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ORIGINAL PAPER

Weather, climate change, and transport: a review

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Abstract
Transportation is affected by weather and extreme weather events, and there is evidence that heatwaves, heavy precipitation, storms, wildfires, and floods increasingly affect transport infrastructures, operations, and travel behavior. Climate change is expected to reinforce this trend, as mean weather parameters change, and the frequency and intensity of extreme events increases. This paper summarizes interrelationships of weather and transport for different transport modes from both supply and demand side perspectives on the basis of a literature review. To further explore the complexity of these interrelationships, it also evaluates news items ($n = 839$) in a sample of global media news outlets covering the world and population-dense world regions. Results confirm that extreme events have become disruptive of transport systems at the micro and macro scale, also affecting transport behavior. There are implications for environment, economy, technology, health, and society. Interrelationships are illustrated and discussed: Climatic impact drivers can be expected to increase transport vulnerabilities and risks, and have relevance for transport planning and adaptation.

Keywords Climate change · Extreme weather events · Transport behaviour · Transport planning · Transport infrastructure

1 Introduction

Weather-related transport disruptions often feature prominently in the media, with regular reports on the adverse effects of heavy rainfall and flooding, snow, storms, wildfires, or heatwaves. While the disruptive character of some of these phenomena has been frequently described, including canceled flights and trains, closed roads, evacuations,

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or damage to infrastructure (e.g., Spiegel 2020; Washington Post 2019), more systemic conceptualizations of these impacts are not currently available. This is of concern given expectations of more intense and more frequent extreme weather events (IPCC 2021).

While some weather phenomena are expected to increase in frequency and intensity, such as rainfall in some regions as a result of warming oceans, evidence also suggests that events with limited relevance in the past have gained importance. Haze from wildfires appears to have become significantly more disruptive, for example, having already caused the cancellation and delay of hundreds of flights in Australia (France24 2020), Italy (Reuters 2015), the United States (The Seattle Times 2020), Indonesia (AINonline 2019) or Malaysia (Daily Express 2015). There is also evidence of new forms of technical failures, such as aircraft being unable to take off in high temperatures (BBC 2017) or train engines overheating and catching fire (Spiegel 2019). Disruptions can be cascading through the transport system, as illustrated by low river water tables disrupting fuel deliveries in Germany, and associated closures of fuel stations and price hikes; phenomena in turn linked to panic buys and changes in transport behavior (Zeit 2018). Weather phenomena, the media has proposed, may even become economic tipping points: for example, the European heatwave in the summer of 2018 dampened UK interest in holidays abroad, and prompted the BBC (2019) to suggest a role of weather in the collapse of tour operator Thomas Cook.

Many of these more recent events remain anecdotal, even though complexities have also been outlined in the scientific literature. Heatwaves, for instance, are linked to traffic injuries (Basagaña et al. 2015; Wu et al. 2018), as higher temperatures contribute to distractedness. Heat island effects in urban environments may disturb sleep patterns, and indirectly affect traffic risks (Donjacour et al. 2010). In combination with air pollution and noise from traffic, heat waves are also linked to an increase in preterm births (Arroyo et al. 2016), illustrating the complexity and interconnectedness of health responses. Not all outcomes of extreme weather events are immediate, however, as illustrated by tourism demand responses. Intense and extended rain periods, for example, affect intentions to re-visit a destination (Dubois et al. 2016; Hübner and Gössling 2012).

As these examples illustrate, weather, extreme weather, and longer-term changes in weather parameters linked to climate change all have important and complex implications for transport systems and transport demand. Against this background, this paper seeks to make three key contributions to this field: First, it systemizes the existing knowledge on transport-weather interrelationships and supply–demand responses in a provisional definition of 'adverse' weather conditions for different transport modes. Second, it provides an account of the diversity of outcomes extreme weather events have reportedly had for transportation, relying on a media analysis, and organizes these in regard to their environmental, economic, technical, health and social impacts. Last, the paper discusses the implications of these insights for transport planning and adaptation.

2 Methodology

To systematically investigate weather-transport interrelationships, the study sets out with a literature review that is focussed on the identification of weather thresholds, i.e., the conditions under which different transport modes become affected by weather. To identify the relevant literature, both Google Scholar and the EBSCO database were searched for specific literature, with crosswords including "weather", "traffic", "transport", and combinations with each of the individual transport modes. Motorcycles were not included, as available studies appear to have focussed on the influence of weather conditions on motorcycle crashes (e.g. Cheng et al. 2017). As the focus is on disruptive events, "extreme weather" is defined, in relation to the IPCC (2023) glossary, as: "An event that is rate at a particular place and time of year, [acknowledging] that characteristics of what is called "extreme" may vary from place to place in an absolute sense." In the context of this paper, extreme weather is defined as weather that produces significant behavioral or modal shifts."

Searches in Google Scholar, EBSCO and specific, iterative searches out of the papers yielded a basis of more than 1500 items, which were screened for relevance (Fig. 1). Duplicates, book chapters, conference reports, forecasting, and other unrelated papers were removed, which then led to a basis of 75 papers included in this literature review. Articles were evaluated for content relevant to the understanding of the complexities underlying weather-transport interrelationships, outcomes of extreme weather events, impacts of other weather parameters (snow, ice, sunshine, humidity, radiation), as well as longer-term outcomes of climate change. This takes the form of a critical examination of existing research (Bryman 2016), to understand complexities, and to establish weather *minima* and *maxima* tolerable by aviation, shipping, railways, public transport, automobility, and active transport modes, the latter including walking, (e-)cycling and (e-)scooters. Importantly, min–max weather parameters need to be understood as thresholds, rather than specific points, and focus on temperature, wind speed and rainfall as the most frequently discussed parameters. This approach provides the basis for a preliminary assessment of the range

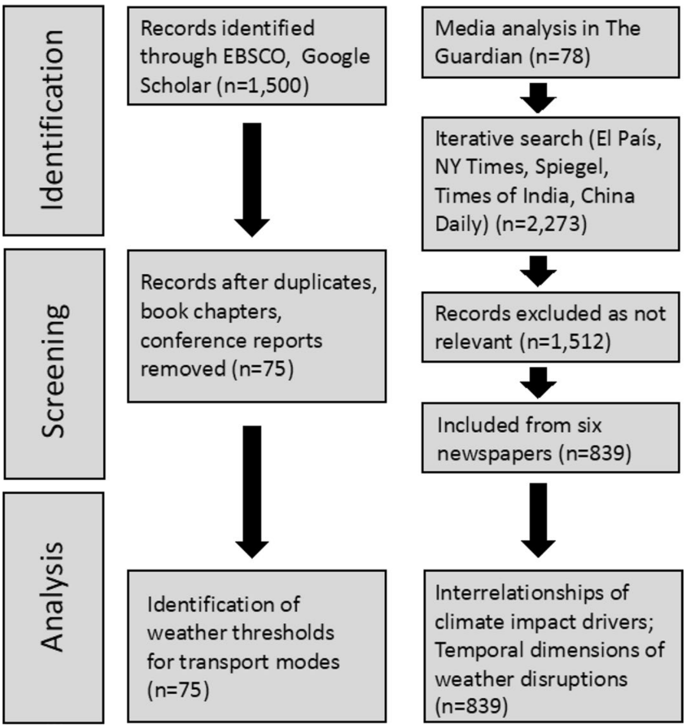

Fig. 1 Research methodology

of optimum vis-à-vis adverse conditions for these parameters and the different transport modes. It is acknowledged that this definition of thresholds does not provide the exactness of the universal thermal climate index (UTCI) that assesses thermal stress categories for human physiological responses (− 40 °C: extreme cold stress/+46 °C extreme heat stress).

The review of the literature is complemented with a media analysis that initially included an evaluation of reports in The Guardian, as a newspaper with global coverage and free online availability. Keyword searches included "weather" and "traffic" as well as "weather" and"transport", and were limited to the period January 2018 to September 2021. This initial 'trial' search yielded 78 news items of relevance, which were analyzed in a grounded theory approach (Glaser and Strauss 2017) to derive a preliminary set of themes. Methodologically, thematic analysis is based on sampling, coding, and analysis involving theoretical saturation in a process of constant comparison (Bryman 2016), with the overall goal to compile and organize data. Comparison is of particular importance, as weather events may have multiple outcomes for transport systems. As the focus of this research is the conceptualization of disruptive impacts, the initial categorization was organized by weather event and transport mode in a table (see Supplement) (Table 2).

To ensure theoretical saturation, i.e. a situation in which no new themes would emerge, an iterative search was then conducted in another five nationally important newspapers covering a wider geography of more recent events, i.e. El País (Spain), The New York Times (USA), Der Spiegel (Germany), Times of India, and China Daily (Table 1). The online search in these five openly available newspapers was limited to 21 months, i.e. the period 1 January 2021 to 30 September 2022, and identified 2273 news items. Of these, 761 were found to have relevance for this research and included in the analysis, i.e. an extension of the table (see Supplement). This qualitative approach seeks to describe the range of disruptive events, and was not continued, as the character of events became repetitive, indicating a degree of theoretical saturation. Yet, the list is not necessarily exhaustive, nor does it address the severity of events (fatality numbers, costs) or their scale (local, regional).

In the next step of the analysis, the data, together with information derived from journal papers, is then used for three different conceptualizations. First, this includes the identification of weather thresholds. Second, interrelationships of climate impact drivers (heat & cold, wet & dry, wind, snow & ice, other; a categorization based on IPCC 2021), their relation to transport modes (air, shipping, railways, vehicles & active transport), and their outcomes (physical, economic, technical, health-related, social) are analyzed. Finally, temporal dimensions of disruptions, which can last from minutes to lifetimes, are derived from the data. Together, this provides novel insights regarding the complexity of interrelationships of weather and transport disruptions.

3 Results and discussion

3.1 Weather and transport

Interrelationships of weather and transport have been investigated on a wide range of scales and regarding different transport modes. A basic insight is that transport patterns are framed by socio-economic and socio-psychological determinants underlying behavior (Heinen et al. 2010). These may include attitudes towards specific transport modes, their accessibility and affordability, views on the relevance of specific trips, or social norms

Table 1 News items reporting on weather and transport

	Identified	Included
Der Spiegel, Germany	128	78
New York Times, USA	610	218
El País, Spain	276	155
New Times of India	707	202
China Daily	552	108
	2273	761

January 2021 to September 2022

(Gössling 2022; Schwanen and Lucas 2011). Weather affects transport mode choices, transport demand, and transport behavior (Zhou et al. 2017). Studies confirm that weather dominates transport decision-making and explains most of the variation in demand on a day-to-day basis, specifically for active transport (An et al. 2019; Aultman-Hall et al. 2009). Where potential users perceive weather as "extreme" outside transport mode-specific boundaries, day and time, or trip purpose, it becomes disruptive, affecting travel decisions (Koetse and Rietveld 2009). Extreme weather can also affect demand through disruptions of operations or infrastructure damage.

Travel motivations have considerable relevance for demand under specific weather conditions, and have been mostly distinguished against the binary of (daily) commutes to work (also: "utilitarian" trips) and "recreational" trips (An et al. 2019; Thomas et al. 2013; Heaney et al. 2019), the latter including visits to friends and relatives, shopping, activities, voluntary work, or health. This line of research suggests that there is considerable variation in the potential for trip substitutability or postponement. Notably, longer-term planning for trips, such as the annual holiday, are also based on longer-term averages (climate) rather than weather forecasts. Short-term negative holiday weather experiences can influence longer-term perceptions of "climate", with repercussions for future travel decisions and destination choices (Gössling et al. 2016).

Often, weather conditions will affect transport modes in similar ways: rainfall, for example, represents an adverse condition for any form of transport. Yet, some transport modes are more susceptible to extreme weather, and in particular active forms of transport (walking, cycling, scooters, etc.) are more exposed. Several papers have provided reviews of these interrelationships, usually with a focus on demand-side implications. In one recent review, Liu et al. (2017: 735) evaluate methodological differences in data collection and interpretation, finding that "there is still a lack of theoretical understanding of how weather is perceived by travelers and affects their travel decisions". They conclude, also with a view to the implications of climate change, that it is "difficult to estimate generic weather parameters in large-scale demand models", echoing earlier insights that "the net impact of climate change on generalized costs of the various transport modes are uncertain and ambiguous" (Koetze and Rietveld 2009: 205).

Böcker et al. (2013) summarize some general interrelationships of weather and transport, such as the positive influence of warm and dry weather on active transport, and the effects of rain, snow, wind, cold and high temperatures above 25–35 °C. Adverse weather conditions cause a switch to "sheltered" transport modes and a decline in trip numbers, specifically when these are leisure-related. However, behavioral responses will depend not only on individual weather parameters, rather than their combination (such as rain *and* wind); involve changes in departure times, travel times, and routes; and vary

Table 2 Supply and demand side effects of weather conditions

	Supply	Demand
Aviation	Thunderstorms, fog, ice, and snow cause delays or runway closures (Palin et al. 2016). High temperatures negatively affect maximum takeoff weight, increasing fuel use (Coffel et al. 2017). There are operational thresholds for wind, rain and temperatures (Borsky and Unterberger 2019)	No documented impact of weather on demand
Shipping	High waves during storms affect operations (Palin et al. 2016), but it will take strong winds to affect ship operations (Ventikos et al. 2016)	No documented impact of weather on demand
Railways	Below-zero and hot temperatures are often problematic for railways, which can be affected by track separation and ice on tracks (cold), thermal expansion (heat), as well as blocked tracks (storms), or indirectly because of staff delays (Xia et al. 2013)	No documented impact of weather on demand
Public transit	Weather affects transit infrastructure, services (Singhal et al. 2014)	Humidity, wind, fog, and rain lead to decline in ridership (Arana et al. 2014; Zhou et al. 2017). Higher temperatures and heavy snow lead to an increase in commuter ridership (Arana et al. 2014; Singhal et al. 2014; Wu and Liao 2020). Older people are the most susceptible to rain, wind & heat, morning commuters—and in particular school children—the least (Wei 2022a, b)
Automobility	Hot weather, rain flooding, windthrow of trees can affect traffic infrastructure (Palin et al. 2016)	Rainfall can modestly affect private car use (Keay and Simmonds 2005), winter storms and snow can cause very significant declines in traffic volumes (Knapp and Smithson 2000). Rain and limited visibility reduce speeds (Romanowska and Budzynski 2022). High temperatures increase crash and injury risks (Liang et al. 2022), as does rain and sun-glare (Becker et al. 2022)
Active transport (walking, cycling, scooter)	No documented impact of weather on supply	Active transport is more attractive in the absence of rain and wind, and higher (spring) temperatures (Prins & van Lenthe 2015). Wind, rain, humidity, high/low temperatures, and snow affect active transport negatively (Nankervis 1999; de Chardon et al. 2017; Heaney et al. 2019; Noland 2021; Thomas et al. 2013). Wildfire smoke can significantly affect all active transport (Doubleday et al. 2021). Storms reduce the visitation frequency and range (Zhang and Li 2022)

geographically, depending on subjective weather interpretations (Dijst et al. 2013). For this reason, it is advisable to consider weather-transport interrelationships for individual transport modes. The following sections summarize the current knowledge regarding aviation, shipping, railways, public transit, vehicles, and active transport.

Aviation. It is well understood that aviation is affected by weather conditions. For example, poor visibility and rain are responsible for most delays in air transport (Koetze and Rietveld 2009). Snow, ice, and fog may cause delays or the closure of runways or airports (Palin et al. 2016). Pejovic et al. (2009) found thunderstorms, snow, and fog to significantly increase the chance of delays in London Heathrow (by 25%), while a linear increase in wind speed of one knot or 0.5 m/s (above mean) increases delay probabilities by 8%. To optimize flight times and to avoid clear-air turbulence zones, airlines may have to deviate from the shortest great circle routes (Kim et al. 2016). Wind-optimal routes are influenced by phases of North Atlantic Oscillation, indicating that wind conditions are highly relevant for airline routing. At airports, operations are influenced by crosswinds, wind, and temperature, with higher temperatures reducing maximum take-off mass and causing take-off distances to increase (Gratton et al. 2020). Thresholds may begin at 4.4 m/s (tailwinds) to 11 m/s (wind); $<0°$ and >35 °C for temperature, and 1.5 mm of rain per hour. Maximum wind speed thresholds may be around 22 m/s, and maximum temperatures around 50 °C (Borsky and Unterberger 2019).

Shipping. Different types of ships (freighters, cruises, ferries) are affected differently by weather. Ocean-going vessels are generally less affected by weather than smaller ships. "Adverse" weather conditions are defined as wave heights exceeding 4.0–5.5 m and 15.7–19.0 m/s mean wind speeds (Ventikos et al. 2016). To avoid adverse weather, all ocean traffic relies on weather routing to reduce operating costs, as ship speed is influenced by wave height and encounter frequency. Calm weather conditions support optimal ship performance (Perera and Soares 2017). Storms and high waves have led to delays in ferry services and the occasional sinking of ships (Palin et al. 2016). In an analysis of 277 shipping accidents between 1990 and 2013, extreme weather conditions were found to affect maneuverability, which then resulted in contact, collision, and grounding accidents. Roll on-roll off ships were found to be disproportionally more often affected by weather conditions, with risks incurred even in lower wave heights (2.5 m) and moderate wind speeds (13 m/s) (Ventikos et al. 2016).

Railways. Xia et al. (2013) investigate the effects of wind, temperature and rain/snow on railways in the Netherlands, estimating that "bad" weather is responsible for 4–8% of railway disruptions, leading to train cancellations, delays, and missed connections. The authors distinguish first and second order effects, such as track issues connected to thermal expansion or ice, forcing operators to reduce speeds. Extreme cold may cause damage to infrastructure including track separation; strong winds may affect train stability or overturn trees blocking tracks. Bad weather may also influence the ability of operating staff to arrive on time, and indirectly affect railway performance. Xia et al. (2013) show that wind gusts exceeding 19 m/s or snow cover of 5 cm or more will have significant effects on disruptions. Greater variation in daily temperature, measured as an increase over standard deviation, will also result in additional disruptions. Specifically, temperatures exceeding 23 °C or falling below -3 °C increase the likelihood of disruptions. Weather may cause 5–10% of all infrastructure failures, as a result of high temperatures, rain, ice, storm, snow, fog, and lightening (ibid.). Trains can also be the cause of vegetation fires (Nezval et al. 2022).

Public transit. There is evidence that adverse weather conditions including rain (and floods), snow, high temperatures, fog, or wind will affect overall demand (trip numbers) and the distances traveled in busses, tramlines, or subway systems. Studies have shown that on rainy and windy days, transport demand will decline (Arana et al. 2014): in one study in Beijing by 5.5% in "moderate" and 8% in "heavy" rain (Wu and Liao 2020). Wei and Liu (2022) find critical rainfall levels of 0.6 and 1.0 mm/h for bus ridership in inner cities and other suburbs, respectively. Higher temperatures increase subway ridership (Arana et al. 2014; Wu and Liao 2020). Singhal et al. (2014) find that heavy snow leads to an increase in subway ridership on weekdays, possibly because travelers shift from road transportation to urban transit, while Böcker et al. (2019) find that dark, cold, wet, and windy conditions make private cars more attractive. Thus, it is possible that on rainy or snowy days in cities without subways, ridership of busses or trams declines, as travelers switch to private cars. Temporal travel shifts in public transport have also been found concurrent with weather conditions (Tao et al. 2018). Air pollution was found to have a significant but small effect on subway ridership on weekends, and a study in Beijing put the maximum share of public transit affected by adverse weather conditions at 12.5% (Zhou et al. 2017). Threshold values for public transit remain insufficiently understood; detailed studies of weather events on the different public transport modes (subways, trams, busses), infrastructure, and operations are missing (Singhal et al. 2014).

Automobility. Road traffic can be affected by various weather conditions, such as hot weather causing the degradation of road surfaces, rain-flooding of infrastructure, or windthrow of trees and other objects onto traffic infrastructure (Palin et al. 2016). A study in Brussels, Belgium found that a small share of automobile commuters reported to change transport modes, departure times, or to divert to alternative routes in "adverse" weather conditions (Khattak and Palma 1997; the authors did not define "adverse"). Keay and Simmonds (2005) observed traffic volumes in Melbourne, Australia, for the period 1989–1996, finding that rainfall led to a modest decline in traffic volumes by 1.35% to 2.11% on wet days in winter and spring. The largest observed reduction was 3.43%. Winter storms and snowfall were found to affect traffic volumes, which in a US study led to a decline in traffic by 16% to 47% (Knapp and Smithson 2000). Precipitation reduces average speeds, but increases accident numbers, by an estimated 75%, with snowfall having a greater effect than rain (Koetze and Rietveld 2009). There are also seasonal effects, as driving may be less desirable in winter, or other transport modes more attractive in warmer periods (e.g. bicycles; Saneinejad et al. 2012), leading to shifts between transport modes. Weather thresholds that support or discourage private car use remain generally insufficiently understood.

Active transport. Walking, cycling, and scooter use are forms of transport that imply greater exposure. Active transport trips are usually short in distance and time, though recreational cycling or hiking may extend over longer periods of time. Temperature, wind, rain, snow, frost (ice), sunshine, humidity, and radiation have all been found to affect active transport (Bean et al. 2021). As with other transport modes, socio-demographic determinants and travel motivations influence adverse weather demand responses, and may lead to trip cancellation, shortening of trips (distance), or mode shifts. Active transport is also characterized by strong seasonal patterns, i.e. following changes in weather parameters over the year (Aultman-Hall et al. 2009; Prins & van Lenthe 2015). The most relevant weather parameters affecting active transport are temperature (too cold, too hot), rain, and wind.

Walking in urban environments is characterized by ideal temperatures ranging between 24 °C-30°C (observational study in downtown Montpelier, Vermont, USA; Aultman-Hall et al. 2009). The study also confirms that significantly colder temperatures and precipitation do lead to a moderate (<20%) decline in walking. Temperatures below 5 °C appear to constitute the lower acceptable limit for walking in Toronto, Canada (Saneinejad et al. 2012). As a result, walking becomes more attractive with higher (spring) temperatures and in the absence of rain and higher wind speeds (Dutch study of older adults; Prins & van Lenthe 2015). Wildfire smoke has recently been documented to lead to a significant decline in walking and cycling (Doubleday et al. 2021).

Cycling is affected by various weather parameters. Nankervis (1999) noted a decline in cycling as a result of wind, rain, and high/low temperatures. This has since been confirmed in a wide range of studies (Bean et al. 2021). Humidity has a negative influence (Nosal and Miranda-Moreno 2014), as has snow (Motoaki and Daziano 2015; Zhao et al. 2018), while sunshine increases the interest in cycling (Thomas et al. 2013). Beyond these general findings, there is complexity regarding the influence of trip motive (An et al. 2019; Heanly et al. 2019; Thomas et al. 2013), gender (Nahal and Mitra 2018; Saneinejad et al. 2012), seasonality (Hong et al. 2020), and level of cycling experience and cycle culture (Motoaki and Daziano 2015).

Ideal cycling temperatures range between 18 °C and 28 °C (An et al. 2019; Bean et al. 2021; Böcker et al. 2019; de Chardon et al. 2017; Heaney et al. 2019). Temperatures below 15 °C represent a lower optimum limit (Saneinejad et al. 2012). Yet, low temperatures do not necessarily deter all cyclists (Bergström and Magnusson 2003). Amiri and Sadeghpour (2015) found a majority of cyclists approached in near-freezing conditions in Calgary, Canada to claim that they would continue to cycle even in very cold temperatures of -20 °C. Prins and Lenthe (2015) find that cycling patterns are influenced by rain, but that effects may be smaller in cities where cycling is a norm. A study of cycling in German cities suggests that "adverse" weather conditions cause at most a 23% decline in cycling activity (Goldmann and Wessel 2021). Böcker et al. (2016) find that dry, calm, sunny, and warm (but not hot) weather stimulates cycling. Interest in cycling is also influenced by wind speeds, with an increase by 1 km/h (0.28 m/s) above the mean leading to a 2% decline in bike-sharing demand (global study; de Chardon et al. 2017). Saneinejad et al. (2012) concluded for Toronto that "wind speed negatively influences cyclists about twice as much as pedestrians. [Rain] affects cyclists more than pedestrians. [Females are] 1.5 times more negatively affected by cold temperatures than males." Findings underline that temperature preferences and threshold ranges are likely to vary between countries and individuals, though further comparative research is needed to confirm this.

Last, *e-scooter and e-bike rentals* are also influenced by wind speed, minimum and maximum temperatures, and humidity, but e-bikes have smaller thresholds for acceptable weather conditions (Noland 2021). Studies suggest that e-scooter use becomes less attractive in rain and snowfall (Ziedan et al. 2021; Reck et al. 2021; 2022), and unattractive in very hot conditions (45 °C) (Almannaa et al. 2021). Dry conditions and higher temperatures encourage e-scooter ridership, though rain is less relevant in warmer conditions (Kimpton et al. 2022).

Table 1 summarizes findings and illustrates that while transport mode choices and travel decisions are influenced by weather conditions, transport systems are relatively robust within standard variations in the key parameters rain, cold/heat and wind. A preliminary conclusion is that up to 20% of transport decisions are influenced by "adverse" conditions, though this will vary depending on transport mode and transport culture. In many situations, "adverse" will be a result of a combination of weather phenomena (for example, strong wind *and* rain *and* low temperatures). Demand-side responses will depend on socio-demography, culture, and climate zone, as well as season. Extreme weather, including storms, cold spells, and heatwaves, as well as fog, ice, or snow can lead to severe disruptions. The review of the literature for the different transport modes also indicates that much emphasis has been placed on either supply or demand side impacts, with a focus on specific locations. Table 2 provides an overview of these interrelationships, suggesting that aviation, shipping, and railways are affected by disruptions on the supply side, i.e. demand is relatively stable irrespective of weather condition. The opposite is true for active transport modes, where demand is more easily affected. Public transit and private car travel can be impacted on both the supply and demand side.

Figure 2 conceptualizes these findings as ranges; this is, as an approximation of thresholds. The figure considers implications for supply and demand, i.e. transport modes may be affected by specific weather conditions (operations; aviation, shipping, railways) when operations become unattractive because of risks or changes in the desirability of trips (operations and demand; automobility), or when conditions become (bio)physically challenging (active transport). The figure shows that beyond specific thresholds, all transport modes will be affected by weather conditions. Some transport modes are relatively stable concerning some parameters (e.g. shipping and railways to rainfall), while others are disrupted when thresholds are reached (e.g. aviation by high tail winds, or shipping by storms causing high waves). Almost all transport modes are susceptible to very cold and very hot conditions. Active transport is disproportionally affected, though there are specific differences: E-scooters appear to be more affected by rain than cycling, and cycling again more than walking. There is a broader optimum for cycling temperatures than for walking, and this optimum is higher for e-scooters due to the cooling effects of riding that does not require physical activity. Cycling is more attractive in colder temperatures than walking as a result of the greater physical exercise generating body heat. Wind is more problematic for cyclists and e-scooters than for people walking, and is interdependent with temperature, as a breeze may be perceived positively by cyclists and e-scooter riders in summer, but not in winter.

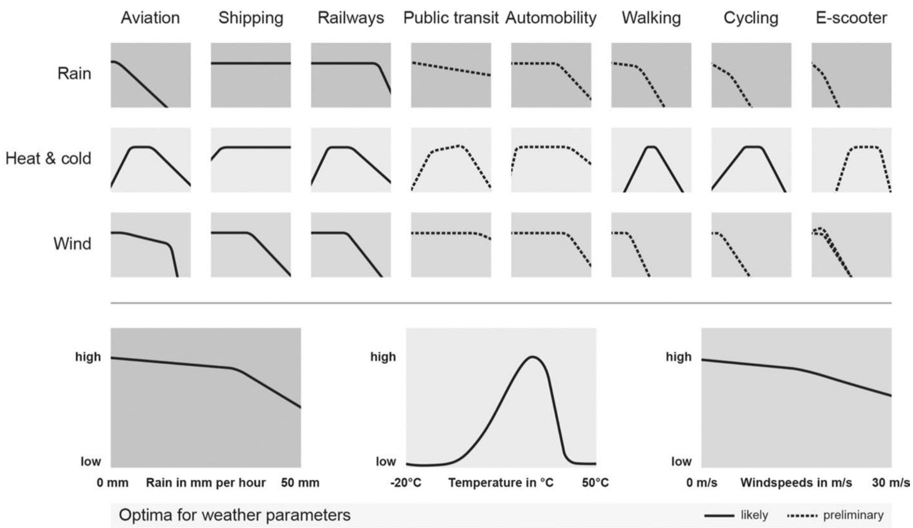

Fig. 2 Provisional transport optimum thresholds for rain, temperature and wind

3.2 Climate change

Longer-term effects of climate change for transport systems will include weather extremes "superimposed on the natural variability of the climate" (TRB 2008: 4–5). The US Transportation Research Board (TRB) concluded in 2008 that increases in very hot days and heatwaves, arctic temperatures, rising sea levels, intense precipitation events, and hurricane intensity would become specifically relevant. Impacts would vary by transport mode and region, yet be widespread and costly, requiring changes in "planning, design, construction, operation, and maintenance of transportation systems" (ibid.: 5). The TRB (2008) also discussed damage to transport infrastructure including provisions, such as pipelines, oil and gas production facilities, and a potential for infrastructure failures (supply) and delays and traffic disruptions (demand). Cascading effects were outlined, as exemplified by floods damaging transport infrastructure, leading to canceled transport (aircraft, trains, public transport), and behavioral adjustments such as mode shifts, rerouted or postponed trips. The following sections summarize the work on climate change impacts for aviation and cycling, the most studied transport modes, as well as more general insights.

Aviation. Studies have concluded that climate change will affect the North Atlantic jet stream and cause an increase in clear-air turbulence in the transatlantic flight corridor (Lee et al. 2019). Williams (2016) shows that this will increase average flight times and fuel burn due to a strengthening of jet-stream winds. Yair (2018) also projects that thunderstorms and lightning strikes will have greater impacts on airports, air-traffic control centers, communication towers, and navigation beacons. Pümpel (2016) highlights that airlines may have to increase maintenance intervals and improve inspection methods to detect risks to aircraft caused by changing weather patterns. Warmer climates will affect maximum take-off total weight, payload, and climb rate (Ren et al. 2019; Zhou et al. 2018). For example, under high emission scenarios, longer-term aircraft-dependent reductions in payload of 8.5% to 19.0% in the high latitudes in the Northern Hemisphere are likely (Ren et al. 2019). Gratton et al. (2020) suggest that the influence of windspeeds on take-offs decreases as a result of climate change, though their study of Greek airports shows a gradual increase in take-off distance as a result of higher temperatures, with a corresponding decline in maximum payload where runways are shorter. Coffel et al. (2017), in a study of 19 major airports around the world, find that under high emission scenarios, 10–30% of annual flights departing during daily maximum temperatures will face payload restrictions of 0.5–4%. As highlighted by Burbidge (2018), precipitation changes and sea-level rise will represent additional challenges for many airports.

Cycling. The implications of climate change for cycling have been studied in various city contexts. Böcker et al. (2013) suggest that winter conditions will become more suitable for walking and cycling by mid-century, as a result of a significant temperature rise and an only modest increase in precipitation (study in Randstad, Netherlands). There are seasonal differences, however: spring weather changes will be supportive of cycling and public transport use, while the car becomes less attractive. Autumn would see an increase in automobility and a decline in walking. In summer, cycling may become less attractive due to higher temperatures. Heaney et al. (2019) find that climate change will affect cycling in New York in a positive way, as time spent cycling and distances covered will grow with warmer temperatures. Yet, there is an expectation that cycling will decline in summer, when temperatures increase beyond the optimum. Bean et al. (2021) conclude that climate change will increase cycling in colder climates and have the opposite effect in already warm climates, though "effects will likely be small" (ibid.: 1). E-scooters may become an alternative transport mode where high temperatures make cycling physically too demanding.

Further insights. Only few studies model changes in transport demand and modal shifts under scenarios of climate change. Saneinejad et al. (2012) suggest that in Toronto, Canada temperature increases by 1° to 6 °C may lead to an increase in trip numbers by up to 17%, while walking, transit, and vehicle use would increase more modestly by up to 2%. Yet, an increase in the frequency of rain would have a moderating effect. In an assessment of infrastructure vulnerability in four US states (Washington D.C., Maryland, Virginia, North Carolina), Koetze and Rietveld (2009) projected that up to 5% of interstates, national highway systems and rails, 4% of principal and minor arterials, 35% of ports, and 3% of airport runways are at risk of inundation through storm surges under a 59 cm sea-level rise scenario. Work on climate change impacts on transport in the US is continued by the EPA (2023).

It is worth noting that some threats such as more frequent and severe flooding incidents or wildfires have emerged only more recently. For example, the TRB (2008) report for US transportation did not mention fires; yet these have gained significance in several US states and worldwide, with risks of damage to infrastructure by fire, or the floods and debris flow occurring in the aftermath of fires (Neary and Leonard 2019). Roads often need to be closed because they are directly passing a wildfire or because of wildfire smoke, which lead to a significant decline in both walking and cycling (Doubleday et al. 2021). This is now acknowledged in the national climate change assessment for transportation (EPA 2023). As far as this is understood, wildfires can have direct and indirect effects on transportation. Fires in Borneo have disrupted river transportation and shipping in the Strait of Malacca (ASEAN & Asian Development Bank 2001). Haze caused an aircraft accident in Indonesia in 1997 with a death toll of 234 (ASEAN & Asian Development Bank 2001). Impacts of wildfires on tourism are reported in a wide range of countries (The World Bank 2019).

Global warming will also have positive outcomes for transportation, as ports become ice-free, the Arctic Northeast Passage opens, and shipping seasons extend, or because infrastructure maintenance costs decline with warmer winters (Chen et al. 2020; Lorentzen 2020), with a lower likelihood of disruptions through snowfall. Overall, Böcker et al.'s (2013: 86) conclusion that the knowledge of the impact of climate change on travel behavior is still "incomplete and fragmented" thus remains valid. A preliminary conclusion is that temporary and locally significant disruptions of transport systems will increase because of extreme events, while longer-term gradual changes in weather parameters are likely to have more modest impacts on transport systems.

3.3 Newspaper analysis

The analysis of newspaper items reveals further insights (Fig. 3, see also Supplement). Results confirm that phenomena including heavy snowfall; frost and ice; heat waves; storms and gales; sandstorms/dust storms; fog; heavy rain; heavy rain/storm combinations; hail; and wildfires all have had significant influence on transport systems. While reports necessarily focus on individual events, media reports reveal that these have partially been lasting (e.g. wildfires), or have had impacts that have been difficult to repair, leading to closed infrastructure even months after the events (e.g. landslides or flooding damaging road systems). Some transport systems are susceptible to multiple types of weather extremes: reports of cancelled or delayed flights, for example, were identified in the context of heavy snowfall, frost & ice, storms, fog, heavy rains, heavy rains and storms. More

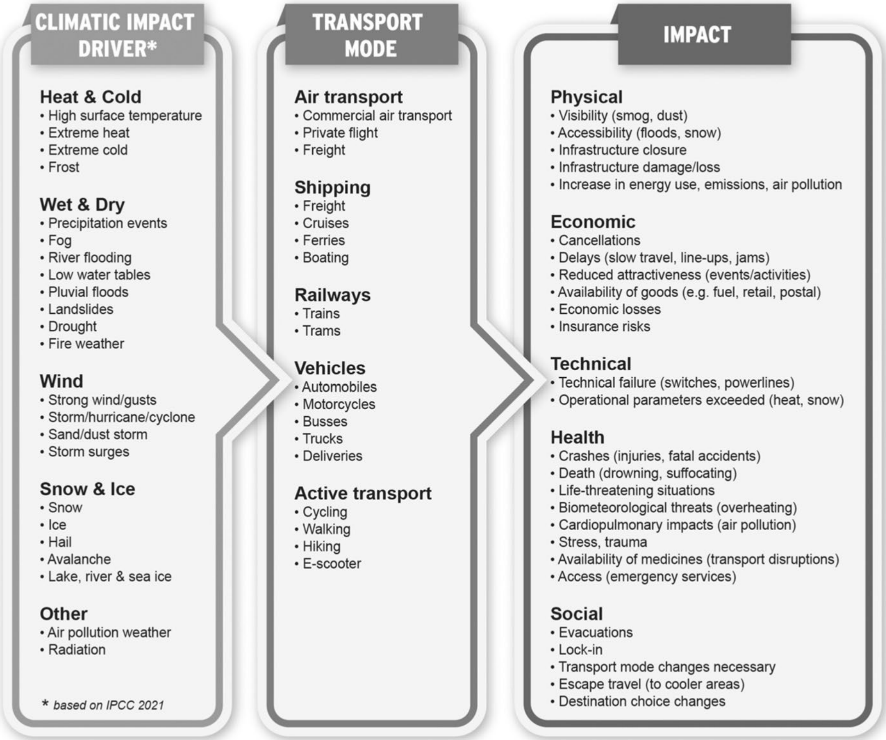

Fig. 3 Interrelationships of weather (extremes) and transportation

recently, they have also been discussed in the context of wildfires and heatwaves (see also BBC 2017; Munich Re 2021). The following section discusses insights as these pertain to the individual transport modes.

Aviation is affected by heat waves, fog, sandstorms, strong winds, and heavy rain, all of which can lead to flight cancellations or delays that affect correspondingly large traveler numbers. Where infrastructure is damaged (flooded runways) or where power cuts occur, this can result in more lasting impacts. No health effects were reported in the context of air travel.

Shipping is mentioned with reference to wave-related damage to harbor infrastructure, canceled ferries, ships run aground, adrift or sunk, as well as disrupted operations because of low river water tables. Storms have hampered rescue efforts and action to contain oil spills. They have also contributed to high-impact events such as the blocking of the Suez Canal by the mega-ship *Ever Given* in March 2021, which caused interruptions in freight deliveries on a global scale (Knoema 2021). Injuries and deaths in shipping appear less common, with the exception of small refugee boats that may capsize and sink in storms with associated high wave phenomena.

Railways and public transport are mentioned in a variety of different contexts. Public transport services may be canceled because of heat, snowfall, frost and ice, storms, and heavy rains (also in combination). Extremes affect operations and infrastructure, resulting in suspended operations and stranded travelers. While this makes rescue efforts necessary, extreme weather more seems to rarely lead to injuries and fatalities among travelers. Disruptive outcomes are more often linked to (larger) traveler numbers not being able to commute to work.

Road transport (vehicles) is the transport mode most often reported on, and in the context of closed roads, crashes, congestion, stranded vehicles, injuries, and deaths. Infrastructure damage to roads (also bridges and tunnels) includes buckling roads, sinkholes, silted or submerged roads, as well as road closures due to toppled trees. Supply chains are disrupted, including retail and postal services, emergency services, and industry. There is also a significant cost in vehicle damage. Longer-term impacts are becoming evident in permafrost melt (see also BBC 2021).

Active transport is mentioned only in the context of injuries because of slips and falls on icy surfaces, and recommendations not to cycle on ice, or to walk or exercise due to wildfire haze. Some reports hint at the vulnerability of active transport users in extreme weather, including injuries and fatalities.

3.4 Conceptualization and summary of findings

Findings can be conceptualized as interrelationships of 'climate impact drivers' (IPCC 2021), transport modes, and impacts; and by considering both the academic literature as well as the media analysis. Figure 3 organizes impacts as physical, economic, technical, health-related, or social. This illustrates that even though the discussion in articles and media often focusses on "disruptions" of transport systems, it is useful to distinguish physical, economic, technical, health-related, and social dimensions, and for different time horizons. This latter aspect is illustrated in Fig. 4, which conceptualizes the duration of weather events and their outcomes for supply and demand. Extreme weather events and their outcomes may be felt for very short periods (delays, travel warnings), days (cancellations, travel to escape adverse weather), weeks (infrastructure damage, disruptions), months (infrastructure damage, changes in transport behavior), years (infrastructure loss, destination choices), and even lifetimes (trauma, with corresponding changes in transport behavior). Many of these interrelationships remain inadequately understood, and Fig. 3 and 4 may be seen as initial attempts at describing complexity.

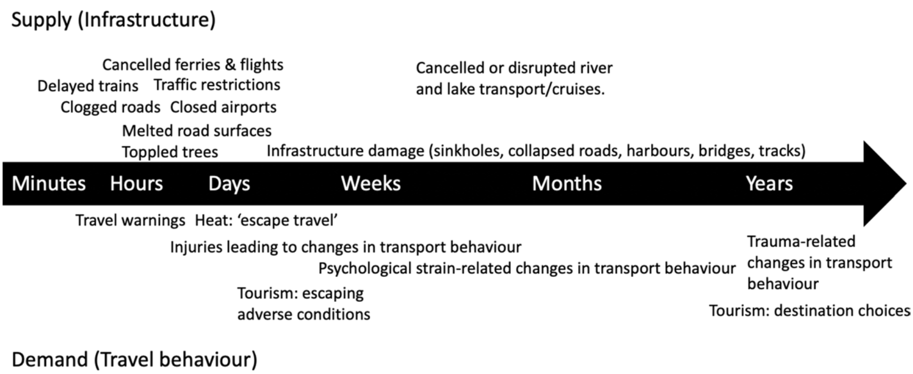

Fig. 4 Temporal dimensions of transport disruptions

4 Conclusions

The combined approach of a literature review and the analysis of media reports has provided several relevant insights. On the demand side, it is understood that weather conditions influence the availability of and preference for transportation. While variation in weather patterns within thresholds causes modest changes in demand responses, extreme weather events are potentially very disruptive in physical, economic, technical, health-related and social dimensions. Research has mostly focussed on physical, economic, and technical issues. Here the analysis of news items adds that physical and mental dimensions of health impacts deserve to be studied in greater detail. Novel relationships highlighted by this assessment also include implications for tourism, specifically regarding destination choices. Findings underscore that impacts can vary in scale, from the local (micro) to the systemic (macro), as well as temporarily, as transport systems and demand may be affected for periods ranging from hours to lifetimes.

There are some caveats. First, "adverse" weather conditions have been preliminarily defined in terms of optima, but these vary depending on transport culture, traveler socio-demographics and psychologies, as well as transport motives. Rain is a very disruptive parameter, and more rain, as projected for warmer futures in many parts of the world, can be expected to affect all transport modes negatively. Higher temperatures will encourage more active transport in some climates, where earlier spring and longer autumn periods increase the number of days within temperature optima. Where thresholds are exceeded, this may discourage active transport, or encourage shifts (for example, from bicycle to e-scooter). Some complexities and dynamics continue to be insufficiently understood, including the impacts of new phenomena such as sandstorms or wildfires. Overall, climate change will affect precipitation, temperatures, wind speeds, hours of sunshine, radiation, and humidity, and remains difficult to assess.

While an increase in climate change risks is foreseeable, the location and timing of extreme events usually is not. The Sixth Assessment Report of the IPCC (2021) on the physical science basis of climate change confirms an *observed* increase in surface temperatures, precipitation over land and weather extremes such as more frequent and intense heatwaves over land, and more frequent and intense heavy precipitation events. There has also been an observed increase in droughts, and it is likely that major tropical cyclones have become more frequent. It is also likely that human influences contribute to an increase in fire weather and compound flooding events. There are new risks related to landslides, severe storms, sand and dust storms, heavy snowfall and ice storm events, hail, air pollution weather, coastal floods, and erosion. Only cold extremes have become less frequent and severe. Land monsoon precipitation has also decreased.

The IPCC (2021) expects the trend towards extremes to continue under all emission scenarios, "in direct relation to increasing global warming", i.e. hot extremes, heavy precipitation and droughts are anticipated to become disproportionally more likely with "every additional increment of global warming". This is likely to cause a significant increase in the cost of extreme events, mostly because of damage to infrastructure (Munich Re 2021).

Results as presented in this paper thus have relevance for planning and adaptation. Planners already proactively address a range of changes, for instance when planning new infrastructure or when retrofitting existing infrastructure (An et al. 2019; Böcker et al. 2016). Evidence of adaptation can also be found in newspaper items, but deserves a systematic review of their own. As one example, Taipei authorities shortened waiting times at traffic lights to reduce pedestrian exposure to high temperatures (Guardian 2022).

Findings in this paper also highlight the adaptive importance of multimodal transport systems, specifically in cities. A choice between different transport modes helps travelers to adjust to specific weather situations and to moderate the impact of extreme weather events. As an example, unusually hot and dry days may see a growing demand for e-scooters, while heavy rain is likely to increase demand for public transport. Multimodal transport systems also reduce car reliance, and hence support mitigation. Adaptive measures may put emphasis on active transport, as it is generally desirable to maintain a high share of cycling and walking in cities. As 'exposed' forms of transportation are disproportionally affected by weather extremes, planners may want to consider impacts of extreme weather events on active mobility. This may for example include natural ventilation, shading, and the expansion of green spaces (heat waves and high radiation), or wind barriers and roofing (rain) (Helbich et al. 2014; Konarska et al. 2014). Again, a more systematic review of options for adaptation is required to comprehensively assess technical and infrastructural measures, building, for instance on work done by OECD (2016) as well as transport adaptation planning in various countries (e.g. Government of Canada 2021).

In summary, the combined literature review and analysis of newspaper items makes various contributions to the understanding of transport—weather interrelationships, as well as the longer-term complexities arising out of climate change. Future research may confirm findings on a more detailed level, for instance based on transport and weather data, and add analytical depth to specific issues.

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