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Multi-sectoral impact assessment of an extreme African dust episode in the Eastern Mediterranean in March 2018

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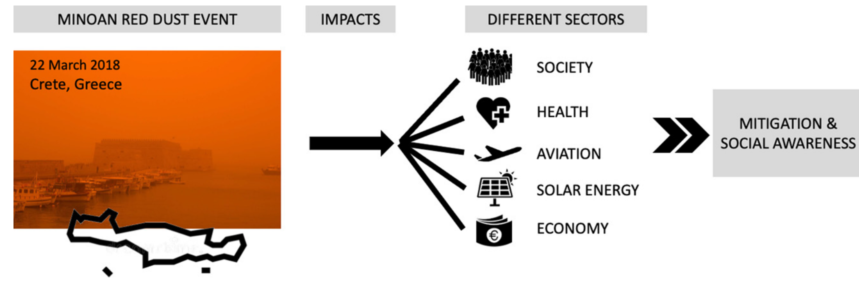
HIGHLIGHTS

- Impacts of an extraordinary episode of African dust transport are investigated.
- Several types of impacts are identified in ecosystems, economy, society and health.
- Increase (3 times) of emergencies responses and hospital admissions.
- Reduction of visibility caused aircraft traffic disruptions in Crete.
- Reduction of solar energy production is estimated on ~10 MW.

GRAPHICAL ABSTRACT



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ABSTRACT

In late March 2018, a large part of the Eastern Mediterranean experienced an extraordinary episode of African dust, one of the most intense in recent years, here referred to as the “Minoan Red” event. The episode mainly affected the Greek island of Crete, where the highest aerosol concentrations over the past 15 yeas were recorded, although impacts were also felt well beyond this core area. Our study fills a gap in dust research by assessing the multi-sectoral impacts of sand and dust storms and their socioeconomic implications. Specifically, we provide a multi-sectoral impact assessment of Crete during the occurrence of this exceptional African dust event. During the day of the occurrence of the maximum dust concentration in Crete, i.e. March 22nd, 2018, we identified impacts on meteorological conditions, agriculture, transport, energy, society (including closing of schools and cancellation of social events), and emergency response systems. As a result, the event led to a 3-fold increase in daily emergency responses compare to previous days associated with urban emergencies and wildfires, a 3.5-fold increase in hospital visits and admissions for Chronic Obstructive Pulmonary Disease (COPD) exacerbations and dyspnoea, a reduction of visibility causing aircraft traffic disruptions (eleven cancellations and seven delays), and a reduction of solar energy production. We estimate the cost of direct and indirect effects of the dust episode, considering the most affected socio-economic sectors (e.g. civil protection, aviation, health and solar energy production), to be between 3.4 and 3.8 million EUR for Crete. Since such desert dust transport episodes are natural, meteorology-driven and thus to a large extent unavoidable, we argue that the efficiency of actions to mitigate dust impacts depends on the accuracy of operational dust forecasting and the implementation of relevant early warning systems for social awareness.

1. Introduction

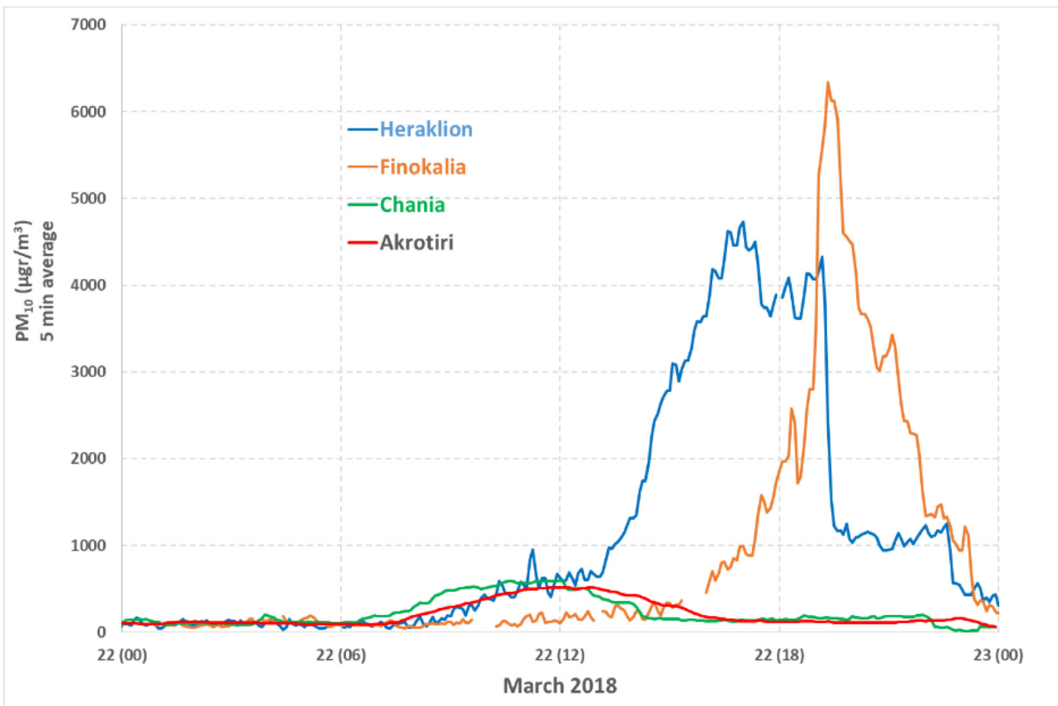
Mineral dust wind-blown from arid land surfaces exerts a range of impacts to different aspects of society and economy (Middleton, 2017; Cuevas et al., 2021). Airborne dust imposes serious risks for human health (Karanasiou et al., 2012; de Longueville et al., 2013; Goudie, 2014; Zhang et al., 2016; Tong et al., 2021) causing cardio-respiratory disorders (Panikkath et al., 2013; Giannadaki et al., 2014; Lelieveld et al., 2015; Al et al., 2018; Dominguez-Rodriguez et al., 2020) or damaging external organs – mostly causing skin and eye irritations (WHO - World Health Organization, European Centre for Environment, 2021). Dust particles may also enhance the risk of infectious disease such as meningitis in sub-Saharan Africa (Pérez García-Pando et al., 2014a; Pérez Garcia-Pando et al., 2014b), Kawasaki disease in Japan (El-Askary et al., 2017) or coccidioidomycosis in USA, Mexico and other parts of Latin America (Hector and Laniado-Laborin, 2005). For solar energy production, the presence of dust in the atmosphere causes attenuation of the surface solar radiation in the atmosphere (e.g. Papadimas et al., 2012; Schroedter-Homscheidt et al., 2013; Kosmopoulos et al., 2017), and a reduction of the solar panel efficiency upon deposition (soiling) (e.g. Maghami et al., 2016; Wolfertstetter et al., 2014; Smestad et al., 2020). Sand and dust storms can also cause significant problems in the transport sector. In regions that are close to dust sources, poor visibility can cause road traffic accidents (Middleton et al., 2019). Strong sand and dust storms can cause disturbances in airport operations leading to rerouting and massive cancellations of scheduled flights (Al-Hemoud et al., 2017; Al-Kheder and Al-Kandari, 2020; Cuevas et al., 2021), as well as mechanical problems including erosion, corrosion, dust melting in turbines, pitot-static tube blockage or engine flame out in flight (Clarkson and Simpson, 2017) and damages to the external surface of the aircraft (Lekas et al., 2011; Nickovic et al., 2021). In arid and semi-arid regions, sand and dust storms have many negative impacts on agriculture (e.g. Hojan et al., 2019) and ecosystems (Arnalds et al., 2014). Desert dust interacts ecosystems and the cryosphere both at far distances from warm deserts as well as in high latitudes and mountains, where cold climate dust sources are located. Desert dust contains iron, a nutrient that limits primary production in many areas of the ocean, so dust deposition could play a role in ocean fertilization, affecting the growth of algae and phytoplankton (Meskhidze et al., 2005). Dust deposited on snow, glaciers and sea ice can enhance snow and ice warming (Painter et al., 2012; Skiles et al., 2012; Meinander et al., 2014; Dagsson-Waldhauserova et al., 2015; Di Mauro et al., 2015; Kylling et al., 2018) and melting (Flanner, 2013; Di Mauro et al., 2019). The accelerated melting of snow and ice also affects runoff availability (Painter et al., 2018), with consequent potential effects on the tourism sector, in particular ski resorts.

Most of the current research into the direct and indirect hazardous impacts of desert dust on human society is focused on individual sectors, including health (e.g. Vodonos et al., 2014; Al-Hemoud et al., 2019), transport (e.g. Brazel and Hsu, 1981; Holyoak et al., 2011) and solar power production (e.g. Kosmopoulos et al., 2015; Kishcha et al., 2020). Many of these desert dust hazards are relatively well-known, but their impacts and their associated economic losses are not equally well-understood and quantified (Middleton et al., 2019). Otherwise, studies about the multi-sectoral impacts for particularly intense sand and dust storms (e.g. Al-Hemoud et al., 2019; Cuevas et al., 2021) or for long-term periods (e.g. Foreman, 2018) are rather infrequent in the literature and focuses on desert dust source regions. The lack of multi-sectoral and regional assessments hinder the development and implementation of effective mitigation and adaptation measures against sand and dust storms (Middleton and Kang, 2017; Ivčević et al., 2019).

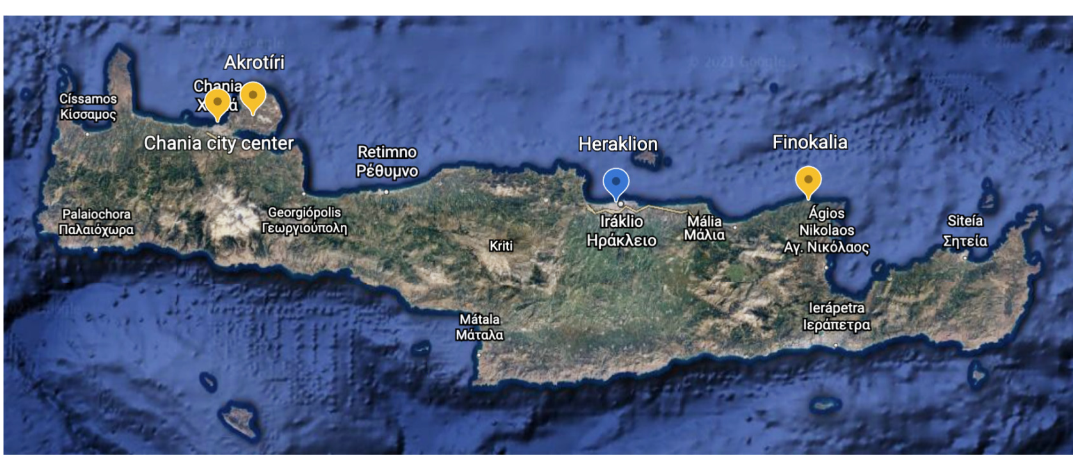
On March 22nd, 2018, an exceptional African dust event affected a large area in the central and eastern Mediterranean region, particularly Crete, where historical PM_{10} concentrations were recorded. It is because of the red colouring of the atmosphere during the event in Crete that we refer hereafter to this event as the "Minoan-Red" event. We provide an assessment of the multi-sectoral impacts and associated economic losses of this episode in Crete. The manuscript is structured as follows: Section 2 presents the episode in terms of the prevailing meteorological conditions and atmospheric particle concentrations. Section 3 presents the impact assessment for the three main sectors (health, solar energy, aviation) and other additional socio-economic effects. Conclusions are drawn in Section 4.

2. The "Minoan-Red" dust episode

The "Minoan-Red" dust event took place on 21–22 March 2018 and affected the Eastern Mediterranean. Considering the time series of the PM_{10} concentrations at Finokalia monitoring station in Crete, during the period of 2004–2020, March 22nd is the day with the maximum daily average in the whole time series with 850 μg/m^3 (the second most severe dust episode observed was at 706 μg/m^3) (N. Kalivitis personal communication). Daily PM_{10} values exceeded 50 μg/m^3 (the EU Air Quality daily PM_{10} threshold, EU directive: https://ec.europa.eu/environment/air/quality/standards.htm) over the Eastern Mediterranean (Fig. 1). In fact, the event was characterized by (5-min) surface concentrations exceeding 1000 μg/m^3 for a period of 4–7 h on the of 22nd, reaching record (5-min) values above 6200 μg/m^3 at the background station of Finokalia on the north coast of Crete about 70 km east of Heraklion city at 16:20 UTC (Crete, Fig. 1). Similarly, 5-min average values higher than 4500 μg/m^3 were observed at Heraklion station while much lower values were observed in the western side of Crete. The exceptional intensity of this African dust event over Crete affected diverse socio-economic sectors that are analyzed in more detail in Section 3.



(a)



(b)

Fig. 1. (a) Five-minute averaged PM_{10} concentrations at the four available sites during the Minoan red dust storm of 22/03/2018. Measurements were performed on the island of Crete at four locations, namely: the environmental research station of the University of Crete at Finokalia, the measurement station of the Region of Crete in Heraklion city center (measurements by University of Crete), the measurement station of the Region of Crete in Chania city center (measurements by Technical University of Crete) and Akrotiri, Chania (measurements by the National Observatory of Athens); (b) Location of the 4 monitoring sites on Crete island (Google Earth image).

Solomos et al. (2018) and Kaskaoutis et al. (2019) provided detailed descriptions of this African dust event based on satellite observations, ground-based measurements and modelling (i.e. reanalysis). Here, we summarise the most important aspects that caused the adverse situation. On March 21st, 2018, a weakening of the Arctic polar vortex allowed the advection of cold polar air masses towards Europe (not shown). Associated with the Arctic cold outbreak, a long-wave trough extended from northeast Europe to the northwestern part of the Sahara during the pre-phase of the dust outbreak (Fig. 2a). This resulted in the development of strong southwesterly winds, with velocities reaching up to 30 m/s in the lower troposphere of the central Mediterranean and Greece. Further, the meridional advection of cold polar air increased the baroclinity of the atmosphere over the central Mediterranean and, hence, created conditions favourable for the development of a depression over northeast Libya (Fig. 2c), resulting in strong winds over northeast Libya and enhancing dust particles' uptake. In the morning of March 21st, an intense plume was observed off the Libyan coast (Fig. 2e) mainly at 3 to 4 km altitude. In the evening of March 21st, that plume moved to the northeast, still at the same main altitude. At 1200 UTC on March 22nd, an upper-level cut-off low was located over southern Italy (Fig. 2b), associated with a well-organized low-pressure system over the northern Ionian Sea (Fig. 2d). The abrupt change in wind direction and the strong temperature gradient allowed a clear identification of the location of the cold front of the low-pressure system at around 15°E. Ahead of the cold front, the warm conveyor belt provided the main

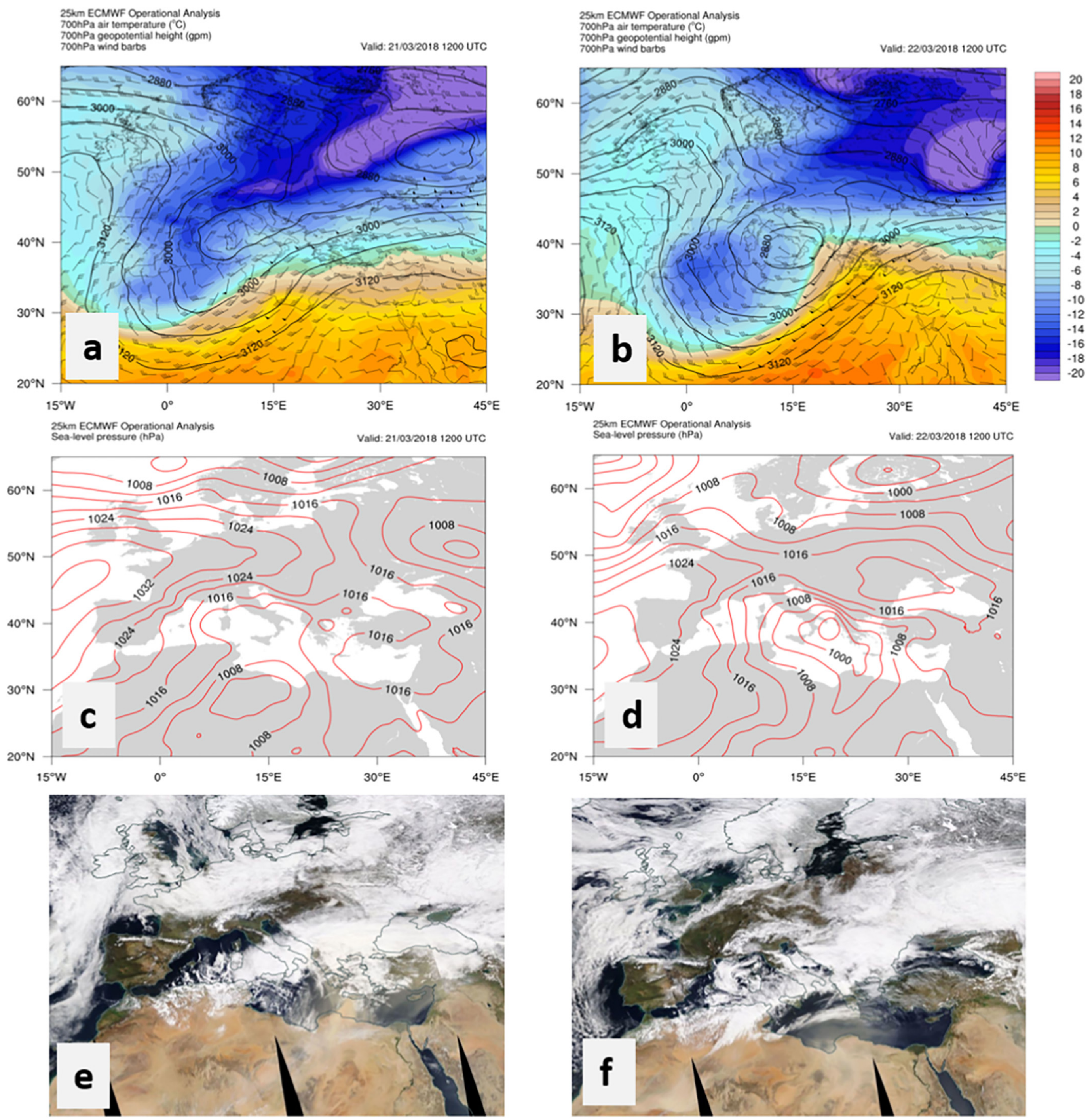


Fig. 2. Synoptic maps of (a, b) 700 hPa geopotential height, temperature and wind, and (c, d) sea-level pressure at 1200 UTC in 2018 from ECMWF operational analysis. NASA/Aqua daily image composite (e,f) from NASA Worldwide. Left panels corresponds to March 21st and right panels to March 22nd.

pathway for the uptake and transport of significant amounts of desert dust towards the Eastern Mediterranean (Fig. 2f).

Multiple clouds were observed together with the dust plume (see Fig. 2e and f), rendering the dust retrievals from satellites difficult. However, satellite-based aerosol dust retrievals show that the most intense part of the plume occurred on March 22nd in the Central and East Mediterranean Sea, affecting mostly Crete, Greece, Cyprus, Turkey, Libya and Egypt (see Fig. 3). Aerosol satellite products such as the aerosol index from NASA Suomi National Polar-orbiting Partnership (SUOMI-NNP) or the vertical profiles based on the Infrared Atmospheric Sounding Interferometer observations and the version 4.1 of the Mineral Aerosol Profiling from Infrared Radiances (IASI-MAPIR) dust retrievals (Callewaert et al., 2019) confirm that the source of the episode was in Libya (large dust load close to the surface, see Fig. 3), and a plume transported over the Mediterranean Sea, initially at about 3.5 km altitude (peak dust concentration), and lowering during transport to about 2.5 km in the Eastern Mediterranean and farther eastwards on the March 22nd (see Fig. 3). Of course, this is the altitude of the largest part of the plume (favouring the transport to northern latitudes), but on the 22nd, dust was also observed in the lowest atmospheric layers.

In the following days, visible dust deposition on snow was detected in Armenia and Turkey as well as Eastern Europe about 2000 km from the source desert (Dumont et al., 2020). Fig. 4 shows a Sentinel 2 cloud-free

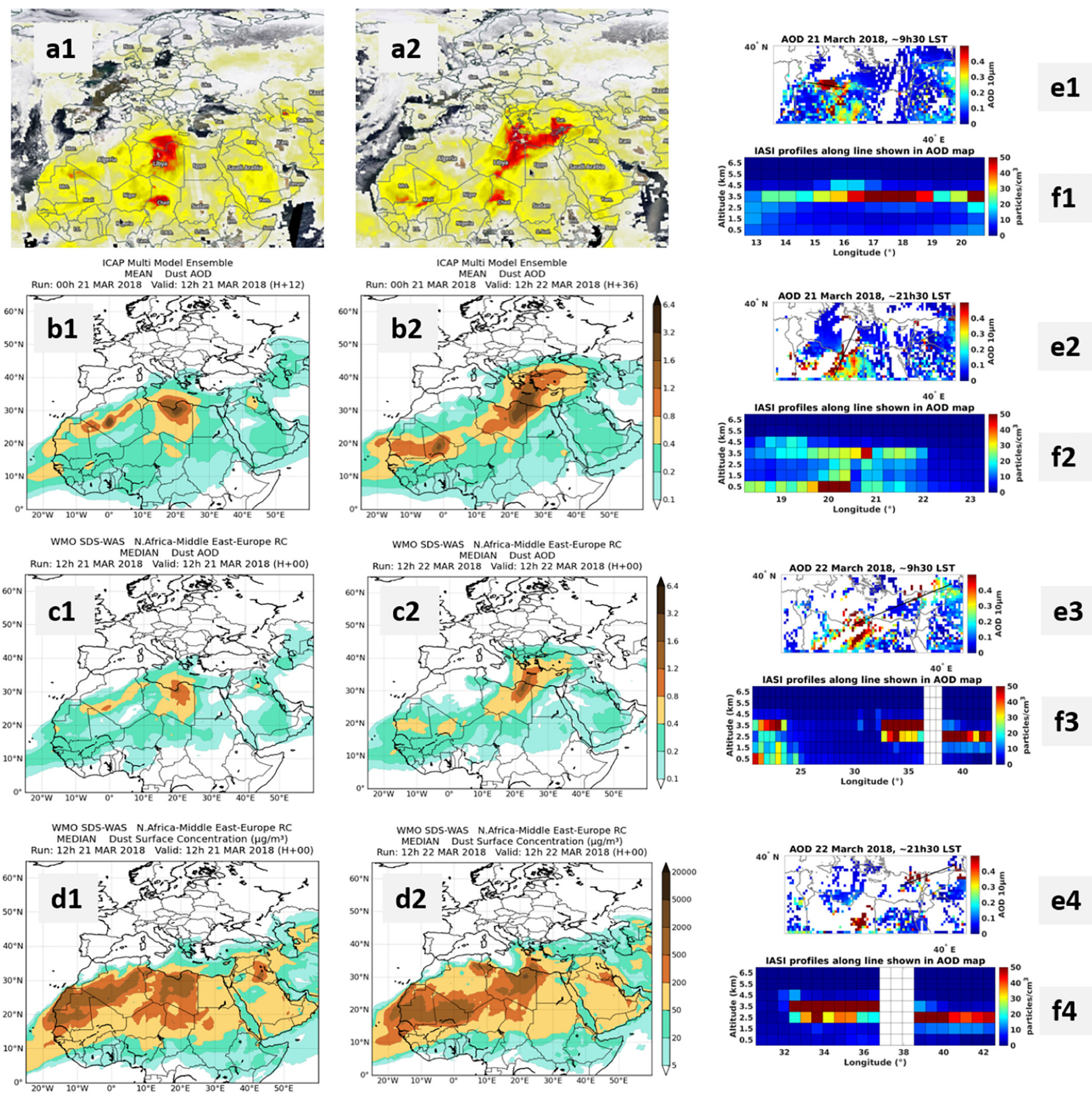


Fig. 3. Observations and forecasts aerosol composition for 21st and 22nd of March 2018. (a) Satellite observations of NASA SUOMI/NNP Aerosol index; (b) dust forecasts AOD at 12UTC from ICAP; (c) dust AOD forecast at 12UTC of the WMO SDS-WAS multimodel; (d) dust surface concentration forecasts of the WMO SDS-WAS multimodel; (e) IASI-MAPIR AOD and (f) IASI-MAPIR particle dust concentration profiles c). IASI-MAPIR dust AOD and vertical profiles considered in panel (e) and (f) show the two IASI overpasses (local solar time of about 9 h30 and 21 h30). The NASA SUOMI/NNP Aerosol index daily composition product was downloaded from the NASA EOSDIS Worldview platform (worldview.earthdata.nasa.gov).

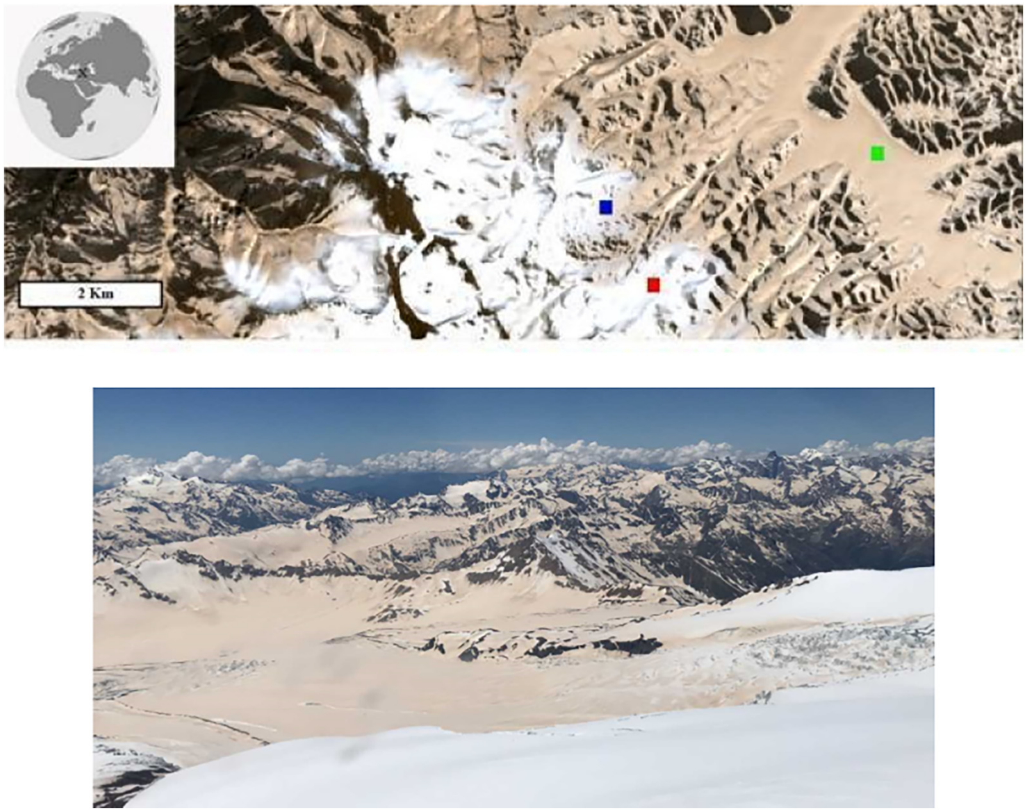


Fig. 4. Top: Focus of the Sentinel 2B image (acquired on March 26th, 2018) on West Turkey (coordinates: 38.11°N, 43.20°E), analyzed for this study. Upper panel: true-colour RGB composite. Bottom panel: Saharan dust covered snow areas in Caucasus on March 23rd, 2018. Albedo was reduced from 0.5 to 0.3. Image by Stanislav Kutuzov.

satellite image of west-Turkey in the vicinity of Lake Van. The image was acquired by the satellite on March 26th, 2018. On March 22nd, brown snow and coloured precipitation were observed in Bulgaria. On March 23rd, yellow and orange snow was observed mainly in northeast Bulgaria, in the region of Besarabiq in Ukraine, Romania and Moldova (see Marmureanu et al., 2019). Snow turned orange in Russia and Romania, affecting many ski resorts (see Fig. 4). The snow already contained large amount of water at this time, followed by series of red and white avalanches the next day (Dumont et al., 2020). Otherwise, analysis of ice core records from Elbrus Mountain (Central Caucasus, Fig. 4) reveal the overall increase in frequency of dust deposition events in recent decades (from two to four-five dust events a year in the last decade; Kutuzov et al., 2019). This emphasises the enhancement of the long-range dust transport towards high latitudes in recent years.

3. Impact assessment

Because of the extremely high dust concentrations observed at the surface in Crete on March 22nd, 2018, the present section overviews the impacts of the 'Minoan-Red' dust episode in Crete for selected socio-economic sectors. Moreover, for those impacts that can be quantified (i.e. emergy response, hospitalisations, energy and traffic management), an estimation of the losses cost associated to this African dust event is included.

3.1. Effects on society

Assessing the impact of dust events on the society is a complex task. Here we aim to propose a relatively simple approach for tracing the level of awareness of the society on this aspect. With this aim, we scanned news archives and emergency response data to acquire a first overview of the most relevant impacts of the dust event in Crete for society at large. Closing schools and cancellation of public and sport events were the main themes on the news during and immediately after the dust event, but other impacts in tranports, energy production/consumption are also reported (see Table 1). In addition, dust related impacts which co-occurred due to the meteorological conditions responsible for the dust intrusion that yielded extreme heat and wind conditions, have been reported. For instance, the National Observatory of Athens (NOA) that holds a database of extreme weather events associated with various impacts (Papagiannaki

Table 1
Socioeconomic impacts reported in the news during and immediately after the Minoan-red dust event in Greece. Source: Nea Kriti news agency [https://www.neakriti.gr]. Level of public attention is based on the result of website's position in the search engine results (Nea Kriti news agency page).

Impact	Description	Level of public attention
Productivity	1. Closed schools 2. Cancelled sports events 3. Cancelled or reduced population activity	1
Compound, heat and wind	1. Extensive fires throughout Crete island 2. Extreme thermal discomfort 3. Damages in the agricultural sector 4. Fallen trees 5. Fishing and recreational sailing disruption	2
Psychological, positive	1. Scenic/aesthetic	3
Psychological, negative	1. Shock 2. Fear 3. Disturbance	4
Transport	1. Flight delays and cancellations 2. Sand on road network 3. Traffic accidents	5
Energy	1. Electricity outages	6
Ecosystems	1. Land fertilizer 2. Sea fertilizer 3. Iron provision	7
Emergency response system	1. Increased loading of the system	8

et al., 2013), has archived the peak day of the desert dust event as an extreme weather day of "strong intensity phenomena with limited impacts", reporting extensive damages in the agricultural sector (plants and infrastructure) due to the extreme winds (source: http://meteo.gr/weather_cases.cfm). Table 1 provides a summary of the impacts reported in the local news, classified in terms of public attention taking into account the number of news published. Health impacts are also reported in the news indirectly through the cancellation of public events (as a mitigation measure of the risk posed by the high PM_{10} concentrations for health), the psychological status of the population or weather conditions. Visits to the emergency room and hospitalisations derived from the event are discussed separately in Section 3.2, whereas aviation and solar energy impacts are discussed more extensively in Sections 3.3 and 3.4, respectively.

Emergency response data from the Hellenic Fire Service (Fig. 5), for emergencies except health and crime, indicate a peak of occurrences during the dust event. The emergencies seem to have continued during the day after, but with less intensity, before returning to normal values. More specifically, 35 events were reported (18 urban emergencies and 17 wildfires – see Fig. 5, left), which is about three times higher than the numbers on the previous days. Regarding wildfires, the increase of emergency calls related to wildfires during the dust events could be ascribed to the atmospheric conditions (high temperature and low humidity) typical of dust events. Using the costs reported by Gourbatsis (2015) related to wildfires, the operational cost for the day of the African dust intrusion is estimated to approximately € 2.7 million, about 5–6 times higher than the background pattern and two time more than the next day (Fig. 5, right). Two injuries during the African dust intrusion and no deaths were reported by the fire service.

Fig. 6 visualizes the geographical distribution of the abovementioned emergency response events on the island of Crete. Maps show that urban emergencies are spread throughout the island but peak in municipalities with large cities (esp. Rethymno, Heraklion, Ag. Nikolaos), highlighting the link between impacts and exposure, whereas wildfires occurred in the island's northwestern parts and in the eastern municipalities of Ag. Nikolaos and Viannos.

Although attribution to the desert dust dimension of the event is difficult in the co-occurrence of extreme heat and wind, the compound effect of desert dust, wind and heat is clearly identifiable in the statistics. This is clear for urban emergencies and wildfires, whereas the day's one traffic accident attribution to dust-induced poor visibility is hypothesized but difficult to be verified, given the concurrent extreme wind conditions; no press releases dedicated to dust were issued by the Police Department or the General Secretariat for Civil Protection in order to investigate this aspect more thoroughly.

3.2. Effects on health

One of the most important impacts of sand and dust storms is the effect the increase of dust particles has on our health. Particles with diameters of ~3 μm or less are sufficiently small to be inaheled deep into the human langs, causing sneezing, coughing, eye irritation, lung tissue swelling, asthma and throat infections. Previously published studies in the geographical region affected by the "Minoan-Red" event (mainly Crete, Cyprus and Greece, and partially Sicily) have reported positive associations between desert dust and respiratory health outcomes. Firstly, Middleton et al. (2008) reported in Nicosia (Cyprus) that hospital admissions, between 1995 and 2004, were 3.1 % higher for respiratory admissions during dust-storm days than non-dust days. Trianti et al. (2017) showed in Athens (Greece), between 2001 and 2006, a considerable increase in the number of emergency room visits for asthma, COPD, and respiratory infections with increases during dust days by 38 %, 57 % and 60 %, respectively. Moreover, Samoli et al. (2011b) also found in Athens a higher effect of particles on asthma admissions during days with desert dust. During dust days the risk increase was 4.1 % per each 10 $\mu g/m^3$ PM_{10} increase, while for non-dust days the risk increase was 2.1 %. More recently, Renzi et al. (2017) showed that PM_{10} originating from deserts was positively associated with respiratory hospitalizations in Sicily (Italy), between 2006 and 2012, reporting a risk increase of 0.5 % per each 10 $\mu g/m^3$ PM_{10} increase.

The potential impact of the "Minoan-Red" event on daily mortality is difficult to assess. To this moment, no epidemiological study has been published. This is possibly because the daily mortality data commonly used in the epidemiological studies for the short-term effects of environmental exposures come from National Statistical Institutes or Health Departments with a delay of several years in most European countries due to data validation procedures. However, previous studies in the affected region suggest an association between desert dust exposures and daily mortality. Neophytou et al. (2013) found in Cyprus, between 2004 and 2007, a significant 2.4 % increase in daily cardiovascular mortality associated with each 10 $\mu g/m^3$ increase in PM_{10} concentrations on desert dust days, but no effect of PM_{10} was found on days without desert dust and also no effects were found for respiratory mortality. Renzi et al. (2018) found positive associations of both non-desert and desert PM_{10} with cause-specific mortality in Sicily, estimating a higher risk for cardiovascular causes in desert PM_{10} (4.5 % per 10 $\mu g/m^3$ increase) than in non-desert PM_{10} (2.4 % per 10 $\mu g/m^3$). While for respiratory mortality, the risk was higher for non-desert than for desert PM_{10}, 8.1 % and 6.3 %, respectively. Oppositely, Samoli et al. (2011a) reported significantly higher effects of PM_{10} during non-desert dust days on all-cause mortality in Athens. Differences in mortality during African dust exposure across the Mediterranean may be

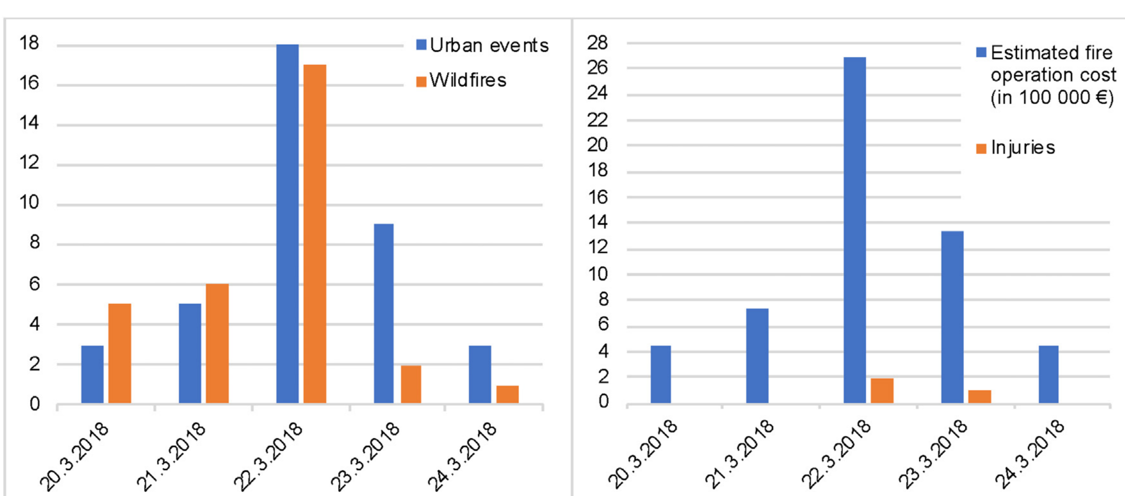


Fig. 5. Emergency response occurrences (left) and indicative socioeconomic impacts (right) before, during and after the event.
Source: Hellenic Fire Service open data: fireservice.gr/el_GR/synola-dedomenon.

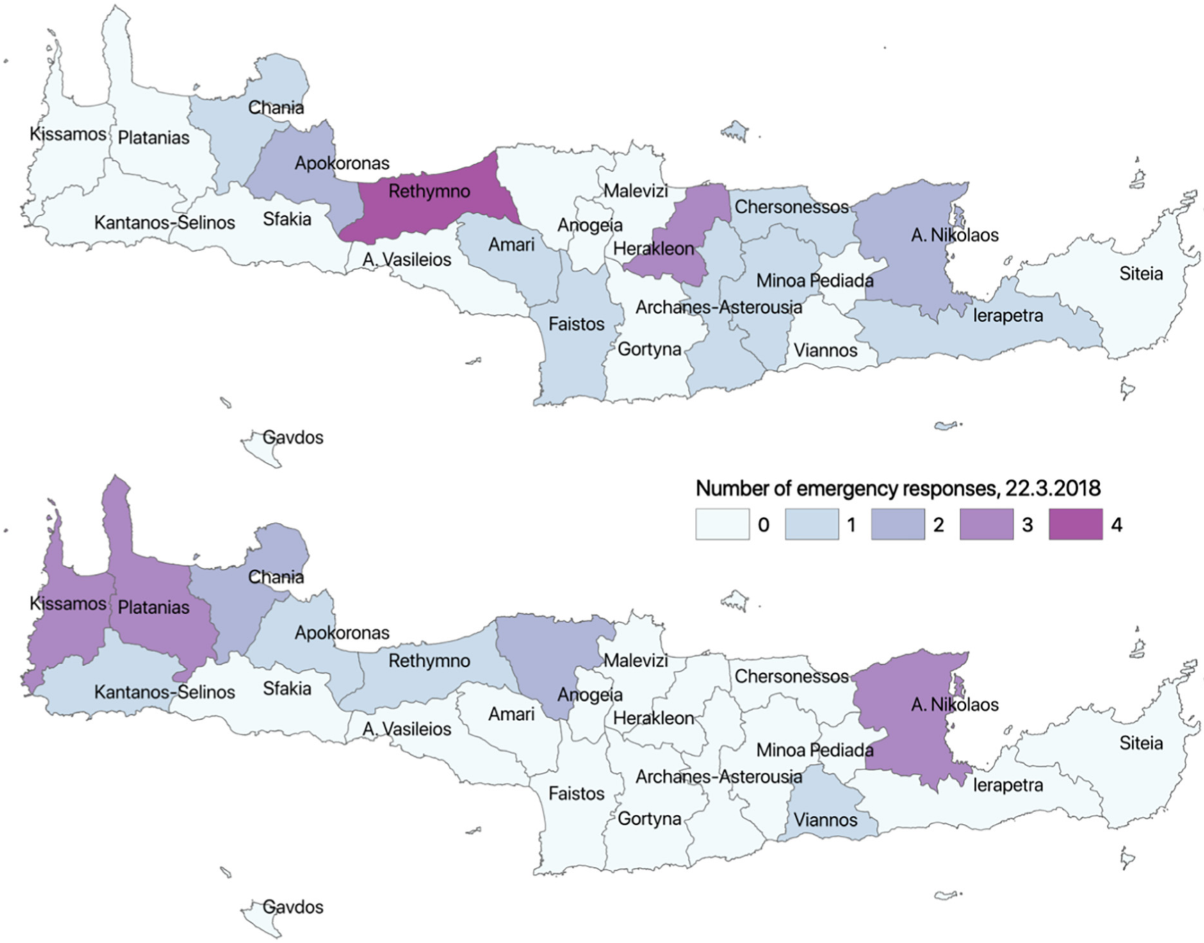


Fig. 6. Geographical distribution of urban emergency response occurrences (top) and wildfire operations (bottom) on March 22nd, 2018. Source: Hellenic Fire Service open data: fireservice.gr/el_GR/synola-dedomenon).

connected with local weather regimes and air quality that can increase the presence of other harmful pollutants as pointed by Samoli et al. (2014).

So far, only one epidemiological study has addressed the short-term effects of the "Minoan-Red" event in the affected area. Lorentzou et al. (2019) identified the effect of extreme increases in desert-derived PM_{10} on emergency department (ED) visits for dyspnoea and Chronic Obstructive Pulmonary Disease (COPD) exacerbations on the related hospital admissions of the University Hospital of Heraklion (Crete). Four desert dust storms were recorded during March 2018 in Heraklion with PM_{10} daily average concentrations in Heraklion of 238 (on March 4th), 203 (March 7th), 1138 (March 22nd) and 310 (March 27th) $\mu g/m^3$ (Fig. 7). Lorentzou et al. (2019) reported a more than twofold increase in the average number of ED visits of patients with dyspnoea (30 and 14.8 visits during desert and non-desert storm days, respectively) and all dyspnoea admissions (9.3 and 4.4 visits, respectively), and a 1.6-fold increase of COPD admissions (3.0 and 1.9 visits, respectively). However, during the extreme desert dust storm on March 22nd (PM_{10} daily average > 1000 $\mu g/m^3$, see Fig. 1) there was a striking increase of ED visits of patients with dyspnoea (3.2-fold versus other days) and COPD exacerbations (4.2-fold versus other days) (Fig. 7).

In Boutsioli (2011), the hospital sector charges in Greece over the last 20 years were analyzed, emphasizing cost efficiency. The total cost estimation of ED and COPD visits during the most extreme day of the "Minoan Red episode" (i.e. March 22nd) can be estimated roughly in ~425 kEUR based on Boutsioli (2011) from Table 5 and the reported costs for unexpected emergency admissions (in total 30 admissions with an associate cost of 6132 EUR per unexpected emergency adminission) and assuming that 5 % of the admitted people have stayed in the hospital for 5 days (i.e. cost of an emergency bed per day 48,202 EUR).

3.3. Effects on aviation

Aviation is one of the key infrastructures of our modern world, but shows great vulnerability with regard to natural hazards. Sand and dust storms are such a hazard, reducing visibility and sometimes causing

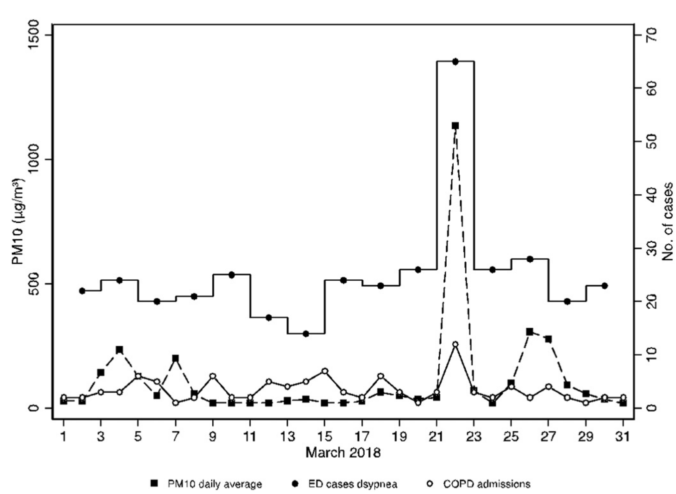


Fig. 7. PM_{10} daily average concentrations and ED cases with dyspnea and COPD admissions at the University Hospital of Heraklion, Crete, during March 2018. Source: Lorentzou et al. (2019).

damages in engines and other aircraft systems (see Section 1). During the “Minoan-Red” episode, flight delays and cancellations were impacts that also got the attention of the media (see Table 1). Even short interruptions can cause economic damage summing up to many millions of Euros. Sand and dust storms can easily impact the flow of air traffic, essentially disrupting take-off and landings due to reduced visibility, sometimes over airports of a whole region and for long periods.

With the aim of studying the impacts of the “Minoan-red” event upon aviation, the released TAF's (Terminal Aerodrome Forecast) and METAR (Meteorological Aerodrome Reports) were collected and analyzed with respect to visibilities at different airports around the Mediterranean Sea. On March 22nd at 12:20, the Heraklion airport's visibility was severely reduced down to 2000 m. Visibility further decreased to 600 m at 14:00 and increased again after 17:50 to 1500 m and to values above 3000 m at 20:50 (see Fig. 8a). For landing at Heraklion airport a visibility of at least 2400 m is required which led to a closure of the airport for landings from 12:20 to 20:50 UTC (8.5 h). At the other airports in the region (e.g. Chania), visibility values stayed above 4000 m, well above the minimum visibility required for take-off and landing at those airports.

Although no emergency regulations were put in place for the upper airspace (and therefore there were likely very few re-routings), there was an evident disruption of usual arrivals and departures (∼ 50 % decrease of the traffic activity) at Heraklion International Airport on the 22nd compared to the day after and to seven and six days before (e.g. 40 operations on March 16th, 21 operations on March 22nd and 48 operations on March 23rd as EUROCONTROL R&D Archive data reports), which serve as representative points of comparison. This is in fact an indication of cancellations and delays, which can be isolated from more detailed, but disaggregated databases and be used as the basis for estimating the total costs of the disruption.

We acquired the proprietary historical flights dataset by Lexis Nexis Risk Solutions (FlightStats.com) and identified eleven cancellations and seven delays listed for the Heraklion International Airport (IATA code HER). There were several flights with unknown status, which were omitted from the analysis. Other airports were not affected, with one notable exception being the Sitia Public Airport (IATA code JSH) which documented three delays. Based on the aircraft type (narrowbody), seat capacity (50–176 seats), type of carrier (traditional carriers) and delay times (between 30 min and 10 h) and following EUROCONTROL's standard input for cost and benefit analyses (EUROCONTROL, 2018), we estimate the total cost of the documented disruptions as ∼360 kEUR, of which 192 kEUR are cancellation costs and 168 kEUR are delay costs. Table 2 enumerates the disruptions, itemized and total costs, and the technical parameters used for the calculations.

3.4. Effects on solar energy production

Focusing on the energy sector, SDS can cause a reduction in solar energy production and, consequently, lead to associated economic losses. The desert dust effect on solar energy is important for the day-to-day market

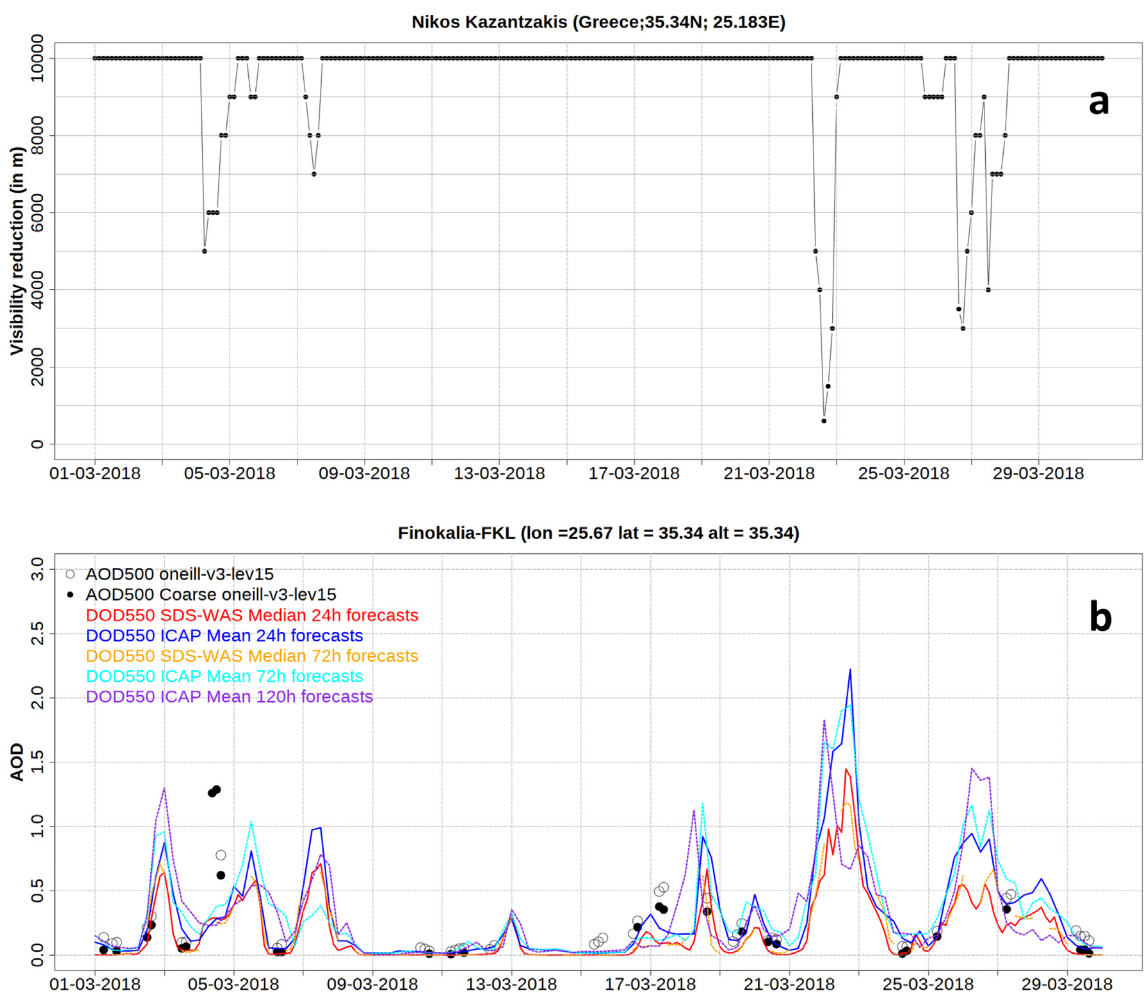


Fig. 8. Visibility (a) and aerosol column load and dust column load (namely Aerosol Optical depth and dust optical depth) b) time series over selected locations in Crete for March 2018. (a) Hourly visibility over the Heraklion airport's (also known as Nikos Kazantzakis airport. (b) 3-hourly dust-AOD over Finokalia. AOD observations from NASA-AERONET site are circles in black and solid lines show dust-AOD forecast from the SDS-WAS and ICAP ensemble forecasts for 24 (red and blue, respectively), 72 (orange and cyan, respectively) and 120-h forecasts (purple).

Table 2
Overview of cancellation and delay incidents and implied costs for March 22nd, 2018 at Heraklion International Airport and Sitia Public Airport.

Airport (IATA code)	Flight	Estimated arrival or departure time	Status	Delay (hh:mm)	Aircraft type	Seats	Cost (EUR)
Heraklion International Airport (HER)	A37304 from Athens	09:30	Cancelled		320	174	15,240
	A37316 from Athens	14:05	Delayed	1:35	320	174	9500
	A37322 from Athens	17:00	Cancelled		320	174	15,240
	A37324 from Athens	19:30	Cancelled		320	174	15,240
	A37714 from Thessaloniki	19:45	Cancelled		320	174	15,240
	A37326 from Athens	21:00	Cancelled		320	174	15,240
	A37328 from Athens	22:50	Delayed	2:16	320	174	13,600
	A3771 to Thessaloniki	10:05	Cancelled		320	174	15,240
	CXI4002 to Tel Aviv	10:45	Delayed	10:08	737	167	120,800
	A37305 to Athens	11:10	Delayed	2:57	320	174	17,700
	A37317 to Athens	14:40	Cancelled		320	174	15,240
	GQ154 to Athens	17:00	Delayed	3:50	AT7	70	2300
	A37323 to Athens	17:35	Cancelled		320	174	15,240
	A37325 to Athens	20:05	Cancelled		320	174	15,240
	A37715 to Thessaloniki	20:20	Cancelled		320	174	15,240
	ELB30 to Athens	21:15	Delayed	2:20	319	144	1400
	A37327 to Athens	21:35	Cancelled		320	174	15,240
	GQ156 to Athens	21:35	Delayed	1:15	AT7	70	7500
Sitia Public Airport (JSH)	A37044 from Athens	11:05	Delayed	0:30	DH8	78	3000
	GQ110 from Heraklion	13:30	Delayed	1:56	J41	50	11,600
	A37045 to Athens	11:30	Delayed	0:44	DH8	78	4400
Total cost of documented cancellations							191,800
Total cost of documented delays							167,640
Total cost							359,440

operations as well as for the public and/or commercial handling entities, where the amount of produced energy and its integration to the electricity grid controls the overall energy flow and the power grid stability (Mueller et al., 2009; Kosmopoulos et al., 2018; Fountoulakis et al., 2021). In Sun-privileged locations like southern Greece, the solar energy potential is high but at the same time the proximity to dust sources (e.g. African and the Middle East deserts) can result in serious attenuation of surface solar radiation (SSR). Beyond the effect of the presence of dust on the incoming solar radiation, soiling from deposited dust particles affects the cleanliness of the concentrated solar plants (CSP) mirrors and impacts their specular reflectance through diffuse reflection, scattering and absorption, and thus diminishes the power output. A laborious cleaning process is required to alleviate the effects of dust sedimentation and dry and wet deposition, increasing plant maintenance costs. Some studies indicated that the losses associated with the presence of mineral dust can reach the order of 80 % and 50 % for photovoltaic (PV) and concentrated solar power (CSP) plants, respectively (Kosmopoulos et al., 2017), these being the most widespread technologies for solar radiation-based energy production.

Here, we attempt an estimation of the impact (in terms of SSR and associted economic losses) the “Minoan-Red” event had on solar energy production from the photovoltaic (PV) and CSP systems in Crete. Greece developed 1 GW of solar energy in 2020 and has linked Crete to the mainland grid as reported by the Hellenic Association of Photovoltaic Companies (Helapco, https://helapco.gr/). At present, there are five large solar power plants operative in Crete. Because no public information is available about energy production during the dates of the event in these commercial solar power plants, an estimation of the desert dust impact on daily solar irradiance is performed for the coordinates of the Finokalia air quality monitoring station (see Fig. 1) that we consider as a representative location for the event.

For the assessment of the reduction in the solar irradiance on the solar panels due to the presence of airborne African dust over Finokalia, we used a state-of-the-art radiative transfer model (RTM), the so-called Solar Energy Nowcasting SystEm (SENSE), in conjunction with AOD forecasts of total particulate matter and dust from the Copernicus Atmosphere Monitoring Service (CAMS). The solar radiation calculation system SENSE used here is described in detail in Kosmopoulos et al. (2018). The complete list of inputs as well as a spectral sensitivity analysis can be found in Taylor et al. (2016) and Kosmopoulos et al. (2018). The AOD and dust AOD predictions at 550 nm were based on the CAMS reanalysis (Eskes et al., 2015) and its aerosol type classification identifier (Penning de Vries et al., 2015), while the spatial and temporal resolution is 0.4° and 3 h, respectively. The desert dust impact on energy production from PV installations was simulated for a hypothetical system with 10 MW nominal power taking into account its realistically feasible efficiency, spatial coverage and combined losses of the materials (PVGIS: Photovoltaic Geographical Information System, 2018). For the corresponding 10 MW CSP plants, the storage facilities, the losses by heat and shading as well as the peak optical efficiency have been considered (Eck et al., 2014).

Fig. 9 depicts the daily energy potential of Global Horizontal Irradiance (GHI, Fig. 9a) and Direct Normal Irradiance (DNI, Fig. 9b) under aerosol-free and dust conditions for the period from 18 to 28 of March 2018 for Finokalia in Crete. The desert dust impact on daily GHI ranges from 0.2 to 0.5 kWh/m^2 under normal aerosol conditions and reaches almost 1 kWh/m^2 under extreme desert dust loads as is occurred in the March 22nd. For DNI the corresponding impact is much higher ranging from 0.5 to 2 kWh/m^2 for most of the period. On March 22nd, the dust corrected DNI energy potential shows larger deviation from DNI estimated from aerosol-free conditions (see Fig. 9b). We note that during March 22nd the daily mean dust AOD as calculated by CAMS was found to be almost 1.3. Similar attenuation results were found in various studies presenting dust impact magnitudes of ~50 % for GHI and >90 % for DNI under similarly high particulate matter conditions (e.g. Shokr et al., 2017; Kosmopoulos et al., 2017, 2018).

For assessing the economical losses of the above differences on the solar irradiance, a financial analysis was performed by using a realistic feed-in tariff of 0.080 EUR/kWh for the region of Greece (HEDNO: Hellenic Electricity Distribution Network Operator S.A., 2018) for the actual produced energy under normal and extreme aerosol loads excluding the soiling effects. Fig. 10 presents the economic impact of dust presence on March 22nd, 2018 on the hypothetical system with 10 MW nominal power in the region of Finokalia as well as the previous and next day for direct comparison reference. The total and dust AOD values (a) exceeded 2.3 at 18:00 UTC but in this time step solar radiation is extremely low and as a result the real impact on solar energy took place from 6:00 to 15:00 UTC with maximum AOD values at 9:00 UTC reaching almost 1.4. Fig. 10b and c represent the temporal evolution of this dust event impact on the produced solar energy from PV (Fig. 10b) and CSP (Fig. 10c) with nominal power of 10 MW as used by Kosmopoulos et al. (2019). For the previous and next day, the daily energy production (EP) for PV was around 7 kWh/m^2 and during the peak of the desert dust event was 5.8 kWh/m^2. For the CSP simulated configuration, we found energy losses of >2.5 kWh/m^2 as

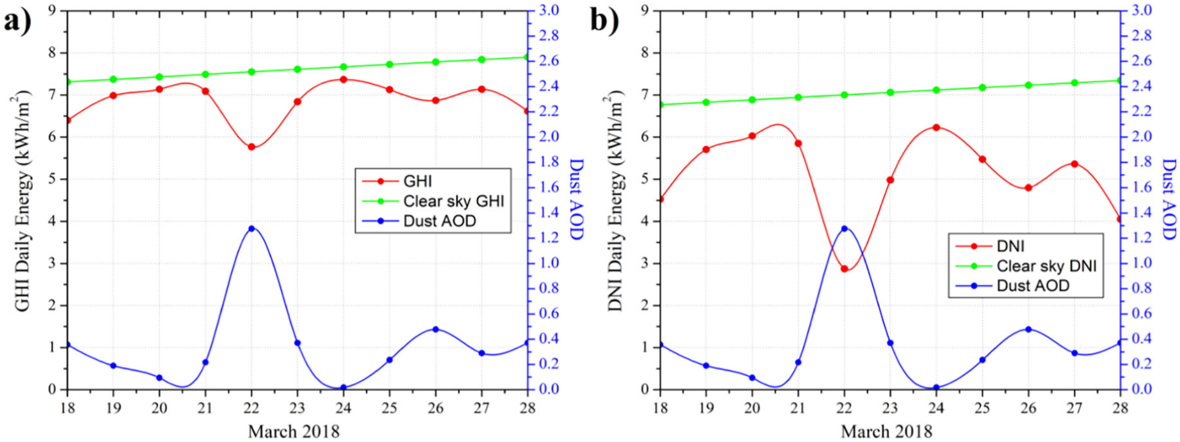


Fig. 9. Daily energy in kWh/m^2 under aerosol-free (green line) and dust aerosol conditions (red lines) for GHI (a) and DNI (b) for the region of Finokalia during the period 18–28 March 2018. The dust AOD is also shown in blue in order to highlight the impact on solar energy, especially during the dust event peak on March 22nd.

compared to the normal aerosol conditions on the previous and next day. This means that the corresponding aerosol and dust financial losses (AFL and DFL, respectively) under such conditions would exceed the daily revenue (DR) values. Indicatively, the DFL during the dust peak for the hypothetical 10 MW CSP plant would be −3040 EUR with the DR at 2284 EUR. Under regular aerosol conditions the corresponding DR values are ~4000 EUR, while the ALF and DFL ranges from 500 to 1600 EUR, highlighting the differences against extreme dust cases and the overall usefulness of such forecasting aerosol (Benedetti et al., 2018) and solar energy model approaches (Mueller et al., 2009; Qu et al., 2017; Kosmopoulos et al., 2019). Overall, for a 10 MW system with an estimated annual revenue that can reach 1.32 MEUR, the dust impact could cause financial losses of between 86 and 256 kEUR respectively for PV and CSP.

4. Mitigation and social awareness

It is increasingly recognized that sand and dust storms have an impact on weather, climate and environment but they also one extreme dust event can impact our daily activities as shown in Section 3. Consequently, efficient mitigation strategies need to be implemented for substantial

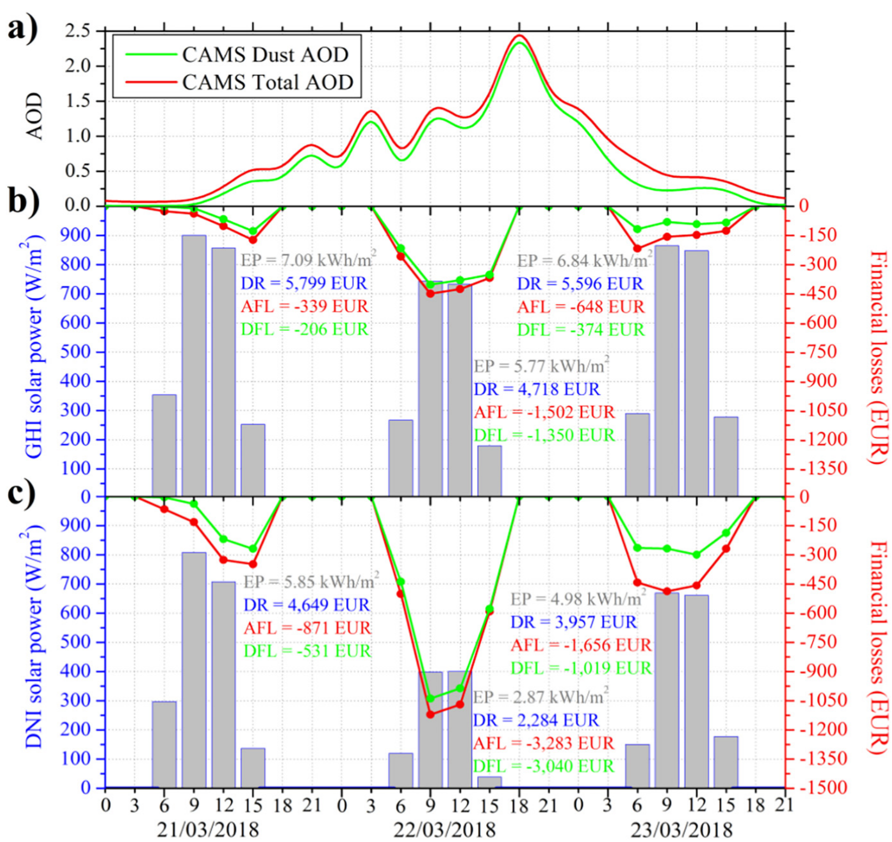


Fig. 10. Temporal 3-hourly evolution and financial analysis of the 21–23 of March 2018 dust event on the total and dust AOD values (a) and on the produced solar energy from photovoltaic (PV) (b) and concentrated solar power (CSP) (c) installations with 10 MW nominal power in the region of Finokalia. The impact was quantified in terms of energy production (EP), daily revenue (DR) and aerosol and dust total financial losses (AFL and DFL, respectively). The red and green lines correspond to financial losses (FL) because of the aerosol and dust, respectively.

environmental, health co-benefits and reducing losses in key socioeconomic sectors. The tactical mitigation applications focus on actions that can be taken in the short term, whenever forecasts predict a dust storm at a certain location and time. For example, dust forecasts can help hospitals anticipate peaks in respiratory-related emergency room visits, manage solar-power generation schedules and cleaning of solar panels, and minimize the time when low-visibility procedures in airports are required.

This is the main goal of the the United Nations (UN) Coalition on Combating Sand and Dust Storms (SDS) that was officially launched in 2019 (UN-EMG, 2019). Its mandate aims to coordinate a unified UN based system response on sand and dust storms, ensure the collaboration and the knowledge exchange among participating countries, to address issues in affected areas is collectively and to build an awareness response system to SDS in those affected regions. The provision of access to such information is fundamental to support the development of early warning systems and mitigation plans. In this context, the World Meteorological Organization Sand and Dust Storm Warning Advisory and Assessment System (WMO SDS-WAS) mission is to enhance the ability of countries to deliver timely and high-quality sand and dust storm forecasts, observations and knowledge to users.

Currently, there are a large number of operational systems (Benedetti et al., 2014) that provide dust forecasts at global scale but also at regional scales, for those regions where desert dust is a contributor to the aerosol budget. Use of ensemble forecast is especially encouraged during unstable weather patterns, or in extreme conditions such as during the Minoan-Red dust outbreak. Multi-model forecasting intends to mitigate the shortcomings of individual models while offering an insight on the uncertainties associated with a single-model forecast. Ensemble approaches are also known to have more skills at longer time ranges (> 5 days) where the probabilistic approach provides more reliable information than a single model run due to the model error increasing over time. Two examples of multi-model ensembles for desert dust prediction operating in the region of northern Africa, the Middle East and Europe are:

- The WMO SDS-WAS multi-model ensemble (Terradellas et al., 2015; Basart et al., 2019) that is built from more than twelve regional and global models (https://dust.aemet.es/), provides 3-days dust forecast.
- The International Cooperative for Aerosol Prediction (ICAP) multi-model ensemble (Sessions et al., 2015) that is built (at present) on nine global aerosol operational forecasts provides 5-days dust forecast (https://www.nrlmry.navy.mil/aerosol/icap.1135.php).

These dust forecasting products were able to reproduce the spatial extension of the event as it was (see Fig. 8b) in comparison with satellites (e.g. MODIS in Fig. 2 and IASI in Fig. 3). Predicted dust surface concetration by the regional ensemble of the WMO SDS-WAS showed values above 500 $\mu g/m^3$ over Crete on March 22nd. Otherwise, the comparison with AERONET observations over Finokalia (Fig. 8b) of the WMO SDS-WAS and ICAP ensembles emphasises the ability of the models to predict the occurrence of the intense “Minoan-Red” dust event (on March 22nd) up to 5 days in advance (see ICAP 120-h dust forecast in Fig. 8b).

As mentioned, this was the highest dust load event for Crete and Greece in the past 15 years, so the ability of the model ensembles to capture this extreme dust situation, provided the evidence that such models can be used for public awareness and also mitigation strategies. The early warning of such extreme weather events is the best defense to mitigate the impacts of these episodes, and the increase of the timeliness of prediction would be an important goal in terms of future developments.

For the case of Cyprus, the Cyprus Department of Labour Inspection (DLI) is the responsible national authority for monitoring air quality. DLI warns the public on the conditions and issues recommendation for limited exposure when the average 24-h concentration is expected to exceed the corresponding PM_{10} EU limit value (50 $\mu g/m^3$ on daily average). This is based on the previous day measurement and the use of dust forecast modelling. During the “Minoan-Red” episode, DLI issued daily warnings and recommendations regarding high hourly concentrations of respirable particles in ambient air throughout the duration of the dust episode from March 20th to March 27th, 2018. Because of the small size of the particles and their negative effect on human health, the public and especially the vulnerable groups of population (children, old people and patients) were advised through local and national media to avoid circulating outdoors and exercising in open spaces during the event. For example, imposing strict restrictions to schools about student outdoor activities. These warnings recommended not to go outside, especially for persons having breathing, heart or kidney issues, or immune system difficulties, or belonging to susceptible groups like children or elderly over 65. At present, the Cypriot National Department of Environment is developing a strategy for the mitigation of the health effects of sand and dust storms in the framework of the EU Life + project MEDEA (https://www.life-medea.eu/en/). This strategy is particularly important considering the fact that the current National Action Plan for the improvement of air quality in Cyprus focuses mainly on anthropogenic pollution and doesn't sufficiently include sand and dust storms.

In Greece, the METEO unit of the National Observatory of Athens, which operates the www.meteo.gr portal and provides weather forecasts (including dust forecasts) and alerts for Greece, issued relevant forecasts for this extreme event. Moreover, they provided continuous information and extended articles about the event with the aim to inform the general public on the adverse prevailing conditions. Specifically, in Crete, an official health warning was disseminated on March 20th 2018 (two days before the peak of the event) implementing the Greek legislation for “Short-term action planning against atmospheric particles pollution”. The warning reported that the phenomenon would have peaked in eastern Crete and advised that: (i) children and adults with breathing issues and adults with heart issues should limit all intensive physical activity and especially outdoor activity; (ii) elderly over 65 should limit physical activity; (iii) people with asthma may need more frequent relief medication. Similarly, on the peak day, officials from the Heraklion Pulmonary Clinic advised people with chronic breathing issues, bronchial asthma and heart issues to minimize outdoor activities, whereas all citizens were advised to avoid intensive physical exercise or strenuous outdoor activities and to expect the appearance of symptoms both during and within two days after the dust event. Additionally, the Association of Pulmonologists in Chania advised the aforementioned target groups to remain in air-conditioned indoor spaces. Considering the recommendations launched by the national authorities in Crete during the days of the event, we can assume that the number of ED visits during the “Minoan-Red” case registered in Crete (see Section 3.2) was significantly mitigated.

In contrast to the health sector, there is no European (at EC or national level) strategic plan for the mitigation of the effects of sand and dust storms for aviation and solar energy sectors. Particularly in the aviation sector, no information on potential sand and dust storm occurrences is considered in the airport or traffic management protocols of EUROCONTROL because the low number of episodes in the European air region (EUROCONTROL, personal communication). However, several initiatives, such as the Smart and Sustainable Aviation for Europe (SESAR), are starting to integrate sand and dust storms as a potential hazard for aviation safety. For solar energy, some projects focus on the development of mitigation strategies directly related to plant operations and the cleaning after an intense and/or frequent sand and dust storm. Cost-effective technologies and strategies that bring about a significant reduction of water requirement for solar plants is fundamental for reducing the impacts on plant operation strategies (Ilse et al., 2019). Private companies with commercial solar plants in countries surrounding the Mediterranean are starting to include dust-content information in their plant operations to enhance the productivity in the plant but also to reduce associated costs.

5. Summary and conclusions

Studies of the multi-sectoral impacts of sand and dust storms and the associated economic losses are essential for the development and implementation of effective mitigation measures in affected regions. In the present study, we gathered environmental and socioeconomic information

Table 3
Summary of the cost estimation losses in Crete on March 22nd for considered sectors.

Sector	Source of the information	Cost (kEUR)
Emergency responses	Hellenic fire service data	2700
Health	Hospital admission data	425
Aviation	Crete airports' data	360
Solar energy	Theoretical estimation for PV and CSP	86 and 256
Total		3.571 to 3.741

associated with an exceptional African dust event, which affected a large area in the central and eastern Mediterranean region (affecting mostly Crete) for performing one of the first multi-sectoral impact assessements in the region.

During March 22nd, 2018 an extraordinary dust outbreak event affected the entire Mediterranean region, with extreme PM_{10} concentrations reaching 850 μg/m^3 in Finokalia and exceeding 1100 μg/m^3 (daily average) in Heraklion city in Crete, being the largest event experienced in this region over the last 15 years. The dust transport covered a distance of >3000 km from the source desert producing also cryospheric impacts (deposition of dust in snow and reduction of albedo) in different areas in Europe, including Armenia, Turkey, Georgia, Ukraine, Moldova, Russia, Bulgaria, and Romania. Impacts are identified in meteorological conditions, agriculture, transport, energy, society (closing of schools and cancellation of population events), and emergency response systems among others. The event led to an increase in emergencies responses (~ 3 times higher than previous days associated to urban emergencies and wildfires), an increase of hospital visits and admissions for Chronic Obstructive Pulmonary Disease (COPD) exacerbations and dyspnoea (~3.5 times more than other days), and also to the reduction of visibility causing aircraft traffic disruptions (eleven cancellations and seven delays) and the reduction of solar energy production. As a result, considering the most intense day of the African dust episode (i.e. March 22nd), we estimated a total losss in the order of 3.4 to 3.8 milion EUR in Crete alone (see Table 3). This can be considered as a lower bound estimate and emphasises the socio-economic impacts that sand and dust storms can have, not only over desert dust sources, but also in regions downwind.

Since dust episodes are difficult to prevent, the most useful actions to mitigate these impacts depend on accurate dust forecasting and its implementation/operation, which will be essential for protecting human exposure to dust pollution; maximizing the solar resource contribution to the national or regional electrical grids and/or support more efficient aviation and airport management. In addition, sensors to accurately measure dust aerosols for both real time monitoring and information, but also for model evaluation are necessary.

This paper has documented many of the multiple effects on society of an extreme desert dust event in the eastern Mediterranean, demonstrating the range of impacts associated with long-range desert dust transport. This study is one of the first attempts to assess the impacts and the associated economic losses of one single sand and dust storm episode over a region affected by long-range dust transport region. Estimating the economic losses is limited by the difficulties on gathering socioeconomic information for the quantification of the associate impacts. This is even more complex in certain regions like Northern Africa or when the information is owned by a private company. Dust modelling products can help to overcome the lack of exposure information, although, facilitating access to real socioeconomic information is fundamental for more detailed and advanced sand and dust storm assessments. Assessing the economic and societal costs associated with desert dust events will supply critical inputs to policy development, inputs that are taking on greater importance as risk management becomes the dominant approach of hazard mitigation policies.

CRediT authorship contribution statement

Alexandra Monteiro: Conceptualization, Methodology, Investigation, Original draft preparation and Reviewing and Editing. Sara Basart: Conceptualization, Methodology, Investigation, Original draft preparation and Reviewing and Editing. Stelios Kazadzis: Original draft preparation, Conceptualization, Methodology, Investigation, Original draft preparation and Reviewing and Editing. Athanasios Votzis: Data curation, Reviewing and Editing. Antonis Gkikas: Original draft preparation, Reviewing and Editing. Sophie Vandenbussche: Methodology, Investigation, and Reviewing and Editing. Aurelio Tobias: Data acquisition; Methodology, Validation. Carla Gama: Reviewing and Editing. Carlos Pérez García-Pando: Supervision, Reviewing and Editing. Enric Terradellas: Data acquisition. George Notas: Data acquisition. Nick Middleton: Visualization, Investigation, Writing- Reviewing and Editing. Jonilda Kushta: Writing- Reviewing and Editing, Validation. Vassilis Amiridis: Data curation. Kostas Lagouvardos: Data curation. Panagiotis Kosmopoulos: Writing- Reviewing and Editing. Vasiliki Kotroni: Data curation, Visualization and Investigation. Maria Kanakidou: Data acquisition. Nikos Mihalopoulos: Reviewing and Editing. Nikos Kalivitis: Data acquisition. Pavla Dagsson-Waldhauserová: Original draft preparation and Reviewing and Editing. Hesham El-Askary: Reviewing and Editing. Klaus Sievers: Reviewing and Editing. Giannaros: Reviewing and Editing. Lucia Mona: Reviewing and Editing. Marcus Hirtl: Original draft preparation and Reviewing and Editing. Paul Skomorowski: Reviewing and Editing. Timo H. Virtanen: Reviewing and Editing. Theodoros Christoudias: Reviewing and Editing. Biagio Di Mauro: Data acquisition. Stanislav Kutuzov: Reviewing and Editing. Outi Meinander: Data acquisition. Slobodan Nickovic: Supervision, Reviewing and Editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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