Eos

How Hail Hazards Are Changing Around the Mediterranean

A new method for studying hailstorms from space offers more consistent and more complete views of how and where hail forms, and how climate change might influence hail's impacts in the future.

By **Sante Laviola**, **Giulio Monte**, **Elsa Cattani,** and **Vincenzo Levizzani**
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Piles of hail sit in the Piazza della Rotonda in Rome in October 2018. Credit: TIZIANA FABI/AFP via Getty Images

The Mediterranean Basin is one of the

An Eye on the Mediterranean

most vulnerable areas on Earth to the effects of rapid climate change. Observed rates of temperature rise indicate that the region is [warming 20% faster]() compared with the global average, inducing a trend toward drier conditions and changing precipitation regimes. Historical data document that annual mean temperatures across the region followed the global pattern throughout most of the 20th century. Since about 1980, however, temperatures in the Mediterranean Basin have abruptly diverged and increased from the global trend, with average temperatures today 1.4°C higher than in the late 19th century [*Cramer et al.*, 2018].

The steep temperature rise increases the vulnerability of the Mediterranean Basin to several hazards that affect ecosystems and human health and security, such as heat waves, droughts, and fires. Along with such events, the frequency and intensity of storm-related hazards also may be amplified around the Mediterranean in a warming climate. Hail is one hazard of interest because of its [dangerous]() and [destructive]() nature, especially when hail particles grow to large sizes.

During summer 2021, for example, a series of hailstreaks heavily damaged crops, vehicles, and infrastructure in northern Italy. One of the most severe events occurred on 26 July 2021 near Fidenza, when a storm produced hailstones larger than 8 centimeters in diameter that caused [vehicle crashes and other damage]() on the A1 highway. A similar synoptic pattern affected northeastern Italy, including the city of

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Pordenone, on 1 August 2021, with very rapid and localized deep convection creating damaging hailstones upward of 5–6 centimeters in diameter.

The links between regional climate change and hail occurrence and damage around the Mediterranean remain unclear, however, in part because of a shortage of historical data documenting hail events and in part because of the complex and varied topography and conditions around the region that affect hail production. This uncertainty complicates efforts to model and forecast hail generation accurately.

Recently, we have been working to improve scientific understanding of hail in the Mediterranean using satellite remote sensing. After developing a new satellite-based method for detecting hail-bearing storms [***Laviola et al.***, 2020a], we have comprehensively quantified the occurrence of hail events around the region during the past 22 years (1999–2021) [***Laviola et al.***, 2022]. Our goal is to explore the distribution, seasonality, and frequency of events to identify "sub-hot-spot" areas within the Mediterranean that are most susceptible to hail events. This work has extended and updated the historical record of Mediterranean hail events, and it should help advance understanding of hail-generating processes, produce a global hail climatology, and illuminate possible ties between hail trends and ongoing climate change.

Detecting Hail from Space

Hail forms when strong updraft winds in storm clouds keep raindrops and ice particles aloft at high altitudes, where temperatures are below freezing and where these particles can collide and freeze into larger pieces. When hailstones become too large to be supported by the updrafts, they fall to the ground. Hailstorms are typically short-lived (<30 minutes) and affect limited geographic areas (<10 kilometers), factors that significantly complicate their observation where ground-based instruments are not available.

Hailstones can vary in diameter from a few millimeters to more than 10 centimeters. The pieces shown here are roughly 8–9 centimeters across. Credit: iStock.com/spxChrome

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Satellite sensors, with their wide range of sounding frequencies, high spatial resolution, and increasing abundance in low Earth orbits, offer substantial promise for hail detection and investigation on regional to global scales.

The **Global Precipitation Measurement Constellation** (GPM-C) is an international mission designed for measuring precipitation using microwave sensors aboard about a dozen satellites. Satellite microwave instruments probe precipitating clouds by sensing perturbations in Earth's natural microwave radiation field caused by liquid or frozen water droplets (hydrometeors). High-frequency microwave channels (>60 gigahertz) on these instruments mostly capture the signal produced by ice hydrometeors, namely, graupels or hailstones, in the upper part of storm clouds. These large ice aggregates scatter microwaves, typically reducing the upwelling radiation field measured by satellites.

The hail detection method we developed, called Microwave Cloud Classification–Hail (MWCC-H), is based on the inverse proportionality between the amount of upwelling radiation and hail cross sections [*Laviola et al.*, 2020a, 2020b]. Through a probability-based model of growth, the MWCC-H interprets the signature from ice aggregates at 150–170 gigahertz to identify and isolate hail-bearing clouds in storm systems. For each detected hail cloud, the method calculates the probability of hail occurrence—and its potential severity—as a function of diameter (Table 1).

Table 1. Categories and Traits of Hail Considered in the Microwave Cloud Classification–Hail Method[a]

CATEGORY DESCRIPTION	PROBABILITY OF HAIL	DIAMETER RANGE, cm	KINETIC ENERGY, J	TERMINAL VELOCITY, $m\ s^{-1}$	POTENTIAL SEVERITY
Hail potential (HP)	0.20–0.36	—	—	—	absent to low
Graupel/hail initiation (HI)	0.36–0.45	<2	$<33.84 \times 10^{-2}$	<19.09	low to moderate
Large hail (H)	0.45–0.60	2–10	33.84×10^{-2} – 423	19.09–42.69	high to severe
Super hail (SH)	>0.60	>10	>423	>42.69	severe to extreme

[a]Adapted from *Laviola et al.* [2022], CC BY 4.0

By applying our new detection method to the high-frequency microwave sensor observations acquired by orbiting GPM-C satellites between 1999 and 2021, we investigated the susceptibility of different areas of the Mediterranean Basin to hail events over that time period [*Laviola et al.*, 2022]. The data set included observations of hail in all four size-severity categories described in Table 1, although we considered only the most severe events—that is, those with large (2- to 10-centimeter-diameter) or super (>10-centimeter) hail—in identifying Mediterranean sub-hot-spots of hail activity.

We divided the Mediterranean Basin into nine subregions and counted the number of occurrences of large or super hail during the April–November hail season from 1999 to 2021. Our analysis showed that parts of southern Europe, especially southern Italy, and central Europe experienced the most severe hail events over this period (Figure 1), and that the peak timing for these events varied somewhat by subregion, delineating their broader seasonality (Figure 2).

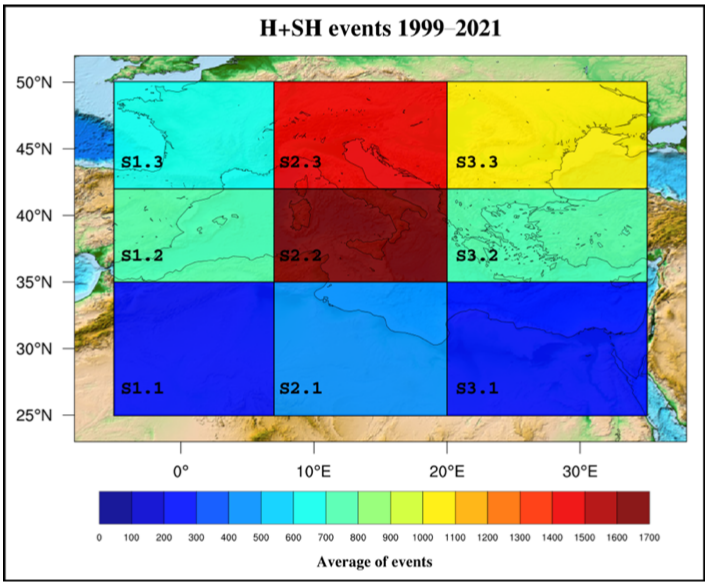

Fig. 1. The average annual number of large and super hail events (H and SH as defined in Table 1) from 1991 to 2021 varied greatly across nine subregions of the Mediterranean Basin. Regions S2.2 and S2.3, including Italy and other parts of southern and central Europe, experienced the most severe hail events over this period. Click image for larger version. Credit: Adapted from *Laviola et al.* [2022], CC BY 4.0

Different climatic and topographic factors influence convective activity, and thus the frequency and seasonality of hail formation, in different areas of the Mediterranean Basin. Western and central Europe (S1.3 and S2.3 in Figure 1), for example, are highly exposed to hail hazard in the summertime. Hail occurrence in these regions mostly relates to how the land surface morphology (e.g., the Alps or the Po Valley lowlands in northern Italy) interacts with atmospheric factors like moisture content and wind shear. In central to eastern Europe (S3.3), convective activity is often forced by local orographic influences of the Balkan and Carpathian mountains.

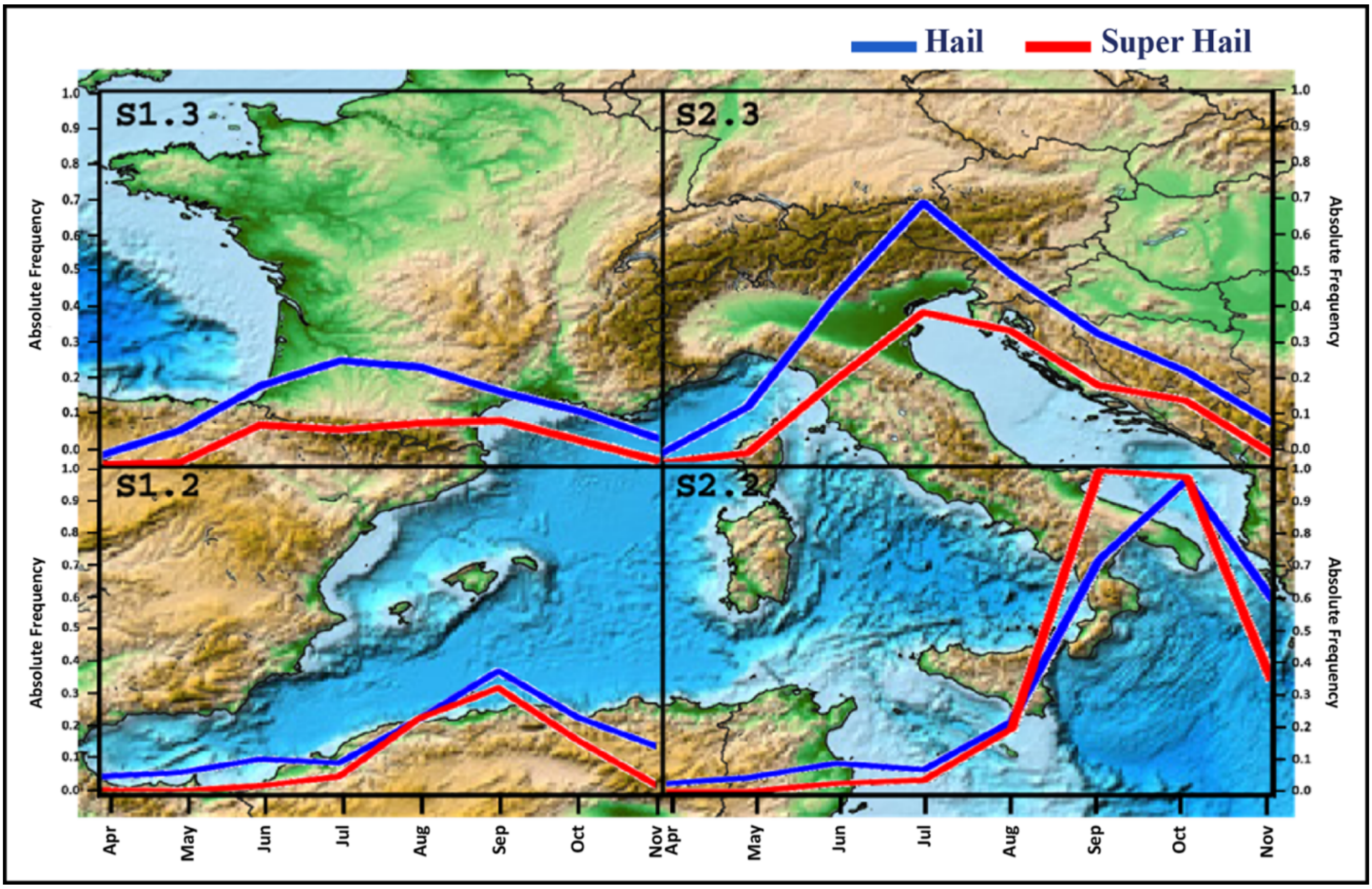

Fig. 2. The seasonality of large hail (blue) and super hail (red) events within the April–November "hail season" also varies across Mediterranean regions. The absolute frequency of events increases in midsummer in regions S1.3 and S2.3, for example, whereas in regions S1.2 and S2.2, events are more frequent in late summer and autumn. These plots are meant to show only the timing (seasonality) of events; the scaling of the *y*-axis differs for the numbers of large and super hail events. Credit: Adapted from *Laviola et al.* [2022], CC BY 4.0

The climate of southern Europe (S1.2, S2.2), including southern Italy and the eastern Iberian Peninsula, is dominated by high solar insolation and effects of the Mediterranean Sea. Across these areas, warm and moist air masses formed over the sea are primarily responsible for convection and the formation of severe hailstorms that peak during late summer and autumn.

In southeastern Europe (S3.2), the climate is influenced by complex local conditions. The Mediterranean and Black seas combined with numerous islands, several gulfs, and large mountain chains (e.g., in the Balkans and Anatolia) create local instabilities that can trigger vigorous convective activity and may play a role in hailstorm formation.

In the southern sectors of the study domain (S1.1, S2.1, S3.1), comprising much of North Africa and the Middle East, far fewer large or super hail events occurred than in other subregions because of the proximity of the arid Sahara desert. Where hail events do sometimes occur in North Africa, however, such as in Tunisia (lower left of S2.2) and Libya (S2.1), the late spring to summer seasonality is similar to that in other Mediterranean sectors.

The Unknown Contribution of Climate Change

Our analysis of the 22-year data set demonstrates, despite high interannual variability, that there are statistically significant (significance > 90%) increasing trends in the numbers of large hail and super hail events across the entire Mediterranean Basin (Figure 3). For both types of events, there has been a roughly 30% increase in the incidence of the phenomena in the past decade (2010–2021) with respect to the preceding 1999–2010 period.

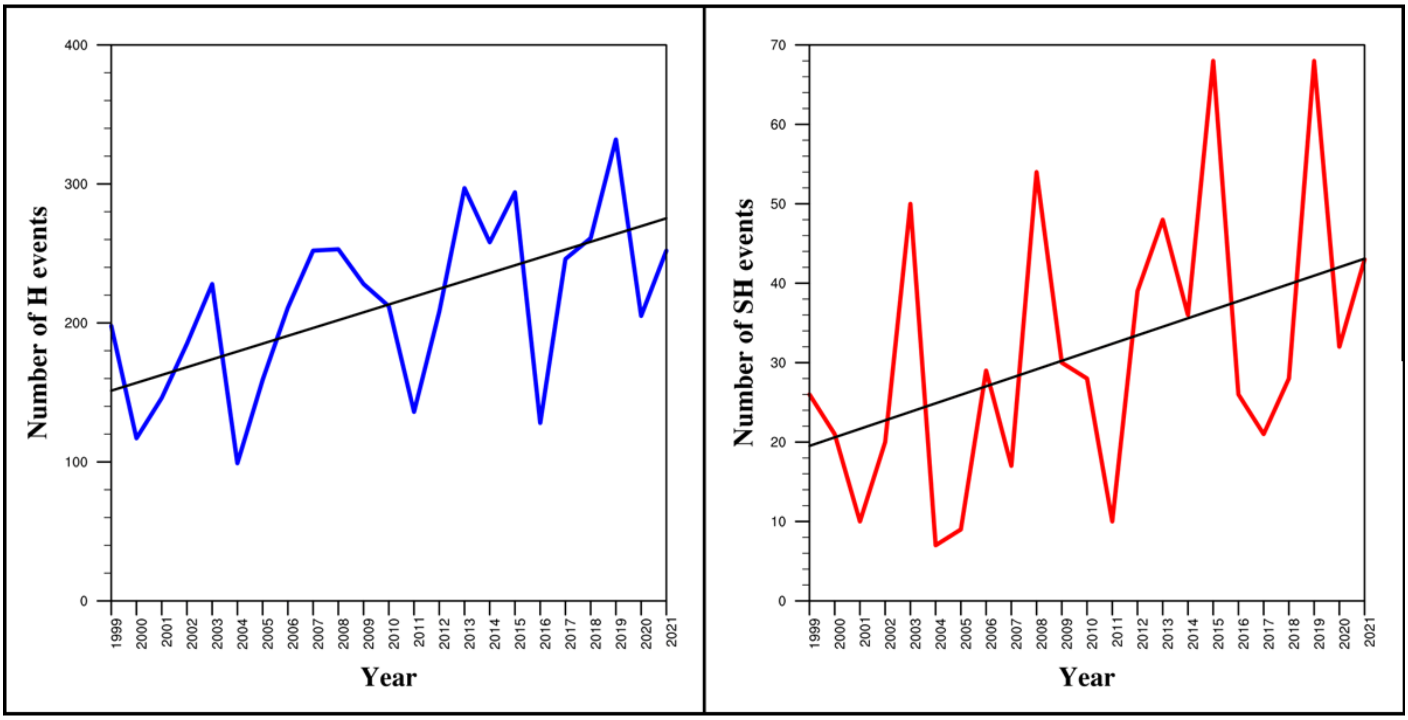

Fig. 3. The temporal evolution from 1991 to 2021 of the annual numbers of H and SH events for the entire Mediterranean Basin considering combined measurements from the NOAA 15, MetOp-A, and MetOp-C satellites. Black lines indicate the linearized trends of the data. Credit: Adapted from *Laviola et al.* [2022], CC BY 4.0

These rising trends raise questions about whether climate change is accelerating the occurrence or severity of hailstorms in the Mediterranean Basin. Such causal attribution is challenging, and these questions are far from answered. However, considering the high stakes for public safety of worsening hail hazards, we are investigating what conditions or factors are most favorable for hail production and how those conditions are changing with climate warming.

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The steep increase in hail events during the past 2 decades motivated us to explore trends around the Mediterranean in atmospheric variables generally thought to be precursors of the deep convective activity that can produce hailstones. These variables include the Convective Available Potential Energy (CAPE), which relates to atmospheric instability; the zero degree level (ZDEGL), or the altitude where the temperature is 0°C, which affects melting of ice hydrometeors; the temperature at 850 hectopascals (T850), which occurs at an altitude of roughly 1.5 kilometers, typically just above the boundary layer; and the sea surface temperature (SST).

Applying the Mann-Kendall test, which assesses monotonic trends in variables over time, to annually averaged data on these four variables from the European Centre for Medium-Range Weather Forecasts' Reanalysis Version 5 (ERA5) for the period 1959–2021 indicates that amid high variability, each of these key variables has increased during the past 62 years (Figure 4).

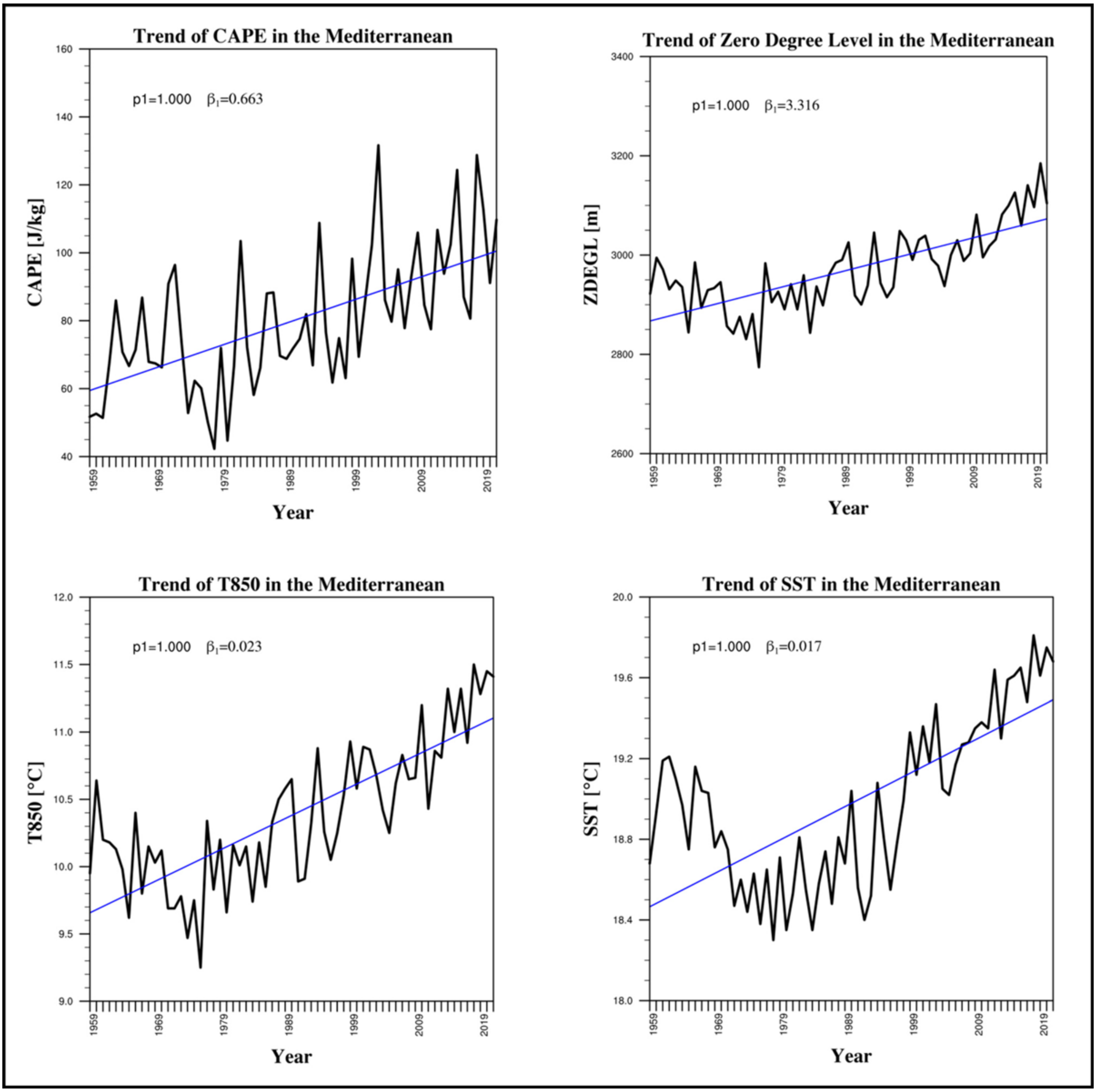

Fig. 4. Annual trends from 1959 to 2021 in the Convective Available Potential Energy (CAPE) in joules per kilogram, zero degree level (ZDEGL) in meters of altitude, temperature at 850 hectopascals (T850), and sea surface temperature (SST) calculated for the entire Mediterranean Sea. Blue lines indicate the linearized trends of the data. Credit: *Laviola et al.* [2022], CC BY 4.0

The approximate doubling of CAPE in the Mediterranean reflects enhanced atmospheric instability and, in turn, the tendency of the environment to form hail-bearing convective systems. The ZDEGL has risen by about 400 meters, on average, meaning hail has a longer distance over which to melt. Although this may allow smaller hail to melt into raindrops on its way to the ground, large and super hailstones that do not melt fully accrue more kinetic energy due to the longer path of their fall, thus making them more dangerous.

Finally, warming of T850 and SST can alter dynamics at the air-sea interface that trigger and intensify vigorous convections in the central basin of the Mediterranean Sea, thereby also potentially influencing hail formation.

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The upward trends in these factors do not prove their roles, or a role of climate change more broadly, in increased hail formation, but they suggest an atmosphere that has become increasingly primed to produce more and bigger hail. And it is widely understood that continuing warming will both amplify the intensity of extreme weather events and influence the probability of their occurrence, quite possibly including the locations and severity of hail impacts. Thus, it is vital that we rapidly improve our scientific understanding of the drivers of hail formation by integrating all available information from ground, air, and space.

Toward a Global Climatology of Hailstorms

Hailstorms are brief and localized events, but they potentially can pose a hazard almost everywhere in the world. Investigations of the phenomenon usually focus on hailstorms over land, where hail impacts are associated with or often derived from damages to agriculture or infrastructure, whereas no information is provided on hail events over the sea. The result is that we have a patchwork and **inconsistent understanding of hail events** and their effects.

Applying our hail detection method to the worldwide observations from GPM-C is the basis of a new approach to producing more complete and uniform hail data sets and thus more consistent hail maps, not just for the Mediterranean but also globally. After initially producing monthly global hail distribution maps with MWCC-H [***Laviola et al.***, 2020b], further advancements have allowed us to experiment with generating such maps at higher temporal resolutions (e.g., daily or even every 3 hours).

Figure 5 presents an experimental daily global map at a grid resolution of 1° × 1° showing the likelihood of hail events having occurred around the world on 10 July 2019. Probabilities for hail potential and hail initiation are used to better define hailstorm dynamics, as these categories are usually associated with the first stages of hail-producing convection. As expected, most large and super hail activity occurred in the tropics, and there were elevated probabilities in parts of the Mediterranean Basin (e.g., the Adriatic Sea and the Balkans) and the central United States, in agreement with the midlatitude seasonality of hail events. Meanwhile, few events were identified in the Southern Hemisphere (winter season).

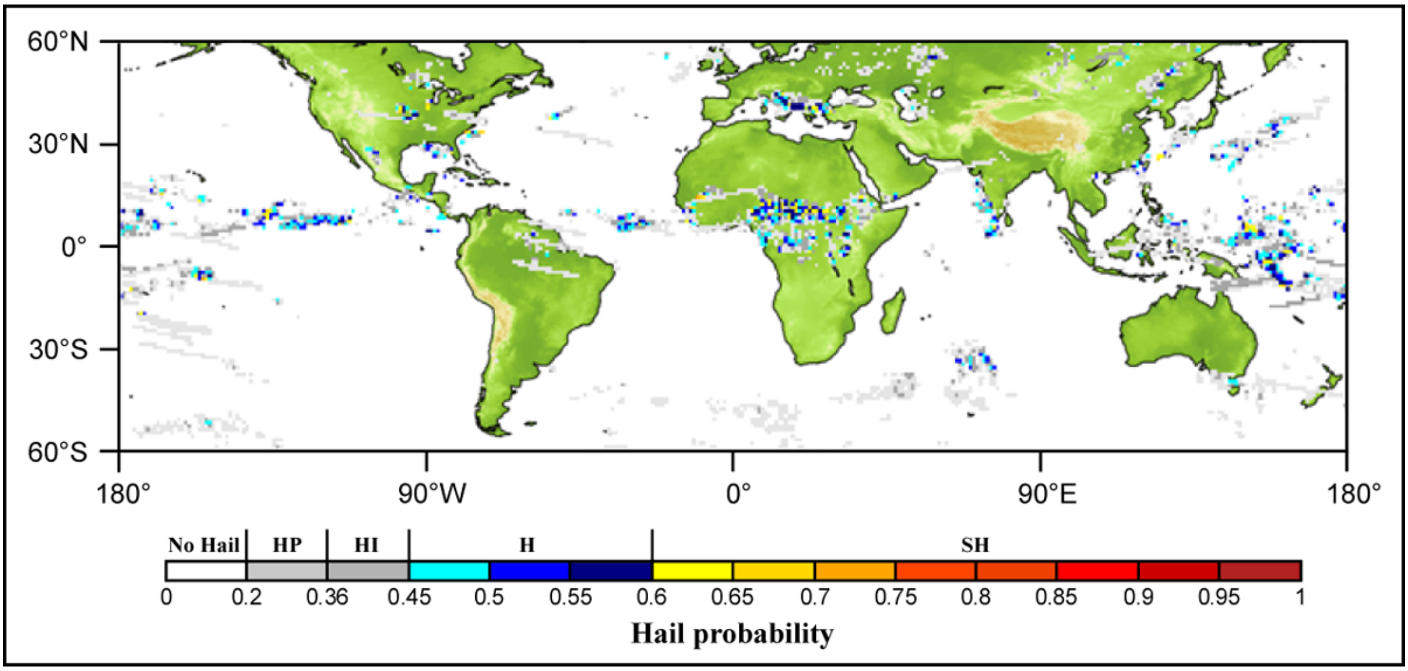

Fig. 5. Daily hail probability map showing the Microwave Cloud Classification–Hail categories (hail potential, HP; hail initiation, HI; large hail, H; and super hail, SH) calculated through the Global Precipitation Measurement Constellation (GPM-C) on 10 July 2019. The data set was retrieved using the daily orbits of nine platforms equipped with microwave radiometers: ATMS (Advanced Technology Microwave Sounder), MHS (Microwave Humidity Sounder), SSMIS (Special Sensor Microwave Imager/Sounder), and GMI (GPM Microwave Imager).

These data sets and global maps may be useful for both climatological studies of hail events and the operational needs of meteorologists. With frequent, recursive observations of worldwide hail distribution and severities affecting different regions, researchers can significantly improve predictive climate and weather models. Observation of hail events at a global scale over land and ocean also may open new paths to [understanding severe phenomena and their connections to climate change](). Further, global hail maps can support risk management with respect to civil protection, insurance, food security, resource management, and energy production, thus mitigating the impacts of hail on human safety and activities.

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