ADVANCING EARTH AND SPACE SCIENCES

Reviews of Geophysics

REVIEW ARTICLE
10.1029/2024RG000853

Mediterranean Cyclones in a Changing Climate: A Review on Their Socio-Economic Impacts

Samira Khodayar[1], Jonilda Kushta[2], Jennifer L. Catto[3], Stavros Dafis[4,5], Silvio Davolio[6,7], Christian Ferrarin[8], Emmanouil Flaounas[9], Pieter Groenemeijer[10,11], Maria Hatzaki[12], Assaf Hochman[13], Vassiliki Kotroni[4], Jaromir Landa[14], Ilona Láng-Ritter[15], Georgia Lazoglou[2], Margarida L. R. Liberato[16], Mario Marcello Miglietta[17], Katerina Papagiannaki[4], Platon Patlakas[9,18], Robert Stojanov[14], and George Zittis[2]

[1]Department of Meteorology and Climate Research, Mediterranean Centre for Environmental Studies (CEAM), Valencia, Spain, [2]Climate and Atmosphere Research Center (CARE-C), The Cyprus Institute, Nicosia, Cyprus, [3]Department of Mathematics and Statistics, University of Exeter, Exeter, UK, [4]Institute for Environmental Research & Sustainable Development, National Observatory of Athens, Athens, Greece, [5]Data4Risk, Paris, France, [6]National Research Council of Italy, Institute of Atmospheric Sciences and Climate (CNR-ISAC), Bologna, Italy, [7]Dipartimento di Scienze della Terra, Università degli Studi di Milano, Milan, Italy, [8]National Research Council of Italy, Institute of Marine Sciences (CNR-ISMAR), Venice, Italy, [9]Hellenic Centre for Marine Research, Institute of Oceanography, Athens, Greece, [10]European Severe Storms Laboratory—Science & Training, Neustadt, Austria, [11]European Severe Storms Laboratory e.V. (ESSL), Wessling, Germany, [12]Department of Geology and Geoenvironment, National and Kapodistrian University of Athens, Athens, Greece, [13]Fredy and Nadine Hermann Institute of Earth Sciences, The Hebrew University of Jerusalem, Jerusalem, Israel, [14]Department of Informatics, Faculty of Business and Economics, Mendel University in Brno, Brno, Czech Republic, [15]Finnish Meteorological Institute, Helsinki, Finland, [16]Faculdade de Ciências, Instituto Dom Luiz (IDL), Universidade de Lisboa, Campo Grande, Portugal, [17]National Research Council of Italy—Institute of Atmospheric Sciences and Climate (CNR-ISAC), Padua, Italy, [18]Department of Physics, National and Kapodistrian University of Athens, Athens, Greece

Key Points:

- Mediterranean cyclones are responsible for many of the meteo-marine hazards that affect the region
- In the context of the growing destructiveness inflicted by Mediterranean cyclones, it is mandatory to create more resilient societies
- Despite advances in our understanding of Mediterranean cyclones, significant gaps remain, particularly regarding their socio-economic impacts

Correspondence to:

S. Khodayar,
Khodayar@ceam.es

Citation:

Khodayar, S., Kushta, J., Catto, J. L., Dafis, S., Davolio, S., Ferrarin, C., et al. (2025). Mediterranean cyclones in a changing climate: A review on their socio-economic impacts. *Reviews of Geophysics*, *63*, e2024RG000853. https://doi.org/10.1029/2024RG000853

Received 19 JUL 2024
Accepted 7 APR 2025

Author Contributions:

Conceptualization: Samira Khodayar
Formal analysis: Samira Khodayar
Funding acquisition: Samira Khodayar
Investigation: Samira Khodayar, Jonilda Kushta
Methodology: Samira Khodayar
Resources: Samira Khodayar
Supervision: Samira Khodayar
Visualization: Jonilda Kushta, Jennifer L. Catto, Stavros Dafis, Silvio Davolio, Christian Ferrarin, Emmanouil Flaounas, Pieter Groenemeijer, Maria Hatzaki, Assaf Hochman, Vassiliki Kotroni, Jaromir Landa, Ilona Láng-Ritter, Georgia Lazoglou, Margarida L. R. Liberato, Mario Marcello Miglietta, Katerina Papagiannaki, Platon Patlakas, Robert Stojanov, George Zittis
Writing – original draft: Samira Khodayar, Jonilda Kushta, Jennifer

Abstract The Mediterranean Basin, renowned for its cultural, ecological, and climatic significance, frequently endures high-impact weather events driven by Mediterranean cyclones (Medcyclones), atmospheric low-pressure systems characterized by counterclockwise wind circulation. These meteorological phenomena, sometimes comparable to hurricanes in their intensity and impact, shape the region's weather and are responsible for diverse natural hazards, including torrential rainfall, flash floods, windstorms, and sea surges. Such events have profound and far-reaching socio-economic and ecological consequences, particularly for coastal and densely populated areas. Despite their critical role, the systematic assessment of Medcyclones' contribution to socio-economic losses and the effective communication of associated risks remains limited. This review synthesizes the existing body of knowledge on the socio-economic impacts of Medcyclones, with a focus on vulnerable sectors such as human health, energy, transportation, agriculture, and cultural heritage. It highlights pressing knowledge gaps, including the need for interdisciplinary research and improved engagement with stakeholders and the public. Advancing the field, this work provides an integrated perspective on Medcyclones' impacts and outlines strategies for resilience, including enhancing predictive models, fostering cross-sectoral impact studies, and improving disaster preparedness. By bridging the knowledge gaps, this review aims to inform policy-making and support the development of adaptive measures to mitigate the escalating threats posed by Medcyclones in the context of a changing climate.

Plain Language Summary The Mediterranean region is known for its culture, environment, and unique climate, but it also faces severe weather caused by Mediterranean cyclones, or "Medcyclones." These storms, sometimes similar to hurricanes in their strength and effects, bring heavy rain, flash floods, strong winds, and dangerous sea conditions. These events can cause serious damages for people, especially in coastal areas and cities, affecting homes, jobs, and natural environments. Despite the importance of Medcyclones, we still don't fully understand how much damage they cause to people's lives and the economy, and there isn't enough clear communication about the risks they bring. This study reviews our current knowledge about Medcyclones impact on key areas like health, energy, transportation, farming, and cultural landmarks. It also identifies gaps in our understanding and calls for better collaboration between scientists, governments, and communities. The study provides new ideas to help protect against Medcyclones, such as improving weather predictions, studying how different areas are affected, and better planning for disasters. By addressing these

L. Catto, Stavros Dafis, Silvio Davolio, Christian Ferrarin, Emmanouil Flaounas, Pieter Groenemeijer, Maria Hatzaki, Assaf Hochman, Vassiliki Kotroni, Jaromir Landa, Ilona Láng-Ritter, Georgia Lazoglou, Margarida L. R. Liberato, Mario Marcello Miglietta, Katerina Papagiannaki, Platon Patlakas, Robert Stojanov, George Zittis
Writing – review & editing: Samira Khodayar, Jonilda Kushta, Jennifer L. Catto, Stavros Dafis, Silvio Davolio, Christian Ferrarin, Emmanouil Flaounas, Pieter Groenemeijer, Maria Hatzaki, Assaf Hochman, Vassiliki Kotroni, Jaromir Landa, Ilona Láng-Ritter, Georgia Lazoglou, Margarida L. R. Liberato, Mario Marcello Miglietta, Katerina Papagiannaki, Platon Patlakas, Robert Stojanov, George Zittis

challenges, this research aims to help decision-makers create strategies to protect people and make communities stronger as the risks from Medcyclones increase with climate change.

1. Introduction

The Mediterranean Basin is a hot spot for climate change (IPCC, 2021), warming up to 1.5 times faster than the global mean (MedECC, 2020; Zittis, Almazroui, et al., 2022). The Mediterranean lies in a transitional zone, between the arid North African climate and the more temperate and wetter central European climate, where additional strong warming is expected in the future, while this will likely coincide with mean precipitation decreases (Cherif et al., 2020; Reale et al., 2022). A consensus exists about the magnification of extreme phenomena in the area under climate change, such as notably prolonged and stronger atmospheric and marine heat waves or more intense droughts (IPCC, 2021). Expected changes in climate extremes will have profound and far-reaching implications for the rapidly increasing Mediterranean population of more than 500 million inhabitants and their socio-economic activities.

Current conditions and future projections consistently point to significant and increasing risks during the coming decades in most impact domains, such as water resources, energy, agriculture and food, health, and human security. In the Mediterranean region, which is already challenged by extreme weather and high-impact events, new weather records are set every year. Extreme heat waves, droughts, desertification, increased number of wildfires, sea storms, extreme precipitation, floods, increased pollution and disease patterns, water rationing, food shortage, and massive migrations, among others, strongly affect societies and ecosystems with the exacerbation of their impact under a changing climate (Hochman et al., 2021; Jacob et al., 2018; MedECC, 2020; Waha et al., 2017; Zittis, Ahrens, et al., 2022; Zittis, Almazroui, et al., 2022).

Mediterranean cyclones (hereafter Medcyclones, Figure 1) are a type of extratropical cyclone (referred to simply as a cyclone in this context), characterized by a central region of relatively low surface air pressure compared to the surrounding atmosphere, with counterclockwise wind circulation in the Northern Hemisphere and clockwise circulation in the Southern Hemisphere. They are responsible for many of the meteo-marine hazards that affect the region, including storm surges, extreme waves, heavy rainfall and flash floods, landslides, windstorms, and even compound events (e.g., Flaounas et al., 2022; Jansà et al., 2014; Lionello et al., 2012, 2019; Portal et al., 2024; Rousseau-Rizzi et al., 2024). Based on climate simulations for the period 2005–2015, Medcyclones have been responsible for up to one-third of annual rainfall (Flaounas et al., 2018) and 70% of the total regional rainfall and wind extremes (Flaounas, Raveh-Rubin, et al., 2015). Around 90% of heavy rainfall cases in the western Mediterranean are typically associated with a cyclone (Jansà et al., 2001) that, regardless their intensity, properly organizes the mesoscale moist flow promoting precipitation. Similarly, destructive sea storms driven by intense cyclones represent the main threat to the Mediterranean coastal communities causing flooding, beach erosion, and infrastructure damage (Lionello et al., 2019 and references therein).

Considering model limitations due to approximations in numerical methods and in the description of physics processes, there is medium-to-high confidence in a future reduction in the number of Medcyclons, particularly during winter and under high-forcing scenarios (e.g., Cherif et al., 2020; Priestley & Catto, 2022; Raible et al., 2010). With respect to their intensity, climate projections are less robust, as some models suggest a decrease in the frequency of the most intense cyclones, while others show a decrease in the intensity of extreme cyclones (Cherif et al., 2020). Moreover, climate projections indicate a decreasing frequency and increasing intensity of Medicanes (e.g., González-Alemán et al., 2019). Medicanes, short for Mediterranean hurricanes, are Medcyclones with tropical-like characteristics, that is, a warm core extending into the upper troposphere, an eye-like feature in its center, an almost windless center surrounded by nearly closed sea surface wind circulation with maximum wind speed within a few tens of km afar. They are associated with high-impact phenomena such as heavy rain, strong wind, and storm surges. Enhanced duration, destructiveness, and tropical features of Medicanes are expected (IPCC, 2021; Tous et al., 2016). In the last decades, advances regarding observational data sets and modeling capabilities, also fostered by international programs in the Mediterranean, such as MEDEX (Jansà et al., 2014), HyMeX (Drobinski et al., 2014) or the EU COST Action CA19109 MedCyclones (Flaounas et al., 2022), have significantly contributed to improving our knowledge concerning the environment,

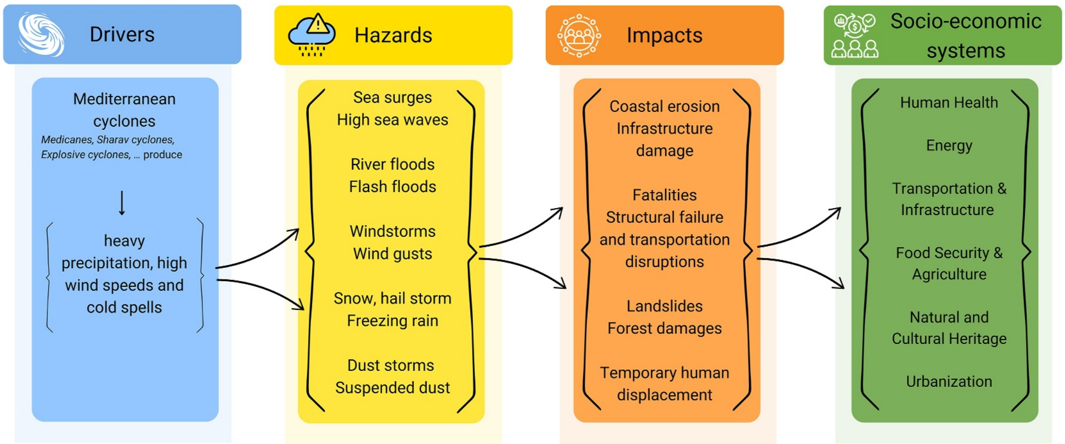


Figure 1. Schematic representation illustrating the chain of hazards, their impacts, and the socio-economic systems affected by Mediterranean cyclones as key drivers in the region.

characteristics, and evolution of Medcyclones, but also the socio-economic impacts. Still, relevant gaps remain, and further investigation is necessary in this field.

The socio-economic impacts of Medcyclones are a consequence of the large spectrum of weather-induced natural hazards related to these phenomena (Flaounas et al., 2022; Lionello et al., 2006). It is through torrential rains, the subsequent potential flash floods, and destructive sea storms driven by cyclones that the main socio-economic damage is inflicted on Mediterranean coastal communities. The damaging effects of Medcyclones disproportionately impact highly vulnerable areas, particularly urban and densely populated coastal regions. Key sectors such as human health, energy, agriculture, critical infrastructure, and transportation are mostly affected, often resulting in significant human casualties and economic losses. However, these impacts are not unavoidable. By implementing robust resilience strategies and proactive measures, societies can mitigate the risks and protect both lives and livelihoods from the challenges posed by Medcyclones.

To go beyond the current state of knowledge, there is a need for a paradigm shift toward impact studies encompassing multi-sectoral effects. This approach will help us evaluate the plausible consequences of climate change on human activities and formulate more effective climate action policies. Therefore, this paper reviews the existing knowledge regarding the socio-economic impacts of cyclones in the Mediterranean area with a particular emphasis on vulnerable sectors. As a consequence of this exercise, the main knowledge gaps in the societal impacts of Medcyclones will be identified, and the vulnerability of the main socio-economic sectors will be assessed. To this end, Section 2 provides a summary of weather-induced natural hazards resulting from the occurrence of Medcyclones and their future projections. Section 3 discusses current knowledge of the socio-economic impacts of Medcyclones, such as human health, energy, infrastructures, food security, and agriculture as well as natural and cultural heritage, and Section 4 provides information on the current operational databases that record and archive weather hazards and related impacts. Finally, Section 5 summarizes the main points of the study and identifies knowledge gaps.

2. Medcyclones

2.1. Physical Understanding of Medcyclones

The Mediterranean Basin emerges for its high cyclogenesis frequency, as already pointed out in pioneering studies between the 50s and the 60s (Petterssen, 1956 among others) and later confirmed by cyclone density statistics based on reanalysis data sets (e.g., Hoskins & Hodges, 2002; Sickmöller et al., 2000). Medcyclones represent a critical component of the atmospheric circulation of the region since they are the primary modulator of the synoptic and mesoscale variability (Buzzi, 2012), also associated with hazardous weather conditions (Lionello et al., 2006). A recent review article (Flaounas et al., 2022) provides a thorough revision of the latest knowledge in the field.

Robust results have been obtained exploiting gridded reanalysis data sets, concerning the seasonal and geographical distribution of Medcyclones (see Figure 1b in Lionello et al., 2016), especially considering intense cyclones (see Figure 1 in Flaounas et al., 2022). The main cyclogenetic areas have been identified as the Gulf of Genoa, the Atlas Mountains, and the Aegean Sea. Also, other regions, such as the Black Sea, the Iberian Peninsula, and the Eastern Mediterranean emerged in the statistics. Climatological studies have revealed that cyclogenesis is concentrated in certain areas located south of the main topographic reliefs surrounding the basin and nearby areas, suggesting that the complex orography of the region plays a role in modulating cyclone activity (Buzzi et al., 2020; Jansà et al., 2014). Finally, a fraction of Medcyclones does not form within the basin but enters from the Atlantic. The occurrence of intense cyclones in the region is characterized by strong seasonal variability (Flaounas et al., 2022), peaking in the colder season and attaining a minimum in summer, although some differences in the annual cycle have been revealed between northern and southern parts of the basin (Hochman et al., 2018). While winter cyclones are often deep systems, shallow thermal lows prevail in summer.

Winter season, from December to March, is also the most favorable period for explosive cyclones, which are rapidly intensifying Medcyclones with a great potential to cause extreme weather events (Carniel et al., 2024). Intense cyclones that predominantly impact the northwestern Mediterranean, either move down along the Tyrrhenian and Adriatic Seas or enter the basin from the southwest or south of the Atlas Mountains. Also, Eastern Medcyclones, often termed "Cyprus Lows," due to their genesis close to the island of Cyprus, and cyclones over the Ionian, Aegean, and Black seas emerge for their high track density (Alpert et al., 1990; Lionello et al., 2016). Upstream synoptic processes over the Atlantic are strictly connected with Mediterranean cyclogenesis, which often occurs in the presence of a large-scale baroclinic precursor, such as an upstream Rossby wave breaking (Hochman, Scher, et al., 2022; Raveh-Rubin & Flaounas, 2017). Medcyclones exhibit specific characteristics that make them different from their extra-tropical counterparts developing over the open ocean, that is, weaker intensity, smaller size, and a shorter lifetime. Within the large variety of cyclone subtypes identified in the Mediterranean (Flaounas et al., 2022), Medicanes have drawn attention, mostly due to their severe impacts. Medicanes usually are sustained by particularly strong diabatic processes (convection and surface fluxes), attaining structural characteristics similar to tropical cyclones. However, dynamical processes in mature Medicanes show pronounced case-to-case variability (Miglietta & Rotunno, 2019).

2.2. Extreme Hazards Related to Medcyclones

Heavy precipitation (HP, Figure 1), commonly exceeding 100 mm day^{-1}, constitutes a major meteorological threat in the western Mediterranean (WMed, Khodayar et al., 2018, 2021, 2022) and it is the main trigger of floods and landslides. Every year, recurrent events affect the area with fatal consequences for infrastructure and human losses. As shown in Flaounas et al. (2018) more than 70% of the total rainfall extremes are associated with a cyclone. Historical trends of heavy precipitation vary in magnitude and sign according to the location, season, and period of interest (Mathbout et al., 2018; Zittis, 2018; Hochman et al., 2018). *Flash floods* are typically poorly observed and understood, hydrological extremes (Amponsah et al., 2018), leading to highly uncertain forecasts of these events; however, they represent one of the most damaging meteorological hazards in the area (Llasat, 2021; Petrucci et al., 2019). While a reduction in flooding in medium and large catchments across southern Europe in recent years has been related to decreasing precipitation and rising evaporation (Blöschl et al., 2019), the observed increase in vulnerability to flooding events has been largely connected to human-induced factors. These include extensive land use changes, accelerated urbanization, and population growth, which exacerbate the impacts of flash floods and heavy precipitation events more significantly than climatic changes alone (Papagiannaki et al., 2022; Tramblay & Somot, 2018). Climate projections indicate a future increase in mean surface pressure as well as a weakening or northward shift of Mediterranean storm tracks resulting in reduced precipitation (Cherif et al., 2020; Hochman et al., 2020). The southern Mediterranean will likely experience the strongest drying during the wet season, October to March, which is also more critical for replenishing scarce water resources (Cherif et al., 2020; Zittis et al., 2019). The response in the northern Mediterranean is the result of compensation between a reduction in the number of Medcyclones and an increase in the precipitation generated by each storm (Zappa et al., 2015), leading to a decrease in the frequency of light to medium events and a future increase in the frequency of high-intensity events (Giorgi et al., 2019). As a result, besides the overall precipitation reduction, the intensity of the most extreme events is expected to increase throughout the Mediterranean (Zittis et al., 2021). According to regional climate projections, this is more evident in the northern part of the basin and under high-emission scenarios (Tramblay & Somot, 2018).

Sometimes, cyclogenesis over the Mediterranean may impact other regions outside the basin. This is the case of Vb cyclones (Hofstätter & Chimani, 2012; Messmer et al., 2015, 2017, 2020), low-pressure systems originating in the Gulf of Genoa, propagating eastward south of the Alps and then north-eastwards toward the Baltic Sea.

10.1029/2024RG000853

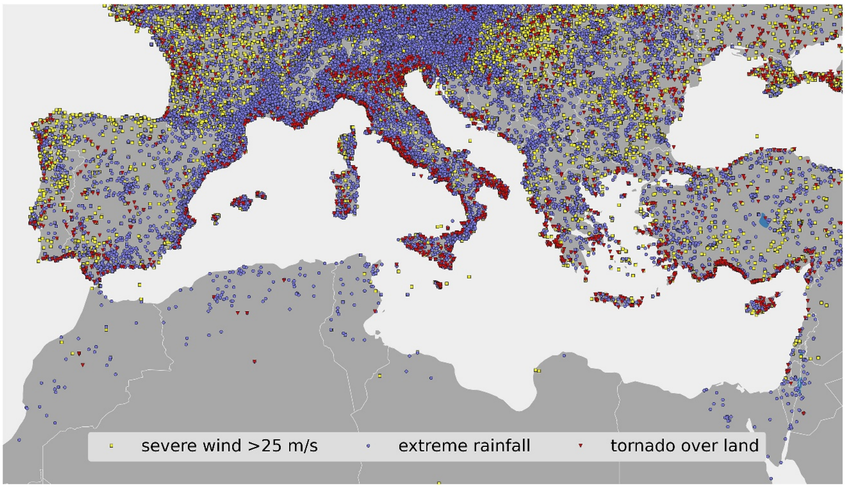


Figure 2. Reports of severe wind, extreme rainfall, and tornadoes between 2008 and 2022 in the Mediterranean region, collected by the European Severe Storm Laboratory (ESSL) and its partners in the European Severe Weather Database (ESWD; Dotzek et al., 2009). The criteria for selecting extreme rainfall events are outlined in the "ESWD Reporting Criteria" document, which can be accessed at https://www.essl.org/cms/european-severe-weather-database/reporting/.

Although rare, they are of particular interest as they have often caused major river flooding over the northern flank of the Alps and Central Europe, especially during the summer season. Simulations for the future period show insignificant changes in Vb-cyclone frequency, mean intensity, and precipitation in the selected catchments of central Europe (Pothapakula et al., 2022a, 2022b).

Lightning events, commonly associated with convective storms, tropical cyclones, or extratropical cyclones (Frame et al., 2017), play a major role in triggering wildfires, especially in remote regions where human activity is minimal. In Mediterranean environments, dry lightning, occurring during thunderstorms that produce little or no rainfall, significantly increases wildfire risk by leaving fire fuel dry (Mariani et al., 2018). High atmospheric instability and vigorous updrafts in these convective storms enhance lightning formation, and even minimal precipitation can evaporate quickly under warm, dry conditions. With climate warming expected to intensify these conditions, the contribution of lightning to wildfire ignitions is likely to grow, as further highlighted by the UNEP report on extraordinary landscape fires (UNEP, 2022).

In this region, intense cyclones contribute to less than 10% of the lightning activity, but under certain conditions, this contribution might reach 20%–30% (Galanaki et al., 2016). Only one-third of intense Medcyclones present lightning activity close to their center. Nevertheless, taking into consideration the frontal structures, then cyclones' contribution to lightning activity is certainly higher but remains an open question. Regarding Medicanes and lightning activity, the latter usually precedes the mature stage associated with tropical-like features (D'Adderio et al., 2022).

Landslides, frequently linked to prolonged or intense rainfall and flash floods, are primarily triggered by Mediterranean extratropical cyclones and Medicanes (Görüm & Fidan, 2021; Lagouvardos et al., 2022; Nastos et al., 2021). These natural hazards rank among the most destructive in the Mediterranean region, causing significant economic losses and numerous fatalities (Camera et al., 2021). A noteworthy example is "Ianos," affected Greece on 17–19 September 2020, the strongest Medicane observed in the Mediterranean, responsible for more than 1,400 landslides in Greece within 2 days (Valkaniotis et al., 2022; Zekkos et al., 2020). Landslides often happen where they have already occurred in the past (Temme et al., 2020). Local studies on future changes in the risk of landslides' hazards show a projected increase of up to 1.5 and 4 times in the near and far future, respectively, under the high-end scenario of climate change (Bernardie et al., 2021).

Extratropical cyclones are also often responsible for *extreme winds* (Figure 2), causing severe damage in the region (e.g., Raveh-Rubin & Wernli, 2016). About two-thirds of such windstorms are caused by cyclones located in the Mediterranean, the rest by Atlantic or Northern European cyclones. Also, the majority of compound rain–wind extremes occur in the neighborhood of a Mediterranean cyclone (Portal et al., 2024). Cyclone forcing is

10.1029/2024RG000853

often enhanced by local topographical features: for instance, the intensity of Mistral, *a strong cold dry northerly wind of southern France*, is determined by the presence of Genoa lows and upper-tropospheric potential vorticity anomaly (Givon et al., 2021) as well as by constriction through the Rhône Valley. The same atmospheric pattern may intensify Sirocco, a south-easterly wind over the Adriatic Sea, through a channeling effect due to the Dinaric Alps (Cavaleri et al., 2019). Future changes in wind speeds are expected to be small, although the poleward shift in the storm tracks could lead to significant changes in extreme values (medium confidence; IPCC, 2021). Using multi-model simulations with global and regional climate models in the IPCC SRES A1B scenario, Donat et al. (2011) found a decrease in extreme wind speeds over the Mediterranean. Nissen et al. (2014) similarly predicted a reduction in windstorms, due to the decline in both the frequency and the intensity of Medcyclones over most of the Mediterranean basin. Zappa et al. (2015) found a decrease of up to 25% in the frequency of extratropical cyclones (and associated windstorms) throughout the Mediterranean basin, with all CMIP5 models agreeing on the sign of the change. Reale et al. (2022) found a robust increase in cyclone-related wind intensity in the central Mediterranean based on an ensemble of fully coupled regional climate models under scenario RCP8.5. For Medicanes, González-Aleman et al. (2019) found an increase in power dissipation due to more durable and intense, although less frequent, events. Hence, while the future conditions imply a decrease in the frequency of Mediterranean windstorms, their impacts will likely be exacerbated during the most extreme events, particularly under high-emission pathways.

Tornadoes (Figure 2) are also potentially dangerous phenomena in the Mediterranean (Antonescu et al., 2016, 2017). Eight of ten tornadoes with the highest fatalities in Europe affected the Mediterranean area (Groenemeijer & Kühne, 2014). Generally, they form in the framework of large-scale cyclonic circulations (Tochimoto et al., 2021). Bagaglini et al. (2021) identified substantial regional variability in the conditions favorable to their intensification between Italian continental and maritime regions.

Although the spatial distribution of reports (Figure 2) does not perfectly align with the actual occurrence of severe weather—largely due to inconsistencies in reporting—a few key patterns emerge. For instance, impactful heavy rainfall events are most common near coastlines and the Alps. Tornado activity, on the other hand, predominantly involves the coastlines, being associated with landfalling waterspouts. An exception to this trend is the Po Valley in Northern Italy, where tornadoes are also frequently observed further inland.

Cyclonic activity has additionally been confirmed to significantly correlate with *dust episodes* in the Eastern Mediterranean (Dayan et al., 2008). Satellite data and model simulations have identified cyclogenesis processes as significant meteorological patterns that result in dust uptake due to the strong surface wind (Rizza et al., 2017). In most such cases, Medcyclones develop close to dust sources, with their core being either over the African continent or farther north in the Mediterranean Sea (Schepanski & Knippertz, 2011). For the Central and Eastern Mediterranean, the primary meteorological situation responsible for transporting large amounts of mineral dust particles is related to cyclonic activity (Kallos et al., 2007; Meloni et al., 2008). In spring and early summer, cyclones develop under the strong thermal contrast between the temperature of the cooler marine waters and the warmer continental surfaces (Saharan thermal lows in the south of Atlas Mountains). These cyclones then propagate eastward, through the thermal gradient path, crossing the Mediterranean between Libya and Egypt and transporting desert dust over the Eastern Mediterranean Basin. Well-developed Medcyclones drive almost a quarter of Saharan dust events, transporting dust through the warm advection ahead of the cold front of these eastward-moving low-pressure systems (Varga, 2020). Categorizing dust events into moderate, high, and extreme cases, Flaounas, Kotroni, et al. (2015) concluded that the cyclone contribution can vary from 20% to 70% of the dust events over the Mediterranean, primarily affecting its central and eastern side (Figure 3). In this study, attributing dust events to cyclones-related circulations was performed by associating the $1° \times 1°$ latitude–longitude grid points fulfilling "dust event criteria" with cyclone circulation criteria (Flaounas, Kotroni, et al., 2015) within the overlapping area. Airborne dust in this aspect is considered to have been transferred by cyclone-induced circulation.

In certain areas of the eastern Mediterranean and the Middle East, increasing dust concentrations can be partly attributed to decreased precipitation, lower soil moisture, reduced relative humidity, and higher temperatures over the past decade, highlighting the sensitivity of dust emissions to climate change (Klingmüller et al., 2016). Future scenarios, particularly the ones related to high emissions of greenhouse gases, imply a notable expansion of desert areas due to the desiccation of ephemeral water bodies (Zittis, Almazroui, et al., 2022).

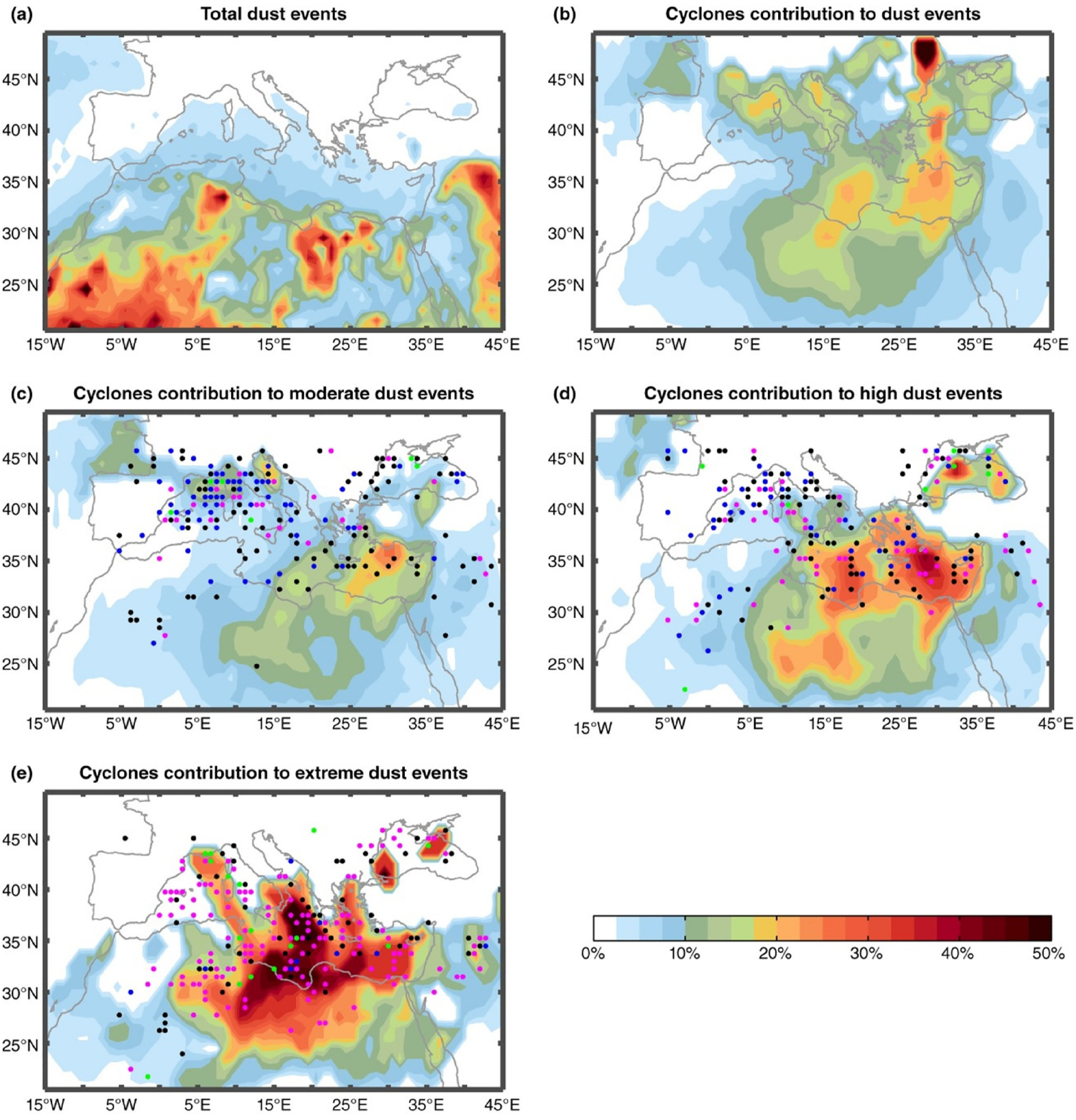


Figure 3. (a) Percentage of days with dust (grid points presenting Ångström Exponent (AE) < 0.7 and Absorption Aerosol Index (AI) > 1) over the Mediterranean region for the whole 8-year period. (b) Percentage of days with dust spatially associated with cyclones. (c–e) Percentage of dust days of moderate (c), high (d), and extreme (e) intensity associated with cyclones defined as 25%–75%, 75%–95%, and 95%–100% quantiles of AOD per grid. Dots represent cyclone locations contributing to dust days of each intensity class (black dots denote winter cyclones, magenta dots denote spring cyclones, green dots denote summer cyclones and blue dots denote autumn cyclones). (*Source*: Flaounas, Kotroni, et al., 2015).

In the Mediterranean, many of the most intense *storms* at sea are generated by strong winds associated with cyclones (Ferrarin, Pantillon, et al., 2023; Lionello et al., 2019; Patlakas et al., 2021). Sea storms represent the main threat to coastal communities because they determine storm surges and severe sea states that may cause beach erosion, flooding of low-lying coastal areas, damage to infrastructure, and the important cultural heritage

10.1029/2024RG000853

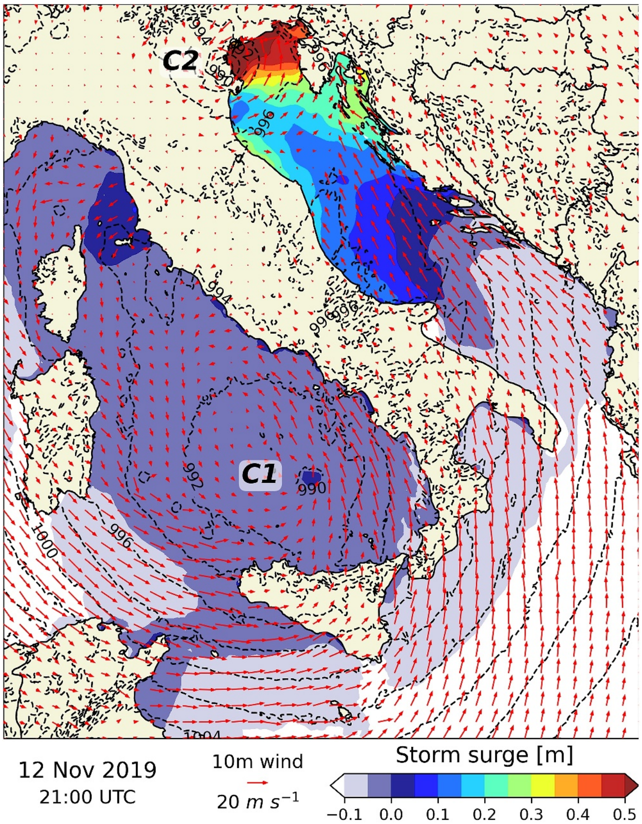


Figure 4. Mean Sea level pressure (black dashed isolines), 10 m wind (red arrows), and storm surge (color shade) on 12 November at 21:00 UTC. Labels C1 and C2 indicate the two cyclones.

exposed to these phenomena (Chaumillon et al., 2017). The city of Venice is a paradigm of exposed historical and cultural values. In fact, the shallow northern Adriatic Sea is the Mediterranean sub-basin where storm surges reach higher values (Marcos et al., 2009), mainly triggered by a strong southeasterly moist and warm wind, called Sirocco, generally caused by cyclones generated in the western Mediterranean Sea (Cavaleri et al., 2019; Lionello et al., 2021). Such a synoptic situation drove the most extreme storm surges and high waves events (in 1966, 1979, 2018, and 2019) (Lionello et al., 2021 and references therein). On 12 November 2019, two cyclones were active simultaneously in the Mediterranean region (Ferrarin et al., 2022; Miglietta et al., 2023): a deep cyclone over the central-southern Tyrrhenian Sea (C1 in Figure 4) and a fast-moving small local depression traveling northwestward over the Adriatic Sea along the Italian coast (C2 in Figure 4).

Such a peculiar meteorological situation caused the rising of the sea level over the whole Northern Adriatic Sea, resulting in flooding and severe damage to the historic center of Venice (with an estimated economic loss of some hundreds of M€; Schlumberger et al., 2022) and the nearby coastal area. Medcyclones also strongly impact the central Mediterranean Sea (Ferrarin, Orlić, et al., 2023; Patlakas et al., 2021; Scicchitano et al., 2021; Toomey et al., 2022), while Medicanes also affect the western Mediterranean Sea, creating hazardous wave conditions in the open sea and along the coast (Toomey et al., 2022). In 2020, a low-pressure system caused the most extreme wave and storm surge ever recorded along the eastern Iberian Peninsula, with floods, damage to coastal infrastructures, coastal erosion, and a total of 13 fatalities (Amores et al., 2020).

The projected future reduction in cyclone activity may result in an associated decrease in storm surges and waves in some regions of the Mediterranean Sea (Flaounas et al., 2022; Toomey et al., 2022). However, a warmer Mediterranean Sea (Pastor et al., 2020) may lead to an increase of Medicanes intensity (Koseki et al., 2021 and references therein). It is worth noting that, in the future, the impact of such events along the Mediterranean coast will be exacerbated by sea level rise resulting in coastal flooding even during non-extreme cyclones (Ferrarin et al., 2022).

Due to the concomitant occurrence of different severe meteo-marine phenomena over large areas (e.g., the storm Vaia in 2018 that impacted Corsica, Liguria, Alps, and several locations along the Adriatic coast; Cavaleri et al., 2019, 2022; Davolio et al., 2020; Giovannini et al., 2021), Medcyclones often represent a *compound multi-hazard* situation. Compound hazards affecting the Mediterranean tend to fall into the categories of wet-windy (Catto & Dowdy, 2021; Owen et al., 2021; Raveh-Rubin & Wernli, 2015, 2016; Ridder et al., 2020), cold-wet (Berkovic et al., 2021; de Luca et al., 2020; Lemus-Canovas, 2022), hot-dry (Ermitao et al., 2021; Feng et al., 2020; Lemus-Canovas, 2022; Vogel et al., 2022), and compound flooding events (where flooding comes from two or more sources such as storm surge and heavy precipitation; Camus et al., 2021; Couasnon et al., 2020; Ridder et al., 2020; Sanuy et al., 2021).

The Mediterranean is particularly a hotspot for co-occurring extreme precipitation and wind events (Catto & Dowdy, 2021; Hochman et al., 2021; Owen et al., 2021; Rousseau-Rizzi et al., 2024; as shown for example in Figure 5), especially during the autumn and the winter season (although also in summer). Figure 5 illustrates the monthly distribution of weather-related events that caused rainfall-related damage, wind-related damage, or a combination of both in Greece from 2000 to 2022. While precise attribution of these events to Medcyclone activity is lacking, it is generally understood that they are mostly associated with extratropical cyclones, often accompanied by embedded thunderstorm environments and frontal systems (Catto & Dowdy, 2021; Messmer & Simmonds, 2021).

Over the western Mediterranean from 60% to 80% of events are linked to an extratropical cyclone (within 1,100 km), while over the central and eastern Mediterranean, this percentage reaches 100%. Several studies focus

10.1029/2024RG000853

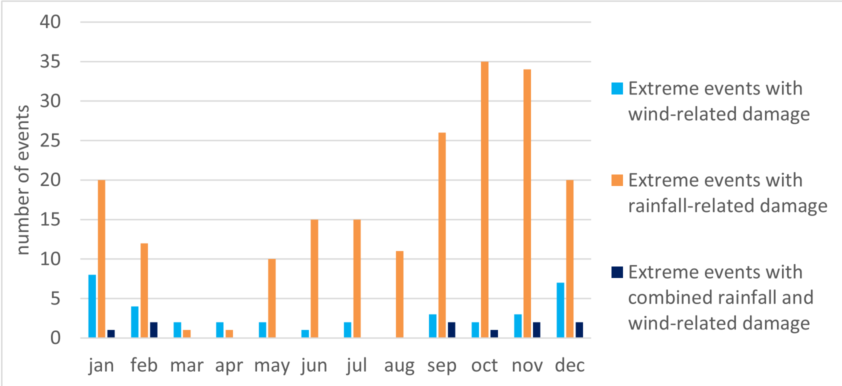


Figure 5. Monthly distribution of extreme weather events that caused rainfall-related damage, wind-related damage, or a combination in Greece in 2000–2022 (*Source*: HIWE-DB, www.meteo.gr/weatherEvents.cfm, Papagiannaki et al., 2013).

on extreme wind, precipitation, and their frequency of occurrence over the Mediterranean without defining explicit links of the events to the Medcyclones (Hillier & Dixon, 2020; Ridder et al., 2020). However, Hénin et al. (2021) found that 85% of the concurrent extreme precipitation and wind events in the Iberian Peninsula are associated with cyclones, mostly Atlantic, and many with atmospheric rivers.

Medcyclones, mainly Cyprus lows (forming in the eastern Mediterranean, around Cyprus), can produce cold and wet compound events over Israel (Berkovic et al., 2021) and the broader Eastern Mediterranean (De Luca et al., 2020; Hochman et al., 2020). These systems transport rain and cold air from the north. Other studies found that cold and wet compound extremes are associated with cold frontal systems (e.g., Zhang et al., 2021). Camus et al. (2021) found the Mediterranean to be a hotspot for the potential for compound flooding when considering the interaction of precipitation, river discharge, storm surge, and waves, particularly on the northern coast.

Co-occurrence is more significant during autumn and during winter. The specific events that can be attributed to Medcyclones remain unknown. Additionally, Medcyclones significantly increase the likelihood of events involving extreme waves (Sanuy et al., 2021). Similarly, cyclones in the North Atlantic, particularly near the Iberian Peninsula, are often associated with compound extreme events, primarily characterized by heavy precipitation. This region of Spain has experienced six compound storm surges and river discharge events over the period 1980–2014, defined as co-occurring annual maxima of these two measures (Couasnon et al., 2020). Many parts of the northern Mediterranean coast have experienced similar numbers of these compound events.

Few studies have considered recent historical trends in the occurrence of compound events, and even fewer are devoted to the projections of compound extremes over the Mediterranean. Lemus-Canovas (2022) found an increase in the dry/warm extremes, but a decrease in wet-cold and dry-cold. The Mediterranean Oscillation (Conte et al., 1989) plays a role in determining the frequency of these extremes and is also a significant factor in the occurrence of Medcyclones. Vogel et al. (2022) found that warm and dry spells have increased in the Mediterranean in the past 40 years primarily due to temperature increases rather than decreases in precipitation. Hot and dry extremes occurring within the same week, month, or year are projected to increase in frequency (Vogel et al., 2020). While precipitation extremes are generally projected to increase, the shift of the storm track away from the Mediterranean (e.g., Priestley & Catto, 2022; Raible et al., 2010) could result in little change or even a decrease in compound wind and precipitation events (Ridder et al., 2022).

In conclusion, Medcyclones are key drivers of weather variability in the region, leading to extreme events such as heavy precipitation, windstorms, storm surges, and compound hazards like flooding and landslides. These storms are influenced by the complex topography of the Mediterranean Basin and ongoing climate change, which increases vulnerability in both coastal and inland areas. Projections suggest varying impacts, with potential decreases in cyclone frequency but increases in the intensity of Medicanes and compound extremes. As sea levels rise and storm tracks shift, coastal communities face growing risks of flooding, erosion, and damage.

3. Derived Socio-Economic Impacts of Medcyclones Activity in the Mediterranean

3.1. Human Health

Medcyclones can affect public health through various natural hazards. These may include floods associated with heavy precipitation (Khodayar et al., 2021), cold spells or heat waves (Khodayar & Paredes-Fortuny, 2024; Paredes-Fortuny & Khodayar, 2023), wind and sand/dust storms (Hochman, Scher, et al., 2022), and others. Besides the exposure to these harsh weather conditions, health impacts strongly depend on socio-economic and demographic factors, mainly age, gender, the existence of pre-existing or chronic diseases, geographic location, level of acclimatization, occupational health and safety, and quality of health services (Linares et al., 2020).

The impact of Medcyclones on public health can generally be separated into direct and indirect effects. Direct effects occur during the passage of a cyclone, which may cause deaths and injuries due to flooding (e.g., drowning), cold (e.g., affecting the homeless), or warm conditions (e.g., in the special case of "Sharav" cyclones in the Eastern Mediterranean), and catastrophic winds (e.g., flying debris, falling trees or road accidents). The indirect effects mainly occur after a storm dies out, inducing power outages or electrocution from damage to electric infrastructure, fires, and burns, and worsening of chronic illnesses due to lack of access to adequate medical care or medication (Goldman et al., 2014). For example, in 2013, during the intense Eastern Mediterranean storm named "Alexa," four people died in Israel directly from the harsh weather conditions of the storm (Hochman, Marra, et al., 2022; Hochman et al., 2019). In 2020, four people lost their lives when Ianos Medicane affected Greece (Lagouvardos et al., 2022). More recently, 14 casualties were reported in Spain from storm Gloria (de Alfonso et al., 2021). In all cases, many regions were disconnected from electricity for many days following the event. This may have caused other health implications that were not reported or attributed to these events. The indirect effects on public health, particularly from cyclones associated with casualties and property loss, may also include short and long-term mental illnesses and disorders, including depression, anxiety, or post-traumatic stress disorders (Mulchandani et al., 2020; Weilnhammer et al., 2021).

Floods are one of the most damaging natural hazards in the Mediterranean region, causing many fatalities every year, particularly across Southern Europe. There are still inconclusive results regarding the observed trends in deaths from floods in the Mediterranean region (Llasat, 2021). However, an analysis of flood fatalities from 1980 to 2018 in eight Euro-Mediterranean countries (Petrucci et al., 2019) showed statistically significant increasing trends in flood fatalities for Greece, Italy, and South France. The reasons for this increase remain inconclusive and may be attributed to either a rise in flood occurrence, a growing population in flood-prone areas, extensive land-use changes or inadequate management practices. According to the results, flood fatalities occurred more often outdoors and mainly on the road while driving to/from work or home. The primary cause of death was drowning while being swept away by a torrent. Males aged between 30 and 65 years were at higher risk than females. Those over 65 were less vulnerable and mainly died indoors, blocked in a flooded room, usually while sleeping. The projections for shorter-lived but more intense heavy precipitation events associated with Medcyclones may exacerbate impacts on human health and mortality (Hochman et al., 2020; Llasat, 2021). The triggering meteorological event, that produced the flood, is rarely reported in the literature. Still, the high percentage of autumn and winter flood fatalities with respect to other seasons (Diakakis et al., 2023) may reasonably be attributed to the high occurrence of Medcyclones during this time of the year (Hochman et al., 2019). Moreover, the collocation of the largest death tolls from extreme floods and extratropical storm occurrences in the western Mediterranean indicates that Medcyclones are probably the main trigger. There is a clear contrast between the reported deaths in the western and eastern parts of the Mediterranean region (https://books.openedition.org/irdeditions/23181?lang=de). In the Eastern Mediterranean, floods have caused fewer casualties, except for the flood in Lebanon on 17 December 1955 (~440 deaths according to the Emergency Events Database (EM-DAT, Guha-Sapir et al., 2021)) induced by an intense Med cyclone. On 26 and 27 November 1927, a torrential rainfall event in Algeria caused more than 400 casualties and more than 1,200 victims of extended flooding (Sardou et al., 2018). Precipitation during this event was nearly half of the average annual total. In 2001, an extremely intense Medcyclone caused one of the most catastrophic windstorms and flood events in Algeria, with over 600 deaths in the country, four deaths, and damage estimated at 37.3 million EUR in the Balearic Islands. The total number of casualties was over 4,500, in the African countries bordering the Mediterranean (Llasat et al., 2010). Another catastrophic flash flood occurred in August 2002 in Spain, Algeria, and Italy, while in France the "Gard event" (8–9 September 2002) caused damages of 1.2 billion EUR and 23 casualties (Llasat et al., 2010). Damaging flash floods occur almost annually in autumn affecting the Spanish Mediterranean coast with catastrophic

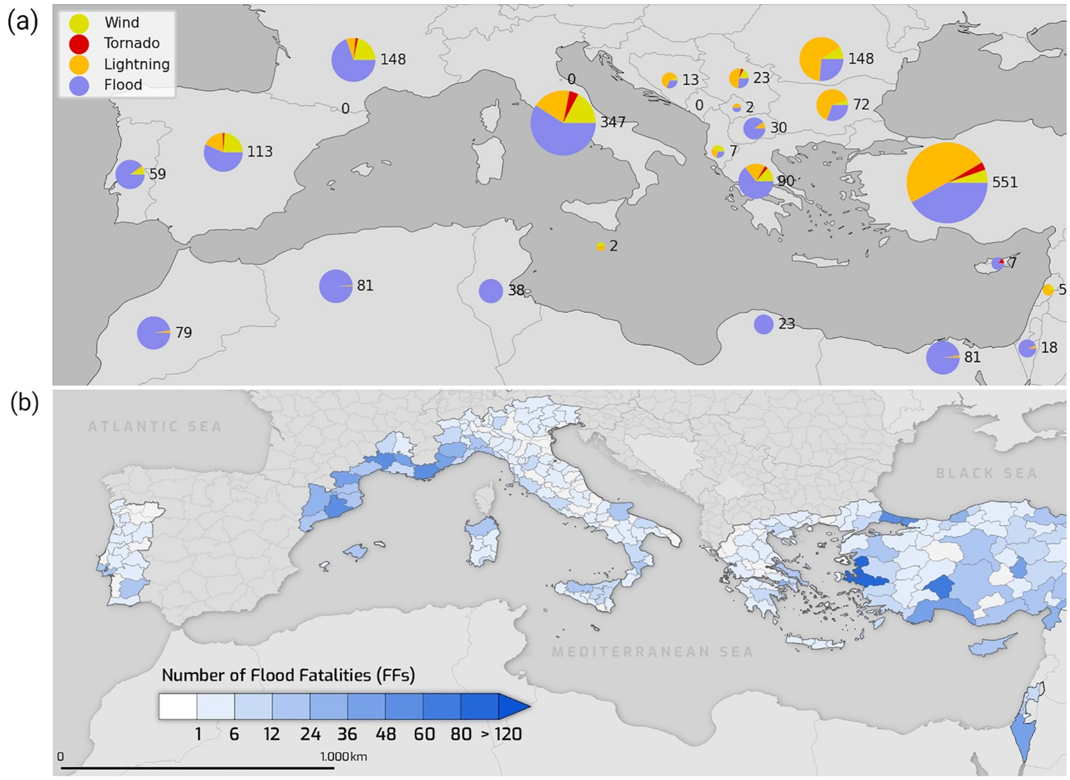


Figure 6. (a) Severe weather fatalities between 2006 and 2021 recorded in the European Severe Weather Database (ESWD) by hazard type, (b) Flood fatalities (FFs) from 1980 to 2020, at the NUTS 3 (territorial units as defined by https://ec.europa.eu/eurostat/web/nuts) level across the Mediterranean study areas of FFEM-DB (Database of Flood Fatalities from the Europe-Mediterranean region. *Source*: Papagiannaki et al., 2022).

consequences due to heavy rainfall events (Khodayar et al., 2018, 2022). In terms of losses, thousands of houses, properties, shops, cars as well as public infrastructure are damaged. Besides damage to agriculture and urban areas, traffic jams bring cities to a standstill. Thousands of people are affected by railway closures, airport operation halts and/or re-routing, and long delays. Buildings, roads, and railways are flooded and damaged and damage can also be caused to sewage systems, electricity, and water systems, in addition to the loss of lives.

Accounting of deaths attributable to catastrophic events is reported in international natural disaster databases (Figures 6a and 6b), however, these estimates might underestimate the number of deaths from low-mortality flood events, which are the majority in Europe. For example, Petrucci et al. (2019) have shown that almost half of the fatal flood events over the period 1980–2020 caused only one fatality. A recent report from the European Environmental Agency also highlights that, despite only 3% of all events being responsible for 60% of economic losses, it is also important to record small- and medium-scale events to fully assess climate change impacts and to support adaptation actions (EEA, 2021 Briefing no. 21/2021).

Based on ESWD recorded severe weather fatalities (Figure 6a) most severe weather-related fatalities since 2006 are caused by the flash floods that occur after heavy rainfall. Especially in eastern Mediterranean countries, many fatalities are also caused by lightning. We speculate that the lower level of mechanization of agriculture in those regions implies more people working in the fields in locations where they are vulnerable to lightning. Outside of North Africa and the Middle East, severe winds also cause a sizable fraction of fatalities. Comparatively, few people are killed by tornadoes, although the number is not negligible in Turkey and Italy.

Medcyclones can drive extreme dust transport, increasing concentrations, expanding exposure, and worsening public health impacts (see Section 2.2). Indeed, about two-thirds of the total yearly dust yield in the Negev Desert in Israel is linked to Medcyclones (Dayan et al., 2008). The human health effects of dust storms range from respiratory disorders (including asthma, tracheitis, pneumonia, allergic rhinitis, and silicosis), to cardiovascular disorders, such as strokes, conjunctivitis, skin irritations, meningococcal meningitis, valley fever, diseases associated with toxic algal blooms, and mortality and injuries related to transport accidents (Aghababaeian et al., 2021; Zhang et al., 2016). Both chronic exposure and short-term elevated concentrations of airborne dust can pose serious risks to human health. In the eastern Mediterranean, premature mortality attributable to chronic PM2.5 (inhalable Particulate Matter with an aerodynamic diameter of less than 2.5 μm) exposure is mainly related to natural Aeolian dust processes (Evans et al., 2013). In the so-called "dust belt" from North Africa across the Middle East and South Asia to East Asia, the fraction of cardiopulmonary deaths caused by atmospheric desert dust can reach 15%–50% (Giannadaki et al., 2014). In several Mediterranean countries, including Cyprus, Italy, Israel, and Spain, cardiovascular and respiratory admissions and mortality rates are enhanced during dust events (Lelieveld et al., 2015; Stafoggia et al., 2016). While MedCyclones that drive most dust storms in the region could be less frequent in a warmer world (see Section 2), the dried lake beds lying in topographically low basins will be highly susceptible to aeolian erosion, therefore, dust emissions in the region, including sources in the Middle East, could be increased (Ludwig & Hochman, 2022a; Zittis, Almazroui, et al., 2022).

Extremely low temperatures, sometimes driven or influenced by Medcyclones, can impact the health and well-being of populations in the Mediterranean. Despite the region's generally mild winters, excess winter mortality and morbidity have been documented in several Mediterranean countries (López-Bueno et al., 2021). Cold extremes have been associated with increased all-cause, cardiovascular, and respiratory mortality (Weilnhammer et al., 2021), though these impacts are strongly linked to socio-economic factors such as energy poverty and building standards (Kyprianou et al., 2019), as well as influenza outbreaks (Antunes et al., 2017). Notably, Hochman et al. (2021) found a significant correlation between Medcyclones and influenza in Israel, the Palestinian Authority, and Jordan.

While future assessments for the region tend to focus on the health effects of heat extremes—under the assumption that a warming climate may reduce cold-related mortality (Gasparrini et al., 2017)—Medcyclones can also contribute to high temperatures. This is particularly evident in the case of "Sharav" cyclones, which are frequent in the eastern Mediterranean during spring (Hannachi et al., 2011). Moreover, higher temperatures during winter in the future may reduce the effects on mortality (de Schrijver et al., 2023).

3.2. Energy

In an energy-dependent society, Medcyclones-related hazards can cause widespread damage to the power infrastructure (production, storage, and grid), leading to severe outages and public disruption. For instance, intense precipitation events leading to floods may affect many aspects of the power system. Flooding can cause severe damage to the equipment, leading to interruptions in service continuity and widespread outages (Movahednia et al., 2022; Sánchez-Muñoz et al., 2020). Heavy rainfall can further increase soil moisture, which, when combined with strong winds, increases the vulnerability of trees to wind damage (Gardiner et al., 2013). Consequently, overhead power lines are at greater risk of damage, primarily due to falling trees (Láng-Ritter et al., 2024). The volume of forest damage follows an approximate power-law relationship with wind gust speed, with an exponent of 10 (Valta et al., 2019). In densely forested countries, the relationship between wind gust speed and power outages is similar, and a recent study shows that the number of power outages increases exponentially with wind gust speed. The highest correlation was found with the tenth power of daily maximum wind gusts, highlighting the critical relationship between wind gust speed and power outages, in densely forested areas (Haakana et al., 2024). In cases where average wind speeds exceed 27 m/s, direct damage to the power grid is possible, and transmission towers may even collapse (Li et al., 2022). In the Mediterranean region, a large share of power lines is overhead, and the total length has increased between 2015 2020 in nearly all examined countries (Figure 7). For example, the passage of the Ianos cyclone over Greece caused major disruptions in the electricity supply of several areas for 4–5 days (Lagouvardos et al., 2022). According to the Hellenic Electricity Distribution Network Operator in Greece, more than 450 points that suffered severe damages, such as broken poles and pipes, were inspected and fixed on the medium (MV) and low voltage (LV) network (Kefalonia, Zakinthos, and Ithaki islands). This network has a total length of 1,148 and 1,771 km, respectively, and supplies 56 MV and 63,300 LV customers. In the area of Karditsa, the profound destruction caused the failure of the electricity supply for 29,000 customers with 6,000 of them being on the mountain network which suffered extensive damages, especially from tree collapsing and landslides, and the rest in areas that overflew with water at lengths ranging from 40 to 100 km. Apart from the overhead lines, extensive damage from intense precipitation events during cyclones can occur in underground substations. Water pumping for the reconnection of these stations asks for strategic restoration plans,

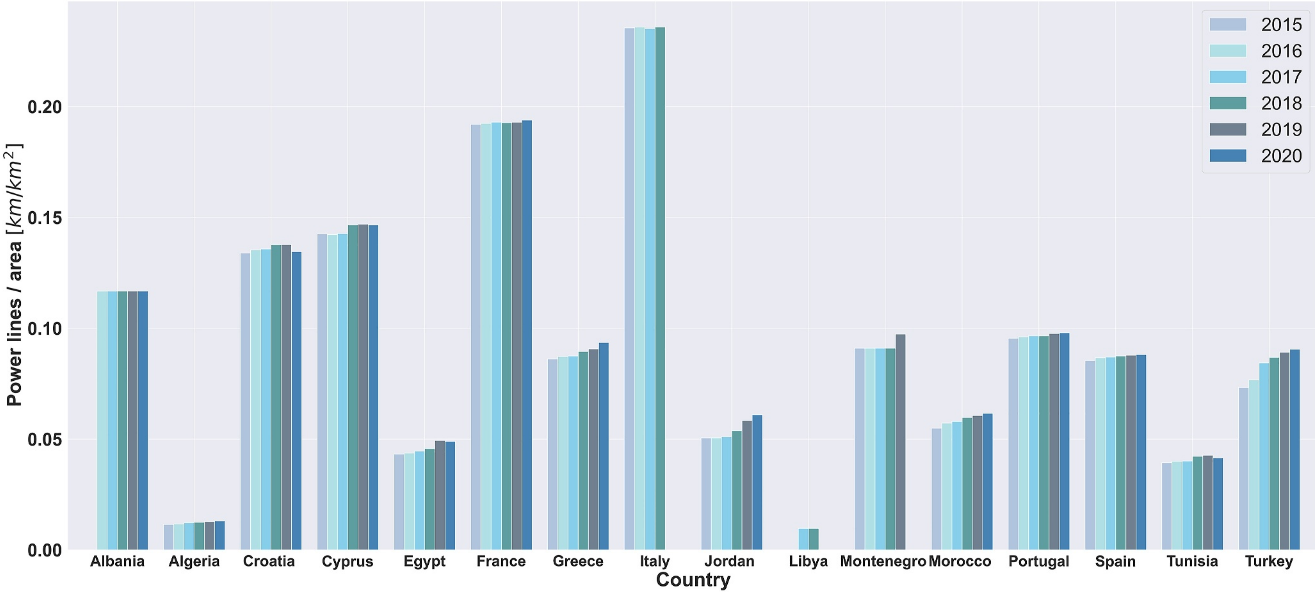


Figure 7. The total length of power lines (overhead lines and ground cables) per area of the country in the Mediterranean region in 2015–2020. Data sources: https://data.med-tso.org/ and https://www.worlddata.info/.

considering that their presence in a wet environment for long time periods increases the risk for further future failures.

Strong winds, freezing-rain storms, and heavy snow-load are some of the major causes of overhead power line failures (Gonçalves et al., 2023). Beginning with the last, tree branches often fail to hold the weight of the accumulated snow, break, and cause extended damage to the power lines. Most power lines in the Mediterranean region are above the ground and indeed most of the encountered issues are principally a consequence of fallen trees (Ciapessoni et al., 2020). It is known that several factors impact tree uprooting, for example, tree type, soil moisture, soil type, and tree canopy (Gardiner et al., 2010; Liu et al., 2022). In addition, there is a direct correlation between the proximity of trees to distribution lines and the vulnerability of the lines to severe windstorms. Such conditions were encountered during a severe snowstorm that affected South Greece, particularly Athens in January 2022. During the storm named "Hope" ("Elpida") heavy snowfall conditions led to power outages that lasted several days under freezing conditions (Patlakas et al., 2024). Freezing rain events are less common near the Mediterranean; however, there are a few examples of massive power outages in Mediterranean countries. For instance, in 2014 Slovenia experienced a historical blizzard and freezing rain event caused by a deepening secondary low-pressure system in the Northern Mediterranean (Markosek, 2014). The damage to power transmission lines was caused by accumulating freezing rain on the power lines as well as the breaking branches of trees due to the snowfall. In total 30 km of power lines were destroyed, and 170 km were inoperative resulting in 250,000 people being without electricity for days (Vajda et al., 2014). A similar freezing rain event paralyzed public transport in Bucharest, Romania due to large power interruptions in 2019 (Andrei et al., 2019).

Regarding energy production, there is a growing interest in wind energy applications and gas exploitation (Abanades, 2019; Kostianoy & Carpenter, 2019). Focusing on renewables, areas characterized by moderate to strong winds, are favorable for wind energy investments. However, extreme winds can lead to structural failures of wind turbines. Overstress and strain in the tower or the blades can lead to tower collapse and blade fracture (Chou et al., 2013, 2018). To protect the system, predefined cut-off thresholds are applied, and wind turbines are switched off, affecting production. Moreover, cyclonic activity and the associated frontal systems can lead to fast changes in wind speed magnitude and direction causing sharp ramps in wind power production. In such scenarios, especially when combined with high energy demands, the power grid can be stressed, posing a challenge to transmission system operators (Steiner et al., 2017).

The Mediterranean is highly favorable for solar energy production due to its high solar resources, which, in some areas of southern Europe, exceed 2,000 kWh/m^2 annually (Hadjipanayi et al., 2016). As a result, solar energy constitutes a significant portion of the region's energy mix. This is also linked to its high versatility, with applications ranging from large solar parks to smaller systems, such as rooftop solar panels on residential and commercial buildings. Medcyclones can affect Photovoltaic (PV) installations in two ways. From a production perspective, increased cloudiness could reduce output, potentially leading to energy droughts. However, the overall long-term effect is minimal. On the other hand, Medcyclones can also be associated with hail (Laviola et al., 2022), which, in extreme cases, can damage PV panels (PVEL, 2021), resulting in economic losses.

Medcyclones also modulate the sea state, which has a severe impact on a spectrum of energy operations from offshore wind energy applications to offshore oil and gas exploration, production, and transfer. Installation, support, and maintenance of such installations require the desired sea state and particular weather windows that guarantee the safety of the people and the infrastructure (Gintautas & Sørensen, 2017). Nuclear power plants require water for the reactor's cooling system and are, therefore, often located close to rivers or seas. There are a few nuclear power plants also located in the Mediterranean region, which Medcyclones can also affect. The high sea level induced by extra-tropical cyclones can cause safety issues in nuclear power plants (Rantanen et al., 2021).

3.3. Transportation and Infrastructure

Medcyclones pose serious threats to populations, assets, critical infrastructure, and human activities, mostly located or taking place in coastal areas (Toomey et al., 2022). The intense winds, precipitation, and coastal flooding due to storm surges and wind waves hitting the coasts (Bakkensen, 2017), and the large amounts of rainfall over small areas and short periods causing pluvial and urban flooding (Diakakis et al., 2017) are the main causes. Floods in the Mediterranean mainly affect urban areas, within 10–20 km of the coastline due to the conversion of water courses into streets (Marra et al., 2022). The damage from flash floods recorded in inhabited areas is due to the vulnerability of the elements at risk in the fluvial-coastal plains examined. Among the causes of the flood frequency increase in the last decades are the effects of the urban expansion in areas of fluvial pertinence and climatic change, namely the interaction between anthropogenic landforms and hydro-geomorphological dynamics (Faccini et al., 2021). So far, one of the most impactful events, the Medicane Rolf that brought flooding to Italy, France, and Spain in November 2011, resulted in total insured losses of more than 1 billion USD in France (Toomey et al., 2022), and a total of 1.25 billion USD including Italy and Spain, most claims for inundated homes, businesses, and vehicles (Llasat, Caumont, et al., 2014; Llasat, Marcos, et al., 2014).

More rarely, when the synoptic conditions are favorable, Medcyclones can lead to significant snowfalls that may result in flight delays, cancellations, or disruptions in ground transportation systems, including highways and railways (Bech et al., 2013). Furthermore, the impact on sea conditions can have a large impact on harbor infrastructures such as flooding of docks, railways, and roads (Sánchez-Arcilla et al., 2016). The wind around the cyclone center is the main cause of positive and negative sea level anomalies, depending on its onshore or offshore direction (Lionello et al., 2019). Strong wind gusts (>17 m/s), often occurring during intensive large-scale low-pressure systems, can harm transportation, as falling trees can block roads and railways, cause electricity cuts, and disrupt airport operation and navigation (Ryley et al., 2020; Vajda et al., 2014). The operation of ports and maritime transport can also be affected by Medcyclones. The associated high waves and storm surges, in parallel with strong winds, and intense precipitation can directly affect harbor infrastructure and ships in route (Hanson & Nicholls, 2012; Sánchez-Arcilla et al., 2016). Indeed, in the Mediterranean Sea, several ship accidents caused by high waves during intense cyclones have been reported (e.g., Bertotti & Cavaleri, 2008; Cavaleri et al., 2012).

The most extreme intensity (and rarer) events significantly impact maritime transport operations (Cherif et al., 2020; Zittis et al., 2021). In particular, the increased coastal flooding and overtopping due to mean sea-level rise are the main contributors to the amplified risk of port operation disruption (Izaguirre et al., 2021). The smaller Mediterranean islands, with a strong dependence on maritime means for transporting goods and passengers, are less resilient to the expected changes (Zittis, Ahrens, et al., 2022).

The impacts of three major cyclones from the past decade, Zorbas (primarily affected Greece, southern Italy, and Turkey on 28–29 September 2018, Ianos primarily affected Greece on 18–19 September 2020), and Daniel impacted Greece, Libya, and parts of the eastern Mediterranean in early September 2023, can serve to illustrate this section, highlighting their effects on transportation and infrastructure in Greece and Libya. These Medcyclones caused significant disruptions to transportation networks and critical infrastructure in Greece and Libya. Cyclone Zorbas brought severe winds, torrential rainfall, and flooding, leading to road closures, damage to coastal highways, and power outages in regions such as Kalamata, Methoni, and Argolis (Kouroutzoglou et al., 2021; Portmann et al., 2020; Scicchitano et al., 2021). Key transport links, including the Evripos Bridge and Eretria-Oropos ferry service, were temporarily suspended. Cyclone Ianos resulted in extensive flooding, landslides, and infrastructure damage, particularly in Thessaly, where over 400 km^2 of land, including urban areas like Karditsa, was inundated. This led to eroded roads, damaged power lines, and blocked transportation routes, severely disrupting socio-economic activities (Diakakis et al., 2023; Zimbo et al., 2022). Cyclone Daniel (Flaounas et al., 2024; Hewson et al., 2024) had an even broader impact, with road collapses, bridge failures, and damage to critical infrastructure in central Greece, compounded by the closure of ports that hampered recovery efforts (Mavroulis et al., 2024; WTW, 2024). In Libya, Daniel triggered catastrophic flooding, resulting in dam failures, the destruction of roads and bridges, and widespread disruption of communication and power networks (ACAPS, 2023).

3.4. Food Security and Agriculture

Agriculture and water resources are closely interlinked in Mediterranean countries and shape the social development in many rural areas (Iglesias et al., 2011). Any environmental stresses on agriculture production, including Medcyclones-related hazards, will pose additional challenges to food security. Medcyclones provide most of the wet-season rainfall, which is critical for replenishing water resources and beneficial for agriculture and ecosystems. However, the most extreme events, associated with intense rainfall and flooding, in addition to severe winds, can threaten plants and agriculture production. Excessive amounts of precipitation and excess water in the soil can be responsible for wheat loss due to the proliferation of pests and diseases, leakage of nutrients, inhibition of oxygen uptake by roots, and interference with agronomical practices (Zampieri et al., 2017).

The reduction of Mediterranean cyclone occurrences is consistent with the overall mean precipitation decrease observed in the region (Trigo et al., 2000). Reale et al. (2022), using a Med-CORDEX ensemble of seven regional coupled system models that downscaled CMIP5 RCP8.5 scenarios, showed an overall decrease in cyclone-related precipitation in future scenarios, too. The projected future decrease in cyclones may have dramatic impacts on water availability. As cyclones are a major source of precipitation in the Mediterranean, their reduction is expected to lead to drier conditions, with serious consequences for agriculture, water storage, and overall water supply.

In a hotter and drier Mediterranean, partly due to fewer Medcyclones (see Section 2), the yield and quality of several key crops for the region, including cereals, vegetables, pulses, grapevines, and olive trees, will be adversely affected, with the impacts being more pronounced in the water-stressed southern and eastern Mediterranean countries (Fraga et al., 2020; Papadaskalopoulou et al., 2020; Santillán et al., 2020; Varotsos et al., 2021).

Furthermore, extreme weather events in relation to cyclonic phenomena have been identified as key climate change-related stressors by the Commonwealth Marine Economics Program (Impacts%20of%20Climate%20Change%20on%20Fisheries%20in%20the%20Coastal%20and%20Marine%20Environments%20of%20Caribbean%20Small%20Island%20Developing%20States;%20SIDS). Turner et al. (2020) acknowledged that changes in intensity, severity, and frequency of storms pose significant threats to fisheries, which can be a challenge for countries in which fisheries constitute a significant sector with implications for several aspects of coastal communities' economic, social, and cultural well-being. Pathways of threat include disruption of fishing-related activities, damage to fishing vessels and coastal infrastructure related to those, the safety of workers at sea and on land, and the jeopardizing of the well-being of fishing households and their entire coastal communities. In the absence of thorough vulnerability assessment and adaptation strategies, this climate stressor will have more immediate and potentially disastrous impacts. Hidalgo et al. (2022) found that an increase in extreme weather events puts more at-risk fishing resources and livelihoods than fishing operations and wider social or economic aspects. Assessing another food security-related sector, aquaculture, Rosa et al. (2012) reported that floods can affect nutrient loads in coastal aquaculture areas, and high inorganic sediment loads can reduce filtration rates of bivalves. High-energy events such as storms and cyclones can also lead to sediment transport leading therefore to increased erosion. Additionally, severe flooding can result in mass mortalities of animals in aquaculture affecting ponds, rafts, lines, or cages in both coastal and offshore areas. Taking into consideration the limitations posed by inland fresh water and sheltered coastal areas, such as their limited carrying capacities, the high risk of harmful accumulation of farm waste products, scarce availability of coastal areas suitable for coastal aquaculture, and the expected increase in future demand for fish, offshore expansion has often been proposed. These structures though will be more exposed to the variability in environmental conditions, especially waves, currents, and winds, that under extreme events such as Medcyclones can induce higher structural loads on and failure of fish cages and moorings as highlighted in Karathanasi et al. (2022).

3.5. Natural and Cultural Heritage

Disaster risk management and climate change adaptation, focusing on cultural heritage preservation, have been highlighted at the United Nations (UN) Sendai Framework for Disaster Risk Reduction 2015–2030 (UNISDR, 2015). Despite these efforts, however, cultural heritage sites are at constant risk and suffer from the adverse effects of natural and/or human-induced hazards (Mentzafou & Dimitriou, 2022). The wide range of weather-induced natural hazards resulting from Medcyclones affect coastal areas with damage to communities, infrastructure, and the cultural heritage exposed to these phenomena (Chaumillon et al., 2017). Throughout human history, floods led to the loss and devastation of several historical monuments or sites and changes in the cultural landscape. Therefore, storms associated with floods, landslides, and hydrogeological risk are among the most critical weather-related hazards in terms of the potential damage to cultural heritage (Figure 8; Bosher et al., 2019; Nicu, 2017).

One of the most recent and infamous examples in Greece is the collapse of the 150-year-old traditional "Plaka" bridge in February 2015 due to intense precipitation and strong river flow, and the damages of Sanctuary of the Great Gods at Samothrace Inland in 2017 due to flooding. In Italy, there are records of floods affecting historical sites; one of the most characteristic examples being the catastrophic flood of 1966 (Sioni et al., 2023), caused by intense convection driven by a Mediterranean low-pressure system, that devastated the city of Florence, killing at least 32 people and causing immense damage to irreplaceable cultural heritage. In the North, the city of Venice represents a paradigm of coastal flooding due to its worldwide recognized cultural heritage relevance and high vulnerability to extremely high sea levels, mostly induced by Medcyclones (Ferrarin et al., 2022; Lionello et al., 2021; Miglietta et al., 2023). However, such a problem is not limited to the city of Venice since several ancient settlements and important natural and cultural heritage sites located in the Mediterranean low-elevation coastal zones (e.g., the Old Town of Dubrovnik, Syracse, Tyre, the Nile, Rhone, and Po deltas) are at risk of coastal flooding and erosion (Prahl et al., 2018; Reimann et al., 2018). In 2018, the fierce wind generated by an explosive Medcyclone (known as Vaia storm, Giovannini et al., 2021; Sioni et al., 2023) was responsible for the largest forest damage ever occurred over the southern Alpine slopes (Chirici et al., 2019), hitting more than 1 million hectares of forest in Northeastern Italy and causing the loss of millions of m^3 of wood in an area including a UNESCO World Heritage such as the Dolomites.

Other cyclone-related hazards, such as extreme winds and waves play a secondary role in affecting and damaging cultural and natural heritage. A characteristic impact is damage to natural and human-made structures due to sea and wind erosion. These factors, combined with changes in relative humidity and temperature, intense rainfall extended droughts, earthquakes, etc. set an alarming mixture of conditions for a potentially hazardous environment for coastal cultural heritage materials. Due to their location's proximity to large sea bodies, the coastal cultural heritage sites are exposed to marine spray. Stones and mortars in coastal cultural heritage buildings are highly affected by the deposition of marine salts leading to pore fracture and, consequently, to the stone and mortars' weakening. These marine aerosols in combination with strong winds and wind-driven rain can lead to the rapid erosion of the surface through material loss (Orr et al., 2018; Sesana et al., 2021). This is a slow process already observed in archeological sites like the one of Delos, Greece. A similar process was associated with the collapse of the Azure Window, a natural arch situated on the west coast of Gozo (Maltese Archipelago). The incident took place in March 2017, and the cause of the collapse of the pillar section is probably associated with erosion at its base. It was, however, triggered by a violent storm that battered the site at the time (Caruana et al., 2022). During the storm wave heights of up to around 3 m, wind speeds larger than 16 m/s, and wind gusts between 18 and 20 m/s were experienced in the region. Furthermore, Medcyclones can induce fire weather conditions in remote areas, as was recently shown by Berkovich and Raveh-Rubin (2022), analysing the processes leading to persistent dry and warm winter events in the eastern Mediterranean.

10.1029/2024RG000853

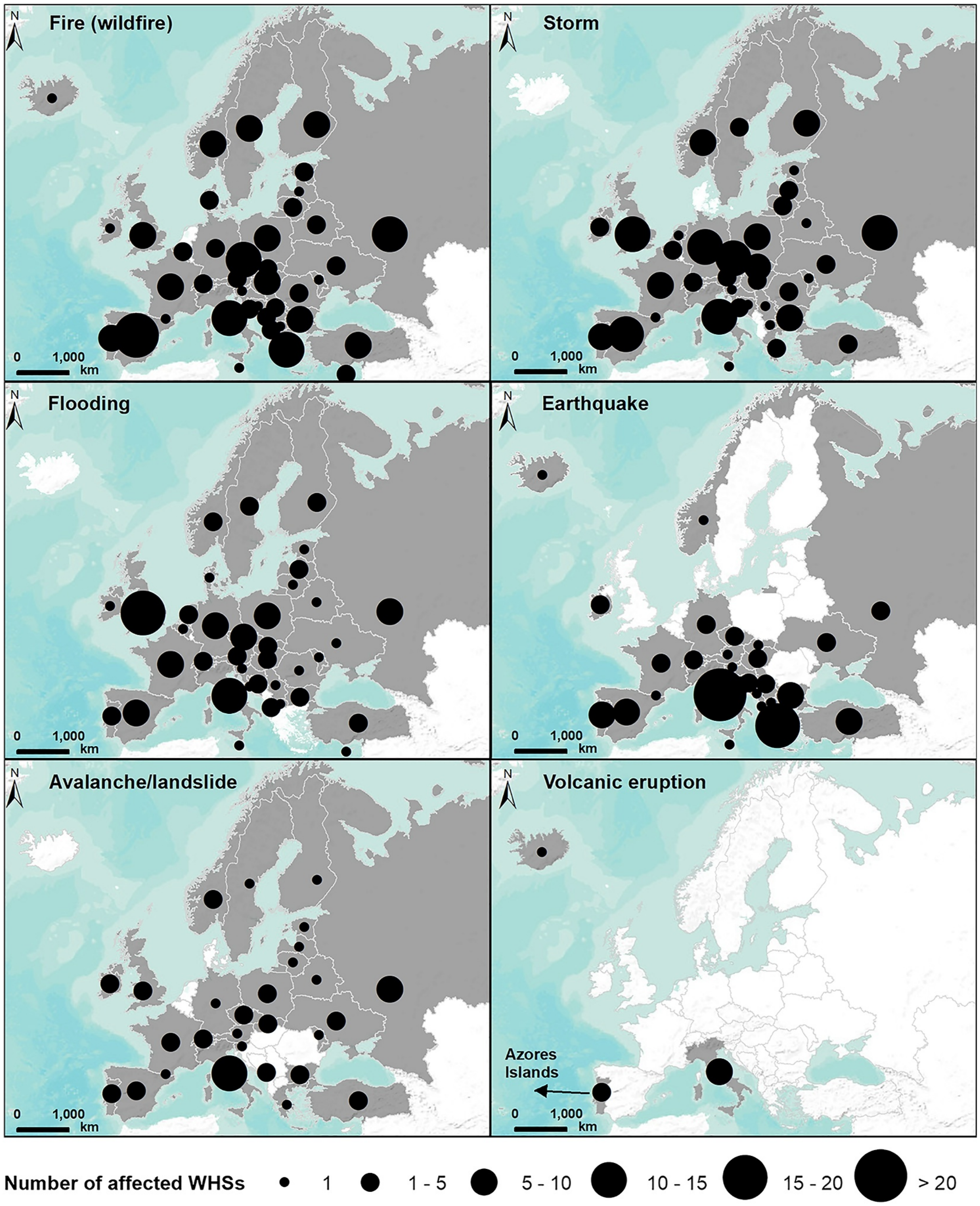


Figure 8. Distribution of six selected world heritage sites (WHS) threats inside the European countries. The size of the dots is a function of the number of affected WHSs in each country. Countries with at least one site affected by the threat are colored in gray (*Source*: Valagussa et al., 2020).

4. Advancing Preparedness for Weather Hazards and Impacts Using Operational Databases

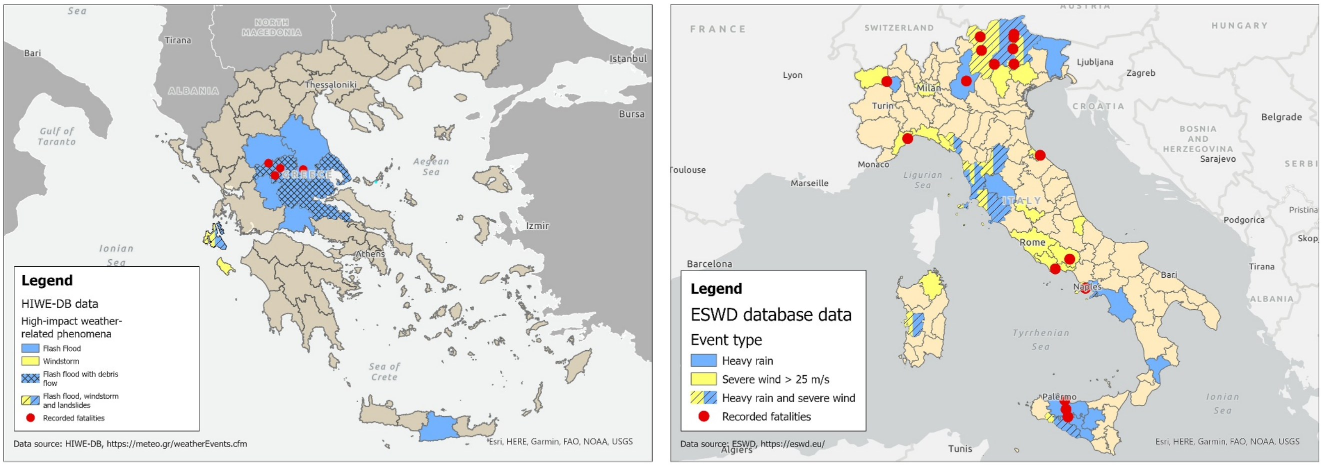
The study of weather hazards and their associated impacts can greatly benefit from the use of operational databases. These databases provide crucial information on the occurrence of severe weather events and their past and ongoing effects on societies, enabling the creation of comprehensive data sets essential for understanding such events. Operational databases are particularly valuable for analyzing the characteristics of different types of weather hazards, as well as identifying trends, patterns, and the variability of impacts across various economic sectors, populations, and regions. This information is vital for identifying potential risk factors and vulnerabilities, ultimately aiding in the development of strategies to mitigate the likelihood and severity of future hazards. Consequently, it is essential to understand the primary sources of data and information that support not only academic research but also media outlets, the private sector (e.g., insurance companies) in shaping business strategies, and policymakers in informing their decision-making processes.

Generally, the number of fatalities associated with weather hazards, thus including those from Medcyclones, is mainly collected from press reports (Papagiannaki et al., 2022). Then, the information is included in databases such as the Emergency Events Database (EM-DAT) International Disaster Database (http://www.emdat.be/), the Dartmouth global archive of large flood events (http://www.dartmouth.edu/~floods/), the Italian bibliographical and archive inventory of landslides and floods in Italy (AVI) flood database (http://avi.gndci.cnr.it/e,n/archivi/piene_en.htm) or the databases of the Hydrological cycle in the Mediterranean EXperiment (HYMEX; https://www.hymex.org/; e.g., Llasat et al., 2013).

An important contribution at the Euro-Mediterranean level is the innovative database of flood fatalities from the Europe-Mediterranean region (FFEM-DB; Papagiannaki et al., 2022) that is now available online at the 4TU Center for Research Data (FFEM-DB%20"Database%20of%20Flood%20Fatalities%20from%20the%20Euro-Mediterranean%20region") and is updated approximately every 2 years, as it contains very detailed data on the fatalities' circumstances and profiles (Petrucci et al., 2022). In its latest version, FFEM-DB includes data on 2,875 flood fatalities from 12 territories (nine of which represent entire countries) in Europe and the broader Mediterranean region from 1980 to 2020. The FFEM-DB contributes to the emerging need for damage and loss indicators (EC, 2021) and is a valuable tool for a broader understanding of flood risk in the region. Adding information about the exact triggering effect could contribute significantly to the attribution of flood fatalities and fatal flood events in Medcyclones.

The European Severe Weather Database (ESWD; https://eswd.eu/) operated by the European Severe Storms Laboratory is another resource with data on severe weather hazards and their impacts that includes the Mediterranean region (Dotzek et al., 2009). As of 2023, this database contains more than 300,000 individual reports of severe weather. The reports are collected from online media and eyewitness reports by a team at European Severe Storm Laboratory (ESSL, https://www.essl.org/cms/) and a network of volunteers throughout Europe. The ESSL staff and trusted partners ensure the quality of the reports by comparing the reports with meteorological data, such as satellite and radar observations, and looking for other sources to confirm the reports.

Unlike EM-DAT, the ESWD does not typically aggregate individual reports into compound events. This allows users to apply their own criteria for grouping events as needed. The exception to this rule is tornadoes—multiple reports referring to the same tornado are merged into a single entry. Across Europe, the database is used by a range of organizations including 16 public weather services, and international organizations (ECMWF, EUMETSAT). In addition, several commercial companies from the reinsurance sector and companies specialized in risk modeling use the data. A relevant example of the capabilities of the ESWD data set is given in Figures 9a and 9b, which illustrates the hazards and the impacts produced by Storm Vaia, 27–30 October 2018, an intense Medcyclone that resulted in severe damage and loss of lives in the Central Mediterranean (Davolio et al., 2020). A representative example of an operational database in the Mediterranean region is the available online database on high-impact weather events in Greece (HIWE-DB, https://meteo.gr/weather_cases.cfm) (Papagiannaki et al., 2013), where weather events with socio-economic impacts in the Greek territory are being systematically recorded since the year 2000. The HIWE-DB draws information from central and local media and includes meteorological observations from the surface weather station network operated by the Meteo unit of the National Observatory of Athens (Lagouvardos et al., 2017). The database makes it possible to link each triggering hazard with the various impacts at the prefecture and/or municipality level. Moreover, each event included in the HIWE-DB is classified in terms of both the meteorological hazard intensity and the impact severity, permitting thus further risk and vulnerability analyses. The Meteorology unit at NOA uses the database operationally to analyze and visualize extreme events and their main impacts. The informative material is then published online on the relevant publicly available website, www.meteo.gr, with over 300,000 daily visitors. A relevant example is given in Figure 9b, which illustrates the hazards and the impacts produced by Medicane Ianos. Ianos affected Greece on 18–19 September 2020, resulting in four fatalities and devastating impacts due to heavy rainfall, gusty winds, and high waves (Lagouvardos et al., 2022).



(a) (b)

Figure 9. Visual representation of affected areas and recorded fatalities (a) for Greece during Ianos passage, 18–19 September 2020 using the HIWE-DB, and (b) Italy during Vaia passage, 25th October to 4th November 2018 using the European Severe Weather Database (ESWD) database.

5. Conclusions, Identification of Gaps, and Recommendations

Medcyclones are responsible for a variety of weather-related hazards, with future scenarios pointing to increasing destructiveness of these phenomena in the region. According to the International Disaster Database (https://emdat.be) of the Center for Research on the Epidemiology of Disasters (CRED), during the last 100 years, more than 14,000 deaths have been attributed to hazards related to Medcyclones, with this number probably being underestimated. While these records provide insight into the recent impacts of Medcyclones, they offer only a limited perspective on their long-term variability. To better assess potential future changes, it is crucial to establish a historical baseline by providing a longer-term view of Mediterranean cyclones. Long-term records, as demonstrated in studies of Atlantic cyclones (e.g., Raible et al., 2018), can help distinguish natural variability from anthropogenic influences and improve future projections. Despite this knowledge, there is a particular lack of systematic quantification of cyclones' contribution to Mediterranean high-impact weather, and a need to step from hazard forecasts to impact-based forecasts (Flaounas et al., 2022; Zhang et al., 2021). This review contributes to this development by collecting and summarizing existing knowledge regarding the societal impacts of Medcyclones and the vulnerability of the main socio-economic sectors.

To efficiently design integrated responses toward climate change impacts and simultaneously create resilient societies, there is a need for a paradigm shift toward impact studies encompassing multi-sectoral effects. This change of paradigm will support decision-makers in adapting socio-economic systems to these evolving risks. Part of the challenge lies in the lack of efficient communication among communities with specific expertise that perceive and evaluate isolated risks. Furthermore, most impact assessments for the region focus on past conditions and historical events, while there is limited literature on future impacts. This is of greater relevance to the southern Mediterranean countries that are also most prone and vulnerable to climatic changes and extreme weather events. Besides changes in the frequency, intensity, and other characteristics of Medcyclones under a warmer climate, their nonlinear impacts strongly depend on the socio-economic conditions and adaptive capacity of each Mediterranean country, including financial and technological means, access to resources, political stability, willingness for transformative changes, and more. Thus, detailed knowledge about each Mediterranean country's socio-economic conditions and adaptive capacity is essential.

Urban areas are more at risk of cyclone impacts from the perspective of the higher population density and the potentially high infrastructural and socio-economic losses. In this respect, growing urbanization with an increasing population demands efficient cyclone management systems, referred to as any decision-support tool to assist in managing the impacts of cyclones. In addition to population growth, internal and international migration is expected to disproportionately increase the population density, particularly in the coastal urban areas (Cosby et al., 2024). Given the projections in terms of sea level rise, the comprehensive impact of extreme rain intensities

10.1029/2024RG000853

and storm surges should be specifically addressed in future planning of coastal cities. Adaptation actions on the environment in coastal areas, in terms of water resources, energy, infrastructure and urban planning, human health, economy, law, and education are recommended. The diversification of local and regional current socio-economic models, which are highly dependent on tourism in islands and coastal regions, is needed to increase the community and national economic, social, and population resilience. Hence, there is a need to consider (a) more comprehensive Medcyclones hazard scenarios in combination with climate change pathways, focusing particularly on sea level rise; (b) more accurate projections of compound extremes over the Mediterranean given the limited studies available despite its relevance, (c) local socio-economic scenarios dealing especially with economic, demographic, and social development; and (d) more diversified adaptation scenarios, in particular for the most populated regions, such as coastal urban areas.

Particularly concerning the direct and indirect impacts resulting from Medcyclones-related weather hazards on priority socio-economic sectors in the region, we conclude that, despite the relevance of the topic, dedicated studies are generally missing. The current trends in cyclone-related hazards in the Mediterranean make us envision significant future changes in many priority sectors for society, thus, not only a historical quantification of cyclones' contribution to Mediterranean high-impact weather and related impacts is desirable, but also future projections. Regarding human health, while the direct physical health impacts of Medcyclones and associated extreme weather are well-understood, the indirect ones, such as mental health impacts, in the context of a changing climate remain an under-researched field, both internationally and in the Mediterranean region (Linares et al., 2020). Research on the health effects of cyclones has largely focused on their immediate physical consequences, while longer-term, indirect impacts receive less attention. Studying the mental health effects of such events presents several methodological challenges (Stanke et al., 2012). Therefore, follow-up evaluations of the health impacts of extreme events should account for both direct and indirect consequences, with particular emphasis on developing innovative methodologies to assess better and document mental health outcomes. Also, extremely cold conditions affecting the health and well-being of the population in relation to Medcyclones are better understood than high temperatures in relation to these phenomena, as is the case of “Sharav” cyclones, abundant during springtime in the eastern Mediterranean (Alpert & Ziv, 1989; Hannachi et al., 2011). The impacts of the latter phenomenon on public health have not been assessed yet.

Energy security is an additional major concern in Mediterranean and European countries. The Mediterranean Basin is a densely populated region where the energy demand increased by 6% from 2010 to 2020 due to economic development and population growth. The demand is expected to continuously increase toward the mid-century (Drobinski et al., 2020). In the future, the energy production of the Mediterranean region will lean increasingly on renewable energy sources, such as solar, wind, and hydro energy. However, under business-as-usual scenarios (e.g., RCP8.5 or SSP5-8.5), hydropower capacity will decrease in the Mediterranean by the 2050s by 5%–15% due to the decrease in precipitation. Thus, we can expect the electricity transmission system to become more exposed to variations in weather in the future (Drobinski et al., 2020). Generally, in the field of energy, there is a significant lack of data and studies associating energy production, distribution, storage, and power outages with natural disasters in the Mediterranean region. This is even more evident when focusing on Medcyclone impacts on the energy sector and particular variables for example, wind extremes, precipitation, and floods. The existing gap in impact data availability strongly affects the development of impact tools and models which could increase the preparedness for power outages and grid failures (e.g., Jasiūnas et al., 2023). Beyond the most obvious impacts often associated with structural damages or impact on energy production, secondary issues can emerge. Forecasting cyclones alongside their paths and potential impacts can be quite challenging, especially in regions such as the Mediterranean Basin (Chaboureau et al., 2012; Flaounas et al., 2022; Pantillon et al., 2024; Portmann et al., 2020; Rodwell et al., 2013). Predictability can have a prominent impact on energy production and demand forecasting, in a sector characterized by large uncertainties. Even relatively small changes in the cyclone path can have a substantial impact on wind power, affecting the estimations employed by the national and international energy markets. Thus, this is a field worth investing in the future to obtain accurate information on energy production and demand.

Regarding **transportation and infrastructure** major disruptions can occur even in countries with highly reliable infrastructure systems. Besides, the expected increase in population in the region in combination with the sea level rise will increase the necessity of adaptation strategies, particularly in urban and coastal areas. While wind and rain damage to overhead power lines is often seen as the primary impact, the issue extends beyond resilience. It involves addressing broader vulnerabilities. Strengthening transmission systems through measures like clearing trees, burying lines, or using stronger poles is important, but a more comprehensive, multi-dimensional approach is needed. Interventions that, however, imply high cost, can include (a) the increase of backup routes during and after extreme weather events, (b) the enhancement of early warning systems, (c) the construction or expansion of coastal defenses, or (d) interventions to increase the height of critical infrastructure (Zittis, Ahrens, et al., 2022). Countries in the Middle East and North Africa (MENA) are particularly exposed given that the population has quadrupled between 1960 and 2015, and the degree of urbanization has risen from 35% to 64% during the same period (Cramer et al., 2018). The growing urbanization, supported by continuing internal migration processes in the region is creating centers of increased vulnerability for local population growth. The focus must therefore be on a multi-faceted approach that includes strengthening transportation and infrastructure resilience, while also considering social and environmental factors like migration, coastal zone management, and long-term urban planning.

The **agricultural** economy constitutes a priority sector in the Mediterranean region, with **food insecurity increasing** and a high risk of worsening in the future (Abis & Demurtas, 2023; Al Sharjabi et al., 2024; Caracciolo & Alessandro, 2018). The agriculture sector will need to adapt promptly and efficiently to tackle the climate-induced challenges of future crop production and meet the increasing food demand of the growing regional population (Hossain et al., 2020; Mrabet et al., 2020; Zittis, Almazroui, et al., 2022). While the impact of mean climate change on agriculture and the role of droughts and heat extremes has been widely investigated (e.g., Biess et al., 2024; Heino et al., 2023; Sutanto et al., 2024), the effect of extreme precipitation events and sea level rise on future crop yields is less studied. In addition, more research is required to fully comprehend the synergies and trade-offs within the regional food-water-energy nexus and identify any potential crop and human health implications under a changing climate.

Parallel to all this, there is increased concern regarding the preservation of **cultural and natural heritage** in a rapidly changing climate (UNISDR, 2015). Despite the protection efforts, reports of damages in historical sites are quite common. The damage and loss of natural heritage occur more and more frequently in association with weather-related hazards, some of them related to the occurrence of Medcyclones, affecting anything from beaches to forests and wildlife. The need to address all these challenges, however, is not reflected by the amount of quality research, especially on a nationwide scale. To this end, communities and stakeholders should focus on four main targets: more resources, high-quality data, advanced research, and stricter laws.

The benefit and value of operational databases of weather hazards and related impacts are unquestionable because they provide essential information about weather-related impacts on society, allowing a deeper understanding of trends and threats. However, adding information to such databases about the exact triggering phenomenon will enable the accurate attribution of relevant damages and lives lost to Medcyclones, also allowing for an individual financial assessment and cost-benefit analysis. Furthermore, given the increasing number of data sets worldwide, and in the Mediterranean, a harmonization of selection criteria and data sets would be desirable to facilitate data processing and to draw robust conclusions.

Since the devastating impact of Cyclone Daniel in the Mediterranean region, there has been a heightened awareness among the general public, stakeholders, and policymakers regarding the severe consequences associated with such extreme weather events. However, despite this increased recognition, significant efforts are still required from the scientific community to advance the understanding of these cyclones, particularly their societal impacts. A deeper understanding of the dynamics, frequency, and future trends of Medcyclones is crucial for improving risk assessment, strengthening early warning systems, and developing more effective mitigation and adaptation strategies. While significant progress has been made in recent years, the assessment of MedCyclones' contribution to socio-economic losses remains largely underexplored. This review advances our understanding in this critical area, providing a foundation for future research and informing strategies to enhance societal resilience.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

All data used in this study come from previously published sources. In Figure 2 data is available through Dotzek et al. (2009). In Figure 3 data is available through Flaounas, Kotroni, et al. (2015). In Figure 4 data is available through Ferrarin, Pantillon, et al. (2023). In Figure 5 data is available through Papagiannaki et al. (2013). In Figure 6 data is available through Papagiannaki et al. (2022). Specifically, the data is freely available in the 4TU. ResearchData repository, at Petrucci et al. (2022), where the user can access and extract all the data (.txt and.csv files) collected for the database FFEM-DB that provides not only the number of fatalities per flood event but also detailed information about the profile of victims and the fatalities circumstances. In Data for Figure 7 is available from https://data.med-tso.org/ (power line length by year) and https://www.worlddata.info/ (country areas). In Figure 8 data is available through Valagussa et al. (2020). In Figure 9 data is available through the HIWE-DB (https://meteo.gr/weather_cases.cfm, https://meteo.gr/weatherEvents.cfm) and ESWD database (https://eswd.eu/). As far as the online version of the HIWE-DB is concerned (Figure 9), the user can search for information about the weather events on https://meteo.gr/weather_cases.cfm based on various criteria: 1. the weather intensity (3-level index) based on the meteorological observations of the stations' network of METEO/National Observatory of Athens (www.meteo.gr), 2. the severity of the socio-economic impacts (3-level index) based on qualitative and quantitative impact data, 3. the year they occurred, and 4. the prefecture they affected. Also, and translated into English, the user can find information about the HIWE-DB events on the dynamic map on https://meteo.gr/weatherEvents.cfm based on various criteria: year, month, specific phenomenon, number of fatalities of the event, number of fatalities in the area that the user zooms in, the weather intensity (3-level index), the impact severity (3-level index).

Acknowledgments

This article is based upon work from COST Action CA19109 "MedCyclones," supported by COST—European Cooperation in Science and Technology (http://www.cost.eu). The authors acknowledge the support of COST Action CA22162—FutureMed: A Transdisciplinary Network to Bridge Climate Science and Impacts on Society (https://futuremedaction.eu/en/), supported by COST—EUROPEAN Cooperation in Science and Technology. JK, GL, and GZ were supported by the EMME-CARE project that has received funding from the European Union's Horizon 2020 Research and Innovation Program, under Grant Agreement No. 856612, as well as matching co-funding by the Government of Cyprus. SD and MMM were supported by the project "FOE-CLIMA Climate change: risk mitigation for sustainable development" funded by the Italian Ministry for Education, University and Research (MIUR). The contribution of AH was partly supported by the Ministry of Science, Innovation, and Technology of Israel (Grant 4749). ILR was partly supported and funded by the European Union's Horizon Europe Programme and project CREXDATA, grant agreement number 101092749. PP was funded by the EU project OCEANIDS, GA No. 101112919. The Mediterranean Centre for Environmental Studies (CEAM) is partly supported by Generalitat Valenciana. The contribution of the first author Samira Khodayar Pardo was supported by the program Generació Talent of Generalitat Valenciana (CIDEGENT/2018/017). The authors sincerely thank the editor, an anonymous reviewer, and Christoph Raible for their insightful comments and suggestions, which contributed to improving this paper.

References

Abanades, J. (2019). Wind energy in the Mediterranean Spanish ARC: The application of gravity based solutions. *Frontiers in Energy Research*, *7*. https://doi.org/10.3389/fenrg.2019.00083

Abis, S., & Demurtas, L. (2023). The geopolitical aspect of food security in the Mediterranean region. In *Med-Dialogues + 2030, FOCUS n. 11*. Retrieved from https://www.ie-med.org/publication/the-geopolitical-aspect-of-fo-od-security-in-the-mediterranean-region/

ACAPS. (2023). Retrieved from https://www.acaps.org/fileadmin/Data_Product/Main_media/20230913_ACAPS_thematic_report_Libya_impact_of_Storm_Daniel_in_eastern_Libya_and_the_collapse_of_dams_in_Derna.pdf

Aghababaeian, H., Ostadtaghizadeh, A., Ardalan, A., Asgary, A., Akbary, M., Yekaninejad, M. S., & Stephens, C. (2021). Global health impacts of dust storms: A systematic review. *Environmental Health Insights*, *15*. https://doi.org/10.1177/11786302211018390

Alpert, P., Neeman, B. U., & Shay-El, Y. (1990). Climatological analysis of Mediterranean cyclones using ECMWF data. *Tellus*, *42*(1), 65–77. https://doi.org/10.1034/j.1600-0870.1990.00007.x

Alpert, P., & Ziv, B. (1989). The Sharav Cyclone: Observations and some theoretical considerations. *Journal of Geophysical Research*, *94*(D15), 18495–18514. https://doi.org/10.1029/JD094iD15p18495

Al Sharjabi, S. J., Al, J. A., Hassan, O. E. H., & Dureab, F. (2024). Understanding the food and nutrition insecurity drivers in some emergency-affected countries in the Eastern Mediterranean region from 2020 to 2024. *Nutrients*, *16*(22), 3853. PMID: 39599639; PMCID: PMC11597532. https://doi.org/10.3390/nu16223853

Amores, A., Marcos, M., Carrió, D. S., & Gómez-Pujol, L. (2020). Coastal impacts of Storm Gloria (January 2020) over the north-western Mediterranean. *Natural Hazards and Earth System Sciences*, *20*(7), 1955–1968. https://doi.org/10.5194/nhess-20-1955-2020

Amponsah, W., Ayral, P. A., Boudevillain, B., Bouvier, C., Braud, I., Brunet, P., et al. (2018). Integrated high-resolution dataset of high-intensity European and Mediterranean flash floods. *Earth System Science Data*, *10*(4), 1783–1794. https://doi.org/10.5194/essd-10-1783-2018

Andrei, S., Antonescu, B., Boldeanu, M., Mărmureanu, L., Marin, C. A., Vasilescu, J., & Ene, D. (2019). An exceptional case of freezing rain in Bucharest (Romania). *Atmosphere*, *10*(11), 673. https://doi.org/10.3390/atmos10110673

Antonescu, B., Schultz, D. M., Holzer, A., & Groenemeijer, P. (2017). Tornadoes in Europe: An underestimated threat. *Bulletin of the American Meteorological Society*, *98*(4), 713–728. https://doi.org/10.1175/BAMS-D-16-0171.1

Antonescu, B., Schultz, D. M., Lomas, F., & Kühn, T. (2016). Tornadoes in Europe: Synthesis of the observational datasets. *Monthly Weather Review*, *144*(7), 2445–2480. https://doi.org/10.1175/MWR-D-15-0298.1

Antunes, L., Silva, S. P., Marques, J., Nunes, B., & Antunes, S. (2017). The effect of extreme cold temperatures on the risk of death in the two major Portuguese cities. *International Journal of Biometeorology*, *61*(1), 127–135. https://doi.org/10.1007/s00484-016-1196-x

Bagaglini, L., Ingrosso, R., & Miglietta, M. M. (2021). Synoptic patterns and mesoscale precursors of Italian tornadoes. *Atmospheric Research*, *253*, 105503. https://doi.org/10.1016/j.atmosres.2021.105503

Bakkensen, L. A. (2017). Mediterranean hurricanes and associated damage estimates. *Journal of Extreme Events*, *4*(2), 1750008. https://doi.org/10.1142/S2345737617500087

Bech, J., Nicolau Pineda, T., Rigo, M., & Aran, M. (2013). Remote sensing analysis of a Mediterranean thundersnow and low-altitude heavy snowfall event. *Atmospheric Research*, *123*, 305–322. https://doi.org/10.1016/j.atmosres.2012.06.021

Berkovic, S., Mendelsohn, O. Y., Ilotoviz, E., & Raveh-Rubin, S. (2021). Self-organizing map classification of the boundary layer profile: A refinement of Eastern Mediterranean winter synoptic regimes. *International Journal of Climatology*, *41*(5), 3317–3338. https://doi.org/10.1002/joc.7021

Berkovich, S., & Raveh-Rubin, S. (2022). Persistent warm and dry extremes over the eastern Mediterranean during winter: The role of North Atlantic blocking and central Mediterranean cyclones. *Quarterly Journal of the Royal Meteorological Society*, *148*(746), 2384–2409. https://doi.org/10.1002/qj.4308

Bernardie, S., Vandromme, R., Thiery, Y., Houet, T., Grémont, M., Masson, F., et al. (2021). Modelling landslide hazards under global changes: The case of a Pyrenean valley. *Natural Hazards and Earth System Sciences*, *21*(1), 147–169. https://doi.org/10.5194/nhess-21-147-2021

Bertotti, L., & Cavaleri, L. (2008). The predictability of the "Voyager" accident. *Natural Hazards and Earth System Sciences*, *8*(3), 533–537. https://doi.org/10.5194/nhess-8-533-2008

Biess, B., Gudmundsson, L., Windisch, M. G., & Seneviratne, S. I. (2024). Future changes in spatially compounding hot, wet or dry events and their implications for the world's breadbasket regions. *Environmental Research Letters*, *19*(6), 064001. https://doi.org/10.1088/1748-9326/acb8b0

Blöschl, G., Hall, J., Viglione, A., Perdigão, R. A. P., Parajka, J., Merz, B., et al. (2019). Changing climate both increases and decreases European river floods. *Nature*, *573*(7772), 108–111. https://doi.org/10.1038/s41586-019-1495-6

Bosher, L., Kim, D., Okubo, T., Chmutina, K., & Jigyasu, R. (2019). Dealing with multiple hazards and threats on cultural heritage sites: An assessment of 80 case studies. *Disaster Prevention and Management: An International Journal*, *29*(1), 109–128. https://doi.org/10.1108/DPM-08-2018-0245

Buzzi, A. (2012). Synoptic-scale variability in the Mediterranean. Predictability in the European and Atlantic regions from days to years. In *ECMWF Seminar Proceedings* (pp. 15–29).

Buzzi, A., Davolio, S., & Fantini, M. (2020). Cyclogenesis in the lee of the Alps: A review of theories. *Bulletin of Atmospheric Science and Technology*, *1*(3–4), 433–457. https://doi.org/10.1007/s42865-020-00021-6

Camera, C. A. S., Bajni, G., Corno, I., Raffa, M., Stevenazzi, S., & Apuani, T. (2021). Introducing intense rainfall and snowmelt variables to implement a process-related non-stationary shallow landslide susceptibility analysis. *Science of the Total Environment*, *786*, 147360. https://doi.org/10.1016/j.scitotenv.2021.147360

Camus, P., Haigh, I. D., Nasr, A. A., Wahl, T., Darby, S. E., & Nicholls, R. J. (2021). Regional analysis of multivariate compound coastal flooding potential around Europe and environs: Sensitivity analysis and spatial patterns. *Natural Hazards and Earth System Sciences*, *21*(7), 2021–2040. https://doi.org/10.5194/nhess-21-2021-2021

Caracciolo, L. & Alessandro, A. (2018). In *Food & migration: Understanding the geopolitical nexus in the Euro-Mediterranean, MacroGeo and Barilla Center for Food and Nutrition*.

Carniel, C. E., Ricchi, A., Ferretti, R., Curci, G., Miglietta, M. M., Reale, M., et al. (2024). A high-resolution climatological study of explosive cyclones in the Mediterranean region: Frequency, intensity and synoptic drivers. *Quarterly Journal of the Royal Meteorological Society*, *150*(765), 5561–5582. https://doi.org/10.1002/qj.4889

Caruana, J., Wood, J., Nocerino, E., Menna, F., Micallef, A., & Gambin, T. (2022). Reconstruction of the collapse of the “Azure Window” natural arch via photogrammetry. *Geomorphology*, *408*, 108250. https://doi.org/10.1016/j.geomorph.2022.108250

Catto, J. L., & Dowdy, A. J. (2021). Understanding compound hazards from a weather system perspective. *Weather and Climate Extremes*, *32*, 100313. https://doi.org/10.1016/j.wace.2021.100313

Cavaleri, L., Bajo, M., Barbariol, F., Bastianini, M., Benetazzo, A., Bertotti, L., et al. (2019). The October 29, 2018 storm in Northern Italy—An exceptional event and its modeling. *Progress in Oceanography*, *178*, 102178. https://doi.org/10.1016/j.pocean.2019.102178

Cavaleri, L., Barbariol, F., Bertotti, L., Besio, G., & Ferrari, F. (2022). The 29 October 2018 storm in Northern Italy: Its multiple actions in the Ligurian Sea. *Progress in Oceanography*, *201*, 102715. https://doi.org/10.1016/j.pocean.2021.102715

Cavaleri, L., Bertotti, L., Torrisi, L., Bitner-Gregersen, E., Serio, M., & Onorato, M. (2012). Rogue waves in crossing seas: The Louis Majesty accident. *Journal of Geophysical Research*, *117*(C11), C00J10. https://doi.org/10.1029/2012JC007923

Chaboureau, J. P., Pantillon, F., Lambert, D., Richard, E., & Claud, C. (2012). Tropical transition of a Mediterranean storm by jet crossing. *The Quarterly Journal of the Royal Meteorological Society*, *138*(664), 596–611. https://doi.org/10.1002/qj.960

Chaumillon, E., Bertin, X., Fortunato, A., Bajo, M., Schneider, J.-L., Dezileau, L., et al. (2017). Storm-induced marine flooding: Lessons from a multidisciplinary approach. *Earth-Science Reviews*, *165*, 151–184. https://doi.org/10.1016/j.earscirev.2016.12.005

Cherif, S., Doblas-Miranda, E., Lionello, P., Borrego, C., Giorgi, F., Iglesias, A., et al. (2020). Drivers of change. In *Climate and environmental change in the Mediterranean Basin—current situation and risks for the future* (pp. 59–128). First Mediterranean Assessment Report. Union for the Mediterranean, Plan Bleu, UNEP/MAP.

Chirici, G., Giannetti, F., Travaglini, D., Nocentini, S., Francini, S., D’Amico, G., et al. (2019). Forest damage inventory after the “Vaia” storm in Italy. *Forest*, *16*(1), 3–9. https://doi.org/10.3832/efor3070-016

Chou, J. S., Chiu, C. K., Huang, I. K., & Chi, K. N. (2013). Failure analysis of wind turbine blade under critical wind loads. *Engineering Failure Analysis*, *27*, 99–118. https://doi.org/10.1016/j.engfailanal.2012.08.002

Chou, J.-S., Ou, Y.-C., Lin, K.-Y., & Wang, Z.-J. (2018). Structural failure simulation of onshore wind turbines impacted by strong winds. *Engineering Structures*, *162*, 257–269. https://doi.org/10.1016/j.engstruct.2018.02.006

Ciapessoni, E., Cirio, D., Pitto, A., Pirovano, G., & Sforna, M. (2020). Modelling the vulnerability of overhead lines against tree contacts for resilience assessment. In *2020 International Conference on Probabilistic Methods Applied to Power Systems (PMAPS)* (pp. 1–6). https://doi.org/10.1109/PMAPS47429.2020.9183607

Conte, M., Giuffrida, A., & Tedesco, S. (1989). The Mediterranean oscillation: Impact on precipitation and hydrology in Italy. In *Conference on Climate and Water* (pp. 121–137).

Cosby, A. G., Lebakula, V., Smith, C. N., Wanik, D. W., Bergene, K., Rose, A. N., et al. (2024). Accelerating growth of human coastal populations at the global and continent levels: 2000–2018. *Scientific Reports*, *14*(1), 22489. https://doi.org/10.1038/s41598-024-73287-x

Couasnon, A., Eilander, D., Muis, S., Veldkamp, T. I. E., Haigh, I. D., Wahl, T., et al. (2020). Measuring compound flood potential from river discharge and storm surge extremes at the global scale. *Natural Hazards and Earth System Sciences*, *20*(2), 489–504. https://doi.org/10.5194/nhess-20-489-2020

Cramer, W., Guiot, J., Fader, M., Garrabou, J., Gattuso, J. P., Iglesias, A., et al. (2018). Climate change and interconnected risks to sustainable development in the Mediterranean. *Nature Climate Change*, *8*(11), 972–980. https://doi.org/10.1038/s41558-018-0299-2

D’Adderio, L. P., Casella, D., Dietrich, S., Sanò, P., & Panegrossi, G. (2022). GPM-CO observations of Medicane Ianos: Comparative analysis of precipitation structure between development and mature phase. *Atmospheric Research*, *273*, 106174. https://doi.org/10.1016/j.atmosres.2022.106174

Davolio, S., Della Fera, S., Laviola, S., Miglietta, M. M., & Levizzani, V. (2020). Heavy precipitation over Italy from the Mediterranean storm “Vaia” in October 2018: Assessing the role of an atmospheric river. *Monthly Weather Review*, *148*(9), 3571–3588. https://doi.org/10.1175/MWR-D-20-0021.1

Dayan, U., Ziv, B., Shoob, T., & Enzel, Y. (2008). Suspended dust over southeastern Mediterranean and its relation to atmospheric circulations. *International Journal of Climatology*, *28*(7), 915–924. https://doi.org/10.1002/joc.1587

De Alfonso, M., Luna, M. Y., Ruiz, M. I., Pérez-Rubio, S., Santos-Muñoz, D., Isabel Ruiz, M., et al. (2021). Storm Gloria: Sea state evolution based on in situ measurements and modeled data and its impact on extreme values. *Frontiers in Marine Science*, *8*. https://doi.org/10.3389/fmars.2021.646873

De Luca, P., Messori, G., Faranda, D., Ward, P. J., & Coumou, D. (2020). Compound warm–dry and cold–wet events over the Mediterranean. *Earth System Dynamics*, *11*(3), 793–805. https://doi.org/10.5194/esd-11-793-2020

de Schrijver, E., Sivaraj, S., Raible, C. C., Franco, O. H., Chen, K., & Vicedo-Cabrera, A. M. (2023). Nationwide projections of heat- and cold-related mortality impacts under various climate change and population development scenarios in Switzerland. *Environmental Research Letters*, *18*(9), 094010. https://doi.org/10.1088/1748-9326/ace7e1

Diakakis, M., Deligiannakis, G., Katsetsiadou, K., Antoniadis, Z., & Melaki, M. (2017). Mapping and classification of direct flood impacts in the complex conditions of an urban environment: The case study of the 2014 flood in Athens, Greece. *Urban Water Journal*, *14*(10), 1065–1074. https://doi.org/10.1080/1573062X.2017.1363247

Diakakis, M., Papagiannaki, K., & Fouskaris, M. (2023). The occurrence of catastrophic multiple-fatality flash floods in the Eastern Mediterranean region. *Water*, *15*(1), 119. https://doi.org/10.3390/w15010119

Donat, M. G., Leckebusch, G. C., Wild, S., & Ulbrich, U. (2011). Future changes in European winter storm losses and extreme wind speeds inferred from GCM and RCM multi-model simulations. *Natural Hazards and Earth System Sciences*, *11*(5), 1351–1370. https://doi.org/10.5194/nhess-11-1351-2011

Dotzek, N., Groenemeijer, P., Feuerstein, B., & Holzer, A. M. (2009). Overview of ESSL's severe convective storms research using the European severe weather database ESWD. *Atmospheric Research*, *93*(1–3), 575–586. https://doi.org/10.1016/j.atmosres.2008.10.020

Drobinski, P., Drobinski, P., Ducrocq, V., Alpert, P., Anagnostou, E., Béranger, K., et al. (2014). HyMeX, a 10-year multidisciplinary program on the Mediterranean water cycle. *Bulletin of the American Meteorological Society*, *95*(7), 1063–1082. https://doi.org/10.1175/BAMS-D-12-00242.1

Drobinski, P., da Silva, N., Bastin, S., Mailler, S., Muller, C., Ahrens, B., et al. (2020). How warmer and drier will the Mediterranean region be at the end of the twenty-first century? *Regional Environmental Change*, *20*(3), 78. https://doi.org/10.1007/s10113-020-01659-w

Ermitao, T., Gouveia, C. M., Bastos, A., & Russo, A. C. (2021). Vegetation productivity losses linked to Mediterranean hot and dry events. *Remote Sensing*, *13*(19), 4010. https://doi.org/10.3390/rs13194010

European Commission (EC). (2021). *Forging a climate-resilient Europe—The new EU strategy on adaptation to climate change* (p. 82). COM.

European Environment Agency (EEA). (2021). Economic losses and fatalities from weather- and climate-related events in Europe (Briefing no. 21/2021). Retrieved from https://www.eea.europa.eu/publications/economic-losses-and-fatalities-from

Evans, J., van Donkelaar, A., Martin, R. V., Burnett, R., Rainham, D. G., Birkett, N. J., & Krewski, D. (2013). Estimates of global mortality attributable to particulate air pollution using satellite imagery. *Environmental Research*, *120*, 33–42. https://doi.org/10.1016/j.envres.2012.08.005

Faccini, F., Luino, F., Paliaga, G., Roccati, A., & Turconi, L. (2021). Flash flood events along the west Mediterranean coasts: Inundations of urbanized areas conditioned by anthropic impacts. *Land*, *10*(6), 620. https://doi.org/10.3390/land10060620

Feng, S., Wu, X., Hao, Z., Hao, Y., Zhang, X., & Hao, F. (2020). A database for characteristics and variations of global compound dry and hot events. *Weather and Climate Extremes*, *30*, 100299. https://doi.org/10.1016/j.wace.2020.100299

Ferrarin, C., Lionello, P., Orlić, M., Raicich, F., & Salvadori, G. (2022). Venice as a paradigm of coastal flooding under multiple compound drivers. *Scientific Reports*, *12*(1), 5754. https://doi.org/10.1038/s41598-022-09652-5

Ferrarin, C., Orlić, M., Bajo, M., Davolio, S., Umgiesser, G., & Lionello, P. (2023). The contribution of a mesoscale cyclone and associated meteotsunami to the exceptional flood in Venice on November 12, 2019. *Quarterly Journal of the Royal Meteorological Society*, *149*(756), 2929–2942. https://doi.org/10.1002/qj.4539

Ferrarin, C., Pantillon, F., Davolio, S., Bajo, M., Miglietta, M. M., Avolio, E., et al. (2023). Assessing the coastal hazard of medicane Ianos through ensemble modelling. *Natural Hazards and Earth System Sciences*, *23*(6), 2273–2287. https://doi.org/10.5194/nhess-23-2273-2023

Flaounas, E., Dafis, S., Davolio, S., Faranda, D., Ferrarin, C., Hartmuth, K., et al. (2024). Dynamics, predictability, impacts, and climate change considerations of the catastrophic Mediterranean Storm Daniel (2023). *EGUsphere*. (preprint). https://doi.org/10.5194/egusphere-2024-2809

Flaounas, E., Davolio, S., Raveh-Rubin, S., Pantillon, F., Miglietta, M. M., Gaertner, M. A., et al. (2022). Mediterranean cyclones: Current knowledge and open questions on dynamics, prediction, climatology and impacts. *Weather and Climate Dynamics*, *3*(1), 173–208. https://doi.org/10.5194/wcd-3-173-2022

Flaounas, E., Kotroni, V., Lagouvardos, K., Gray, S. L., Rysman, J.-F., & Claud, C. (2018). Heavy rainfall in Mediterranean cyclones. Part I: Contribution of deep convection and warm conveyor belt. *Climate Dynamics*, *50*(7–8), 2935–2949. https://doi.org/10.1007/s00382-017-3783-x

Flaounas, E., Kotroni, V., Lagouvardos, K., Kazadzis, S., Gkikas, A., & Hatzianastassiou, N. (2015). Cyclone contribution to dust transport over the Mediterranean region. *Atmospheric Science Letters*, *16*(4), 473–478. https://doi.org/10.1002/asl.584

Flaounas, E., Raveh-Rubin, S., Wernli, H., Drobinski, P., & Bastin, S. (2015). The dynamical structure of intense Mediterranean cyclones. *Climate Dynamics*, *44*(9–10), 2411–2427. https://doi.org/10.1007/s00382-014-2330-2

Fraga, H., Pinto, J. G., Viola, F., & Santos, J. A. (2020). Climate change projections for olive yields in the Mediterranean Basin. *International Journal of Climatology*, *40*(2), 769–781. https://doi.org/10.1002/joc.6237

Frame, T., Harrison, G., Hewson, T., & Roberts, N. (2017). Meteorological risk: Extra-tropical cyclones, tropical cyclones and convective storms. In K. Poljansek, M. Marin Ferrer, T. De Groeve, & I. Clark (Eds.), *Science for disaster risk management 2017: Knowing better and losing less* (pp. 246–256). Publications Office of the European Union.

Galanaki, E., Flaounas, E., Kotroni, V., Lagouvardos, K., & Argiriou, A. (2016). Lightning activity in the Mediterranean: Quantification of cyclones contribution and relation to their intensity. *Atmospheric Science Letters*, *17*(9), 510–516. https://doi.org/10.1002/asl.685

Gardiner, B., Blennow, K., Carnus, J.-M., Fleischer, P., Ingemarson, F., Landmann, G., et al. (2010). Destructive storms in European forests: Past and Forthcoming impacts (No. 07.0307/2009/SI2.540092/ETU/B.1), final report to European Commission—DG environment.

Gardiner, B., Schuck, A., Schelhaas, M.-J., Orazio, C., Blennow, K., & Nicoll, B. (2013). *Living with storm damage to forests: What science can tell us*. European Forest Institute, EFI, Joensuu, Finland. https://doi.org/10.13140/2.1.1730.2400

Gasparrini, A., Guo, Y., Sera, F., Vicedo-Cabrera, A. M., Huber, V., Tong, S., et al. (2017). Projections of temperature-related excess mortality under climate change scenarios. *The Lancet Planetary Health*, *1*(9), e360–e367. https://doi.org/10.1016/S2542-5196(17)30156-0

Giannadaki, D., Pozzer, A., & Lelieveld, J. (2014). Modeled global effects of airborne desert dust on air quality and premature mortality. *Atmospheric Chemistry and Physics*, *14*(2), 957–968. https://doi.org/10.5194/acp-14-957-2014

Gintautas, T., & Sørensen, J. D. (2017). Improved methodology of weather window prediction for offshore operations based on probabilities of operation failure. *Journal of Marine Science and Engineering*, *5*(2), 20. https://doi.org/10.3390/jmse5020020

Giorgi, F., Raffaele, F., & Coppola, E. (2019). The response of precipitation characteristics to global warming from climate projections. *Earth System Dynamics*, *10*(1), 73–89. https://doi.org/10.5194/esd-10-73-2019

Giovannini, L., Davolio, S., Zaramella, M., Zardi, D., & Borga, M. (2021). Multi-model convection-resolving simulations of the October 2018 Vaia storm over northeastern Italy. *Atmospheric Research*, *253*, 105455. https://doi.org/10.1016/j.atmosres.2021.105455

Givon, Y., Keller, D., Jr., Silverman, V., Pennel, R., Drobinski, P., & Raveh-Rubin, S. (2021). Large-scale drivers of the mistral wind: Link to Rossby wave life cycles and seasonal variability. *Weather and Climate Dynamics*, *2*(3), 609–630. https://doi.org/10.5194/wcd-2-609-2021

Goldman, A., Eggen, B., Golding, B., & Murray, V. (2014). The health impacts of windstorms: A systematic literature review. *Public Health*, *128*(1), 3–28. https://doi.org/10.1016/j.puhe.2013.09.022

Gonçalves, A., Correia Marques, M., Loureiro, S., Nieto, R. L. R., & Liberato, M. (2023). Disruption risk analysis of the overhead power lines in Portugal. *Energy*, *263*, 125583. https://doi.org/10.1016/j.energy.2022.125583

González-Alemán, J. J., Pascale, S., Gutierrez-Fernandez, J., Murakami, H., Gaertner, M. A., & Vecchi, G. A. (2019). Potential increase in hazard from Mediterranean hurricane activity with global warming. *Geophysical Research Letters*, *46*(3), 1754–1764. https://doi.org/10.1029/2018GL081253

Görüm, T., & Fidan, S. (2021). Spatiotemporal variations of fatal landslides in Turkey. *Landslides*, *18*(5), 1691–1705. https://doi.org/10.1007/s10346-020-01580-7

Groenemeijer, P., & Kühne, T. (2014). A climatology of tornadoes in Europe: Results from the European severe weather database. *Monthly Weather Review*, *142*(12), 4775–4790. https://doi.org/10.1175/mwr-d-14-00107.1

Guha-Sapir, D., & Below, R., & Hoyois. (2021). P. EM-DAT: The CRED/OFDA international disaster database. Retrieved from www.emdat.be

Haakana, J., Räisänen, O., Karhunen, M., Láng-Ritter, I., & Lassila, J. (2024). Impact of wind speed and soil frost on electricity distribution system reliability. *Heliyon*, 10–24. https://doi.org/10.1016/j.heliyon.2024.e40846

Hadjipanayi, M., Koumparou, I., Philippou, N., Paraskeva, V., Phinikarides, A., Makrides, G., et al. (2016). Prospects of photovoltaics in southern European, Mediterranean and Middle East regions. *Renewable Energy*, *92*, 58–74. https://doi.org/10.1016/j.renene.2016.01.096

Hannachi, A., Awad, A., & Ammar, K. (2011). Climatology and classification of Spring Saharan cyclone tracks. *Climate Dynamics*, *37*(3–4), 473–491. https://doi.org/10.1007/s00382-010-0941-9

Hanson, S., & Nicholls, R. J. (2012). Extreme flood events and port cities through the twenty-first century. In R. Asariotis & H. Benamara (Eds.), *Maritime transport and the climate change challenge. (Earthscan Climate)* (pp. 243–265). Earthscan from Routledge.

Heino, M., Kinnunen, P., Anderson, W., Ray, D. K., Puma, M. J., Varis, O., et al. (2023). Increased probability of hot and dry weather extremes during the growing season threatens global crop yields. *Scientific Reports*, *13*(1), 3583. https://doi.org/10.1038/s41598-023-29378-2

Hénin, R., Ramos, A. M., Pinto, J. G., & Liberato, M. L. R. (2021). A ranking of concurrent precipitation and wind events for the Iberian Peninsula. *International Journal of Climatology*, *41*(2), 1421–1437. https://doi.org/10.1002/joc.6829

Hewson, T., Ashoor, A., Boussetta, S., Emanuel, K., Lagouvardos, K., Lavers, D., et al. (2024). Medicane Daniel: An extraordinary cyclone with devastating impacts. *ECMWF Newsletters*, *179*, 33–47.

Hidalgo, M., El-Haweet, A. E., Tsikliras, A. C., Tirasin, E. M., Fortibuoni, T., Ronchi, F., et al. (2022). Risks and adaptation options for the Mediterranean fisheries in the face of multiple climate change drivers and impacts. *ICES Journal of Marine Science*, *79*(9), 2473–2488. https://doi.org/10.1093/icesjms/fsac185

Hillier, J. K., & Dixon, R. S. (2020). Seasonal impact-based mapping of compound hazards. *Environmental Research Letters*, *15*(11), 114013. https://doi.org/10.1088/1748-9326/abbc3d

Hochman, A., Alpert, P., Harpaz, T., Saaroni, H., & Messori, G. (2019). A new dynamical systems perspective on atmospheric predictability: Eastern Mediterranean weather regimes as a case study. *Science Advances*, *5*(6). https://doi.org/10.1126/sciadv.aau0936

Hochman, A., Alpert, P., Kunin, P., Rostkier-Edelstein, D., Harpaz, T., Saaroni, H., & Messori, G. (2020). The dynamics of cyclones in the twentyfirst century: The Eastern Mediterranean as an example. *Climate Dynamics*, *54*(1–2), 561–574. https://doi.org/10.1007/s00382-019-05017-3

Hochman, A., Harpaz, T., Saaroni, H., & Alpert, P. (2018). Synoptic classification in 21st century CMIP5 predictions over the eastern Mediterranean with focus on cyclones. *International Journal of Climatology*, *38*(3), 1476–1483. https://doi.org/10.1002/joc.5260

Hochman, A., Marra, F., Messori, G., Pinto, J. G., Raveh-Rubin, S., Yosef, Y., & Zittis, G. (2022). Extreme weather and societal impacts in the eastern Mediterranean. *Earth System Dynamics*, *13*(2), 749–777. https://doi.org/10.5194/esd-13-749-2022

Hochman, A., Scher, S., Quinting, J., Pinto, J. G., & Messori, G. (2021). A new view of heat wave dynamics and predictability over the eastern Mediterranean. *Earth System Dynamics*, *12*(1), 133–149. https://doi.org/10.5194/esd-12-133-2021

Hochman, A., Scher, S., Quinting, J., Pinto, J. G., & Messori, G. (2022). Dynamics and predictability of cold spells over the Eastern Mediterranean. *Climate Dynamics*, *58*(7–8), 2047–2064. https://doi.org/10.1007/s00382-020-05465-2

Hofstätter, M., & Chimani, B. (2012). Van Bebber's cyclone tracks at 700 hPa in the Eastern Alps for 1961–2002 and their comparison to circulation type classifications. *Meteorologische Zeitschrift*, *21*(5), 459–473. https://doi.org/10.1127/0941-2948/2012/0473

Hoskins, B. J., & Hodges, K. I. (2002). New perspectives on the Northern Hemisphere winter storm tracks. *Journal of the Atmospheric Sciences*, *59*(6). https://doi.org/10.1175/1520-0469(2002)059<1041:NPOTNH>2.0.CO;2

Hossain, A., EL Sabagh, A., Barutcular, C., Bhatt, R., Çiğ, F., Seydoşoğlu, S., et al. (2020). Sustainable crop production to ensuring food security under climate change: A Mediterranean perspective. *Australian Journal of Crop Science*, *14*(3), 439–446. https://doi.org/10.21475/ajcs.20.14.03.p1976

Iglesias, A., Mougou, R., Moneo, M., & Quiroga, S. (2011). Towards adaptation of agriculture to climate change in the Mediterranean. *Regional Environmental Change*, *11*, 159–166. https://doi.org/10.1007/s10113-010-0187-4

IPCC. (2021). In V. Masson-Delmotte, P. Zhai, A. Pirani, S. L. Connors, C. Péan, et al. (Eds.), *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press. https://doi.org/10.1017/9781009157896

Izaguirre, C., Losada, I. J., Camus, P., Vigh, J. L., & Stenek, V. (2021). Climate change risk to global port operations. *Nature Climate Change*, *11*(1), 14–20. https://doi.org/10.1038/s41558-020-00937-z

Jacob, D., Kotova, L., Teichmann, C., Sobolowski, S. P., Vautard, R., Donnelly, C., et al. (2018). Climate impacts in Europe under +1.5°C global warming. *Earth's Future*, *6*(2), 264–285. https://doi.org/10.1002/2017EF000710

Jansa, A., Alpert, P., Arbogast, P., Buzzi, A., Ivancan-Picek, B., Kotroni, V., et al. (2014). MEDEX: A general overview. *Natural Hazards and Earth System Sciences*, *14*(8), 1965–1984. https://doi.org/10.5194/nhess-14-1965-2014

Jansa, A., Genoves, A., Picornell, M. A., Campins, J., Riosalido, R., & Carretero, O. (2001). Western Mediterranean cyclones and heavy rain. Part 2: Statistical approach. *Meteorological Applications*, *8*(1), 43–56. https://doi.org/10.1017/S1350482701001049

Jasiūnas, J., Heikkinen, T., Lund, P. D., & Láng-Ritter, I. (2023). Resilience of electric grid to extreme wind: Considering local details at national scale. *Reliability Engineering & System Safety*, *232*, 109070. https://doi.org/10.1016/j.ress.2022.109070

Kallos, G., Astitha, M., Katsafados, P., & Spyrou, C. (2007). Long-range transport of anthropogenically and naturally produced particulate matter in the Mediterranean and North Atlantic: Current state of knowledge. *Journal of Applied Meteorology and Climatology*, *46*(8), 1230–1251. https://doi.org/10.1175/JAM2530.1

Karathanasi, F. E., Soukissian, T. H., & Hayes, D. R. (2022). Wave analysis for offshore aquaculture projects: A case study for the Eastern Mediterranean Sea. *Climate*, *10*(1), 2. https://doi.org/10.3390/cli10010002

Khodayar, S., Davolio, S., Di Girolamo, P., Lebeaupin Brossier, C., Flaounas, E., Fourrie, N., et al. (2021). Overview towards improved understanding of the mechanisms leading to heavy precipitation in the western Mediterranean: Lessons learned from HyMeX. *Atmospheric Chemistry and Physics*, *21*(22), 17051–17078. https://doi.org/10.5194/acp-21-17051-2021

Khodayar, S., Kalthoff, N., & Kottmeier, C. (2018). Atmospheric conditions associated with heavy precipitation events in comparison to seasonal means in the western Mediterranean region. *Climate Dynamics*, *51*(3), 951–967. https://doi.org/10.1007/s00382-016-3058-y

Khodayar, S., & Paredes-Fortuny, L. (2024). Uneven evolution of regional European summer heatwaves under climate change. *Weather and Climate Extremes*, *43*, 100648. ISSN 2212-0947. https://doi.org/10.1016/j.wace.2024.100648

Khodayar, S., Pastor, F., Valiente, J. A., Benetó, P., & Ehmele, F. (2022). What causes a heavy precipitation period to become extreme? The exceptional October of 2018 in the Western Mediterranean. *Weather and Climate Extremes*, *38*, 100493. https://doi.org/10.1016/j.wace.2022.100493

Klingmüller, K., Pozzer, A., Metzger, S., Stenchikov, G. L., & Lelieveld, J. (2016). Aerosol optical depth trend over the Middle East. *Atmospheric Chemistry and Physics*, *16*(8), 5063–5073. https://doi.org/10.5194/acp-16-5063-2016

Koseki, S., Mooney, P. A., Cabos, W., Angel Gaertner, M., De La Vara, A., & Jesus Gonzalez-Aleman, J. (2021). Modelling a tropical-like cyclone in the Mediterranean Sea under present and warmer climate. *Natural Hazards and Earth System Sciences*, *21*(1), 53–71. https://doi.org/10.5194/nhess-21-53-2021

Kostianoy, A. G., & Carpenter, A. (2019). Oil and gas exploration and production in the Mediterranean Sea. In A. Carpenter & A. G. Kostianoy (Eds.), *Oil pollution in the Mediterranean Sea: Part I. The international context*, *The handbook of environmental Chemistry* (Vol. 83, pp. 53–77). Springer. https://doi.org/10.1007/698_2018_373

Kouroutzoglou, J., Samos, I., Flocas, H. A., Hatzaki, M., Lamaris, C., Mamara, A., & Emmannouil, A. (2021). Analysis of the transition of an explosive cyclone to a Mediterranean tropical-like cyclone. *Atmosphere*, *12*(11), 1438. https://doi.org/10.3390/atmos12111438

Kyprianou, I., Serghides, D. K., Varo, A., Gouveia, J. P., Kopeva, D., & Murauskaite, L. (2019). Energy poverty policies and measures in 5 EU countries: A comparative study. *Energy and Buildings*, *196*, 46–60. https://doi.org/10.1016/j.enbuild.2019.05.003

Lagouvardos, K., Karagiannidis, A., Dafis, S., Kalimeris, A., & Kotroni, V. (2022). Ianos-A hurricane in the Mediterranean. *Bulletin of the American Meteorological Society*, *103*(6), 1–31. https://doi.org/10.1175/BAMS-D-20-0274.1

Lagouvardos, K., Kotroni, V., Bezes, A., Koletsis, I., Kopania, T., Lykoudis, S., et al. (2017). The automatic weather stations network of the National Observatory of Athens: Operation and database. *Geoscience Data Journal*, *4*(1), 4–16. https://doi.org/10.1002/gdj3.44

Láng-Ritter, I., Laurila, T. K., Mäkelä, A., Gregow, H., & Sinclair, V. A. (2024). Classifying extratropical cyclones and their impact on Finland's electricity grid: Insights from 92 damaging windstorms. *EGUsphere*. (preprint). https://doi.org/10.5194/egusphere-2024-3019

Laviola, S., Monte, G., Cattani, E., & Levizzani, V. (2022). Hail climatology in the Mediterranean basin using the GPM constellation (1999–2021). *Remote Sensing*, *14*(17), 4320. https://doi.org/10.3390/rs14174320

Lelieveld, J., Evans, J. S., Fnais, M., Giannadaki, D., & Pozzer, A. (2015). The contribution of outdoor air pollution sources to premature mortality on a global scale. *Nature*, *525*(7569), 367–371. PMID: 26381985. https://doi.org/10.1038/nature15371

Lemus-Canovas, M. (2022). Changes in compound monthly precipitation and temperature extremes and their relationship with teleconnection patterns in the Mediterranean. *Journal of Hydrology*, *608*, 127580. https://doi.org/10.1016/j.jhydrol.2022.127580

Li, J., Gao, F., Wang, L., Ren, Y., Liu, C., Yang, A., et al. (2022). Collapse mechanism of transmission tower subjected to strong wind load and dynamic response of tower-line system. *Energies*, *15*(11), 3925. https://doi.org/10.3390/en15113925

Linares, C., Díaz, J., Negev, M., Martínez, G. S., Debono, R., & Paz, S. (2020). Impacts of climate change on the public health of the Mediterranean Basin population—Current situation, projections, preparedness and adaptation. *Environmental Research*, *182*, 109107. https://doi.org/10.1016/j.envres.2019.109107

Lionello, P., Bhend, J., Buzzi, A., Della-Marta, P. M., Krichak, S. O., Jansa, A., et al. (2006). Cyclones in the Mediterranean region: Climatology and effects on the environment. In P. Lionello, P. Malanotte-Rizzoli, & R. Boscolo *Mediterranean climate variability, developments in Earth and environmental sciences* (Eds.) (Vol. 4, pp. 325–372). Elsevier. https://doi.org/10.1016/S1571-9197(06)80009-1

Lionello, P., Cavaleri, L., Nissen, K. M., Pino, C., Raicich, F., & Ulbrich, U. (2012). Severe marine storms in the Northern Adriatic: Characteristics and trends. *Physics and Chemistry of the Earth*, *40–41*, 93–105. https://doi.org/10.1016/j.pce.2010.10.002

Lionello, P., Conte, D., & Reale, M. (2019). The effect of cyclones crossing the Mediterranean region on sea level anomalies on the Mediterranean Sea coast. *Natural Hazards and Earth System Sciences*, *19*(7), 1541–1564. https://doi.org/10.5194/nhess-19-1541-2019

Lionello, P., Nicholls, R. J., Umgiesser, G., & Zanchettin, D. (2021). Venice flooding and sea level: Past evolution, present issues, and future projections (introduction to the special issue). *Natural Hazards and Earth System Sciences*, *21*(8), 2633–2641. https://doi.org/10.5194/nhess-21-2633-2021

Lionello, P., Trigo, I. F., Gil, V., Liberato, M. L. R., Nissen, K. M., Pinto, J. G., et al. (2016). Objective climatology of cyclones in the Mediterranean region: A consensus view among methods with different system identification and tracking criteria. *Tellus A: Dynamic Meteorology and Oceanography*, *68*(1), 29391. https://doi.org/10.3402/tellusa.v68.29391

Liu, S., Ji, X., & Zhang, X. (2022). Effects of soil properties and tree species on root–soil anchorage characteristics. *Sustainability*, *14*(13), 7770. https://doi.org/10.3390/su14137770

Llasat, M. C. (2021). Floods evolution in the Mediterranean region in a context of climate and environmental change. *Cuadernos de Investigación Geográfica*, *47*(1), 13–32. https://doi.org/10.18172/cig.4897

Llasat, M. C., Caumont, O., Flores, I., Garrote, L., Gilabert, J., Llasat-Botija, M., et al. (2014). *The November 2011 flood event in Catalonia: Analysis using the DRIHM infrastructure (Report)*. University of Calabria.

Llasat, M. C., Llasat-Botija, M., Petrucci, O., Pasqua, A. A., Rosselló, J., Vinet, F., & Boissier, L. (2013). Towards a database on societal impact of Mediterranean floods within the framework of the HYMEX project. *Natural Hazards and Earth System Sciences*, *13*(5), 1337–1350. https://doi.org/10.5194/nhess-13-1337-2013

Llasat, M. C., Llasat-Botija, M., Prat, M. A., Porcú, F., Price, C., Mugnai, A., et al. (2010). High-impact floods and flash floods in Mediterranean countries: The FLASH preliminary database. *Advances in Geosciences*, *23*, 47–55. https://doi.org/10.5194/adgeo-23-47-2010

Llasat, M. C., Marcos, R., Llasat-Botija, M., Gilabert, J., Turco, M., & Quintana-Seguí, P. (2014). Flash flood evolution in North-Western Mediterranean. *Atmospheric Research*, *149*, 230–243. https://doi.org/10.1016/j.atmosres.2014.05.024

López-Bueno, J. A., Navas-Martín, M. Á., Díaz, J., Mirón, I. J., Luna, M. Y., Sánchez-Martínez, G., et al. (2021). The effect of cold waves on mortality in urban and rural areas of Madrid. *Environmental Sciences Europe*, *33*(1), 72. https://doi.org/10.1186/s12302-021-00512-z

Ludwig, P., & Hochman, A. (2022). Last glacial maximum hydro-climate and cyclone characteristics in the Levant: A regional modelling perspective. *Environmental Research Letters*, *17*(1), 014053. https://doi.org/10.1088/1748-9326/ac46ea

Marcos, M., Tsimplis, M., & Shaw, A. (2009). Sea level extremes in southern Europe. *Journal of Geophysical Research*, *114*(C1), C01007. https://doi.org/10.1029/2008JC004912

Mariani, M., Holz, A., Veblen, T. T., Williamson, G., Fletcher, M. S., & Bowman, D. M. J. S. (2018). Climate change amplifications of climate-fire teleconnections in the Southern Hemisphere. *Geophysical Research Letters*, *45*(10), 5071–5081. https://doi.org/10.1029/2018GL078294

Markosek, J. (2014). Severe freezing rain in Slovenia. In *European Forecaster newsletter series* (pp. 38–42). The Working Group on Cooperation between European Forecasters (WGCEF). Retrieved from http://www.euroforecaster.org/newsletter20/meteosi.pdf

Marra, F., Armon, M., & Morin, E. (2022). Coastal and orographic effects on extreme precipitation revealed by weather radar observations. *Hydrology and Earth System Sciences*, *26*(5), 1439–1458. https://doi.org/10.5194/hess-26-1439-2022

Mathbout, S., Lopez-Bustins, J. A., Royé, D., Martin-Vide, J., Bech, J., & Rodrigo, F. S. (2018). Observed changes in daily precipitation extremes at annual timescale over the eastern Mediterranean during 1961–2012. *Pure and Applied Geophysics*, *175*(11), 3875–3890. https://doi.org/10.1007/s00024-017-1695-7

Mavroulis, S., Mavrouli, M., Lekkas, E., & Tsakris, A. (2024). Impact of the September 2023 storm Daniel and subsequent flooding in Thessaly (Greece) on the natural and built environment and on infectious disease emergence. *Environments*, *11*, 163. https://doi.org/10.3390/environments11080163

MedECC. (2020). Climate and environmental change in the Mediterranean Basin—Current situation and risks for the future. In W. Cramer, J. Guiot, & K. Marini (Eds.), *First Mediterranean assessment report*, *Union for the Mediterranean, Plan Bleu* (p. 632). UNEP/MAP.

Meloni, D., di Sarra, A., Monteleone, F., Pace, G., Piacentino, S., & Sferlazzo, D. M. (2008). Seasonal transport patterns of intense Saharan dust events at the Mediterranean island of Lampedusa. *Atmospheric Research*, *88*(2), 134–148. https://doi.org/10.1016/j.atmosres.2007.10.007

Mentzafou, A., & Dimitriou, E. (2022). Hydrological modeling for flood adaptation under climate change: The case of the ancient messene archaeological site in Greece. *Hydrology*, *9*(2), 19. https://doi.org/10.3390/hydrology9020019

Messmer, M., Gomez-Navarro, J. J., & Raible, C. C. (2015). Climatology of Vb-cyclones, physical mechanisms and their impact on extreme precipitation over Central Europe. *Earth System Dynamics*, *6*(2), 541–553. https://doi.org/10.5194/esd-6-541-2015

Messmer, M., Gomez-Navarro, J. J., & Raible, C. C. (2017). The impact of Vb-cyclones to ocean temperature and soil moisture changes in sensitivity experiments with WRF. *Earth System Dynamics*, *8*(3), 477–493. https://doi.org/10.5194/esd-8-477-2017

Messmer, M., Gomez-Navarro, J. J., & Raible, C. C. (2020). The impact of climate change on the climatology of Vb-cyclones. *Tellus*, *72*, 1–18. https://doi.org/10.1080/16000870.2020.1724021

Messmer, M., & Simmonds, I. (2021). Global analysis of cyclone-induced compound precipitation and wind extreme events. *Weather and Climate Extremes*, *32*, 100324. https://doi.org/10.1016/j.wace.2021.100324

Miglietta, M. M., Buscemi, F., Dafis, S., Papa, A., Tiesi, A., Conte, D., et al. (2023). A high-impact meso-beta vortex in the Adriatic Sea. *The Quarterly Journal of the Royal Meteorological Society*, *149*(751), 637–656. https://doi.org/10.1002/qj.4432

Miglietta, M. M., & Rotunno, R. (2019). Development mechanisms for Mediterranean tropical-like cyclones (Medicanes). *The Quarterly Journal of the Royal Meteorological Society*, *145*(721), 1444–1460. https://doi.org/10.1002/qj.3503

Movahednia, M., Kargarian, A., Ozdemir, C. E., & Hagen, S. C. (2022). Power grid resilience enhancement via protecting electrical substations against flood hazards: A stochastic framework. *IEEE Transactions on Industrial Informatics*, *18*(3), 2132–2143. https://doi.org/10.1109/TII.2021.3100079

Mrabet, R., Savé, R., Toreti, A., Caiola, N., Chentouf, M., Llasat, M. C., et al. (2020). Food. In W. Cramer, J. Guiot, & K. Marini (Eds.), *Climate and environmental change in the Mediterranean Basin—Current situation and risks for the future*, *First Mediterranean assessment report* (pp. 237–264). Union for the Mediterranean, Plan Bleu. UNEP/MAP.

Mulchandani, R., Armstrong, B., Beck, C. R., Waite, T. D., Amlôt, R., Kovats, S., et al. (2020). The English National Cohort Study of Flooding & Health: Psychological morbidity at three years of follow up. *BMC Public Health*, *20*, 1–7. https://doi.org/10.1186/s12889-020-8424-3

Nastos, P. T., Dalezios, N. R., Faraslis, I. N., Mitrakopoulos, K., Blanta, A., Spiliotopoulos, M., et al. (2021). Risk management framework of environmental hazards and extremes in Mediterranean ecosystems. *Natural Hazards and Earth System Sciences*, *21*(6), 1–32. https://doi.org/10.5194/nhess-21-1935-2021

Nicu, I. C. (2017). Natural hazards-a threat for immovable cultural heritage. A review. *International Journal of Conservation Science*, *8*(3).

Nissen, K. M., Leckebusch, G. C., Pinto, J. G., & Ulbrich, U. (2014). Mediterranean cyclones and windstorms in a changing climate. *Regional Environmental Change*, *14*(5), 1873–1890. https://doi.org/10.1007/s10113-012-0400-8

Orr, S. A., Young, M., Stelfox, D., Curran, J., & Viles, H. (2018). Wind-driven rain and future risk to built heritage in the United Kingdom: Novel metrics for characterising rain spells. *Science of the Total Environment*, *640–641*, 1098–1111. https://doi.org/10.1016/j.scitotenv.2018.05.354

Owen, L. E., Catto, J. L., Stephenson, D. B., & Dunstone, N. J. (2021). Compound precipitation and wind extremes over Europe and their relationship to extratropical cyclones. *Weather and Climate Extremes*, *33*, 100342. https://doi.org/10.1016/j.wace.2021.100342

Pantillon, F., Davolio, S., Avolio, E., Calvo-Sancho, C., Carrio, D. S., Dafis, S., et al. (2024). The crucial representation of deep convection for the cyclogenesis of Medicane Ianos. *Weather and Climate Dynamics*, *5*(3), 1187–1205. https://doi.org/10.5194/wcd-5-1187-2024

Papadaskalopoulou, C., Moriondo, M., Lemesios, I., Karali, A., Konsta, A., Dibari, C., et al. (2020). Assessment of total climate change impacts on the agricultural sector of Cyprus. *Atmosphere*, *11*(6), 608. https://doi.org/10.3390/atmos11060608

Papagiannaki, K., Lagouvardos, K., & Kotroni, V. (2013). A database of high-impact weather events in Greece: A descriptive impact analysis for the period 2001–2011. *Natural Hazards and Earth System Sciences*, *13*(3), 727–736. https://doi.org/10.5194/nhess-13-727-2013

Papagiannaki, K., Petrucci, O., Diakakis, M., Kotroni, V., Aceto, L., Bianchi, C., et al. (2022). Developing a large-scale dataset of flood fatalities for territories in the Euro-Mediterranean region, FFEM-DB. *Scientific Data*, *9*(1), 166. https://doi.org/10.1038/s41597-022-01273-x

Paredes-Fortuny, L., & Khodayar, S. (2023). Understanding the Magnification of Heatwaves over Spain: Relevant changes in the most extreme events. *Weather and Climate Extremes*, *42*, 100631. https://doi.org/10.1016/j.wace.2023.100631

Pastor, F., Valiente, J. A., & Khodayar, S. (2020). A warming Mediterranean: 38 years of increasing sea surface temperature. *Remote Sens-Basel*, *12*(17), 2687. [2020ART26]. https://doi.org/10.3390/rs12172687

Patlakas, P., Chaniotis, I., Hatzaki, M., Kouroutzoglou, J., & Flocas, H. A. (2024). The eastern Mediterranean extreme snowfall of January 2022: Synoptic analysis and impact of sea-surface temperature. *Weather*, *79*(1), 25–33. https://doi.org/10.1002/wea.4397

Patlakas, P., Stathopoulos, C., Tsalis, C., & Kallos, G. (2021). Wind and wave extremes associated with tropical-like cyclones in the Mediterranean basin. *International Journal of Climatology*, *41*, E1623–E1644. https://doi.org/10.1002/joc.6795

Petrucci, O., Aceto, L., Bianchi, C., Bigot, V., Brázdil, R., Pereira, S., et al. (2019). Flood fatalities in Europe, 1980–2018: Variability, features, and lessons to learn. *Water*, *11*(8), 1682. https://doi.org/10.3390/w11081682

Petrucci, O., Aceto, L., Bianchi, C. C., Brázdil, R., Diakakis, M., Inbar, M., et al. (2022). FFEM-DB “database of flood fatalities from the Euro-Mediterranean region” (Version 3) [Dataset]. *4TU.ResearchData*. https://doi.org/10.4121/14754999.V3

Petterssen, S. (1956). *Weather analysis and forecasting* (Vol. 1). McGraw-Hill.

Portal, A., Raveh-Rubin, S., Catto, J. L., Givon, Y., & Martius, O. (2024). Linking compound weather extremes to Mediterranean cyclones, fronts, and airstreams. *Weather and Climate Dynamics*, *5*(3), 1043–1060. https://doi.org/10.5194/wcd-5-1043-2024

Portmann, R., González-Alemán, J. J., Sprenger, M., & Wernli, H. (2020). How an uncertain short-wave perturbation on the North Atlantic wave guide affects the forecast of an intense Mediterranean cyclone (Medicane Zorbas). *Weather and Climate Dynamics*, *1*(2), 597–615. https://doi.org/10.5194/wcd-1-597-2020

Pothapakula, P. K., Hoff, A., Obermann-Hellhund, A., Keber, T., & Ahrens, B. (2022a). Vb-cyclones and associated North-Western Mediterranean Sea state in regional coupled climate simulations: Evaluation and projection. *Earth System Dynamics*. (preprint). https://doi.org/10.5194/esd-2022-24

Pothapakula, P. K., Hoff, A., Obermann-Hellhund, A., Keber, T., & Ahrens, B. (2022b). Vb-cyclones and associated North-Western Mediterranean Sea state in regional coupled climate simulations: Evaluation and projection. *Earth System Dynamics*. https://doi.org/10.5194/esd-2022-24

Prahl, B., Boettle, M., Costa, L., Kropp, J. P., & Rybski, D. (2018). Damage and protection cost curves for coastal floods within the 600 largest European cities. *Scientific Data*, *5*(1), 180034. https://doi.org/10.1038/sdata.2018.34

Priestley, M. D. K., & Catto, J. L. (2022). Future changes in the extratropical storm tracks and cyclone intensity, wind speed, and structure. *Weather and Climate Dynamics*. https://doi.org/10.5194/wcd-2021-75

PVEL. (2021). *From random to repeatable: Inside the hail stress sequence for PVEL's PV module product qualification program*. PVEL, LLC. Retrieved from https://www.pvel.com/wp-content/uploads/PVEL_White-Paper_Hail-Stress-Sequence-for-PV-Modules.pdf

Raible, C. C., Messmer, M., Lehner, F., Stocker, T. F., & Blender, R. (2018). Extratropical cyclone statistics during the last millennium and the 21st century. *Climate of the Past*, *14*(10), 1499–1514. https://doi.org/10.5194/cp-14-1499-2018

Raible, C. C., Saaroni, H., Ziv, B., & Wild, M. (2010). Winter cyclonic activity over the Mediterranean Basin under future climate based on the ECHAM5 GCM. *Climate Dynamics*, *35*(2–3), 473–488. https://doi.org/10.1007/s00382-009-0678-5

Rantanen, M., Särkkä, J., Räihä, J., Kämäräinen, M., & Jylhä, K. (2021). Synthetically generated low-pressure systems to support studies of sea level extremes. In *EMS Annual Meeting 2021* (p. EMS2021132). https://doi.org/10.5194/ems2021-132

Raveh-Rubin, S., & Flaounas, E. (2017). A dynamical link between deep Atlantic extratropical cyclones and intense Mediterranean cyclones. *Atmospheric Science Letters*, *18*(5), 215–221. https://doi.org/10.1002/asl.745

Raveh-Rubin, S., & Wernli, H. (2015). Large-scale wind and precipitation extremes in the Mediterranean: A climatological analysis for 1979–2012. *The Quarterly Journal of the Royal Meteorological Society*, *141*(691), 2404–2417. https://doi.org/10.1002/qj.2531

Raveh-Rubin, S., & Wernli, H. (2016). Large-scale wind and precipitation extremes in the Mediterranean: Dynamical aspects of five selected cyclone events. *The Quarterly Journal of the Royal Meteorological Society*, *142*(701), 3097–3114. https://doi.org/10.1002/qj.2891

Reale, M., Cabos, W., Cavicchia, L., Conte, D., Coppola, E., Flaounas, E., et al. (2022). Future projections of Mediterranean cyclone characteristics using the Med-CORDEX ensemble of coupled regional climate system models. *Climate Dynamics*, *58*(9–10), 2501–2524. https://doi.org/10.1007/s00382-021-06018-x

Reimann, L., Vafeidis, A. T., Brown, S., Hinkel, J., & Tol, R. S. J. (2018). Mediterranean UNESCO World Heritage at risk from coastal flooding and erosion due to sea-level rise. *Nature Communications*, *9*(1), 4161. https://doi.org/10.1038/s41467-018-06645-9

Ridder, N. N., Pitman, A. J., Westra, S., Ukkola, A., Hong, X. D., Bador, M., et al. (2020). Global hotspots for the occurrence of compound events. *Nature Communications*, *11*(1), 5956. https://doi.org/10.1038/s41467-020-19639-3

Ridder, N. N., Ukkola, A. M., Pitman, A. J., & Perkins-Kirkpatrick, S. E. (2022). Increased occurrence of high impact compound events under climate change. *Npj Climate and Atmospheric Science*, *5*(1), 3. https://doi.org/10.1038/s41612-021-00224-4

Rizza, U., Barnaba, F., Miglietta, M. M., Mangia, C., Di Liberto, L., Dionisi, D., et al. (2017). WRF-Chem model simulations of a dust outbreak over the central Mediterranean and comparison with multi-sensor desert dust observations. *Atmospheric Chemistry and Physics*, *17*(1), 93–115. https://doi.org/10.5194/acp-17-93-2017

Rodwell, M. J., Magnusson, L., Bauer, P., Bechtold, P., Bonavita, M., Cardinali, C., et al. (2013). Characteristics of occasional poor medium-range weather forecasts for Europe. *Bulletin America Meteorology Social*, *94*(9), 1393–1405. https://doi.org/10.1175/BAMS-D-12-00099.1

Rosa, R., Marques, A., & Nunes, M. L. (2012). Impact of climate change in Mediterranean aquaculture. *Reviews in Aquaculture*, *4*(3), 163–177. https://doi.org/10.1111/j.1753-5131.2012.01071.x

Rousseau-Rizzi, R., Raveh-Rubin, S., Catto, J. L., Portal, A., Givon, Y., & Martius, O. (2024). A storm-relative climatology of compound hazards in Mediterranean cyclones. *Weather and Climate Dynamics*, *5*(3), 1079–1101. https://doi.org/10.5194/wcd-5-1079-2024

Ryley, T., Baumeister, S., & Coulter, L. (2020). Climate change influences on aviation: A literature review. *Transport Policy*, *92*, 55–64. https://doi.org/10.1016/j.tranpol.2020.04.010

Sánchez-Arcilla, A., Sierra, J. P., Brown, S., Casas-Prat, M., Nicholls, R. J., Lionello, P., & Conte, D. (2016). A review of potential physical impacts on harbours in the Mediterranean Sea under climate change. *Regional Environmental Change*, *16*(8), 2471–2484. https://doi.org/10.1007/s10113-016-0972-9

Sánchez-Muñoz, D., Domínguez-García, J. L., Martínez-Gomariz, E., Russo, B., Stevens, J., & Pardo, M. (2020). Electrical grid risk assessment against flooding in Barcelona and Bristol Cities. *Sustainability*, *12*(4), 1527. https://doi.org/10.3390/su12041527

Santillán, D., Garrote, L., Iglesias, A., & Sotes, V. (2020). Climate change risks and adaptation: New indicators for Mediterranean viticulture. *Mitigation and Adaptation Strategies for Global Change*, *25*(5), 881–899. https://doi.org/10.1007/s11027-019-09899-w

Sanuy, M., Rigo, T., Jiménez, J. A., & Llasat, M. C. (2021). Classifying compound coastal storm and heavy rainfall events in the north-western Spanish Mediterranean. *Hydrology and Earth System Sciences*, *25*(6), 3759–3781. https://doi.org/10.5194/hess-25-3759-2021

Sardou, M., Maouche, S., Sabeur, B., & Missoum, H. (2018). The November 26 and 27, 1927 devastating flood event (NW Algeria): Characterization and reconstruction using historical data. *Arabian Journal of Geosciences*, *11*(10), 229. https://doi.org/10.1007/s12517-018-3590-7

Schepanski, K., & Knippertz, P. (2011). Soudano-Saharan depressions and their importance for precipitation and dust: A new perspective on a classical synoptic concept. *The Quarterly Journal of the Royal Meteorological Society*, *137*(659), 1431–1445. https://doi.org/10.1002/qj.850

Schlumberger, J., Ferrarin, C., Jonkman, S. N., Diaz Loaiza, A., Antonini, A., & Fatorić, S. (2022). Developing a framework for the assessment of current and future flood risk in Venice, Italy. *Natural Hazards and Earth System Sciences*, *22*(7), 2381–2400. https://doi.org/10.5194/nhess-22-2381-2022

Scicchitano, G., Scardino, G., Monaco, C., Piscitelli, A., Milella, M., De Giosa, F., & Mastronuzzi, G. (2021). Comparing impact effects of common storms and Medicanes along the coast of south-eastern Sicily. *Marine Geology*, *439*, 106556. https://doi.org/10.1016/j.margeo.2021.106556

Sesana, E., Gagnon, A. S., Ciantelli, C., Cassar, J. A., & Hughes, J. J. (2021). Climate change impacts on cultural heritage: A literature review. *WIREs Clim Change*, *12*(4), e710. https://doi.org/10.1002/wcc.710

Sickmöller, M., Blender, R., & Fraedrich, K. (2000). Observed winter cyclone tracks in the northern hemisphere in re-analysed ECMWF data. *Quarterly Journal of the Royal Meteorological Society*, *126*(563), 591–620. https://doi.org/10.1002/qj.49712656311

Sioni, F., Davolio, S., Grazzini, F., & Giovannini, L. (2023). Revisiting the atmospheric dynamics of the two century floods over north-eastern Italy. *Atmospheric Research*, *286*, 106662. https://doi.org/10.1016/j.atmosres.2023.106662

Stafoggia, M., Zauli-Sajani, S., Pey, J., Samoli, E., Alessandrini, E., Basagaña, X., et al. (2016). Desert dust outbreaks in Southern Europe: Contribution to daily PM10 concentrations and short-term associations with mortality and hospital admissions. *Environmental Health Perspectives*, *124*(4), 413–419. https://doi.org/10.1289/ehp.1409164

Stanke, C., Murray, V., Amlôt, R., Nurse, J., & Williams, R. (2012). The effects of flooding on mental health: Outcomes and recommendations from a review of the literature. *PLOS Currents*, *4*, e4f9f1fa9c3cae. https://doi.org/10.1371/4f9f1fa9c3cae

Steiner, A., Köhler, C., Metzinger, I., Braun, A., Zirkelbach, M., Ernst, D., et al. (2017). Critical weather situations for renewable energies—Part A: Cyclone detection for wind power. *Renewable Energy*, *101*, 41–50. https://doi.org/10.1016/j.renene.2016.08.013

Sutanto, S. J., Zarzoza Mora, S. B., Supit, I., & Wang, M. (2024). Compound and cascading droughts and heatwaves decrease maize yields by nearly half in Sinaloa, Mexico. *Npj Natural Hazards*, *1*(1), 26. https://doi.org/10.1038/s44304-024-00026-7

Temme, A. J. A. M., Guzzetti, F., Samia, J., & Mirus, B. (2020). The future of landslides' past—A framework for assessing consecutive landsliding systems. *Landslides*, *17*(7), 1519–1528. https://doi.org/10.1007/s10346-020-01405-7

Tochimoto, E., Miglietta, M. M., Bagaglini, L., Ingrosso, R., & Niino, H. (2021). Characteristics of extratropical cyclones that cause tornadoes in Italy: A preliminary study. *Atmosphere*, *12*(2), 1–13. https://doi.org/10.3390/atmos12020180

Toomey, T., Amores, A., Marcos, M., Orfila, A., & Romero, R. (2022). Coastal hazards of tropical-like cyclones over the Mediterranean Sea. *Journal of Geophysical Research: Oceans*, *127*(2), e2021JC017964. https://doi.org/10.1029/2021JC017964

Tous, M., Zappa, G., Romero, R., Shaffrey, L., & Vidale, P. L. (2016). Projected changes in medicanes in the HadGEM3 N512 high-resolution global climate model. *Climate Dynamics*, *47*(5–6), 1913–1924. https://doi.org/10.1007/s00382-015-2941-2

Tramblay, Y., & Somot, S. (2018). Future evolution of extreme precipitation in the Mediterranean. *Climatic Change*, *151*(2), 289–302. https://doi.org/10.1007/s10584-018-2300-5

Trigo, I., Davies, T., & Bigg, G. (2000). Decline in Mediterranean rainfall caused by weakening of Mediterranean cyclones. *Geophysical Research Letters*, *27*(18), 2913–2916. https://doi.org/10.1029/2000GL011526

Turner, R., McConney, P., & Monnereau, I. (2020). Climate change adaptation and extreme weather in the small-scale fisheries of Dominica. *Coastal Management*, *48*(5), 436–455. https://doi.org/10.1080/08920753.2020.1795970

UNISDR-United Nations International Strategy for Disaster Reduction. (2015). *Sendai framework for disaster risk reduction 2015–2030* (1st ed.). UNISDR.

United Nations Environment Programme. (2022). *Spreading like wildfire—The rising threat of extraordinary landscape fires*. A UNEP Rapid Response Assessment.

Vajda, A., Tuomenvirta, H., Juga, I., Nurmi, P., Jokinen, P., & Rauhala, J. (2014). Severe weather affecting European transport systems: The identification, classification and frequencies of events. *Natural Hazards*, *72*(1), 169–188. https://doi.org/10.1007/s11069-013-0895-4

Valagussa, A., Frattini, P., Crosta, G. B., Spizzichino, D., Leoni, G., & Margottini, C. (2020). Hazard ranking of the UNESCO world heritage sites (WHSs) in Europe by multicriteria analysis. *Journal of Cultural Heritage Management and Sustainable Development*, *10*(4), 359–374. https://doi.org/10.1108/JCHMSD-03-2019-0023

Valkaniotis, S., Papathanassiou, G., Marinos, V., Saroglou, C., Zekkos, D., Kallimogiannis, V., et al. (2022). Landslides triggered by medicane Ianos in Greece, September 2020: Rapid satellite mapping and field survey. *Applied Sciences*, *12*(23), 12443. https://doi.org/10.3390/app122312443

Valta, H., Lehtonen, I., Laurila, T. K., Venäläinen, A., Laapas, M., & Gregow, H. (2019). Communicating the amount of windstorm induced forest damage by the maximum wind gust speed in Finland. *Advances in Science and Research*, *16*, 31–37. https://doi.org/10.5194/asr-16-31-2019

Varga, G. (2020). Changing nature of Saharan dust deposition in the Carpathian Basin (Central Europe): 40 years of identified North African dust events (1979–2018). *Environment International*, *139*, 105712. https://doi.org/10.1016/j.envint.2020.105712

Varotsos, K. V., Karali, A., Lemesios, G., Kitsara, G., Moriondo, M., Dibari, C., et al. (2021). Near future climate change projections with implications for the agricultural sector of three major Mediterranean islands. *Regional Environmental Change*, *21*(1), 16. https://doi.org/10.1007/s10113-020-01736-0

Vogel, J., Paton, E., Aich, V., & Bronstert, A. (2022). Increasing compound warm spells and droughts in the Mediterranean Basin. *Weather and Climate Extremes*, *32*, 100312. https://doi.org/10.1016/j.wace.2021.100312

Vogel, M. M., Hauser, M., & Seneviratne, S. I. (2020). Projected changes in hot, dry and wet extreme events' clusters in CMIP6 multi-model ensemble. *Environmental Research Letters*, *15*(9), 094021. https://doi.org/10.1088/1748-9326/ab90a7

Waha, K., Krummenauer, L., Adams, S., Aich, V., Baarsch, F., Coumou, D., et al. (2017). Climate change impacts in the Middle East and Northern Africa (MENA) region and their implications for vulnerable population groups. *Regional Environmental Change*, *17*(6), 1623–1638. https://doi.org/10.1007/s10113-017-1144-2

Weilnhammer, V., Schmid, J., Mittermeier, I., Schreiber, F., Jiang, L., Pastuhovic, V., et al. (2021). Extreme weather events in Europe and their health consequences—A systematic review. *International Journal of Hygiene and Environmental Health*, *233*, 113688. https://doi.org/10.1016/j.ijheh.2021.113688

WTW. (2024). Retrieved from https://www.wtwco.com/en-ch/insights/2024/04/storm-daniel-a-cautionary-tale-on-the-need-to-maintain-infrastructure-before-its-too-late?utm_source=chatgpt.com

Zampieri, M., Ceglar, A., Dentener, F., & Toreti, A. (2017). Wheat yield loss attributable to heat waves, drought and water excess at the global, national and subnational scales. *Environmental Research Letters*, *12*(6), 064008. https://doi.org/10.1088/1748-9326/aa723b

Zappa, G., Hawcroft, M. K., Shaffrey, L., Black, E., & Brayshaw, D. J. (2015). Extratropical cyclones and the projected decline of winter Mediterranean precipitation in the CMIP5 models. *Climate Dynamics*, *45*(7–8), 1727–1738. https://doi.org/10.1007/s00382-014-2426-8

Zekkos, D., Zalachoris, G., Alvertos, A. E., Amatya, P. M., Blunts, P., Clark, M., et al. (2020). The September 18–20 2020 medicane Ianos impact on Greece—Phase I Reconnaissance report. In *Geotechnical extreme events reconnaissance report*, GEER-068. https://doi.org/10.18118/G6MT1T

Zhang, W., Luo, M., Gao, S., Chen, W., Hari, V., & Khouakhi, A. (2021). Compound hydrometeorological extremes: Drivers, mechanisms and methods. *Frontiers of Earth Science*, *9*. https://doi.org/10.3389/feart.2021.673495

Zhang, X., Zhao, L., Tong, D. Q., Wu, G., Dan, M., & Teng, B. (2016). A systematic review of global desert dust and associated human health effects. *Atmosphere*, *7*(12), 158. https://doi.org/10.3390/atmos7120158

Zimbo, F., Ingemi, D., & Guidi, G. (2022). The tropical-like cyclone "Ianos" in September 2020. *Meteorology*, *1*, 29–44. https://doi.org/10.3390/meteorology1010004

Zittis, G. (2018). Observed rainfall trends and precipitation uncertainty in the vicinity of the Mediterranean, Middle East and North Africa. *Theoretical and Applied Climatology*, *134*(3–4), 1207–1230. https://doi.org/10.1007/s00704-017-2333-0

Zittis, G., Ahrens, B., Obermann-Hellhund, A., Giannakis, E., Risto, D., Gamez, M. A., et al. (2022). Maritime transport disruption risk for EU islands under a changing climate. *Euro-Mediterranean Journal for Environmental Integration*. https://doi.org/10.21203/rs.3.rs-2346923/v1

Zittis, G., Almazroui, M., Alpert, P., Ciais, P., Cramer, W., Dahdal, Y., et al. (2022). Climate change and weather extremes in the Eastern Mediterranean and Middle East. *Reviews of Geophysics*, *60*(3), e2021RG000762. https://doi.org/10.1029/2021RG000762

Zittis, G., Bruggeman, A., & Lelieveld, J. (2021). Revisiting future extreme precipitation trends in the Mediterranean. *Weather and Climate Extremes*, *34*, 100380. https://doi.org/10.1016/j.wace.2021.100380

Zittis, G., Hadjinicolaou, P., Klangidou, M., Proestos, Y., & Lelieveld, J. (2019). A multi-model, multi-scenario, and multi-domain analysis of regional climate projections for the Mediterranean. *Regional Environmental Change*, *19*(8), 2621–2635. https://doi.org/10.1007/s10113-019-01565-w