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Review Article: Wind and storm damage: From Meteorology to Impacts

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Abstract

Wind and windstorms cause severe damage to natural and human-made environments. Thus, wind-related risk assessment is vital for the preparation and mitigation of calamities. However, the cascade of events leading to damage depends on many factors that are environment-specific and the available methods to address wind-related damage often require sophisticated analysis and specialization. Fortunately, simple indices and thresholds are as effective as complex mechanistic models for many applications. Nonetheless, the multitude of indices and thresholds available requires a careful selection process according to the target environment. Here, we first provide a basic background on wind and storm formation and characteristics, followed by a comprehensive collection of both indices and thresholds that can be used to predict the occurrence and magnitude of wind and storm damage. We focused on five key environments: forests, urban, transport, agriculture, and wind-based energy

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production. For each environment we described indices and thresholds relating to physical properties such as topography and land cover but also to economic aspects (e.g. disruptions in transportation or energy production). In the face of increased climatic variability, the promotion of more effective analysis of wind and storm damage could reduce the impact on society and the environment.

1. General introduction

Wind is a common feature of our day-to-day weather just like temperature and precipitation. Wind is per definition a sustained air movement in the atmosphere, which can range from still conditions to extraordinary values, from very local to global spatial scales, and has a wide range of temporal scales from seconds to decades. Winds can have both a beneficial and detrimental effect on society, infrastructure, and agriculture. On one hand, very strong winds can lead to considerable damage in infrastructure and forestry, e.g. storm Kyrill in 2007 (Fink et al., 2009), contribute to widespread forest fires, e.g. Australia 2020 (van Oldenborgh et al., 2021), or enhance evaporation, thus, drying out the soil (e.g., Bittelli et al., 2008). On the other hand, moderately strong winds can have positive effects on wind energy production and cause a stronger mixing in the boundary layer (cancelling detrimental thermal inversions to agriculture) or – in the case of nightly slope winds - alleviate summer heat conditions in valleys and cities (e.g. Ganbat et al., 2015).

The damage associated with strong winds is primarily due to short-term wind gusts, and lead to a substantial increase in wind speed (e.g. Brasseur, 2001). Strong wind gusts often lead to uprooting or breaking of trees, damaging of crops in fields (Gardiner et al. 2016), lifting of roofs, and damaging critical infrastructure like bridges and roads (e.g., Klawa and Ulbrich, 2003; Mitchell-Wallace et al. 2017). In coastal areas, strong winds and wind gusts may lead to storm surges and coastal flooding (e.g. Flather, 2001). The exact impacts of strong winds depend also on other factors besides wind speed thresholds. For example, damage to forests depend on many other factors like precipitation and topography (Gardiner, 2021). Thus, to predict damage or identify areas at risk of wind or storm damage, indices are a vital tool in assessing the likelihood and magnitude of damage for an environment. Indices can be used to predict damage caused directly by wind, or to quantify how the wind modulates the damage caused by another process such as fire or drought. Furthermore, the choice of indices depends also on land use as it influences the interaction between land surfaces and the wind; tree species and forest structures can have considerable influence on the damage probability (e.g. Gardiner, 2021). The understanding of wind, storm dynamics, and the ability to predict the damage they cause requires an interdisciplinary approach. However, much of the relevant literature is in specialized journals. Here, we aim to bring these different disciplines together to provide an interdisciplinary synthesis of the topic. To bridge the gap between the different communities we provide a basic background on wind and storm formation and intra-seasonal variability in section 2. Section 3 focuses on the interaction between wind and surface structures which are prone to wind-damage. Section 4 focusses on wind- and storm-related indices and thresholds. Indices and thresholds are typically easy to use and are efficient in terms of the time required to understand and use them, as compared with complex mechanistic modelling approaches. In particular, we cover the following environments: forests, urban areas, transport, agriculture, and energy. Additionally, we discuss compound indices and thresholds used by national weather services. Finally, in section 5 we provide an outlook and discuss open research questions.

2. Wind and storm formation – mechanisms and concepts

2.1. The general circulation and wind generation

The general circulation of the atmosphere is driven by the differential heating of the Earth (Held 2019); the equatorial regions receive more solar radiation than higher latitudes, while in the polar regions the atmosphere is losing heat into space. This differential heating in the Earths' surface causes pressure differences in the atmosphere. As a result, a pressure gradient force acts on the air masses, leading to a movement from high to low pressure centers to alleviate this pressure difference. Since the atmosphere moves toward an equilibrium, it causes a meridional heat transport towards the poles through the atmosphere and ocean, which takes place mainly through the movements of circulation systems and storms (Bjerknes 1922; Schultz et al. 2019; Ma et al. 2021). Mid-latitude weather systems include both cyclones and anticyclones, but strong wind situations are primarily associated with intense cyclones. The main paths that weather systems and storms take, are called storm tracks (Hoskins and Valdez 1990; Blender et al. 1997; Chang et al. 2002; Ulbrich et al. 2009). Storm tracks form over the major ocean basins of the Northern and Southern hemispheres and are closely related to atmospheric jet-streams, which are areas of maximum upper-level wind speeds and determine the areas that are prone to storms as discussed below in section 2.4 below. These regimes set the propensity with which weather systems take a more poleward or equatorward path on intra-seasonal time scales, thus, offering potential predictability.

In its most basic form, atmospheric jet-streams (e.g. Feldstein and Franzke 2017) are a product of the pressure gradient force, induced by the above-mentioned latitudinal temperature gradients, and the Coriolis force. For large-scale movements in the atmosphere, the wind is diverted to the right (left) in the Northern (Southern) Hemisphere due to the Coriolis force. The resulting winds in the free atmosphere, above the boundary layer, blows parallel to lines of equal pressure, in a balance between the pressure gradient and the Coriolis force; also called geostrophic wind. The strength of the dominant westerly winds over Western Europe is determined by the pressure difference between the subpolar and subtropical regions over the eastern North Atlantic. The stronger the pressure difference, the stronger the mid-latitude westerlies.

In the boundary layer, the pressure gradient and Coriolis force are not in balance, because the surface characteristics, local conditions, vertical stability, and other effects play crucial roles in modifying the winds. Under the influence of the surface friction, the air movements are not parallel to the lines of equal pressure but have a tangential component from high to low pressure centers. On the regional to local scale, wind systems like the land-sea-breeze, and mountain-valley wind systems develop due to differential heating conditions within comparatively small distances, which vary between day- and nighttime.

Under hypothetical unperturbed conditions, the bands of maximum wind speed – called jet-streams – sit at 30° and 60° latitude in either hemisphere at upper levels of the troposphere, due to surface friction. However, differential diabatic heating over land and the ocean, or orographic surface features, such as mountains, do perturb the jet-stream in multiple ways. As a result, in the extra-tropics of the northern hemisphere the jet-stream is commonly split into a subtropical and mid-

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latitudinal branch. While the former is mainly driven by angular momentum transport by the thermally direct Hadley circulation (Held and Hou 1980), the latter is primarily driven by the eddy momentum flux convergence provided by short waves that form in regions of enhanced baroclinicity (Held 1975). Accordingly, the mid-latitudinal jet-stream is referred to as an eddy-driven or polar jet-stream due to its proximity to polar latitudes.

In the atmosphere unstable conditions are needed for weather systems to form (Holton and Hakim 2012). So-called baroclinically unstable conditions occur where we find strong horizontal and vertical temperature gradients. These areas are conducive to the generation of positive vorticity, which is linked to upper-level divergence, which in turn causes the formation of short-wave troughs. Vorticity is a variable which measures the local rotation of the atmosphere (Holton and Hakim 2012). For example, the North Atlantic is an ideal source region for baroclinically unstable conditions as very cold polar air is advected over moderately warm ocean waters, leading to excessive temperature gradients and, thus, pressure gradients, which – under the influence of the Coriolis force – generate positive vorticity and enhanced baroclinicity.

2.2. How do cyclones form?

While anti-cyclones are primarily associated with low wind conditions in its center and strong winds are only found around its edges (i.e. co-located with another pressure system), cyclones feature typically strong pressure gradients and are thus associated with strong winds and wind gusts. Many extra-tropical cyclones develop under the influence of the mid-latitude jet-stream, its associated baroclinicity and upper-air flow divergence. Other cyclones develop as secondary cyclones in the trailing cold fronts of pre-existing systems and are more influenced by lower-level processes such as latent heat release (Parker, 1998; Dacre and Gray, 2009). Another large group of cyclones develop by the interaction of atmospheric waves with orography (McGinley, 1982; Radinovic, 1986). Focusing on the North Atlantic sector for a European perspective, baroclinically driven (primary) cyclones develop typically over the North Atlantic (e.g., Dacre and Gray, 2009), secondary cyclones develop further downstream often close to the eastern North Atlantic (e.g. Priestley et al., 2020a), and the orographically driven cyclones dominate in the Mediterranean basin (e.g., Trigo et al., 1999).

The most common models to describe extra-tropical cyclone development are the Norwegian and the Shapiro-Keyser models (Bjerknes, 1922, Schultz et al. 2019, Dacre 2020). According to the Norwegian model, a stationary front forms between cold and warm air, initiating strong vertical wind shear within the troposphere. A front is a density discontinuity and, hence, separates cold and warm air masses. Typically triggered by an upper-level trough, a cyclone begins to grow along this front where it develops a warm and a cold front. As the cyclone deepens, both fronts become better defined and a warm sector develops. When the cold front catches up to the warm front, the so-called occlusion process starts. At this stage, the cyclone reaches its most intense period (Bjerknes 1922), followed by cyclone decay. In the Shapiro-Keyser model, the initial development is similar, but the cold front does not overtake the warm front, but rather builds a T-bone structure [see Fig. 16-24 of Schultz et al. (1999)] instead of a narrowing warm sector during occlusion as in the classical model (Shapiro and Keyser 1990).

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In order to quantify the impact of storms, it is important to know the parts of a storm where the strongest wind speeds typically occur. There are three zones where strong winds can occur: the warm jet, the cold jet, and the sting jet (Clark and Gray, 2018). Hewson and Neu (2015; see their Fig. 1) have developed a conceptual windstorm model to describe how strong winds may develop associated with the passage of a cyclone during different stages of its development. In most cases, the strongest winds are often associated with the passage of the cold jet at the cold front. However, Shapiro-Keyser cyclones may rarely feature sting jets, which, if reaching the surface, may lead to even more damaging wind speeds (Clark and Gray, 2018).

The potentially most damaging events affecting Europe are commonly assigned to slow movers, rapid developers, or serial storms (Mailier et al. 2006). Slow mover cyclones lead to large accumulations of precipitation in the same area, often triggering severe floodings (Grams et al., 2014). Rapid developers are fast deepening cyclones, often fulfilling the conditions for a “bomb” (Gyakum and Danielson, 2000). When occurring close to Europe, many of these are secondary cyclones. Finally, serial storms (also known as cyclone families) indicate that multiple and related cyclones affect the same area within a comparatively short period of time, leading potentially to severe cumulative losses (Mailier et al., 2006; Pinto et al., 2014). In these clustering periods, the passage of storms occurs more frequently than may be expected from a random process (e.g. Vitolo et al., 2009; Franzke, 2013; Blender et al., 2015). Two physical reasons are given in the literature (Economou et al., 2015; Dacre and Gray 2020): i) the steering through the large-scale flow, typically characterized by an intensified, quasi-stationary jet-stream extending towards Europe and ii) the occurrence of secondary cyclogenesis.

2.3. Storm’s spatial characteristics

To analyse cyclones and storms, objective identification and tracking methods are needed (Ulbrich et al., 2009, Neu et al., 2013). This leads to a Lagrangian perspective where certain properties during the life cycle of the cyclone can be defined, e.g. radius, propagation speed, and spatial wind distribution. Various objective methods for the identification and tracking of extra-tropical cyclones have been used to investigate their characteristics (Neu et al., 2013; Pinto et al., 2005; Ulbrich et al.; 2009; Zappa et al., 2013; Priestley et al., 2020a).

In the North Atlantic-European region, cyclone track densities show maximum values over the western North Atlantic with a second maximum over the Mediterranean (Ulbrich et al., 2009; Pinto et al., 2005). North Atlantic cyclone activity shows a tilt towards the northern North Atlantic. While this can be found in different reanalysis products, CMIP5 simulations are characterised by a bias of the maximum and tilt in the North Atlantic, leading to more zonally oriented storm tracks (Zappa et al. 2013). While many cyclones can be identified in the extra-tropics, only a subset of strong cyclones lead to high wind speeds. See section 4.1 for related storm indices.

2.4. Large-scale Circulation Characteristics and their impact on wind

Storms and their related wind gusts are local in nature. Nonetheless, the large-scale background circulation can still provide information in which areas strong winds are likely to occur. Here, we apply the concept of atmospheric weather regimes (e.g. Hannachi et al., 2017) to determine the characteristics of the large-scale circulation. Atmospheric weather regimes are recurrent, dynamically relevant circulation patterns and allow the description of low-frequency variability due to transitions between distinct regimes. Because of their preferred occurrence locations, they potentially provide prediction and downscaling possibilities for smaller scale weather events and extremes (Cassou et al. 2005).

To demonstrate the relation of specific regimes to preferred jet-stream patterns and storms, we show weather regimes based on sea-level pressure fields from ERA5 (Hersbach et al. 2020) over the North-Atlantic-Eurasian region (30-90°N, 90°W-90°E) for winters (December through March, DJFM) from 1979-2020. The details of the applied regime analysis are described in Crasemann et al. (2017). We identify 5 regime states (Fig. 1a): (1) Scandinavian/Ural blocking (SCA-URAL BL), (2) the North Atlantic oscillation in the positive phase (NAO+), (3) blocking over the North Atlantic (ATL BL), (4) North Atlantic trough (ATL TR) and (5) the NAO in its negative phase (NAO-).

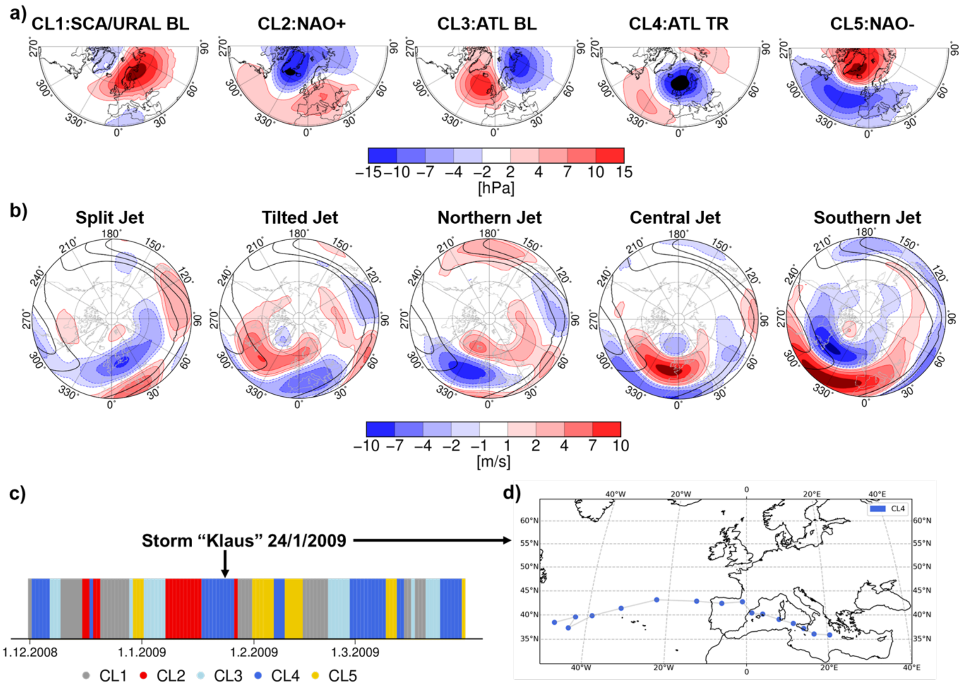

Figure 1: a) Weather regimes determined from ERA5 reanalysis data for December to March (DJFM). Shown are the regime patterns in terms of Sea Level Pressure anomalies (shading), black contours indicate the climatology for DJFM, shown are isolines at 1000, 1005, 1010 and 1015 hPa. b) The patterns for the associated jet regimes, obtained by composites of zonal wind anomalies at 250hPa (shading), black contours indicate the zonal wind climatology for DJFM, shown are isolines at 20, 30, and 40 m/s. c) Time series of sequences of weather regimes (CL1-CL5). The date where maximum wind speed was identified over land for storm 'Klaus' is marked by a red arrow. d) eXtreme WindStorms storm track for storm 'Klaus' based on ERA5 data, identified with the method of Leckebusch et al (2008). Storms are defined by the exceedance of the local 98th percentile of near surface wind speed. Each dot represents the position of the wind field center of storm "Klaus" for 6 hr time steps from 22

January 2009, 06:00 to 26 January 2009, 00:00. The color of the dots shows the weather regime of that date.

The characteristic patterns for the jet-stream associated with these weather regimes have been obtained by compositing the zonal wind anomalies at 250 hPa over the days assigned to each regime. The 5 jet regimes (Fig. 1b) are very similar to those obtained by previous studies (Dorrington and Strommen, 2020; Woollings et al., 2010; Franzke et al., 2011).

The regime analysis assigns the atmospheric circulation of each day over the period 1979-2020 to one specific cluster and enables a characterization of the large-scale background for specific windstorm events. As one example, Figs. 1b and 1c show the evolution of the prevailing weather regimes over the winter season 2008/2009. From Jan 22 to Jan 26, 2009 the extreme storm 'Klaus' evolved. 'Klaus' moved eastward along an unusual southerly storm track and was characterized by strong and record-breaking wind speeds over northern Iberia and southern France (Liberato et al., 2011). During the formation, intensification, and eastward movement of 'Klaus' the Atlantic trough weather regime associated with the central jet-stream configuration prevails. This central jet-stream pattern set the necessary large-scale background flow for the development and movement of this extreme storm (Liberato et al., 2011).

The concept of weather regimes enables the characterization of the large-scale atmospheric circulation, in particular the jet-stream pattern, during extreme storm events. If changes in the occurrence of these extremes can be related to an anomalous frequency of occurrence of a specific weather regime, the use of these regime states offers potentially predictability of large- as well as small-scale wind impacts.

2.5. Storm's temporal characteristics - Seasonal Variability

The occurrence of extreme wind speeds and storms is subject to a strong seasonal pattern in Europe. According to Young et al. (1999), windstorms occur 30% more frequently in winter than in summer (see also Fig. S1). We compared the wind gusts from three reanalysis products (ERA5 (Hersbach et al., 2020), COSMO-REA6 (Bollmeyer et al., 2015) and COSMO-REA2 (Wahl et al., 2017)), to 145 German station observations (Kaspar et al., 2013). While a direct comparison is difficult, qualitative statements on seasonality can be made with all data sets. The number of occurrences of wind gusts is determined for certain wind intervals, which are shown against the warning levels (WL) of the DWD. Reanalyses show an underestimation of the frequencies of the wind gusts compared to the observations, which become more extreme the higher the wind speed. Thereby, COSMO-REA2 shows a significantly better agreement with the reference, especially for WL3 in summer and WL4 in winter. The benefit of the higher resolution provided by regional reanalyses compared to their global counterparts is well documented for near surface wind speeds (Niermann et al., 2019). Results shown in Fig. S1 emphasize the importance of using high resolution models to represent extreme wind gusts in reanalysis products.

Above 25 m/s there is a clear difference between summer and winter months, which becomes stronger the higher wind speeds are considered. In summer wind speeds over 30 m/s do not appear in the coarser reanalysis products ERA5 (~30km) and COSMO-REA6 (~6km) at all and also for the high-resolution reanalysis COSMO-REA2 (2km) and the point observations the occurrence of wind gusts of WL3 or WL4 in summer is smaller than in winter by a factor of 10 to 100.

The intraseasonal variability is not only visible in meteorological data but also in loss data from insurance companies, which shows the strong impact of storms and especially winter storms on society and economic areas (Klawa and Ulbrich, 2003). One sector that is strongly affected by the occurrence of windstorms, and especially their seasonal variability, is the energy sector. Due to the worldwide effort to convert the energy system to renewable sources, the industry will have to deal more with seasonal fluctuations in energy availability. The interest and the need for precise knowledge of the wind conditions in various regions is therefore growing, as energy production directly depends on it; for more details about wind-based energy production please see section 4.6.

2.6. Convectively induced winds

Most of the wind damage in temperate latitudes are due to extra-tropical cyclones. However, damage can also occur to structures, crops and forests from winds produced by convective storms (e.g. Gatzen et al., 2020; Parodi et al., 2019); since our focus is more on extra-tropical storms, we keep this part rather brief. The following conditions need to be met for convection to occur (Wallace and Hobbs 2006): (1) The atmosphere needs to be conditionally unstable, (2) there needs to be a reservoir of substantial moisture in the boundary layer, and (3) there needs to be sufficient lifting due to low level convergence to cross the threshold to start the instability.

Convective systems and storms can lead to severe wind speeds connected to tornadoes, gust fronts and downbursts (Wallace and Hobbs 2006). Tornadoes are rapidly rotating air systems which connect with the ground and can lead to devastatingly strong winds. Downbursts are downward directed winds due to the negative buoyancy of the downdraft air. Convective storms can have gust fronts. The gust fronts form due to downdrafts in the convective storm by forming a pool of cold, dense air which replaces the warmer, buoyant air of the environment.

These downdrafts can lead to severe wind speeds at the surface (Bunkers and Hjelmfelt, 2021) with speeds of up to 150 km h^{-1}. So far, relatively little attention has been paid to wind damage to infrastructure, forests and agriculture from such events besides the studies by e.g. Jim and Liu (1997) and Peterson (2000). Forest damage from thunderstorms from areas, which previously were rarely affected, such as eastern parts of Europe (e.g. Nosnikau et al., 2018; Sulik and Kejna, 2020) are nowadays more commonly reported. It is expected that anthropogenic global warming will lead to an increase of this type of convective activity (Diffenbaugh et al. 2013).

Another type of convective storm is derechos, which are a clustering of downbursts, organized by a line of thunderstorms (also called a squall line), that lead to widespread straight-line winds, and can cause damaging winds. They occur frequently in the Great Plains area of the USA (Ashley and Mote, 2005) but can occur around the world, including Central and Eastern Europe (Gatzen et al., 2020). Some examples of the devastating impact of derechos on forests are described in Goff et al. (2021), and Negrón-Juárez et al. (2010).

3 Wind-surface interaction

3.1. The physics of fine scale interactions between surfaces and wind

The characteristics of the wind field and speed in a given environment are dependent on surface characteristics, such as its roughness, all of which are highly influential on the levels of damage caused by wind. The momentum of the mean horizontal wind is vertically transferred by turbulence, i.e. near the surface, large whirling air packages break up in smaller ones and their momentum dissipates into thermal energy or is absorbed by roughness elements, such as trees and buildings. The strength of the wind is altered by orography and the roughness of the surface (Stull, 2017; Kaimal and Finnigan, 1994). Thus, the damage level can vary dramatically at small scales (Gromke and Ruck 2018, Forzieri et al. 2019). Typically, the boundary layer above the earth's surface is subdivided into three sublayers: 1) a roughness sublayer that is characterized by the flow around obstacles and varies locally and where mechanical turbulence dominates, 2) one or more inertial sublayers, where the influence of the individual obstacles and surfaces is blended together and the vertical energy fluxes are constant with height and 3) a mixing layer above, where the Coriolis force gains influence and is often separated from the free atmosphere by a capping inversion and an entrainment zone (Stull, 1988; Kaimal and Finnigan, 1994). The effect of buoyancy and thermal stability is very important for the formation of strong winds, i.e. for cyclones and thunderstorms. During storm events, high wind speed increases friction within the lower boundary layer and form drag by obstacles. The instability of the shear in the flow created by the drag of the surface leads to turbulence, which affects the vertical exchange of mass, momentum, and scalars. Thermal gradients near the surface are reduced or disappear due to this mixing, which results in neutral stratification near the surface, i.e. thermal stability need not be considered in the equations of the vertical wind profile (Stull, 1988).

As turbulent movements play a major role in the momentum transfer to the surface it is important to regard shear forces and gustiness as the damaging characteristics of the wind field (Gromke and Ruck 2018). For example, in forest ecosystems trees are blown down at mean wind-speeds considerably lower than those estimated by pulling experiments (Oliver and Mayhead, 1974; Milne, 1991). Boundary-layer eddies create a local increase in wind speed and windshear close to the surface (Romanic und Hangan, 2020) and leading to coherent eddies (Raupach et al., 1996). The loading due to these turbulent structures with higher energy and momentum can be accounted for in a gust factor (Hale et al., 2015; Chen et al., 2018; Holland et al., 2006; Usbeck et al., 2010). Since trees react to gusts like damped harmonic oscillators (Mayer, 1987; Gardiner, 1992) there has been considerable debate about whether the arrival frequencies of these coherent eddies could lead to resonant failure (Gardiner, 1995; Peltola, 1996); however, this does not happen (Schindler and Mohr, 2019; Schindler and Kolbe, 2020; Kamimura et al., 2022), probably due to the efficient damping of trees (Spatz and Theckes, 2013). Besides the drag force of a plant (Rudnicki et al., 2004; Queck et al., 2012), the level of damage depends also on the acclimation of plants to the wind (Telewski, 1995; Nicoll et al., 2019), which is a function of the maximum wind speed (Bonnesoeur et al., 2016; Dèfossez et al., 2022). They are adapted to wind forces and build stronger root and wood structures depending on the main wind direction and magnitude (Nicoll and Ray 1996, Tomczak et al. 2020).

Furthermore, the development of turbulence above and within the canopy is different between naturally uneven aged woods and managed forests or plantations. Experiments showed that the inflection of the wind profile (i.e. maximum gradient of wind speed) is weaker in heterogeneous compared to homogeneous canopies, and that it occurs deeper within the canopy, i.e. the displacement height is lower (Cionco, 1972; Belcher et al., 2012; Queck et al. 2016). Furthermore, homogeneous forests are more vulnerable than naturally uneven aged woods (Everham and Brokaw, 1996; Mitchell 2013). Obviously, the adaptation to wind stress is not restricted to single trees but extends to the structure of natural mixed woods too. The characteristics of the tree (height, diameter, canopy size, wood properties), and the tree resistance to uprooting and breakage are all affected by the level of wind exposure (Gardiner et al. 2016). These adaptations of plants to living in a windy environment must be considered when modelling the risk of wind damage to tree stands.

3.2. Mean wind and gust rates for different landscapes

The gustiness of the wind is critically important for assessing the likely impact of strong winds on forests, agriculture, and structures (e.g. Usbeck et al. 2010; Gardiner et al. 2016). The level of gustiness is known to be influenced by surface roughness (Table 1), the height above the ground, and wind speed (Ashcroft 1994, Verkaik 2000). Gust ratios are also affected by wind speed (see Born et al., 2012; their Fig. 2) and by the type of storm (Krayer and Marshall 1992, Harper et al. 2010).

Roughness Class	**Aerodynamic roughness length**	**Gust Ratio (3s to 10 min)**	**Gust Ratio (3s to 60 min)**
1	0.003	1.36	1.44
2	0.01	1.42	1.49
3	0.03	1.48	1.56
4	0.1	1.58	1.66
5	0.3	1.74	1.85

Table 1. Wind rate (mean/gusts) for different landscapes. 3 s gust to 10 min and 60 min mean wind at 10 m height, by terrain category. From Ashcroft (1994). Roughness Classes: 1: off-sea wind onto flat coastal areas; 2: level grass plains, e.g. marsh; 3: standard category: fairly level terrain-mostly open fields with a few houses and buildings; 4: fairly level terrain with more hedges, trees and villages, farm buildings; 5: many trees and hedges, or fairly level wooded country or more open suburban areas.

4. Wind and storm related indices and critical thresholds

Wind and storm related indices and thresholds are a vital tool in assessing the likelihood and magnitude of damage. While there are many definitions for indices and thresholds, here an index is a number or a category, serving as an aggregated measure of a quality, which can be reached by means of observation, arithmetic calculation, or different modelling techniques. A threshold is defined here as a value taken or calculated from a numerical or a categorical range, and when the threshold value is crossed, it indicates a significant increase in the probabilities for an event to take place or for a certain condition to be fulfilled. Indices can be used to predict damage caused directly by wind or a storm, or when wind modulates the damage caused by another process such as fire or drought. Since indices and thresholds can be as effective as complex mechanistic models but more cost-effective, it is of no surprise that there is a plethora of indices. There are general indices that are not bound to a given environment, but many of the indices and thresholds available require a careful selection process according to the target environment. Below we provide an extensive review of available indices, focusing on five terrestrial environments: forests, urban, transport, agriculture, and wind-based energy production.

4.1. General storm indices - Storm severity indices

Several storm severity indices have been developed to quantify the severity of a windstorm regardless of the environment type. These indices are used to identify severe winter-storms and analyze their impacts and to investigate storm trends in past and future climate conditions. They often include the cube of the wind speed, assuming a proportionality of the dissipation rate of the wind kinetic energy to damage. A selection of these indices is presented in Table S1. From an historical context, one of the earliest storm severity indices was developed by Lamb (1991) to grade and rank storms based on the greatest observed wind speed over land, the area affected by damaging winds and the overall duration of occurrence of damaging winds. Later, in a study by Klawa and Ulbrich (2003), the wind speed values were scaled with the local 98th percentile. Based on this approach, Leckebusch et al. (2008) identified and tracked windstorms in time and space and computed an event-based storm severity index that quantifies the potential impact of a storm. This index considers the relation of the maximum daily wind speed to a certain local percentile of daily maximum wind speed (e.g. the 95th or 98th) as well as the affected area. For example, in their study they found a trend for an increase in severity of storms during 1960–2000 and for 2070-2100 under anthropogenic climate change conditions. Pinto et al. (2012) extend this approach by taking into account the exposure and including local population levels in a Loss Index, resulting in the finding that the maximum storm losses for current climate conditions are likely to be exceeded in the future. Additionally, Haylock (2011) used a storm severity index to identify the severest storms for 72h storm footprints. This index considers the latitude and the excess of the maximum wind speed over a 72h period taken from six-hourly values over a threshold (e.g. the local 90th percentile of wind speeds).

4.2. Forests

4.2.1. Topographic indices

Many topographic indices have been used for assessing the risk of wind damage to forests (see Table S2). These indices can be based on elevation, slope characteristics such as compass angle, aspect, and curvature, or are more complex such as TOPEX (Topographic exposure, Quine and White, 1998) which was developed as part of a risk assessment method (Windthrow Hazard Classification) to predict the height at which trees could be expected to be first damaged (Miller, 1986). TOPEX is the sum of the angle to the horizon in the eight principal points of the compass and can be calculated for different distances from the point of interest. Furthermore, such indices can be used to create even more complex predictive systems. For instance, when TOPEX is combined with elevation and aspect it produces a system called DAMS (Detailed Aspect Method of Scoring; Quine and White, 1993) for predicting wind speed variation in the landscape. This system is entirely based on topographic measures and compares favorably with modelling systems based on solutions of the fluid equations (Suárez et al., 1999).

The actual variation of wind speed with height above the ground is a function of the surface roughness and the topography. Predicting variations of wind speed across flat surfaces is relatively straight forward, especially for strong winds by using a measure of the aerodynamic roughness of the surface and a logarithmic wind profile (Garratt, 1980; Stull, 1988). Even in stable or unstable conditions the profile can be modified with the addition of the diabatic term ψm (Kaimal and Finnigan, 1994; Panofsky and Dutton, 1984). Often the roughness of the surface is simplified into different roughness classes (Troen and Petersen, 1989) to allow for easier estimation of the surface roughness. However, when even-strong-winds flow over topography the simple logarithmic profile breaks down and the shape of the wind profile strongly varies between the upwind slope, the crest of the hill and the downwind slope, where the flow may even separate (Belcher et al., 2012). Thus, one should not only calculate topographic indices for the target locations but calculate also for the neighboring environment and assess the change in value between the target location and its surroundings (Ruel et al., 1997; Schindler et al., 2012; Murshed and Reed, 2016).

We reviewed the literature, focusing on studies using topographic indices to assess and predict damage caused by strong winds, as topographic indices are a common feature in modelling wind damage in forests (Table S3). The most commonly used variables were (Fig. 2): elevation, slope, aspect and TOPEX. We assessed the usefulness of the four most commonly used topographic indices in modelling forest damage according to their inclusion in final models and according to the importance/influence metrics reported. We note that most studies employed a multivariate modelling approach, thus, a certain variable may appear less useful due to overlap in the variance explained with another variable, but not necessarily due to the variable's lack of explanatory power (Scott and Mitchell, 2005). Furthermore, there are other topographic indices that were not tested so far for their contribution in forest damage prediction (e.g. see Florinsky, 2017).

Elevation was useful in about a third of the studies, and was particularly useful when the study area was very large, encompassing an entire region, state or country (Díaz-Yáñez et al., 2019; Kramer et al., 2001; Torun and Altunel, 2020; Mayer et al., 2005) or when there was a strong gradient of elevation, preferably reaching above 900 m asl (Krejci et al., 2018; Pasztor et al., 2015; Torun and Altunel, 2020; Kramer et al., 2001; Mayer et al., 2005). This relevance assessment for elevation is new to our best of knowledge. The trend in the correlation between elevation and forest damage was both found to be inconclusive, to be both positive (Díaz-Yáñez et al., 2019; Krejci et al., 2018; Pasztor et al., 2015;) and negative (Mayer et al., 2005; Albrecht et al., 2013), or only present for a certain range of elevation (Albrecht et al., 2013; Torun and Altunel, 2020;). While there is an expectation for an increase in forest damage with higher altitudes due to an increase in wind speed (Machar et al., 2014), diversity of trends can stem from the involvement of other topographic indices that may contain the similar information (e.g. slope or TOPEX), and also due to varying levels of acclimation of trees to the wind conditions present at different altitudes (Gardiner 2021).

The slope was shown to be useful in about half of all articles, however it is difficult to observe a clear relation to forest damage. In articles that identified a contribution of slope, the relation of damage with slope was found to be either positive (Díaz-Yáñez et al., 2019) or negative (Mayer et al., 2005; Morimoto et al., 2019; Schütz et al., 2006). But an important deciding factor can be the aspect of the slope (useful in about 40% of all articles) as there is often an interaction between the two (Suvanto et al., 2018, 2016; Díaz-Yáñez et al., 2019; Hanewinkel et al., 2014). In this sense, the aspect likely indicates the forest's susceptibility to wind coming from a certain direction, as in most cases of usefulness of aspect, the slope was also useful. Finally, TOPEX was found by 77% of articles as useful, and when a trend was reported, all studies reported higher damages or probabilities for forest damage being associated with more exposed locations (Albrecht et al., 2013, 2012; Jung et al., 2016; Morimoto et al., 2019; Mitchell et al., 2001; Taylor et al., 2019). One of the reasons for TOPEX's usefulness is that it does not strongly overlap with the information contained in other wind-based variables (Albrecht et al., 2019; Schindler et al., 2012). However, when TOPEX is calculated only for a certain cardinal direction (e.g. west) it contains information that is very similar to aspect.

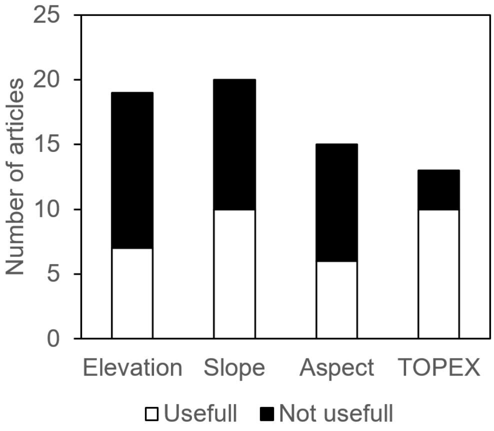

Figure 2. An assessment of the usefulness of the most commonly used topographic indices.

4.2.2. Fine scale wind and surface interactions

Interactions between the surface and the wind field are controlled by surface roughness, absolute wind velocity and atmospheric stability. The commonly used index related to surface interactions that is relevant for wind and storm damage is the critical wind speed (CWS). CWS defines the threshold wind speed for overcoming the maximum resistance to stem breakage or uprooting of a tree (Gardiner et al., 2016, Peterson et al., 2019, Hale et al., 2015, Chen et al., 2018, Holland et al., 2006). One of the governing quantities to describe the interactions between wind forces and stem breakage or uprooting is the applied maximum bending moment (BMmax) (Quine et al. 2021), which is the sum of wind forces in the tree crown and the additional turning moment due to stem bending and deflection of the stem and crown of a tree (Peltola, 2006). The amplitude of BMmax depends on wind speed and is a function of tree species, tree size, inter-tree spacing and tree location relative to any forest edges.

The probability of occurrence of CWS, as a measure of storm damage risk for specific forest stands, depends on the statistics of wind velocity, e.g., on hourly maximum synoptic winds (umax: Usbeck et al., 2010, Chen et al., 2018) or maximum geostrophic wind speed (Blennow and Olofsson, 2008). CWS is used to parameterize impact models for the estimation of storm risk in forests such as ORCHIDEE-CAN (Chen et al., 2018), SWAN/ADCIRC (Akbar et al., 2017), GALES and HWIND (Peltola et al., 1999, Gardiner et al., 2000, 2008).

The key parameter in the calculation of CWS is DBH, which is a standard parameter in forest inventories and is defined as the stem diameter in 1.3 m above the ground (Peterson et al., 2019, Gardiner, 2021, Hale et al., 2015, Chen et al., 2018, Holland et al., 2006, Hanewinkel et al., 2014, Beck and Dotzek, 2010, Gardiner et al., 2008, Peltola, 2006). DBH is the most used structural parameter due to the easy and practicable measurement and due to its widespread application in forest management (Liu et al., 2018). DBH is also used to derive other structural parameters like tree height and Leaf Area Index (LAI) which can also be derived from NDVI as a standard product of satellite remote sensing. These structural quantities are important both for statistical analysis and for the parameterization of storm risk models.

Other important parameters for calculating CWS are the drag coefficient (cd) which is part of the equation of the drag force (Vogel, 1989, Akbar et al., 2017, Dupont et al., 2015), turbulence intensity, gust duration, gust factor (Hale et al., 2015, Chen et al., 2018), tree density (Peterson et al., 2019, Albrecht et al., 2015), tree height, crown projection area and crown volume (Peterson et al., 2019, Gardiner, 2010, 2021, Albrecht et al., 2015, Hale et al., 2015, Chen et al., 2018, Dupont et al. 2015, Peltola, 2006), and tree species (Hanewinkel et al., 2014). Additionally, the edge factor index describes the influence of a tree's position relative to a forest edge, the shape of the forest edge and the width of any upwind gap (Chen et al., 2018, Gardiner et al., 2010, Peltola, 2006).

The severity of storm damage depends on the ability of a tree to resist the applied bending moment from the wind and on the stability of the root soil complex (Nicoll et al., 2006;). If soil water content is close to saturation the critical resistive moment of trees (BMcrit) can be reduced significantly during storm events which could become increasingly important with the increasing frequency of heavy winter rain in temperate forests in the context of regional climate change (Défossez et al., 2021).

The uncertainty of critical wind speed results from the consecutive solving of analytic equations including accumulated uncertainties of the different input quantities. Additional uncertainties result from the differences in the models used. Sensitivity tests using GALES (Locatelli et al, 2017) and HWIND with a variation of the input parameters of +/-20% lead to more than 20% change in critical wind speed. For example, CWS is especially sensitive to changes in diameter of breast height. The measurement uncertainty of the diameter of breast height ranges between 2 and 10% dependent on the absolute diameter (Qin et al., 2019). Applied in HWIND and GALES the variation of diameter of breast height of +/- 20% lead to changes of Critical wind speed of +30% and -46% (Gardiner et al., 2000). The most comprehensive analysis of wind risk model uncertainty was made by Locatelli et al., (2017) who found that tree DBH, tree height and inter tree spacing were the most critical factors.

Classical wind scales are defined by phenomena caused by the interactions between wind and the surface. A very prominent example is given by the Beaufort scale (Stull, 2017). It classifies the effect of wind on wave generation, tree movement and the damage of buildings. Similar scales exist for tornados, e.g., the Fujita scale and the Torro scale (Kirk, 2014), which relates the tornado intensity to damage description. As short gusts and shear forces are very important factors of storm risk, the Enhanced Fujita scale includes further information to derived maximal tangential 3s gust speeds (Fujita, 1981). Recently an improved wind speed scale and damage description has been suggested for Central Europe (Feuerstein et al., 2011). Finally, The Saffir–Simpson hurricane wind scale (Ellis et al., 2020) is based on the highest wind speed averaged over a one-minute interval 10 m above the surface. It can provide some indication of the potential damage a hurricane will cause upon landfall.

4.3. Urban

The urban boundary layer

The small-scale interactions of the wind field with urban surfaces are significantly different from natural surfaces due to high three-dimensional variability of impermeable artificial obstacles (buildings). These differences lead to a higher mean surface roughness of the urban surface (Grimmond and Oke, 1999; Oke et al., 2017) combined with a general attenuation of the mean wind speed (Chen et al., 2020), as compared with more natural surfaces. The level of increase in roughness depends on the morphology - density, size, and composition - of the obstacles along the flow direction. The height of the roughness layer is 2-3 times the mean height of the buildings. Within this layer, mechanical turbulence generation dominates, and average wind profiles can only be assumed above the roughness layer, within the inertial sublayer. The averaged roughness of an urban surface is described by roughness length z0 within equations for vertical wind profiles. This parameter serves as an useful index for the prediction of turbulent impulse transfer and also for damage prediction, which are derived on the basis of building height, areal fraction and frontal area index (Grimmond and Oke, 1999). At finer scales, wind speed shows high spatio-temporal variability. Thus, when using indices based on averaged wind speed, it is also important to consider that due to the small-scale aerodynamic and thermal heterogeneities of urban infrastructure (buildings and trees), the local magnitude of the wind speed is temporarily larger than under rural conditions (Droste et al., 2018). The reasons for this anomaly are again the inflexibility and impermeability of technical structures and buildings. These features cause canalization of flows and stronger turbulence generation compared to natural surfaces. There is also a diurnal-nocturnal distinction in the formation of local thermal wind systems, with street canyon wind during the day and a nocturnal inflow to the urban heat island (Droste et al., 2018; Lindén and Holmer, 2011). Thus, indices in urban areas should account for both spatial and temporal heterogeneities.

Indices for estimating damage to individual buildings

Damage occurs either directly by wind pressure or indirectly by the impact at high speed of objects and debris moved by the wind (Tamura, 2009). At the level of individual buildings, air movement results in wind pressure on the building surface and an applied force called the wind load. Damages to buildings caused by extreme wind loads include resonance and vibration induced damage, damage to roof tiles or sheet roofing, roof lift off and the collapse of walls or entire houses.

The occurrence and type of damages depend on the level of exposure as well as the structural vulnerability of the individual buildings to local severe winds. The European wind loading code EN 1991-1-4 regulates how to adapt the structural design of buildings to the local wind climate. The code defines basic wind velocities for different geographical wind zones based on the 50-year return level of 10-minute wind speeds at a 10 m height. In Germany, for example, the basic wind velocities range from 22.5 m/s in wind zone 1 (inland areas in southern Germany) up to 30 m/s in wind zone 4 (coastal areas). The basic wind velocities are further adjusted based on the height above ground and the terrain roughness to account for short term wind fluctuations. Terrain roughness is classified in five categories ranging from coastal areas to cities with a high building density. Additionally, where orography (e.g. hills, cliffs etc.) increases wind velocities by more than 5% the effect is taken into account using an orography index, as the ratio of the mean wind velocity at the height above the terrain to the mean wind velocity above flat terrain. Finally, the wind speeds are used to compute the local peak velocity pressure which is a fundamental index for the determination of all wind loads for a specific building (Schmidt 2019). Nonetheless, assigning critical wind speed thresholds to building damage is rather difficult given the heterogeneity of buildings, topography and environments.

Storm loss models: estimating damage on a district level

Often there is little to no information on the actual damage to individual buildings or small-scale urban structures. Instead, storm loss models come into play, and they relate wind speeds to actual building damage data, usually by applying statistical modeling techniques. In some cases, these models rely on the use of wind indices like the exceedance of local wind speeds over a critical threshold to calculate monetary loss. In other cases, the model itself calculates a damage index. The purpose of storm loss models is, among other things, to assess current risk to residential structures or to estimate expected losses in future climate conditions. It is often assumed that the maximum daily wind speed is the most influential factor compared to other wind parameters like daily mean wind speed or wind direction and is commonly used in indices as well as in loss models (Donat et al., 2011; Klawa & Ulbrich, 2003; Leckebusch et al., 2008; Pardowitz et al., 2016; Welker et al., 2021).

Building damage data on a district level is usually provided by insurance companies and is analyzed in the form of the loss ratio, which is the amount of insured loss per day and district, divided by the corresponding sum of insured value, or claim ratio, which is the number of affected insurance contracts per day and district, divided by the corresponding total number of insurance contracts (Prahl et al. 2015).

The functional relationships between wind and damage are usually referred to as damage functions. As the relationship between damage and wind depends strongly on local condition like building or city structure, there is no universal function or model and instead a variety of different damage function formulations are in use. A detailed overview can be found in Prahl et al. (2015). Power-law damage functions are common. Different exponents for these functions can be found in the literature ranging from 2 to 12 (Münchener Rückversicherungs-Gesellschaft. 1993, Heneka et al 2006, Prahl et al. 2012). Some damage functions also assume an exponential form (Prahl et al., 2015).

Another type of model are probabilistic models which calculate the probability that a certain loss threshold is exceeded (Pardowitz et al., 2016; Prahl et al., 2012). Some examples for existing models are shown in Table 2. Most models still need to be fitted to local conditions and validated with existing damage data. Model selection depends on the available data.

$L(v_{max}) = 2.48 * 10^7 * exp(0.48v)$	Dorland et al. (1999)
$D(v) = \left(\frac{v_{max}}{v_{98}} - 1\right)^3$	Klawa & Ulbrich (2003)
$LR(v, f(v_{crit}), \Delta v) = \int_{-\infty}^{v} f\,(v_{crit}) G(v) dv_{crit}$ $G(v) = \begin{cases} 0, v < v_{crit} \\ D(v), v_{crit} \le v \le v_{tot} \\ 1, v_{tot} \le v \end{cases}$ $D(v) = \left(\frac{v - v_{crit}}{v_{tot} - v_{crit}}\right)^2$	Heneka et al. (2006)
$P(LR > th) = \frac{exp(a + b * v)}{1 + exp(a + b * v)}$	Pardowitz et al. (2016)

Table 2; A selection of damage functions including exponential damage relationships (Dorland et al. 1999), power law damage functions (Klawa & Ulbrich 2003, Heneka et al. 2006) and probabilistic damage functions (Pardowitz et al. 2016). *a*, *b* denote coefficients, *D* a damage index, *f* (v_{crit}) a normal distribution of the critical wind speed, *G* a damage ratio, *L* a loss, *LR* a loss ratio, *P(LR>th)* a probability that a certain loss threshold will be exceeded, *th* a loss threshold, *v* a mean daily wind speed, v_{98} the 98th percentile of the local wind speed, v_{crit} the critical wind speed at which buildings suffer damage, v_{max} the maximum daily gust speed, and v_{tot} the buildings total wind speed at which maximum damage is reached.

4.4. Transport

Transport systems are the backbones of modern societies. Disruptions within the transport systems can have serious cascading effects that can cause large costs. Weather in general, and windstorms in particular, can affect all aspects and functions of transport systems (Leviäkangas et al. 2011). However, relevant thresholds of wind speeds and their impacts are different depending on the mode of transport. Vajda et al. (2014) identify three wind gust thresholds of increasing magnitude, which they relate to general impacts and consequences within different parts of the European transport system: (i) Wind gusts >17 m/s: Adverse impacts on the transport system may start to occur, especially if the resilience of the exposed part of the system is low, but disruptions are rather local. For example, some windthrow of trees can occur along railways and roads, leading to local problems to road and rail traffic. Furthermore, operation of smaller boats could be suspended due to reduced maneuverability, (ii) Wind gusts > 25 m/s: Some adverse impacts can be expected, such as windthrow and electricity cuts occurring on a larger scale. In addition, delays and cancellations in air, rail, road traffic and disturbances of ferry traffic can be expected, and (iii) Wind gusts > 32 m/s adverse impacts are very likely to occur, windthrow of trees can be expected on a large scale, leading to long lasting power failures and delays, and cancellation of rail and road traffic. Furthermore, damages to traffic control devices and structures can occur, airports can be closed and ferries stay in harbour due to reduced visibility and high waves.

The effect of wind on road safety is not extensively explored in the literature (Theofilatos and Yannis 2014). In general, the number of road vehicle crashes caused by strong wind is small compared to the total number of crashes (Edwards, 1998). However, studies have identified specific types of crashes which typically occur under strong wind conditions: overturning, side slip and rotation crashes (Baker, 1986), with high-sided lorries, vans, or buses being particularly affected (Baker 1992). A critical rollover wind velocity of 20 m/s was found for high-sided lorries in crosswind situations (Snaebjornssonet al. 2007). Particularly dangerous situations with strong crosswinds can occur on bridges (Wang et al., 2014; Charuvisit et al., 2004). A vehicle overturning model is applied by the British Meteorological Office (Hemingway et al. 2020). It estimates the risk of overturning based on wind gust thresholds ranging from 23 to 45 m/s, depending on vehicle type, loading, driving speed and wind direction. In addition to direct effects of high wind speeds on road vehicles, indirect effects like blocked roads due to falling trees or drifting snow can affect road transport (Leviäkangas et al., 2011).

The most frequent impact of high wind speed on railway transport is the blockage of tracks due to windthrow of trees or drifting snow, as well as loss of electricity due to damaged overhead lines (Leviäkangas et al. 2011). Only in rare cases, extreme gusts exceeding 40 m/s can blow trains off the track (Sprenger et al., 2017). Mean winds above 17 m/s or wind gusts above 30 m/s have been identified as thresholds relevant for wind induced damages to railway transport (Thornes and Davis 2002). Shaking of overhead cables can cause damage to masts and pantographs on trains. Consequences of windthrow can be collisions of trains with fallen trees. Precursory measures to prevent collisions are reduced traveling speeds or canceling/limiting train services, commonly leading to wide spread delays.

The most common impacts on ports are delays due to the disruption of loading and unloading procedures, as well as direct damages to infrastructure. For example, maximum wind speeds recommended for crane operations are around 18 m/s, depending on the design of the crane (TT Club et al. 2011). This can have effects on the overall efficiency of ports (Garcia-Alonso et al. 2020). From 88 disruptive events affecting ports and their surrounding seas in the UK between 1950 and 2014, 36% were attributed to wind storms and 12% to storm surges, while the others were mainly related to human error and mechanical faults (Adam et al. 2016).

In the case of inland waterway transport, there is generally no large impact of wind on vessels, since they are sufficiently wide and stable (Leviäkangas et al. 2011). However, at specific locations with high local wind speeds due to topography or at locations which are difficult to navigate, navigation of pushed convoys without bow thrusters may be suspended in case of high wind speeds. In addition to location-specific issues, the vulnerability of vessels to strong wind is strongly dependent on the vessels characteristics (Schweighofer, 2014). For specific types of inland container vessel mean wind speeds of 18 m/s can lead to flooding of open cargo-holds due to heeling and rolling (Hofman and Bačkalov 2010) and increase the risk of sliding of empty containers on the upper tiers.

In the case of deep sea shipping, vessels like large container ships are rarely lost at sea. However, high wind speeds impose the danger of container losses (Allianz, 2019). The global average annual loss of containers is estimated up to 10,000 per year (Frey and DeVogelaere 2014). These numbers are low

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compared to a total number of more than 200 million containers transported per year, but each container lost at sea can lead to a significant safety and environmental hazard. In contrast to container ships, losses of dry bulk carriers are often related to heavy weather conditions (INTERCARGO, 2018). Forecasts of ocean surface conditions are important for route planning to avoid areas affected by windstorms (Kite-Powell 2011).

Airplanes are affected by strong winds mainly during take-off and landing. Dangerous situations related to wind are mainly caused by abrupt changes in wind speed due to wind gusts, wind shear or microbursts (strong downward movements of air within and below thunderstorms). In the USA, for example, 48% of weather-related aviation accidents are due to adverse wind conditions, and of those wind-related accidents 34% are due to crosswinds and 29% due to wind gusts (Jenama and Kumar, 2013). Therefore, for safety reasons, separation distances between airplanes are increased under high-wind conditions. Furthermore, depending on the wind direction, runways may need to be closed. At London Heathrow, for example, tailwinds of more than 5 knots (2.6 m/s) and crosswinds above 25 knots (13 m/s) are avoided by changing flight direction or runways (Pejovic et al. 2009). This can lead to delays, diversions and cancellations of flights. At London Heathrow Airport, an increase in wind speed of 1 knot (0.5 m/s) above the mean will increases the probability of delay by 8% (Pejovic et al. 2009).

4.5. Agriculture

The agricultural sector is crucial for the European economy and is a key employer in rural areas. Wind leads to substantial environmental, social, and economic losses and has distinct impacts on agriculture: physical damage to crops and related infrastructure, soil erosion including nutrient and soil carbon removal, dust storms, higher evapotranspiration rates of plants, as well as negative impacts on flowering, pollinators and fruits (e.g. Torshizi et al. 2020).

Wind can damage crops through various mechanisms. Most vegetables already react to low wind speeds of around 4 m/s with physiological adaptations that affect the quantity or quality of the harvest (Rouse and Hodges, 2004). Most kinds of crops can also be directly damaged by abrasion from windblown dust particles or rubbing leaves (Brandle et al., 2004). In orchards, wind can cause a considerable loss by breaking branches or damaging the fruit set (Gardiner et al., 2016). For cereals, lodging (i.e. flattening) is probably the most important impact of wind (Berry et al. 2004). For instance, wheat yield is usually reduced about 25% when fields are lodged (Baker et al., 2014), but the loss can reach up to 50-68% (Berry and Spink, 2012) and also the yield of other cereals can decrease by 35-50% under these conditions (Rajkumara, 2008). In most cases lodging is caused by strong wind accompanied by heavy rain, whereby the maximum wind speed is the critical parameter (Mohammadi et al., 2020; Niu et al., 2016). The vulnerability of plants to lodging depends on many factors, for example, excessive usage of nitrogen fertilizers increases lodging vulnerability of wheat (Berry et al., 2019). It is therefore difficult to determine general threshold values for critical wind speeds. However, typical lodging threshold wind speeds at 10 m above the ground for maize, oilseed rape, oats and wheat can be assumed to be 11.5, 14.8, 15.1 and 16.5 m/s respectively (Joseph et al., 2020; Baker et al., 2014).

In general, plants exposed to wind are shorter and have thicker leaves and mature plants are less vulnerable to wind stress than younger plants (Brandle et al., 2004). Therefore, land users must carefully balance between the investment in wind adaptation measures and yields (Wiréhn et al. 2020). However, the careful selection of wind resistant varieties with short-stems (Berry et al., 2014), climate resilient plants, or the use of cultivar mixtures can significantly improve wind lodging stress resistance, as demonstrated in wheat (Kong et al. 2022). Field fruits react differently to wind exposure: vegetables in general have a very low tolerance to wind stress, cucumber, pepper, and cabbage for example can be damaged by even low wind speeds of around 5m/s, corn and cotton are a bit more resistant than most vegetables, but also susceptible to wind damage when wind speed exceeds 6m/s (Rouse & Hodges 2004). Overall, critical thresholds for damage linked to wind speeds vary substantially.

Most of the studies that investigated climatic indices relevant for agriculture focused on indices related to temperature and precipitation (Kitsara et al., 2021; Sun et al., 2016; Tschurr et al., 2020), but a few took wind into consideration as well. Crespi et al. (2020) propose a set of 32 climate-related hazard indicators for Europe. Only two of these indicators refer to wind: ‘mean wind speed’ and the ‘extreme wind speed days’ index. Peña-Angulo et al. (2020) analyzed the trend of 125 climatic indices which are important for agriculture, five of which concern wind. For Europe, none of these five wind indicators showed a significant trend or influence. This may be because the reanalysis data used may not be ideal for such trend analyses. What adds to the uncertainty is that less well simulated phenomena such as convective storms could become more frequent and more severe, increasing the risk for damage from downbursts and straight-line winds.

Wind erosion, dust storms and agricultural drought

In regions with open and sandy arable land, wind can cause wind erosion and dust storms. Wind erosion refers to the loss of fertile topsoil, whereas dust storms are singular events where strong winds displace huge amounts of soil in a short time. Dust storms are particularly frequent in the so-called dust belt reaching from the north of Africa through the Middle east to central Asia (Gholizadeh et al., 2021). However, soil loss due to wind erosion is also an important issue in less erosion-prone areas such as Europe (Borrelli et al., 2017). While wind is the main forcing factor, there are other climatic factors such as precipitation, soil moisture and radiation which affects the soil surface and thus influence soil erosion (Bärring et al. 2003).

The threshold values for the wind speed at which soil particles start to be dislodged vary greatly depending on the type and condition of the soil (Shahabinejad et al., 2019). According to Rouse and Hodges (2004) the minimum wind speed to create erosion is normally about 5-6 m/s at 30 cm above the ground. Shahabinejad et al. (2019) found critical threshold values of 5.7-8.9 m/s at 10 m height for soils in Iran. Plants can suffer from dust storms due to loss of plant tissue through abrasion resulting in reduced photosynthesis and burial of seedlings (Stefanski and Sivakumar, 2009). This can result in considerable economic losses for farmers. For example, Gholizadeh et al. (2021) demonstrate that a dust storm lasting one hour can reduce the annual income of farmers by up to 1.2%. Erosion reduces soil fertility for long periods due to removal of soil containing essential nutrients. In many cases, extreme drought conditions precede dust storms (Sivakumar, 2005; Sissakian et al., 2013), as dry soil disaggregates faster and thus dislodge more easily enhancing erosion. Wind erosion is thereby closely related to land use practices.

Physiological water stress can be enhanced by increased evapotranspiration, due to high wind speeds. The longer such wind conditions last, the more severe the risk as exemplified for a recent drought event in India (Masroor et al. (2020). Thus, wind can exacerbate drought conditions and lead to crop failure. While wind speeds are not expected to increase as a global average (McVicar et al., 2012), evapotranspiration likely will in many regions due to the increased evaporation caused by higher temperatures (Tomas-Burguera et al., 2020) and a reduced number of days with rainfall. The fact that some plants react to hot and windy weather conditions by closing their stomata, may balance some of the enhanced evapotranspiration deficit. However, this is at the expense of plant growth.

Protection measures against wind

Because of the direct wind damages in agriculture, it is necessary or even indispensable to take countermeasures to minimize the risks. Such measures can be a better choice of location according to topographic features or using windbreaks. Windbreaks usually consist of natural barriers such as tree rows. The most important aspect of a windbreak is its height (Brandle et al. 2004). Indeed, windbreak effects on adjacent crop result in a yield reduction due to water and light competition up to a distance of one to two windbreak heights, which is followed by a yield increase up to a distance 8–12 heights (Weninger et al. 2021). To moderate effects of wind flow around the windbreak, it should be at least ten times as broad as it is high (Brandle et al. 2004).

4.6. Wind-based energy production

Wind indices are of interest for estimating the wind potential and wind energy. Extreme wind events, e. g. storms, affect the energy production and the stability of wind turbines. Even small-scale variations in the wind field, due to the time of day, atmospheric stability, and terrain, can affect the energy yield and the system safety.

Wind indices are typically defined as the ratio of the current values of a variable (wind speed- or energy production-related) to the long-term mean. In practice, the wind farm operators are interested in the current wind speeds, but also in an assessment of the annual wind energy yields in comparison to the long-term average. Extreme wind events are directly related to wind data-based indices. To identify the energy potential at a site, the Power Density Wind Index can be used (Katinas et al., 2018; Celik, 2003). The Power Density Index results in significantly higher variations than the real energy production of the wind turbine at the location and should be applied carefully.

When addressing wind climate at a location, including the occurrence of strong wind events, much attention was given to the connection between the wind climate and the wind energy potential (Carta and Mentado, 2007). In comparison to the wind speed-based indices, the production-based indices use the energy yield of turbines as input data. The Wind Energy Production Index can be based on a Wind Speed Index (Ritter et al., 2015) calculated from wind speed data by an additional application of a power curve (Hahn and Rohrig, 2003; Ding et al., 2005). Another possibility is the use of energy yield data of a wind turbine directly. The BDB index (BDB, 2021) describes the ratio of monthly reported energy yields from wind turbines in a region to the long-term mean yields of these wind turbines. High wind speeds or wind shear due to storms or low-level jets need to be taken into account when calculating wind speed indices. However, the energy production-based indices, contain the effects of such events only when the wind turbine is working, i.e. until reaching the turbine cut-out wind speed. Due to their design, most systems switch off at wind speeds above 25 m/s (Christakos et al., 2016), but there are also slightly higher and lower shutdown wind speeds for different system types (Chauhan and Saini et al., 2014). An analysis showed that high-impact storms had a positive effect on the wind energy production for Southwestern Europe and the Iberian Peninsula (Gonçalves et al. 2020, 2021). As such, the highest values of wind energy production result for stormy weather conditions (Petrović and Bottasso, 2014). Climate change impacts on wind energy have been investigated for a few years (e. g., Pryor and Barthelmie, 2010; Moemken et al., 2018). The studies are mostly in agreement on a minimal effect of climate change on the wind energy production (e. g., Jung and Schindler, 2020).

Topographic effects are another example of small-scale effects on the wind field, leading to a local wind speed-up, separation, and reattachment. These processes can be studied by numerical models (Uchida and Ohya, 2003, 2008, 2011; Uchida and Li, 2018; Uchida, and Sugitani, 2020). Uchida and Kawashima (2019) defined two indices to evaluate the terrain-induced turbulence and the fatigue damage based on the measurement data and the design value. These studies indicated the need for further development of standards. A commonly used turbulence index is the effective turbulence for site-specific fatigue assessment of wind turbines (Slot et al., 2019). Additionally, the usage of the effective turbulence index significantly reduces the number of aero-elastic simulations needed for checking if the loads on major components of the wind turbine.

4.7. Compound indices

Wind often co-occurs with other phenomena and their co-occurrence affects the damage levels observed. This is an integral part of the compound event concept in which multiple phenomena or hazards form a complex causal chain of events that can lead to a more extreme impact than each phenomenon by itself (Zscheischler et al. 2018). A compound event is characterised by an impact which is caused by a hazard (Zscheischler et al. 2020). The hazard, in its turn, is caused by a driver. Finally, a modulator influences the location, frequency and intensity of drivers and thereby hazards. Strong wind can therefore either be a hazard itself or a modulator for hazards like drought and wildfire.

Precipitation. Strong wind speeds often co-occur with heavy precipitation (Martius et al. 2016), causing multivariate compound events. Additionally, it is argued that wind and precipitation enhance the impact by extratropical cyclones, since cyclones with a precipitation extreme often have a longer lifetime than cyclones with only extreme wind speed (Messmer & Simmonds, 2021). Furthermore, the impact of such multivariate compound events is much higher than a hazard containing only wind or precipitation (Martius et al. 2016). In coastal environments, even when wind is not considered as a hazard itself, wind together with heavy precipitation can cause storm surges and coastal flooding (e.g. Wahl et al. 2015; Couasnon et al., 2020). Furthermore, precipitation is important when saturating the soil prior to the occurrence of a windstorm. Soil water content is an index that governs the stability of the root sector of trees during storm events (Everham and Brokaw, 1996; Défossez et al. 2021).

Temperature. Wind and low temperatures are both drivers, causing wind chill as human health and agricultural hazards among other risks. Each driver, when acting by itself, would have caused less of an impact than the compound effect (Danielsson, 1996). Wind chill is a threat mainly in cold climates, where enhanced wind speeds increase the heat transfer from an object. Such heat loss can cause injuries and mortality both in animals and plants. Windchill can be calculated as the wind chill temperature, also called wind chill factor (Quayle and Steadman, 1998; Bluestein and Zecher, 1999), which is usually taken as the temperature at which there would an equivalent rate of heat loss. Also, low temperatures can lead to the freezing of soil and enhance the stability of trees against windthrow during windstorms (Pasztor et al., 2015). In contrast, trees in frozen soil are more likely to undergo stem breakage than uprooting (Everham and Brokaw, 1996; Peltola, 2006).

Drought. The impact of wind on drought is relatively small. Wind is only included in some drought indices through evapotranspiration in the Penman or Penman-Monteith equation, such as in the Baumgartner index (Baumgartner et al., 1967). These indices are therefore short-term indices that operate on a scale of days and typically do not take into account the long-term impacts of drought on the risk of wind damage to forests. Drought can be considered as a pre-condition, that potentially amplifies the impact of winds. Csilléry et al. (2017) showed that long-term drought can increase the risk of wind damage on sites where drought can lead to a weakening of trees but can also decrease the risk of damage on normally extremely wet sites.

Fire. Indices used for assessing fire risk include often wind and topography to determine the rate of spread and damage caused by a wildfire. Wind and slope are viewed as the major factors influencing fire development (Byram 1959a, 1959b;, Sharples 2008). The most used indices for fire risk are based on the Canadian Forest Fire Weather Index (FWI) system (Van Wagner, 1987) that uses information on fuel loading and meteorological conditions (rainfall, temperature, humidity, and wind speed) to predict the probability of a fire starting and then the probable spread of the fire. Humidity, wind speed and temperature are used to calculate the day-to-day drying of the fuel load. The Initial Spread Index is then used to adjust the FWI as an exponential function of wind speed (doubles the FWI for every increase of wind speed by 19 km/h or 5.3 m/s). The spread of the fire will also be affected by the topography and, in particular, how the topography modifies in wind speed and direction.

Wind can alter the angle of the fire toward unburnt fuel, extending the preheating range and increasing the rate of spread. Slope has a similar effect by affecting the distance between the flames and the fuel. Thus, typically the greatest rate of spread is found when an upslope is combined with upward winds and vice versa (Sharples 2008). Since topography influences wind traits, it can create a channeling effect enhancing fire intensity, but with the strength of the effect depending on the overlap between wind direction and landscape orientations (Barros 2012, Mansuy 2014). Kushal (1997) found in a review of four articles that a higher relative elevation, proximity to ridges and increased exposure to wind, all led to greater fire damages in forests. Additionally in six articles, aspects that are associated with greater exposure to dry winds increased fire damage in forests, and damage was lower in aspects with cold and moist winds. We are aware of an index combining slope, aspect, and wind speed (wind-topo), but it had a rather low importance for the final model chosen for statistical interpretation (Masoudvaziri 2020).

4.8. Wind speed warning-levels used at national meteorological services and environment-related critical thresholds

Advanced storm-warnings are crucial for the protection of property and lives. Meteorological services operate a structured warning system for windstorms and recommend appropriate protective measures and rules of conduct depending on the warning level. The warnings will be published, when the event reaches a certain probability level to occur, can be well spatially located and especially when the warning criterion is met, such as wind speed or precipitation exceed a certain threshold value. These threshold values are set individually by all meteorological services. For example, the DWD uses 6 different gust wind speed thresholds: 14, 18, 25, 29, 33 and 39 m/s (Primo, 2016), referring to 4 warning levels (WL), WL2 and WL3 are divided into two intervals (DWD, 2021). In some cases, the weather services already indicate possible consequences due to the wind speeds, by warning of damage to infrastructure, forests, or energy systems at differing warning levels.

We collected many critical thresholds from the literature for the five sectors which are the focus of this manuscript. The vulnerability of each environment to wind speed is illustrated in Table S1. Figure 3 provides a synthesis and comparison of thresholds from the five environments. The agriculture sector seems to be the most sensitive to wind, as negative effects are already noticeable at gust wind speeds well below the first official warning level of the DWD (WL1 = 14 m/s). At WL2 (18-29 m/s), initial restrictions must already be expected in all 5 sectors, but these are initially localized. In the forest, individual trees and areas may be affected, buildings may show slight roof damage but no structural damage yet, in road traffic there may be some accidents and delays in train and air traffic. For the wind energy sector, no damage is expected yet, but depending on the type of turbine, precautionary shutdowns of turbines may occur. For WL3 (29-39 m/s), the literature describes significant impacts in the forest, building, and transportation environments. Damage will be significant, and impacts are already affecting regional areas. Especially in the transportation sector, storms can quickly impact society at regional to national levels. Severe damage is described at the national level from WL4 onwards, including damage to wind turbines, massive building damage, or even the shutdown of entire transport sectors (air and railway). While forest, urban and transport are affected by wind speeds at the same order of magnitude (i.e. locally at WL2, regionally at WL3 and nationally at WL4), the wind energy sector shows strong impacts at higher wind speeds (when only damage is considered) and the agricultural sector at much lower wind speeds.

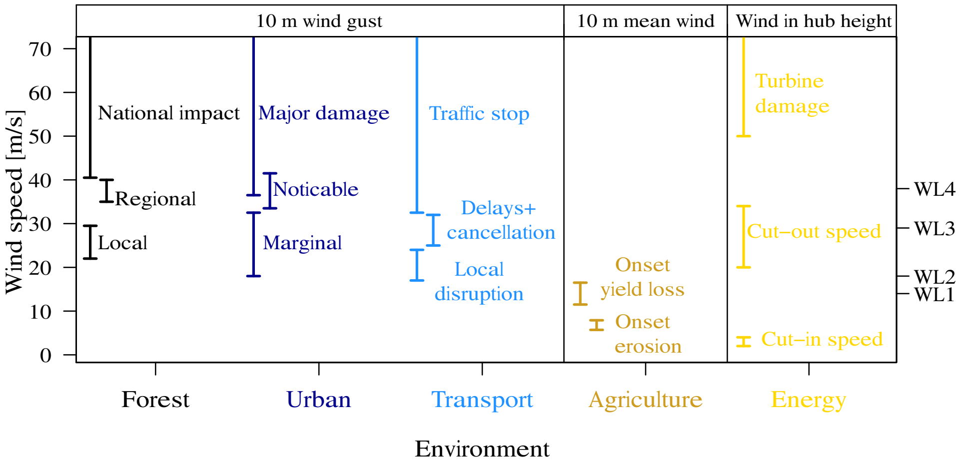

Figure 3: Critical thresholds of wind speed for five affected sectors. Warning levels (WL 1-4 at speeds of 14, 18, 29 and 39 m/s, respectively) of the DWD for wind gusts (Primo, 2016) are marked on the right axis. For each sector different ranges of critical wind speed from the literature are plotted, to show the wind speed (or gust), where impacts are expected. Thresholds in the first three sectors (forest, urban and transport) refer to wind gusts at 10 m height, for agriculture we present the mean wind speed at 10 m height and the shown thresholds for the energy sector refers to the wind speed measured at the height of the wind turbines. The upper bar (e.g. "National impact") are left open as damage will occur also at higher wind speeds.

5. Outlook & open research questions

In this review we covered a wide range of topics dealing with wind damage to terrestrial ecosystems with an emphasis on studies dealing with central Europe. To conclude, we address trends of importance in the near future and topics that require further research. The most intriguing question in this field is how wind-related damage levels may change in future decades, given the strong dominance of decadal variability (e.g. Feser et al., 2015). Therefore, attention was given to identifying drivers of future changes in windstorms and cyclone characteristics which are particularly important for the predictability of present-day and long-term trends in socio-economic damages (Koks and Haer 2020, Franzke 2021). The key current drivers that contribute to future changes in storms are well known; many studies assume that the atmospheric moisture content will increase due to global warming (IPCC 2021). Idealized studies suggest that this increase in moisture will lead to a stronger circulation, more intense storms (including stronger winds and more rainfall) and, thus, to an expansion of the windstorm footprint (Catto et al. 2019). Additionally, studies show that the lower-tropospheric meridional temperature gradient will decrease due to Arctic amplification, whereas the upper-tropospheric meridional temperature gradient will increase due to the warming of the tropical upper troposphere and the cooling of the polar lower stratosphere (Lee et al. 2019). However, it is still uncertain how these contrasting forcing mechanisms will contribute to the future changes in storms quantitatively (Catto et al., 2019; their Fig. 2). The recently extended ERA5 reanalysis product could enable further studies to deal with wind-related damages in the past, present and future, reducing uncertainties. Indeed, increasing the resolution of climate models may improve their capacity to quantify statistical storm properties. CMIP6 models already indicate a general improvement in future storm tracking (Priestley et al. 2020b, Harvey et al. 2020). As a result, more accurate projections of wind and storm damage based on future emission scenarios and climate change may be attainable in the future. According to a recent study, winter-storm-related wind gusts could increase towards the 2nd half of the 21st century in Germany (Jung und Schindler 2021). This demonstrates the need for more studies in damage analysis.

Methodologically, the usage of indices in damage analysis has many advantages, but their creation can be time consuming, and their usage may lead to statistical pitfalls. We emphasize the importance of choosing indices while trying to avoid an overlap in variability explained by different indices (e.g. Mitchel 2001). In this sense, we are lacking a clear methodology that can address the most efficient manner to select indices in advance. Such a methodology needs to be developed on a large spatial scale to evaluate in which regions certain groups of indices are useful. A possible solution can be to first assess the relative contribution of an index or a group of indices according to their relative contribution to a given metric (e.g. R^2, AUC) when running models with all possible combinations of explanatory variables. Thus, enabling us to assess their contribution as a standalone variable (more useful for simple logistic regression) or their relative contribution when using many explanatory variables at the same time (e.g. when using machine learning algorithms).

We identify that the area most in need of new indices for wind-related damage analysis are compound events. Damage from extreme climatic events most commonly occurs through interactions between different hazards (Zscheischler et al., 2020). The main challenge is to handle the different time scales of each factor, for example, a storm may last from hours to days, but drought can last years. Therefore, we require indices that incorporate a multitude of factors that are very site specific, as both the topography and the land cover can strongly modify these interactions.

We lack information in several key areas. In a forest setting, there are very few measurements of tree damage due to storms (Kamimura et al., 2022) and very few studies of the dynamic nature of damage at the time scale of a storm. Such studies are required to understand damage initiation and propagation during storms (Dupont et al., 2015). In addition, predicting airflow over complex terrain is still difficult when there are steep slopes and multiple changes in vegetation height (Finnigan et al., 2020). Similarly, there is a need for improvement of land surface information, and in particular, the acquirement of highly resolved 3D distributions of vegetation elements at the landscape scale to enable the creation of fine scale maps for risk assessment. Recent developments in remote sensing techniques (terrestrial and airborne laser scanning) promise effective assessments of surfaces structures (Favorskaya and Jain, 2017). However, terrestrial laser scanning is accurate but confined to small areas, and an effective assessment for larger areas using airborne laser scanning and satellite data are not at a sufficient resolution and need further development. The main research questions for the future are: How does the structure of a forest canopy influence the turbulence within and above the canopy? And, as they grow, stems, roots and canopies acclimate to the wind forces, so, what is the optimal cultivation and canopy structure to reduce damage (Dèfossez et al., 2022)? These questions and points made above are important in forests but also in agricultural setting even though the surface is typically smoother than in forests.

In urban settings, storm, and loss indices as well as damage functions do not usually consider differences in the exposure and vulnerability of different building types or types of urban areas. To further assess wind damage risks on a smaller spatial scale investigations of individual building damage or damage to specific types of neighborhoods are needed, together with modelling of urban environments. However, damage data at a fine spatial scale is difficult to obtain, and it is a priority to improve the documentation of urban damage to support the development of new indices.

Furthermore, it will be important to follow the influence of climate change projections on wind energy production. With the increase in the reliance on renewable energy, it will be important to reduce uncertainties in wind potential and the risk for technical and safety issues in the operation of the wind turbines. In conclusion, predicting and assessing the damage caused by wind and storms is a complex matter but there are effective and simple methodologies to support assessment and decision making. In the light of the future uncertainties, it is vital to continue developing tools to prepare for the next calamities that are bound to occur.

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