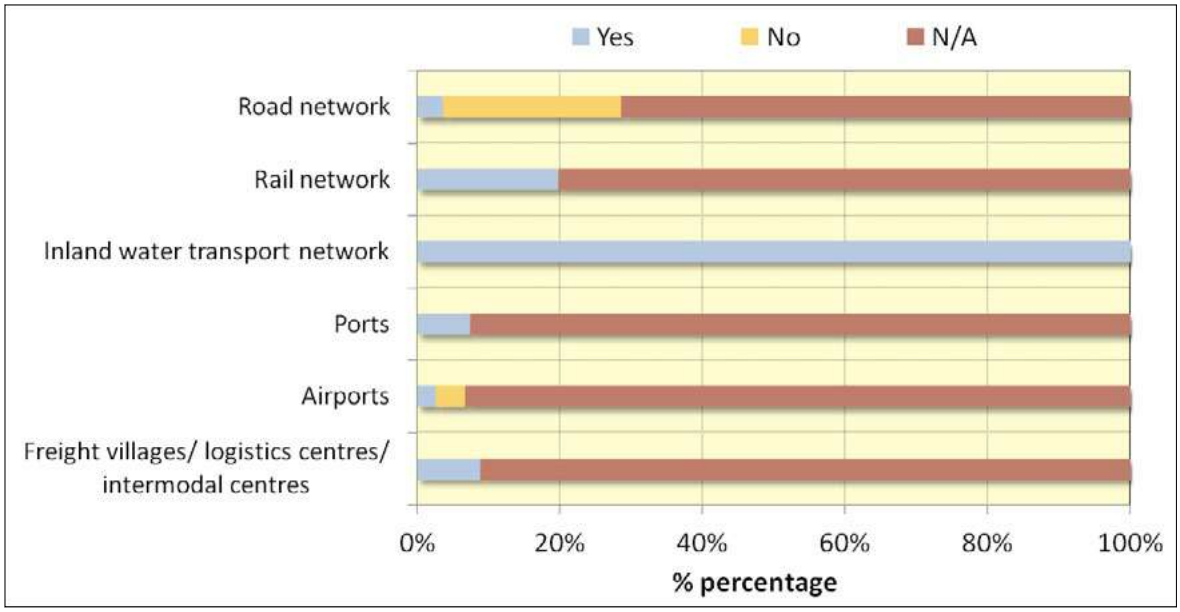

Inland water transport network
Precipitation and floods
Temperature
Winds
River water levels
Coastal sea levels and storm waves/surges
25
75
25
75
25
75
100
0
25
75
YES
NO
0
20
40
60
80
100
% percentage


Ports
Precipitation and floods
Temperature
Winds
River water levels
Coastal sea levels and storm waves/surges
54
46
31
69
31
69
54
46
31
69
YES
NO
0
20
40
60
80
100
% percentage

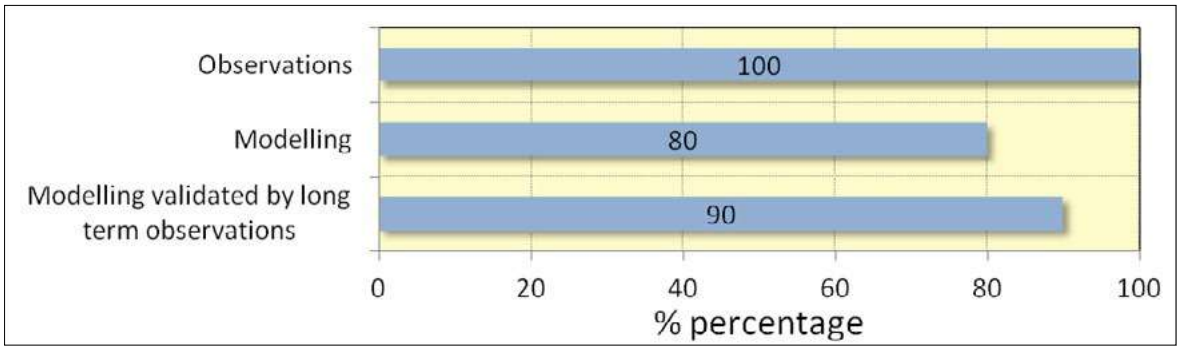


Question 9: If yes, have the observed trends already necessitated or will require adaptation responses?

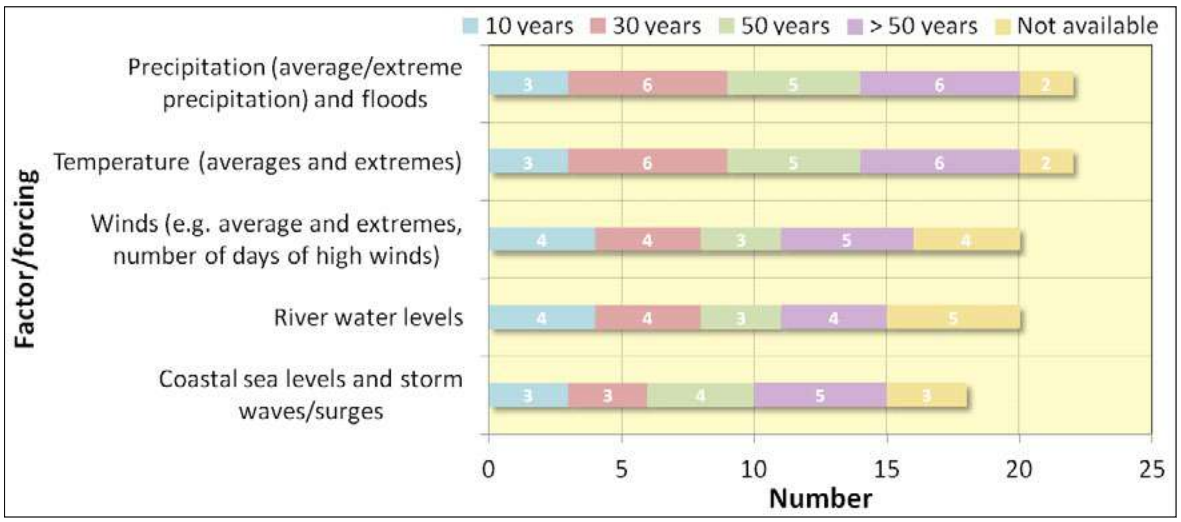
Turkey counted as N/A



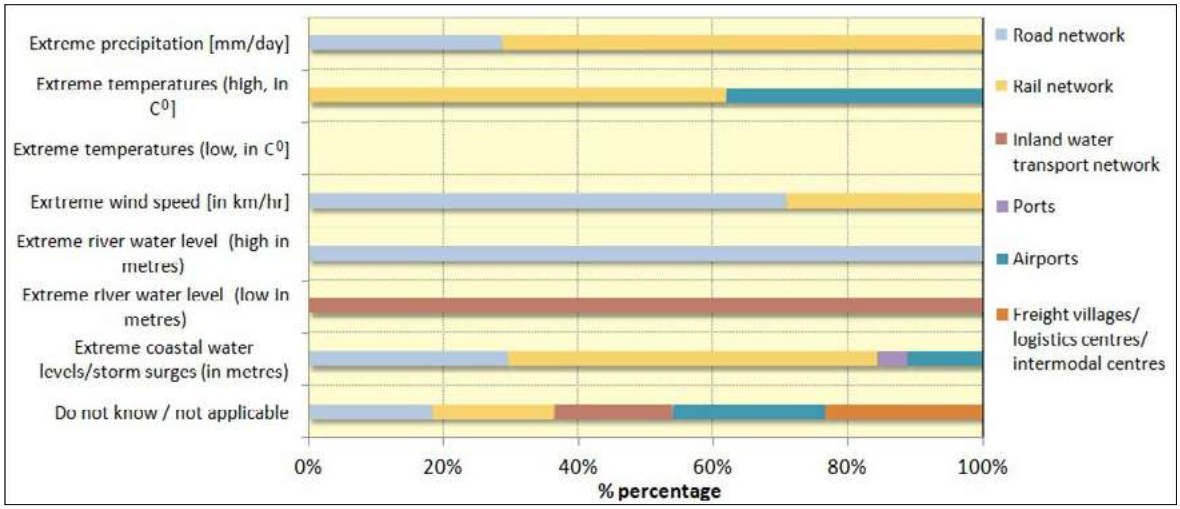
Question 10: Please indicate the basis for weather/climate information used in the estimation of impacts and the design of response measures regarding your critical infrastructure (check all that apply)



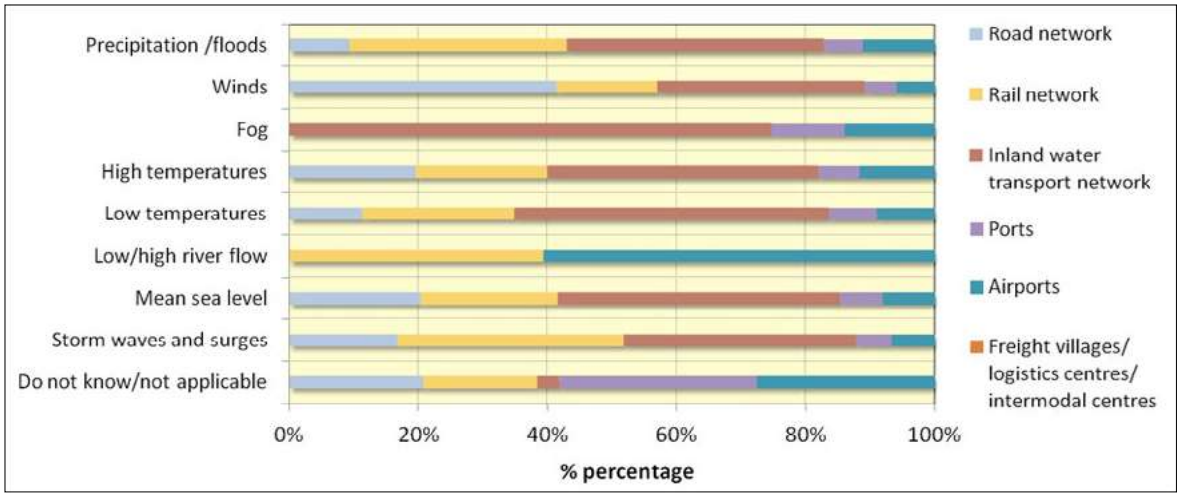
Question 11: Are downscaled forecasts or assessments available for your critical infrastructure regarding the following climate forcing and factors? If so, at which time scale? (Check all that apply)



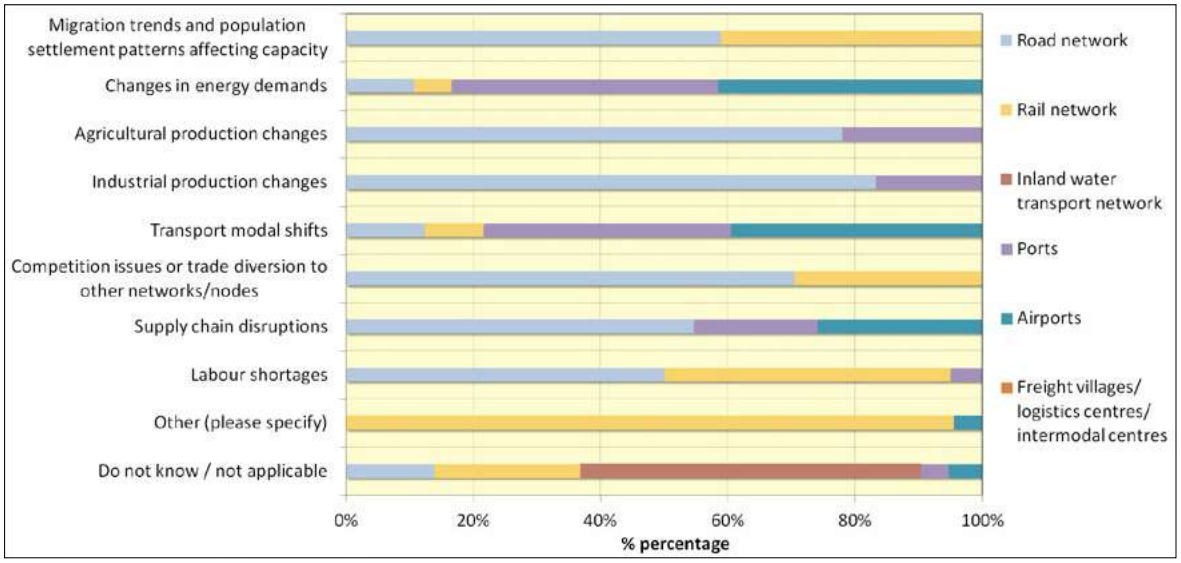
Question 12: Are At which thresholds do you expect that the integrity and functionality of the critical infrastructure of your country/region/organization will be significantly impaired? Indicate critical infrastructure of networks or nodes (multiple entries)



Question 13: Has your Government / Organization assessed or is planning to assess impacts/ vulnerabilities to weather or climate related events for the above-mentioned critical infrastructure? If yes, which of the following have been or are going to be considered in these assessments? Indicate critical infrastructure network (multiple entries, i.e. R1 road network, 1st entry)



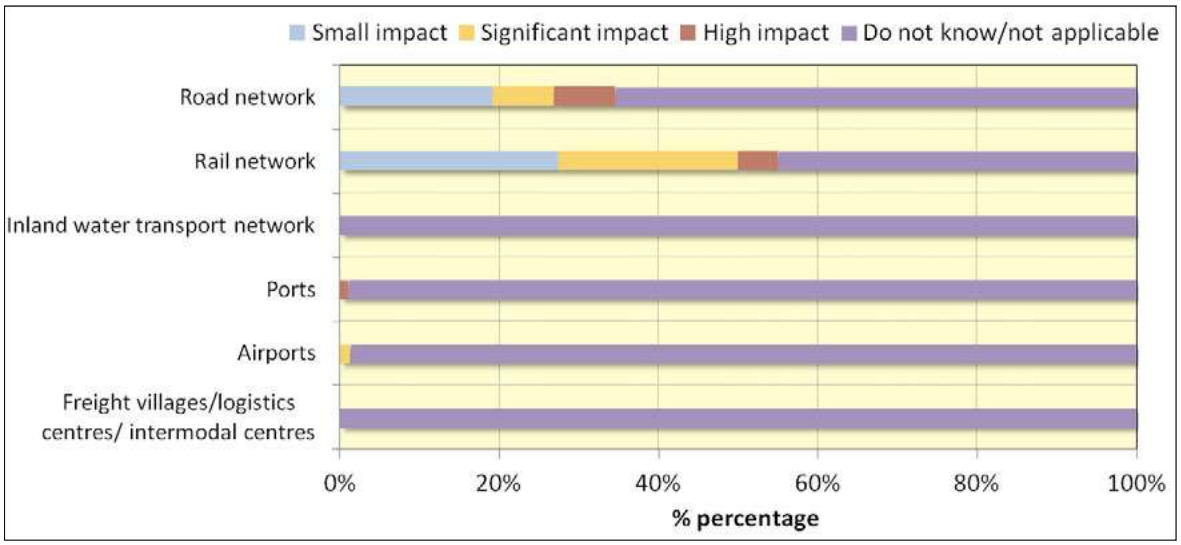
Question 14: Do you expect that the critical infrastructure in your country/region /organization will be (indirectly) affected by weather and/or climate induced changes to the following? (Check all that apply). Indicate critical infrastructure (if applicable, multiple entries-networks and nodes)



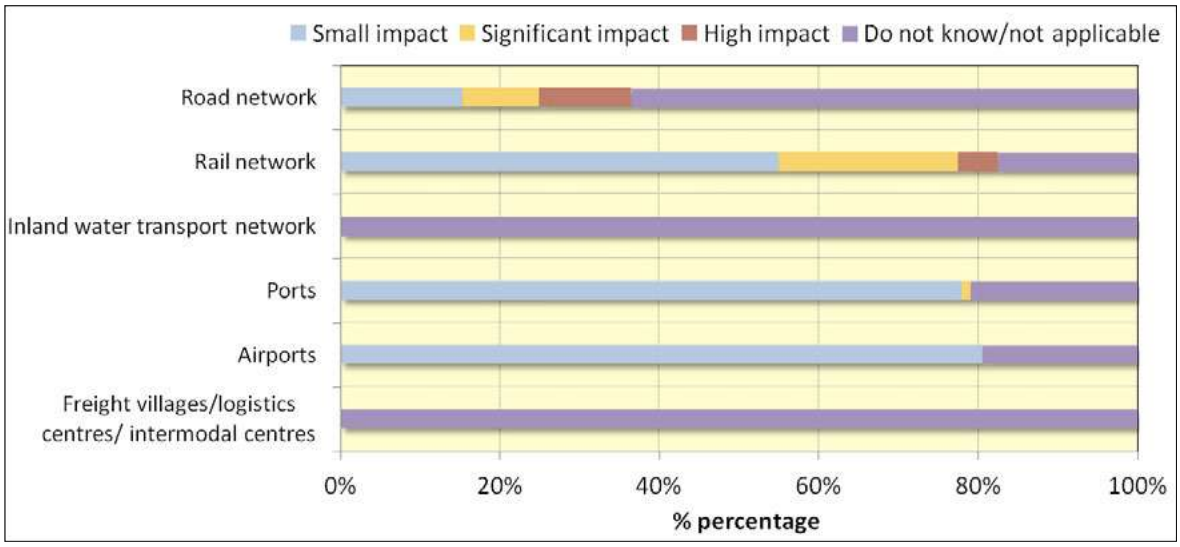
Question 15: Has any of the critical infrastructure mentioned above ever been impacted by weather and/or climate related factors, including extreme events? If yes, indicate the type and extent of impact (check all that apply):

Critical infrastructure network or node (multiple entries, i.e. R1, road network 1st entry)

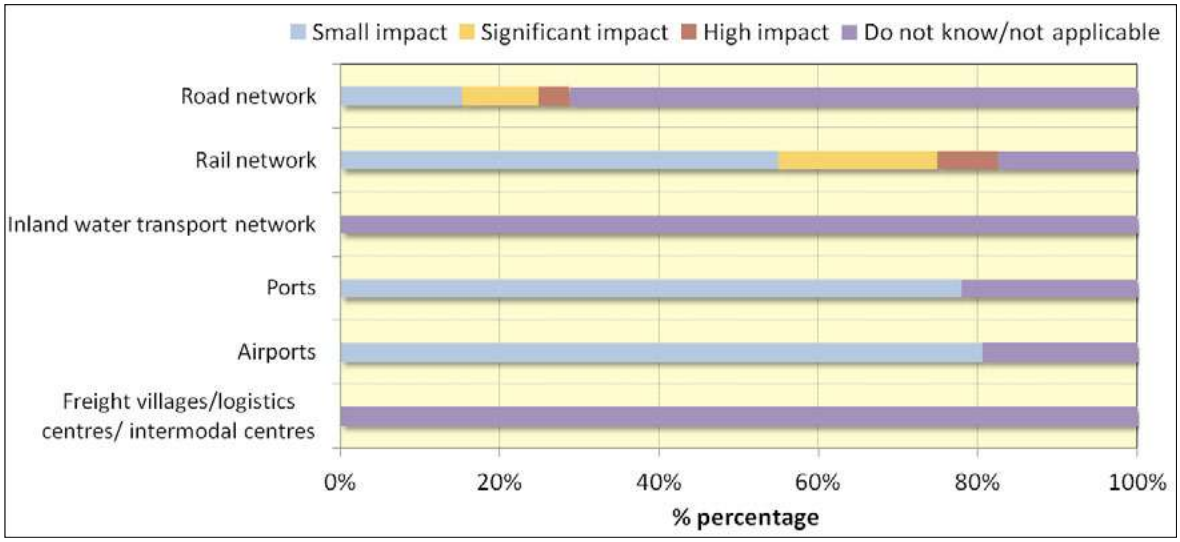
Extent of impact for Physical damage



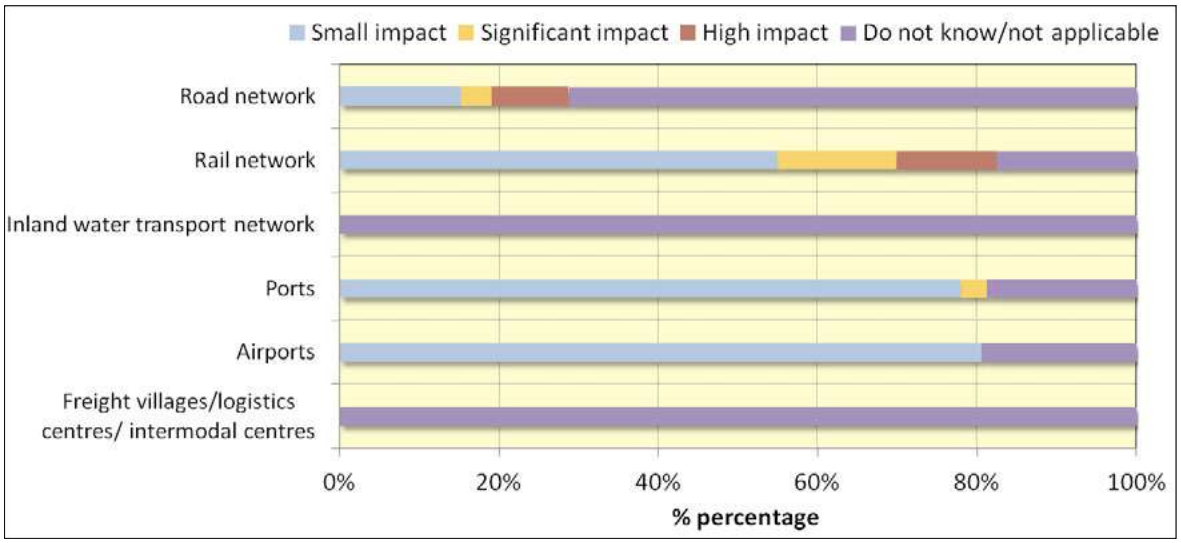
Extent of impact for Operational problems



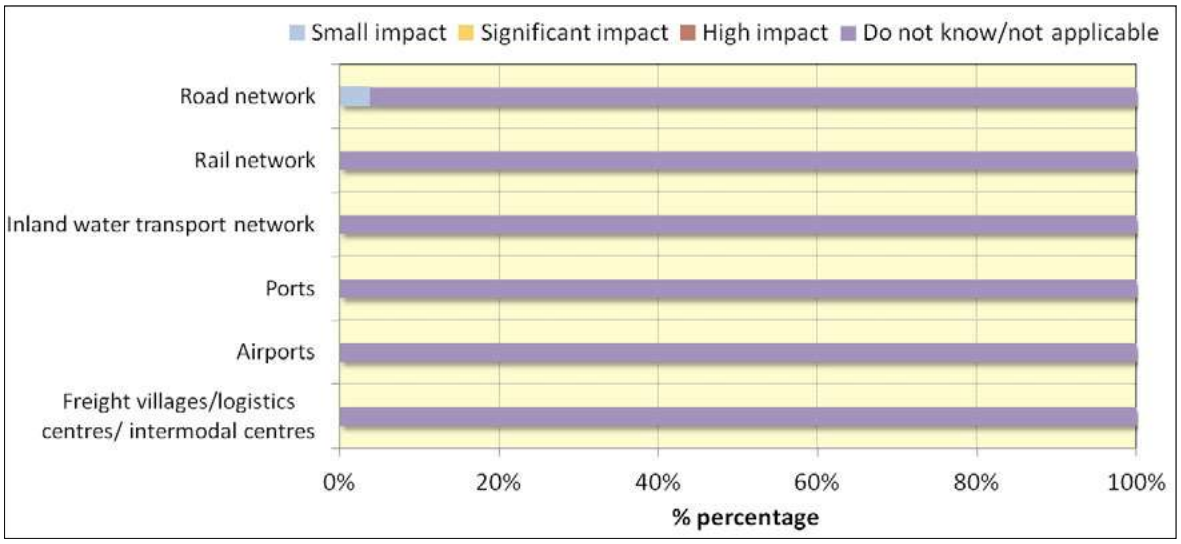
Extent of impact for Delays



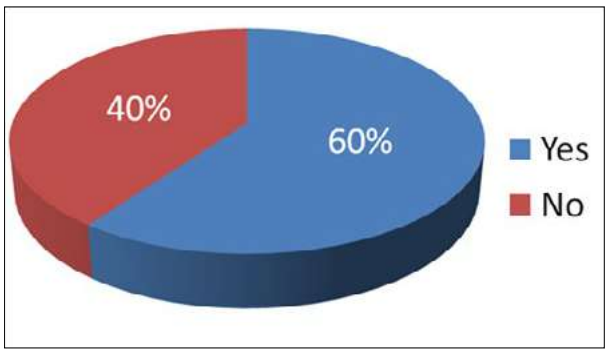
Extent of impact for Interruptions



Extent of impact for Other type



Question 16: Has your Government / organization mainstreamed weather and/or climate related considerations in planning, design and construction of transport infrastructure? If yes please specify.



References

Ademmer, M., Jannsen, N., Kooths, S. & S. Mösle (2019): Niedrigwasser bremst Produktion. Wirtschaftsdienst 2019. DOI: 10.1007/s10273-019-2399-7.

Alfieri L., Dottori F., Betts R., Salamon P., Feyen L., 2018. Multi-model projections of river flood risk in Europe under global warming. Climate 6, 16 doi:10.3390/cli6010016

Alfieri L., Feyen L., Dottori F. and Bianchi A., 2015. Ensemble flood risk assessment in Europe under high end climate scenarios. Global Environmental Change 35,199-212. (doi:10.1016/j.gloenvcha.2015.09.004)

AMAP, 2012. Arctic Climate Issues 2011: Changes in Arctic Snow, Water, Ice and Permafrost. SWIPA 2011.Overview Report

Androulidakis Y.S., Kombiadou K.D., Makris C.H., Baltikas V.N. and Krestenitis Y.N. 2015 Storm surges in the Mediterranean Sea: Variability and trends under future climatic conditions. Dynamics of Atmospheres and Oceans 71, 56–82.

Arnell N. et al 2014. Global-scale climate impact functions: the relationship between climate forcing and impact. Climate Change (134), 475–87.

Asariotis R., Mohos-Naray V., Benamara H., 2017. Port Industry Survey on Climate Change Impacts and Adaptation. UNCTAD Research Paper No. 18, UNCTAD/SER.RP/2017/18. 37 pp plus Appendices.

Auerbach, M., Herrmann, C., Krieger, B., Mayer, S. (2014) Klimawandel und Straßenverkehrsinfrastruktur. Straße und Autobahn 65, 531-539.

Becker A., Acciaro A., Asariotis R., Cabrera E. et al., 2013. A note on climate change adaptation for seaports: A challenge for global ports, a challenge for global society. Climatic Change, 120, 683-695.

Beniston M. and Diaz H.F. 2004. The 2003 heat wave as an example of summers in a greenhouse climate? Observations and climate model simulations for Basel, Switzerland. Global and Planetary Change 44, 73–81.

Bertin X., Prouteau E. and Letetrel C. 2013. A significant increase in wave height in the North Atlantic Ocean over the 20th century. Global and Planetary Change 106, 77–83.

Binnenschifffahrt (2018): Niedrigwasser lässt Umschlag in Mannheim absacken. Press release Nov 14 2018. Accessed Apr 04 2019.

Binnenschifffahrt (2019): Niedrigwasser schlägt auf Mannheims Umschlag. Press release Jan 25 2019. Accessed Apr 04 2019.

BMVI (2014): KLIWAS - Impacts of Climate Change on Waterways and Navigation in Germany. Concluding report of the BMVI. 111 p.

BMVI (2017) BMVI Network of Experts: Knowledge – Ability – Action. Federal Ministry of Transport and Digital Infrastructure (BMVI), Berlin.

BMVI, (2015) KLIWAS: Impacts of Climate Change on Waterways and Navigation in Germany, Concluding report of the BMVI. Federal Ministry of Transport and Digital Infrastructure (BMVI), Berlin.

Buth, M., Kahlenborn, W., Greiving, S., Fleischhauer, M., Zebisch, M., Schneiderbauer, S., Schauser, I., (2017) Guidelines for Climate Impact and Vulnerability Assessments, Recommendations of the Interministerial Working Group on Adaptation to Climate Change of the German Federal Government. Umweltbundesamt, Dessau-Roßlau, p. 48.

Buth, M., Kahlenborn, W., Savelsberg, J., Becker, N., Bubeck, P., Kabisch, S., Kind, C., Tempel, A., Tucci, F., Greiving, S., Fleischhauer, M., Lindner, C., Lückenkötter, J., Schonlau, M., Schmitt, H., Hurth, F., Othmer, F., Augustin, R., Becker, D., Abel, M., Bornemann, T., Steiner, H., Zebisch, M., Schneiderbauer, S., Kofler, C., (2015) Vulnerabilität Deutschlands gegenüber dem Klimawandel. Umweltbundesamt, Dessau-Rosslau, p. 690.

Camus P., Losada I.J., Izaguirre C., Espejo A., Menéndez M., Pérez J., 2017. Statistical wave climate projections for coastal impact assessments. Earth's Future 5, 918–933. https://doi.org/10.1002/2017EF000609

Cannon, A.J., S.R. Sobie, and T.Q. Murdock, 2015: Precipitation by Quantile Mapping: How Well Do Methods Preserve Changes in Quantiles and Extremes? Journal of Climate, 28(17), 6938-6959, doi:10.1175/JCLI-D-14-00754.1.

Carson M., Kohl A., Stammer D. et al., 2016. Coastal sea level changes, observed and projected during the 20th and 21st century. Climatic Change 134, 269-281. (doi: 10.1007/s10584-015-1520-1).

CCNR (2019): Market Insight. Inland Navigation in Europe. April 2019.

CEM, 2002. Coastal Engineering Manual. U.S. Army Corps of Engineers, Washington, DC.

Cheng L., Abraham J., Hausfather Z., Trenberth K.E., 2019a. How fast are the oceans warming? Observational records of ocean heat content show that ocean warming is accelerating. Science 363 (6423), 128–129.

Cheng L., Zhu J., Abraham J. et al., 2019b. Continues Record Global Ocean Warming. Advances in Atmospheric Sciences 36 (3), 249–252. doi.org/10.1007/s00376-019-8276-x.

Christodoulou A., Demirel H., 2018. Impacts of climate change on Transport. A focus on airports, seaports and inland waterways. EUR 28896 EN, Publications Office of the European Union, Luxembourg, 2018, ISBN 978-92-79-97039-9, doi:10.2760/378464, JRC108865,

Christodoulou, A., Christidis, P. and Demirel, H. (2019). Sea-level rise in ports: a wider focus on impacts. Maritime Economics and Logistics 21, 482-496 doi: 1057/s41278-018-0114-z.

Church J.A., Clark P.U., Cazenave A., et al., 2013. Sea level change. In Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. (T.F. Stocker, Qin D., Plattner G.-K. et al. [eds]) Cambridge; UK 1137–1216.

Conte, D. and Lionello, P. 2014. Storm Surge Distribution Along the Mediterranean Coast: Characteristics and Evolution, Procedia -Social and Behavioral Sciences 120, 110–115. (ISSN 1877-0428).

Coumou D. and Robinson A., 2013. Historic and future increase in the global land area affected by monthly heat extremes. Environmental Research Letters 8 (3) iopscience.iop.org/article/10.1088/1748-9326/8/3/034018/meta.

Coumou, D. and Rahmstorf, S. 2012. A decade of weather extremes. Nature Climate Change 29, 491-496. (doi:10.1038/nclimate1452).

Dai A., 2013. Increasing drought under global warming in observations and models. Nature Climate Change 3, 52–58.

De Conto R.M. and Pollard D., 2016. Contribution of Antarctica to past and future sea-level rise. Nature 531, 591-596. (doi: 10.1038/nature17145)

DESTATIS (2018): Güterverkehrsstatistik der Binnenschifffahrt. Fachserie 8, Reihe 4. December 2018.

DESTATIS (2019a): Güterverkehrsstatistik der Binnenschifffahrt Dezember 2018. Fachserie 8 Reihe 4.

DESTATIS (2019b): Verkehr aktuell. Fachserie 8 Reihe 1.1.

DESTATIS (2019c): Volkswirtschaftliche Gesamtrechnungen der Länder (Entstehungsrechnung). Table 82111-0002

Deutscher Wetterdienst (2019): Monatlicher Klimastatus Kompakt für das Deutsche Gewässerkundliche Jahrbuch 2018. DWD, Geschäftsbereich Klima und Umwelt, Offenbach, 13 p.

Dieng H. et al., 2017b. New estimate of the current rate of sea level rise from a sea level budget approach. Geophysical Research Letters, 44, doi: 10 .1002/ 2017GL073308.

Dieng H.B., A. Cazenave, B. Meyssignac, K. von Schuckmanc and H. Palanisamya, 2017a. Sea and land surface temperatures, ocean heat content, Earth's energy imbalance and net radiative forcing over the recent years. Int. J. Climatol. (2017), 12 pp., doi: 10.1002/joc.4996.

Dole et al., 2011. Was there a basis for anticipating the 2010 Russian heat wave? Geophysical Research Letters 38, L06702.

Dutton A., Carlson A.E. , Long A. J. et al., 2015. Sea-level rise due to polar ice-sheet mass loss during past warm periods. Science 349, 6244 https://marine.rutgers.edu/pubs/private/Science-2015-Dutton-.pdf

Ebner von Eschenbach, A.-D. (2017): Simulation der Wasserbewirtschaftung des Nord-Ostsee-Kanals – Herausforderungen und Lösungsansätze. BfG-Veranstaltung. Kolloquiumsbeitrag „Modellierung aktueller Fragestellungen zur Wassermengenbewirtschaftung an Bundeswasserstraßen“ am 13./14. September 2016 in Koblenz.

EC, 2012. Impacts of Climate Change on Transport: A focus on road and rail transport infrastructures, (F. Nemry and H. Demirel), JRC Scientific and Policy Reports. Publications Office of the European Union, Luxembourg, ISBN 978-92-79-27037-6.

ECE, 2013. Climate Change Impacts and Adaptation for International Transport Networks, United Nations Economic Commission for Europe, New York and Geneva, 2013, 248 pp. www.unece.org/fileadmin/DAM/trans/main/wp5/publications/climate_change_2014.pdf

ECE, 2015. Transport for Sustainable Development: The case of Inland Transport. United Nations Economic Commission for Europe, Transport Trends and Economics Series ECE/TRANS/251. www.unece.org/fileadmin/DAM/trans/publications/Transport_for_Sustainable_Development_UNECE_2015.pdf

EEA, 2010. The European environment: State and outlook 2010, Adapting to climate change. European Environmental Agency, Copenhagen. (ISBN 978-92-9213-159-3).

EEA, 2012. Climate change, impacts and vulnerability in Europe 2012. An indicator-based report. European Environmental Agency (EEA), Copenhagen, Denmark, 300 pp. (ISBN 978-92-9213-346-7)

EEA, 2015a, Global megatrends assessment: Extended background analysis complementing the SOER 2015 'Assessment of global megatrends'. European Environmental Agency, Copenhagen. (ISSN 1725-2237).

Emanuel K. 2005. Increasing destructiveness of tropical cyclones over the past 30 years. Nature 436, 686-688.

EPA, 2015. Precipitation Worlwide, 1901-2013 [Online image]. Available from: https://www3.epa.gov/climatechange/science/indicators/weather-climate/precipitation.html [Accessed 03/02/2016].

Forzieri G., Feyen L., Russo S. et al. 2016. Multi-hazard assessment in Europe under climate change. Climatic Change 137, 105 - 119. https://doi.org/10.1007/s10584-016-1661-x.

German Federal Government, (2008) German strategy for adaptation to climate change, Berlin, p. 73.

Giorgi, F., 2019, Thirty years of regional climate modelling: where are we and where are we going next? JGR Atmospheres, doi: 10.1029/2018JD30094

Greenan, B.J.W., James, T.S., Loder, J.W., Pepin, P., Azetsu-Scott, K., Ianson, D., Hamme, R.C., Gilbert, D., Tremblay, J-E., Wang, X.L. and Perrie, W. (2018): Changes in oceans surrounding Canada; Chapter 7 in (eds.) Bush and Lemmen, Canada's Changing Climate Report; Government of Canada, Ottawa, Ontario, p. 343–423. https://changingclimate.ca/site/assets/uploads/sites/2/2018/12/CCCR-Chapter7-ChangesInOceansSurroundingCanada.pdf

Grinsted A., Moore J.C. and Jervejeva S., 2010. Reconstructing sea level from paleo and projected temperatures 200 to 2100 AD. Climate Dynamics 34, 461–472.

Grinsted, A., Jevrejeva, S., Riva, R.E.M., and D. Dahl-Jensen (2015): Sea level rise projections for northern Europe under RCP8.5, Climate Research, 64, 15–23. doi.org/10.3354/cr01309

Hallegatte S., Green C., Nicholls R. J. and Corfee-Morlot J., 2013. Future flood losses in major coastal cities,Nature Climate Change 3, 802–806. (doi:10.1038/NCLIMATE1979)

Hambly, D., J. Andrey, B. Mills and C. Fletcher, 2012. Projected implications of climate change for road safety in Greater Vancouver, Canada. Climatic Change. (doi: 10.1007/s10584-012-0499-0.

Hanna E. et al., 2013. Ice sheet mass balance and climate change. Nature 498, 51–59.

Hänsel S, Schade N, Nilson E, Helms M, Brendel C, Heinrich H, Herrmann C, Klose M, Lifschiz E, Rauthe M, Gratzki A. (2018). Adapting the German transport system to climate change and extreme weather events – First case study results connected to extreme precipitation. Zenodo. http://doi.org/10.5281/zenodo.1473580 (conference paper of 7th Transport Research Arena TRA 2018, Vienna, 16-19 April 2018)

Hansen J., Sato M., Hearty P. et al., 2016. Ice melt, sea level rise and superstorms: Evidence from paleoclimate data, climate modeling, and modern observations that 2°C global warming could be dangerous. Atmos. Chem. Phys. 16, 3761-3812 (doi:10.5194/acp-16-3761-2016).

Hawkins, E., and Sutton, R., 2009, The potential to narrow uncertainty in regional climate predictions, Bull. Amer. Meteor. Soc. 90, 1095-1107.

Hay C.C., Morrow E., Kopp R.E. and Mitrovica J.X., 2015. Probabilistic reanalysis of twentieth-century sea-level rise. Nature 517, 481–484.

Hooper, E. and L. Chapman, 2012. Chapter 5 - The Impacts of Climate Change on National Road and Rail Networks. In Transport and Climate Change, Transport and Sustainability, Vol. 2., T. Ryley and L. Chapman, eds., Emerald Group Publishing Ltd, pp. 105–136. Available from dx.doi.org/10.1108/S2044-9941(2012)0000002008

Horton R., Herweijer C, Rosenzweig C, Liu J, Gornitz V, and Ruane AC, 2008. Sea level rise projections for current generation CGCMs based on the semi-empirical method. Geophysical Research Letters 35 DOI:10/1029/2007GL032486.

Horton, B.P., Rahmstorf, S., Engelhart, S.E. and Kemp, A.C. 2014. Expert assessment of sea-level rise by AD 2100 and AD 2300. Quaternary Science Reviews, 84, 1–6.

unctad.org/en/PublicationsLibrary/ser-rp-2017d18_en.pdf

IPCC SREX, 2012. Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation [Field C.B., Barros V., Stocker T.F. et al. (eds.)]. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change (IPCC). Cambridge University Press, Cambridge, UK, and New York, NY, USA. 582 pp.

IPCC, 2007. Climate Change 2007. The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (Solomon S, D Qin, M Manning, Z Chen, M Marquis, KB Averyt, M Tignor and HL Miller (eds)). Cambridge University Press, Cambridge, UK and New York, NY, USA, 996 pp.

IPCC, 2013. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker T.F., Qin D., Plattner G.-K. et al. (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

IPCC, 2014. Summary for policy makers. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Field C.B.,. Barros V.R Dokken D.J., et al. (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1-32.

IPCC, 2018: Summary for Policymakers. In: Global warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty [V. Masson-Delmotte, P. Zhai, H. O. Pörtner et al. (eds.)]. World Meteorological Organization, Geneva, Switzerland 32 pp. www.ipcc.ch/site/assets/uploads/sites/2/2018/07/SR15_SPM_High_Res.pdf Jacob, D., et al. 2014, EURO-CORDEX: new high-resolution climate change projections for European impact research, doi: 10.1007/s10113-013-0499-2.

Jevrejeva S., Jackson L.P., Riva R.E.M., Grinsted A., Moore J.C., 2016. Coastal sea level rise with warming above 2°C. Proc. Natl. Acad. Sci. 113, 13342 LP-13347. https://doi.org/10.1073/pnas.1605312113.

Jevrejeva S., Moore J.C. and Grinsted A. 2012. Sea level projections to AD2500 with a new generation of climate change scenarios. Global and Planetary Change 80–81, 14–20. (doi:10.1016/j.gloplacha.2011.09.006) .

Jevrejeva S., Moore J.C. and Grinsted A., 2010. How will sea level respond to changes in natural and anthropogenic forcings by 2100? Geophysical Research Letters 37. DOI: 10.1029/2010GL042947.

Jonkeren O., P. Rietveldand J. van Ommeren, 2007. Climate Change and Inland Waterway Transport: Welfare effects of low water levels on the river Rhine. Journal of Transport Economics and Policy 41 (3), 387–411.

Karl T.R., Melillo J. T. and Peterson T. C. 2009. Global Climate Change Impacts in the United States. Cambridge University Press, 189 pp.

King D., Schrag D., Dadi Z., Ye Q. and Ghosh A. 2015. Climate Change: A Risk Assessment. Centre for Science and Policy, University of Cambridge. (www.csap.cam.ac.uk/media/uploads/files/1/climate-change--a-risk-assessment-v9-spreads.pdf)

Koks E.E., Rozenberg J., Zorn C., Tariverdi M., Vousdoukas M.I., Fraser S.A.Hall J.W., and Hallegatte S., 2019. A global multi-hazard risk analysis of road and railway infrastructure assets. Nature Communications 10. 2677 (doi.org/10.1038/s41467-019-10442-3)

Kopp R., Simons F., Mitrovica J., Maloof A. and Oppenheimer M., 2009. Probabilistic assessment of sea levelduring the last interglacial stage. Nature 462, 863–867. (doi:10.1038/nature08686).

Korn, M., Leupold, A., Mayer, S., Kreienkamp, F., Spekat, A., (2017) RIVA – Risikoanalyse wichtiger Verkehrsachsen des Bundesfernstraßennetzes im Kontext des Klimawandels, Berichte der Bundesanstalt für Straßenwesen. Straßenbau. German Federal Highway Research Institute p. 131.

Lantuit, H. and W.H. Pollard, 2008. Fifty years of coastal erosion and retrogressive thaw slump activity

Leijstra, M., Muiswinkel, K. van, Leendertse, W. and Bles, T. 2018. Development of a Climate Adaptation Strategy for the InnovA58 highway in the Netherlands. Proceedings of the 7th Transport Research Arena TRA 2018, Vienna, Austria

Losada I.J., Reguero B.J., Mendez F.G., et al., R. 2013. Long-term changes in sea level components in Latin America and the Caribbean. Global and Planetary Change 104, 34–50.

Mann, M.E., Rahmstorf, S., Kornhuber, K., Steinman, B.A., Miller, S.K. & D. Coumou (2018): Influence of Anthropogenic Climate Change on Planetary Wave Resonance and Extreme Weather Events. Scientific Reports, 7:45242. DOI: 10.1038/srep45242

Marcos M., Jorda G., Gomis D. and Perez B. 2011. Changes in storm surges in southern Europe from a regional model under climate change scenarios. Global and Planetary Change 77(3–4), 116–128. (doi:10.1016/j.gloplacha.2011.04.002)

Mathis, M., Elizalde, A., and U. Mikolajewicz (2017): Which complexity of regional climate system models is essential for downscaling anthropogenic climate change in the Northwest European Shelf?, Climate Dynamics, 50(7-8), 2637-2659. doi.org/10.1007/s00382-017-3761-3

McKenney, D. W., M. F. Hutchinson, P. Papadopol, K. Lawrence, J. Pedlar, K. Campbell, E. Milewska, R. F. Hopkinson, D. Price, and T. Owen, 2011: Customized Spatial Climate Models for North America. Bull. Amer. Meteor. Soc., 92 12, 1611-1622.

Menendez M. and Woodworth P.L. 2010. Changes in extreme high water levels based on a quasi-global tidegauge data set. Journal of Geophysical Research, 115, C10011. (doi:10.1029/2009JC005997).

Menounos, B., Hugonnet R., Shean D. et al., 2018. Heterogeneous Changes in western North American glaciers linked to decadal variability in zonal wind strength. Geophysical Research Letters 45, https://doi.org/10.1029/2018GL08094.

Mentaschi L., M. I. Vousdoukas E. Voukouvalas A. Dosio, and L. Feyen, 2017. Global changes of extreme coastal wave energy fluxes triggered by intensified teleconnection patterns. Geophys. Res. Let. 44, 2416–2426, doi:10.1002/2016GL072488.

MetOffice, 2014. Climate risk An update on the science. Met Office, Handley Center, Devon, UK, 9 pp.

Meyer-Christoffer A., Becker A., Finger P. et al., 2015. GPCC Climatology Version 2015 at 0.25°: Monthly Land-Surface Precipitation Climatology for Every Month and the Total Year from Rain-Gauges Built on GTS-Based and Historic Data; GPCC: Offenbach, Germany, 2015.

Milly P.C.D., Betancourt J., Falkenmark M. et al., 2008. Stationarity is dead: Whither water management? Science 319, 573–574.

Ministerium für Energiewende, Landwirtschaft, Umwelt und ländliche Räume des Landes Schleswig-Holstein, Generalplan Küstenschutz des Landes Schleswig-Holstein - Fortschreibung 2012. www.schleswig-holstein.de/DE/Fachinhalte/K/kuestenschutz/Downloads/Generalplan.html

Monioudi I. N., Asariotis R. Becker A. et al., 2018. Climate change impacts on critical international transportation assets of Caribbean Small Island Developing States (SIDS): The case of Jamaica and Saint Lucia. Regional Environmental Change, 18 (8), 2211–2225.

Mora C., Dousset B., Caldwell I.R. et al., 2017. Global risk of deadly heat. Nature Climate Change 7, 501-507. DOI: 10.1038/NCLIMATE3322

Mori N., Shimura T., Yasuda T. and Mase H., 2013. Multi-model climate projections of ocean surface variables under different climate scenarios—Future change of waves, sea level and wind. Ocean Engineering, http://dx.doi.org/10.1016/j.oceaneng.2013.02.016i

Moss R. et al., 2010. The next generation of scenarios for climate change research and assessment. Nature 463, 747–756.

Nemry, F, Demirel, H., 2012, Impacts of Climate Change on Transport: A focus on road and rail transport infrastructures, JRC Scientific and Policy Reports, ISBN 978-92-79-27037-6

Nilson, E., & P. Krahe (2013): Rheinschifffahrt und Klimawandel. Geographische Rundschau 7–8 | 2013. 26-33

Nilson, E., Ehlers, B.-M., Abalichin, J., Bilal, A., Brauch, J., Dröse, M., Eichler, D., Fischer, H., Janssen, F., Keller, G.-M., Rothe, R., Stachel, H., Schröder, M., Stegert, C., van Pham, T., Walter, A., and N. Winkel (2019): ProWaS – Climate Projection service for Waterways and Navigation in Germany (Pilot study). Geophysical Research Abstracts. Vol. 21, EGU2019-13688-1, 2019.

Nilson, E., Krahe, P., Lingemann, I., Horsten, T., Klein, B., Carambia, M., Larina, M. (2014): Auswirkungen des Klimawandels auf das Abflussgeschehen und die Binnenschifffahrt in Deutschland. Schlussbericht KLIWAS-Projekt 4.01. KLIWAS-43/2014. BfG, Koblenz.

Nilson, E., Lingemann, I., Klein, B. & . Krahe (2012): Impact of hydrological change on navigation conditions. EU-ECCONET Report 1.4.

NOAA, 2015. 2014 State of the Climate: Carbon Dioxide [WWW] Available from: https://www.climate.gov/news-features/understanding-climate/2014-state-climate-carbon-dioxide

NOAA, 2016. Global Analysis - Annual 2015: 2015 year-to-date temperatures versus previous years [WWW] National Centers for Environmental Information. Available from: www.ncdc.noaa.gov/sotc/global/2015/13/supplemental/page-3 [Accessed 122/02/2016]

NOAA, 2017a. National Centers for Environmental Information (NCEI). 2016 Officially Warmest Year on Record. (Published online January 2017, accessed on May 24, 2017 www.nnvl.noaa.gov/MediaDetail2.php?MediaID=1989&MediaTypeID=3&ResourceID=105007/

NOAA, 2017c. National Centers for Environmental Information (NCEI) U.S. Billion-Dollar Weather and Climate Disasters. www.ncdc.noaa.gov/billions/

NSIDC, 2017. National Snow and Ice Data Center. Snow, Ice and Climate Change (retrieved on May 24, 2017 from nsidc.org/cryosphere/climate-change.html

Palko, 2017. (2017). Synthesis. In K. Palko and D.S. Lemmen (Eds.), Climate risks and adaptation practices for the Canadian transportation sector 2016 (pp. 12-25). Ottawa, ON: Government of Canada. www.nrcan.gc.ca/sites/www.nrcan.gc.ca/files/earthsciences/pdf/assess/2016/Chapter-2e.pdf

Pérez J., Menendez M., Mendez F. and Losada I. 2014. Evaluating the performance of CMIP3 and CMIP5 global climate models over the north-east Atlantic region. Climate Dynamics 43, 2663–2680.

Pfeffer W., Harper J. and O' Neel S., 2008. Kinematic constraints on glacier contributions to 21st century sea level rise. Science 321, 1340–1343. (doi:10.1126/science.1159099).

PIANC, 2008. Waterborne transport, ports and waterways: A review of climate change drivers, impacts, responses and mitigation. EnviCom - Task Group 3Climate Change and Navigation. 58pp. www.pianc.org/uploads/publications/reports/287223envicom-free-tg3.pdf

PIARC, 2012. Dealing with the effects of climate change on road pavements. World Road Association (PIARC) Technical Committee D.2 Road Pavements, 146 pp. (ISBN: 2-84060-247-4).

PIARC, 2015, International Climate Change Adaptation Framework for Road Infrastructure, World Road Association (PIARC), Technical Committee E.1..

Rahmstorf S., 2012. Climate Change: State of Science . In: Maritime Transport and the Climate Change Challenge, R. Asariotis and H. Benamara, eds., Earthscan, pp. 3–11.

Rahmstorf S., Cazenave A., Church J.A. et al., 2007. Recent climate observations compared to projections. Science 316, 709–709.

Ranasinghe R., 2016. Assessing climate change impacts on open sandy coasts: A review. Earth Science Reviews 160, 320-332.

Rignot E., Mouginot, J., Scheuchl, B. et al., 2019. Four decades of Antarctic Ice Sheet mass balance from 1979–2017. PNAS doi.org/10.1073/pnas.1812883116

Rohling E., Grant K., Hemleben C. et al., 2008. High rates of sea level rise during the last interglacial period. Nature Geosciences 1, 38–42. (doi:10.1038/ngeo.2007.28).

Rona, J., 2011. Climate Change Adaptation and Transport – UK and Rail. Presentation at the second session of the Group of Experts on Climate change impacts and adaptation for international transport networks, UNECE, Geneva, 8 November 2011.

Rueda A., Vitousek S., Camus P. et al., 2017. A global classification of coastal flood hazard climates associated with large-scale oceanographic forcing. Scientific Reports 7, 5038. doi.org/10.1038/s41598-017-05090-w

Ruggiero P. 2013. Is the intensifying wave climate of the U.S. Pacific Northwest increasing flooding and erosion risk faster than sea-level rise? Journal of Waterway, Port, Coastal, and Ocean Engineering 139 (2), 88–97.

Ruggiero P., Komar P.D. and Allan J.C., 2010. Increasing wave heights and extreme value projections: The wave climate of the U.S. Pacific Northwest. Coastal Engineering 57, 539–552.

Schneider U., Finger P., Meyer-Christoffer A., 2017. Evaluating the Hydrological Cycle over Land Using the Newly-Corrected Precipitation Climatology from the Global Precipitation Climatology Centre (GPCC). Atmosphere ,8 (52), doi: 10.3390/atmos8030052.

Schröder, M., Wurms, S. (2014): Verkehrswasserbauliche Regelungs- und Anpassungsoptionen an klimabedingte Veränderungen des Abflussregimes. Schlussbericht KLIWAS-Projekt 4.03. KLIWAS-45/2014. BAW / BfG, Koblenz. DOI: 10.5675/Kliwas_45/2014_4.03

Schuur EAG, McGuire A.D., Schädel C., et al., 2015. Climate change and the permafrost carbon feedback. Nature 520, 171–179. 10.1038/nature14338

Sigurður Sigurðarson 2018: Lágsvæði – viðmiðunarreglur fyrir landhæð, Road and coastal administrations 2018.

Steffen, W. 2009. Climate Change 2009: Faster Change and More Serious Risks. Report to the Department of Climate Change, Australian Government.

Streletskiy D.A., N.I. Shiklomanov and F.E. Nelson (2012). Spatial variability of permafrost active-layer thickness under contemporary and projected climate in Northern Alaska. Polar Geography 35 (2) 95-116.

Taalas P., 2019. WMO presentation, UN Oceans Meeting, 7–8 February 2019, Geneva.

Trenberth K.E., Cheng L., Jacobs P., Zhang Y., Fasullo J.T., 2018. Hurricane Harvey links to ocean heat content and climate change adaptation. Earth's Future 6, 730–744. doi.org/10.1029/2018EF000825

UNFCCC, 2015. The Paris Agreement by Parties to the United Nations Framework Convention on Climate Change. unfccc.int/meetings/paris_nov_2015/items/9445.php.USDOT, 2012. Impacts of Climate Change and Variability on Transportation Systems and Infrastructure: The Gulf Coast Study, Phase II. A report by the US Department of Transportation, Center for Climate Change and Environmental Forecasting [Choate A, W Jaglom, R Miller, B Rodehorst, P Schultz and C Snow (eds.)]. Department of Transportation, Washington, DC, USA, 470 pp.

Velicogna I., Sutterley T. C. and van den Broeke M. R. 2014. Regional acceleration in ice mass loss from Greenland and Antarctica using GRACE time-variable gravity data. Geophys. Res. Lett., 41(22), 8130-8137.

Vellinga P. et al. 2008. Exploring high-end climate change scenarios for flood protection of the Netherlands.International Scientific Assessment for the Delta Committee. SR WR-2009-05. KNMI, Alterra, The Netherlands. www.knmi.nl/bibliotheek/knmipubWR/WR2009-05.pdf.

Vermeer M. and Rahmstorf S., 2009 Global sea level linked to global temperature. Proceedings of the National Aceademy of Sciences USA 106, 21527–21532. (doi:10.1073/pnas.0907765106).

Vogel M.M., R. Orth, F. Cheruy , S. Hagemann , R. Lorenz, B.J.J.M. van den Hurk, and S.I. Seneviratne, 2017. Regional amplification of projected changes in extreme temperatures strongly controlled by soil moisture temperature feedbacks. Geophys. Res. Letters, 44, 1511–1519. doi:10.1002/ 2016GL071235.

Vousdoukas M.I., E. Voukouvalas, L. Mentaschi, F. Dottori, A. Giardino, D. Bouziotas, A. Bianchi, P. Salamon and L. Feyen, 2016b. Developments in large-scale coastal flood hazard mapping. Nat. Hazards Earth Syst. Sci. 16, 1841–1853, doi:10.5194/nhess-16-1841-2016.

Vousdoukas M.I., L. Mentaschi, E. Voukouvalas, M. Verlaan, and L. Feyen, 2017. Extreme sea levels on the rise along Europe's coasts. Earth's Future 5, 304–323. doi:10.1002/2016EF000505.

Vousdoukas M.I., Mentaschi L., Voukouvalas E., Verlaan M., Jevrejeva S., Jackson L.P., Feyen L., 2018. Global probabilistic projections of extreme sea levels show intensification of coastal flood hazard. Nat. Commun. 9, 2360. doi.org/10.1038/s41467-018-04692-w.

Vousdoukas M.I., Voukouvalas E., Annunziato A., Giardino A. and Feyen, L., 2016a. Projections of extreme storm surge levels along Europe. Climate Dynamics doi: 10.1007/s00382-016-3019-5.

Wada Y., van Beek L.P.H., Weiland F.C.S. et al., 2012. Past and future contribution of global groundwater depletion to sea-level rise. Geophys Res Letters 39, L09402. (doi: 10.1029/2012GL051230)

Werner, A.T. and A.J. Cannon, 2016: Hydrologic extremes–an intercomparison of multiple gridded statistical downscaling methods. Hydrology and Earth System Sciences, 20(4), 1483-1508. doi:10.5194/hess-20-1483-2016

Wilby, R.L., Troni, J., Biot, Y., Tedd, L., Hewitson, B.C., Smith, D.M., and Sutton, R.T., 2009, A review of climate risk information for adaptation and development planning, International Journal of Climatology, 29, 1193-1215, DOI: 10.1002/joc.1839

Willway, T., Baldachin L., Reeves S. et al., 2008. The effects of climate change on highway pavements and how to minimise them: Technical report. PPR184, TRL Limited. ISBN 978-1-84608-734-9. United Kingdom

WMO, 2014. Statement on the status of the global climate in 2014, World Meteorological Organization, WMO-No. 1152, Chairperson, Publications Board, Geneva, 22 pp. (ISBN: 978-92-63-11152-4.)

WMO, 2016. WMO Statement on the Status of the Global Climate in 2015, World Meteorological Organization, WMO-No. 1167, Chairperson, Publications Board, Geneva, Switzerland, 26 pp. (ISBN: 978-92-63-11167-8.). See also www.indiaenvironmentportal.org.in/content/421694/provisional-statement-on-the-status-of-global-climate-in-2011-2015/ .

WMO, 2017. WMO Statement on the State of the Global Climate in 2016. World Meteorological Organization Report 1189, library.wmo.int/opac/doc_num.php?explnum_id=3414) .

WMO, 2018. WMO Statement on the State of the Global Climate in 2017. World Meteorological Organization Report 1212. library.wmo.int/doc_num.php?explnum_id=4453 .

WSV (2017): Veränderungen des Schiffsbestandes der deutschen Binnenflotte im Jahr 2017. Zentrale Binnenschiffsbestandsdatei.

www.nature.com/articles/srep10285

www.vegagerdin.is/vefur2.nsf/Files/lagsvaede_vidmidunarreglur_2018/$file/L%C3%A1gsv%C3%A6%C3%B0i-vi%C3%B0mi%C3%B0unarreglur-%C3%9Atg%C3%A1fa%20A-04%202018.pdf

Zhang, X., Flato, G., Kirchmeier-Young, M., Vincent, L., Wan, H., Wang, X., Rong, R., Fyfe, J., Li, G., Kharin, V.V. (2019): Changes in Temperature and Precipitation Across Canada; Chapter 4 in Bush, E. and Lemmen, D.S. (Eds.) Canada's Changing Climate Report. Government of Canada, Ottawa, Ontario, pp 112-193.

Climate Change Impacts and Adaptation for Transport Networks and Nodes

Inland transport networks and nodes are instrumental to the safe, efficient and reliable movements of people to their destinations and goods to market. Medium to longer-term disruptions to these networks and nodes may lead to adverse economic and social effects. Extreme weather events as well as slower onset climate changes (for example, sea level rise) and cumulative effects can result in transportation infrastructure damages, operational disruptions, and pressures on supply chain capacity and efficiency. As such, the United Nations Economic Commission for Europe (ECE) Group of Experts on Climate Change Impacts and Adaptation for Transport Networks and Nodes (the Group of Experts) has been analysing the impacts of climate change on main transport assets in the ECE region, as presented in this report. The Group of Experts considered the main networks and nodes in the ECE region, observed climate changes, as well as future projections. In this context, the report presents the analyses of several climate variables relevant to transport networks and nodes within the ECE region. Regional maps have been produced in Geographical Information System (GIS) format, showing the main transportation networks, which have been overlain by the spatial distribution of the climate change projections, thereby presenting an initial perspective of areas of potential risk which could warrant more in-depth assessment. The Group of Experts has also reviewed and presented country experiences in the form of case studies, demonstrating a range of efforts that have been undertaken to analyse climate change impacts on transport assets and operations. With its work, the Group of Experts wishes to raise awareness on the importance of considering climate change and extreme weather and of strengthening the climate resilience of inland transport assets, networks and nodes. It also aims to stimulate the continuation of work to establish the necessary analytical basis to facilitate local or regional assessments, leading to the identification of specific transport assets at risk which may require adaptation efforts. The Group of Experts also formulated a series of lessons learned which have served as a basis to recommend future action at national and international levels towards improved transportation system climate resilience. It is especially recommended to invest efforts in:

- Creating awareness and understanding of the urgent need to assess the impacts from climate change on inland transport infrastructure and operations, and to identify and implement adaptation measures;
- Obtaining consistent climate projection data sets for the entire ECE region;
- Analysing a broader range of climate indices so that current knowledge on impacts from a changing climate and extreme events on inland transport infrastructure can be strengthened and made available to countries through a ECE GIS; and
- Conducting projects that seek to more fully understand vulnerabilities to climate change and extreme weather across countries' inland transportation systems, and with the results supporting the creation of a knowledge base to share experiences, lessons learned and good practices.

Information Service
United Nations Economic Commission for Europe

Palais des Nations
CH - 1211 Geneva 10, Switzerland
Telephone: +41(0)22 917 12 34
E-mail: unece_info@un.org
Website: www.unece.org

United Nations publication
Sales No. E.20.II.E.23
ISBN 978-92-1-117237-9

Layout and Printing at United Nations, Geneva – 1921941 **(E)** – February 2020 – 576 – **ECE/TRANS/283**