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Investigation of Atmospheric Circulation Regimes for Wildfire, Flood and Rainfall Extremes in Greece

Stelios Karozis *, Maria Gavrouzou, Diamando Vlachogiannis and Athanasios Sfetsos

National Centre for Scientific Research "Demokritos", 15310 Agia Paraskevi, Greece; m.gavrouzou@cyi.ac.cy (M.G.); mandy@ipta.demokritos.gr (D.V.); ts@ipta.demokritos.gr (A.S.)
* Correspondence: skarozis@ipta.demokritos.gr; Tel.: +30-210-650-3403

Abstract

Greece and the eastern Mediterranean are among the regions that are most exposed to climate-driven natural hazards, with wildfires, floods, and extreme rainfall events consistently producing significant socioeconomic and environmental impacts. Although previous literature has addressed each hazard type individually, a systematic, comparative analysis of the atmospheric circulation regimes associated with all three hazard categories within a unified Lagrangian framework has not yet been conducted for Greece. In this study, a 96 h HYSPLIT back-trajectory analysis driven by ERA5 reanalysis data, combined with k-means clustering, is employed to characterise the air mass origins associated with extreme events in Greece from 2000 to 2020 at two atmospheric levels: 750 m and 3000 m above sea level. Wildfire events are predominantly linked to short-distance northeast airflow at 750 m, and are directly associated with the Etesian wind system and to a coherent northwest-west Mediterranean signal at 3000 m, reflecting the influence of the summer blocking anticyclone over Europe. Conversely, flood events are dominated by northerly flow at 750 m, driven by the eastern flank of Mediterranean depressions. These results indicate that flooding in Greece is primarily conditioned by surface cyclogenesis, regardless of the upper-level flow geometry. Extreme rainfall events exhibit the most complex structure, with a dominant upper-level cluster that describes a recurving trajectory consistent with cut-off low dynamics. Cross-hazard comparisons demonstrate that similar near-surface trajectory patterns may arise from different atmospheric drivers, underscoring the necessity of integrating Lagrangian trajectory classification with additional context, such as thermodynamic and seasonal, to enable robust multi-hazard attribution and enhance early warning capabilities in the eastern Mediterranean.

Keywords: back-trajectory analysis; k-means clustering; wildfires; floods; extreme rainfall; HYSPLIT

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Academic Editor: Gilles Grandjean

Received: 11 May 2026
Revised: 4 June 2026
Accepted: 5 June 2026
Published: 13 June 2026

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1. Introduction

Greece and the broader eastern Mediterranean region are widely recognised as a climate change hotspot, where rising temperatures, shifting precipitation patterns, and increasing atmospheric instability are projected to amplify the frequency, intensity, and socioeconomic impact of natural hazards in the coming decades. Among the most damaging of these hazards are wildfires, flash floods, and extreme rainfall events, all of which have caused significant loss of life, destruction of infrastructure, and long-term environmental degradation across the Greek territory in recent decades.

The atmospheric circulation patterns associated with extreme events in Greece are usually studied by hazard type. Previous research on wildfires has consistently identified the Etesian wind system as the dominant driver of fire weather conditions [1,2]. Refs. [3,4] characterised the atmospheric configurations related to high-impact wildfire events in Greece, pinpointing the role of Atlantic high-pressure systems and European-scale circulation anomalies in driving fire-prone conditions. More recently, ref. [5] provided a comprehensive climatological perspective on the atmospheric circulation patterns related to fire weather across the country. In case of flood events, ref. [6] demonstrated the role of Mediterranean low-pressure systems in driving cold-season heavy rainfall and flooding, while ref. [7] describes a systematic climatological study of cyclonic tracks associated with flood events in Crete. The authors of ref. [8] studied the multi-scale atmospheric and hydrological drivers of the catastrophic Mandra flash flood of November 2017, whereas the authors of ref. [9] performed a thorough analysis of atmospheric circulation types associated with flood occurrence across Greece. Moreover, studies concerning extreme rainfall identified distinct atmospheric circulation clusters corresponding to intense precipitation in different regions of Greece [10], while others [11] linked specific circulation patterns, like eastern Mediterranean troughs and anomalous upper-level disturbances, to high-impact rainfall episodes in Crete and the southern Aegean islands.

The aforementioned studies have addressed individual hazard types in isolation, using varying methodologies, datasets, and time periods, which limits the possibility of direct cross-hazard comparison. Despite research on extreme events in Greece, a comparative multi-hazard analysis of air mass origins has not yet been conducted, especially using a consistent Lagrangian trajectory framework. It remains unclear whether the atmospheric circulation regimes associated with different hazard types share common characteristics at the near-surface and free-tropospheric levels or are governed by fundamentally distinct large-scale dynamical drivers. The latter is important for developing a unified, physically consistent understanding of extreme event climatology in the eastern Mediterranean, with direct implications for multi-hazard early warning and climate risk assessment.

Lagrangian back-trajectory analysis has emerged as a useful tool for characterising air mass origins and transport pathways in studies of atmospheric composition, pollution episodes, and meteorological extremes [12–16]. The Hybrid Single-Particle Lagrangian Integrated Trajectory model [17,18], when combined with clustering Machine Learning algorithms, allows for the identification of dominant air mass transport patterns associated with specific atmospheric conditions or events. Specifically, the k-means clustering algorithm has been widely applied to classify back-trajectory datasets due to its computational efficiency and robustness to large datasets [19,20]. The present study applies this integrated approach to a harmonised database of 589 extreme events that occurred in Greece between 2000 and 2020, drawing on multiple European and national databases (EFFIS, EFAS, HNMS, EM-DAT, and the Greek Ministry of Environment). In the current study, the goal is (i) to characterise the origins of near-surface and free-tropospheric air masses associated with wildfires, floods, and extreme rainfall in Greece; (ii) to compare the atmospheric circulation regimes across hazard types; and (iii) to discuss the implications of these findings for the physical understanding of Mediterranean extreme events and for operational hazard monitoring and early warning.

2. Extreme Events in Greece

2.1. Data Collection

In the current section, the external data repositories and databases utilized in the current study is presented (see Table 1).

Table 1. Databases used for the identification of the extreme events that took place in Greece from 2000 to 2020.

Database	Time Period	Source
European Forest Fire Information System (EFFIS)	2008–2020	https://forest-fire.emergency.copernicus.eu/apps/data.request.form, accessed on 10 March 2025
European Flood Awareness System (EFAS)	2000–2020	https://data.jrc.ec.europa.eu/collection/id-0068#datasets, accessed on 10 March 2025
Hellenic National Meteorological Station (HNMS)	2014–2020	http://oldportal.emy.gr/emy/en/climatology/climatology_extreme, accessed on 10 March 2025
Greece Historic Events from Ministry of the Environment	2000–2011	https://ypen.gov.gr/, accessed on 10 March 2025
EM-DAT	2000–2020	https://www.emdat.be/, accessed on 10 March 2025

2.1.1. European Forest Fire Information System (EFFIS)

The European Forest Fire Information System (EFFIS) [21] is a European Commission-supported platform developed in cooperation with national fire administrations to provide harmonised information on forest fires in Europe and neighbouring regions. It offers both historical and near-real-time fire data and supports the monitoring of fire activity and fire regimes. In this study, EFFIS was used to retrieve wildfire occurrences in Greece for the period of 2008–2020.

2.1.2. European Flood Awareness System (EFAS)

The European Flood Awareness System (EFAS) [22,23] is part of the Copernicus Emergency Management Service and provides flood-related monitoring, forecasting, and archived information at the European scale. Its data products include hydro-meteorological variables, modelled runoff, probabilistic flood forecasts, and related warning information. For the purposes of this study, the EFAS v5.0 hydrological reanalysis dataset was used to identify flood events in Greece for the period of 2000–2022 [24].

2.1.3. Hellenic National Meteorological Service (HNMS) Climatic Data

The database of significant weather and climatic events maintained by the Hellenic National Meteorological Service (HNMS) includes major meteorological events observed in Greece from 2014 to 2022 (http://oldportal.emy.gr/emy/en/climatology/climatology_extreme, accessed on 10 March 2025). Event selection follows World Meteorological Organization guidance and is based on factors such as spatial extent, duration, severity, casualties, and impacts. This database was used to identify extreme weather events relevant to the present analysis.

2.1.4. Historic Events in Greece from the Ministry of the Environment

The national historical flood database of Greece, maintained by the Ministry of the Environment (https://ypen.gov.gr/, accessed on 10 March 2025), records flood events from 1980 to the present. The database includes information on event location, date of occurrence, flood type, mechanism, source, affected area, damage characteristics, and reported losses. In the present study, it was used as an additional source for the identification of flood events.

2.1.5. EM-DAT

EM-DAT is an internationally recognised disaster database maintained by the Centre for Research on the Epidemiology of Disasters and UCLouvain. It contains information on natural and technological disasters at the country level, including human and economic losses. In this study, EM-DAT was used as a complementary source for the identification of extreme events in Greece.

2.2. Database

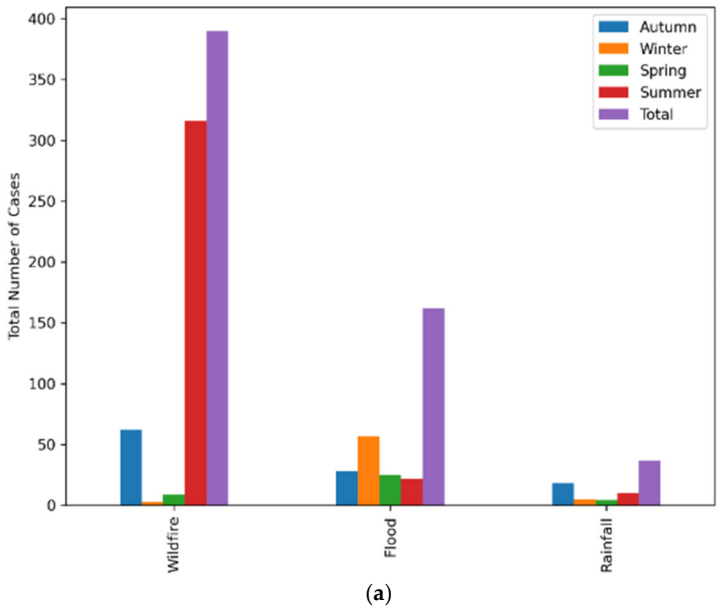
The different kinds of hazard data described in Section 2.1 were gathered together to create a homogeneous database of all types of extreme events, namely wildfires, floods and rainfall, that took place from 2000 to 2020 in the Greek area. The format of the created database is presented in Table 2.

Table 2. Extreme events database format.

Date	Longitude	Latitude	Area	Type
YYYYMMDDTIME	° (Degrees)	° (Degrees)	City/Village	Wildfire/Flood/Rainfall

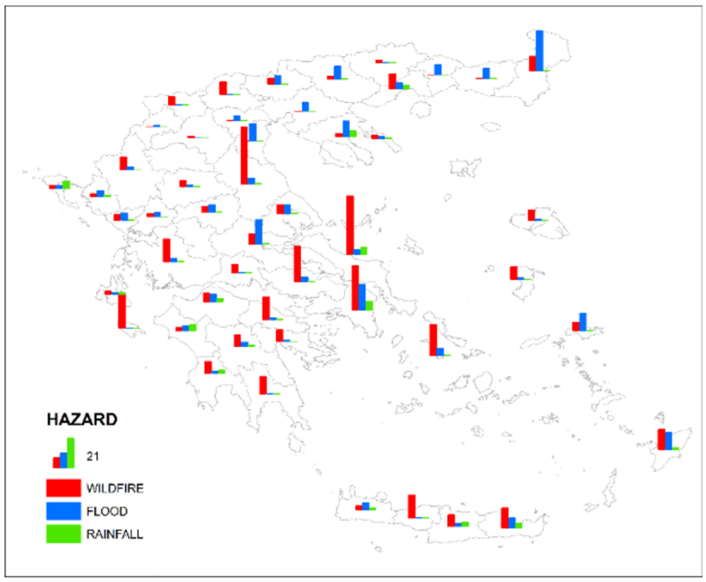
In total, 589 extreme events were identified. As shown in Figure 1a, the most frequent extreme event was wildfire (390 cases), followed by floods (162 cases) and rainfall (37 cases). Regarding seasonality, the majority of wildfires (316 of 390 cases) occurred during the summer period with 62 wildfire events in autumn, 9 in spring, and only 3 in winter. In contrast, floods occurred with similar frequency in winter (57 cases) and autumn (58 cases), as well as in spring (25 cases) and summer (22 cases). Finally, extreme rainfall events were most common in autumn (18 cases) and summer (10 cases), and relatively rare in winter (5 cases) and spring (4 cases).

Figure 1b displays the total number of cases by hazard type for each regional department. On the map, bars indicate the observed extreme events. The number shown next to each bar in the legend corresponds to the value represented by the longest bar in the chart, while the shorter bar represents half that value. All the bars are scaled so that the longest bar equals the largest attribute value, and the shorter bar is half that size. For example, if the highest number of cases in a region is 42, half of that is 21. According to the results, the highest number of wildfire cases were recorded in Larisa and Evia (approximately 42 cases), which are located in the eastern part of Greece and are affected by Etesian winds [2]. A significant number of wildfires also occurred in Attiki (approximately 30 cases), Voiotia (approximately 21 cases) and Zakynthos (approximately 21 cases). In contrast, floods were more frequent in Evros (approximately 30 cases), Attiki (approximately 15 cases) and Fthiotida (approximately 15 cases). Finally, most cases of extreme rainfall were observed in Attiki (approximately 5 cases).



(**a**)

Figure 1. *Cont.*



(**b**)

Figure 1. Frequency histograms of the number of events (**a**) for each type of hazard per season and (**b**) for each type of hazard per regional department.

3. Methodology

3.1. Description of the Overall Methodology

In the current study, the methodology relies on the aforementioned extreme events dataset in Greece (see Section 2) and historical atmospheric data from ERA5. The atmospheric data served as input to the HYSPLIT Lagrangian trajectory model along with the necessary parameterisation to create back-trajectories. The resulting trajectory dataset was further processed and transformed into a format suitable for clustering algorithms. This approach enabled the assessment of the weather patterns. Figure 2 illustrates the entire process, and a detailed description is presented in the following sections.

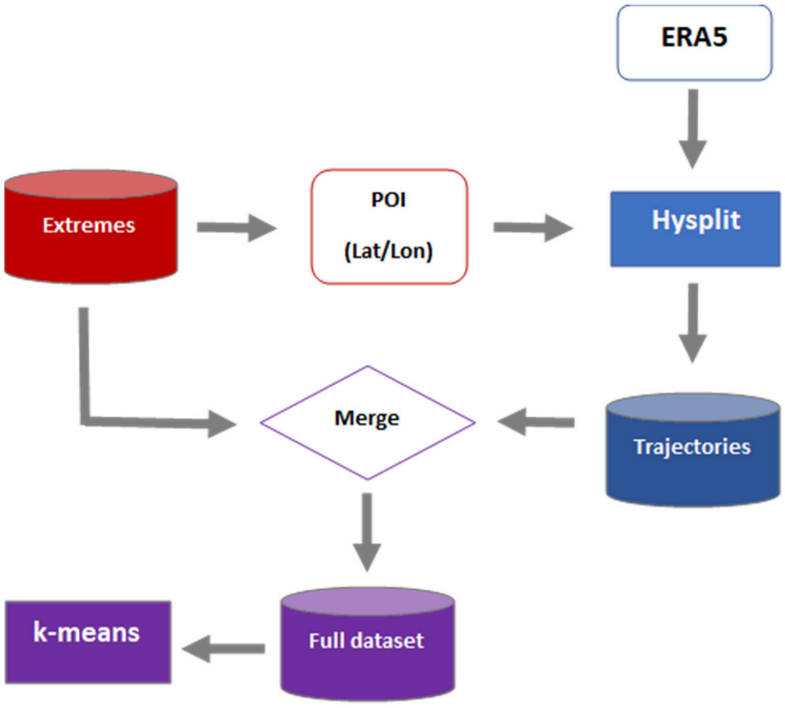


Figure 2. Illustration of methodology flow process.

3.2. Backward Trajectory Analysis

The ERA5 atmospheric dataset was used as input to the Hybrid-Single Particle Lagrangian Integrated Trajectory (HYSPLIT for Unix, v4.2) model. HYSPLIT performs air mass trajectory calculations and dispersion of atmospheric pollutants and deposition simulations. The model can simulate pollutant events; the transport of volcanic ash, desert dust, smoke from wildfires; and radioactive dispersion [18,19]. For the current study, the trajectory travel time was set to 96 h to allow for the identification of air masses reaching the boundaries of Europe, a commonly used duration in similar studies [13,15,16]. The 4-day (96 h) backward trajectories were estimated, arriving at noon (12:00 UTC) at the Point of Interest (POI) where the extreme events occurred. In addition, two different heights were selected: (a) 750 m ASL, which is well below the Planetary Boundary Layer (PBL) at noon and strongly influenced by local conditions and turbulence, and (b) 3000 m ASL, which is located in the free troposphere [14,17].

3.3. Data Preparation

To apply AI/ML techniques, the extreme events database and the 3-dimensional trajectories produced by HySPLIT must be merged and processed appropriately. In the trajectory results, a data scheme was applied that specifies the instances included in each trajectory and defines the features as the geographical coordinates (latitude (LAT), longitude (LON)) for every 6 h span (32 features in total). In addition, the LAT/LON values were projected and transformed into metric distances to satisfy the requirements of the clustering algorithms. As such, a Cartesian projection of LAT/LON suitable for the region under study and the available distance metric were applied with parameters that define LCC as False Easting, False Northing, Central Meridian, Standard Parallel 1, Standard Parallel 2, Scale Factor, and Latitude Of Origin, with values equal to 0.0, 0.0, 16.0, 30.0, 60.0, 1.0, and 42.5, respectively. The final dataset was merged with the extreme events data, resulting in the complete information needed for the analysis.

3.4. k-Means Clustering

In this study, the k-means algorithm was selected to assess the meteorological patterns associated with extreme events due to its simplicity and strong performance with large datasets [20,21]. Compared with other clustering approaches, k-means offers a practical balance between simplicity, robustness, and interpretability for the present application. Since the objective of the study was to identify the dominant air-mass transport patterns associated with each hazard type, a method that yields clear and physically interpretable representative clusters was preferred. For this reason, k-means was considered appropriate for the classification of back trajectories in the current analysis. The cluster analysis grouped trajectories according to their distance from the origin, considering wind speed and wind direction. Key elements that require extra attention are the number of clusters and the initial position of the centroids. In this study, the normalised "compactness and separation" criterion proposed in [25] was used to estimate the number of clusters. The dependency of the solution on the initial position of the cluster centroids was addressed conducting multiple trials with different seed numbers; the differences among the resulting clusters were found to be statistically insignificant using Levene's statistical test [26].

4. Results

4.1. Wildfires

Following the methodology described in previous sections, the air masses arriving at 750 m ASL in Greece on days when wildfires occurred were grouped into three back trajectory clusters, each with varying frequencies (Figure 3). The dominant pattern shown

in blue (53.8%) corresponds to short-distance northeasterly airflow. This wind direction is associated with the persistent regional-scale "Etesian winds", which blow from May to September in the lower atmosphere over the Aegean Sea. Etesian winds have also been associated with Greek wildfires in previous studies. The authors of refs. [2,3], who attempted to link weather types and wildfires in Greece during the periods of 1985–2004 and 1985–2002, respectively, found that most wildfires occurred under the prevalence of Etesian winds. More recently, the authors of [6], who investigated atmospheric circulation patterns related to fire weather in Greece, also confirmed the association of Etesian winds with wildfires. The second, more frequent (26.7%) back-trajectory pattern associated with wildfires is represented by the green line in Figure 3, which corresponds to a short-distance west-northwest airflow. This finding is consistent with previous studies. For example, the authors of [4], who studied the wildfire that occurred on 9 July 2000, identified WNW airflow in the Korinthia regional department of Greece, which was driven by an Atlantic high/Central and Eastern European low-pressure system. Additionally, WNW airflow was also observed on 23 July 2018, when the MATI wildfire broke out [5]. Finally, the 19.5% of back-trajectories at 750 m ASL during wildfires in Greece were associated with long-distance northwest airflow (orange points in Figure 3). Similar airflow trajectories were found by Papadopoulos [4] for wildfires that occurred on 9 July 2000 and 28 July 2001 in the Korinthia and Evros regional departments of Greece.

In Figure 4, the clustering analysis results for the back trajectories of air masses arriving at 3000 m ASL in the Greek area on the days when wildfires began are presented. Similarly to the results at 750 m ASL, three clusters were found. The two dominant patterns, with frequencies of 45.2% (orange points in Figure 4) and 34.0% (green points in Figure 4), correspond to short-distance airflow from the northwestern and western Mediterranean, while a less frequent pattern (with a frequency of 20.8%) originated from the North Atlantic Ocean. The orange and green airflow paths shown in Figure 4 can be associated with positive geopotential height anomalies over western and northern Europe during the Greek wildfires [6]. On the other hand, the western wind flow (blue pattern in Figure 4) agrees with similar studies [5] that investigated atmosphere-fire interactions during two high-impact wildland fire events (Mati, Kineta) that took place on 23 July 2018 in the Attica Region.

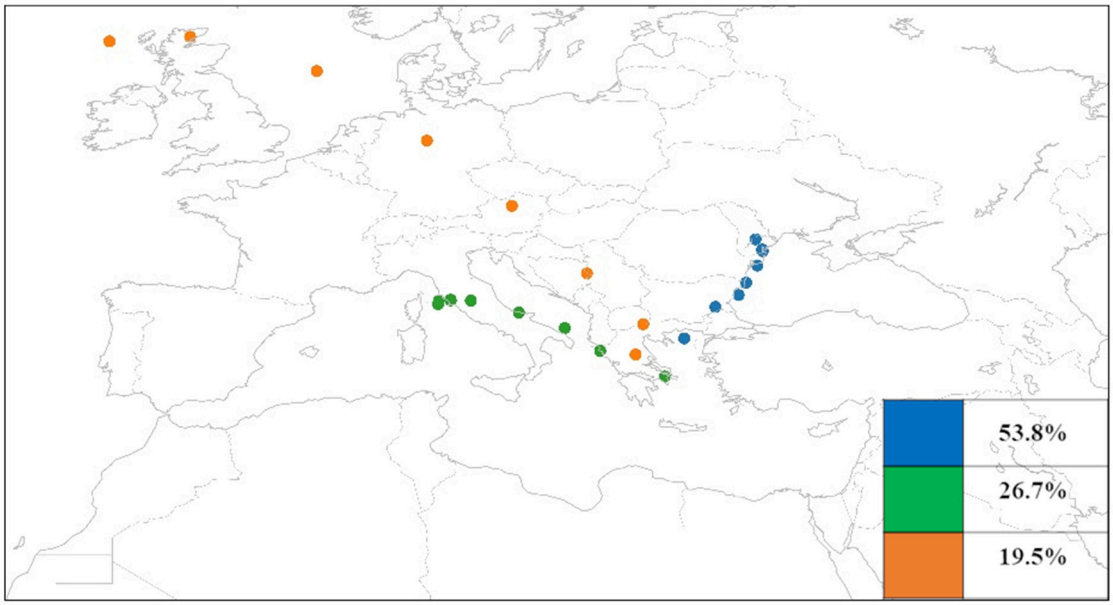


Figure 3. Back-trajectory clusters at 750 m for wildfire events in the period of 2000–2020. The table on the right shows the percentage of observations in each cluster.

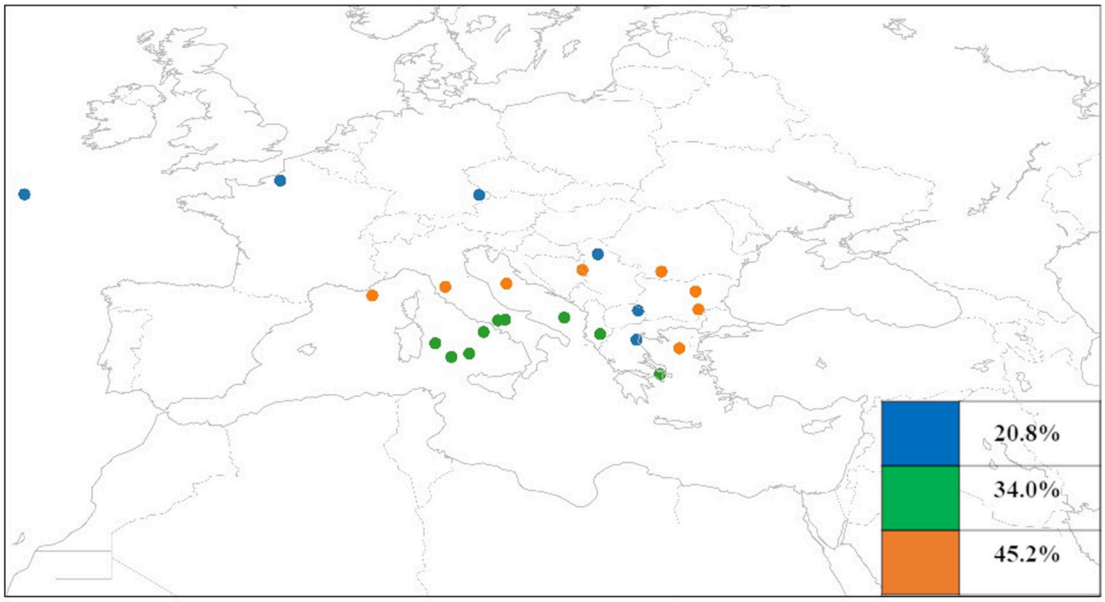


Figure 4. Back-trajectory clusters at 3000 m for wildfire events in the period of 2000–2020. The table on the right shows the percentage of observations in each cluster.

4.2. Floods

In the case of floods, the air masses arriving at 750 m ASL over Greece on days when a flood event occurred were grouped into three clusters of back trajectories with varying frequencies of occurrence (Figure 5). As shown in Figure 5, the dominant pattern is the blue one (54.3%), which corresponds to short-distance northeast airflow. This pattern is consistent with the cyclonic surface circulation over Greece reported by the authors of [8] in their climatological analysis of cyclonic tracks associated with flood events in Crete: when a depression is positioned to the west of the Greek peninsula, the cyclonic flow produces northeast winds at low levels over the Aegean and mainland Greece. The second most frequent (40.7%) back-trajectory pattern is the green one in Figure 5, which corresponds to northwest airflow of Atlantic-UK origin. The authors of ref. [7] reached similar conclusions, arguing that a low-pressure system positioned over Italy drives northwest flow near the surface over Greece while simultaneously establishing southwesterly airflow at 850 and 500 hPa, a configuration in which the surface component corresponds well to the northwest trajectory identified here. Finally, only 4.9% of the back trajectories at 750 m ASL during flood events were associated with northwest airflow of more proximal origin, with trajectories passing above northern Italy before reaching Greece (orange pattern in Figure 5). This less frequent pattern, also discussed in the context of flood-generating atmospheric conditions in Greece in [27], likely reflects the influence of localised Mediterranean cyclogenesis over the Adriatic-Apennine sector, which can produce intense but spatially limited precipitation episodes.

In Figure 6, the clustering analysis results for the back trajectories of the air masses arriving at 3000 m ASL over Greece on the days when flood events began are presented. Unlike the clear dominance observed at 750 m ASL, the three clusters at 3000 m ASL show nearly equal frequencies: 36.7% for the blue pattern (west airflow originating from northern Spain), 33.5% for the orange pattern (northwest airflow originating from the Slovenia-Croatia region), and 29.7% for the green pattern (southwest airflow originating from Morocco). This almost equal distribution of upper-level trajectory clusters suggests that Greek flood events are not associated with a single dominant free-tropospheric circulation regime but rather develop under a variety of large-scale upper-level configurations. These pathways imply that the lower-tropospheric moisture convergence and cyclonic

organisation, rather than a specific upper-level flow direction, constitute the primary precondition for flooding in Greece. The west and northwest upper-level patterns (blue and orange clusters) are consistent with the deep-layer southwest transport documented in [9], which showed that southwest airflow at 700 hPa, driven by a low-pressure system over the western Mediterranean Sea, was the primary mechanism of moisture transport during the Mandra flash flood of 15 November 2017 in Attica. The southwest upper-level pattern (green cluster, 29.7%) was mentioned in a previous study [10] that identified low-pressure systems over the eastern Mediterranean Sea as a systematically recurring synoptic configuration associated with flood occurrence across Greece. This suggests that this cluster reflects the role of eastern Mediterranean cyclogenesis in providing upper-level forcing for flood-producing precipitation.

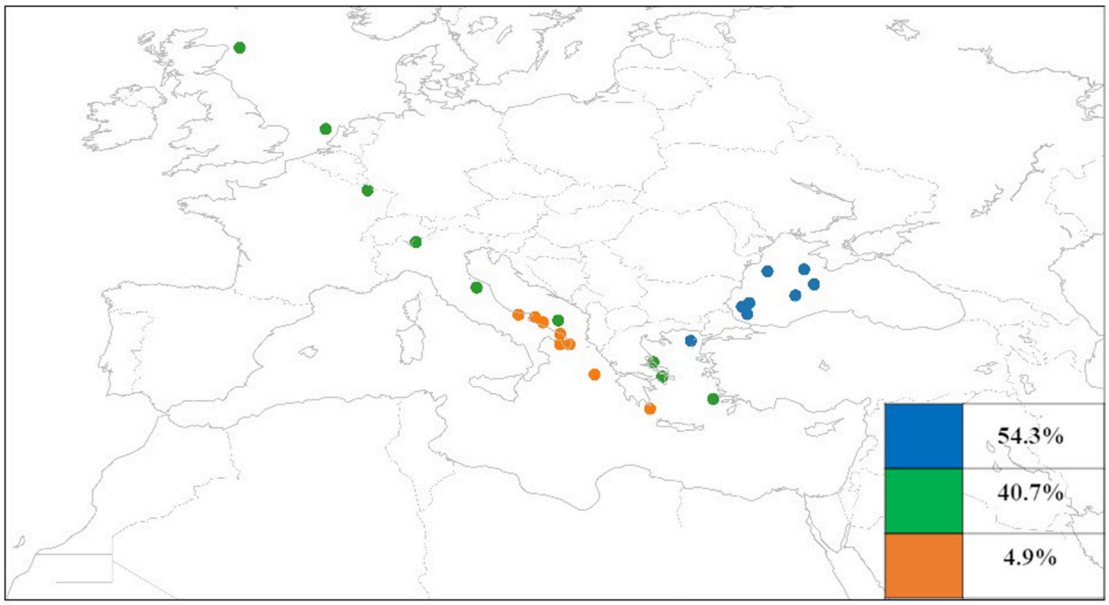


Figure 5. Back-trajectory clusters at 750 m for flood events in the period of 2000–2020. The table on the right shows the percentage of observations in each cluster.

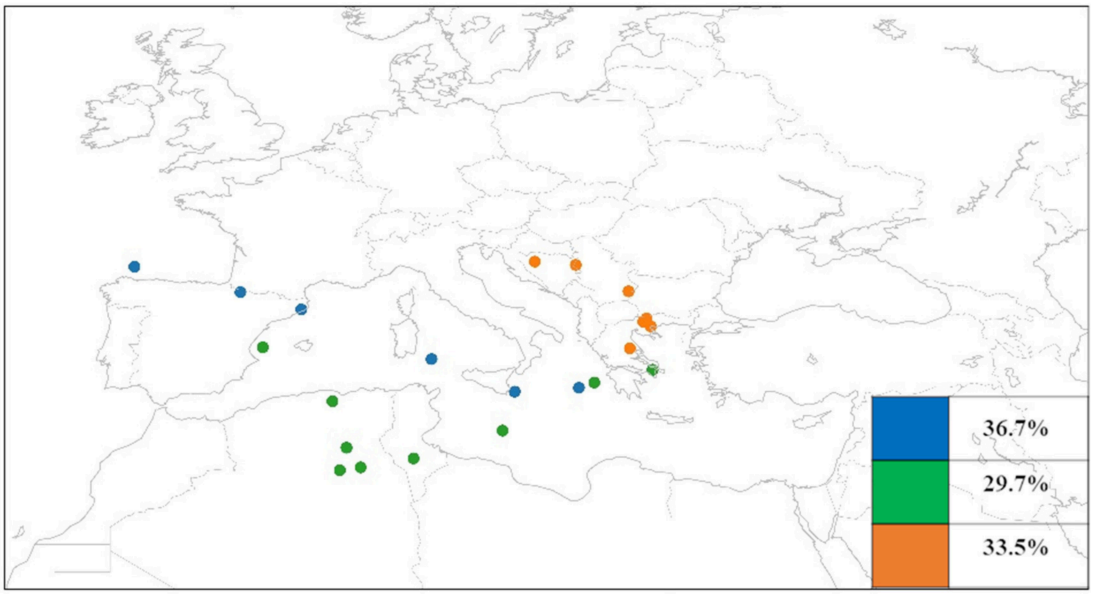


Figure 6. Back-trajectory clusters at 3000 m for flood events in the period of 2000–2020. The table on the right shows the percent observations in each cluster.

4.3. Rainfall

For extreme rainfall events, the air masses arriving at 750 m ASL over Greece on the relevant days were grouped into three clusters of back trajectories with varying frequencies of occurrence (Figure 7). The results at 750 m ASL show two clusters with identical frequencies of 44.4%: the green pattern, corresponding to south airflow originating from Egypt, and the orange pattern, corresponding to northeast airflow originating from the Georgia-Black Sea region (Figure 7). These two equally frequent clusters had contrasting source regions. This suggests that extreme rainfall in Greece at this atmospheric level is not driven by a single prevailing circulation pattern but rather by two pathways with almost equal probability. One pathway comes from the southern Mediterranean and North Africa, and the other from the northeastern continental sector. This finding is consistent with [11], which demonstrated that distinct atmospheric circulation clusters correspond to extreme precipitation in different geographical regions of Greece, implying that the two equally dominant clusters identified here may preferentially drive intense rainfall in different parts of the country. The northeast orange cluster is supported by other studies [12], which associated northeast flow over Athens with heavy rainfall events in Crete. These events are driven by a trough over the eastern Mediterranean combined with a ridge over the western Mediterranean Basin. Lastly, only 11.1% of the back trajectories at 750 m ASL during extreme rainfall were associated with westward airflow of proximal origin. These trajectories passed above northern Italy before reaching Greece (blue pattern in Figure 7), reflecting the occasional contribution of Atlantic–Mediterranean synoptic systems to extreme rainfall in Greece.

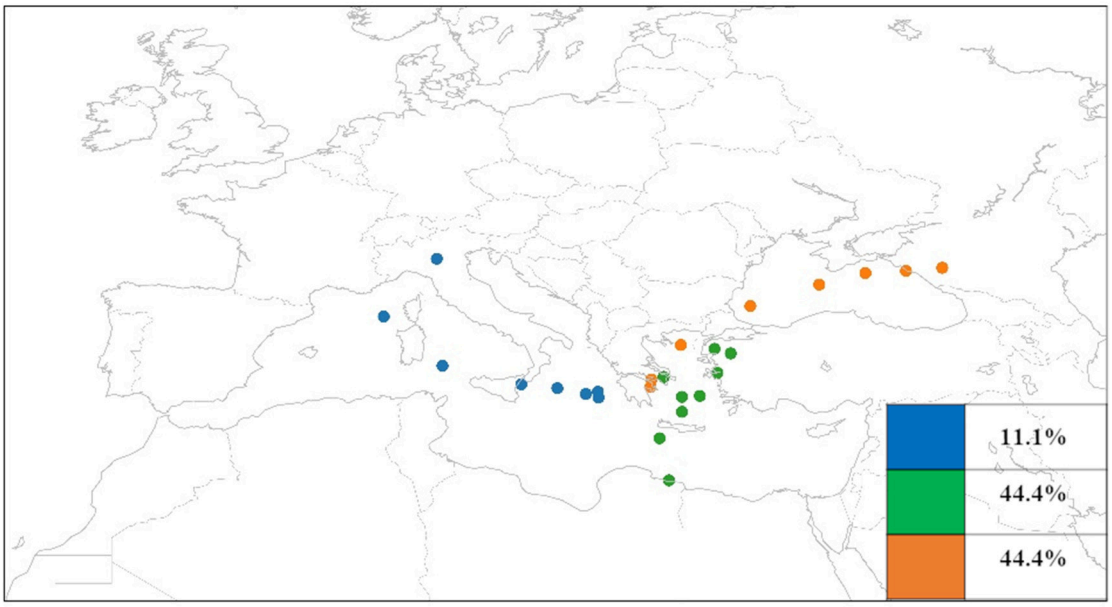


Figure 7. Back-trajectory clusters at 750 m for rainfall events in the period of 2000–2020. The table on the right shows the percent observations in each cluster.

Figure 8 presents the clustering analysis results for the back trajectories of air masses arriving at 3000 m ASL over Greece during extreme rainfall events. Three clusters were identified, with the dominant one being the green pattern (48.7%), which presents a complex, recurving western trajectory. These air masses originated from northwestern Africa, travelled westward and southward into the eastern Atlantic, and then re-entered the Mediterranean from the west and reached Greece from the southwest via central Italy. This pattern is characteristic of a cut-off low or blocking anticyclone, where a detached low-pressure system becomes isolated from the main westerly flow and recirculates air masses.

Such configurations are known to be associated with prolonged and intense precipitation episodes in the Mediterranean region [28]. The second most frequent cluster was the blue one (37.8%), which corresponds to a more direct western low-pressure system originating from southern Spain. This is consistent with the western airflow at 3000 m, which was described in [29] based on a back-trajectory analysis of extreme rainfall in southern Greece and the Aegean islands. Lastly, 13.5% of the back trajectories at 3000 m ASL were associated with northerly airflow originating from Ukraine (orange pattern in Figure 8), a less frequent pattern that the authors of [11] suggested may preferentially correspond to extreme rainfall in specific northern or northwestern regions of Greece, where orographic enhancement of continental cold-air advection can trigger convective precipitation.

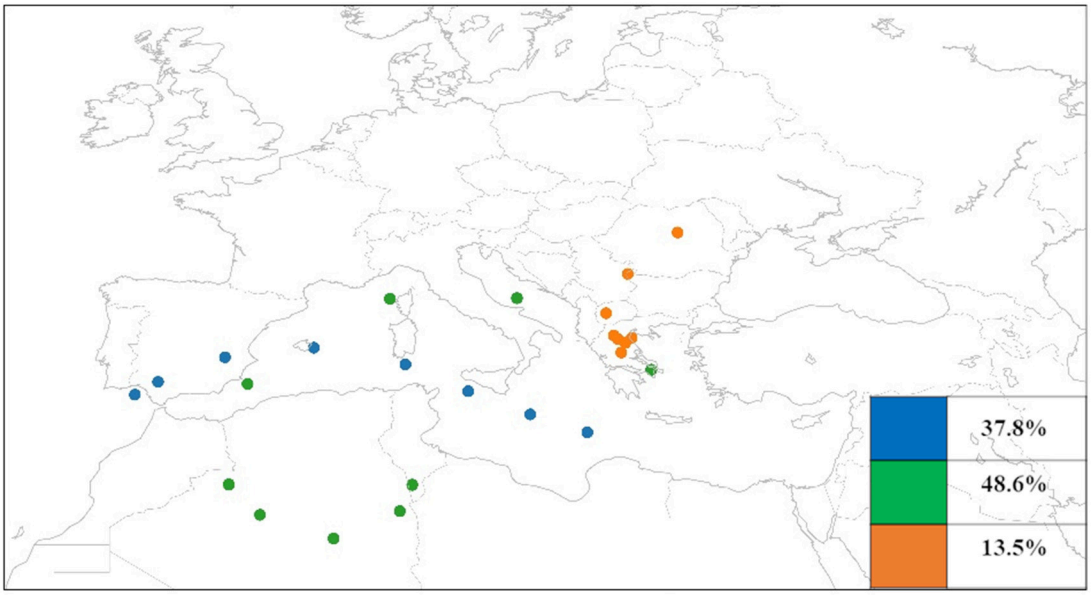


Figure 8. Back-trajectory clusters at 3000 m for rainfall events in the period of 2000–2020. The table on the right shows the percent observations in each cluster.

5. Discussion

The back-trajectory clustering analysis in this study reveals distinct, hazard-specific patterns, which partially overlap in terms of atmospheric circulation. Each hazard type displays its own characteristic air mass pattern, yet the comparative analysis uncovered both physical contrasts and shared mechanisms, revealing patterns of extreme event climatology in the eastern Mediterranean. It is noted that while the 96 h backward trajectories allow for the identification of synoptic-scale transport pathways, they may not fully represent shorter-lived mesoscale features. In addition, the ERA5 reanalysis, despite its high quality and broad applicability, may not completely resolve localised convective dynamics and terrain-related effects, especially for flash-flood events. These limitations should be considered when interpreting the resulting trajectory clusters.

5.1. Near-Surface Circulation

At 750 m ASL, both wildfires and floods are dominated by a northeast cluster (53.8% and 54.3%, respectively), a similarity that reflects different physical mechanisms. For wildfires, the northeast flow aligns with the Etesian wind system, a persistent anticyclonic circulation active from May to September over the Aegean Sea, characterised by dry, stable, and hot conditions that promote fuel desiccation and fire spread [2,3,6]. In contrast, for floods, the northeast cluster represents the eastern flank of a westward-positioned Mediterranean depression. The latter configuration is associated with moisture advection,

cyclonic convergence, and enhanced precipitation [7,8]. Thus, trajectory-only analysis can be insufficient, as identical near-surface flow geometries may arise from entirely opposite drivers, and the physical attribution of a cluster cannot be separated from its seasonal context and the associated thermodynamic state of the atmosphere. In cases of extreme rainfall events at 750 m ASL, two clusters were present, each sharing an identical frequency of 44.4%. This suggests that intense precipitation in Greece develops with near-equally probability under two contrasting moisture pathways; (i) one of North African origin and (ii) one of continental northeastern origin. This highlights the strong regional variability of Greek rainfall-producing circulation types [11].

5.2. Free-Tropospheric Circulation

At 3000 m ASL, the three hazard types diverge considerably in their clustering structure, reflecting different large-scale dynamical mechanisms. Wildfire events displayed the strongest upper-level signal, with two dominant clusters, one from the northwestern Mediterranean (45.2%) and one from the western Mediterranean (34.0%), jointly accounting for 79.2% of the trajectories. This pattern is physically consistent with a persistent summer blocking anticyclone over western and northern Europe. Its positive geopotential height anomaly establishes the warming and drying weather that provides the ideal conditions for extreme fire weather in Greece [6]. The remaining 20.8% of wildfire upper-level trajectories originated from the North Atlantic, likely corresponding to late- or early-season events when the summer anticyclone weakens and Atlantic systems begin to penetrate the Mediterranean basin. This hypothesis requires further investigation by cross-referencing with the seasonal distribution of wildfire events.

On the other hand, flood events at 3000 m ASL show a nearly equal three-way split among the west (36.7%, northern Spain origin), northwest (33.5%, Slovenia–Croatia origin), and southwest (29.7%, Morocco origin) clusters. This near-uniform distribution implies that Greek flood events are not conditioned by a single dominant circulation mechanism but rather develop under a variety of upper-level configurations. This suggests that the predominant factor in flood generation is not the large-scale flow direction but the organisation of low-level circulation and moisture convergence over or near the Greek peninsula [9,10].

In case of extreme rainfall events, the most complex upper-level structure between the three hazard types was observed. The dominant cluster at 3000 m ASL (48.7%, green pattern) describes a recurving trajectory in which air masses originating from northwestern Africa travel westward and southward into the eastern Atlantic, reverse direction northward, re-enter the Mediterranean from the west, and arrive over Greece from the southwest via central Italy. This pathway is a known signature of a cut-off low and closed upper-level cyclonic circulation. Those patterns become detached from the main western jet stream and recirculate air masses through an anomalous trajectory before delivering them to the eastern Mediterranean. They are considered triggers of extreme precipitation events in the Mediterranean basin [28]. The second upper-level cluster (37.8%, west of southern Spain) is consistent with the western airflow at 3000 m [29] during extreme rainfall episodes in southern Greece and the Aegean islands. The north cluster from Ukraine (13.5%) may preferentially correspond to orographically enhanced rainfall in the northern and northwestern regions of the country.

5.3. Implications for Early Warning and Risk Assessment

The results of this study have practical implications for the early warning of extreme events in Greece. The strong association between wildfires and the Etesian wind regime provides a robust and physically interpretable precursor signal that can be monitored operationally through standard analysis. For floods, the diversity of both near-surface and

upper-level trajectory clusters highlights the need for multi-scale monitoring strategies. The latter should prioritise detecting Mediterranean surface cyclogenesis instead of relying solely on a single upper-level precursor. In the case of extreme rainfall, the cut-off low signature cannot be utilised as the dominant upper-level driver as is, and an accurate medium-range numerical weather prediction beyond the 5–7-day horizon is necessary. In general, integrating Lagrangian trajectory-based air mass classification into operational hazard monitoring frameworks for the eastern Mediterranean can complement and existing mesoscale approaches and support them.

6. Conclusions

This study applied a Lagrangian back-trajectory approach combined with k-means clustering to characterise the origins of air mass associated with three categories of extreme events, wildfires, floods, and extreme rainfall, that occurred in Greece between 2000 and 2020. Analyses were conducted at two atmospheric levels (750 m and 3000 m ASL), enabling simultaneous examination of near-surface and free-tropospheric circulation patterns. The results demonstrate that each hazard type is associated with a distinct atmospheric circulation pattern. A cross-hazard comparison further revealed that similar near-surface trajectory patterns may arise from different drivers, highlighting the need to integrate trajectory analysis with additional contextual information. Operationally, the analysis provides suggestions for hazard-specific early warning strategies, such as monitoring the Etesian regime for wildfire risk, tracking Mediterranean surface depressions for floods, and improving numerical simulations for extreme rainfall forecasting.

Notably, the dataset covers the period of 2000–2020 and is sufficiently large for wildfires (390 cases) and floods (162 cases); however, the extreme rainfall sample (37 cases) is relatively small, which may limit the statistical robustness of the rainfall clustering results. Additionally, the HYSPLIT trajectory analysis is purely kinematic and does not account for the thermodynamic properties of transported air masses, such as moisture content, temperature, or stability indices. Furthermore, although ERA5 reanalysis data (~29 km) are state of the art, this spatial resolution may not fully resolve mesoscale features relevant to localised extreme events over the complex terrain of Greece. Therefore, future research could extend this framework in several directions, including the incorporation of thermodynamic variables along computed trajectories, application of the methodology to projected future climate conditions and expansion of the analysis to additional hazard types and regions. These enhancements would provide more information to aid in interpreting the identified clusters and allow for the assessment of potential shifts in air mass origins and their implications for the future frequency and intensity of extreme events in Greece.

Author Contributions: Conceptualization, S.K., M.G. and A.S.; methodology, S.K. and M.G.; data curation, S.K. and M.G.; formal analysis, S.K. and M.G.; writing—original draft preparation, S.K. and M.G.; writing—review and editing, S.K., D.V. and A.S.; visualisation, M.G.; supervision, S.K. and A.S.; project administration, S.K. and A.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The data presented in this study are available from multiple public repositories. These data were derived from the following resources available in the public domain: EM-DAT (https://www.emdat.be/, accessed on 10 March 2025), EFFIS (https://forest-fire.emergency.copernicus.eu/apps/data.request.form, accessed on 10 March 2025), EFAS (https://data.jrc.ec.europa.eu/collection/id-0068#datasets, accessed on 10 March 2025), HNMS (http://oldportal.emy.gr/emy/en/climatology/climatology_extreme, accessed on 10 March 2025), and Greece Historic Events from the Ministry of the Environment (https://ypen.gov.gr/, accessed on 10 March 2025).

Acknowledgments: During the preparation of this manuscript, the authors used Peplexity AI to polish language and style for first draft version. The authors have reviewed and edited the output and take full responsibility for the content of this publication.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

ASL	Above Sea Level
DG ECHO	European Commission Humanitarian Office
DG ENV	Directorate General for Environment
EFAS	European Flood Awareness System
EFFIS	European Forest Fire Information System
EM-DAT	Emergency Events Database
ERCC	Emergency Response Coordination Centre
HNMS	Hellenic National Meteorological Service
HYSPLIT	Hybrid Single-Particle Lagrangian Integrated Trajectory
JRC	Joint Research Center
LAT	Latitude
LON	Longitude
PBL	Planetary Boundary Layer
POI	Point of Interest
WNW	West-Northwest

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