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Discussions on the final report of the Group of Experts

An Overview of Recent Climate Change Trends and projections affecting transportation in the ECE Region (Part II)

Note by the secretariat[*]

I. Mandate

1. This document has been prepared in line with the output/activities of cluster 2: “Transport trends and economics (including Euro-Asian transport links)” of the programme of work of the transport subprogramme for 2016-2017 (ECE/TRANS/2016/28/Add.1, para. 2.2) and the Terms of Reference of the United Nations Economic Commission for Europe (UNECE) Group of Experts on Climate Change impacts and adaptation for transport networks and nodes (ECE/TRANS/2015/6) as adopted by the Inland Transport Committee on 24-26 February 2015 (ECE/TRANS/248, para. 34).

II. Climate Change: Recent Trends and Projections

A. Recent Climate Projections

2. The now better recorded/understood climatic factor dynamics (e.g. land/sea surface temperature, sea level, arctic ice extent, glacier mass balance) suggest a significant and, in

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[*] This document was submitted late due to delayed inputs from other sources.

some cases, accelerating climatic change. This information and more recent evidence suggest that transport-affecting climatic factors (ECE, 2013) are 'deteriorating'.

3. The ocean will warm in all RCP scenarios. The strongest ocean surface warming is projected for the subtropical and tropical regions. At greater depths, warming is projected to be most pronounced in the Southern Ocean. Best estimates of ocean warming in the upper 100 m are about 0.6 °C (RCP2.6) to 2.0 °C (RCP8.5), and for the upper 1,000 m 0.3 °C (RCP2.6) to 0.6 °C (RCP8.5) by the end of the twenty-first century. For RCP4.5, half of the energy taken up by the ocean will be within the uppermost 700 m and 85 per cent in the uppermost 2000 m. Due to the long-time scales of this heat transfer from the surface to deeper waters, ocean warming will continue for centuries, even if GHG emissions were stabilized (IPCC, 2013).

4. With regard to the atmospheric air temperature, a long-term increasing trend is clear. Concerning temperature projections for the end of the twenty-first century, it is expected that the atmospheric temperature will increase between 1.0 and 3.7 °C (mean estimates, see Table 1), depending on the scenario. Forced by a range of possible Greenhouse Gas (GHG) concentration scenarios (IPCC, 2013), the central (mean) estimate for the warming has been predicted to be 1.0-2.0°C for the period 2046-2065 compared to the mean of the period 1986-2005, whereas by the late twenty-first century (2081-2100) increases of 1.0-3.7 °C are projected. However, the range of the projections broadens to 0.3-4.8 °C when model uncertainty is included

Table 1

Forecasts of global mean surface temperature and global mean sea level changes for the period 2081-2100 (means and likely ranges) with respect to the period 1986-2005, according to different scenarios (after IPCC, 2013)

(Predictions are made according to 4 radiative forcing scenarios (Representative Concentration Pathways-RCP)[1]: RCP 8.5, 6184 Gt C02 (2012-2100 cumulative CO2 emissions); RCP 6.0 3890 Gt C02; RCP 4.5, 2863 Gt CO2; and RCP 2.6, 991 Gt CO2. Global mean surface temperature changes are based on the CMIP5 ensemble (5-95per cent model ranges). Sea level rise estimates are based on 21 CMIP5 models (5-95per cent model ranges). The contributions from ice sheet rapid dynamical change and anthropogenic land water storage are treated as having uniform probability distributions, and as largely independent of scenario, as the current knowledge state does not permit quantitative assessments of the dependence.[2])

	Temperature		*Sea level rise*	
Scenario	*Mean (°C)*	*Likely Range (°C)*	*Mean (m)*	*Likely Range (m)*
RCP 2.6	1.0	0.3-1.7	0.40	0.26-0.55
RCP 4.5	1.8	1.1-2.6	0.47	0.32-0.63
RCP 6.0	2.2	1.4-3.1	0.48	0.33-0.63
RCP 8.5	3.7	2.6-4.8	0.63	0.45-0.82

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[1] The recent IPCC Assessment Report AR5 (2013) forecasts are made on the basis of the Representative Concentration Pathways-RCP scenarios and not the IPCC SRES scenarios. The CO2 equivalent concentrations have been set to (e.g. Moss et al., 2010): RCP 8.5, 1370 C02-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).

[2] According to the scenarios the sea level will not stop rising in 2100, but will continue rising during the following centuries; median sea level rises of 1.84 for the lowest and 5.49 m for the highest forcing scenario (RCP 8.5) have been projected for 2500 (Jevrejeva et al., 2012).

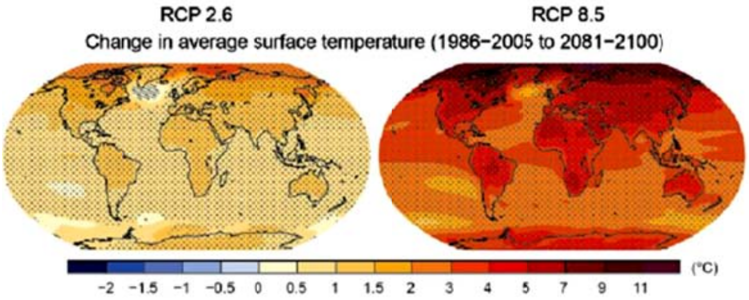
1.2.1 Temperature and Precipitation

5. Climate does not change uniformly, with temperatures close to the poles rising faster than at the equator (Figs. 21 and 22). Precipitation is changing in a much more complex manner, with some regions becoming wetter and others dryer (ECE, 2013). Such trends are expected to pick up pace in the future, as e.g. in the E. Mediterranean where mean rainfall has been predicted to decrease by up to 25 per cent in the decade 2020-2029 compared to that of the decade 1990-1999 (IPCC, 2007). Under both low-moderate (RCP 4.5) and high emission (RCP8.5) scenarios, large increases in surface temperatures are projected, particularly for the northern ECE region (IPCC, 2013).

6. Climate model projections suggest widespread droughts across most of South-Western North America and many other subtropical regions by the mid to late twenty-first century (Milly et al., 2008; IPCC, 2013). In contrast, while summers are expected to become (overall) drier by 2100 over the United Kingdom of Great Britain and Northern Ireland (UK), precipitation events may become heavier. Model simulations suggest that intense rainfall associated with flash flooding (more than 30 mm in an hour) could become almost 5 times more frequent (MetOffice, 2014)

Figure 21

Projected changes in average temperatures in 2081-2100 relative to 1986-2005 for low (RCP2.6) and high emission (RCP8.5) scenarios (IPCC, 2013)

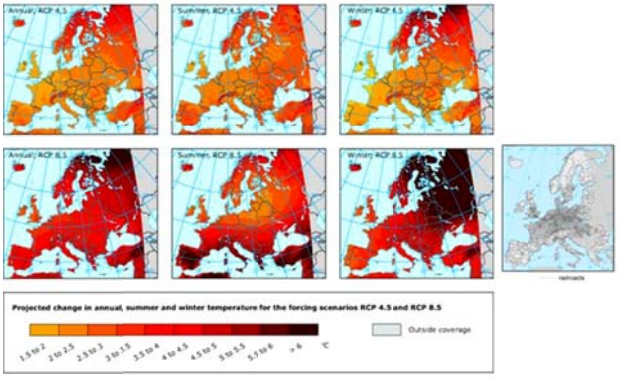


7. Studies also project decreases in the duration/intensity of droughts in the South Europe and the Mediterranean, the central Europe and parts of the North America (e.g. IPCC, 2013). At the same time, recent studies suggest severe/widespread droughts for the next 30-90 years (Dai, 2013) for most of South-Western North America and subtropical regions (IPCC, 2013). Vogel et al. (2017) have suggested that the multimode mean of daily maximum temperature (TX_X) increases globally in simulations (CTL and SM20c models) until the end of the century.

Figure 22

Projected changes in annual (left), summer (middle) and winter (right) surface air temperature (°C) in 2071-2100 compared to 1971-2000 for forcing scenarios RCP4.5 (top) and RCP8.5 (bottom)

(Model simulations from RCMs (EURO-CORDEX initiative). (EEA, 2014a))

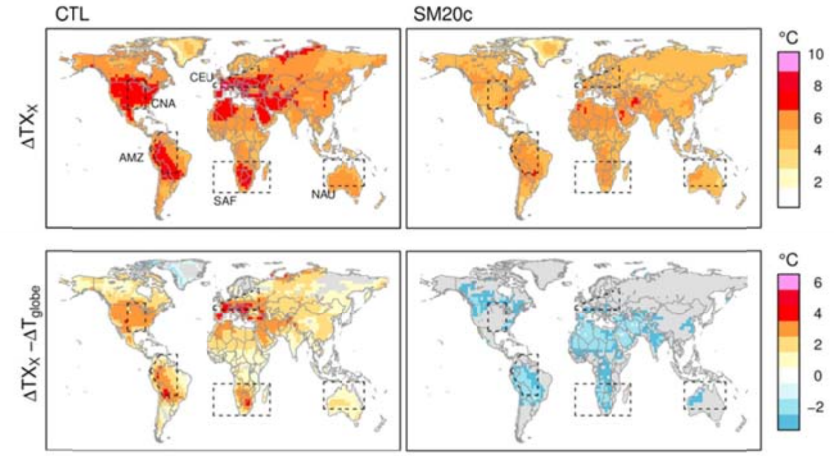


8. Projected changes are more pronounced in CTL, with regional increases of up to 10 °C, whereas in SM20c simulations temperature changes vary between 1°C and 6°C (Fig. 23, top). There also appear to be large regional differences between the projected TX_X increase in Central Europe, Central North America, Northern Australia and Southern Africa. Such differences may indicate soil moisture-climate feedbacks for extreme temperatures in these regions.

Figure 23

Projected changes in TX_X (top row) between 2081-2100 and 1951-1970 and additional increase of TX_X versus Tglobe (bottom row) between 2081-2100 and 1951-1970 for CTL (left) and SM20c (right)

(Grey colour denotes insufficient model agreement; i.e. fewer than 4 models show the same change signal. The upper colour bar corresponds to top row, the lower colour bar to bottom row (Vogel et al., 2017))



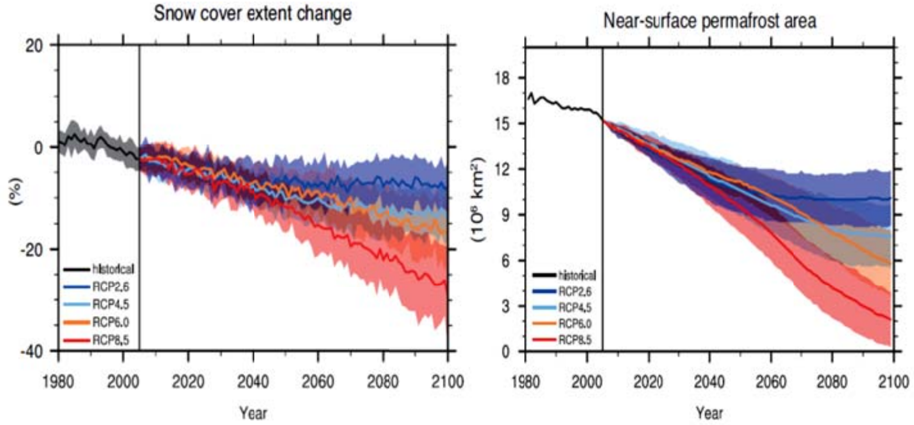
1.2.2 Arctic ice, snow and permafrost melt

9. Snowfall and rainfall are projected to increase in all seasons in the Arctic regions, mostly in winter; thus winter maximum snow depth over many areas is projected to increase, with the most significant increase (15 to 30per cent by 2050) taking place in

Siberia. However, snow will tend to stand for 10 to 20 per cent less time each year over most of the Arctic regions, due to earlier spring melting (AMAP, 2012). Spring snow cover in the North Hemisphere (NH) will decrease by 7 per cent (RCP2.6) and 25 per cent (RCP8.5), by 2100 (Fig. 24a). As for mountain glaciers and ice caps, climate model projections show 10 to 30 per cent mass reduction by the end of the century (AMAP, 2012). Models also project continued thawing of permafrost due to rising global temperatures and changes in snow cover (AMAP, 2012). Current warming rates at the European permafrost surface are 0.04 - 0.07 ^{0}C yr^{-1} (EEA, 2015a). Although there are challenges in assessing the magnitude of permafrost change, including those related to soil processes, climate forcing scenarios and model physics, permafrost extent is expected to decrease by 37 per cent and 81 per cent for RCP2.6 and RCP8.5 scenarios, respectively, by the end of the twenty-first century (medium confidence) (Fig. 24b).

Figure 24

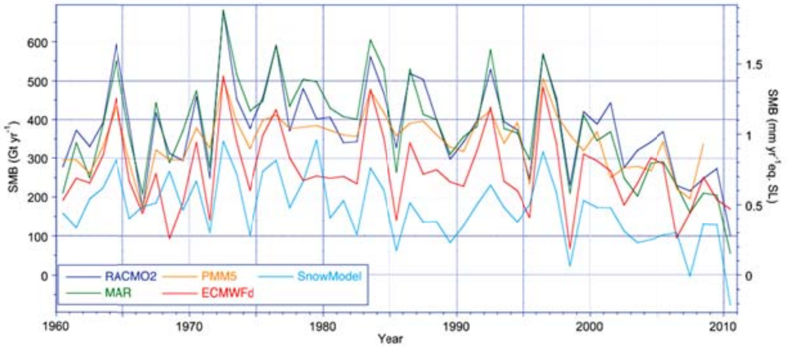
Projected (a) snow cover extent and (b) near-surface permafrost changes for 4 Representative Concentration Pathways-RCPs (from CMIP5 model ensemble) (IPCC, 2013)



10. Such changes could impose substantial problems in the development/maintenance of transport infrastructure in the Arctic regions (ECE, 2013), that could constrain the development of transport networks to take advantage of new Arctic Ocean routes made possible by the projected Arctic sea ice thaw.

Figure 25

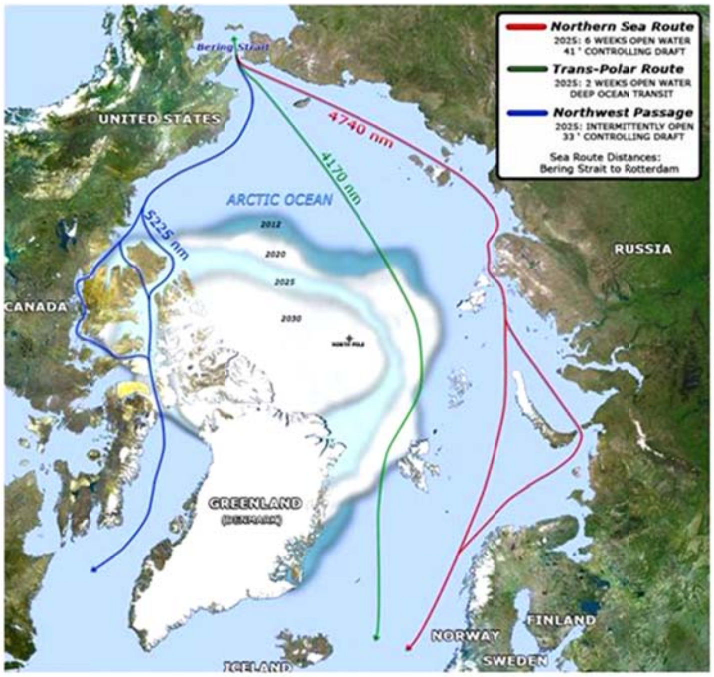
Annual mean Surface Mass Balance (SMB) for the Greenland Ice Sheet (GIS), simulated by 5 regional climate models for the period 1960-2010 (Hansen et al., 2016)



11. It is likely that the Arctic sea ice will continue to decrease in extent/thickness as global mean surface temperature rises, although there will be considerable inter-annual variability. Based on the CMIP5 model ensemble, Arctic sea ice extent is projected to decrease considerably. In the period 2081-2100, reductions of 8 to 34 per cent (in February) and of 43 to 94 per cent (in September) compared to the average extents in 1986-2005 are projected; the lower and upper projections refer to the RCP2.6 and RCP8.5, respectively (IPCC, 2013).

12. Continuing global warming will have a strong impact on the Greenland Ice Sheet (GIS) in the following decades. In the present climate, Greenland Surface Mass Balance (SMB) is positive but shows a decreasing trend, implying an increasing contribution to mean SLR. Based on the available evidence, it is unlikely that SMB changes will result in a collapse of the GIS in the twenty-first century, but likely on multi-centennial to millennial time scales (IPCC, 2013). The average and standard deviation of accumulation (precipitation minus sublimation) estimates for 1961-1990 is -1.62 ± 0.21 mm yr^{-1}. All information indicates that the Greenland SMB showed no significant trend from the 1960s to the 1980s, but started to become less positive in the early 1990s (on average by 3 per cent per year). This results in a statistically significant and increasing contribution to the rate of mean SLR (Fig. 25). IPCC (2013) has suggested that, during the next century, dynamical change of GIS could contribute to SLR by 20 to 85 mm (RCP8.5), and 14 to 63 mm for all other scenarios (medium confidence). Other studies project SMBs of 0.92 ± 0.26 mm yr^{-1} (compared to the 1961-1990) (Hansen et al., 2016). In comparison, the Antarctic ice sheet SMB is projected to increase under most scenarios due to an increasing snowfall trend. Nevertheless, it should be noted that negative Antarctica SMBs have the potential to contribute more than 1 m of sea level rise by 2100 (De Conto and Pollard, 2016).

Figure 26
New Arctic shipping routes. (U.S. Climate Resilience Toolkit, 2015)



13. Concerning Arctic ice, the US Navy anticipates the development of 3 major shipping routes by 2025 (Fig. 26); these are, however, associated with several environmental risks and development challenges. There may be new economic opportunities for Arctic communities, as reduced ice extent facilitates access to the substantial hydrocarbon deposits (at Beaufort and Chukchi seas) and international trade. At the same time, CV & C will affect existing infrastructure and all future development due to thawing permafrost and coastal wave activity (see below).

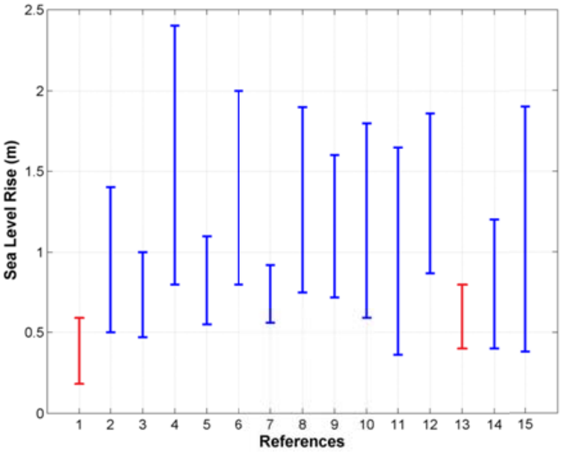
1.2.3 Sea level

14. Process-based predictions of sea-level rise (SLR) are limited by uncertainties surrounding the response of the GIS and WAIS (Pritchard et al., 2012), steric changes (Domingues et al., 2008), contributions from mountain glaciers (Raper and Braithwaite, 2009), as well as from groundwater pumping for irrigation purposes and storage of water in reservoirs (Wada et al., 2012). Antarctic ice sheet melting could potentially contribute by more than 1 m of SLR by 2100 (De Conto and Pollard, 2016).

Figure 27

Recent sea level rise projections for 2100 compared to that of IPCC (2007a)

(Key: 1, IPCC (2007a), 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 of the projections reflects differences in assumptions and approaches.)



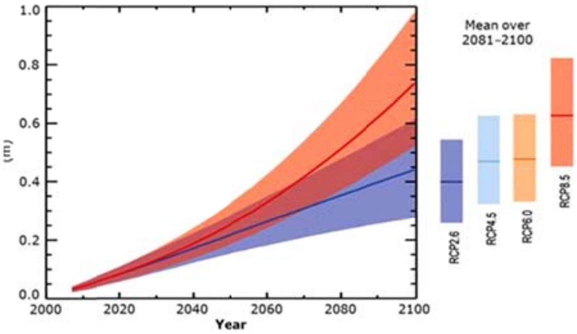
15. Global mean sea level has risen by 0.19 m between 1901 and 2013 (average rate 1.7 mm yr^{-1}), whereas in the last two decades, the rate has accelerated to almost 3.2 mm yr^{-1}. Models project a likely rise in 2081-2100 (compared to 1986-2005) in the range 0.26-0.54 m for RCP2.6 and 0.45-0.82 m for RCP8.5. It is thought that the steepening of the curve of the SLR in recent decades is mostly due to the increasing contribution of ice loss from the Greenland and Antarctic ice sheets (e.g. Rignot et al., 2011; Hanna et al., 2013; IPCC, 2013). Sea level estimates based on alternative approaches project a mean SLR much higher than that predicted a decade earlier (IPCC, 2007); it must be noted that the IPPC consistently provides conservative estimates (Fig. 27). Sea-level rise (Fig. 28) will not cease in 2100 (e.g. Jevrejeva et al., 2012), as changes in ocean heat content could affect thermal expansion for (at least) several centuries, whereas melting and dynamic ice loss in Antarctica and Greenland will also continue well into the future.

16. It should be noted that due to the large spatial variability observed (and projected) in sea level rise (Fig. 29), the regional trends should be considered when assessing potential impacts along any particular coast (e.g. Carson et al., 2016).

17. In addition to the global processes, regional factors may also contribute to observed coastal sea level changes, such as changes in ocean circulation (e.g. Meridional Overturning Circulation-MOC) and differential rates in regional glacial melting, and glacio-isostatic adjustment (GIA) and coastal sediment subsidence (IPCC, 2013; King et al., 2015; Carson et al., 2016). Palaoclimatic, instrumental and modelling studies have shown that combinations of global and regional factors can cause relatively rapid rates of SLR along particular coasts that can exceed significantly the current global rate of about 3 mm yr^{-1} (e.g. Cronin, 2012).

Figure 28

Projected global MSLR over the twenty-first century relative to 1986-2005 (IPCC, 2013)

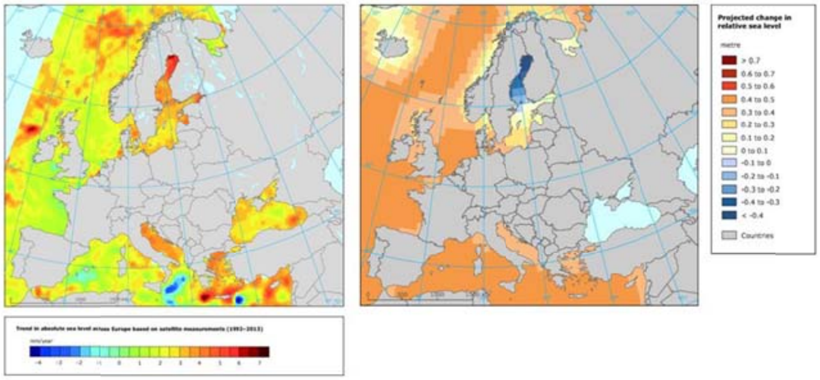


18. Sea level rise for the UK for the twenty-first century has been projected to be 0.12 - 0.76 m (excluding land level changes) depending on the emission scenario, with greater rises predicted in the case of additional ice sheet melting (Lowe et al., 2009). For the Netherlands coast, Katsman et al. (2011) have estimated sea level rises of 0.40-1.05 m for a plausible high end emission scenario. Marcos and Tsimplis (2008) have predicted a temperature-driven sea level rise of 0.03-0.61 m in the Mediterranean for the twenty-first century on the basis of 12 global climate models and for 3 emission scenarios; this rise should be combined with salinity driven changes of up to 0.31 m (see also EEA, 2012).

Figure 29

Trends in absolute sea level in European Seas from satellite measurements (1992-2013) (EEA, 2014b)

(Projected change in relative sea level in 2081-2100 compared to 1986-2005 for the medium-low emission scenario RCP4.5 (from an ensemble of CMIP5 climate models). No projections are available for the Black Sea. (EEA, 2014c))



1.2.4 Extreme events

Heat waves

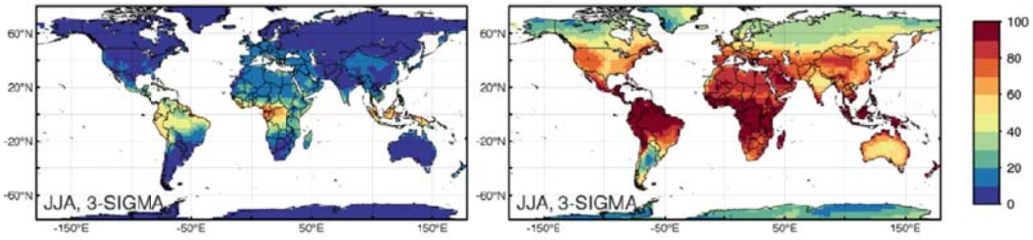
19. Increases in hot extremes and decreases in cold winter extremes are expected by the end of the twenty-first century, with the frequency, duration and magnitude of the events being affected by anthropogenic forcing (IPCC, 2013). Greater changes in hot days are expected to take place in sub-tropic and mid-latitude regions (Fig. 30), whereas the frequency of cold days will decrease in all regions. Projections show that very hot summers will occur much more frequently in the future under all Climate Change scenarios.

20. It is also likely that the frequency and duration of heat waves (prolonged period of excessive heat) will increase, mainly due to the increasing seasonal mean temperature trends (Fig. 31). For most land regions it is likely that the frequency of a current 20-year hot event will be doubled (though in many regions it might even occur every 1-2 years), while the occurrence of a current 20-year cold event will dramatically be reduced, under the RCP8.5 scenario (IPCC, 2013). Large increases in heat waves are projected for Europe along with the probability of high summer temperatures particularly under RCP8.5 (Fig. 30).

Figure 30

Projected changes in hot seasonal temperature extremes in 2071-2100 for RCPs 2.6 and 8.5

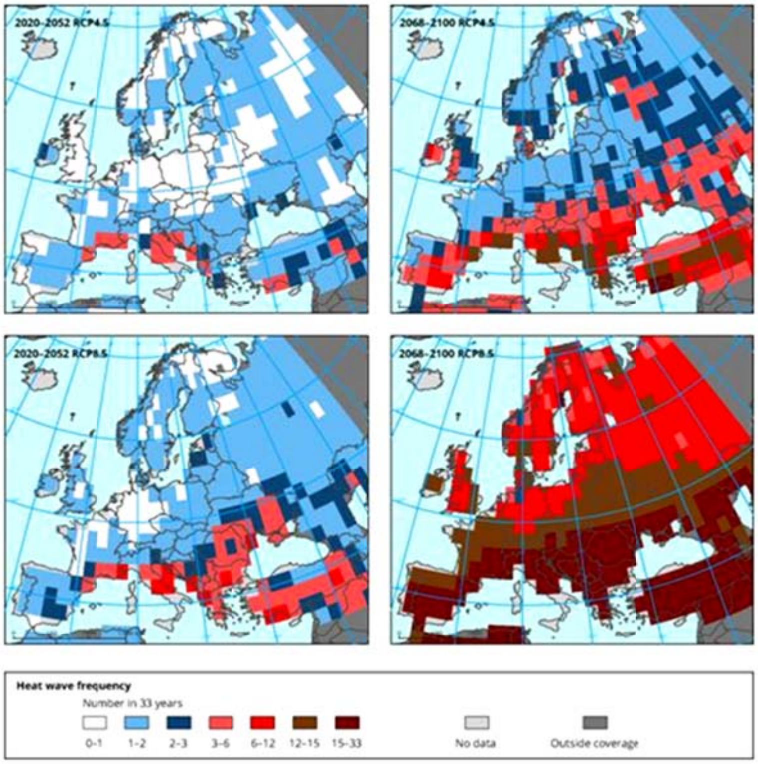
(Yellow, orange/red areas show regions where (at least) 1 every 2 summers will be warmer that the warmest summer in 1901-2100 (Coumou and Robinson, 2013))



21. Heat waves as severe as that of 2003 are expected to occur about once a century for the current climate; in early 2000s, it was expected to take place approximately once every several thousand years. An attribution study has suggested that anthropogenic influence at least doubled the odds of occurrence of such events (MetOffice, 2014). Furthermore, recent studies suggest that the probability of occurrence of an extreme heat wave like that occurred in the Russian Federation in 2010 may increase by 5 to 10 times until 2050 (Dole et al., 2011).

Figure 31

Median of the projected number of heat waves (from a model ensemble) in the near (2020-2052) and long (2068-2100) term under the RCP4.5 and RCP 8.5 scenario (EEA, 2015b)

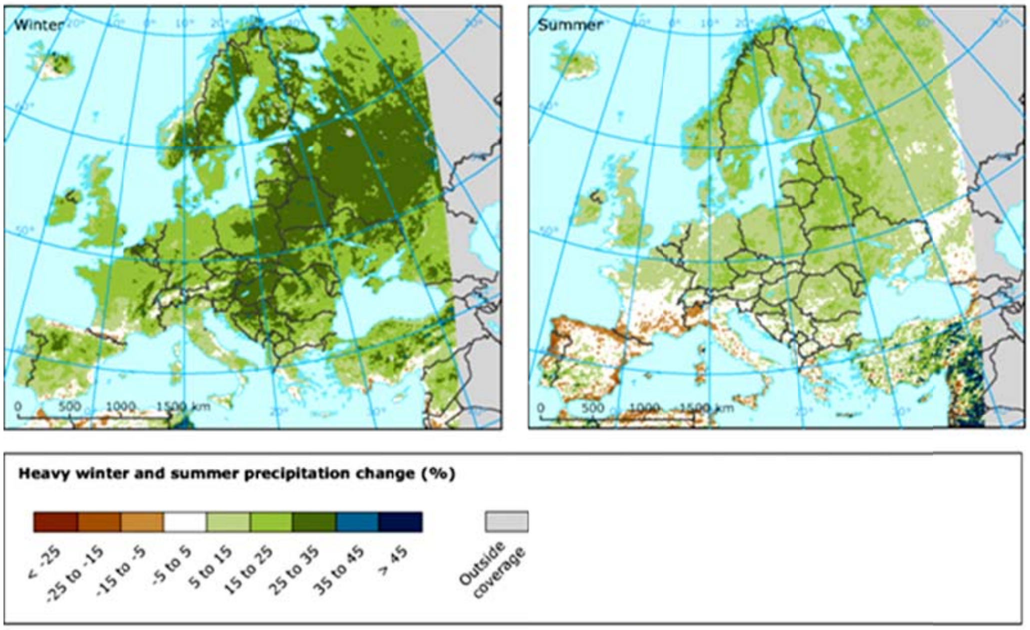


Downpours

22. Extremes linked to the water cycle, such as droughts, heavy rainfall and floods, are already causing substantial damages. As temperature rises, average precipitation will exhibit substantial spatial variation. It is likely that precipitation will increase in high and mid latitude land regions and decrease in subtropical arid and semi-arid regions by the end of the century under the RCP8.5 scenario. Extreme precipitation events will likely be more intense over most of the mid-latitude and wet tropical regions (IPCC, 2013). For central and NE Europe, projections demonstrate large increases (25 per cent) in heavy precipitation by the end of the century (Fig. 32). High resolution climate models indicate that extreme summer rainfalls could intensify with climate change (MetOffice, 2014). For the UK, although summers will become drier overall, the occurrence of heavy summer downpours (more than 30 mm in an hour) could increase almost 5 times (MetOffice, 2014).

Figure 32

Projected changes in heavy precipitation (in per cent) in winter and summer from 1971-2000 to 2071-2100 for the RCP8.5 scenario based on the ensemble mean of regional climate models (RCMs) nested in general circulation models (GCMs) (EEA, 2015c)



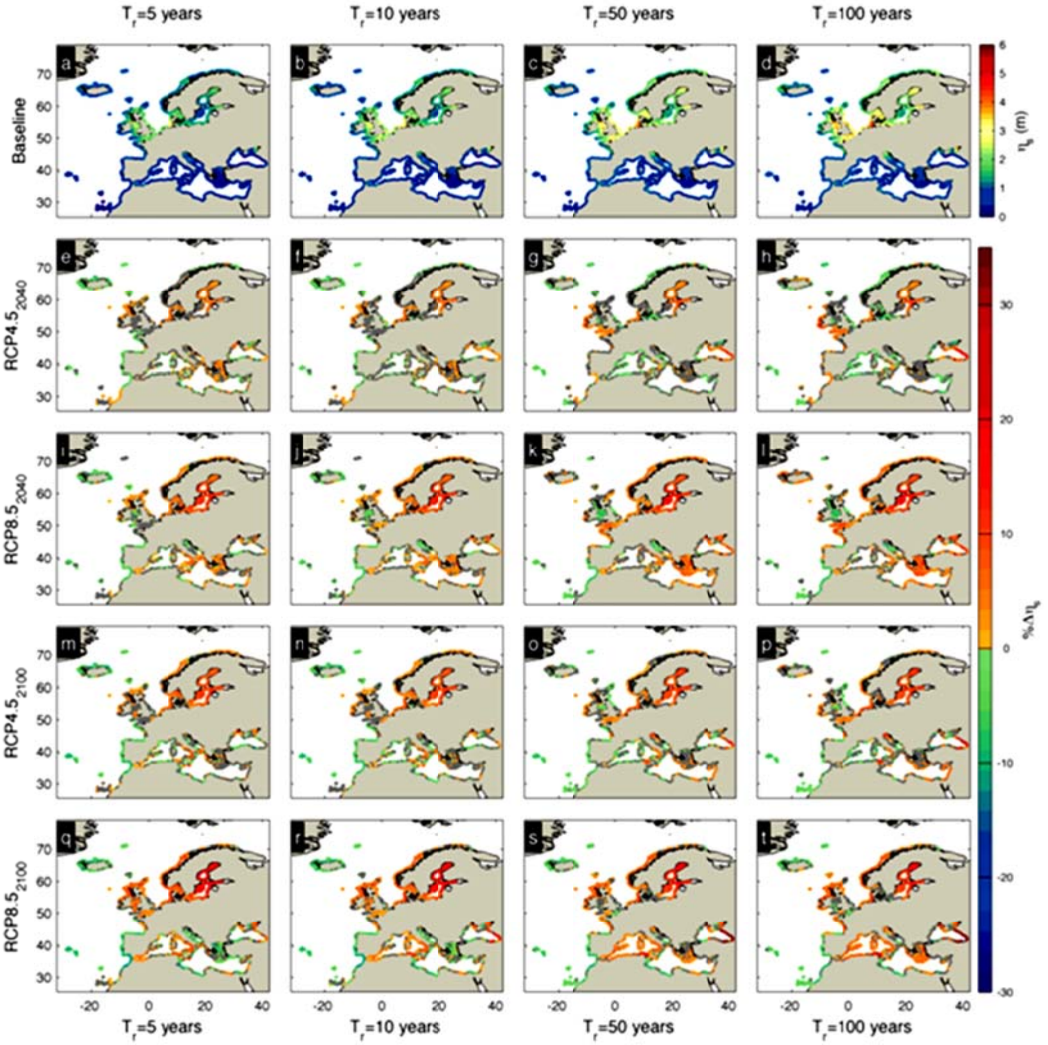
Sea storm and riverine floods

23. Despite the emerging risks associated with the changes in extreme coastal water levels, there is still limited information on storm surge levels (SSLs) under the Representative Concentration Pathways (RCPs) (IPCC 2013). That’s mainly because most previous studies are at local/regional scale which implies that (a) there are several regions for which there is no information on projected SSL and (b) the use of different GHG emission scenarios, climate and ocean models, as well as the diversity of the coastal environments make it difficult to draw general conclusions at global or regional scales.

Figure 33

Ensemble mean of extreme SSL (m) along the European coastline obtained for 5, 10, 50, and 100 years return periods (shown in different columns), for the baseline period (a-d), as well as their projected relative changes under RCP4.52040 (e-h), RCP8.52040 (i-l), RCP4.5 2100 (m-p), RCP8.52100 (q-t) scenarios (shown in different lines)

(Warm/cold colours express increase/decrease, respectively; while points with high model disagreement are shown with grey colours (Vousdoukas et al., 2016a))



24. For Europe, projections show larger storm surge levels for the Atlantic and Baltic coast/ports under all scenarios and extreme storm events tested (Vousdoukas et al., 2016a; Vousdoukas et al., 2017). The North Sea is an area subject to some of the highest SSLs in Europe (Fig. 33), with the projections indicating an increase in the extremes, especially along its eastern coast. Storm surges are projected to increase along the Atlantic coast of the UK and Ireland, due mostly to a consistent increase in the winter extremes. The Atlantic coast of France, Spain and Portugal is also exposed to very energetic waves (Pérez et al. 2014). The Mediterranean Sea has been studied in terms of projected storm surge dynamics and there is consensus among studies based on SRES scenarios for no changes, or even a

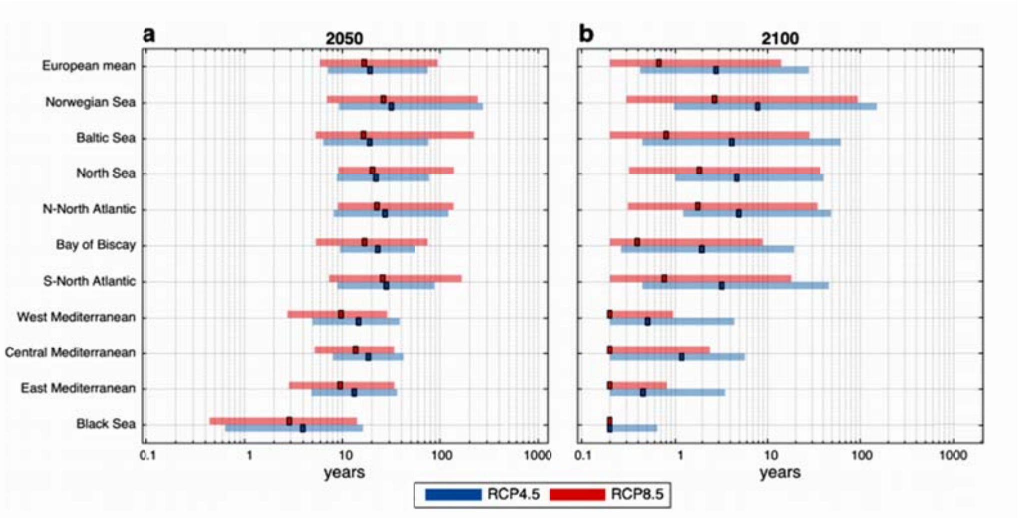
decrease in the frequency and intensity of extreme events (Conte and Lionello 2013; Androulidakis et al. 2015). This is in agreement with reported historical trends (Menéndez and Woodworth 2010), as well as with more recent findings, projecting changes mostly in the ±5 per cent band, either positive or negative (Vousdoukas et al., 2016a). The North Adriatic is a region which has been studied more thoroughly due to the highly vulnerable (and socio-economically important) Venice area, with most previous projections reporting no statistically significant change, or even decreases (Mel et al. 2013), even though Lionello et al. (2012) projected increases in the frequency of extreme events around Venice, under a B2 SRES scenario.

25. It should be noted that more than 200 million people worldwide live along coastlines less than 5 m above sea level; this figure is estimated to increase to 400-500 million by the end of the twenty-first century. Growing exposure (population and assets), rising sea levels due to climate change, and in some regions, significant coastal subsidence due to human coastal water drainage/groundwater withdrawals will increase the flood risk to varying degrees. For instance, a 1 m rise in relative sea-level can increase the frequency of current 100 year flood events by about 40 times in Shanghai, about 200 times in New York, and about 1000 times in Kolkata (WMO, 2014).

Figure 34

Return period of the present day 100-year ESLs under RCP4.5 and RCP8.5 in 2050 (a) and 2100 (b). Coloured boxes express the ensemble mean value and coloured patches the inter-model variability (best-worst case)

(The values shown are averages along the European coastline as well as along the coasts of 10 geographical regions (Vousdoukas et al., 2017))

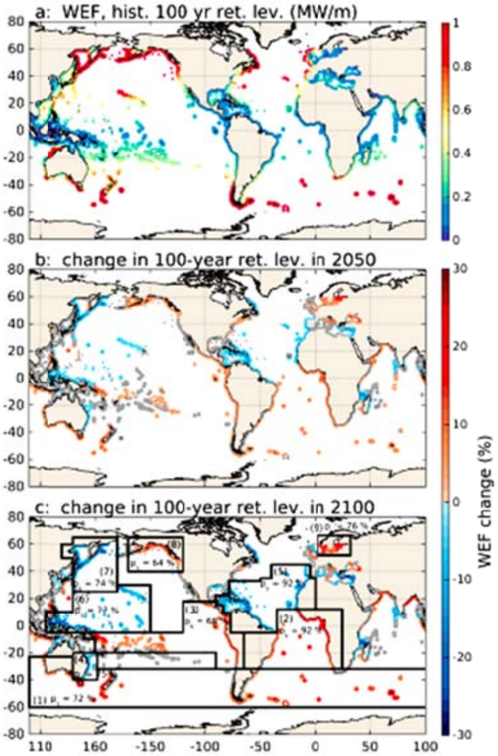


26. For the next 50 years or so, Hallegatte et al. (2013) suggested that for the 136 largest coastal cities: (i) damages could rise from US$ 6 billion/year to US$ 52 billion/year solely due to increase in population and assets; (ii) annual losses could approach US$ 1 trillion or more per year if flood defences are not upgraded; (iii) even if defences would be upgraded, losses could increase as flood events could become more intense due to the water depths increasing with relative sea-level rise. This raises the question of whether there are potential thresholds which, if passed, could reverse the current and projected trends of coastal population growth (King et al., 2015). Taking into account the standards of coastal flood protection works and uncertainties concerning the probability of their failure, about 5 million people in Europe could potentially be affected by the present day 100-year extreme sea level-ESL (Vousdoukas et al., 2016b).

Figure 35

Projections of wave energy flux-WEF along the global coastline: (a) baseline 100-year return level and relative change of the 100-year WEF for the year (b) 2050, and (c) 2100

(Grey dots correspond to locations with no significant change. In (c), areas of significant change are reported together with the percentage ps of points where increase is significant. (1) Southern temperate zone, (2) S. Atlantic, (3) sub-equatorial-tropical E. Pacific, (4) E. Australia, (5) N. tropical Atlantic, (6) NW tropical Pacific, (7) NW Pacific, (8) NE Pacific, and (9) Baltic Sea (Mentaschi et al., 2017))



27. Averaged over Europe's coastlines, the present 100-year ESL[3] is projected to occur approximately every 11 years by 2050, and every 3 and 1 years by 2100 under RCP4.5 and RCP8.5, respectively (Fig. 34). Hence, the 5 million Europeans currently at risk once every 100 years, may be flooded at an almost annual basis by the end of the century (Vousdoukas et al., 2017). Some regions are projected to experience an even higher increase in the frequency of occurrence of extreme events, most notably along the Mediterranean and the Black Sea, where the present day 100-year ESL is projected to occur even more often.

28. For the end of the twenty-first century, recent modelling results under a high emission scenario (RCP8.5) suggest a significant increase of up to 30 per cent in the 100 year return level wave energy fluxes (WEF) for the majority of the coastal areas of the southern temperate zone, with the exception of Eastern Australia, the Southern Atlantic, and the sub-equatorial-tropical E. Pacific (Mentaschi et al., 2017). In comparison, large coastal areas in the NH are projected to have a negative trend, with the exception of the NE Pacific and the Baltic Sea (Fig. 35) which are projected to show positive trends (rises of up to 30 per cent).

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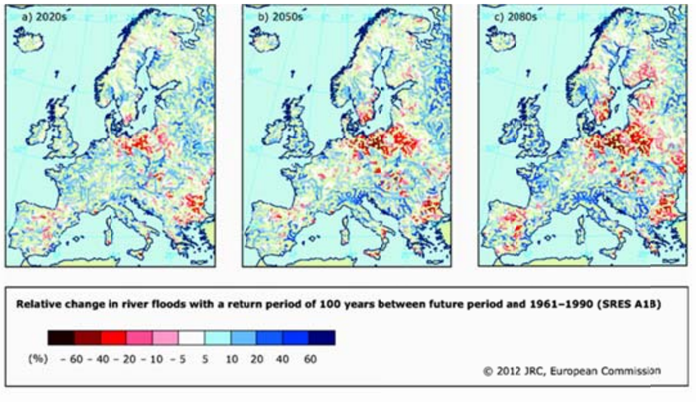
[3] The extreme sea level (ESL) is the combination of mean sea level, the tide, the storm surge level (SSL) and the wave set up (Losada et al., 2013).

Figure 36

Relative change in minimum river flow for a) 2020s, b) 2050s and c) 2080s compared to 1961-1990 for SRES A1B scenario (EEA, 2012)

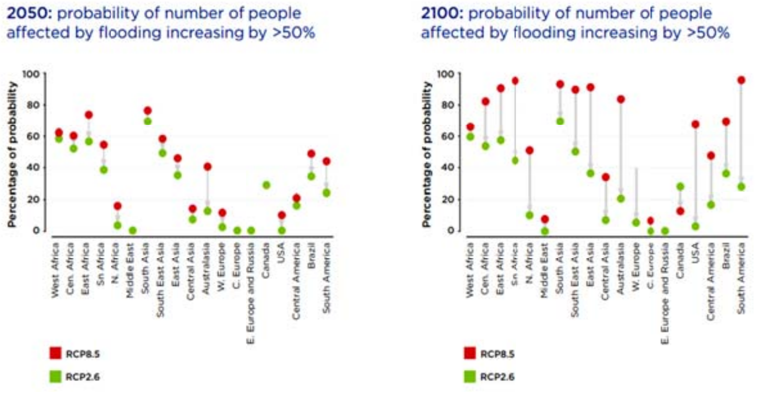


29. River flooding also poses a significant threat to the global population with observed increases in extreme runoffs being well documented (Feyen et al., 2010). Damage magnitude is mainly due to increasing human and infrastructure exposure in flood risk areas (IPCC, 2013). Changes in river floods projected for Europe are presented in Fig. 36).

30. Fig. 37 shows the flood risk by region that climate change increases by more than 50per cent the numbers of people affected by a current 30-year flood, relative to the situation without climate change. By the 2050s, there is at least a 50 per cent chance that climate change alone would lead to a 50 per cent increase in flooded people across sub-Saharan Africa, and a 30 to 70 per cent chance that such an increase would also take place in Asia. By 2100, risks will be higher (King et al., 2015). Population change alone will increase the numbers of people affected by flooding. Global total increases very substantially, by around 5-6 times over the course of the century for the high emissions pathway (RCP8.5), mainly due to increases in South, South-East and East Asia (King et al., 2015). Concerning the ECE region, flood impacts in 2050 are projected to be milder than in the other regions; nevertheless the situation for some ECE regions is projected to deteriorate significantly in 2100 (Fig. 37).

Figure 37

Probability that climate change will increase by more than 50per cent the number of people affected by the current 30-year flood, relative to the situation with no climate change, under two RCPs. Medium growth population projection is assumed (King et al., 2015)



1.3 Implications for Transport: A short review

31. With regard to the sensitivity of transport networks to CV & C, a recent review (ECE, 2013) has found that: (a) transportation assets tend to be more sensitive to extreme events, such as storm surges, heavy precipitation events, heat waves and high wind events than to incremental changes in the mean of the climate variables; (b) maintenance, traffic conveyance and safety are generally more sensitive to climate forcing than physical assets, as thresholds for e.g. delaying/cancelling transport services are generally lower than those for damages to infrastructure and (c) transport assets are sensitive to stressors whose occurrence is relatively unlikely in comparison to typical weather variability. For example, the superstructure of the US Gulf Coast bridges proved to be vulnerable to loading from direct wave impacts due to the unprecedented coastal sea levels induced by the storm surge of the Katrina (2005) hurricane (USDOT, 2012).

32. Hydro-meteorological extremes, such as heavy rainfall/floods and droughts are already causing substantial damages to transport infrastructure and services. Changes in extreme precipitation may result in river floods that might be particularly costly for inland transport networks (Hooper and Chapman, 2012), as major roadways and railways are located within and/or crossing flood plains; they can also have significant effects on bus/coach stations, train terminal facilities and inland waterway operations. There can be direct damages during, and immediately after, a heavy precipitation event that require emergency response as well as measures to support the structural integrity and maintenance of roads, bridges, drainage systems, and tunnels (USDOT, 2012).

33. Road and railway networks are projected to face significant risks of flooding as well as bridge scouring, whereas the projected increases in downpours/floods will also cause more rain-related road accidents (due to vehicle and road damages and poor visibility), delays, and traffic disruptions (e.g. Hambly et al., 2012). Road networks are expected to be severely affected by the projected increases in heavy downpours and flooding, through diverse impacts on the different types of pavement, asphalt and concrete; these would require adaptive maintenance practices such as construction of adequate drainage and the use of permeable pavements and polymer modified binders (e.g. Willway et al., 2008). Regions where flooding is already common will face more frequent and severe problems. Standing flood waters could have severe impacts and high costs; for example, the costs due to long-term road submersion in Louisiana have been estimated as US$50 million for 200 miles of the state highways (Karl et al., 2009). In the USA, adaptation costs for (road and rail) bridges vulnerable to river flooding have been estimated as $140-$ 250 billion through the twenty-first century (Wright et al., 2012). For the EU27 cost estimations are lower: future costs for bridge protection against flooding have been estimated as up to €0.54 billion per year (EC, 2012; ECE, 2015).

34. Railway infrastructure could be also impacted severely, with impacts including track and line side equipment failure, flood scours at bridges and embankments due to high river levels and culvert washouts, landslides, as well as problems associated with personnel safety and the accessibility of fleet and maintenance depots. In the UK, costs related to extreme precipitation/floods and other extreme events, which are already estimated as £50 million a year, might increase to up to £500 million a year by the 2040s (Rona, 2011). Extreme winds are also projected to be more catastrophic in the future (e.g. Rahmstorf, 2012), particularly at coastal areas where they can cause coastal defence overtopping and flooding of coastal/estuarine railways. Extreme winds could also cause infrastructure failures and service interruptions though wind-generated debris (e.g. (PIARC, 2012; ECE, 2013; 2015).

35. The projected increase in the frequency of heat waves may also pose substantial challenges in the railway, road (and airport) operations and services, due to rail buckling,

road pavement damages and necessary reductions on aircraft payloads. The projected increases in the number of days with temperatures above about 38 ^{0}C (Vogel et al., 2017) can lead to increasing road infrastructure failures. Drier and hotter summers will cause pavement deterioration and/or subsidence, affecting performance and resilience (PIARC, 2012). Model predictions (EC, 2012) have estimated the additional annual costs for the upgrade of asphalt binder for the EU27 under the SRES scenario A1B[4] as €38.5-135 million in the period 2040-2070 and €65-210 million in 2070-2100. Nevertheless, it should be noted that as road surfaces are typically replaced every 20 years, such climate change impacts could be considered at the time of replacement.

36. Arctic warming may lengthen the arctic shipping season and introduce new shipping routes. There may be new economic opportunities for Arctic communities, as reduced ice extent facilitates access to the substantial hydrocarbon deposits (at Beaufort and Chukchi Seas) and international trade. At the same time, Arctic warming will result in (a) greater coastal erosion due to increased wave activity at the polar shorelines of Canada, the Russian Federation and the USA (e.g. Lantuit and Pollard, 2008) and (b) increasing costs in the development and maintenance of transport infrastructure due to thawing permafrost (ECE, 2015). Permafrost thawing (e.g. Streletskiy et al., 2012) presents serious challenges for transportation, such as settling and/or frost heaves that can affect road structural integrity and load-carrying capacity (ECE, 2013). In Arctic areas many highways are located in areas with already discontinuous, patchy permafrost, resulting in substantial maintenance costs as well as usage restrictions (Karl et al., 2009). Such disruptions are projected to increase substantially under the predicted increases in the extent/depth of permafrost thaw (EEA, 2015a).

37. Inland waterways can also be affected by both floods and droughts. Floods can have major impacts such as suspension of navigation, silting, changes in the river morphology and damage of banks and flood protection works (ECE, 2013). Inland waterways can also be affected by low water levels during droughts. Recent research[5], which has used the Rhine-Main-Danube (RMD) corridor as a case study, has found that over a period of 20 years, average annual losses due to low water levels were about €28 million (see also Jonkeren et al., 2007). Projections from different climate models, however, do not show significant effects of the low flow conditions on the RMD corridor until 2050; nevertheless, ‘dry’ years may lead to a 6-7 per cent increase in total transport costs compared to ″wet″ years.

38. Impacts of CV & C on the European transport systems were studied in two recent European projects[6]. Both projects found that there is a lack of reliable information relevant to the vulnerability of the different transport modes. Direct costs borne by the transport sector, such as those from infrastructure repair/maintenance and vehicle damage and increased operational costs, have been estimated for the period 1998-2010 as € 2.5 billion annually, and indirect costs from transport disruptions as €1 billion annually. Rail has been the most affected transport mode, with ‘hot spots’ in E. Europe and Scandinavia, whereas the effects on roads (mainly from weather related road accidents) have been found to be more evenly distributed.

39. Coastal transport infrastructure (coastal roads, railways, seaports and airports) will be dis-proportionally impacted by the CV & C as, in addition to the above challenges, they will have to adapt to increasing marine coastal flooding. In the ECE region, mean SLR and

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[4] This scenario is roughly equivalent to the IPCC AR5 scenario RCP6.0.

[5] EU FP7-ECCONET Project, www.tmleuven.be/project/ecconet/home.htm

[6] The EU-FP7 WEATHER www.weather-project.eu and EWENT Projects (www.weather-project.eu/weather/inhalte/research-network/ewent.php)

increasing storm surges and waves, particularly along the NW Europe, the Baltic Sea and the NE Pacific coast the of US and Canada (e.g. Vousdoukas et al., 2016a; Mentaschi et al., 2017), may induce major 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 (ECE, 2013; 2015). Pecherin et al. (2010) have estimated that one meter increase in the ESLs above the inundation level of the current 1-in 100 year-storm event[7], would result in damages and repair costs of up to €2 billion for mainland French A-roads, excluding operational and connectivity costs. Another study (EC, 2012) has provided an initial estimate of the future risk of the European coastal transport infrastructure due to mean sea level rise-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 the 4.1 per cent of the total, with an asset value of about €18.5 billion. As however, more detailed projections on future extreme sea levels-ESLs and coastal wave power are starting to become available (Vousdoukas et al., 2016b; 2017; Mentaschi et al., 2017) for the ECE region (and beyond), it will be a worthwhile exercise to assess again the potential inundation impacts on the ECE transport infrastructure under different CV & C scenarios.

40. Finally, it should be noted that the transport industry is a demand-driven industry. Climate Variability and Change can have significant effects in, almost all, sectors of economy, and thus affect indirectly transport services through e.g. changes in commodity demand and tourism transportation (ECE, 2015).

1.4. Summary

41. In this Chapter a review of the long-term and recent trends and variability of different climatic factors that can affect transportation has been presented, together with a review of the recent projections on the evolution of these factors in the twenty-first century under different emission scenarios. The major findings are summarized below.

Trends

42. There is overwhelming evidence for a warming world since the nineteenth century from scientific observations from the upper atmosphere to the ocean deeps. The global average surface temperature has risen by 1.1 ^{0}C since the late nineteenth century, with the most recent 6-year period (2011-2016) being the warmest on record. 2016 has also been the hottest year on record (1.1 ^{0}C higher than the 1901-2000 average of 14.0 ^{0}C). In the ECE region, temperatures were more than 1 ^{0}C above the 1961-1990 average over most of Europe, Northern Asia and the South-Western US and reaching about 3 ^{0}C above average in regions of the Russian Arctic. The integrated ocean heat content within the 0-700 m layer was higher than any previous time and sea surface temperatures (SSTs) were above average in most of the oceans. Evidence suggests that warm extremes have become warmer and cold extremes less cold in many regions.

43. Land precipitation data reveal an increasing trend in the twentieth century, especially in mid and high latitudes and a strong regional variability which, in many cases, appears to be influenced by the large climatic modulations such as the ENSO and NAO. Land precipitation in the most recent period (2011-2016) was strongly influenced by the

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

ENSO, i.e. the La Niña conditions in 2011-2012, and the strong El Niño of 2015-2016. In 2016, precipitation above the 90th percentile was observed in a large swath of land extending from Kazakhstan across the Western Russian Federation into Finland, N. Sweden and Norway; at the same time, large areas of the Northern and Central Russian Federation were dry, with much of the region between the Urals and Lake Baikal and to the north of 55 ^{0}N showing precipitation below the 10th percentile.

44. There has been also an increase in heavy precipitation events (in intensity and/or frequency) in many areas of the ECE region. One of the clearest trends appears to be the increasing frequency/intensity of heavy downpours in areas that there is already a significant flood risk (for the 1 in a 100-year events), such as the Central and Eastern Europe, Central Asia and along the large S-N drainage basins of Siberia. Consequently, flood damages are expected to rise considerably by the end of the century, being generally higher in the north than in the south. In some regions, there is also evidence to suggest increases in the frequency/intensity of heat waves, as well as of droughts (e.g. in the Mediterranean).

45. Over the past few decades, there appears to be a downward trend in the extent/duration of snow cover in the Arctic. Snow cover has declined (in the month of June) by 11.7 per cent per decade over the period 1967-2012. However, this trend is not uniform; some regions (e.g. the Alps and Scandinavia) show consistent decreases at low elevations but increases at high elevations, whereas other regions (e.g. the Carpathians, Pyrenees, and Caucasus) show no consistent trends. There has been a decrease in the number of frost days in mid-latitude regions. Arctic sea ice continued its steep decline. In 2016, sea ice extent was well below average and at record low levels for large parts of the year; March seasonal maximum was 14.52 million km^2, the lowest seasonal maximum in the 1979-2016 satellite record. Mountain glaciers also continued to decline. Permafrost extent also continued to decrease; recently, there has been warming down to 20 m depth in Arctic permafrost regions.

46. Since 1860, sea level has increased by about 0.20 m, with the rate of increase becoming progressively greater, particularly since the 1990s. SLR trend over the satellite record (1993-2015) has been 3-3.2 mm yr^{-1}, considerably higher than the 1900-2010 average (1.7 mm year^{-1}).

47. Extreme hydro-meteorological events (e.g. heat and cold waves, tropical cyclones, floods, droughts and intense storms) causing significant losses/damages also appear to be on the rise; fortunately, human loss did not follow the steep upward trend of the economic losses associated with these extreme events.

Projections

48. Recent projections on the climatic factors that could impact transport infrastructure and operations are presented below. Generally, challenges that are already imposed by certain climatic factors on the present day transport infrastructure will increase significantly.

49. By the end of the twenty-first century, the mean atmospheric temperature is projected to increase between 1.0 and 3.7 ^{0}C above the mean temperature of the period 1986-2005, depending on the RCP scenario. Oceans will warm under all scenarios, with the highest SSTs projected for the subtropical and tropical regions. Increases in hot extremes and decreases in cold extremes are expected by the end of the twenty-first century, particularly in mid-latitude regions. Large regional differences are projected for temperature maxima (TX_X); these may increase in central Europe, central N. America and N. Australia. The frequency/duration of heat waves is projected to increase for many regions (and in Europe), particularly under high emission scenarios. For most land regions

it is considered likely that the frequency of the current 20-year hot event will be doubled; in some areas, such an event might even occur every 1-2 years. At the same time, the occurrence of the current 20-year cold event will substantially decrease in the future.

50. As temperature rises, average precipitation will exhibit substantial spatial variation in its patterns. Land precipitation is projected to increase in high and mid latitudes and decrease in sub-tropical arid and semi-arid regions. Extreme precipitation events will likely be more intense over most of the mid-latitude and wet tropical regions. For central and NE Europe, projections demonstrate large increases (by 25 per cent) in heavy precipitation events by the end of the century. At the same time, widespread droughts across most of South-Western North America are projected for the mid to late twenty-first century. In comparison, decreases are projected for the duration/intensity of droughts in Southern Europe and the Mediterranean, central Europe and other areas of North America.

51. Snowfall and rainfall are projected to increase in the Arctic regions, mostly in winter. However, although winter maximum snow depth will likely increase (particularly in Siberia), early melt will result in considerable decreases (by up to 25 per cent) in spring snow cover in the Northern Hemisphere (NH). Mountain glaciers and ice caps are projected to show a 10 to 30 per cent mass reduction by the end of the century. Models also project accelerating thawing of permafrost, due to rising temperatures and changes in snow cover. Current rates of warming of the European permafrost surface are 0.04 - 0.07 ^{0}C yr^{-1} and, although there are challenges in assessing permafrost change, its extent in 2100 is expected (medium confidence) to decrease by 37 per cent and 81 per cent for the RCP2.6 and RCP8.5 scenarios, respectively.

52. It is also likely that the Arctic sea ice will continue to decrease in extent/thickness, although there will be considerable inter-annual variability. In the period 2081-2100, reductions in Arctic ice extent of 8 to 34 per cent (in February) and of 43 to 94 per cent (in September) are projected (compared to the average extents in 1986-2005) for RCP2.6 and RCP8.5. These may result in the development of major Arctic shipping routes which, however, could be associated with environmental risks and development difficulties, such as those imposed by the projected permafrost thaw on the development/maintenance of the necessary coastal and land transport infrastructure to service these routes.

53. CV & C risks to ECE coastal transport infrastructure are also expected to rise. Sea level rise for the ECE region depends on the emission scenario, with greater rises predicted in the case of additional ice sheet melting. For the North Sea coast, for instance, mean sea level rises of 0.40 to 1.05 m are expected, with slightly lower rates projected for the Mediterranean coast. Larger storm surge levels are projected for the Atlantic, North Sea and Baltic coasts (and ports) under all scenarios and extreme storm events. For Southern Europe, however, projections are better, with expected changes in the storm surge levels mostly in the ±5 per cent band.

54. Recent research suggests a negative trend in the wave energy fluxes-WEF (for the 100-year return event) along the ECE coast, with the exception of the NE Pacific and the Baltic coasts which are projected to show increases in the WEF of up to 30 per cent. With regard to the extreme sea levels (ESLs) and taking into account the presence/standards of coastal flood protection works and uncertainties concerning the probability of their failure, about 5 million people in Europe could potentially be affected by the present day 100-year ESL. Averaged over Europe’s coastlines, such an event is projected to occur approximately every 11 years by 2050, and every 1 to 3 years by 2100 (RCP4.5 and RCP8.5). Hence, the millions of Europeans currently at risk once every 100 years may face flooding at an almost annual basis by the end of the century. Some regions are projected to experience an even higher increase in the frequency of occurrence of extreme events, most notably along the Mediterranean and the Black Sea; in these areas, such events are projected to occur even

more often. It appears that the effects of these events on the coastal transportation infrastructure (and related supply chains) should be urgently assessed in more detail.

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